JOURNAL AND PROCEEDINGS

OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 103

PARTS 1 - 4

1969-70

PUBLISHED BY THE SOCIETY,
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

Royal Society of New South Wales

OFFICERS FOR 1969-1970

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PUBLISHED BY THE SOCIETY
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ISSUED JANUARY 20, 1971

Registered for posting as a periodical—Category A.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 1–3, 1970

A Solar Charge and the Perihelion Motion of 1566 Icarus

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Abstract—If, as suggested by V. A. Bailey, the Sun possesses a net charge, it will induce a dipole moment in a planet or other body. The resulting electrostatic force leads (using non-relativistic mechanics) to an advance of perihelion, which is calculated here for an orbit of arbitrary eccentricity. The formula obtained is applied to observational results for Icarus.

1. Introduction

Bailey (1960*a*, 1960*b*, 1960*c*, 1965) gave explanations of a number of astrophysical and terrestrial phenomena by postulating the presence of a net electric charge on the Sun, on other stars, and on planets. Two possible sources for such a charge were suggested, one of which involved a five-dimensional unified field theory (Taylor and Bailey, 1962). It is thus of interest to discuss the possible effect of a solar charge on the motions of planets and other bodies.

General relativity appears to account with an accuracy of about 1% (Dicke and Goldenberg, 1967) for the observed residual advance of the perihelion of Mercury left after planetary perturbations have been accounted for. Various alternative or supplementary explanations have been suggested from time to time, both before and after the advent of general relativity. For example, it has been suggested (Dicke and Goldenberg, 1967) that some (perhaps 8%) of the observed residual is due to solar oblateness, thus threatening the agreement between general relativity and observation ; agreement with theory is then restored by postulating a long-range scalar field. Non-relativistic explanations were discussed by Gerjuoy (1956) ; one of these involves an electric charge on the Sun (perhaps in its atmosphere).

A net solar charge would induce a dipole moment in a planet. The resulting electrostatic force perturbs the orbit, causing an advance in the perihelion. Gerjuoy (1956) quoted a formula for this motion, for an orbit of very small eccentricity. Values deduced by Bailey for the solar charge lead to quite small perihelion advances for Mercury (Burman, 1970). In this note a formula is obtained which allows for eccentricity, since this is large in the case of Icarus (minor planet 1566).

2. Basic Theory

Suppose that the Sun is a sphere of mass M_1 with a net electrostatic charge Q e.s.u. distributed symmetrically about its centre, and that the planet or other body concerned is an uncharged conducting sphere of mass M_2 and radius α at a distance r from the Sun. The solar charge induces a dipole moment in the planet. With r much greater than both α and the solar radius, the force on the planet becomes $\hat{\mathbf{r}}F(r)$, where $\hat{\mathbf{r}}$ is a unit vector directed radially outwards from the Sun and

$$F(r) = -\frac{GM_1M_2}{r^2} - \frac{2f^2Q^2\alpha^3}{r^5}. \qquad (1)$$

Here G is the gravitational constant, and the factor f^2, where $0 \leqslant f \leqslant 1$, allows for partial screening of the solar charge by the surrounding plasma (Bailey, 1965).

Orbits under a central force $\hat{\mathbf{r}}F(r)$ satisfy

$$\frac{d^2u}{d\theta^2} + u = -\frac{F/M_2}{h^2u^2}, \qquad (2)$$

where $u=1/r$, θ is the angular co-ordinate, and h is the orbital angular momentum. Using (1), (2) becomes

$$\frac{d^2u}{d\theta^2}+u=\frac{1}{l}+\beta u^3 \qquad (3)$$

where

$$l=\frac{h^2}{GM_1} \quad \text{and} \quad \beta=\frac{2f^2Q^2\alpha^3}{GM_1M_2l}. \qquad (4a,\ b)$$

Neglecting β leads, with suitable choice of the origin of θ, to the solution $lu=1+e\cos\theta$, e being the eccentricity. Substituting this solution into the last term in (3) results in

$$\frac{d^2u}{d\theta^2}+u\doteqdot C+D\cos\theta+E\cos 2\theta+F\cos 3\theta \qquad (5)$$

where

$$C=\frac{1}{l}+\frac{\beta}{l^3}\left(1+\frac{3}{2}e^2\right),\quad D=\frac{3\beta e}{l^3}(1+\tfrac{1}{4}e^2), \qquad (6a,\ b)$$

$$E=\frac{3\beta e^2}{2l^3} \quad \text{and} \quad F=\frac{\beta e^3}{4l^3}. \qquad (6c,\ d)$$

Equation (5) has the solution

$$lu=lC+e\cos\theta+l(\tfrac{1}{2}D\theta\sin\theta-\tfrac{1}{3}E\cos 2\theta-\tfrac{1}{8}F\cos 3\theta), \qquad (7)$$

which reduces to $lu=1+e\cos\theta$ when β is neglected. Equation (7) can be written, for small $lD\theta/2e$,

$$lu\doteqdot lC+e\cos\left[\left(1-\frac{lD}{2e}\right)\theta\right]-l(\tfrac{1}{3}E\cos 2\theta+\tfrac{1}{8}F\cos 3\theta). \qquad (8)$$

This shows that there is a perihelion advance δ where

$$\delta\doteqdot 2\pi\left[\left(1-\frac{lD}{2e}\right)^{-1}-1\right]\doteqdot\frac{\pi lD}{e} \qquad (9)$$

in radians per revolution. The last term in (8) is of period 2π, and so does not contribute to the perihelion motion. Using (6b), (4b) and $l=b(1-e^2)^{\frac{1}{2}}$, b being the semi-minor axis of the elliptical orbit, it follows that

$$\delta\doteqdot\frac{6\pi f^2Q^2}{GM_1M_2}\left(\frac{\alpha}{b}\right)^3\frac{1+\frac{1}{4}e^2}{(1-e^2)^{3/2}}. \qquad (10)$$

When $e=0$, this reduces to the result used earlier (Burman, 1970) for Mercury.

3. Application to Icarus

The values of $-Q$ deduced by Bailey were around 10^{27} to 10^{28} e.s.u. For Icarus, $b=0{\cdot}186$ AU, $e=0{\cdot}827$, and its orbital period is 409 days. Photometric observations during its close approach to Earth in 1968 showed Icarus to be nearly spherical (Miner and Young, 1969 ; Veverka and Liller, 1969). Taking it to be spherical with a uniform density of $3{\cdot}5$ gm./cm.^{3}, using $Q=-2{\cdot}2\times 10^{28}$ e.s.u. (Bailey, 1960c), and neglecting screening, results in a perihelion advance of $27{\cdot}0$ seconds of arc per century. That predicted by general relativity is $10{\cdot}05''$/century (Gilvarry, 1953).

If Icarus is regarded not as a perfect conductor but as a homogeneous dielectric, of dielectric constant K, (10) is modified by a factor $(K-1)/(K+2)$ on the right.

For planets, the observability of the motions of their perihelia can be expressed by a figure of merit kev (Gilvarry, 1953) ; v is the perihelion advance per unit time, e is the eccentricity, and the weighting factor k allows for the relative suitability of the planet for making accurate observations. To include minor planets, Gilvarry (1953) generalized the above figure of merit to $kl\eta v$, where $\eta=e/(1-e^2)^{3/2}$, and l allows for the restricted number of observations possible in a period of revolution. For a planet l is near unity, and $\eta\doteqdot e$ since $e^2\ll 1$; then $kl\eta v$ reduces to kev. Using values of v obtained from general relativity, Gilvarry calculated a figure of merit for Icarus of several times that for Mercury. Icarus could provide a more sensitive test of perihelion motion theories than Mercury.

Shapiro, Ash and Smith (1968) have analysed observations of Icarus and find a perihelion motion which agrees with the prediction of general relativity to within 20%. So if general relativity is accepted as the correct theory of gravitation, the electrostatic mechanism does not contribute more than 2″/century; taking Icarus to be a perfectly conducting sphere, (10) shows that $|fQ|<6\times10^{27}$ e.s.u. The corresponding limit obtained from Mercury is about 10^{28} e.s.u.

4. Conclusion

The values of $-Q$ deduced by Bailey were around 10^{27} or 10^{28} e.s.u. From observations on the perihelion motion of Icarus it has been indicated above that $|fQ|<6\times10^{27}$ e.s.u. With further observational data on Icarus, a more stringent upper limit should be obtainable.

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(Received 19 June 1970)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 5–9, 1970

James Cook and the Transit of Venus*

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Abstract—The history of the use of the transits of Venus in measuring the distance of the Sun is sketched with emphasis on the part played by the *Endeavour* voyage in the 1769 observations.

The prime reason for the voyage of the *Endeavour* was to observe from Tahiti the passage of the planet Venus across the disk of the Sun. The Royal Society of London had petitioned the British Government to organize the expedition. Why was this event so important as to justify such a long and arduous voyage? The reason was that such observations could be used to measure the distance of the Earth from the Sun. This distance is commonly called the Astronomical Unit and gives the scale for all distances within the Solar System and the base line from which the distances of the stars are measured.

Interest in this distance dates back even to Greek times, and a worthwhile suggestion was put forward by Aristarchus about 250 B.C. The way he tried to measure the distance was to measure the angle between the Sun and the Moon near the time of first quarter or last quarter. He based his measurement on the fact that at the precise time of half Moon the angle between the Earth and the Sun as seen from the Moon would be exactly 90°. He measured the angle between the Sun and the Moon as approximately 87° at the time of half Moon. From this he calculated that the Sun was approximately 20 times as far away as the Moon. We now know that this was greatly underestimated; the method is inherently inaccurate because the rough surface of the Moon makes it impossible to estimate when it is exactly half illuminated even when using a telescope. About 150 years after Aristarchus, Hipparchus made a very good measurement of the distance of the Moon by comparing the apparent size of the Moon with the size of the Earth's shadow at the time of a lunar eclipse. He determined that the Moon's distance was 59 times the radius of the Earth, which is quite a good figure. Combining this with Aristarchus' result gives the distance of the Sun as about 1,200 Earth radii or about 8,000,000 kilometres. This is much too small, but it remained the accepted figure until the time of Kepler (1571–1630).

From observations made by Tycho Brahe, Kepler established his laws of motion for the planets. He showed that the planetary orbits are ellipses with the Sun at one focus and that the distances of the planets from the Sun are related to their periods of revolution around the Sun. Thus it was possible to produce a scale map of the Solar System just by observing the motion of the planets against the background of the stars. However, it was not possible to put a scale on the map until the distance of one object could be measured. Kepler realized that the distance of the closer planets such as Mars and Venus could in principle be measured by observing their positions against the background of the stars from two places on the Earth as widely separated as possible. The two observations could be made by different observers or else one observer could use the rotation of the Earth to shift him between the two observations. This kind of observation is known as the parallax method, and the parallax of the Sun is often quoted instead of the distance. This is the angular displacement of the Sun caused by a movement through a distance equal to the Earth's radius, or what amounts to the same thing, the angle which the Earth's radius subtends at the distance of the Sun. Because the Earth's orbit is an ellipse it is the mean solar parallax which is sought. Kepler concluded that since he could observe no obvious parallactic displacement of Mars the accepted distance of the Sun must be underestimated. He considered that the solar

* The preparation and printing of this lecture, which was delivered on 3rd June, 1970, was supported by the Captain Cook Bicentenary Committee (Arts and Historical Committee).

parallax must be less than one minute of arc and that therefore the Sun's distance must be at least 22,000,000 kilometres, and was probably much greater.

The first result with any sort of accuracy was obtained in 1671–1673 by Richer, who observed Mars from Cayenne in French Guiana, together with Picard and Cassini, who observed from Paris. Their results gave the parallax as 9″·5 and thus the distance of the Sun as about 138,000,000 kilometres, with an uncertainty of perhaps 30,000,000 kilometres.

The inner planets Mercury and Venus can pass across the face of the Sun when they are directly between the Earth and the Sun at inferior conjunction. A transit occurs only rarely, especially in the case of Venus, because the planes of the orbits of the planets are not quite in the same plane as the Earth's. This means that transits occur only when Venus, for example, at the time of inferior conjunction, is near to one of the points in its orbit where the two orbits cross (the nodes). Inferior conjunctions occur at intervals of 584 days, the synodic period, and five of these periods are very nearly equal to eight years. Also, 152 synodic periods are almost exactly equal to 243 years. Consequently, transits can, and at present do, occur in pairs separated by eight years, followed by another pair after an interval of 235 years. In the long interval another pair of transits occurs at the opposite node, again separated by eight years. Only five transits of Venus have so far been observed, namely in December 1639, June 1761 and 1769, and December 1874 and 1882. The next pair will occur in June 2004 and 2012.

Because it is closer to the Sun, transits of Mercury occur much more frequently. The longest interval between successive transits is only about 13½ years, and 13 or 14 transits occur every century. In this case the Earth is near the nodes in May and November. Mercury is closer to the Sun at the point in its orbit corresponding to the November transits, so these are about twice as frequent as the May ones.

The first transit of Venus to be observed was predicted by Jeremiah Horrox, a young man who, at the time of the observation, was curate at Hoole in Lancashire. Horrox, although self-taught, achieved many original discoveries in astronomy and may well have gone on to greater heights if his career had not been cut short by his early death. Kepler, in 1629, had predicted that Venus would cross the Sun's disk in 1631, and not again until 1761.

The transit of 1631 was looked for in Paris by Gassendi, who had observed a transit of Mercury in the same year, also predicted by Kepler. He did not succeed because the transit occurred at night time in Europe. Horrox, from his observations and from examination of the tables of Kepler, detected an error in them and concluded that another transit would be possible in 1639. Horrox asked his brother Jonas at Liverpool and his friend William Crabtree also to attempt the observation. He prepared for the observation by setting up his telescope in a room and projecting the image of the Sun on to a screen. He had predicted that the transit would occur on 24th November, 1639 Julian calendar (corresponding to 4th December, Gregorian calendar), which was a Sunday, but he began looking even throughout the day before. On the Sunday he was torn between his duties in the church and his desire to observe such a rare phenomenon, and it was not until after three in the afternoon that he was able to observe the Sun uninterrupted. Fortunately, the clouds cleared at just the right time and he was able to see the disk of the planet just enter at the edge of the Sun and to continue the observation until the Sun set about half an hour later. The only other observer was Crabtree, who caught a glimpse of the planet on the Sun's disk through a break in the clouds but was unable to make accurate observations. However, his later recollection agreed with those of Horrox. Horrox died only a little over a year later and his results were not published till almost 30 years after his death.

In the paper "Advice to the Curious in Things Celestial" (Kepler, 1629), in which he predicted the 1631 transits, Kepler gave the first hint as to their use for measuring the solar parallax.

"The diurnal parallax, if this is going to happen, will be four times that of the Sun in the case of Venus and about one and a half times for Mercury. And in both cases it helps and prolongs its appearance. For if either planet grazes the northern edge of the Sun the parallax in moving it south will move it closer to the centre of the Sun."

["Parallaxis diurna, si qua futura est, solaris quadrupla erit in Venere, in Mercurio sescupla circiter. Atque ea utrobique adjuvat et prolongat suum phaenomenon. Cum enim septentrionalem Solis oram perstringat uterque planeta, parallaxis eos in austrum promovens centro Solis propius admovebit."]

James Gregory, the Scottish mathematician, was rather more explicit when at the end of a problem on the determination of the parallaxes of two planets by observations at their conjunction he stated (Gregory, 1663) :

" This problem has a very beautiful application, although perhaps laborious, in observations of Venus or Mercury when they obscure a small portion of the Sun ; for by means of such observations the parallax of the Sun may be investigated."

[" Hoc problema pulcherrimum habet usum, sed forsan laboriosum, in observationibus Veneris vel Mercurii particulam solis obscurantis ; ex talibus enim solis parallaxis investigari poterit."]

The translation is that given by Grant (1852).

The first detailed exposition of the use of the transits of Venus for measuring the solar parallax was given by the great English astronomer Edmond Halley. Halley's interest in using the transits of Venus began when he observed a transit of Mercury from St. Helena in 1677. He had travelled to St. Helena to observe and form a catalogue of the southern stars which are not visible from Europe. He concluded that observations of the transit of Venus which would be nearest to the Earth at the time could yield a reliable figure for the distance of Venus, and therefore of the Sun, if they were made from a number of places widely scattered over the Earth in order to measure the parallactic displacement of the planet on the face of the Sun.

" There remains one observation by which the problem of the distance of the Sun from the Earth might be solved. The solution will be available to astronomers in later centuries when Venus displays itself for inspection on the disc of the Sun, which will not happen before 1761 May 26 (Old Style). So if the parallax of Venus relative to the Sun is observed in the way just explained it will be almost three times greater than that of the Sun itself and the necessary observations are of the simplest kind, . . . " (Halley, 1679).

[" Unica manet observatio cujus ope Problema de distantia Solis a Terra, se Astronomis insequentis Seculi solutum dabit, *viz.* cum Veneris Stella, se in disco Solari spectandam praebuerit, quod non accidit ante Annum 1761 *Maii* 26. St. Vet. Tunc etenim, si modo nuper explicato Parallaxis Veneris a Sole inquiratur, erit ea triplo fere major ipsa Solari, & observationes requisitae sunt omnium facillimae, ..."]

He elaborated these ideas (Halley, 1716), and this paper may be taken as the starting point for the interest in the transits of 1761 and 1769. Halley particularly proposed that the displacement of the planet on the Sun's disk could be most accurately determined by measuring at each place of observation the time interval between the first entering of Venus on to the Sun's disk (ingress) and the time when it moved off (egress). The reason why the duration would be the most useful measurement was that the precise time of either ingress or egress would be difficult to measure in Greenwich Mean Time because it was difficult to measure longitudes accurately at that time.

It was realized that the time could most accurately be observed at the time of internal contact when the planet's disk first comes fully on to the Sun and the corresponding phase when the planet is leaving the Sun's disk. Only from a limited part of the world would it be possible to see both the ingress and the egress, and Halley proposed that expeditions should be sent to those areas, with some observers as far north and others as far south as possible in order to get the greatest difference of duration. In the 1761 transit the part where the whole of the duration could be seen included Asia and the northern part of Europe, part of the Indian Ocean and the East Indies. For the 1769 transit the favoured area was a portion of the south and north Pacific Oceans, the western part of North America and the northern part of Europe and Asia. Because both the transits occurred in June the north declination of the Sun permitted the phenomena to be observed throughout the North Polar Zone.

Interest in the coming transits was maintained especially in France by Joseph Nicholas Delisle. A number of expeditions were prepared, particularly in France and England. By the time of the 1761 transit, England and France were at war, and this handicapped some of the expeditions. Partly because of this the distance of the Sun calculated from the 1761 transit observations was more uncertain than Halley had hoped. In any case the timing of the contacts proved to be much more difficult than he had expected. It was found that the internal contact did not appear suddenly but that different observers at the same place could differ by even 20 or 30 seconds, whereas Halley had considered that the timing could be made with an accuracy of one second. Due to the unsteadiness of the Earth's atmosphere, as the dark body of the planet began to pull away from the edge of the Sun an irregular zone appeared which was sometimes seen as a dark drop, the breaking of which was indefinite and not possible to time accurately. As a result of this, calculations of the parallax ranged from 8″·3 to 10″·6 and the distance of the Sun from 159,000,000 to 124,000,000 kilometres.

However, the lack of success did not cause any slackening of interest in the problem and plans were soon made to observe the 1769 transit. Once again the principal participants were the French and the British. Chappe, who had observed the first transit from Siberia, this time travelled to California, which was then a Spanish possession, and observed the transit successfully. Unfortunately he and several of his assistants died of an epidemic disease which broke out in this region. The British effort was initiated by the Royal Society of London, who proposed to send observers to Fort Churchill on Hudson's Bay, to North Cape at the northern end of Norway, and to the South Seas. Dymond and Wales observed from Hudson's Bay, Bayley and Dixon observed from northern Scandinavia.

It was first proposed that the South Sea expedition would be commanded by Alexander Dalrymple, but he was unwilling to undertake the voyage except as commander of the ship. However, the Admiralty insisted that a naval ship could be commanded only by a naval officer, and the choice fell on James Cook, who had made a name for himself as a navigator and marine surveyor in the St. Lawrence River during the Seven Years War, and around the coast of Newfoundland. Charles Green, an assistant astronomer at Greenwich Observatory, was also appointed a member of the expedition. It was decided that the *Endeavour* should sail for Tahiti, which had recently been visited by Samuel Wallace. The observations of Cook, Green and Solander at Tahiti in June, 1769, were quite successful, although Cook reported that the different observers had widely different timings.

" *1769 Saturday, 3rd June :* This day proved as favourable to our purpose as we could wish. Not a Cloud was to be seen the whole day, and the Air was perfectly Clear, so that we had every advantage we could desire in observing the whole of the Passage of the planet Venus over the Sun's Disk. We very distinctly saw an Atmosphere or Dusky shade round the body of the planet, which very much disturbed the times of the Contact, particularly the two internal ones. Dr. Solander observed as well as Mr. Green and myself, and we differ'd from one another in Observing the times of the Contact much more than could be expected. Mr. Green's Telescope and mine were of the same Magnifying power, but that of the Doctor was greater than ours. It was nearly calm the whole day, and the Thermometer Exposed to the Sun about the Middle of the day rose to a degree of heat we have not before met with " (Cook, 1893). The observations were presented to the Royal Society (Green and Cook, 1771).

The results of the calculation of the solar parallax from the 1769 observations were again regarded as disappointing, and to this day some popular accounts of Cook's voyage speak of the transit observations as a failure. In fact the results obtained by the various calculations for the parallax ranged from 8″·5 to 8″·8, giving distances of 155,000,000 to 149,000,000 kilometres, which was a great improvement on any previous result. To give an example, Hornsby (1771) from a discussion of collected observations, including those from Tahiti and using Halley's method, gave the mean parallax as 8″·78, as against 8″·794 now accepted by the International Astronomical Union. The accuracy which Halley had forecast perhaps still influenced the thinking of the astronomers of the period and caused the continuing disappointment. In fact the whole 1761–1769 campaign can be looked on as the first major international effort in observational astronomy and the part which Cook, Green and Solander played in it, by virtue of their geographical position and careful observations, was no small one.

The transits of 1874 and 1882 were observed very widely with the hope of improving on the results of a century before. It is worth noting that the 1874 transit was widely observed in Australia. The New South Wales observations were initiated by the Government Astronomer, H. C. Russell, who organized a number of teams of observers at Sydney Observatory and at Woodford, Goulburn and Eden. The purpose of this was to give a greater chance of obtaining a clear sky. Actually, all sites were favoured with good conditions and the transit was timed successfully. The 1882 transit was only partly visible in Australia ; only the egress could be observed soon after sunrise, and this was not seen at Sydney because of cloud. Once again rather disappointing results were obtained when the distance of the Sun was calculated and the final result was no great improvement on the 18th century observations.

From then on observations of the Sun's distance were concentrated mainly on parallax observations of outer planets, firstly of Mars and then of a number of minor planets, culminating in the large-scale observation of Eros in 1931, which was co-ordinated and reduced by Spencer Jones. Several other methods have been used during this century and they agree in giving a mean distance of the Sun close to 149,600,000 kilometres. The most accurate method available now is to measure the distance of Venus by radar, and this has led to a mean distance of the Earth from the Sun of 149,597,893 kilometres, and this is probably accurate to about 200 kilometres (Muhleman, 1969).

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(Received 16 October 1970)

Journal and Proceedings, Royal Society of New South Wales Vol. 103, pp. 11–14, 1970

A Note on Some Non-Calcareous Stalactites from the Sandstones of the Sydney Basin, N.S.W.

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Abstract Lamellar limonitic stalactites common in Hawkesbury Sandstone consist of alternating layers of common opal and a mixture of limonitic and sideritic material. Manganesian stalactites of lower Narrabeen age also contain common opal but do not exhibit any particular internal structure. The formation of the stalactites is believed to be closely associated with plant decay processes. Explanations for the lamellar structure of the former and the absence of iron in the latter are proposed.

1.0. Introduction

Stalactites apparently of lamellar limonite are fairly common under ledges and on cave roofs in the sandstones of the Sydney Basin. Well-formed specimens have been collected near the bottom of Cataract Waterfall at Lawson in the Blue Mountains, under a rock ledge on the cliffs behind Little Marley Beach in the Royal National Park, on a near-vertical rock face near the confluence of two creeks at Girrakool Reserve south of Gosford and near a small waterfall about half a mile upstream in the valley of Deep Creek at Narrabeen. However, apart from a brief mention by Lovering (1952), who noted the thin coating of common opal on the limonitic stalactites from Calna Creek north of Hornsby, they do not appear to have received any further attention in the literature.

2.0. Limonitic Stalactites

2.1. *Description.* The stalactites may reach a length of up to 20 cm. Longer specimens have been observed in places where the stalactites, growing close to vertical or near-vertical rock face, have actually been joined to it along their side, thus deriving additional support for their growing weight. This is particularly important in the case of the faster growing and consequently rather porous stalactites which lack internal strength and tend to break apart under their own wet weight. Elongated crusts, thick in the centre and thinning towards the sides exhibiting the same lamellar internal structure co-occur with the stalactites. Occasionally the lamellar structure merges into irregular patches of rusty-brown earthy material.

Often both the stalactites and the crusts are coated with a thin film of white or greyish common opal. In the absence of such a coating their colour varies from shiny black to dull rusty-brown. All occurrences of actively growing stalactites were associated with extensive areas of decaying vegetation. Sometimes the seepage responsible for their formation exhibited bright diffraction colours similar to those displayed by an oil film on water.

2.2. *Chemical Examination.* A chemical analysis of a dry stalactite (" dead " in Lovering's words) from Cataract Waterfall near Lawson (Table 1) revealed, in view of the thinness of the visible coating of opal, a surprisingly high silica content. Digestion of some powdered stalactite material with warm hydrochloric acid yielded an insoluble residue of pure white opal. The absence of quartz, such as particles of sand, in this residue was established by its complete and almost instantaneous solution in cold dilute aqueous sodium hydroxide. In order to establish the distribution of this opal a whole stalactite was immersed for several months in dilute (5%) hydrochloric acid. The insoluble residue consisted of lamellar opal (Figure 1). Its refractive index varied between 1·40 and 1·44. Its average water content was 10·9%. An identical alternation of limonitic material and opal was observed in all specimens studied.

Material from stalactites actively growing (i.e. wet) at the time of collection (such as from Deep Creek, Girrakool and Little Marley) effervesced strongly with warm dilute hydrochloric acid, the gas given off being carbon dioxide. The solution gave a positive test for ferrous iron. Since no effervescence was observed with cold acid, it is suggested that ferrous carbonate, i.e. siderite, is present in the stalactites. No attempt was made to determine the respective proportions of ferrous and ferric iron. Owing to the porosity of the stalactites, aerial oxidation is likely to proceed rapidly and in a haphazard fashion. Consequently, a separate determination of the two valency states of iron would serve little useful purpose.

Table 1

*Chemical Analyses**

	A	B	C
Fe as Fe_2O_3 ..	79·0	86·8	Trace
Mn as MnO_2 ..	5·7	Trace	8·6
SiO_2	4·9	2·7	58·4
Loss on ignition ..	10·7	12·3	33·1
Total	100·3	101·8†	100·1

A. Limonitic stalactite from Cataract Waterfall, Lawson.

B. Limonitic stalactite from Deep Creek, Narrabeen·

C. Manganesian stalactite from Neate's Glen.

* The material was dried at 105°.

† The sum is greater than 100 owing to the presence of some divalent iron.

2.3. *Mode of Formation.* The components of the stalactites undoubtedly derive from the sandstone itself. It is unlikely, though, that a mechanism involving simple solution followed by deposition at a suitable site could satisfactorily explain their formation. The solubility of ferric hydroxide and of silica gel in water is too low, of the order of 3×10^{-10} g.-moles/l. (Jellinek and Gordon, 1924; Oka, 1940) and about 120 p.p.m. respectively (Krauskopf, 1967) to allow rapid deposition such as that observed, at Berowra (*vide infra*).

More significantly, actively growing stalactites and allied crusts have never been observed on sites lacking abundant decaying plant matter. It is therefore suggested that solution of iron oxides and of silica is facilitated in the presence of compounds produced during plant decay.

Indeed, Bloomfield (1951), Bétrémieux (1951) and Ng and Bloomfield (1960) have shown that sterile plant extracts, and particularly plant fermentation liquors, are capable of dissolving considerably greater amounts of ferric oxide than pure water. In addition, provided anaerobic conditions are maintained, ferric iron is reduced to the ferrous state, the latter being stabilized by complex formation. The abundant carbon dioxide released during plant decay no doubt assists in maintaining such anaerobic conditions as well as in converting some of the divalent iron to the soluble ferrous bicarbonate.

Fermentation liquors are also known to mobilize silica (Bétrémieux, 1951), which is transported in the form of a negatively charged, colloidal solution. Colloidal solutions of silica are very stable and, provided organic colloids (humic acids, etc.) are present, flocculation by cations is slow and incomplete (Rankama and Sahama, 1950). Thus, co-transport with ferrous iron solutions is possible.

When conditions become aerobic, i.e. the seepage leaves the protective cover of decaying vegetation or during periods of dry weather, stalactite formation may be initiated by several simultaneously occurring processes, in particular loss of carbon dioxide resulting in the precipitation of siderite and aerial oxidation of various complexes of divalent iron to the trivalent state followed by flocculation of ferric hydroxide. Since observation of a growing stalactite at Berowra disclosed a fairly constant and continual flow of water, it is thought that precipitation of silica on the limonitic surface is unlikely to be the result of concentration by evaporation during periods of reduced flow. Instead, it is suggested that the freshly precipitated limonitic materal retains some of the protecting organic matter, such as humic acids, which cause it to retain a negative charge. Once aerial or microbiological oxidation has destroyed all organic matter, the limonitic surface becomes cationic in nature and will coagulate the negatively charged silica sol.

The fact that the silica gel layer is deposited on the external face of the limonitic layer, i.e. facing the atmosphere and not in between two already existing layers, may be inferred from Lovering's (1952) finding that particles of clay, i.e. dust, have been trapped by the gelatinous silica and also from the uneven, tooth-like appearance of the internal face of the opal lamina facing an earlier deposited limonitic layer as opposed to the smooth external face (Figure 1). The extreme ease of interconversion between ferrous and ferric iron will almost certainly complicate the processes just outlined. Humate-protected ferric colloids will

FIGURE 1.—Lamellar opal. (12 × 20 mm.)

probably accompany divalent iron (Gruner, 1922; Bloomfield, 1969).

Supporting evidence for a microbiological origin of the stalactites has been obtained from the Berowra locality. Here the stalactites are directly due to the action of sewage overflowing from the absorption trench connected to a septic tank. The effluent flows for about 25 ft. along the surface of a slightly inclined sandstone platform, covered by up to 6 in. of sandy soil supporting the growth of some grass, but otherwise devoid of decaying plant matter before flowing over the overhanging edge. Beneath it, rapid deposition of lamellar crusts and small stalactites is taking place. Some of these crusts, composed once again of alternating layers of limonitic and sideritic material and opal, grew to a thickness of 2 cm. in slightly less than three months before breaking off after a period of particularly heavy rain. Before the installation of the septic tank system, when seepage was entirely due to meteoric waters, no limonitic stalactites had ever been observed under the ledge.

3.0. Manganesian Stalactites

Near Neate's Glen, along the path from Evan's Lookout to Beauchamp Falls in the Grose Valley in the Blue Mountains, an isolated occurrence of black manganese-bearing stalactites was discovered. The stalactites, up to 10 cm. long, were found under a sandstone ledge which, on the basis of Goldbery's (1966) map of the area, belongs to the Grose Sandstone Formation of the Narrabeen Group.

As in the case of the limonitic stalactites, abundant decaying vegetation was present. The stalactites, extremely porous, criss-crossed by roots of ferns and containing considerable adsorbed water, do not exhibit any particular internal structure. On air-drying they lose about 60–70% of their weight and crumble completely. Leaching in dilute hydrochloric acid leaves a residue of greyish opal which is almost completely soluble in dilute sodium hydroxide solution. An analysis revealed the presence of manganese. Iron was virtually absent (Table 1).

Bétrémieux (1951) has shown that manganese is readily mobilized by fermenting organic matter, a fact corroborated by Ng and Bloomfield (1960). The latter authors also suggested that reduction of quadrivalent manganese is involved in its solution. Bromfield (1958) has shown that washings of the roots of oat plants dissolve manganese dioxide. Once dissolved, the manganese is transported as the bicarbonate and, should conditions become aerobic, as a colloidal solution of quadrivalent hydroxide, probably stabilized by humic compounds (Rankama and Sahama, 1950). Since sols of both silica and quadrivalent manganese oxides are negatively charged, they will flocculate together, and thus no zoning within the stalactite is observed.

The reason for the total absence of iron is not quite clear. It has been found (Behrend, 1924) that the addition of an electrolyte to a colloidal solution of ferric and manganic hydroxide results in precipitation of all the manganic hydroxide, leaving most or even all of the iron in solution. An examination of sandstone analyses (Joplin, 1965) shows that the alkali and alkaline earth content ($Na_2O+K_2O+CaO+MgO$) rises from about 1–2·5% in the case of a typical Hawkesbury sandstone to 3·6% in an example from the Gosford Formation, and even to 8·2% in a sandstone obtained at a depth of 1,900 ft. from a Rose Bay bore corresponding probably to middle Narrabeen age. It appears, therefore, that weathering of Narrabeen sandstones will provide greater amounts of mono- and divalent cations than Hawkesbury sandstones, and the resulting solutions may well reach the necessary electrolyte concentration needed for preferential precipitation of manganese.

4.0. Conclusion

Whilst it is not possible to assign any definite stratigraphic significance to these stalactite occurrences, it can nevertheless be seen that the chemical composition of the stalactites is related to the composition of the parent sandstone. The limonitic variety has been encountered so far only in the quartz-rich sandstones of the Hawkesbury Sandstone and upper Narrabeen Group (Lawson occurrence; Goodwin, 1969). The rarer manganesian stalactites are confined to the more lithic sandstones in the middle of the Narrabeen Group.

Specimens of the limonitic stalactites from Lawson, before and after leaching with acid, were exhibited at a meeting of the Geological Section of the Royal Society of N.S.W. on 21st July, 1967.

5.0. Acknowledgements

The author is indebted to Mr. D. Llewellyn for the gift of a limonitic stalactite from Little Marley Beach and to Mr. J. Sigley for photographic assistance.

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(Received 13 August 1970)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 15–30, 1970

The Lower-Middle Palaeozoic Stratigraphy of the Bowan Park Area, Central-Western New South Wales

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Abstract—Basalts, andesites and breccias of the Cargo Andesite (pre-Upper Gisbornian) are the oldest outcropping rocks in the area. Above them is the Bowan Park Group, a thick accumulation of shallow water carbonates, which has been correlated with the Upper Gisbornian (or ? Lower Gisbornian) at its base and the Upper Eastonian at its top. This Ordovician limestone sequence has been subdivided into three formations which, in ascending order, are : Daylesford Formation, comprising various lithologies which are thinly bedded in its lower portions and massive towards the top ; the extremely fossiliferous Quondong Formation, consisting of thinly bedded limestones and marls ; and the massively bedded, generally unfossiliferous Ballingoole Formation.

The Malachi's Hill Beds (Bolindian) conformably overlie the Bowan Park Group. They consist of laminated siltstones, brown siltstones, lithic and volcanic sandstones and some andesite and basalt in their lower portions, and andesite, basalt and breccias in their upper portions. Silurian rocks (= " Panuara Formation ") are separated from Ordovician rocks by a major fault, and consist mainly of mudstones, shale and some limestone. Emplacement of an intrusive body, the Marylebone Dolerite, in post-Silurian times appears related to this fault.

Introduction

The area described is situated some 20 miles to the west of Orange, New South Wales (Figure 1), and lies within the tectonic unit, the Molong geanticline (Packham, 1960). The Bowan Park area first received attention when Carne and Jones (1919) surveyed the limestone as part of a major project on New South Wales limestone deposits. Later, Joplin *et al.* (1952) produced a reconnaissance map of the region incorporating this area but showing only the outcrop of the major rock types. Stevens (1956) was next to study the area. He examined it in some detail, defined the Malachi's Hill Formation, and showed the outcrop distribution of the various formations.

This paper describes the stratigraphy of the area and includes new subdivisions of the Bowan Park Limestone. It is hoped to present a more detailed account of the limestone in a later publication.

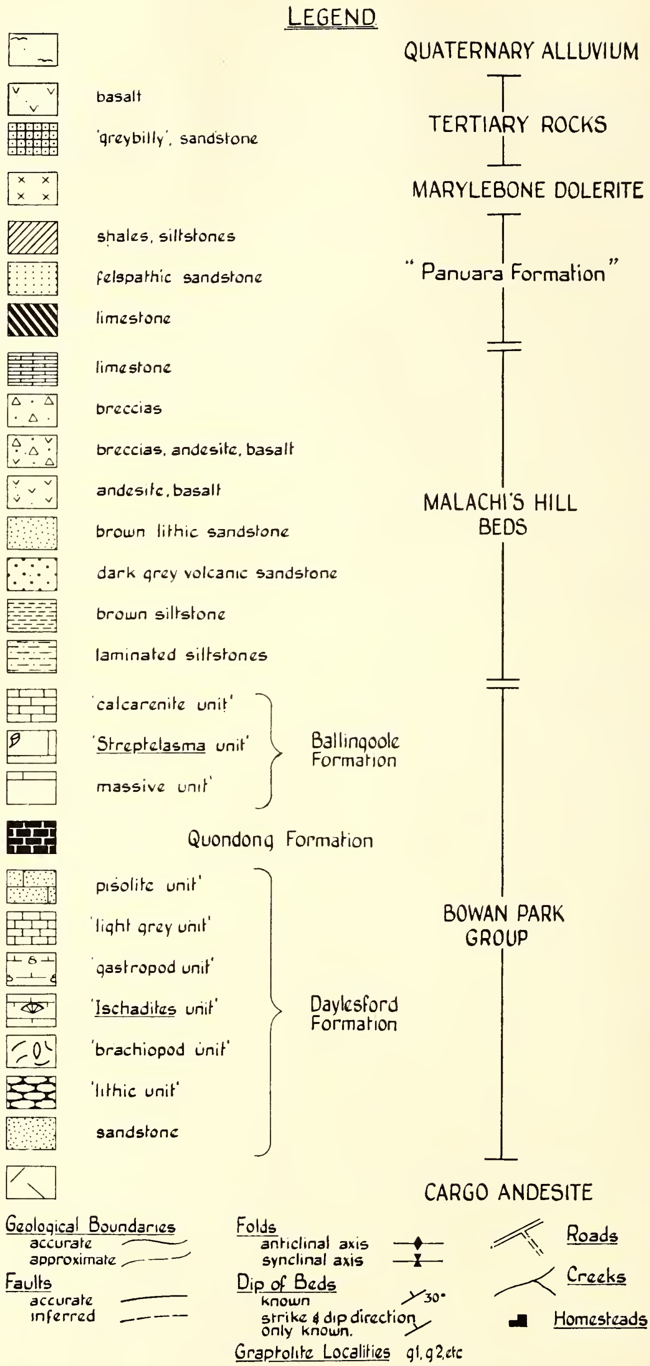
Cargo Andesite

The oldest rocks cropping out in the area belong to the Cargo Andesite (Stevens, 1950, 1956). Basalts and andesites (identified by their texture) and breccias are the main rock types, but since exposure is poor the lateral extent and relationships of these rock types is unknown.

Petrography

Basalts are porphyritic with altered plagioclase or altered plagioclase and augite phenocrysts in a microcrystalline groundmass. The plagioclase phenocrysts are euhedral and up to 10 mm. long, while colourless augite occurs as anhedral or euhedral phenocrysts up to 1 mm. in size. The groundmass consists of a felt-like aggregate of felspar laths (now largely altered), commonly 0·1 mm. long, granules of an opaque mineral, pyroxene grains, pseudomorphs after euhedral olivine, and patches of calcite and quartz. The basalts commonly show ophitic to subophitic textures.

The andesites also tend to be porphyritic with phenocrysts of hornblende and plagioclase in a microcrystalline groundmass. The plagioclase occurs as well-shaped crystals up to 3 mm. long and is altered. Dark green hornblende occurs as euhedral phenocrysts with a maximum length of 1·5 mm. ; it is commonly rimmed by an opaque mineral, presumably magmatically corroded. The groundmass consists of an equidimensional aggregate (average size 0·01 mm.) of mica, felspar, clay minerals, opaque minerals and variable amounts of chlorite, quartz and prehnite ; its texture suggests that it has recrystallized from an original glassy groundmass. Less commonly the groundmass consists of felspar showing trachytic texture.


LEGEND
QUATERNARY ALLUVIUM
basalt
'greybilly', sandstone
TERTIARY ROCKS
MARYLEBONE DOLERITE
shales, siltstones
felspathic sandstone
limestone
" Panuara Formation "
limestone
breccias
breccias, andesite, basalt
andesite, basalt
brown lithic sandstone
dark grey volcanic sandstone
brown siltstone
laminated siltstones
MALACHI'S HILL BEDS
'calcarenite unit'
'Streptelasma unit'
massive unit'
Ballingoole Formation
Quondong Formation
pisolite unit'
'light grey unit'
'gastropod unit'
'Ischadites unit'
'brachiopod unit'
'lithic unit'
sandstone
Daylesford Formation
BOWAN PARK GROUP
CARGO ANDESITE
Geological Boundaries
accurate
approximate
Faults
accurate
inferred
Folds
anticlinal axis
synclinal axis
Dip of Beds
known
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strike & dip direction only known.
Graptolite Localities g1, g2, etc
Roads
Creeks
Homesteads

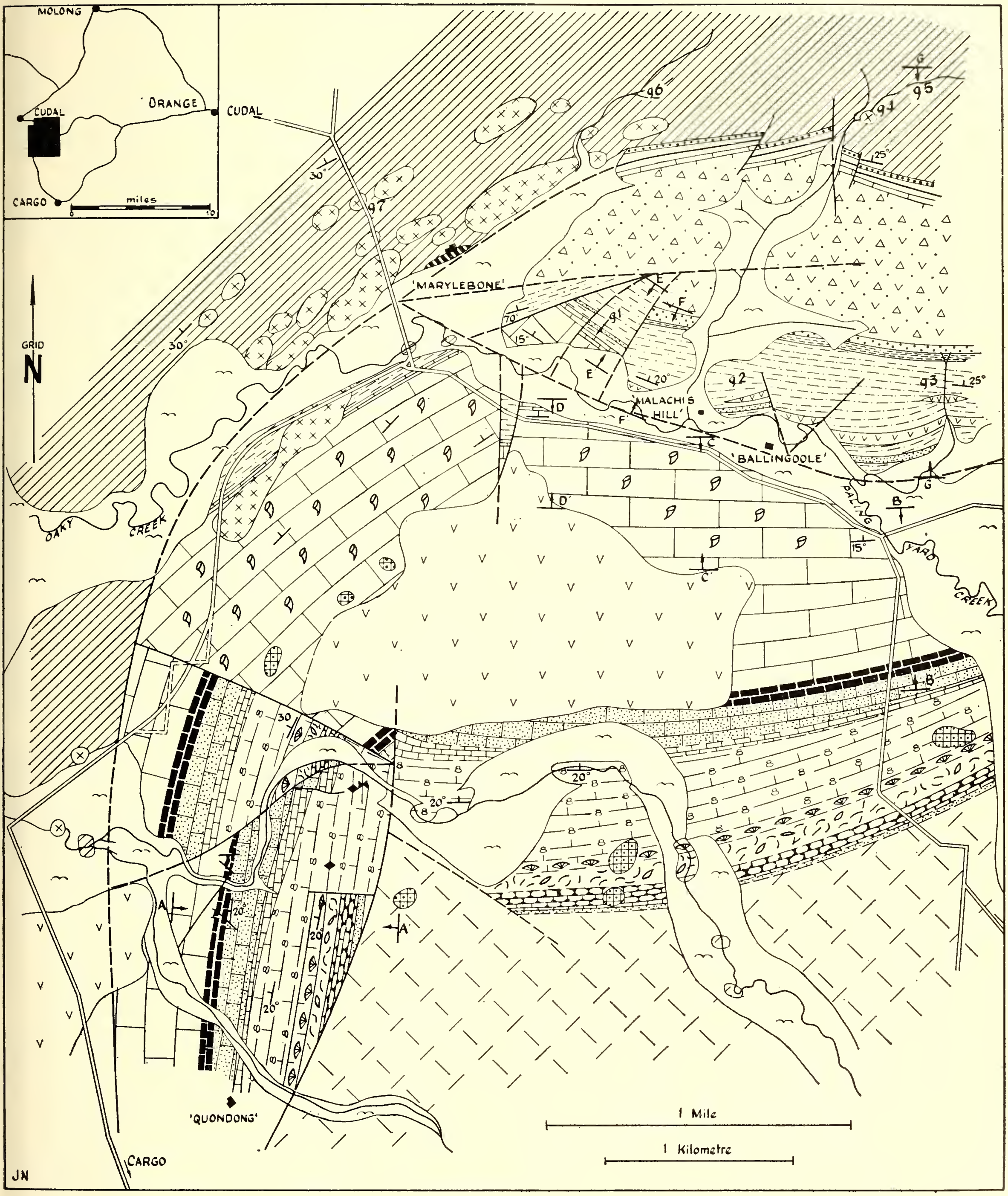

Figure 1.—Geological map of the Bowan Park area.

Breccias are found throughout the sequence and form massive outcrops. They consist of well-rounded and angular fragments of effusive rock (commonly andesite) in a poorly sorted matrix. The pebbles and fragments of effusive rock are up to 15 cm. in size, though mostly 3–8 cm. in size, and constitute up to 70% of the rock. The matrix is composed of poorly sorted volcanic rock (andesitic) and crystals; its average grainsize is 0·2 mm. These breccias represent the rubble derived from a predominantly volcanic terrain, where well-rounded water-transported volcanic rock pebbles have been mixed with locally derived pyroclastic material.

Alteration

The Cargo Andesite has undergone low-temperature alteration, and the minerals chlorite, prehnite, pumpellyite, calcite and albite are found in many thin sections. The groundmass of the effusive rocks appears to be the most affected, altered to patches of chlorite, calcite, pumpellyite, quartz and clay minerals to such an extent that all original mineral identity is virtually lost.

Plagioclase is the most altered of the phenocrysts. It has either been completely albitized or suffered heavy alteration to clay minerals, epidote, and patches of albite or calcite. Augite seems to have remained relatively fresh as phenocrysts but it may show patchy or complete alteration to chlorite. Hornblende, too, is found partly altered to chlorite and in cases complete pseudomorphism has occurred.

Veins occur in most of the rocks and contain calcite, chlorite or quartz. Some are more complex and contain a mixture of minerals which may include calcite, chalcedony, chlorite and a needle-like mineral (possibly apatite). Amygdules, common in some of the rocks, are filled with a similar assemblage of secondary minerals, viz. prehnite, quartz, chlorite.

The secondary mineral assemblage described above is similar to that described by Ryall (1965) and Smith (1966, 1968) for Ordovician volcanic sequences in the Mandurama-Canowindra area to the south of Bowan Park. It indicates a low-temperature grade of metamorphism comparable to the prehnite-pumpellyite-metagreywacke facies of Coombs (1960).

Bowan Park Group

The Bowan Park Limestone has been recorded by a number of workers, including Carne and Jones (1919), Brown (1952), Stevens (1956), Phillips-Ross (1961) and Packham (1967, 1969). Although Stevens (1956) was the first to name it, no one to date has formally described it. The writer has been able to subdivide the limestone into 10 mappable units, using bedding, lithological, and fossil differences. These units are grouped into three formations (Figure 2), and the Bowan Park Limestone is elevated to group status. The proposed formations are as follows:

(Top):

- Ballingoole Formation: Massive, generally unfossiliferous limestones; it is 280 m. thick and subdivided into three units.
- Quondong Formation: Extremely fossiliferous thinly bedded limestones and marls, 34 m. thick.
- Daylesford Formation: Limestones of various lithologies, thinly bedded in its lower portions and massive towards the top; subdivided into six units and totals 250 m. in thickness.

Daylesford Formation

The Daylesford Formation takes its name from a property some three miles to the east of the area. Its designated type section is on the property of "Quondong" (Figure 1, section A–A'). The units within it are, in ascending order, the "lithic unit", the "brachiopod unit", the "*Ischadites* unit", the "gastropod unit", the "light grey limestone unit" and the "pisolite unit" (Figure 2).

Overlying the Cargo Andesite is the "lithic unit", which has a 4 m.-thick sandstone developed at its base, and is altogether 34 m. thick. It consists of a variety of thinly bedded, often nodular, marly lithologies which include burrowed micrites and biomicrites, biosparites and pelsparites. Fossils collected include the algae *Solenopora* and *Girvanella*, corals *Tetradium apertum* Safford, *Heliolites* and *Propora*, stromatoporoids *Stratodictyon columnare* Webby, *S. ozakii* Webby and a cylindrical labechiid (gen. et sp. nov., Webby, pers. comm.), brachiopods *Catazyga* and *Protozyga*, gastropods *Lophospira* and others, bryozoans, trilobites, and orthoconic nautiloids.

The "brachiopod unit" is 16 m. thick and consists of thinly to massively bedded, dark grey and brown biomicrites. It contains an abundance of the large, thick-shelled, inarticulate brachiopod, cf. *Eodinobolus*, usually occurring in bands and often in the position of growth (Figure 3). The commonest fossils in this unit are cf. *Eodinobolus*, *Tetradium* cf. *cellulosum* (Hall), *T. apertum*, *T. compactum* Hill, a

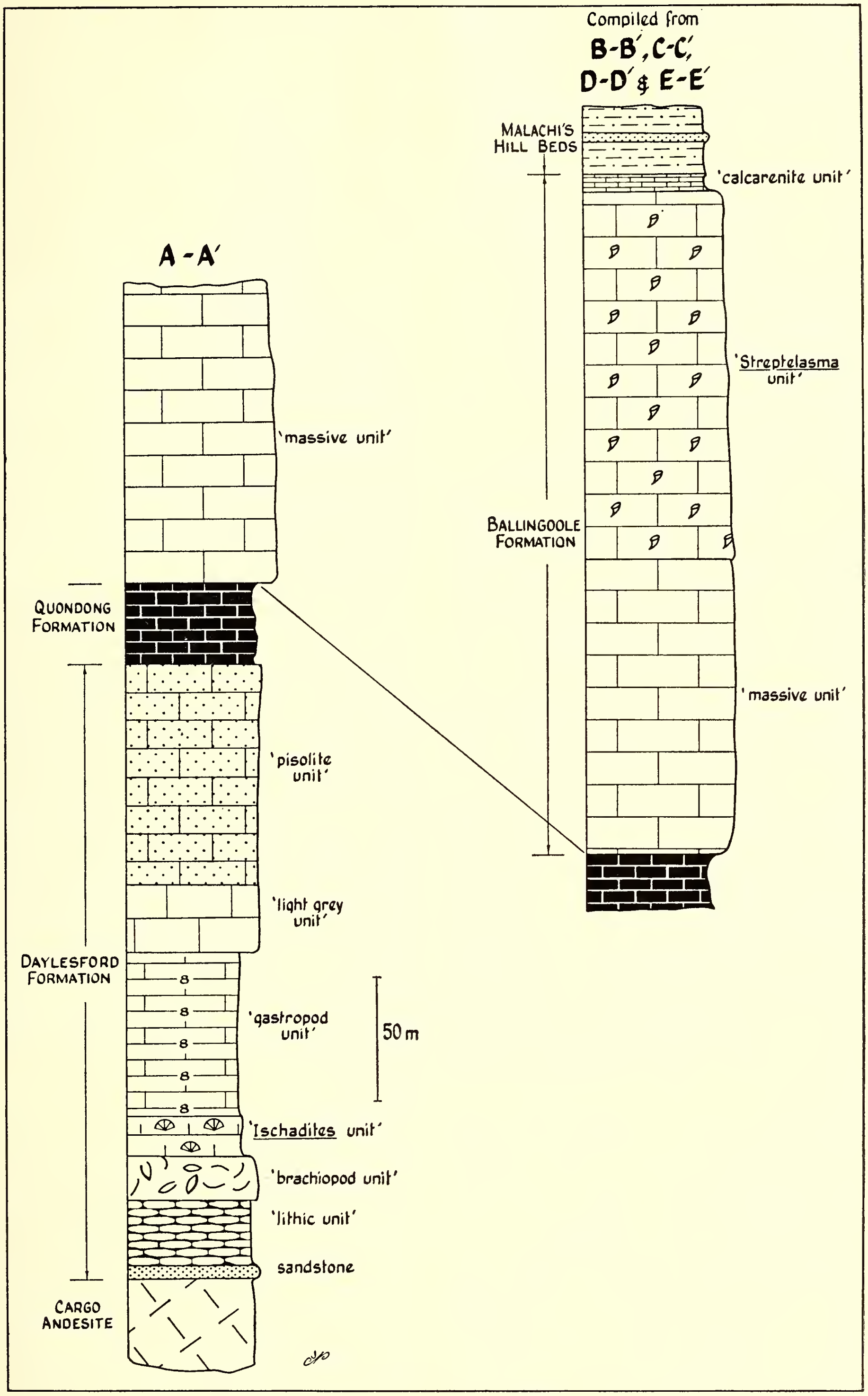

FIGURE 2.—Stratigraphic sections of the Bowan Park Group. For section localities, see Figure 1.

cylindrical labechiid, and *Lophospira milleri* (Miller); other fossils are less abundant and include *Solenopora*, *Girvanella*, corals *Nyctopora stevensi* Hill, *Heliolites* and *Propora*, bryozoans *Stictopora* and *? Prasopora*, brachiopods *Catazyga*, *Protozyga*, bivalves *? Ctenodonta* and indeterminable taxodonts, trilobite *Pliomerina* and ostracod cf. *Kloedinia*. Black chert nodules occurring along bedding planes and *Chondrites* burrows are also found in these limestones.

FIGURE 3.—Bedding plane surface of limestone from the " brachiopod unit ". Most of the shells of cf. *Eodinobolus* are articulated and *in situ*.

The " *Ischadites* unit " is thinly bedded and consists of dark grey biomicrites (Pl. II, Fig. 2) and lithoclast-bearing biosparites and is 16 m. thick. Its distinctive feature is the occurrence of the large alga *Ischadites* cf. *lindstroemi* Hinde. Other fossils are relatively scarce and include *Tetradium* cf. *syringoporoides* Ulrich, *Nyctopora stevensi*, *Lophospira milleri*, *Protozyga*, cf. *Kloedinia*, *Solenopora* and *Girvanella*. *Chondrites* burrows, chert nodules (Pl. I, Fig. 2), and dolomite mottling (Pl. I, Fig. 3) are also found in this unit.

The " *Ischadites* unit " is followed by the " gastropod unit ", comprising thinly bedded, dark grey biomicrites, which are extensively burrowed (*Chondrites* burrows; Pl. I, Fig. 6). Gastropods and, to a less extent, other fossils occurs in bands throughout the unit; chert nodules and dolomitized animal tracks and burrows (Pl. I, Fig. 4) are found at many horizons This unit is 64 m. thick and may be, subdivided on a faunal basis. In the lower 30 m. the gastropod *Maclurites* is the most conspicuous fossil; *Lophospira milleri*, *Heliolites*, large orthoconic nautiloids (Pl. I, Fig. 5) and brachiopods also occur. The upper 30 m. contains a more varied fauna which includes *L. milleri* (abundant), *Ectomaria*, *Hardmanoceras*, *Maclurites*, large orthoconic nautiloids, *Catazyga*, *Tetradium* cf. *syringoporoides*, *Heliolites*, a coral resembling *Pycnostylus*, and *Pliomerina*.

Overlying the " gastropod unit " is a massively bedded, strongly outcropping, mottled light grey limestone which is named the " light grey limestone unit ". Its lithologies include biomicrites and biosparites. The unit is fairly barren throughout its 25 m. thickness but has occasional coral or brachiopod bands. *Tetradium* and *Plasmoporella* have been found but are not common. In thin sections fragments of gastropods, trilobites, brachiopods, coral and calcareous algae have been encountered.

The upper unit of the Daylesford Formation is the " pisolite unit " (95 m. thick), a thinly to massively bedded sequence of biointrasparites, biosparites and biomicrites. The lower portion consists mainly of pisolitic lithoclast-bearing biointrasparites which are thinly to massively bedded; some beds are finely laminated and exhibit gently inclined cross bedding. The upper portion consists of massively bedded biomicrites and some biosparites and biointrasparites; black chert nodules also occur in this upper part. Fossils are common, especially in the lower portion, and the corals *Tetradium cribriforme* (Etheridge), *Propora*, *Heliolites*, *Plasmoporella*, *Coccoseris*, and the stromatoporoids *Ecclimadictyon nestori* Webby, *E. amzassensis* (Khalfina) and *Clathrodictyon* aff. *mammillatum* (Schmidt) dominate. Less common fossils include the stromatoporoid *Labechia variabilis* Yabe and Sugiyama, the brachiopod *Leptellina*, and *Lophospira milleri*.

The contact between the massive, dark grey limestones of the " pisolite unit " and the marly limestones of the overlying Quondong Formation is abrupt and erosional.

Quondong Formation

The formation is well developed on the property of " Quondong " (Por. 289, Parish of Bowan) and its designated type section is A–A′ (Figure 2). It is lithologically distinct from the other formations and consists of thinly (and some thickly) bedded marls and limestones which are extremely fossiliferous. Lithologies within it include biomicrites, biomicrudites, biosparites, biosparrudites, intrasparites, pelmicrites and micrites.

Previous work on this formation has been mainly palaeontological and has included descriptions or listings of corals, bryozoans, brachiopods or gastropods. Dun (*in* Andrews and Morrison, 1915) determined *Heliolites, Hormotoma, Lophospira, Naticopsis, Trematospira, Lituites* and *? Columnopora*. Although the exact location from where these were collected is not given it seems likely that they were collected from this, the most fossiliferous formation. Brown (1952) listed *Spanodonta* (=*Sowerbyites*; Packham, pers. comm.) and *Tritoechia* and was first to conclude that the limestone was Ordovician. Stevens (1956) listed *Propora, Heliolites* and *Eofletcheria* (all determined by Dorothy Hill) and also *Coccoseris* and dasycladacean algae. In 1957 Hill described *Propora bowanensis* Hill, *Eofletcheria gracilis* Hill and *Heliolites digitalis* Hill from the formation and suggested an Upper Ordovician or late Middle Ordovician age for the fauna. Phillips-Ross (1961) described *Homotrypa* cf. *fenestrata* Phillips-Ross, *Stictopora bowanensis* Phillips-Ross and *S. quondongensis* Phillips-Ross and commented on the abundance of " brachiopods, corals, gastropods, ostracods, bryozoans, nautiloids, stromatoporoids, algae and trilobites ".

Fossils in the formation occur in bands as shell and coral calcirudites or as shell calcirudites in a matrix of calcarenite or calcilutite (Pl. I, Fig. 7); very few fossils are in their position of growth, unless they occur as encrusting forms on shells and other fauna. Less fossiliferous beds are invariably burrowed (*Chondrites* and other varieties of burrow).

Brachiopods, corals and, to a less extent, bryozoans and gastropods dominate the fauna. Of the forms present *Eofletcheria gracilis, E. contigua* Hill, *Tetradium cribriforme, Propora bowanensis, P. mammifera* Hill, *Heliolites digitalis*, and a tryplasmatid are the common corals, while *Leptellina* and *Catazyga* are the common brachiopods. Amongst the bryozoans *Stictopora bowanensis, S. quondongensis* and *Prasopora simulatrix* Ulrich are the most abundant, while *Lophospira milleri* is the common gastropod.

Other fossils are less abundant and are determined as follows: *Girvanella, Solenopora* and dasycladacean algae, corals *Eofletcheria subparallela* Hill, *Plasmoporella, Coccoseris, Palaeophyllum* cf. *rugosum* Billings, and an indeterminate auloporid, stromatoporoids *Ecclimadictyon nestori* and *E. amzassensis*, brachiopods *Protozyga, Hesperorthis, Strophomena, Ptychopleurella, Hallina, Sowerbyites*, gastropods *Hormotoma* and *Maclurites*, bivalves *? Ctenodonta*, orthoconic nautiloids, edrioblastoid *Astrocystites*, trilobites *Pliomerina* and other indeterminate fragments, and the ostracod cf. *Kloedinia*.

The boundary with the overlying Ballingoole Formation is a transitional one. The transitional rocks are thinly bedded and fossiliferous but grade upwards within 2 m. into massive, relatively unfossiliferous limestone.

Ballingoole Formation

The Ballingoole Formation is well developed, though incomplete, along the road which runs east–west through the area, and takes its name from a homestead on the north side of this road. The type section of the formation is designated at Malachi's Hill but the complete stratigraphy has been compiled from sections A–A′, B–B′, C–C′, D–D′ and E–E′. The formation consists of massive limestones (mainly biosparites, biomicrites, pelmicrites, micrites and intrasparites) throughout its 280 m. thickness, but thinly bedded calcarenites, lithic calcilutites and a limestone breccia are developed at the top. The formation is divided into three units (Figure 2).

Fossils are rare in the lower portion of the formation, named the " massive unit ", but fragmentary heliolitids and *Pseudostylodictyon inequale* Webby have been found near the base. The more fossiliferous upper portion is termed the " *Streptelasma* unit " and in it are found *Streptelasma, Plasmoporella inflata* Hill, *Plasmoporella*, and the stromatoporoids *Ecclimadictyon nestori, E. amzassensis, Clathrodictyon* cf. *microundulatum* Nestor, and *Pseudostylodictyon inequale*. *Maclurites* and *Sowerbyites* are found in horizons near the base, and *Halysites praecedens* Webby and Semeniuk, *Palaeofavosites* cf. *alveolaris* (Goldfuss) and pentamerid brachiopods are found in horizons near the top. A poorly preserved *Tetradium* sp. is also found in some horizons throughout the unit.

In the " calcarenite unit " (Figure 2) the lower portion consists of thinly bedded calcarenites which contain the trilobite cf. *Bumastus* and less commonly the rugose coral *? Palaeophyllum*. The upper portion of this unit consists of laminated lithic calcilutites and fossils found in them include graptolites like those found in the basal portions of the Malachi's Hill Beds. A limestone breccia is developed near the top of the unit with derived limestone fragments similar to the types occurring throughout the Bowan Park group. The only identifiable fossil found to date is *Palaeofavosites* cf. *balticus* (Rukhin). Above the limestone breccia more lithic calcilutites are found, and they grade rapidly (within 3 m.) into siliceous laminated siltstones of the overlying Malachi's Hill Beds. The boundary between the Ballingoole Formation and the Malachi's Hill Beds is drawn at the top of these higher lithic calcilutites.

Petrography

The Bowan Park Group presents a variable suite of carbonate rocks and an account of the rock constituents and commoner rock types is presented below.

Preservation of original texture and structure within the limestone is often remarkably good (despite the age, the proximity to large-scale thrusting, and the low-temperature regional metamorphism of the limestone). For example, skeletal structure is found intact in brachiopods (Pl. II, Fig. 7), trilobites and some corals, fibrous calcite cement is found still preserved (Pl. II, Fig. 3), *Girvanella* threads are still discernible (Pl. II, Fig. 6) and much of the micrite in these rocks has not suffered appreciable grain growth.

Alteration and recrystallization, however, has occurred to some extent throughout the limestones. Some of the more obvious changes involve dolomitization, brecciation and sometimes intense veining near fault zones. Patchy to complete recrystallization of micrite to microspar or pseudospar (Folk, 1965), recrystallization of pore-filling cement fabrics, and obliteration of skeletal structures either by recrystallization or leaching are also common features of these limestones. Finally, calcite veining and slight to intense stylolitization is found throughout the sequence.

The variety of rock constituents in the limestones include terrigenous clay and silt, lime mud, skeletal silt, skeletal sand and gravel, pellets, intraclasts, lithoclasts, algally-coated grains (pisolites), drusy and blocky cements and replacement minerals such as dolomite, silica and pyrite.

Biomicrites and biomicrudites dominate the lithologies in the lower portions of the group and become less important in the upper parts. They consist of one or more macro-fossils, such as a gastropod or brachiopod, set in a slightly to intensively burrowed (usually dark grey) lime mudstone. In thin section a high degree of skeletal fragmentation down to silt size is evident (Pl. II, Fig. 2). Burrowing, when present, usually contrasts against its surroundings by its darker colour and/or differing skeletal content (Pl. II, Fig. 4).

Biosparites and biosparrudites are probably the second most important group in the sequence, being best developed in the Quondong Formation. They may consist of a few or a variety of skeletal grain types. These can be recognized by such diagnostic features as fibrosity of shell (e.g. brachiopods, Pl. II, Fig. 7, and trilobites), shell shape (e.g. trilobites and gastropods) and internal structures (e.g. algal stems, Pl. II, Fig. 5). Often, however, recrystallization and micritization of grains has rendered the identification of skeletons impossible ; only vague shapes and incomplete alteration suggest that these are not intraclasts. Cement, for the most part in these rocks, has been recrystallized to blocky calcite, with some development of lustre mottling. In many cases, however, parts of a thin section will show ghost remnants of drusy calcite, while another portion has been fully recrystallized to blocky calcite.

Intrasparites are found in all the members but have their best development in the " pisolite unit ". As a group they are less abundant than the biosparites and biosparrudites. In thin section some of the rocks contain a reasonable proportion of skeletal fragments, and these are termed biointrasparites. The intraclasts, sand to pebble sized, are mostly micrite (Pl. II, Fig. 8), biomicrite, pelsparite, or pelmicrite fragments ; in some cases *Girvanella*-bearing micrites and dolomite-bearing micrites are found.

Pelmicrites, found mostly in the Ballingoole Formation and Quondong Formation, are not a common rock type throughout the sequence. They consist of extremely well sorted pellets, lying in the size range 0·05–0·1 mm., which are ovoid to spherical to irregular in shape and are composed of dark brown micrite. The pellets are set in a matrix of lighter coloured micrite with microspar patches (Pl. II, Fig. 1).

Other lithologies form a less significant proportion of the rock types developed in the group and will be described in detail in a later publication.

Age of the Bowan Park Group

The Bowan Park Group is important in this region because it appears to be the only Ordovician limestone which spans the three faunal zones established by Webby (1969). The faunal zones as they apply in the Bowan Park Group are as follows (Tentative correlations with the Victorian Stages are taken from Webby, 1969.) :

Fauna III (correlated with the U. Eastonian) : Containing the first appearances of *Streptelasma*, *Halysites praecedens*, *Palaeofavosites* cf. *alveolaris*, *Plasmoporella inflata*.

Fauna II (correlated with the L. East. or ? U. Gisborn.) : Containing the first appearances of *Ecclimadictyon*, *Clathrodictyon*, *Palaeophyllum* ; and containing *Tetradium cribriforme* and *Labechia variablis*.

Fauna I (correlated with the U. or ? L. Gisbornian) : Containing *Tetradium apertum*, *T. compactum*, *T.* cf. *cellulosum*, *T.* cf. *syringoporoides*, *Stratodictyon columnare* and *S. ozakii*.

Graptolites collected from the lower part of the overlying Malachi's Hill Beds are Lower Bolindian or near the Eastonian-Bolindian boundary in age and thus essentially agree with the above correlations.

Malachi's Hill Beds

Stevens (1956) originally defined the Malachi's Hill Formation as the sequence of sedimentary and volcanic rock, approximately 200 m. thick, overlying the Bowan Park Limestone and underlying Silurian limestone and shale. The formation, however, has a faulted contact with overlying Silurian rocks, and some of the limestone lenses in the east of the area determined by Stevens to be Silurian are, in part, limestone boulder beds with a fauna suggestive of an uppermost Ordovician age, (Bolindian). These boulder beds appear to be best included in the upper parts of the formation. Similar limestone boulder beds are found in the upper parts of the formation and stratigraphically well below limestones of a known Lower Silurian age in the Borenore region (Partridge, pers. comm., 1970).

The Malachi's Hill Beds therefore are herein defined as the sequence of sedimentary and effusive rocks and breccias, including the limestone boulder beds, which conformably overlie the Bowan Park Limestone and have a faulted contact with Silurian limestone and shale (Figures 1 and 5)

Stratigraphy and Petrography

The base of the sequence is exposed on the south-west slopes of Malachi's Hill and the basal boundary is drawn at the top of the lithic calcilutites of the Ballingoole Formation. The lower part of the formation is exposed as cliff sections along Oaky Creek, where it is possible to trace units for hundreds of metres ; north of Oaky Creek the upper part of the sequence is poorly exposed and is restricted to several massive outcrops and numerous boulder piles. The sequence of units is illustrated in Figure 4. The fault occurring between Malachi's Hill and the " Malachi's Hill " homestead has resulted in the loss of an unknown thickness of beds, possibly not more than 30 m.

Finely laminated siltstones dominate the lower part of the sequence. They are hard, siliceous, well-jointed rocks fairly constant in their character vertically and along strike. An abundance of sedimentary structures are found within them and small-scale slumps, minor contemporaneous faults and small-scale lenticular layering are the most common ; load casts, minor drag folds on the upper surfaces of laminations, siltstone injections into overlying layers, small-scale cross laminations and small-scale graded bedding also occur. The laminations, due to the alternation of organic-rich and organic-poor layers, give the rock a dark grey/buff banded aspect. Laminations are also defined by thin sandstone layers. In thin sections grains appear well sorted, ranging in size from 0·02–0·1 mm., though most are 0·04 mm. Quartz forms up to 80% of the rock (which is unusual considering that most of the other sedimentary grain types in this formation have been derived from basaltic to andesitic volcanic rocks) ; basaltic and andesitic rock fragments, devitrified glass fragments, albite, minor amounts of (? syngenetic) pyrite, and siliceous sponge spicules also occur.

The coarse, brown lithic sandstones which are intercalated with the laminated siltstones (Figure 4) are massive and do not exhibit any obvious sedimentary structures or fossils. They consist of poorly sorted grains, angular to subangular in shape, and mostly 0·4–1·0 mm. in size. Rock fragments make up the bulk of the sand grains and consist of basaltic and andesitic rock and devitrified glass. Pyroxene fragments, plagioclase and opaque minerals total less than 10% of the rock.

A brown siltstone which is found above the laminated siltstones (Figure 4) is thinly bedded and irregularly jointed. It contains small orthoconic nautiloids but no other fauna. In thin section the rock consists of plagioclase (altered), rock fragments, quartz and minor amounts of opaque minerals. Most of the grains are too small to identify, grain sizes being 0·05 mm.

Overlying the brown siltstone is a massive, unfossiliferous, dark grey volcanic sandstone

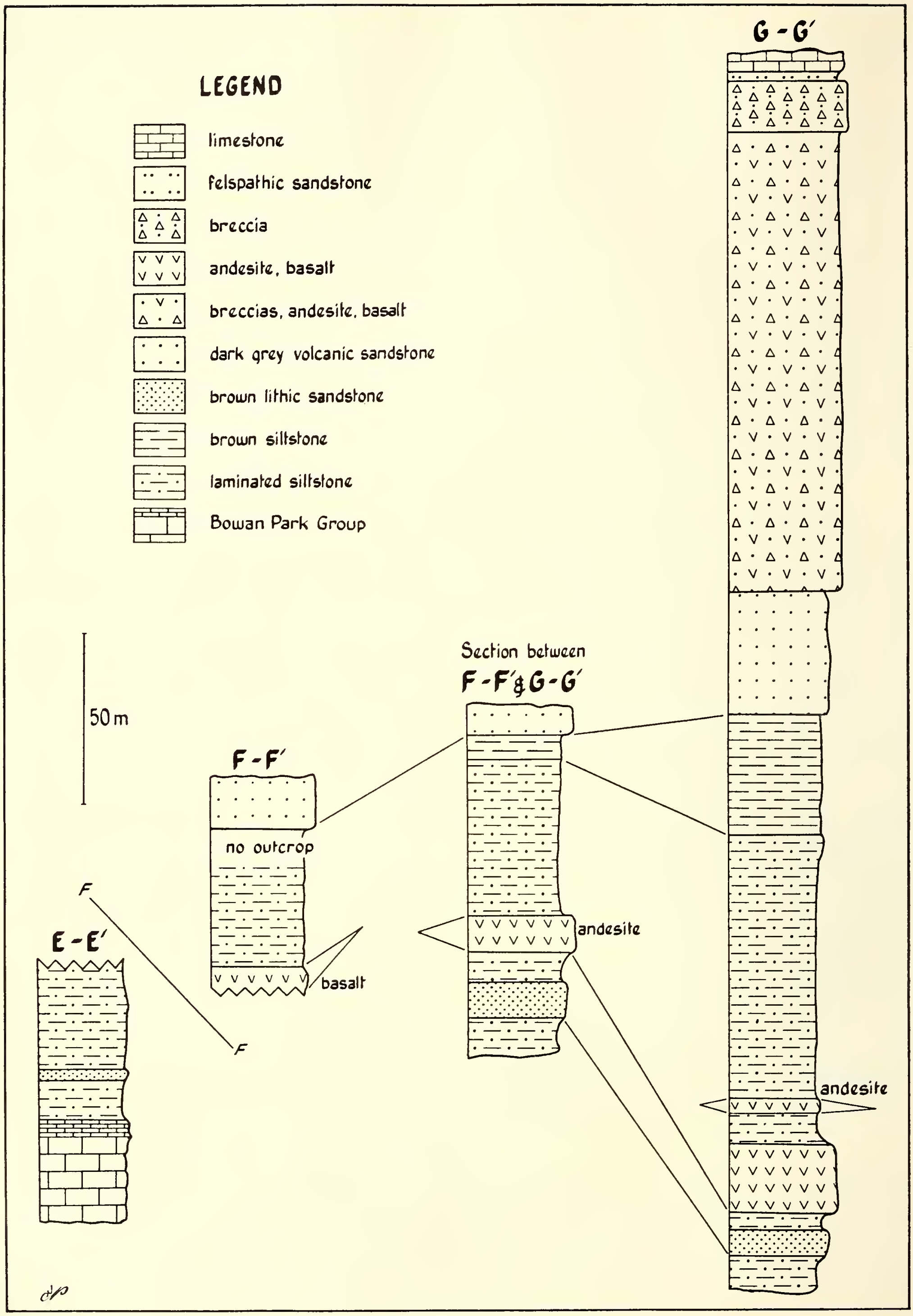

FIGURE 4.—Stratigraphic sections of the Malachi's Hill Beds. For section localities, see Figure 1.

(Figure 4) which is fine to coarse grained, 0·2–0·6 mm. respectively. Basaltic and andesitic rock fragments and plagioclase make up the bulk of the sandstone ; pyroxene (15%), opaque minerals (10%), and minor amounts of hornblende and quartz make up the remainder of the grains.

The two andesitic flows intercalated with the laminated siltstones in the lower part of the sequence (Figure 4) are very similar. They are vesicular in places and porphyritic with laths of altered plagioclase up to 2·5 mm. in length forming subradiating groups, comprising 15% of the rock. Augite (colourless in thin sections) also occurs as phenocrysts (1·0–1·5 mm. long) and forms 15% of the rock. The groundmass consists of patches of relict plagioclase, calcite, chlorite and granules of an opaque mineral.

A little higher in the sequence a basalt occurs (Figure 4). It has altered plagioclase laths as phenocrysts (showing flow orientation) up to 4 mm. long and forming 10% of the rock. The groundmass consists of a felt-like aggregate of relict plagioclase microlites with interstitial pyroxene, now chlorite ; opaque mineral granules and patches of calcite (replacing the groundmass) are also common. Field evidence (an erosional surface contact with overlying sediments within an essentially contemporaneous sequence, Pl. I, Fig. 1), and thin section data point to an extrusive origin for these volcanic rocks described above.

Porphyritic volcanic rocks and breccias dominate the upper portions of the sequence (Figure 4) and at least three different effusive rock types can be recognized in widely scattered but different stratigraphic positions. The upper part of the formation is left, therefore, largely undifferentiated, but the rock types are described below. Immediately above the dark grey volcanic sandstone (Figure 4) a porphyritic andesite with phenocrysts of altered plagioclase, augite and relict amphibole crops out. The plagioclase forms up to 30% of the rock as phenocrysts 1 mm. in length. Colourless augite and relict amphibole each form 10% of the rock. The relict amphibole has been completely altered to chlorite and biotite and all that remains is the crystal outline defined by an opaque mineral rim (originally this may have been a magmatic corrosion rim). The groundmass of this rock consists of interlocking grains of calcite, chlorite, opaque minerals, felspar and minor amounts of pyroxene.

An andesite with only pyroxene phenocrysts occurs somewhat higher above the last described rock. The pyroxene, of average grain size 1·5 mm., is augite and forms 25% of the rock. The groundmass consists of microlites of felspar 0·01 mm. long ; opaque mineral granules, calcite, epidote and chlorite also occur, but make up less than 10% of the rock. A basalt porphyritic in plagioclase (altered) and augite outcrops stratigraphically just beneath the massive volcanic pebble-limestone pebble breccia near the top of the formation. Plagioclase laths 1 mm. in length form up to 30% of the rock, while augite phenocrysts up to 1·5 mm. long form up to 10%. The groundmass consists of a very fine aggregate of felspar, opaque minerals, chlorite and calcite ; there is a scattering of pseudomorphs after olivine crystals (less than 10%). The breccias occurring throughout this upper portion of the Malachi's Hill Beds consist of angular fragments of rock up to 30 cm. in size, and the various types of porphyritic volcanic rocks described above are found in them.

The topmost units of the Malachi's Hill Beds consist of a massive volcanic pebble-limestone pebble breccia which is strongly outcropping and is overlain by 3 m. of thinly bedded brown felspathic sandstone containing limestone pebbles in its upper portions. This is overlain by a limestone band (Figure 4). The lower part of this limestone is bouldery (this is the limestone breccia referred to in Webby and Semeniuk, 1969, p. 357) ; the upper part is a fine to coarse calcarenite containing large boulder-like algal limestone masses.

Alteration

Low-temperature burial metamorphism has affected the rocks, and secondary mineral assemblages similar to that described from the Cargo Andesite (p. 18) are found. Notable again is the alteration of the groundmass of the porphyritic rocks to chlorite, calcite, pumpellyite, clay minerals and quartz. In the sedimentary rock suite the plagioclase, pyroxene and rock fragments which make up a sizeable proportion of the sandstones show the same types of alteration features as the igneous rocks.

Palaeontology and Age

Graptolites and small orthoconic nautiloids were the only fauna found in the lower portion of the Malachi's Hill Beds. The graptolites, although not extremely abundant in any one horizon, occur throughout the laminated siltstones, and enable the formation to be dated. *Orthograptus truncatus* Lapworth, *Retiograptus* aff. *pulcherrimus* Keble and Harris, and *Diplo-*

graptus were found in the more calcareous siltstones at the base of the formation (graptolite locality g. 1—see Figure 1), *Climacograptus bicornis tridentatus* Lapworth, *C. bicornis* (Hall), *C.* cf. *missilis* Keble and Harris, *Dicellograptus complanatus ornatus* Elles and Wood, *Leptograptus flaccidus* Hall, *Orthograptus truncatus* Lapworth, *Diplograptus* and indeterminate dendroids from the overlying laminated siltstones (graptolite localities g. 2 and g. 3). From the overlapping ranges of these various forms (Thomas, 1960) it seems as though the age of the lower part of the formation is near the Eastonian-Bolindian boundary or Lower Bolindian.

The fauna collected from the volcanic pebble-limestone pebble breccia and the overlying limestone boulder beds are mainly corals, and include *Catenipora* sp. nov., *Quepora*, *Palaeofavosites* cf. *hystrix* Sokolov, *Palaeofavosites* spp., *Plasmoporella*, *Heliolites*, *Palaeophyllum*, *Favistina*, *? Streptelasma* and *? Lambeophyllum*. In addition, trilobites, brachiopods and pelmatozoan ossicles are found in the limestone pebbles.

It would appear that these limestone pebbles and boulders were being formed, eroded and transported from an adjacent area contemporaneous with the deposition of the Malachi's Hill Beds, for the fauna in the limestone is younger than any in the Bowan Park Limestone, and is obviously derived. From preliminary work it appears that the assemblage is uppermost Ordovician (Bolindian) in age.

" Panuara Formation "

Silurian sediments referable to the " Panuara Formation " (Packham and Stevens, 1954; Packham, 1969) outcrop in the north and west of the area, and are separated from the Ordovician rocks by a structure which has been interpreted as a major fault (Figure 1). The steepening of Silurian strata and dolomitization of the Ballingoole Formation near the structure, the emplacement of the Marylebone Dolerite in the region of its flexure, and a wide crush zone in the north of the area, suggests that it is a major fault rather than an unconformity.

The best exposed Silurian section, consisting of graptolite-bearing mudstones and shales, crops out in a creek in the north-east extremity of the area and is illustrated in Figure 5. A thinly bedded brown felspathic (quartz-rich) sandstone forms the base of the sequence in that section. It is overlain by burrow-mottled, buff-coloured mudstones which have thin felspathic sandstone and grey shale intercalations, especially towards the base. Fragmentary dendroids and retiolitids have been collected from near the base of this unit, and *Monograptus testis* Barrande and *M.* cf. *vomerinus* (Nicholson) have been collected from near the top (g. 4 and g. 6, Figure 1). Overlying this is a green splintery mudstone which contains small to large calcareous nodules (up to 1·3 m. in size); this is overlain by a crystal tuff bed 5 m. thick. Finely laminated grey shales, containing *M. dubius* (Suess) and, higher up, *M. bohemicus* (Barrande), occur at the top of the sequence (g. 5 and g. 7). The graptolites collected from the formation suggest a Wenlock to Ludlow age.

The limestone lens outcropping at the " Marylebone " homestead is surrounded on most sides by the Marylebone Dolerite (see below) and is not traceable laterally. It consists of a lower portion of grey biomicrites and an upper portion of hematite-rich biosparrudites. A fauna including *Halysites magnitibus* Buehler and *Acanthohalysites gamboolicus* (Etheridge) suggests a Lower Silurian age, and a correlation with the Rosyth Limestone (Walker, 1959) further to the east, notably in the Borenore area (Byrnes, pers. comm., 1970). The limestone appears to be older than any of the terrigenous sediments occurring in the creek section described above. The absence of the limestone in the eastern portions of the area may be due to faulting between it and the Ordovician rocks (Figure 5), or it may have been erosionally removed prior to the accumulation of the basal brown felspathic (quartz-rich) sandstone and succeeding beds.

Marylebone Dolerite

It is proposed here to name the large intrusion in the north-west of the area the Marylebone Dolerite. It takes its name from the " Marylebone " property on which it is best developed. The intrusion crops out discontinuously as a series of isolated elliptical pods in an arc 4·5 km. long and 800 m. wide; at both ends of the arc the outcrops become more widely spaced.

The bodies intrude Upper Ordovician to Upper Silurian sediments and two features suggest that its emplacement was structurally controlled: (i) the parallel trend of the elliptical outcrops to a major fault separating the Ordovician and Silurian sequences (Figure 1), and (ii) the restriction of the intrusion to a zone about 800 m. wide.

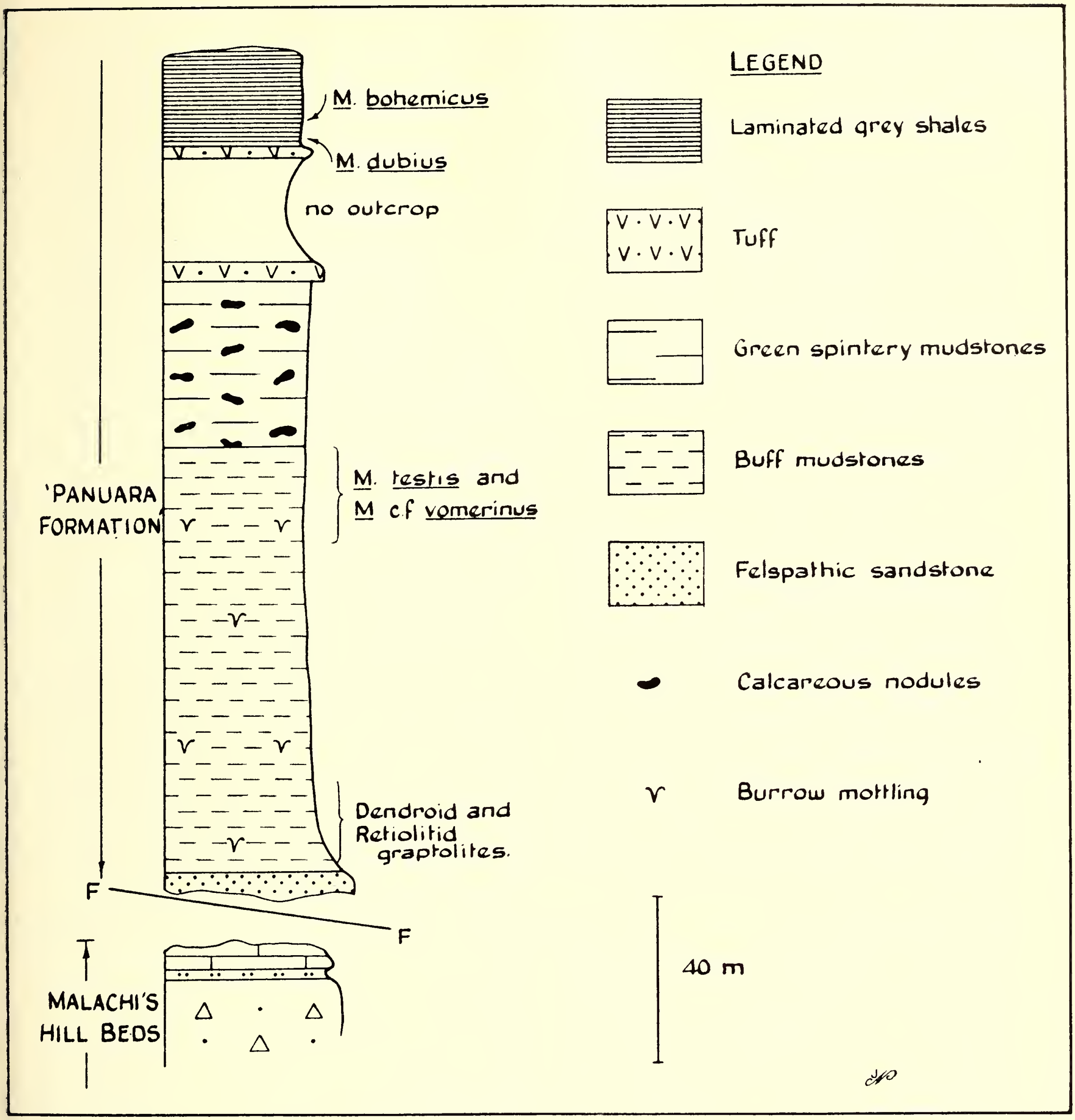

FIGURE 5.—Stratigraphic section of the " Panuara Formation ". This traverse is a continuation of G–G′, though most of the outcrop is along a creek just west of this line.

The surrounding sediments appear to have suffered little contact metamorphism and little or no mineralization. Quartz-rich Silurian mudstone outcropping within 3 m. of the intrusion is silicified and shows patches of slight grain-size increase. The actual contact between the intrusion and the country rock is not exposed.

Petrography

Three rock types occur within the intrusion. Over 90% of it is dolerite, consisting of a medium-grained aggregate of felspar and mafic minerals. In thin sections it is an equigranular rock with an average grain size of 2 mm. Plagioclase constitutes about 65% of the rock ; it shows simple and lamellar twinning as well as normal zoning. The plagioclase, however, has invariably been altered. Euhedral grains of augite (colourless in thin sections) form about 10% of the rock and they commonly show subophitic textural relationships with the plagioclase. In some rocks the augite has been partly altered to chlorite, while in others it has remained relatively fresh. Interstitial material forms up to 20% of the rock and includes prehnite, chlorite, ilmenite and minor amounts of quartz. Prehnite occurs as spherulites or as intergrowths with chlorite and quartz; in other cases chlorite and quartz may be intergrown together, or ilmenite may be graphically intergrown with pyroxene and plagioclase. Needles of apatite occur throughout the rock.

Veins transect the dolerite body. They may be up to 30 cm. wide, but usually are only 5 cm. wide. In handspecimen they appear pink and consist of euhedral crystals of felspar and patches of mafic minerals. In thin sections they are equigranular with an average grain size of 1 mm. Mineralogically, they are similar to the dolerite except that crystals of K-felspar showing relict perthitic intergrowths form up to 10% of the rock; the K-felspar is now heavily altered. Interstitial prehnite and quartz are also more abundant. Finally, a porphyritic dolerite occurs within the main intrusion. It is found as a small boulder (less than 30 cm. across) *in situ* surrounded by weathered dolerite, so that its relationship to the main mass could not be determined. It probably represents a xenolith.

Age of the Intrusion

Similar dolerite bodies intruding Ordovician to Silurian sediments in central western New South Wales have been recorded by Basnett and Colditz (1945), Stevens (1948), Strusz (1960) and Savage (1968). Packham (1968, p. 151) considers these bodies as the possible source of dolerite fragments in the calcarenites of the " Nubrigyn Formation ", thereby assigning them an age of Lower Devonian. The Marylebone Dolerite, since it intrudes sediments containing *M. bohemicus* (g. 7, Figure 1), must be at least post-Upper Silurian in age. Its upper age limit is a problem, but its mineral alteration is similar to that of the Cargo Andesite (p. 18) and the Malachi's Hill Beds and suggests intrusion in the Middle Palaeozoic.

Tertiary Rocks and Quaternary Alluvium

Tertiary rocks are represented by basalt, " greybilly ", silicified earths and massive hill-capping quartzose sandstones. Of these, basalt is the most extensive; it covers a large part of the central portion of the area (Figure 1) but it has been deeply weathered to red soil and bouldery outcrops.

Vesicular and non-vesicular varieties of basalt have been found. The vesicular variety occurs in the north-east extremity of the central outlier. In thin section it consists of euhedral phenocrysts of olivine and plagioclase (An 50) set in a groundmass of small plagioclase laths, clinopyroxene granules and opaque minerals. Vesicles are commonly unfilled, but may be partly or (rarely) completely filled with calcite. The non-vesicular basalt consists of plagioclase phenocrysts in a groundmass of plagioclase (An 55), clinopyroxene granules and opaque minerals. The phenocrysts commonly show oscillatory zoning and have an inner marginal zone of opaque mineral and silicate inclusions. Xenocrysts of orthopyroxene rimmed by granular clinopyroxene form a minor portion of this rock.

" Greybilly " is more scattered in outcrop and is often surrounded by loose pebbles of silicified earth and jasper. In hand specimen it is a hard, well-cemented sandstone containing large angular chips of dark grey mudstone and pebbles of quartz. Thin sections show that the sand fraction consists of mainly quartz and some mudstone grains cemented by fine-grained silica and iron oxide. The occurrence of " greybilly " at levels always topographically lower than the basalt suggests it may owe its silicified nature to the basalt.

Much of the alluvium in the area is incised and being reworked by the present streams. In general, it consists of pebbles and boulders belonging to the various formations in the area set in a sandy matrix. However, there is an unusual occurrence of large boulders and pebbles (up to 60 cm. diameter) of an Upper Devonian quartzite which crops out on the Black Rock Range, some four miles to the east of the area. These boulders may be also found forming ancient alluvial terraces, some with appreciable relief.

Geological History

Extensive vulcanicity occurred in pre-Upper Gisbornian (or ? Lower Gisbornian) times, probably with the formation of volcanic islands. This resulted in the accumulation of lavas and breccias of the Cargo Andesite. After the cessation of volcanic activity, limestone deposition commenced on what had become a broad, shallow, submerged platform. Relative stability was maintained during the accumulation of approximately 560 m. of the Bowan Park Group. Then about Upper Eastonian times the region sank (? or sea-level rose), accompanied by submarine ? faulting, which resulted in slumps producing the limestone breccia at the top of the Bollingoole Formation, and shallow water limestones passed into deeper water siltstones of the Malachi's Hill Beds. These siltstones appear to have lacked benthonic life and their environment of deposition was quiet with alternating reducing and oxidizing conditions. Slope conditions, or instability of the sea floor, probably produced the abundant sedimentary structures found in them. Volcanic activity in the region was intermittent and contributed the material of the lithic and volcanic sandstones in the formation.

By Upper Bolindian times the environment had once again become predominantly volcanic with a thick sequence of effusive rock and breccia accumulating. Tectonism towards the end of the Ordovician, possibly related to the Benambran Orogeny, produced a difference in relief and localized slumps, as seen from the limestone boulder beds at the top of the Malachi's Hill Beds. The Silurian sedimentation that followed consisted predominantly of terrigenous muds, shallow water accumultations of limestone, and some volcanic activity. The emplacement of the Marylebone Dolerite, preceded (or accompanied ?) by large-scale thrusting and faulting, was the last major event in the Palaeozoic preserved in this area.

In the Tertiary basaltic outpourings from Mt. Canobolas extended at least as far as Bowan Park. Subsequently, there has been erosion of these lavas, leaving the present outliers.

Acknowledgements

The author wishes to thank Dr. B. D. Webby for his helpful criticism and comments while the manuscript was being written, and for his help in identifying the stromatoporoids. Thanks are also due to Professor T. G. Vallance, Dr. G. H. Packham and Mr. J. G. Byrnes for their comments and discussions on earlier drafts of the manuscript.

Finally, acknowledgement is due to Mrs. J. P. Nielsen for drafting the text-figures, and to Messrs. K. and B. Watts for providing accommodation during the field season.

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Explanation of Plates

Plate I

Fig. 1.—Laminated siltstones filling an erosional hollow in andesite (mottled rock in lower right-hand corner). This feature occurs in the section between F–F′ and G–G′ (see Figure 4). The height of the section along the left margin is 1·3 m.

Fig. 2.—Thinly bedded limestones of the " *Ischadites* unit " with dark chert nodules exposed on the bedding plane surface. The thickness of the bed along the right margin is 18 cm.

Fig. 3.—Silicified *Ischadites* cf. *lindstroemi* and dolomite mottling from the " *Ischadites* unit ".

Fig. 4.—Numerous dolomitized animal tracks on a bedding plane surface of limestone from the " gastropod unit ".

Fig. 5.—Large silicified orthoconic nautiloid from the lower portions of the " gastropod unit ".

Fig. 6.—*Chondrites* burrows on a bedding plane of limestone.

Fig. 7.—Polished slab of biomicrudite showing a lower zone of gastropods and an upper portion of disarticulated *Leptellina* valves. Note the geopetal structures (arrowed) where lime mud has partly filled skeletal cavities and the remaining pore space has been filled with clear calcite.

Plate II

Fig. 1.—Gastropod and other skeletal débris in pelmicrite from the Quondong Formation.

Fig. 2.—Biomicrite from the " *Ischadites* unit ", showing a large *Ischadites* fragment and fragmented skeletal material in lime mudstone.

Fig. 3.—Fibrous calcite lining a void in limestone from the " brachiopod unit ". The remainder of the void has been filled with blocky calcite.

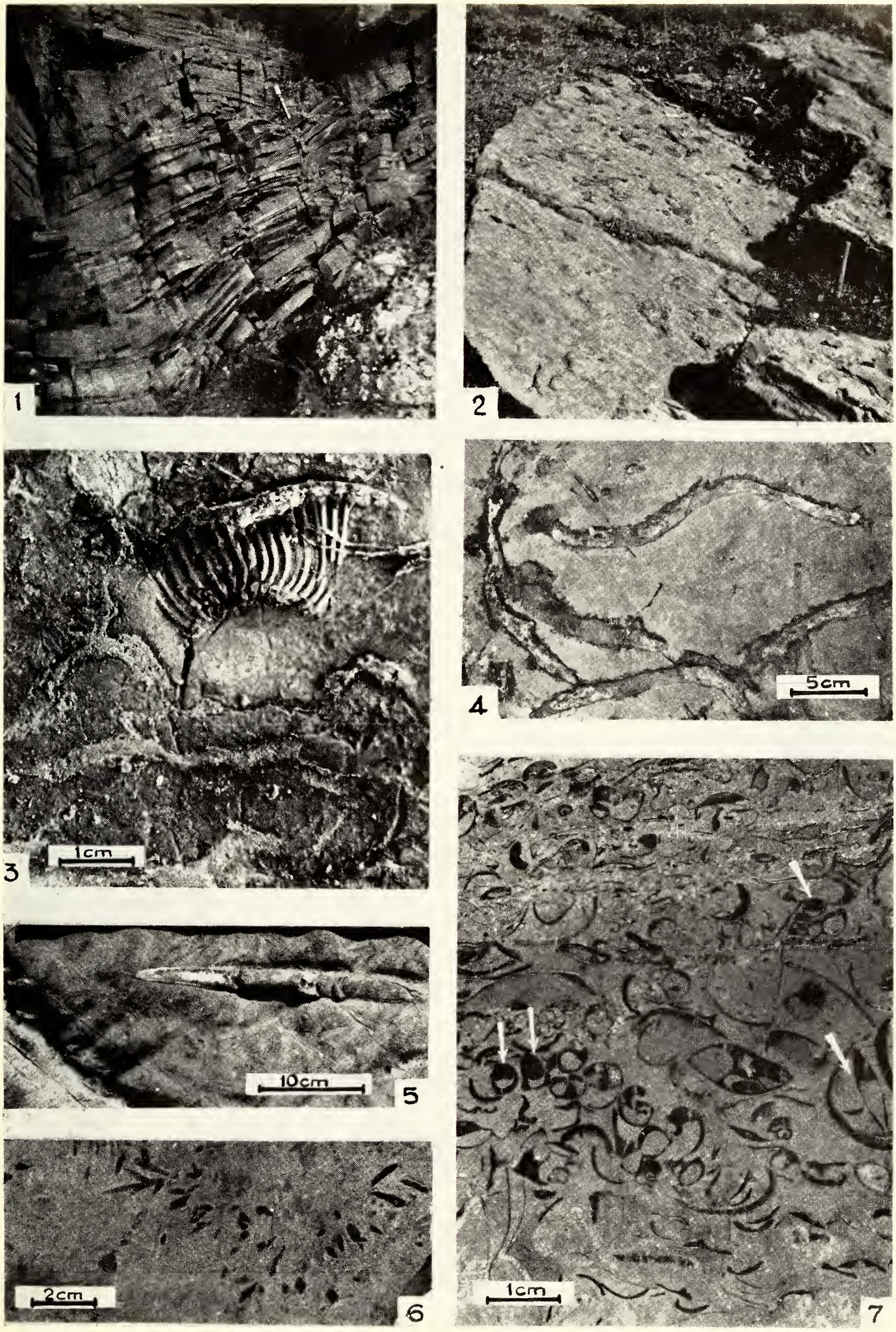
Fig. 4.—Burrowed micrite from the " gastropod unit ", showing a section across one burrow.

Fig. 5.—Biosparite from the " *Streptelasma* unit ". The skeletal fragments include molluscan and calcareous algal débris.

Fig. 6.—*Girvanella* threads visible in the laminae of a pisolite from the " pisolite unit ".

Fig. 7.—Biointrasparite from the " pisolite unit ", showing intraclasts (lower portion of photomicrograph), gastropod skeleton and algally coated brachiopod valve. Note the fibrous nature of the brachiopod valve.

Fig. 8.—An erosional contact between intrasparite and micrite from the Quondong Formation.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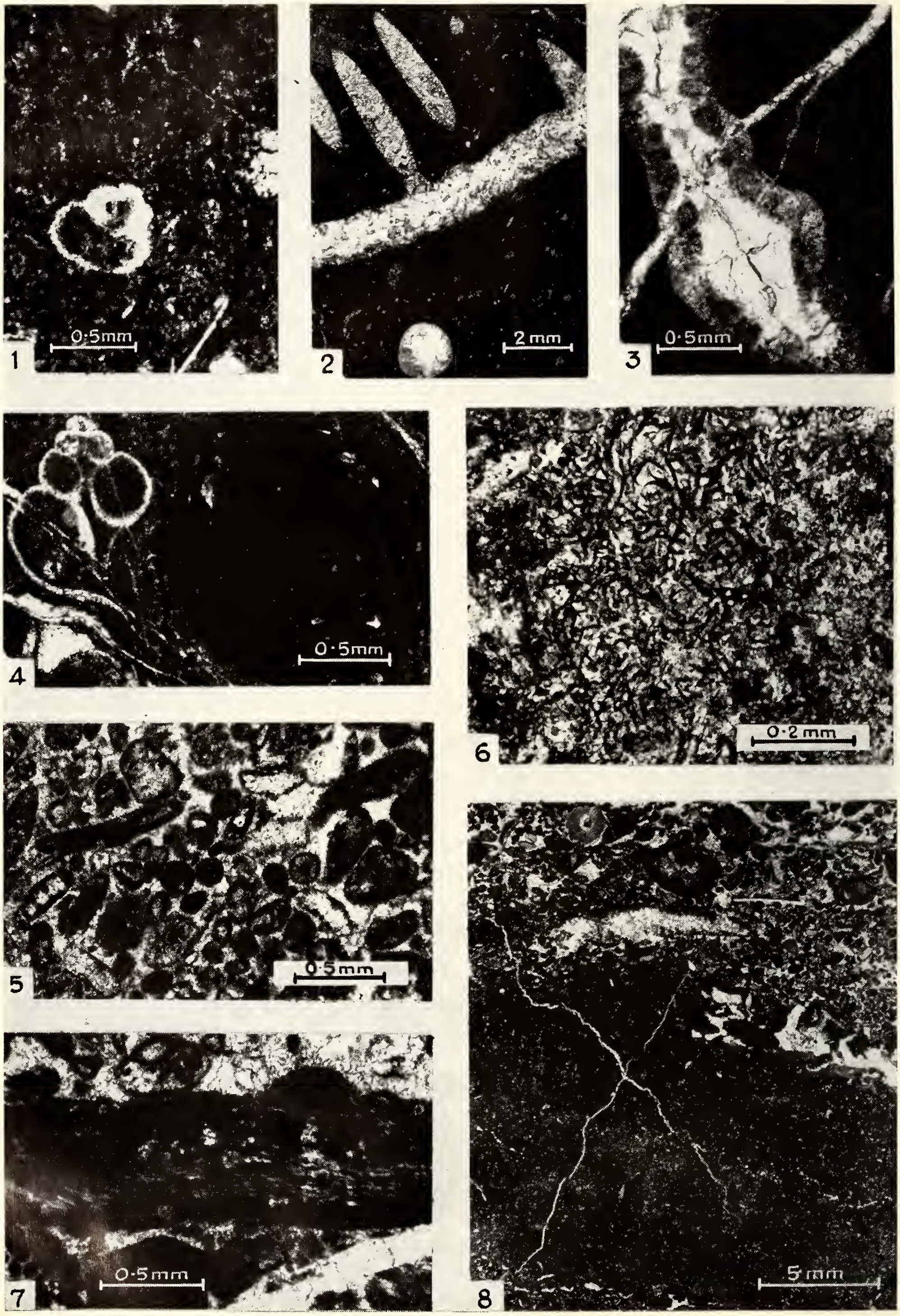
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Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 31–34, 1970

On a Classical Pair of Equations

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Summary

Take the pair of integral equations

$$\int_0^{\infty} y^{1+\alpha} J_\nu(yx) f(y) \mathrm{d}y = g(x), \quad 0<x<b,$$

and

$$\int_0^{\infty} y J_\nu(yx) f(y) \mathrm{d}y \quad = 0, \qquad x>b.$$

with $x^{\frac{1}{2}}g(x) \in L^2(0,b)$.

Then in order that there should be a solution $f(y)$ with $y^{\frac{1}{2}}f(y) \in L^2(0,\infty)$ it is necessary and sufficient that $g(x)$ should have an extension $g_e(x)$ with $x^{\frac{1}{2}}g_e(x) \in L^2(0,\infty)$. So that

$$K(x,\tfrac{1}{2}\alpha) = (2^{1-\frac{1}{2}\alpha}/\Gamma(\tfrac{1}{2}\alpha))x^{-\nu-\frac{1}{2}\alpha}\int_0^x (x^2-t^2)^{\frac{1}{2}\alpha-1} t^{\nu+1} g_e(t)\mathrm{d}t$$
$$= 0 \text{ for } x>b.$$

When $\frac{1}{2}\alpha = m$ (an integer) the necessary and sufficient conditions for the existence of $g_e(x)$ are that given by equation (11). In this case $g_e(x)=0$.

When $\frac{1}{2}\alpha$ is not equal to an integer, then it is necessary that $g(x)$ should satisfy equation (13), and then $x^{\frac{1}{2}}g_e(x)$ should belong to $L^2(b,\infty)$ where $g_e(x)$ is given by equation (14).

In this paper, we consider the classical integral equation pair

$$\int_0^{\to\infty} y^{1+\alpha} J_\nu(yx) f(y) \mathrm{d}y = g(x), \quad 0<x<b \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

and

$$\int_0^{\to\infty} y J_\nu(yx) f(y) \mathrm{d}y = 0, \qquad x>b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where

(i) $\alpha>0$, $\nu>-\frac{1}{2}$;

(ii) $y^{\frac{1}{2}}f(y)$ and $y^{\frac{1}{2}+\alpha}f(y) \in L^2(0,\infty)$;

(iii) The notation $\int_0^{\to\infty}$ in (1) and (2) is used in the following sense :

Put $g_n(x) = \int_0^n y^{1+\alpha}J_\nu(yx)f(y)\mathrm{d}y$, then $x^{\frac{1}{2}}g_n(x)$ converges in $L^2(0,\infty)$ to $x^{\frac{1}{2}}g(x)$.

We write $g(x)$ as in (1). The definition in (2) follows similarly.

The solution of (1), (2) has been known for many years (see, for example, Titchmarsh, 1948). Erdelyi and Sneddon (1962) discuss a more general problem than that considered here. Their paper contains a list of references on our problem. It is not always realized that it is not true that the equations have a solution for all $x^{\frac{1}{2}}g(x) \in L^2(0,b)$. Reference to Awojobi and Grootenhuis (1965) will show such a situation. We will find necessary and sufficient conditions on $g(x)$ that there should be an $f(y)$.

We will assume that the reader is familiar with the classical theory of the Hankel transform in L^2 (see references at the end of this paper).

We will be using a theorem of the author (Griffith, 1955) which states with some change of notation

G: Suppose that

$$\int_0^{\to\infty} yJ_\nu(xy)f(y)\mathrm{d}y=F(x)$$

then $x^{\frac{1}{2}}F(x)\ \varepsilon\ L^2(0,b)$ and $F(x)=0$ for $x>b$, if and only if

(*a*) $z^{-\nu}f(z)$ is analytic for all z (removable singularity at $z=0$);

(*b*) $f(ue^{i\pi})=e^{i\nu\pi}f(u)$ for $u>0$;

(*c*) $u^{\frac{1}{2}}f(u)\ \varepsilon\ L^2(0,\infty)$;

(*d*) $z^{\frac{1}{2}}f(z)=0(e^{(b+\varepsilon)\,\mathrm{Im}\,z})$ as $|z|\to\infty$, $\mathrm{Im}\,z>0$ for all $\varepsilon>0$.

We assume that $f(y)$ satisfies (1), (2) and (ii) and that $g(x)$ is defined by equation (1) for all $x>0$. We will call this extension $g_e(x)$. We will show later, equation (7), that $g_e(x)$ can be formulated directly in terms of $g(x)$. It is immediate that

(iv) $x^{\frac{1}{2}}g_e(x)\ \varepsilon\ L^2(0,\infty)$.

We now define

$$K(x,\beta)=(2^{1-\beta}/\Gamma(\beta))x^{-\nu-\beta}\int_0^x (x^2-t^2)^{\beta-1}t^{\nu+1}g_e(t)\mathrm{d}t. \quad\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Then using formula (6) and the work of Erdelyi (1940, section 9, p. 300), we find that $K(x,\beta)$ exists almost everywhere for all β, and

(v) $x^{\frac{1}{2}}K(x,\beta)\ \varepsilon\ L^2(0,\infty)$.

We now use formula (2.7) of Erdelyi and Sneddon (1962), which will show that

$$K(x,\beta)=\int_0^{\to\infty} y^{1+\alpha-\beta}J_{\nu+\beta}(xy)f(y)\mathrm{d}y. \quad\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

We now refer back to equation (2) and Theorem G. We write $h(z)=z^{\frac{1}{2}\alpha}f(z)$. So

(a_1) $z^{-\nu-\frac{1}{2}\alpha}h(z)$ is analytic for all z (from (*a*));

(b_1) $h(ue^{i\pi})=e^{i\pi(\nu+\frac{1}{2}\alpha)}h(u)$ for $u>0$ (from (*b*));

(c_1) $u^{\frac{1}{2}}h(u)\ \varepsilon\ L^2(0,\infty)$ from (ii));

(d_1) $z^{\frac{1}{2}}h(z)=0(e^{(b+\varepsilon)\,\mathrm{Im}\,z})$ as $|z|\to\infty$, $\mathrm{Im}\,z>0$ for all $\varepsilon>0$ (from (*d*)).

So from equation (4) with $\beta=\frac{1}{2}\alpha$, we see that

(vi) $K(x,\frac{1}{2}\alpha)=0$ for $x>b$.

We now suppose that $g_e(x)$ satisfies (iv), (v) and (vi).

We define $f(y)$ by

$$y^\alpha f(y)=\int_0^\infty xJ_\nu(xy)g_e(y)\mathrm{d}y. \quad\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Then again by the method of proof for equation (4) we show that

$$\int_0^\infty xJ_{\nu+\beta}(xy)K(x,\beta)\mathrm{d}x=y^{\alpha-\beta}f(y). \quad\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Suppose now that (vi) holds, then $h(z)=z^{\frac{1}{2}\alpha}f(z)$ satisfies (a_1), (b_1), (c_1) and (d_1). It is then immediate that (a_1), (b_1) and (d_1) imply that (*a*), (*b*) and (*d*) hold. Equations (5) and (6) imply that (*c*) holds. So by Theorem G, (2) holds.

We have proved to this point that:

In order that (1), (2) and (ii) should hold, it is necessary and sufficient that $g(x)$ should have an extension $g_e(x)$ so that $x^{\frac{1}{2}}g_e(x)$, $x^{\frac{1}{2}}K(x,\beta)\ \varepsilon\ L^2(0,\infty)$ $\beta>0$ and that $K(x,\frac{1}{2}\alpha)=0$ for $x>b$.

If $x^{\frac{1}{2}}g_e(x)$ is any $L^2(0,\infty)$ of $g(x)$, then $x^{\frac{1}{2}}K(x,\beta) \in L^2(0,\infty)$ for all $\beta>0$. We show that there is only one extension $g_e(x)$, so that $K(x,\frac{1}{2}\alpha)=0$ for $x>b$.

With a slight change of variables

$$2^{\frac{1}{2}\alpha}w^{\frac{1}{2}(\nu+\frac{1}{2}\alpha)}K(w^{\frac{1}{2}},\tfrac{1}{2}\alpha)=(1/\Gamma(\tfrac{1}{2}\alpha))\int_0^w (w-u)^{\frac{1}{2}\alpha-1}u^{\frac{1}{2}\nu}g(u^{\frac{1}{2}})du.$$

Put $n=[\frac{1}{2}\alpha]+1$. Then using fractional integral methods (or Erdelyi and Sneddon, 1962, p. 688, (2.3)),

$$(1/\Gamma(n))\int_0^v (v-w)^{n-1}w^{\frac{1}{2}\alpha}g_e(w^{\frac{1}{2}})dw$$
$$=(1/\Gamma(n-\tfrac{1}{2}\alpha))\int_0^v (v-w)^{n-\frac{1}{2}\alpha-1}2^{\frac{1}{2}\alpha}w^{\frac{1}{2}(\nu+\frac{1}{2}\alpha)}K(w^{\frac{1}{2}},\tfrac{1}{2}\alpha)dw.$$

Since $K(w^{\frac{1}{2}},\frac{1}{2}\alpha)=0$ for $w>b^2$, for $v>b^2$,

$$v^{\frac{1}{2}\nu}g_e(v^{\frac{1}{2}})=\frac{1}{\Gamma(\frac{1}{2}\alpha)\Gamma(n-\frac{1}{2}\alpha)}\left[\frac{d}{dv}\right]^n\int_0^{b^2}(v-w)^{n-\frac{1}{2}\alpha-1}dw\int_0^w (w-u)^{\frac{1}{2}\alpha-1}u^{\frac{1}{2}\nu}g(u^{\frac{1}{2}})du. \quad \ldots\ldots (7)$$

We now suppose that $\frac{1}{2}\alpha=m$, an integer, then obviously

$$g_e(v^{\frac{1}{2}})=0 \text{ for } v>b^2 \quad \ldots\ldots (8a)$$

It is clear that we will require

$$\int_0^v (v-w)^{m-1}w^{\frac{1}{2}\nu}g_e(w^{\frac{1}{2}})dw=0 \text{ for } v>b^2. \quad \ldots\ldots (8b)$$

By an examination of the continuity of the integral in (8*b*) we see that

$$\int_0^{b^2} (b^2-w)^{m-p-1}w^{\frac{1}{2}\nu}g(w^{\frac{1}{2}})dw=0, \quad p=0, 1, 2, \ldots, m-1. \quad \ldots (8c)$$

By using integration by parts, it is easy to show that (8*c*) and (8*a*) together imply (8*b*).

Suppose that $\frac{1}{2}\alpha$ is not an integer, then

$$\int_0^v (v-w)^{\frac{1}{2}\alpha-1}w^{\frac{1}{2}\nu}g_e(w^{\frac{1}{2}})dw=0 \text{ for } v>b^2 \quad \ldots\ldots (9a)$$

So again by the continuity of the integral

$$\int_0^{b^2} (b^2-u)^{\frac{1}{2}\alpha-m-1}u^{\frac{1}{2}\nu}g(u^{\frac{1}{2}})du=0 \quad \ldots\ldots (9b)$$

for $m=0, 1, \ldots, [\frac{1}{2}\alpha]-2$,

and

$$\int_0^{b^2} (v-u)^{\frac{1}{2}\alpha-m-1}u^{\frac{1}{2}\nu}g_e(u^{\frac{1}{2}})du=0, \; v>b^2. \quad \ldots\ldots (9c)$$

for $m=0, 1, 2, \ldots, [\frac{1}{2}\alpha]-1$.

Using (9*b*), equation (7) can be reduced to

$$v^{\frac{1}{2}\nu}g_e(v^{\frac{1}{2}})=\frac{1}{\Gamma(\beta)\Gamma(-\beta)}\int_0^{b^2}(v-w)^{-\beta-1}\int_0^w (w-u)^{\beta-1}u^{\frac{1}{2}\nu}g(u^{\frac{1}{2}})du \quad \ldots\ldots (10)$$

for $v>b^2$, where $\beta=\frac{1}{2}\alpha-[\frac{1}{2}\alpha]$.

By elementary work it can be shown that if (9*b*) and (10) hold, then (9*a*) follows. We will not show this.

Before reviewing our work, we make the following comments.

If in (10) we put $\nu=0$, $\frac{1}{2}\alpha=\beta$, $\frac{1}{2}<\beta<1$, $g(u^{\frac{1}{2}})=1$, we can show that $g_e(v^{\frac{1}{2}})\sim C(v-b)^{-\beta}$ as $v\to b+$, so $g_e(v^{\frac{1}{2}}) \notin L^2(b,\infty)$. Thus for $\frac{1}{2}<\beta<1$ additional conditions are required for $g_e(v^{\frac{1}{2}}) \in L^2(b,\infty)$. If we assume in (10) that $\int_0^w (w-u)^{\beta-1}u^{\frac{1}{2}\nu}g(u^{\frac{1}{2}})du$ is absolutely continuous with

$$\int_0^{b^2} (b^2-u)^{\beta-1}u^{\frac{1}{2}\nu}g(u^{\frac{1}{2}})du=0,$$

it is easy to show that $g_e(v^{\frac{1}{2}}) \in L^2(b,\infty)$ for all $0<\beta<1$.

Further, for $0<\beta<\frac{1}{2}$ it is sufficient to assume that $\int_0^w (w-u)^{\beta-1}u^{\frac{1}{2}\nu}g(u^{\frac{1}{2}})du$ is bounded to ensure that $g_e(v^{\frac{1}{2}}) \varepsilon L^2(b,\infty)$.

Changing the variables to the original variables in the summary, we have shown that the equations (1) and (2) have a solution $f(y)$ with $y^{\frac{1}{2}}f(y) \varepsilon L^2(0,\infty)$ if and only if $g(x)$ has an extension $g_e(x)$ with $x^{\frac{1}{2}}g_e(y) \varepsilon L^2(0,\infty)$, so that $K(x,\frac{1}{2}\alpha)=0$ for $x>b$.

When $\frac{1}{2}\alpha=m$, an integer, it is necessary and sufficient that

$$\int_0^b (b^2-w^2)^{m-p-1}w^{\nu+1}g(w)dw=0, \quad p=0, 1, \ldots, (m-1). \qquad \ldots\ldots\ldots (11)$$

In this case

$$g_e(x)=0, \quad x>b. \qquad \ldots\ldots\ldots (12)$$

If $\frac{1}{2}\alpha$ is not an integer, then it is necessary that

$$\int_0^b (b^2-w^2)^{\frac{1}{2}\alpha-m-1}w^{\nu+1}g(u)du=0 \qquad \ldots\ldots\ldots (13)$$

$m=0, 1, \ldots, [\frac{1}{2}\alpha]-2.$

In this case

$$g_e(x)=\frac{4x^{-\nu}}{\Gamma(\beta)\,\Gamma(-\beta)}\int_0^b (x^2-w^2)^{-\beta-1}wdw\int_0^w (w^2-u^2)^{\beta-1}u^{\nu+1}g(u)du \qquad \ldots\ldots\ldots (14)$$

where $\beta=\frac{1}{2}\alpha-[\frac{1}{2}\alpha]$.

For a solution, it is sufficient that $g(u)$ should satisfy (13) and that when $g_e(x)$ is defined by (14) $x^{\frac{1}{2}}g_e(x) \varepsilon L^2(b,\infty)$.

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(Received 6th March 1970)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 35–42, 1970

Devonian Stromatoporoids from the Broken River Formation, North Queensland

C. W. Mallett *

Abstract—Family Stromatoporellidae is considered to include all genera with a layer of cellules in the laminae (ordinicellular tissue) but the microstructure of the pillars is not critical, and may be compact, vacuolate, or tubulate. Five species are described from the Broken River Formation, of which three are new: *Stictostroma porosum* sp. nov., *S. pustulosum* sp. nov., *S. ? tubulosum* sp. nov. *S. ? tubulosum* has tubules piercing the tissue of both pillars and laminae. The variation in the distribution of pillars and laminae within each coenosteum and within the whole collection is given, to enable quantitative comparisons to be made with other collections.

Family Stromatoporellidae Lecompte

Stromatoporoids are common in the limestone members of the Broken River Formation on Pandanus Creek Station, Shield Creek Holding, north Queensland. The collection area is located on the Clarke River 1 : 250,000 map, sheet E/55B, Australian National Grid, approximately at latitude 19° 15′ S. and longitude 144° 45′ E. Pandanus Creek Station is 150 miles north-west of Charters Towers.

Members within the Broken River Formation have been defined by Jell (1968), who also described the rugose corals (Jell, 1967). The stratigraphic distribution of members in various parts of Pandanus Creek Station is indicated in Figure 1, and the locations of collections are shown. Fossils are stored in the Department of Geology and Mineralogy, University of Queensland, and are catalogued with fossil numbers (e.g., F. 47608) and fossil locality numbers (e.g., L. 3018).

The variation in the distribution of the pillars and laminae is given for the new species described. The tables have been based on five measurements of each parameter (number of laminae in 5 mm. in vertical section, number of pillars in 5 mm. in vertical section, number of pillars in 1 mm.^{2} in tangential section) in each coenosteum. For each parameter the following data are given.

M = The overall mean of all measurements in the collection (five measurements in each coenosteum).

σM = The standard deviation from the overall mean, of the means of the individual coenostea.

Lt = The limits of the means of the individual coenostea.

σm = The average standard deviation within coenostea from their respective means.

This information is sufficient to allow future comparisons with other specimens which are thought to belong to these species.

Where species are allocated to previously described species, only the limits of the means of values are given, as there are no descriptions in the literature sufficiently detailed to allow comparison of dimensions.

The measurements given in the descriptions are not intended as a key to speciation as the species are determined on the arrangement and structure of the skeletal elements as well as their dimensions. The dimensions and spacing, in practice, do serve as very good indicators of species in a preliminary examination of a collection, but they must be considered in association with other features.

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Order STROMATOPOROIDEA Nicholson and Murie, 1878

Family Stromatoporellidae Lecompte, 1951

Family Stromatoporellidae Lecompte, 1951, p. 152, 1956, p. F131; Nestor, 1966, p. 81.

Genus *Stromatoporella* Nicholson, 1886

Stromatoporella Nicholson, 1886, p. 92, 1891, p. 202; Parks, 1936, p. 90; Lecompte, 1951, p. 152, 1956, p. F131; Galloway and St. Jean, 1957, p. 129; Galloway, 1957, p. 436; Yavorsky, 1963, p. 19; Stearn, 1966, p. 93; St. Jean, 1967, p. 436; Flügel and Flügel-Kahler, 1968, p. 572.

Stromatoporella granulata Nicholson
Plate I, Figs. 1–2

Stromatopora granulata Nicholson, 1873, p. 94, pl. 4, figs. 3–3*a* (pars).

Stromatoporella granulata Nicholson, 1886*a*, p. 10, 1891, p. 202, pl. 1, figs. 4, 5, 15, pl. 4, fig. 6, pl. 7, figs. 5–6 ; Parks, 1936, p. 95, pl. 15, figs. 6–7, pl. 16, figs. 1–6 ; Ripper, 1937, p. 191, pl. 9, figs. 3–5 ; Lecompte, 1951, p. 160, pl. 21, fig. 1 ; Galloway and St. Jean, 1957, p. 131, pl. 7, figs. 3*a*–3*b* ; Stearn, 1966, p. 93, pl. 15, figs. 6, 7.

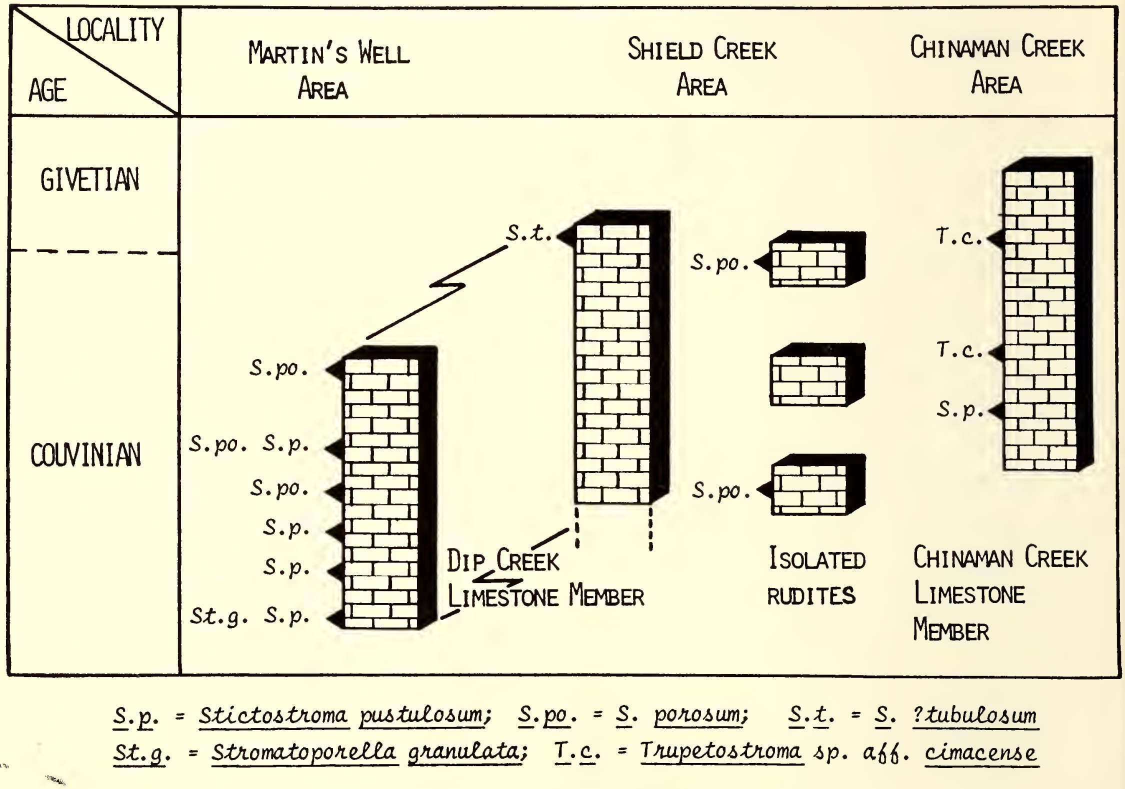

FIGURE 1.—Fossil localities in the Broken River Formation.

Holotype

Nicholson's specimen, No. 329 British Museum (Natural History), London, is from the Middle Devonian of the Hamilton Formation in the vicinity of Arkona (Givetian ?), Ontario, Canada.

Diagnosis

A non-encrusting species of *Stromatoporella* characterized by laminae 0·03–0·14 mm. thick, with 20–25 in 5 mm., and pillars 0·05–0·20 mm. diameter, with 18–25 in 5 mm. Ring pillars have a diameter 0·20–0·31 mm.

Description of Broken River Specimens

Laminae and pillars are composed of porous compact tissue. The exact nature of the microstructure is difficult to determine ; the tissue appears in two modes of preservation. The most common type is compact tissue composed of uniformly distributed specks 1–2μ diameter, which is crossed by elongated cellules 0·01 mm. diameter, that open into the galleries. Sometimes there is a clear axial zone. The other type of preservation shows the laminae bounded at top and bottom and crossed by clear tissue (similar to tubules), thus forming rectangular to subrounded cellules of compact tissue ; in tangential section the laminae appear as sheets of compact tissue, but in areas of good preservation cross-sections of tubular structures can be seen.

In *vertical section* laminae are 0·03–0·08 mm. thick, and there are 22–27 in 5 mm. They are continuous and undulate gently, except where they are upturned sharply to form ring pillars. Pillars are short, straight, and spool-shaped. Galleries are rectangular and have varying degrees of lateral extension, some up to 10 times as long as high. Dissepiments are common and are usually vertical. Astrorhizal systems are continuous through the whole thickness of the coenosteum, and are included in mamelons.

The coenosteum is pierced by syringoporids, but the coral does not disrupt or distort the laminae.

In *tangential section* laminae show many pores corresponding to the ring pillars. Normal pillars are round in cross-section with a diameter 0·05 mm. Ring pillars have a diameter 0·2 mm. and a lumen 0·10 mm. The ring pillars are distributed irregularly, some interlaminary spaces having only rare ring pillars, and others having up to 80% ring pillars. Approximately half of the pillars are ring pillars. There are 13–18 pillars and ring pillars in 1 mm.^{2} Curved dissepiments connect pillars and corallites of syringoporids, sections of syringoporids are prominent but are larger than ring pillars. Astrorhizae, 1–2 cm. apart, are contained in slight mamelons and surrounded by concentric laminae. From a group of axial canals, 0·3 mm. diameter, extensive branching networks of radiating canals, 0·2 mm. diameter, extend along interlaminary spaces, their outline being defined by dissepiments. The radiating canals can extend up to 1 cm. from the axial canals.

Genus *Stictostroma* Parks, 1936

Stictostroma Parks, 1936, p. 77 ; Lecompte, 1951, p. 132 ; Galloway and St. Jean, 1957, p. 124 ; Galloway, 1957, p. 435 ; Stearn, 1966, p. 96.

Discussion

The tissue is frequently altered, and the types of alteration which are found in the Broken River specimens are listed below.

(1) Compact tissue enclosing one or more layers of clear cellules (considered as the least altered) ; rare (Plate I, Fig. 5 ; Plate II, Fig. 1).
(2) Flocculent tissue enclosing one or more layers of dark concentrations 10–30μ in diameter ; fairly common.
(3) Transversely fibrous tissue with canals opening into galleries, or may be bordered at the top and bottom by dark flocculent marginal tissue ; common.
(4) Dark flocculent margins surrounding a clear axial zone ; rare.
(5) Laminae composed of flocculent to melanospheric tissue, with concentrations of the specks along the margins of the laminae ; very common.

Stictostroma pustulosum sp. nov.
Plate II, Figs. 1–3

Holotype

F.47994, from South Chinaman Creek at the base of the Chinaman Creek Limestone Member, Broken River Formation, on Pandanus Creek Station, north Queensland, Couvinian.

Diagnosis

A species of *Stictostroma* characterized by laminae with axial cellules 15×25μ, a thickness 0·06–0·12 mm. and with 19–27 in 5 mm. Pillars are frequently superimposed and have a diameter 0·06–0·18 mm., with 19–26 in 5 mm. and 19–30 in 1 mm.^{2} Astrorhizae are pustular 2–4 mm. diameter.

Description

The coenostea are encrusting or irregularly globular. They are usually enclosed in lime mud, and frequently incorporate mud in the structure. Mamelons do not occur on the surface.

Laminae are composed of compact tissue, with a central layer of cellules 15×25μ ; the cellules are vertically elongated. The membrane separating the cellules is 5–8μ thick. Tissue is frequently altered and the varying effects were described above in the discussion of the genus.

In *vertical section* laminae are continuous, subparallel, and slightly irregularly spaced. Some specimens show considerable irregularity, including other organisms and fine sediments. The average thickness of laminae varies from 0·06–0·12 mm. There are occasional breaks in the laminae corresponding to large pores. Pillars are usually superimposed, but this is variable. The pillars are spool-shaped, and their tissue frequently spreads on to the laminae.

Laminae are upturned for small areas around pustular astrorhizal systems, which have a diameter of 2–4 mm. Galleries are rounded, varying in diameter from 0·08–0·25 mm.

In *tangential section* laminae occur as sheets of cellular tissue, which are pierced by pores 0·1–0·15 mm. in diameter. The relatively thick laminae occupy a major part of the tangential sections. In cross-section pillars are approximately circular. Astrorhizal systems are well developed, and may be spaced at 5 mm. intervals.

The variation in the distribution of skeletal elements in 15 specimens is given in Table 1.

TABLE 1
The Distribution of Pillars and Laminae in Stictostroma pustulosum *sp. nov.*

Number of Laminae in 5 mm. Vertical Section	Number of Pillars in 5 mm. Vertical Section	Number of Pillars in 1 mm.² Tangential Section
M= 24·0 σM= 1·73 Lt= 19–27 σm= 1·52	M= 22·1 σM= 1·72 Lt= 19–26 σm= 1·41	M= 23·2 σM= 2·72 Lt= 19–30 σm= 1·59

Stictostroma porosum sp. nov.
Plate I, Figs. 3–5

Holotype

F.48244, from a locality on the Pandanus Creek-Wandovale Road, 2,000 m. south of Pandanus Creek Homestead, Pandanus Creek Station, north Queensland, Broken River Formation, Couvinian.

Diagnosis

A species of *Stictostroma* characterized by laminae containing one or more layers of axial cellules, 10–30μ in length, pierced by pores 0·2–0·5 mm. in diameter ; laminae thickness is 0·1–0·25 mm. and there are 9–14 in 5 mm. Pillars may be superimposed, with a diameter 0·05–0·20 mm., and there are 10–15 in 5 mm. and 5–11 in 1 mm.² Astrorhizae are pustular, 2–5 mm. diameter.

Description

The coenostea are irregularly globular. Small mamelons occur irregularly over the surface and contain pustular astrorhizal systems.

Laminae consist of one or more layers of cellules enclosed in compact tissue. The cellules vary in shape from square to rectangular, and are elongated in a vertical direction. The length of the sides of the square cellules is from 10–20μ, and when cellules are elongated vertically may attain 30μ. In some states of preservation lines of cellules appear as dark or light microlaminae with a thickness 10–20μ. The membranes separating the cellules are 10–20μ thick. Thicker laminae, up to 0·25 mm., often include several rows of cellules which are aligned regularly, and the membranes separating the cellules join to form microlaminae within the laminae. There may be as many as four in one lamina.

Pillars are composed of finely and coarsely vacuolate and melanospheric tissue, but no alignment or pattern of the cellules could be seen.

In *vertical section* laminae are evenly spaced, parallel, and gently undulating. There are numerous breaks in laminae corresponding to large pores. Laminae sometimes lens out laterally. The width of the laminae varies from 0·10–0·25 mm. Pillars are spool-shaped and are frequently superimposed through many laminae, but in other areas are restricted to one interlaminary space. Galleries are square or rectangular. Dissepiments do not occur. Astrorhizal systems are pustular with an average diameter of 2 mm., but some attain 5 mm. Axial canals, 0·3 mm. diameter, are occasionally present, and a few radiating canals 0·02 mm. diameter are usually seen.

In *tangential section* laminae occur as sheets of porous cellular tissue. They are commonly pierced by pores 0·2–0·5 mm. diameter. Breaks in the laminae in vertical section are partly explained by these pores, but discontinuities up to 1 mm. wide occur frequently. Circular structures resembling ring pillars occur, but they are always associated with laminae and represent sections through areas of laminae which have been thickened by the pillar tissue. The pillar diameters vary from 0·05–0·20 mm. In the centre of the interlaminary spaces pillars have their smallest diameter and are close to circular in cross-section. Near their junction with the laminae the pillars increase their diameter, and their cross-section alters to elliptical or irregular. Laminae are concentrically arranged around astrorhizal systems.

The variation in the distribution of pillars and laminae in 10 specimens is given in Table 2.

TABLE 2
Distribution of Pillars and Laminae in Stictostroma porosum *sp. nov.*

Number of Laminae in 5 mm. Vertical Section	Number of Pillars in 5 mm. Vertical Section	Number of Pillars in 1 mm.² Tangential Section
M= 12·0 σM= 0·76 Lt= 9–14 σm= 0·6	M= 11·9 σM= 1·11 Lt= 10–15 σm= 0·74	M= 8·1 σM= 0·93 Lt= 5–11 σm= 0·66

Stictostroma ? tubulosum sp. nov.

Plate II, Figs. 6–8

Holotype

F.47866, from 150 m. north-east of the creek crossing, 6·8 km. south of Pandanus Creek Homestead, Pandanus Creek Station, north Queensland; Dip Creek Limestone Member of the Broken River Formation, Givetian.

Diagnosis

A species assigned to *Stictostroma* characterized by laminae 0·03–0·20 mm. thick with 11–16 in 5 mm., which may be compact or have dark or clear axes, pillars, 0·07–0·18 mm. diameter, with 13–19 in 5 mm. in vertical section and 11–18 in 1 mm.^{2} in tangential section. Tissue is normally pierced by vertical tubules 0·02–0·04 mm. diameter, with 10–15 tubules in 0·5 mm.^{2} in tangential section.

Description

Coenostea can be laminar (non-encrusting), 2·5 cm. thick, or globular, up to 15 cm. in diameter. Low mamelons may be present on the surface.

Pillars and laminae are composed of compact tissue. This is all that can be seen in the usual preservation, but in some specimens there may be some concentration of specks along the centre of the laminae. Several of the better preserved specimens show the tissue pierced by vertical tubes 0·02–0·04 mm. in diameter. They are not observed over the whole of the vertical section, either because they were not developed or they have been destroyed. In tangential section they only occur in circular cross-sections, and are common in sections of pillars and laminae. There is usually only one in each pillar and 10–15 in 0·5 mm.^{2} of laminae. Clear axial zones are sometimes developed in laminae.

In *vertical section* the development of the laminae is variable, some areas having strong thick laminae and others having thin, almost discontinuous, laminae between the pillars. The thickness can vary from 0·03–0·20 mm. Pillars are spool-shaped and commonly superimposed, but may also be restricted to one interlaminary space. Their diameter varies from 0·07–0·18 mm. Galleries are rounded, reduced in size, and vary from elongated vertically to square and elongated horizontally. Astrorhizae may be present, and are 0·5 mm. high, with branching radiating canals, giving a diameter of 0·5 mm. Dissepiments may be numerous but some specimens have none.

The *tangential section* is occupied by a large percentage of tissue, due to the reduction in the size of the galleries. Laminae occur as thick porous sheets of compact tissue. They are pierced regularly by small pores 0·1–0·2 mm. diameter. In some areas the pores are so numerous that the laminae are reduced to a network of processes reminiscent of *Actinostroma*. Pillars are very irregular in shape, although in section they approximate to a circle. Curved, thin dissepiments less than 0·01 mm. thick join the pillars in the coenostea, in which they are present. Astrorhizal systems are spaced 0·5–1·0 cm. apart and have axial canals surrounded by 6–8 branching canals 0·1–0·2 mm. diameter.

The variation in the distribution of pillars and laminae in 10 specimens is given in Table 3.

TABLE 3

Distribution of Pillars and Laminae in Stictostroma ? tubulosum *sp. nov.*

Number of Laminae in 5 mm. Vertical Section	Number of Pillars in 5 mm. Vertical Section	Number of Pillars in 1 mm.^{2} Tangential Section
M= 13·3 σM= 1·6 Lt= 11–16 σm= 0·84	M= 16·1 σM= 1·2 Lt= 13·11 σm= 0·94	M= 14·9 σM= 1·6 Lt= 11–18 σm= 1·02

Remarks

This species has vertical tubules cutting the laminae and pillars, and the laminae also show dark and clear axes. Stromatoporoids with this type of structure have previously been described by Nicholson and Lecompte and placed in the genus *Stromatoporella*. The species showing this structure are *S. eifeliensis* Bargatzky, and to a lesser extent *S. solitaria* Nicholson. The tubules in the species from Broken River are usually vertical, but the tubules in the European species are in the centre of the laminae, not transverse across them.

The presence of tubules in *S. eifeliensis* has been reported by Nicholson (1892), Lecompte (1951) and Stearn (1966). Stearn stated that the microstructure corresponded to no described stromatoporoid genus, but that he included the species, for the time, in *Clathrocoilona*, until the tissue structure was found to be more widespread. It is significant that the structure of the Broken River species resembles that of *S. eifeliensis* in the number and arrangement of laminae and pillars, and that the tissue is pierced by tubules of a similar size. However, a new genus to embrace these forms is not at present proposed, as, firstly, the exact nature of the tubules is not known, and they could be the result of a parasitic or commensal relation with another organism, and secondly, the tubules are not observed in all specimens, though this could be due to the mode of preservation, as they are not visible in the holotype, where there is recrystallization.

If the tubular nature of the laminae and pillars is neglected, it is still very difficult to place the species within a genus with any certainty. The genus which shows the greatest similarity in arrangement of pillars and laminae is *Stictostroma* Parks, but the laminae in the Broken River specimens do not usually have an axial row of cellules, but are thin, compact, tubular, and discontinuous. Parts of some coenostea show tripartite laminae and reduced galleries, and thus conform better to the type species of *Stictostroma*. Stearn removed *S. eifeliensis* to the genus *Clathrocoilona*, but that species and Broken River species resemble *Stictostroma* more, particularly in the large, vertically elongated galleries.

The similarity of *Stictostroma ? tubulosum* sp. nov. to *Stictostroma eifeliensis* (Bargatzky) is quite marked. There is a similar number of laminae and pillars in 5 mm., but the laminae seem to be thicker and more continuous in *S. eifeliensis*. The tubules in the European species also seem to be in the centres of the laminae and pillars, whereas in the Broken River specimens they are usually transverse in the laminae and may occur at any position in the pillars.

Genus *Trupetostroma* Parks, 1936

Trupetostroma Parks, 1936, p. 52 ; Lecompte, 1952, p. 219 ; Galloway, 1957, p. 439 ; Yavorsky, 1963, p. 66 ; Stearn, 1966, p. 102 ; St. Jean, 1967, p. 430.

Discussion

The evidence from the single Broken River species supports the suggestion of Stearn (1966) that the clear or dark axial microlaminae originate from an original ordinicellular tissue. If this is correct the genus falls naturally into the family Stromatoporellidae as redefined by Nestor (1966).

Trupetostroma cimacense Lecompte

T. cimacense Lecompte, 1952, p. 234, pl. 41, fig. 3, pl. 42, fig. 1.

Holotype

Specimen No. 5137 in the Royal Institute of Natural Sciences, Brussels, which was collected from the Frasnian of Chimay, Belgium.

Trupetostroma sp. aff. *cimacense* Lecompte

Plate I, Figs. 6–8

Description

Coenostea are globular. The laminae are composed of clear microlaminae 0·02–0·03 mm. thick, surrounded by porous tissue. Pillars are composed of similar porous tissue, with round pores 0·04 mm. diameter distributed irregularly. The tissue is not preserved well, and is usually flocculent or melanospheric.

In *vertical section* laminae are continuous, evenly spaced and evenly curved, with a thickness 0·10–0·20 mm. The average number in 5 mm. for each coenosteum varies from 13–16. Pillars are superimposed and spool-shaped between laminae, with a diameter varying from 0·05–0·20 mm. The average number in 5 mm. for each coenosteum varies from 11–16. Laminae are upturned and grouped irregularly in the vicinity of astrorhizal systems.

In *tangential section* amalgamate tissue occupies a large part of the section, due to the reduced size of the galleries and the curved laminae, but areas of free standing pillars occur. The average number of pillars in 1 mm.^{2} varies from 8–13. Astrorhizae 0·10–0·15 cm. in diameter are spaced 8 cm. apart, and usually have a large axial canal 0·5 mm. diameter, with radiating branching canals 0·2–0·3 mm. diameter, and up to 8 mm. long. Galleries are reduced and rounded with a diameter of 0·13–0·18 mm.

Discussion

The specimens of this species show marked variation in dimensions and arrangement of skeletal elements, but none corresponds to any described species of *Trupetostroma*. As there are only three specimens, and they vary among themselves, there is not enough precise data to define a new species. Instead, it is compared with *T. cimacense* Lecompte, with which it shares many characteristics. Among the comparable features are the similar development of laminae and pillars in vertical section, amalgamate tissue in tangential section and prominent astrorhizae with many radiating branching canals. The main difference lies in the greater number of laminae in 5 mm. in vertical section in *T. cimacense*, 22–29 compared with 13–16 for the Australian forms. The vertical section of this species also resembles

T. warreni Parks in the continuous clear microlaminae, and the distribution of pores and vacuoles in the pillars, but is clearly distinguished by the amalgamate tissue in tangential section.

Stearn (1966, p. 105) considered that *Trupetostroma cimacense* Lecompte should be placed in the genus *Hermatostroma*, but there is no concentration of vacuoles or cellules near the borders of the pillars or laminae in Lecompte's illustrations.

Acknowledgements

This paper is part of a study of the stromatoporoids of the Broken River area submitted for a M.Sc. degree at the University of Queensland. The project was suggested and supervised by Professor Dorothy Hill. Dr. J. Jell kindly loaned some specimens and indicated many suitable localities for collecting material.

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Explanation of Plates

Plate I

Figs. 1–2.—*Stromatoporella granulata* Nicholson, F.47611 from locality L.2977, Dip Creek Limestone Member, Couvinian.

1. Tangential section, ×10.
2. Vertical section, ×10.

Figs. 3–5.—*Stictostroma porosum* sp. nov., F.48244, holotype, from a limestone rudite on the Pandanus Creek-Wandovale Road, 2,000 m. south of Pandanus Creek Homestead, Pandanus Creek Station, north Queensland, Couvinian or Givetian of the Broken River Formation, locality L.2698.

3. Vertical section, ×5.
4. Tangential section, ×5.
5. Vertical section, ×20.

Figs. 6–8.—*Trupetostroma* sp. aff. *cimacense* Lecompte, F.48153 from L.2510, Chinaman Creek Limestone Member, Givetian.

6. Vertical section, ×5.
7. Vertical section, ×30.
8. Tangential section, ×5.

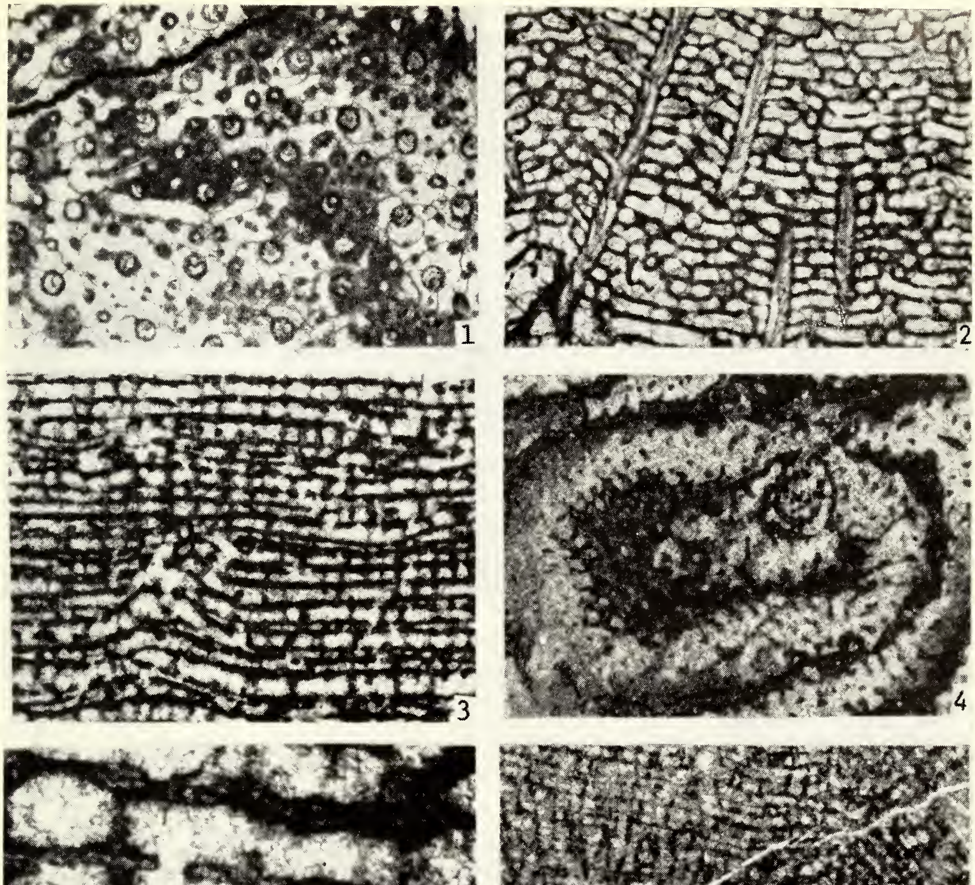
PLATE II

Figs. 1–4.—*Stictostroma pustulosum* sp. nov., F.47994, holotype, from the base of the Chinaman Creek Limestone Member, in Chinaman Creek South, Pandanus Creek Station, north Queensland, L.2509.

1. Vertical section, ×50.
2. Vertical section, ×5.
3. Tangential section, ×5.
4. Tangential section, ×20.

Figs. 5–8.—*Stictostroma ? tubulosum* sp. nov., F.47866, holotype, from the ridge, 150 m. N.E. of creek crossing, 6·8 km. south of Pandanus Creek Station Homestead, on Wandovale Road, Givetian.

5. Tangential section, ×5.
6. Vertical section, ×5.
7. Vertical section, ×30.
8. Tangential section, ×15.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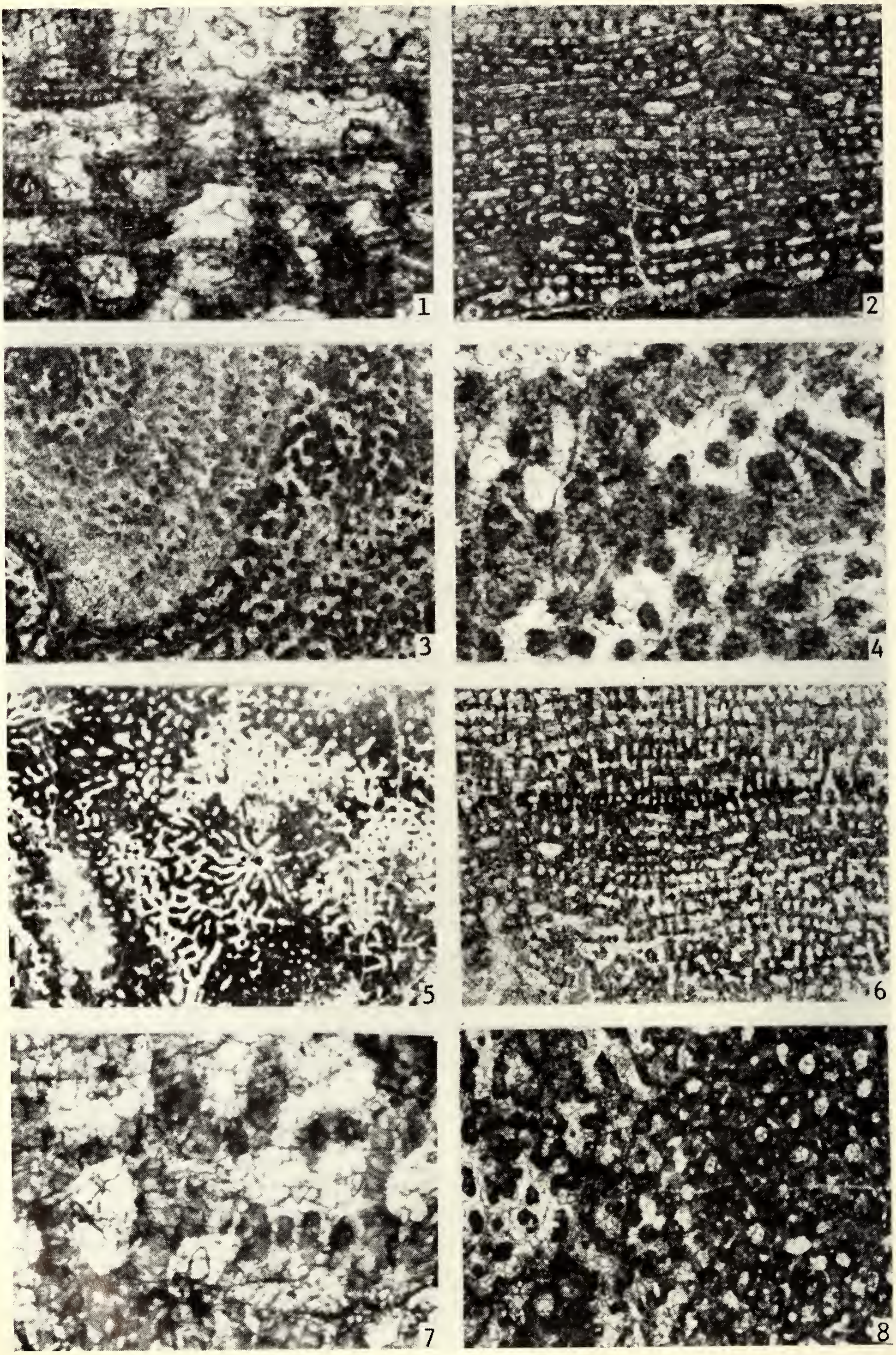
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Report of the Council for the Year Ended 31st March, 1969

Presented at the Annual General Meeting of the Society held 2nd April, 1969, in accordance with Rule 18 (*a*).

At the end of the period under review the composition of the membership was 360 members, 15 associate members, and 7 honorary members ; 23 new members were elected. Eleven members and two associate members resigned ; two names were removed from the list of members in accordance with Rule 5 (*b*).

It is with extreme regret that we announce the loss by death of :

Mr. William Lindsay Price (elected 1927).
Sir Harold George Raggatt (elected 1922).
Mr. Ethelbert Ambrook Southee (elected 1919).
Dr. Frederick G. N. Stephens (elected 1914).
Dr. Andrew Ungar (elected 1952).
Dr. Hans Samuel Arthur Rosenthal (elected 1961). (associate member).

Nine monthly meetings were held. The abstracts of all addresses have been printed on the notice paper. The proceedings of these will appear later in the issue of the *Journal and Proceedings*. The members of Council wish to express their sincere thanks and appreciation to the 11 speakers who contributed to the success of these meetings, the average attendance being 58.

The May meeting was a combined meeting with Middle Harbour Group of the N.S.W. Association of the University Women Graduates.

The September meeting was held at the Wollongong University College, and the programme included a buffet meal and a tour of the grounds.

The Annual Social Function was held at the University of New South Wales Union and was attended by 51 members and guests.

The Council has approved the following awards :

The *Clarke Medal* for 1969 to Professor S. W. Carey, D.Sc., Department of Geology, University of Tasmania.

The *Society's Medal* for 1968 to Mr. H. H. G. McKern, Deputy Director, Museum of Applied Arts and Sciences, Sydney.

The *Walter Burfitt Prize* for 1968 to Professor L. E. Lyons, Ph.D., of Chemistry Department, University of Queensland.

The *Edgeworth David Medal* for 1968 to Dr. Robert M. May, of the Department of Physics, University of Sydney.

The *Archibald D. Ollé Prize* was not awarded.

The Seventeenth Liversidge Research Lecture was delivered by Professor R. D. Brown, Ph.D., F.A.A., of the Department of Chemistry, Monash University, Victoria, on 17th July. The title of the lecture was " Where are the Electrons ? ".

The Society has again received a grant from the Government of New South Wales, the amount being $1,500. The Government's continued interest in the work of the Society is much appreciated.

The Society's financial statement shows a surplus of $2,864.07.

The New England Branch of the Society's meetings will be included in the proceedings of the Branch, to follow.

The President represented the Society at the Commemoration of the Landing of Captain James Cook at Kurnell ; at the Reception to meet members of the Administrative Board of the International Association of Universities ; and at the Dinner held on the occasion of the Tenth Commonwealth Universities Congress.

The Senior Vice-President, Professor A. H. Low, represented the Society at a State Luncheon held in honour of His Royal Highness the Duke of Edinburgh.

The President attended the annual meeting of the Board of Visitors of the Sydney Observatory.

We congratulate Mr. G. P. Whitley, F.R.Z.S., Honorary Associate of the Australian Museum, on the award of the Australian Natural History Medallion for 1967.

The Society's representatives on Science House Management Committee were Mr. H. F. Conaghan and Mr. J. W. G. Neuhaus.

Two parts of the *Journal and Proceedings* have been published during the year, and Parts 3–4 are to be issued before the end of April.

The Centenary Volume, entitled " A Century of Scientific Progress ", was issued during October, 1968.

A television programme of half-hour sessions publicizing the Centenary Volume of the Society appeared on Channel ATN 7 during the latter part of the year (1968).

During the year restoration work was carried out on the portraits of the Rev. W. B. Clarke and Professor John Smith.

A new Branch, to be called the South Coast Branch of the Royal Society of New South Wales, was formed on 29th March, 1969.

Council held 11 ordinary meetings and one special meeting, and the attendance was as follows : Prof. A. Keane, 12 ; Mr. Conaghan, 4 ; Dr. Day, 9 ; Prof. Le Fevre, 6 ; Prof. Low, 8 ; Prof. Voisey, 9 ; Mr. Neuhaus, 9 ; Mr. Poggendorff, 7 ; Prof. Griffith, 11 ; Mrs. Krysko v. Tryst, 11 ; Mr. Burg, 4 ; Mr. Cameron, 10 ; Mr. Griffin, 3 (resigned from Council in September) ; Mr. Kitamura, 12 ; Mr. Pollard, 9 ; Mr. Puttock, 11 ; Mr. Robertson, 7 ; Prof. Smith, 11 ; Prof. Stanton (N.E. representative), 1.

The Library.—During the year a referendum regarding retention or disposal of the Library was held, the result being 72 for retention and 80 for disposal. Forty-four voted for disposal by gift, and 93 for disposal by sale.

Periodicals were received by exchange from 393 societies and institutions. In addition, the amount of $303.57 was expended on the purchase of 11 periodicals. Repairs to the binding of some of the rarer sets of periodicals amounted to $245.

Among the institutions which made use of the Library through the inter-library loan scheme were :

N.S.W. Government Departments : Agriculture ; Electricity Commission ; Geological Survey ; South-West Regional Library, Young ; State Office Block Library ; Water Conservation and Irrigation Commission.

Commonwealth Government Departments : Australian Atomic Energy Commission ; Commonwealth Acoustics ; Labour and National Service ; National Biological Standards ; C.S.I.R.O. Divisions : Library, Canberra ; Animal Genetics, Prospect ; Coal Research ; Fisheries and Oceanography, Cronulla ; Food Preservation, Ryde ; National Standards Laboratory ; Radiophysics Library ; Soils, South Australia ; Textile Physics, Ryde ; Chemical Research, Melbourne ; Tropical Pastures, Brisbane.

Universities and Colleges : Australian National University ; Macquarie University ; University of New England ; University of Newcastle ; University of New South Wales, Main Library ; Bio-medical Library ; University of Sydney ; University of Queensland ; University of Western Australia ; Broken Hill University College ; Townsville University College.

Companies : A.C.I. Ltd., A.I. & S. Co. Ltd., AMDEL. C.S.R. Co. Ltd. (H.O.), Commonwealth Steel Co. Ltd., International Engineering Service Consortium Pty, Ltd., Kodak Pty. Ltd., Unilever, A. Webster Pty. Ltd.

Research Institutes : Children's Hospital, St. Vincent's Hospital, B.H.P. Co. Ltd., C.S.R. Co. Ltd. (Research Laboratories), Institute of Dental Research, Riker's Laboratory.

Museum : The Australian Museum.

Miscellaneous : Australian Medical Association ; Geological Survey (Qld.) ; Institution of Engineers, Aust. ; Mt. Stromlo Observatory ; Dept. of Primary Industry, Brisbane ; Royal Society of South Australia Inc.

Total borrowings for the year : 368.

J. L. Griffith,
Honorary Secretary.

2nd April, 1969.

Honorary Treasurer's Report

I am pleased to report that the Society has had a good year financially. A deficit of $480 for the year ended March, 1968, has been converted into a surplus of $2,864. The main contributing factors were a substantial increase in the moneys received as the Society's share of Science House surplus, namely $8,415, compared with $5,537 for 1967–68, and the sale of three sets of the *Journal and Proceedings* yielded $1,350.

The long-awaited centenary volume was published late in 1968. This volume, perhaps the most ambitious venture in the Society's history, cost $9,469, excluding advertising. The Department of Education had made a grant in 1966 of $4,000 towards the printing of this book. On delivery of 1,000 copies the Department made a further payment of $1,000. The generous attitude of the Department of Education has greatly relieved the financial burden of publication and has ensured a measure of success for the book. Nevertheless, more than half the volumes remain unsold. As it is expected that sales will continue, the unsold copies are shown as an asset.

The policy of repairing rare and valuable books has been continued, resulting in the expenditure of $245. The cost of subscriptions to journals has again increased, and some $310 were spent on this item.

The cost of publishing the Society's *Journal and Proceedings* has continued to rise—$2,165 for the year ended March, 1969. The increase of $374 was largely due to increased printing charges.

It should be noted that membership subscriptions do not cover the cost of publication of the *Journal.*

The increase noted under the item Salaries in the balance sheet was due to the increases in the basic wage.

J. W. G. Neuhaus,
Honorary Treasurer.

Abstract of Proceedings

3rd April, 1968

The one hundred and first Annual and eight hundred and twenty-sixth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Associate Professor A. H. Low, was in the chair. There were present 30 members and visitors.

Colin Rex Ward was elected a member of the Society.

The following awards of the Society were announced :

The Society's Medal for 1967 : Mr. A. F. A. Harper.

The Clarke Medal for 1968 : Professor H. G. Andrewartha, F.A.A.

The Edgeworth David Medal for 1967 : Joint award made to Dr. D. H. Green and Dr. W. J. Peacock.

The Archibald D. Ollé Award to Dr. J. R. Conolly.

The Annual Report of the Council and the Financial Statement were presented and adopted.

Office-bearers for 1968–69 were elected as follows :

President : A. Keane, Ph.D.

Vice-Presidents : H. F. Conaghan, M.Sc., Alan A. Day, Ph.D. (Cantab.), R. J. W. Le Fevre, D.Sc., F.R.S., F.A.A., A. H. Low, Ph.D., A. H. Voisey, D.Sc.

Hon. Treasurer : J. W. G. Neuhaus, M.Sc.

Hon. Librarian : W. H. G. Poggendorff, B.Sc.Agr.

Hon. Secretaries : J. L. Griffith, B.A., M.Sc. (General), (Mrs.) M. Krysko v. Tryst, B.Sc., Grad.Dip. (Editorial).

Members of Council : R. A. Burg, A.S.T.C., J. C. Cameron, M.A., B.Sc. (Edin.), D.I.C., R. J. Griffin, B.Sc., T. E. Kitamura, B.A., B.Sc.Agr., J. P. Pollard, Dipp.Appl.Chem., M. J. Puttock, B.Sc.(Eng.), A.Inst.P., W. H. Robertson, B.Sc., W. E. Smith, Ph.D. (N.S.W.), M.Sc. (Syd.), B.Sc. (Oxon.).

Horley & Horley were re-elected Auditors to the Society for 1968–69.

The following papers were read by title only :

" Mesozoic Geology of the Gunnedah-Narrabri District ", by J. A. Dulhunty.

" Some Blockstreams of the Toolong Range, Kosciusko State Park, N.S.W.", by N. Caine and J. N. Jennings.

The retiring President, Associate Professor A. H. Low, delivered his Presidential Address, entitled " Initial Value Problem in Two-Dimensional Water Wave Theory ".

The retiring President then welcomed Professor Keane to the Presidential Chair.

1st May, 1968

The eight hundred and twenty-seventh General Monthly Meeting, which was a combined meeting with the Middle Harbour Group of the N.S.W. Association of the University Women Graduates, was held in the Hall of Science House, 157 Gloucester Street, Sydney, at 7.45 p.m.

The President, Professor A. Keane, was in the chair. There were present 84 members and visitors.

The following were elected members of the Society : John Hamilton Bryan, Philip Richard Evans, Brian Bertram Guy, Reginald Leslie Hardwick, Michael John Randal Mackellar, James Albert Morgan, Peter Joseph O'Halloran, Ralph William Suters and Albertus Theodorus van Brakel.

The following paper was read by title only : " Magnetic Studies of the Canobolas Mountains, Central Western New South Wales ", by R. A. Facer.

An address entitled " Chemicals and Human Happiness " was delivered by Professor J. M. Swan, Professor of Organic Chemistry, Monash University, Victoria.

5th June, 1968

The eight hundred and twenty-eighth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor A. Keane, was in the chair. There were present 52 members and visitors.

The following paper was read by title only : " The Geology of the Narooma Area, N.S.W.", by C. J. L. Wilson.

An address entitled " The Interpretation of Special Relativity—Its Relevance to Recent Cosmological Observations " was delivered by Mr. S. J. Prokhovnik, M.A., B.Sc., of the School of Mathematics, The University of New South Wales, Kensington.

3rd July, 1968

The eight hundred and twenty-ninth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor A. Keane, was in the chair. There were present 62 members and visitors.

It was announced that the Seventeenth Liversidge Research Lecture would be delivered by Professor R. D. Brown, Ph.D., F.A.A., of the Department of Chemistry, Monash University, Victoria. The title of the lecture is " Where are the Electrons ? " and will be held in Lecture Theatre No. 2, School of Chemistry, University of Sydney, on Wednesday, 17th July, 1968, at 5.30 p.m.

Members were informed that at the meeting of the Council held 28th May, 1968, it was decided to introduce a new By-law, reading as follows :

Annual Reports and Inspections.

(*a*) It shall be the duty of the President, Vice-Presidents, Hon. Treasurer, Hon. Secretaries and Hon. Librarian at least once annually to examine and report to the Council upon the state of

(i) the Society's house and effects,
(ii) the keeping of the official books and correspondence,
(iii) the library, including maps and drawings,
(iv) the Society's cabinets and collections.

(*b*) The keepers of the Society's cabinets and collections shall give a list of the contents and report upon the condition of the same to the Council annually.

(*c*) The Hon. Secretaries and the Hon. Treasurer shall see that all documents relating to the Society's property, the obligations given by members, the policies of insurance, and other securities shall be lodged in a safe deposit, the receipt for which shall be kept, and such list shall be signed by the President or one of the Vice-Presidents at the annual inspection.

As no resolution to the contrary was moved, the above, in accordance with Rule 25, now becomes By-law 15.

The following paper was read by title only: "The Petrography of a Coal Seam from the Clyde River Coal Measures, Clyde River Gorge, N.S.W.", by A. C. Cook and H. W. Read.

An address entitled "The National Geodetic and Topographic Survey of Australia" was delivered by Mr. B. P. Lambert, Director, Department of National Mapping, Canberra, A.C.T.

7th August, 1968

The eight hundred and thirtieth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney, at 7.45 p.m.

The President, Professor A. Keane, was in the chair. There were present 46 members and visitors.

The following were elected members of the Society: N. Edith Lack and Peter Henry Wilibald Korber.

The following papers were read by title only: "The Film Badge Service in New South Wales", by A. W. Fleischmann; "The Geology of the Manildra District, New South Wales", by N. M. Savage.

An address entitled "New Foods—A Look in the Crystal Ball" was delivered by Dr. F. H. Reuter, Associate Professor of Food Technology, The University of New South Wales, Kensington.

4th September, 1968

The eight hundred and thirty-first General Monthly Meeting was held at Wollongong University College, Wollongong, at 8.00 p.m.

The President, Professor A. Keane, was in the chair. There were present 85 members and visitors.

A paper entitled "A Note on Convex Distributions", by J. L. Griffith, was read by title only.

The following addresses were delivered: "The Royal Society of New South Wales", by J. L. Griffith, Hon. Secretary of the Society; "High Resolution Observations of Solar Flares", by R. G. Giovanelli, F.A.A., C.S.I.R.O. Division of Physics, Sydney; "Twentieth Century Breeding", by B. J. Doyle, Director, Artificial Breeding Centre, Berry.

2nd October, 1968

The eight hundred and thirty-second General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney, at 7.45 p.m.

The President, Professor A. Keane, was in the chair. There were present 35 members and visitors.

The following were elected members of the Society: Alan Cecil Cook, Ian Harry Hackett, Robert Henry Goodwin and Robert William Upfold.

A paper entitled "A Tessellated Platform, Ku-ring-gai Chase, N.S.W.", by D. F. Branagan, was read by title only.

An address entitled "Recent Advances in the Earth Sciences" was delivered by Dr. J. J. Veevers, of the School of Earth Sciences, Macquarie University, North Ryde.

6th November, 1968

The one hundred and thirty-third General Monthly Meeting was held in the Hall of Science House, Sydney, at 7.45 p.m.

The President, Professor A. Keane, was in the chair. There were present 52 members and visitors.

The Chairman announced the death of Sir Harold George Raggatt, on 2nd November, 1968, a member since 1922.

The following were elected members of the Society: James Edgar Osbourne Beale, Arthur Joseph Gilks, Peter Marcus Martin.

The following paper was read by title only: "Progressive and Retrogressive Metamorphism in the Tumbarumba-Geehi District, N.S.W.", by B. B. Guy.

Address.—The President of the Sydney Speleological Society, Mr. Ben Nurse, gave an address on the caves at Colong and Church Creek. Faun, geology and historical background were discussed. The address was illustrated with films and slides of the caves and reserve.

4th December, 1968

The eight hundred and thirty-fourth General Monthly Meeting was held in the Hall of Science House, Sydney, at 7.45 p.m.

The President, Professor A. Keane, was in the chair. There were present 71 members and visitors.

The following were elected members of the Society: Emery Gellert, Francis Michael Hall, Frances Wheelhouse and Dennis Edwin Winch.

The following papers were read by title only: "The Martiniacean Species Occurring at Glendon, New South Wales, the Type Locality of *Notospirifer darwini* (Morris)", by John Armstrong; "Mesozoic Stratigraphy of the Narrabri-Couradda District", by J. A. Dulhunty.

An address entitled "Geology, Mythology and Classical Buildings in Greece" was delivered by Dr. Ilias Mariolakos of the Institute of Geology and Palaeontology, University of Athens, Greece.

THE ROYAL SOCIETY OF NEW SOUTH WALES

BALANCE SHEET AS AT 28th FEBRUARY, 1969

LIABILITIES

1968		$	$
$			
38	Accrued Expenses		—
46	Subscriptions Paid in Advance		61.10
128	Life Members' Subscriptions—Amount carried forward		115.50
	Trust Funds (detailed below) :		
4,268	Clarke Memorial	4,444.11	
2,528	Walter Burfitt Prize	2,590.34	
1,496	Liversidge Bequest	1,439.10	
606	Ollé Bequest	630.26	
			9,103.81
4,000	Centenary Volume—Amount held in Reserve		—
57,287	Accumulated Funds		60,011.47
8,425	Library Reserve Account		8,898.49
	Contingent Liability (in connection with Perpetual Lease)		
$78,822			$78,190.37

ASSETS

1968		$	$
6,306	Cash at Bank and in Hand		2,223.66
	Investments—		
	Commonwealth Bonds and Inscribed Stock—At Face Value—held for :		
3,600	Clarke Memorial Fund	3,600.00	
2,000	Walter Burfitt Prize Fund	2,000.00	
1,400	Liversidge Bequest	1,400.00	
9,680	General Purposes	9,680.00	
			16,680.00
541	Fixed Deposit—Long Service Leave Fund		547.94
	Debtors for Subscriptions	314.60	
	Less Reserve for Bad Debts	314.60	
—			—
30,470	Science House—One-third Capital Cost		30,470.43
13,600	Library—At Valuation		13,600.00
9,600	Library Investment—Special Bonds		9,600.00
1,601	Furniture and Office Equipment — At Cost, *less* Depreciation		1,590.70
22	Pictures—At Cost, *less* Depreciation		20.58
2	Lantern—At Cost, *less* Depreciation		2.00
	Centenary Volume :		
	Stock	3,253.28	
	Reprints	201.78	
—			3,455.06
$78,822			$78,190.37

TRUST FUNDS

	Clarke Memorial	Walter Burfitt Prize	Liversidge Bequest	Ollé Bequest
	$	$	$	$
Capital at 28th February, 1969	3,600.00	2,000.0	1,400.00	—
Revenue—				
Balance at 29th February, 1968 ..	668.29	527.61	96.52	605.76
Income for Period	176.32	97.82	69.12	84.50
	844.61	625.43	165.64	690.26
Less : Expenditure	0.50	35.09	126.54	60.00
	$844.11	$590.34	$39.10	$630.26

ACCUMULATED FUNDS

	$	$
Balance at 29th February, 1968		57.287.31
Add : Surplus for Period		2,864.07
		60,151.38
Less :		
Increase in Provision for Bad Debts	114.71	
Subscriptions Written Off	25.20	
		139.91
		$60,011.47

Auditors' Report

The above Balance Sheet has been prepared from the Books of Account, Accounts and vouchers of the Royal Society of New South Wales and is a correct statement of the position of the Society's affairs on 28th February, 1969, as disclosed thereby. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

HORLEY & HORLEY,
Chartered Accountants.

Registered under the Public Accountants
Registration Act 1945, as amended.

65 York Street,
Sydney.
20th March, 1969.

(Signed) J. W. G. NEUHAUS,
Hon. Treasurer.

A. KEANE,
President.

INCOME AND EXPENDITURE ACCOUNT

1st MARCH, 1968, TO 28th FEBRUARY, 1969

1968 $			$
51	Advertising		58.80
58	Annual Social		58.88
80	Audit		100.00
50	Branches of the Society		50.00
312	Cleaning		300.90
85	Depreciation		84.80
72	Electricity		71.78
18	Entertainment		24.83
83	Insurance		104.19
295	Library Purchases	$310.17	
	Library Binding	245.00	
			555.17
449	Miscellaneous		417.61
299	Postages and Telegrams		444.57
	Printing—Journal—Vol. 101, Parts 1–2	$2,041.95	
	Binding Vol. 100	65.00	
	Postages	115.35	
3,286			2,222.30
189	Printing—General		180.66
2,983	Rent—Science House Management		4,159.00
5	Repairs		41.42
—	Restoration of Portraits		75.00
3,094	Salaries		3,323.01
82	Telephone		87.83
			12,360.75
—	Surplus for the Period		2,864.07
$11,491			$15,224.82

1968 $		$
1,973	Membership Subscriptions	2,267.15
12	Proportion of Life Members' Subscriptions	12.60
1,500	Government Subsidy	1,500.00
5,537	Science House Management—Share of Surplus	8,415.66
490	Interest on General Investments	470.12
4	Donations	6.05
725	Sale of Reprints	356.55
705	Subscriptions to Journal	840.47
35	Sale of Back Numbers	1,299.12
30	Refund—Postages	57.10
480	Deficit for the Period	—
$11,491		$15,224.82

Section of Geology

Abstract of Proceedings, 1968

Five meetings were held during this year, the average attendance being about 14 members and visitors.

MARCH 15th (Annual Meeting) :

(1) Election of office-bearers : Chairman, Mr. E. K. Chaffer ; Hon. Secretary, Mr. C. R. Ward.

(2) Address by Mr. K. Glasson, " The Iron Ore of the Hamersley Ranges ". In his review, Mr. Glasson covered the early history of exploration of the area and then proceeded to discuss the stratigraphic sequence which has been adopted by the Western Australian Geological Survey in its recent Bulletin, No. 117.

He pointed out that in the Hamersley Group there were three major iron formations : Boolgeeda Iron Formation, 700 ft. ; Hamersley Iron Formation, 2,200 ft. ; Marra Mamba Iron Formation, 600 ft. These iron formations in the Hamersley Group were part of a vast period of sediments formed by chemical deposition in the Lower Proterozoic, which followed the clastic sediments and basic volcanics of the Fortesque Group.

The Brockman Iron Formation is the most important from the economic point of view, since both the Mt. Tom Price and Mt. Whaleback deposits are associated with this formation in structurally complex areas, where supergene processes over a long period of time (i.e. since early Palaeozoic age) have permitted enrichment of the original iron beds.

Considerable discussion arose as to the origin of the banded iron formations. The talk was illustrated by slides, and in addition a collection of various lithologies were available for examination.

MAY 17th :

Three addresses : (1) Dr. D. F. Branagan, (2) Mr. L. H. Hamilton, (3) Mr. E. J. Minty.

(1) Dr. D. F. Branagan, " Palaeovulcanology in N.S.W.". Volcanic activity in New South Wales has been a feature of almost every geological period. Details of the distribution in time and space were given, and the stratigraphic importance of volcanic rocks in the geological history of the State was briefly discussed.

The oldest recognizable volcanic rocks occur north of Broken Hill, and appear to pre-date the Torrowangee Group of Proterozoic age. Neither these nor the Cambrian volcanics to the east are particularly extensive.

Volcanic activity in the Lachlan Geosyncline in the Lower Palaeozoic produced thick and extensive sequences and are common along geanticlines. These were followed by Upper Devonian acid volcanics, and then by intermediate dacitic and trachytic types in the Carboniferous.

Permian volcanics and intrusives occur in the Sydney Basin, but there is very little in the Triassic except for tuffs in the Clarence Moreton Basin. Basaltic flows of Jurassic age occur near Merrygoen, and the alkaline intrusives of the Sydney Basin are also dated as Jurassic.

The Cretaceous period saw little activity, but Tertiary volcanics are extensive. Trachytes and basalts were common, and centres such as Mt. Canobolas, the Warrumbungle Mountains and Mt. Warning area are also developed.

Dr. Branagan concluded by indicating a few of the still unsolved problems of stratigraphic significance in N.S.W. vulcanicity.

(2) Mr. L. H. Hamilton, " Origin of the Breccia Pipes in the Region of Sydney ". An intrusive origin was postulated by Wilshire (1961) for the breccia pipes in the region of Sydney, based mainly on the occurrence of underformed shale over the Richardson's Farm pipe and on the occurrence of folded country rock. He proposed that fluidization took place at depth and near their present outcrop positions the pipes were emplaced by wedging. New evidence does not support this theory.

Coal fragments in the breccia have not been carried upward from Permian strata, but instead are Triassic age and have moved slightly downward. Centroclinal dips of the wall rocks in a highly deformed peripheral zone are much more suggestive of slumping than compressional folding. At some localities where Hawkesbury sandstone is the exposed wall rock signs of wall rock deformation are generally lacking. Many of the volcanic fragments in the breccia are highly amygdaloidal and fine-grained to glassy. Glass shales have also been found in the breccia.

The intrusive theory does not adequately account for the space occupied by the breccia (there is no evidence of piston-like displacement), or the low pressure and rapid cooling required by the vesiculation, fragmentation and supercooling of the magma which produced the bulk of the material in the pipe.

The breccia pipe at Richardson's Farm could represent a buried volcano. This would account for the shale cover and would imply a Triassic age for the volcano. Alternatively, and less probably, the cover may be accounted for by inclined vents. An intrusive volcanic origin is postulated for the breccia pipes. The volcanoes were probably similar to those which have produced Recent maars in western Victoria.

(3) Mr. E. J. Minty, " Modern Views on the Prospect Intrusion ". The geometry of the igneous intrusion at Prospect and the distribution of rock types within it were described using colour slides and geological maps. A brief review of the historical aspects of the discovery of the lopolith and its development as a quarry was presented, covering the period since the first published notes in the early nineteenth century.

An important feature is the evidence of the sinking of the roof into the centre of the intrusion, and the dynamic implications of this were discussed. It was also noted that the surrounding shales of the Wiannamatta Group were indurated to a greater distance away from the intrusion beneath the lopolith than they were above it.

The genesis of the various phases was discussed, including the chilled margin of basalt, the basal picrite phase and the occurrence of disconnected pods of pegmatite material.

Petrographical features which have a bearing on the suitability of the various rock types quarried included both mineralogy and texture. This becomes especially important where the rock is to be subject to alternate exposure to air and water.

It was also noted that a shear zone, lying north-south in the shales of the Wiannamatta Group, intersects the Prospect lopolith. This may represent the location of the feeder channel along which magma was injected.

JULY 29th :

Dr. B. J. Warris, " Ordovician Conodonts in Regional and Intercontinental Correlation ". The area of study covered some 10,000 square miles in north-western N.S.W. and contained a composited section of 68,000 feet of Proterozoic, Cambrian, Ordovician and Devonian sediments. The Ordovician was marine and richly fossiliferous, the best locality being at Mount Arrowsmith, where some 5,000 specimens of conodonts were extracted.

This conodont fauna was identical to that from the Horn Valley Siltstone of the Amadeus Basin, and confirmed the general correlations based on lithology and the trilobite fauna.

On a world-wide basis, the fauna contained a mixed Lower and Middle Ordovician assemblage, and this created a problem. However, the Middle Ordovician forms were all new species, while the Lower Ordovician forms could all be recognized to species level. This suggested that the fauna was Lower Ordovician, and that the Middle Ordovician North American type genera, developed earlier in Australia and migrated to North America.

At an attempt for finer correlation, the Mount Arrowsmith succession could be subdivided into three assemblage zones. These zones were independent of lithology and the macrofauna and were deemed to be true evolutionary zones. In ascending order they are : (i) *Scolopodus ex* (150 ft.), (ii) *Paltodus volchoversis* (150 ft.), and (iii) *Oepikodus multidentatus-Gothodus communis* (300 ft.). Assemblage zones (i) and (ii) correlate with conodont assemblage from the *Asaphus broggeri* and *Megalaspis planilimbata* trilobite zonules (Lower Arenig) of the Baltic Shield, while assemblage zone (iii) correlates with the *Grothodus communes-Oepikodus multidentatus* faunas from the Upper Arenig of western North America. By careful analysis an Arenig age was established for this fauna.

It is believed that conodonts are the internal skeletal supports of an unknown animal. This animal is not a fish, annelid worm or any familiar group ; it is a conodont, a unique animal of unknown appearance. It is probably both benthonic and pelagic, based on what has been outlined in this lecture.

SEPTEMBER 20th :

Dr. F. M. Quodling, " Rock Types and Landscape in Norway ". During this meeting Dr. Quodling showed coloured slides and specimens of her trip to Norway for five weeks in 1967.

Of particular interest were various gneisses and porphyroblastic schists of Verma and Skei ; banded granite gneisses of Hammerfest and North Cape ; schists quarried as roofing slates, in the Arctic region near Alta and from the same thrust plate from Vaenangefjellet ; schists showing conspicuous shear strain effects with grooving on schistosity planes. Discussed also were a blue quartz rock from Vatnahalsen, anorthosite mined at special aggregate and garnet amphibolites from Mjolfjell, all from thrust sheets on nappes further south, adjacent to Sognefjord.

Then some geomorphological aspects were considered. Fjord topography was illustrated by the contrased geiranger and Langs fjords, glacial valleys between Andalsnes and Dombas in the Western Fjord country viewed ; valley glaciers, extensions from the Jostedal Plateau Ice Field were illustrated ; so too were glaciers at Langs fjord, where, due to high latitude, they descend to sea-level. Here too cirques, corries and fantastically ice-sculptured rocks were brought to members' attention.

NOVEMBER 15 :

Professor F. C. Loughnan, " The Tonstein Controversy ". The term tonstein as originally proposed by Bishoff was defined and it was shown that, in its present usage, the term is ambiguous.

Similarities between the kaolin-coal tonsteins of Europe and the flint clays of the U.S.A. and South Africa, and also the bauxitic clays of Scotland and the Russian Platform, were pointed out. This was followed by a brief account of the " tonstein " occurrences in N.S.W

A discussion of the origin of these ricks and their implications on palaeoclimates was presented.

The talk was illustrated with projector slides and some specimens.

Report of the South Coast Branch of the Royal Society of New South Wales

The South Coast Branch was initiated at a meeting at the Wollongong University College on 26th March, 1969. Nine members of the Society were present, these being Mr. A. Cooke, Associate Professor E. Gellert, Mr. J. Gilks, Mr. F. Hall, Professor A. Keane, Mr. P. O'Halloran, Dr. J. Stephens, Mr. R. W. Upfold and Associate Professor C. A. Wilkins.

A Committee was elected, consisting of :

Chairman : A. Keane.
Vice-Chairman : E. Gellert.
Secretary : R. W. Upfold.
Treasurer and Representative on the Council : Mr. P. O'Halloran.

The meeting discussed the possible forms that future meetings would take and decided that an inaugural meeting should be held within the next two months. The Chairman was asked to investigate means to make this a memorable occasion.

In addition to those listed above, the following six members are also within the area of the South Coast Branch : Mr. C. Chiarella, Mr. E. Beale, Mr. R. Facer, Professor C. A. M. Gray, Dr. E. Kokot, Emeritus Professor O. U. Vonwiller and Mr. D. Thompson.

R. W. Upfold,
Secretary.

Honorary Member

William Rowan Browne was born in County Derry, Ireland, on 11th December, 1884. After migrating to Australia, he attended the University of Sydney from 1907 to 1909, where he obtained B.Sc. with First-class Honours in Mathematics and Geology and the University Medal in Geology. In 1922 the University of Sydney conferred on him the degree of D.Sc. with the University Medal for his work on the geology of the Broken Hill district.

After a false start in Astronomy, he joined the Geology Department of Sydney University as a junior demonstrator in 1911. From 1913 to 1923 he was a Lecturer, from 1923 to 1939 Assistant Professor, and from 1939 to 1950 Reader in Geology at Sydney University.

Dr. Browne joined the Society in 1913, served on its Council for many years, and was its President in 1932 and Honorary Secretary in 1934 and 1935. He has contributed 23 papers to the *Journal*, many of which are of such importance in the development of Australian geological thought that they are still frequently referred to. Especially is this true of his paper " Notes on Bathyliths and Some of Their Implications " (1931).

For his distinguished contributions to geology to that time Dr. Browne was awarded the Clarke Medal by the Society in 1942 and was invited to deliver the Clarke Memorial Lecture in 1949. Seven years later the then Council had the pleasure of awarding him the Society's Medal in recognition of his scientific contributions and services to the Society.

Between 1935 and 1950 Dr. Browne gave a lot of his effort to editing and revising the manuscript on the Geology of Australia, which the late Sir T. W. Edgeworth David had started. The *Geology of the Commonwealth of Australia*, in three volumes, is a major contribution to geological literature.

Dr. Browne has given significant service to science in general, not only by his work in and for the Royal Society of New South Wales, but also as President of the Linnean Society of New South Wales on two occasions (1928, 1944) and as a member of the Council and in recent years as Honorary Secretary of that Society. He had a long and fruitful association with the National Research Council during its existence, and was President of Section C of A.N.Z.A.A.S. in 1949. He was elected a Fellow of the Australian Academy of Science in 1954 and Honorary Life Member of the Geological Society of Australia in 1957.

Volume 99 of the *Journal and Proceedings*, which was published in 1966, was dedicated to Dr. Browne as a tribute to the long and outstanding service he has given to Australian science. Tonight, the Society is pleased to confer upon Dr. Browne its last remaining honour—Honorary Membership of the Society.

Citations

The Society's Medal for 1968

The Society's Medal is awarded to a member of the Society for " meritorious contributions to the advancement of science. This may include administration and organization of scientific endeavour." The award for 1968 is made to Mr. Howard H. G. McKern of the Museum of Applied Arts and Sciences, Sydney, in recognition of his valuable contributions in the field of chemistry and for services to the Society.

Mr. McKern, A.S.T.C., M.Sc.(Chem.), was born at Sydney in 1917 and educated at Newington College. He studied Science, receiving the Diploma in Chemistry at the Sydney Technical College and the degree of Master of Science of the University of New South Wales. At the Museum of Applied Arts and Sciences, where he is now Deputy Director, he has been engaged since 1945 in research into the chemistry of the volatile oils of the Australian flora, and is author or co-author of some 30 papers in this field, 11 of which have been published in the Society's *Journal and Proceedings*.

Mr. McKern was elected a Fellow of the Royal Australian Chemical Institute, 1957 ; President of the University of New South Wales Chemical Society, 1960–1961 ; Chairman, Sixth Australian Phytochemical Conference, University of Sydney, 1962. Mr. McKern was elected to membership of the Society in 1943 and was a member of the Council of the Society during 1959–1960 and 1962–1963 ; he was elected President in 1963–1964 and served as Vice-President from 1964 to 1967.

The Clarke Medal for 1969

The Clarke Medal is awarded each year for distinguished work in the Natural Sciences done in, or on, the Australian Commonwealth and its territories. The award for 1969 is made to Professor Samuel Warren Carey of the Department of Geology, University of Tasmania, for distinguished contributions in the field of Geology.

Samuel Warren Carey was born at Campbelltown, N.S.W., in 1911. He graduated from the University of Sydney with the degree of Bachelor of Science, gaining First-class Honours in Geology in 1933 and being awarded also the John Coutts and Deas Thompson and Commonwealth Scholarships. His thesis, entitled " Tectonic Evolution of New Guinea and Melanesia ", gained him the Doctor of Science degree in 1938.

In 1934 he went to Papua with Oil Search Ltd., and remained there to perform outstanding and courageous service during the Second World War.

He was appointed Government Geologist of Tasmania in 1944, and from there moved to the Chair of Geology at the University of Tasmania, a position which he has occupied since 1947.

Professor Carey has continuously carried out his research over the years, and he has published a large number of scientific papers on many aspects of geology, notably those relating to the growth and relative movement of land masses. He has travelled widely and lectured in many continents.

Besides his scientific contributions, Professor Carey has contributed deeply and extensively to governmental and industrial organizations. He has been closely associated with the Tasmanian developments in hydroelectricity, being Geological Consultant to the Commission from 1946 to 1959.

In 1967 he delivered the Clarke Memorial Lecture, the title of which was " Tectonics of New Guinea ".

He is currently organizing research work on the tectonic evolution of New Guinea and related aspects of its geological structure.

Professor Carey was elected to membership of the Society in 1938, and two of his papers have been published in the *Journal and Proceedings*.

Professor Carey has always been an inspiring and colourful character and is a worthy recipient of a medal commemorating the Reverend W. B. Clarke.

Edgeworth David Medal for 1968

The Edgeworth David Medal is awarded to Australian research workers under the age of 35 years for work done mainly in Australia or its territories or contributing to the advancement of Australian Science. The award for 1968 is made to Dr. Robert M. May of the School of Physics, University of Sydney, in recognition of his outstanding contributions in the field of physics, particularly his work on theoretical plasma physics.

Dr. May was born on 8th January, 1936, in Sydney, and was educated at Sydney Boys' High School and the University of Sydney, where he graduated B.Sc. (1956) and later was awarded a Ph.D. (1959) after a brilliant academic record including the Physics Medal.

He has already published 40 papers, making significant contributions to a number of fields in theoretical physics.

His early work was in the field of solid state physics, and included useful contributions to the development of the basic theory of superconductivity. In his main field of theoretical plasma physics Dr. May has made important advances in (*a*) atomic processes, with particular relation to charge exchange phenomena; (*b*) magneto-hydrodynamics, particularly non-linear effects with large amplitude plasma waves; (*c*) developments in the theory of production of highly excited neutral atoms for plasma injection experiments. He has also made significant contributions to theoretical low-energy nuclear physics.

Walter Burfitt Prize for 1968

The Walter Burfitt Prize is awarded every three years to the worker whose contributions, published during the past six years, are deemed of the highest scientific merit, account being taken only of investigations described for the first time and carried out by the author mainly in Australia and New Zealand.

The award for 1968 is made to Professor Lawrence E. Lyons of the Chemistry Department, University of Queensland, for his outstanding contributions to the understanding of the organic solid state.

Professor Lyons was the first to point out, on the basis of symmetry and energetic considerations of the wave functions, the significance of charge transfer states in the spectroscopy of one-component molecular crystals. He has contributed significantly to the knowledge of absolute electron affinities of organic molecules, and made the first and nearly the only measurements on the absolute amounts of light absorption by molecular crystals.

He has provided the only theory of the effect of high pressure on the number of charges in crystals of neutral molecules, thus explaining the major effect of pressure on their electrical conductivity.

Professor Lyons has contributed firm results and ideas to the theory of the mode of action of tranquillizing drugs.

Also, he has provided basic information on the electronic properties of purine and pyrimidine bases and of NAD^+.

He has contributed significantly to the knowledge of a factor group splitting in molecular crystal spectra, proving amongst other things that quadrupole interactions are significant in the anthracene spectrum.

Professor Lyons has been a member of the Society since 1948, and two of his papers have been published in the *Journal and Proceedings*.

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Royal Society of New South Wales

OFFICERS FOR 1968-1969

NOTICE

The Royal Society of New South Wales originated in 1821 as the " Philosophical Society of Australasia " ; after an interval of inactivity it was resuscitated in 1850 under the name of the " Australian Philosophical Society ", by which title it was known until 1856, when the name was changed to " Philosophical Society of New South Wales ". In 1866, by the sanction of Her Most Gracious Majesty Queen Victoria, the Society assumed its present title, and was incorporated by Act of Parliament of New South Wales in 1881.

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JOURNAL AND PROCEEDINGS

OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 103 | 1970 | PART 2

CONTENTS

PUBLISHED BY THE SOCIETY
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

ISSUED JUNE 15, 1971

Registered for posting as a periodical—Category A.

NOTICE TO AUTHORS

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Papers should be prepared according to the general style adopted in this Journal. They should be as concise as possible, consistent with adequate presentation. Particular attention should be given to clarity of expression and good prose style.

The typescript should be double-spaced preferably on quarto paper, with generous side margins. Headings should be typed without underlining; if a paper is long, the headings should also be given in a table of contents typed on a separate sheet, for the guidance of the Editor.

The approximate positions of Figures, Plates and Tables should be indicated in the text between parallel ruled lines. Captions of Figures and Plates should be typed on a separate sheet.

The author's institutional or residential address should be given in the title of the paper, the relevant author's initials being attached in brackets to the appropriate address in cases of papers written jointly.

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Vick, C. G., 1934. *Astr. Nach.*, **253**, 277.

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Line Diagrams. Line diagrams, fully lettered, should be made with dense black ink on either white bristol board, blue linen or pale-blue ruled graph paper. Tracing paper is unsatisfactory because it is subject to attack by silverfish and also changes its shape in sympathy with the atmospheric humidity. The thickness of lines and the size of letters and numbers should be such as to permit photographic reduction without loss of detail.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 55–56, 1970

Occultations Observed at Sydney Observatory during 1969

K. P. Sims

The following observations of occultations were made at Sydney Observatory with the 11½-inch telescope. A tapping key was used to record the times on a chronograph. The reduction elements were computed by the method given in the occultation Supplement to the *Nautical Almanac* for 1938 and the reduction completed by the method given there. Since the observed times were in terms of coordinated time (UTC), a correction which was derived from *Bureau International De L'Heure Circulaire D* was applied to the 1969 observations to convert them to UT2. In 1969 a correction of +0·01111 hour (=40 seconds) was applied to the time in UT2 to convert it to ephemeris time with which *The Astronomical Ephemeris for 1969* was entered to obtain the position and parallax of the Moon. The apparent places of the stars of the 1969 occultations were provided by H.M. Nautical Almanac Office.

Table I gives the observational material. The serial numbers follow on from those of the previous report (Sims, 1969). The observers were W. H. Robertson (R), K. P. Sims (S), and H. W. Wood (W). Except for occultation 545, which was a reappearance at the bright limb, the phase observed was disappearance at the dark limb. Table II gives the results of the reductions which were carried out in duplicate. The star numbers given in Table I are from the *Catalog of 3539 Zodiacal Stars for Equinox* 1950·0 (Robertson, 1940) and the *Smithsonian Astrophysical Observatory Star Catalog.*

References

Robertson, A. J., 1940. *Astronomical Papers of the American Ephemeris,* Vol. X, Part II.

Sims, K. P., 1969. *J. Proc. Roy. Soc. N.S.W.*, **102**, 119; Sydney Observatory Papers No. 61.

Table I

Serial No.	S.A.O. or Z.C. No.	Mag.	Date	U.T.2	UT2–UTC	Observer
535	0850	6·0	1969 Jan. 29	12 40 10·96	+0·04	R
536	1122	3·9	1969 Jan. 31	10 50 33·05	+0·04	R
537	1081	6·2	1969 Feb. 27	11 43 06·05	+0·04	W
538	1032	5·5	1969 Mar. 26	9 17 50·21	+0·03	S
539	1644	4·1	1969 Apr. 28	7 22 33·53	+0·03	R
540	1886	5·7	1969 Apr. 30	15 31 45·72	+0·03	S
541	1712	3·8	1969 May 26	8 47 09·81	+0·02	R
542	2286	5·4	1969 June 27	11 23 03·15	+0·02	R
543	139026	8·2	1969 July 21	10 31 22·01	+0·02	R
544	2366	1·2	1969 July 25	7 27 13·52	+0·02	R
545	2366	1·2	1969 July 25	8 27 23·73	+0·02	R
546	2373	6·2	1969 July 25	8 34 40·53	+0·02	R
547	2723	6·7	1969 July 27	8 10 50·14	+0·02	W
548	2018	6·4	1969 Sep. 15	9 24 29·59	+0·01	S
549	183039	8·9	1969 Sep. 16	8 53 55·61	+0·01	R
550	2134	6·1	1969 Sep. 16	8 54 46·87	+0·01	R
551	2273	5·9	1969 Sep. 17	8 39 06·95	+0·01	S
552	183968	8·5	1969 Sep. 17	10 04 47·98	+0·01	S
553	186138	8·7	1969 Sep. 19	9 25 20·25	+0·01	S
554	186286	7·3	1969 Sep. 19	11 42 21·96	+0·01	S
555	186281	8·2	1969 Sep. 19	11 44 12·05	+0·01	S
556	2617	4·7	1969 Sep. 19	12 24 12·98	+0·01	S
557	183700	8·4	1969 Oct. 14	9 38 04·73	0·00	R
558	183713	7·4	1969 Oct. 14	9 51 32·82	0·00	R
559	165118	8·5	1969 Nov. 17	10 28 19·69	0·00	R
560	3313	6·8	1969 Nov. 17	13 04 11·09	0·00	S

Table II

Serial No.	Lunation No.	p	q	p²	pq	q²	Δσ	pΔσ	qΔσ	Coefficient of Δα	Coefficient of Δδ
535	570	+100	+6	100	+6	0	—0·4	—0·4	0·0	+13·0	+0·11
536	570	+95	+31	90	+29	10	—1·9	—1·8	—0·6	+13·1	+0·15
537	571	+43	—90	18	—39	82	—0·9	—0·4	+0·8	+4·0	—0·95
538	572	+95	—31	90	—29	10	—3·6	—3·4	+1·1	+12·0	—0·40
539	573	+84	—54	71	—45	29	+0·5	+0·4	—0·3	+7·3	—0·87
540	573	+100	—6	100	—6	0	—0·5	—0·5	0·0	+12·7	—0·51
541	574	+99	+15	98	+15	2	+0·2	+0·2	0·0	+14·1	—0·34
542	575	+40	+92	16	+37	84	—1·5	—0·6	—1·4	+8·2	+0·79
543	576	+95	—32	90	—30	10	0·0	0·0	0·0	+10·3	—0·72
544	576	+91	+42	82	+38	18	—1·0	—0·9	—0·4	+13·0	+0·24
545	576	—69	+72	48	—50	52	+0·9	—0·6	+0·6	—7·4	+0·83
546	576	+75	+66	56	+50	44	+0·4	+0·3	+0·3	+11·5	+0·51
547	576	+76	+65	58	+49	42	+0·4	+0·3	+0·3	+9·3	+0·72
548	578	+92	+38	85	+35	15	—1·0	—0·9	—0·4	+14·4	—0·02
549	578	+100	—10	99	—10	1	—2·0	—2·0	+0·2	+12·6	—0·43
550	578	+99	—11	99	—11	1	0·0	0·0	0·0	+12·6	—0·43
551	578	+97	+26	93	+25	7	—0·9	—0·9	—0·2	+13·6	+0·02
552	578	+83	+56	69	+46	31	—1·5	—1·2	—0·8	+12·7	+0·35
553	578	+83	+56	69	+46	31	—1·5	—1·2	—0·8	+10·8	+0·57
554	578	+100	+2	100	+2	0	—0·4	—0·4	0·0	+13·2	+0·05
555	578	+79	—61	63	—48	37	+1·8	+1·4	—1·1	+10·7	—0·59
556	578	+81	—59	65	—48	35	+0·9	+0·7	—0·5	+10·9	—0·57
557	579	+96	—28	92	—27	8	—3·0	—2·9	+0·8	+11·7	—0·52
558	579	+99	+17	97	+17	3	+1·2	+1·2	+0·2	+13·7	—0·09
559	580	+87	+49	76	+43	24	—1·8	—1·6	—0·9	+8·3	+0·82
560	580	+69	—72	48	—50	52	+2·2	+1·5	—1·6	+14·0	—0·33

(Received 19 October 1970)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 57–75, 1970

The Clarke Memorial Lecture for 1969

Origin of the Moon

A. E. Ringwood

Department of Geophysics and Geochemistry, Australian National University

1. Introduction

This lecture was delivered at a time when the only information available to me on lunar rocks consisted of preliminary chemical data obtained by the Lunar Sample Preliminary Examination Team (LSPET, 1969) and some preliminary investigations on the mineralogy and petrology of Apollo 11 samples which were being studied in Canberra. Preparation of this paper was inadvertently delayed, and a vast amount of detailed data on the lunar rocks has since been published, principally in *Science*, Vol. 167, No. 3918, 1970, and in the *Proceedings of the Apollo 11 Lunar Science Conference*, Vols. 1, 2 and 3. In this paper I shall cover much the same ground as was covered in the Clarke Lecture, but will incorporate more recent chemical and petrological information where appropriate. Fortunately, most of the more general boundary conditions on which I based my discussion of the origin of the moon have been amply confirmed by the new data. This is a tribute to the excellence of the work carried out by the Lunar Sample Preliminary Examination Team.

2. Nature of Apollo 11 Crystalline Rocks

(*a*) *General Properties and Distribution*

Perhaps the single most important discovery of the Apollo 11 mission which landed in Mare Tranquilitatus was that the crystalline samples returned were clearly identifiable as mafic igneous rocks closely related to basalts and dolerites. The principal minerals were pyroxene, plagioclase and ilmenite, with smaller amounts of olivine, other ore minerals, cristobalite, glass and other minor minerals. The textures were typically igneous and similar to those of terrestrial basalts and dolerites (Figure 1). Major element chemical compositions of nearly all rocks were very similar. Detailed trace element and isotopic studies (Compston *et al.*, 1970*a*, 1970*b*) revealed, however, that they could be divided into two groups with slightly different average compositions, probably representing two separate flows (Table 1). These results gave strong support to the earlier hypothesis (e.g. Baldwin, 1963), based upon a variety of observational evidence that the maria consisted of great floods of basaltic rocks. Alternative hypotheses, e.g. that the maria were dried-up lake sediments or deep seas of dust, could be discarded for all practical purposes.

Table 1

Average Compositions of Group 1 and Group 2 Apollo 11 Crystalline Rocks after Compston et. al. (*1670*b) *compared with Analyses of Terrestrial Oceanic Tholeiite* (*Engel* et al., *1965*) *and Typical Basaltic Achondrite* (*Duke and Silver, 1967*)

Group 1 and 2 compositions represent averages of six analyses

	Apollo 11 Crystalline Rocks		Basaltic Achondrite	Oceanic Tholeiite
	Group 1	Group 2		
SiO_2	40·28	40·47	49·54	49·34
TiO_2	11·88	10·32	0·68	1·49
Al_2O_3	8·95	10·41	12·69	17·04
Fe_2O_3	—	—	—	1·99
FeO	19·91	18·72	18·57	6·82
MnO	0·24	0·27	0·53	0·17
MgO	7·60	6·66	6·86	7·19
CaO	10·53	11·48	10·36	11·72
Na_2O	0·64	0·49	0·42	2·73
K_2O	0·31	0·09	0·05	0·16
P_2O_5	0·18	0·11	—	—
S ..	0·23	0·16	—	—

The question is often asked whether we are entitled to make broad generalizations from a single grab-sample from one spot on the moon. What kind of conclusions might we reach if we attempted to infer the history of the earth from samples obtained at a single random location ? The moon is kinder to the scientist in this respect than the earth. It does not possess a hydrosphere or atmosphere ; the major geological cycle which operates on the earth does not appear to have operated on the moon. The evolution of the lunar surface appears to have been much more simple than that of the earth, and the principal features were generated more than three billion years ago and have not been greatly disturbed since. The principal agent altering the lunar surface has been meteorite impact, and this has had the effect of extensively redistributing and stirring near-surface material, so that any single sample of "soil" contains small rock fragments which have been derived from a very large area of the lunar surface. It is most significant that about 95% of the recognizable rock fragments in the soil are composed of the same mineral assemblage as was found in the larger crystalline rocks of local origin, and most of the smaller glass fragments and spheres were also shown after analysis to be derived ultimately from mafic igneous rocks. We have also the evidence (Turkevich *et al.*, 1969) of the Surveyor 5 analysis from a location some tens of kilometres away on the same mare and the Surveyor 6 analysis from a different and distant mare (Sinus Medii—Franzgrote *et al.*, 1970). Both of these chemical analyses yielded compositions approximately similar to Apollo 11 rocks and indicated the widespread occurrence of rocks of this general nature. Finally, the preliminary analyses of Apollo 12 rocks from Oceanus Procellarum are generally similar to those of Apollo 11 rocks (LSPET, 1970). Although there are some important second order differences the Apollo 12 rocks are clearly recognizable as first cousins to Apollo 11 rocks. All of this evidence strongly supports the overall characterization of the lunar maria as consisting of mafic igneous rocks. High resolution Orbiter photography suggests that the maria may be composed of large numbers of overlapping thin flows of basaltic type rocks analogous to plateau-basalts.

Having recognized lunar basalts as chemically and petrologically closely related to terrestrial basalts, it is natural to consider the hypothesis that their origins are analogous. Terrestrial basalts are known to form by partial melting process at substantial depths in the earth's mantle, and the chemistry and phase relationships involved in this process are now reasonably well understood (Green and Ringwood, 1967). It is tempting to hypothesize that lunar basalts have formed by analogous partial melting process in the lunar interior. This hypothesis has been forcefully advocated by Baldwin (1963) on the basis of his investigations of the physiographic relationships between lunar maria and impact craters. There is, however, an alternative hypothesis that the lunar maria have formed by impact melting when large planetesimals collided with the moon during its final stages of formation (Urey, 1952; Öpik, 1967).

These two hypotheses have very different consequences with respect to information which the lavas are capable of providing about the lunar interior. If lunar basalts are of internal origin, we can study their chemistry and phase relationships in order to place strong constraints upon the nature of the source regions from which they were derived, using experimental methods similar to those employed by Green and Ringwood (1967). This approach has been employed by Ringwood and Essene (1970*b*). On the other hand, if lunar lavas are of impact origin, we obtain information only about near-surface material. After studying the preliminary data provided by the LSPET team, my colleagues and I formed the opinion that the Apollo 11 lavas were very probably of internal origin and proceeded on this assumption. Nevertheless, several scientists strongly advocated the impact melting hypothesis at the Houston Apollo 11 meeting, and a controversy developed. The accumulation of subsequent detailed evidence has made it practically certain that the Apollo 11 rocks and probably all maria are indeed of internal origin. We will review some of this evidence later.

(*b*) *Major Element Composition*

Relative abundances of most major components (SiO_2, Al_2O_3, CaO, FeO, MgO) fall within the same range as are displayed by terrestrial basalts and basaltic achondrites (Table 1). There are, however, some significant differences, notably the abundance of TiO_2 in lunar basalt is much higher than in terrestrial basalts and achondrites. Cr_2O_3 is also much higher in lunar basalt (av. 0·3% Cr_2O_3) than in terrestrial basalt (av. 0·01% Cr_2O_3), but is similar to the achondritic abundance (av. 0·3% Cr_2O_3). On the other hand, Na_2O is much lower in Apollo 11 basalt compared to terrestrial basalt and is generally similar to the achondrites. It appears that the very high abundance of TiO_2 in the *rocks* from the Apollo 11 site may be somewhat atypical. The TiO_2 abundance in the lunar *soil* was substantially lower, as were the TiO_2 abundances in Apollo 12 rocks and at the Sinus Medii (Surveyor 6) site. Sodium and chromium abundances, on the other hand, appear to be uniform in samples from all sites measured.

FIGURE 1.—Photograph of thin section of a typical Apollo 11 crystalline rock.

A notable feature is the comparative constancy of $\frac{FeO}{FeO+MgO}$ ratios in nearly all lunar rocks and the high and uniform abundances of Cr_2O_3. Microprobe analyses (Essen *et al.*, 1970) showed that the $\frac{FeO}{FeO+MgO}$ ratios of the earliest ferromagnesian crystals to form from all the lunar samples were approximately constant and equal to 0·25.

(*c*) *Incompatible Non-volatile Trace Elements, e.g. U, Th, Zr, Ba, light rare earths, Ta*

Incompatible elements are those possessing ionic radii and charges which inhibit their ready substitution in the principal rock-forming minerals. As a result, these elements tend to become strongly concentrated in the liquid phase during crystal-liquid differentiation processes. Results by the LSPET, amply confirmed by many other workers, demonstrated that this class of elements is concentrated in Apollo 11 basalts by factors of 30 to 100 over chondritic (primordial) abundances. This implies that extraordinarily efficient crystal-liquid fractionation mechanisms were involved during the formation of Apollo 11 rocks. Most absolute abundances of these elements fall in the concentration ranges observed for varieties of terrestrial alkali basalts. However, the relative abundances differ in important respects from those of terrestrial basalts. This is seen in figure 2 from Gast and Hubbart (1970), which shows the abundances of Ba and some rare earths in Apollo 11, Apollo 12 and basaltic achondrites normalized to chondritic abundances. The generally sub-parallel patterns which would have been reinforced if other incompatible elements (e.g. U, Th) had been included strongly imply derivation from source material possessing the chondritic abundances of this group of elements. Notice the spectacular depletions of europium—a feature which has caused a great deal of discussion. This is primarily due to the highly reduced state of lunar basalts (see below) which causes europium to occur dominantly in the divalent state, Eu^{2+}, possessing different crystal chemical properties to the neighbouring trivalent rare earths Sm^{3+} and Gd^{3+}. In more oxidized terrestrial systems most europium occurs as Eu^{3+}, and europium anomalies of this magnitude are not observed in mafic rocks.

An important feature of Figure 2 is the intermediate position of the Apollo 12 patterns between the abundance patterns of Apollo 11 rocks and basaltic achondrites. There appears to be a complete continuum between these two extremes. These relationships, together with the very close mineralogical and petrological resemblances between lunar basalts and basaltic achondrites which were commented upon by numerous workers at the Apollo 11 Conference in Houston, strongly suggest that the basaltic achondrites might also be derived from the moon.

(*d*) *Volatile Metals: Na, K, Rb, Cs, Zn, Cd, Hg, Bi, Tl, In, Ga, Pb, Sb, As*

Preliminary analyses by the LSPET indicated that, when appropriately normalized, the elements Rb, K, Na, Zn, Pb and Ga were systematically depleted in lunar basalts compared to terrestrial basalts by factors of 3 to 9. This group of elements is characterized by relatively high volatility under high-temperature, reducing conditions. In the Clarke Lecture, I placed great emphasis upon the significance of depletion of this class of elements, and assumed it to be characteristic of the source regions from which the lunar basalts were derived.

Subsequent accurate analyses by Keays *et al.* (1970), Baedecker and Wasson (1970), Morrison *et al.* (1970) and Smales *et al.* (1970) have confirmed this fundamental depletion pattern and extended it to many more volatile elements. It is now clear that Na, K, Rb, Cs, Zn, Cd, Hg, Bi, Tl, In, Ge, Pb, Sb and As are depleted relative to terrestrial basalts by factors which vary from 3 to 100. In turn, terrestrial basalts are depleted in this group of elements compared to primordial abundances by factors of 3 to 10 (Ringwood, 1966*a*).

At the Houston meeting a controversy developed about the origin of these depletions in lunar material. One group insisted that the depletions were characteristic of the source regions of lunar basalt and accordingly provide a clue of fundamental importance to the chemical processes by which the moon formed (e.g. Ringwood and Essene, 1970*a*; Ringwood, 1970). The other group claimed that the volatile elements had simply distilled from the lunar lava flows after extrusion, and hence their relative depletions were not characteristic of the source regions (e.g. O'Hara *et al.*, 1970*a*, 1970*b*).

This controversy is now settled for all practical purposes. Isotopic Rb-Sr studies (Compston *et al.*, 1970*b*; Albee *et al.*, 1970; Ganapathy *et al.*, 1970; Gast *et al.*, 1970; Hurley and Pinson, 1970) and Pb-U studies (Compston *et al.*, 1970; Tatsumoto, 1970; Gopalan *et al.*,

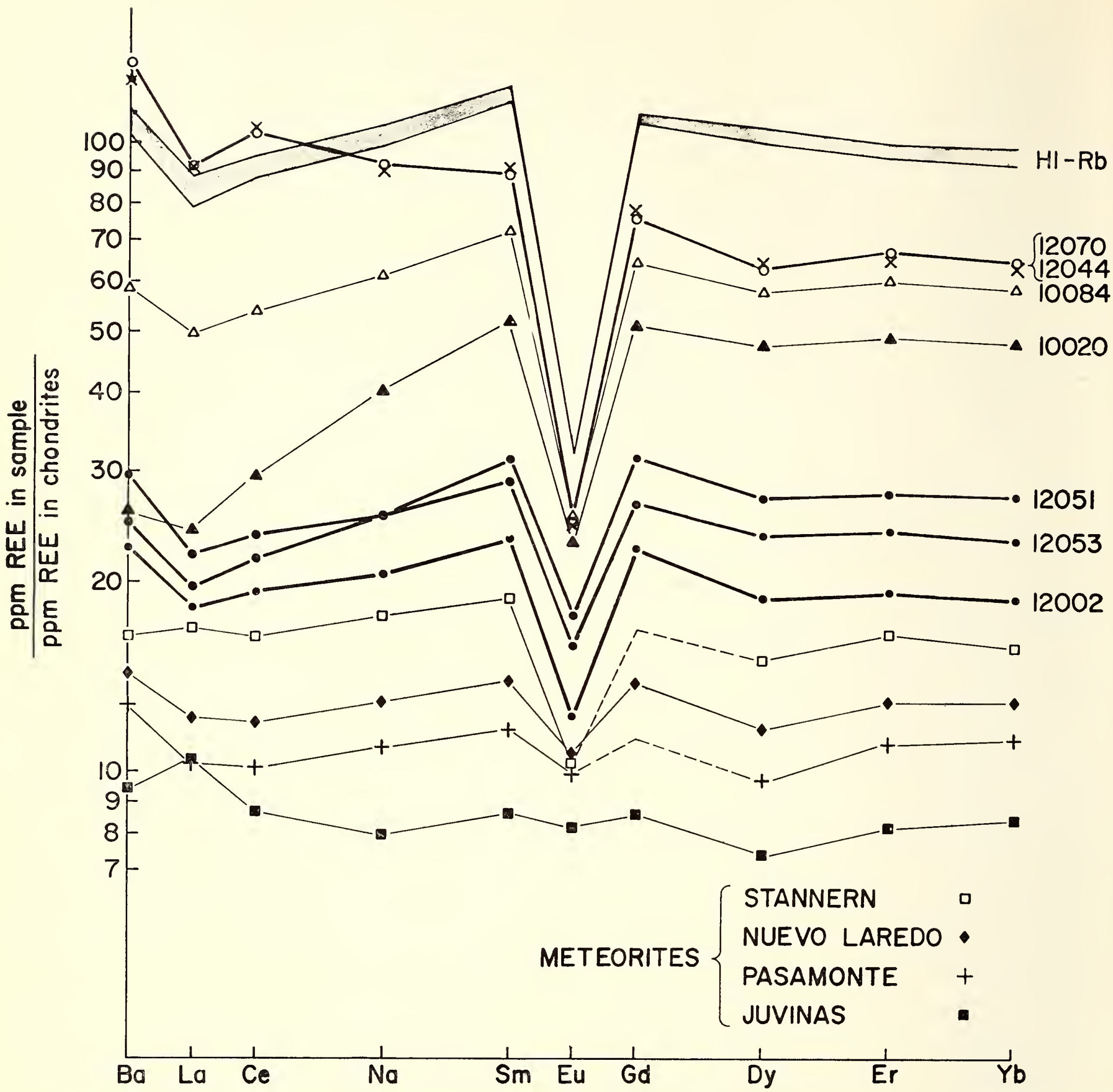

FIGURE 2.—Rare earth and barium abundances from Apollo 11 and 12 lunar samples and from some basaltic achondrites. The Hl–Rb group and sample 10020 represent Apollo 11 rocks. Most of the Apollo 11 rocks fall between these samples, as does the Apollo 11 soil 10084. In contrast, the Apollo 12 rocks 12051, 12053 and 12002 occupy a generally intermediate position between the Apollo 11 rocks and the basaltic achondrites (meteorites). Apollo 12 soils 12070 and 12044 have much higher rare earth abundances than the corresponding rocks and fall within the Apollo 11 range. (*After* Gast and Hubbard, 1970.)

1970) showed that strong depletion of Rb and Pb (relative to Sr and U) in lunar basalts as compared to terrestrial basalts occurred about 4·6 billion years ago during the formation of the moon and long *before* the lunar basalts were erupted. This feature must, therefore, be a characteristic of the source regions. Additional arguments by Ringwood and Essene (1970*b*) and Goles *et al.* (1970) showed that the depletions of Na and K almost certainly did not occur by volatilization from the lunar lavas during and after extrusion. If it is accepted that the depletions of Rb, Pb, Na and K are of primary origin, it is reasonable to assume that the corresponding depletions of other volatile metals are similarly primary.

(*e*) *Siderophile Elements: Ni, Cu, Ga, Ag, Au, Ir*

LSPET preliminary results indicated that the siderophile elements Ni (strongly) and Cu (significantly) were depleted in lunar basalt compared to terrestrial basalts. Subsequent accurate analyses by Keays *et al.* (1970) have confirmed and extended this pattern. Ni, Cu, Ga, Ag, Au and Ir were found to be depleted compared to terrestrial basalts by factors of 3 to 10. This is attributed to equilibration of lunar basalts with metallic iron as a consequence of their lower oxidation states than terrestrial basalts (see below) followed by partial removal of the metal phase.

(*f*) *Oxidation State*

Numerous workers drew attention at the Houston Conference to the fact that Apollo 11 basalts commenced to crystallize at an oxygen fugacity of $10^{-13.5}$ atm. (1200° C.) as compared to the corresponding oxygen fugacity for terrestrial basalts at about 10^{-8} to 10^{-9} atm. As a result, the Fe^{3+} ion is not detectable in ore minerals and pyroxenes from lunar rocks (Agrell *et al.*, 1970; Hafner and Virgo, 1970), whereas it is always a significant component of corresponding terrestrial minerals. The low oxidation state is also responsible for the widespread occurrence of free metal in Apollo 11 basalts as well as species such as Ti^{3+} and Cr^{2+} inferred to occur in solid solution in some ore minerals and olivine respectively. A further consequence of the low oxidation state of lunar basalts is the absence of any evidence of the presence of hydrated minerals and carbonates in the crystalline lunar rocks. The species CO_2 and H_2O are dominantly reduced to CO and H_2 at the oxygen fugacity prevailing.

(*g*) *Melting Relationships at One Atmosphere*

Several workers have carried out melting experiments upon Apollo 11 basalts or upon synthetic analogues. In general, the results are closely concordant, although there are a few discrepancies arising out of inadequate control of oxidation states during experiments. Ringwood and Essene (1970*a*, 1970*b*) showed that the liquidus phases at 1050° C. were armacolite (a new mineral: $(Fe_{0.5}Mg_{0.5})Ti_2O_5$, with the pseudobrookite structure) and olivine (Fo_{74}). With falling temperature, armacolite reacted with liquid to produce ilmenite (1120° C.) whilst olivine reacted to form pyroxene (1120° C.). At this temperature the degree of crystallization increased rapidly with abundant cotectic crystallization of pyroxene, plagioclase and ilmenite. These phases continued to crystallize until the solidus was reached at about 1090° C.

The experimental phase relationships closely matched those observed in natural Apollo 11 basalts. Several workers found armalcolite as an early phase and inferred a reaction relation with ilmenite. Likewise, olivine in Apollo 11 samples was interpreted to be in reaction relationship with pyroxene. The crystallization sequence of Apollo 11 rocks inferred from petrological criteria was identical with that of the synthetic specimen.

The relatively late crystallization of plagioclase is an important feature. In our experiments plagioclase did not appear until about 30% of the liquid had crystallized as olivine, pyroxene and ore minerals. This feature was observed by all other experimenters. In some experiments on another Apollo 11 basalt slightly different in composition more than 50% of the rock crystallized before plagioclase appeared (Weill *et al.*, 1970). Clearly, the magma was far from being saturated with plagioclase on extrusion.

In most experimental work the crystallization interval between solidus and liquidus was found to be quite small, between 60° C. and 120° C. Furthermore, the temperature interval between entry of the major phases—olivine, pyroxene, ore and plagioclase—was mostly also found to be quite small and of the order of 30 to 40° C.

O'Hara *et al.* (1970*a*, 1970*b*) have made much of this feature, claiming that it demonstrates that Apollo 11 basalts were " almost cotectic indicating that lunar basalts are not primary magma, but the residual liquids of advanced near-surface crystal fractionation ". This conclusion is clearly wrong. The closeness of Apollo 11 basalts to a cotectic of major minerals is to be measured not by temperature intervals but by the amount of crystallization necessary to bring the liquid from its observed composition to the cotectic composition. We have seen that Apollo 11 basalt must crystallize 30% to 50% of ores and ferromagnesian minerals before the plagioclase-ilmenite-pyroxene cotectic is reached. Clearly, they were far from the low-pressure cotectic when erupted and could not have undergone extensive near-surface fractionation. Additional arguments relating to this point are given later.

(*h*) *Ages*

Only two research groups were successful (by January, 1970) in the difficult task of determining accurately the ages of Apollo 11 rocks by Rb-Sr methods. Albee *et al.* (1970) obtained an age of $3 \cdot 65 \pm 0 \cdot 10$ billion years, whereas Compston *et al.* (1970*a*) obtained $3 \cdot 78 \pm 0 \cdot 10$ billion years. These methods were based on internal mineral isochrons and date the time of crystallization. Turner (1970) obtained a group of ages close to $3 \cdot 7$ by using the argon 40/argon 39 dating method. Ages obtained by the lead-uranium method were also consistent with these values (Tatsumoto, 1970). More recently, Papanastassiou and Wasserburg (1970) have obtained a Rb/Sr age (internal mineral isochron) for Apollo 12 rocks of $3 \cdot 3$ billion years.

(*i*) *High Pressure Behaviour*

A detailed investigation of high pressure-phase relationships in typical Apollo 11 basalt and in possible source materials was undertaken by Ringwood and Essene (1970*a*, 1970*b*). Their results are shown in Figure 3. Less extensive but generally concordant results on a lunar rock were reported by O'Hara *et al.* (1970*a*, 1970*b*.) An interesting feature is the relatively low pressure at which Apollo 11 basalt (density $3 \cdot 3$ gm./cc.) transforms to a very dense eclogite ($3 \cdot 7$ gm./cc.). It was possible to show conclusively that the moon could not be composed entirely of Apollo 11 rock, or indeed, of any basaltic rock, because these would lead to too high a mean density and would contradict the moon's moment of inertia (Ringwood and Essene, 1970*a*, 1970*b*). Thus, the Apollo 11 basalts must represent differentiates from a more primitive source material with lower Fe/Mg ratio. Further studies on possible source materials by Ringwood and Essene showed that to satisfy the moon's moment of inertia coefficient ($I/MR^2 = 0 \cdot 402 \pm 0 \cdot 002$), which is very close to that of a sphere of uniform density, the moon could not contain more than 6% Al_2O_3, and very probably not more than 6% CaO. It was concluded that the moon's interior was dominantly composed of ferromagnesian silicates low in Al and Ca.

3. Petrogenesis of Apollo 11 Basalt

The high and variable abundances of the incompatible elements (Figure 2, section 2c) in Apollo 11 basalts imply the operation of efficient crystal-liquid fractionation processes. Opinion at the Houston meeting was divided between two views:

(i) Apollo 11 basalts were produced by a small degree of partial melting in the lunar interior which permitted strong concentration of incompatible elements into the first liquid to form. The liquid was then separated from the source region and ascended to the surface (e.g. Ringwood and Essene, 1970*a*, 1970*b*).

(ii) The strong concentrations of incompatible elements were produced by advanced high-level crystallization differentiation in large lava lakes. The Apollo 11 lavas are thus regarded as the residual liquids resulting from this extensive, near-surface fractionation process (e.g. O'Hara *et al.*, 1970*a*, 1970*b*).

Grounds for further controversy no longer exist, since the second alternative has been shown not to be feasible (Ringwood and Essene, 1970*b*). Initially, the argument was based upon the claim that Apollo 11 basalts were near or at the cotectic of three major phases. We have seen that this is not correct and that, to the contrary, Apollo 11 basalts are far removed from the pyroxene-plagioclase-ilmenite cotectic. Extensive high-level fractionation would indeed drive the lavas toward the cotectic. Conversely, the fact that they are far removed from cotectic composition means that extensive low pressure fractionation has not operated.

This conclusion is amply verified by several other lines of evidence. Consider Figure 2, which demonstrates the occurrence of a ten-fold variation in the abundances of incompatible elements among Apollo 11 and 12 rocks. If these are to be explained by fractional crystallization, more than 90% of the original magma must have crystallized to produce the rocks with the highest incompatible element abundances. However, this would imply corresponding major changes in the $\frac{FeO}{FeO+MgO}$ ratios of the rocks which serve as an index of the degree of fractional crystallization. In fact, the variations of $\frac{FeO}{FeO+MgO}$ ratios between different rocks are small. The high concentrations and relatively uniform distribution of Cr_2O_3 (av. $0 \cdot 3$%) among Apollo 11 and 12 rocks is another indication that they have not undergone extensive absolute or relative fractionation by crystallization differentiation. Chromium is strongly concentrated in the first crystallizing opaque pyroxenes. Extensive fractional crystallization leads rapidly to almost complete removal of chromium from the magma (Ringwood and Essene, 1970*b*).

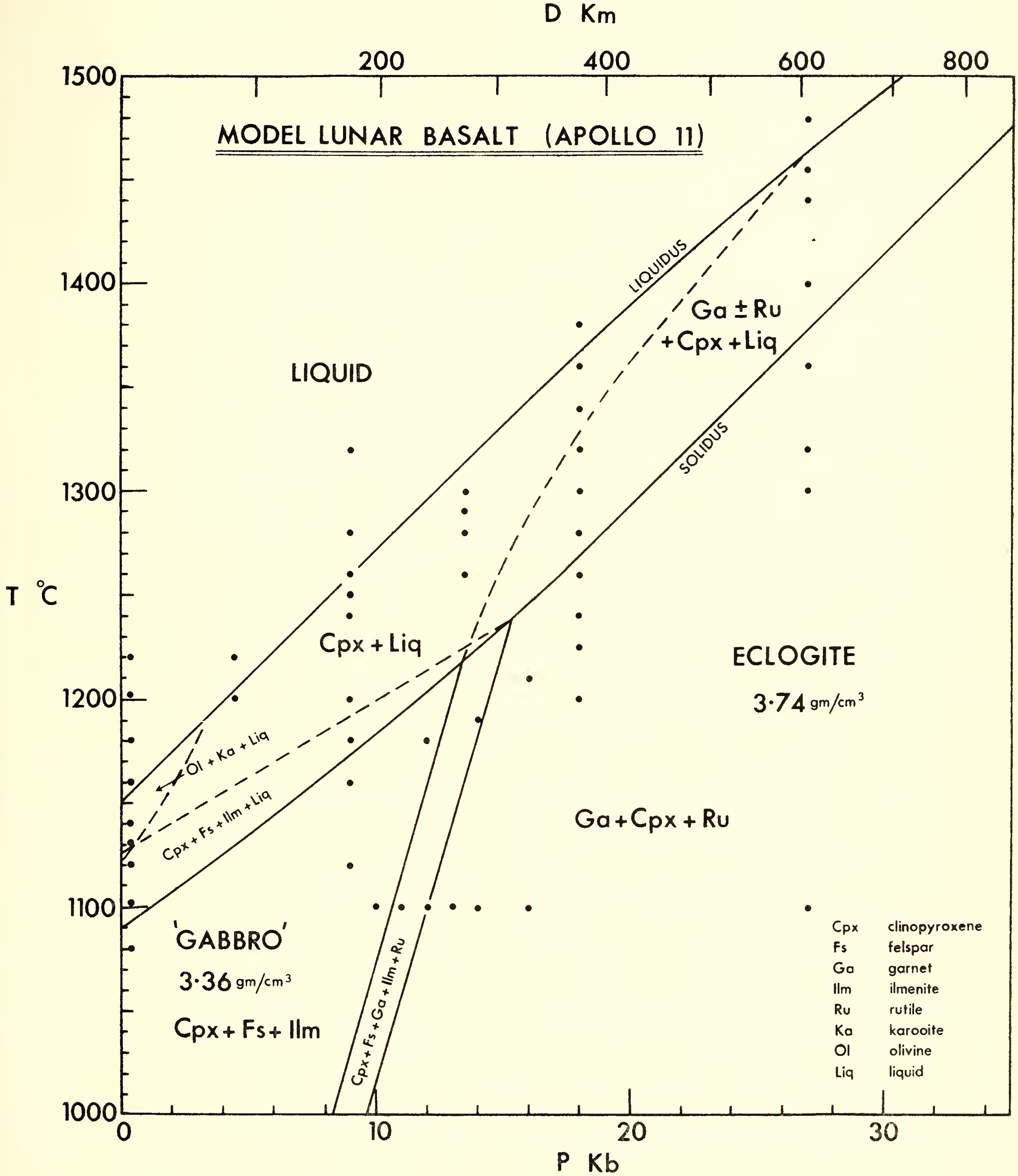

FIGURE 3.—Stability fields of mineral assemblages and melting equilibria in average Apollo 11 basalt composition at high pressures and temperatures. Each dot represents a separate experiment. Armalcolite is now the approved mineral name corresponding to the term " Karooite " used in the Figure.

The abundance patterns of Figure 2 combined with the major element compositions of the rocks are characteristic of partial melting processes where the major elements in the liquid are buffered by equilibrium with residual unmelted phases in the source regions, whilst incompatible elements are strongly concentrated into the liquid phase according to the degree of partial melting. Haskin *et al.* (1970) and Gast and Hubbard (1970) showed that to account for the enrichment of rare earths shown in Figure 2 by fractional crystallization at high levels up to 95% of the original liquid would need to have crystallized as plagioclase. This is clearly impossible since plagioclase is not on the liquidus of Apollo 11 rocks. Several other arguments showing that Apollo 11 lavas were formed by a small degree of partial melting of source material in the lunar interior and not by extensive high-level crystallization differentiation are given by Ringwood and Essene (1970*b*).

If we accept that Apollo 11 basalts were generated by a process involving a small degree of partial melting of source material, at what depth in the lunar interior did the partial melting occur, and what was the nature of the source material? There are two approaches to this problem. Ringwood and Essene determined the compositions of the liquidus and near-liquidus phases of Apollo 11 basalts as a function of pressure (Figure 3). Since the equilibrium between crystals and magma is independent of the proportions of crystals and liquids present, it follows that Apollo 11 basalt could have formed by a small degree of partial melting of mineral assemblages composed dominantly of the observed liquidus phases.

From Figure 3 we see three distinct pressure regimes according to the nature of the liquidus phase: a *low pressure regime*, in which the liquidus phases are olivine and armalcolite, an *intermediate pressure regime* in which the liquidus phase is a highly sub-calcic clinopyroxene (7% CaO, 4% Al_2O_3, $Fs_{21}En_{64}Wo_{15}$) and a *high pressure regime* in which clinopyroxene and garnet are near-liquidus phases. Ringwood and Essene (1970*b*) showed that the mineral assemblages of the low pressure and high pressure regimes were too dense to be representative of the lunar interior. On the other hand, the pyroxenite composition of the intermediate pressure regime (depths of 200 to 500 km.) went much closer towards providing an explanation of the moon's mean density and moment of inertia. Further detailed studies showed that Apollo 11 basalt was almost saturated with orthopyroxene at near-liquidus temperatures between 10 and 15 kb. It was possible, therefore, that substantial amounts of orthopyroxene might be present in the source region in addition to the sub-calcic clinopyroxene. These studies permitted the synthesis of a model lunar pyroxenite (Table 2) capable of yielding the average Apollo 11 basalt composition by a small degree of partial melting at depths of 200 to 500 km. Experimental studies (Figure 4) of the P, T stability fields of mineral assemblages displayed by this pyroxenite showed that it was capable of providing a satisfactory explanation for the observed mean density and moment of inertia of the moon.

Table 2

Composition of Model Lunar Pyroxenite which is capable of yielding Apollo 11 Basalts by a small degree of partial melting. If the moon were composed of material of this composition, the observed lunar density and moment of inertia would be satisfied. This composition is not unique, and it is possible that olivine was also a constituent of the source region. (*After Ringwood and Essene, 1970*b)

SiO_2	52·0
TiO_2	1·0
Al_2O_3	5·0
Cr_2O_3	0·4
FeO	13·5
MgO	22·5
CaO	4·0
Na_2O	0·1

The experimental studies thus led to a very simple model for the origin of the lunar basalts. Although the experiments permit some variability in the composition of the source region, and it is possibe that olivine may be present, as a separate phase in addition to the pyroxenes, there can be little doubt that the Ca and Al contents of pyroxenes and the olivine/pyroxene ratio in the lunar basalt source region are substantially lower than in the earth's mantle. Within the framework of our present understanding of high pressure phase equilibria, it does not appear possible to generate Apollo 11 and terrestrial basalts from source materials possessing similar major element abundances.

Further arguments indicating that if the Apollo 11 basalts formed by a partial melting process, the source region must lie deep in the lunar interior are derived from considerations of the moon's thermal history and strength. The Apollo 11 and 12 basalts crystallized 1·0 to 1·3 billion years after the moon had formed. Regardless of any reasonable assumptions which can be made about initial temperature distribu-

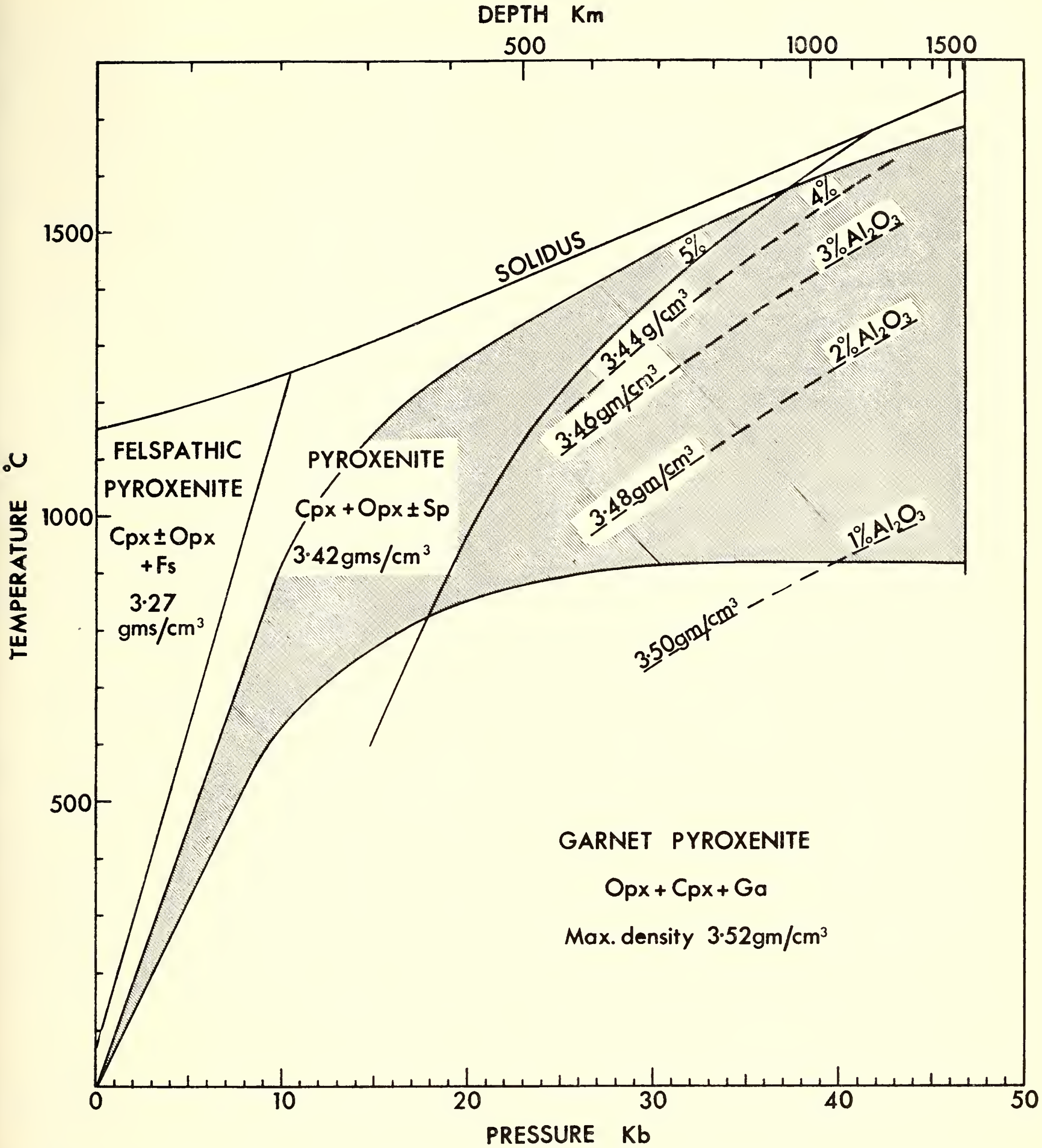

FIGURE 4.—Stability fields and densities of mineral assemblages displayed by model lunar pyroxenite (Table 2) in relation to the probable range of lunar internal temperature distributions (shaded region). (*After* Ringwood and Essene, 1970*b*.)

tion and distribution of radioactivity, the outer 200 km. of the moon would have cooled by thermal conduction over this period to a mean temperature of about 500° C. (maximum temperature at 200 km. is about 1000° C.). Because of its larger area-to-volume ratio, cooling on the moon is effective to greater depths than on the earth, and the lunar lithosphere is accordingly much thicker and stronger than the earth's. It is most difficult to understand how any partial melting process could, therefore, occur in the cool outer 200 km.

of the moon. The source would need to be deeper, in a region which had not been affected by cooling and in which increase of temperature by accumulation of radioactive heat was still possible. Another argument is connected with the preservation of mascons-circular regions characterized by high positive gravity anomalies which occur in some maria. Urey (1968) and others have emphasized that these require that the lunar lithosphere beneath the maria and mascons has possessed substantial strength ever since the maria and mascons were formed, and that, therefore, the lithosphere must have been quite cool at the time the mascons formed. It would be difficult to form the maria by partial melting within the lithosphere and at the same time have this region sufficiently cool to possess the considerable long-term strength necessary to support the mascons.

To avoid these latter difficulties, Urey appealed to a near-surface origin of the maria with the melting caused by meteorite impact. However, we have previously demonstrated that the maria are strongly fractionated relative to the average composition of the moon. Urey's hypothesis implies that the fractionation must have occurred by crystallization differentiation near the surface of the moon. We have previously shown that the observed fractionation could not have been caused by crystallization differentiation and Urey's hypothesis must, therefore, be rejected. Additional arguments against an impact origin for the maria were given by Ringwood and Essene (1970*b*).

All the evidence discussed so far points to an origin of the maria by a small degree of partial melting at a depth greater than 200 km. I should mention one important observation which is believed by some workers not to be consistent with this hypothesis. This is the spectacular europium anomaly shown in Figure 2 which is caused by europium being present in the divalent state under lunar redox conditions, so that it has crystal chemical properties rather similar to Sr^{2+}. Those workers who studied rare earth distributions in lunar basalts concluded that plagioclase should be present in the source regions of lunar basalt and that the deficiency was caused by Eu^{2+} remaining behind in plagioclase relatively to the other trivalent, rare earths, during partial melting. A source region of plagioclase and high-Mg pyroxenes was therefore, favoured.

This hypothesis leads to several difficulties. The most serious is that Apollo 11 basalts were not saturated with plagioclase when they were erupted. If plagioclase had been a component of the residual mineral assemblage remaining behind after partial melting, all magmas reaching the surface should have been saturated with plagioclase, which should, therefore, have been on the liquidus. As we saw previously, this is not the case. The difficulty is of a fundamental nature and a solution is not in sight. Further difficulties arise from the high pressure observations that the postulated plagioclase-bearing mineral assemblage is unstable at a high pressure and would not persist below about 200 km. I have previously detailed the arguments against an origin of lunar basalts by partial melting in the outer 200 km. of the moon.

An explanation of the europium anomaly in terms of the model of partial melting of a pyroxenite source region is by no means ruled out. The relevant partition cofficients for this system are not yet determined at the redox state existing on the moon. I think that there is a good chance that this model will be able to explain the anomaly. Experiments are now under way to measure appropriate partition cofficients, and will provide a key test by the model advocated here.

4. Some Boundary Conditions for Theories of Lunar Origin

Some of the more important properties of lunar basalts have been summarized in the preceding section. Reasons for believing that they have been formed by a small degree of partial melting deep within the lunar interior have been stated. If we accept this hypothesis, what are the important points of resemblance between lunar basalts and terrestrial basalts and between their respective source regions? What are the important differences? What bearing do these relationships have on theories of lunar origin?

(*a*) *Overall Similarities between Earth and Moon*

(i) The moon and the earth's mantle are both dominantly composed of ferromagnesian silicates with subordinate CaO and Al_2O_3.

(ii) The relative abundances of most of the non-volatile, incompatible class of trace elements in the source regions of lunar and terrestrial basalts appear to have been similar and closely related to chondritic or primordial abundances.

(iii) The absolute abundances of most of the non-volatile oxyphile elements in lunar basalts fall within the range of concentrations of these elements displayed by terrestrial basalts.

(iv) Elements which are comparatively volatile under high temperature reducing conditions, e.g. K, Rb, Pb, Tl, Bi, In, are relatively depleted in the earth (by factors of 5–10) compared to the probable abundances of these elements in the primordial solar nebula (Gast, 1960; Ringwood, 1966*a*, 1966*b*). Likewise, this group of volatile elements is also relatively depleted in the moon.

The above similarities, particularly (iv), might be taken to indicate that some of the fundamental chemical fractionation processes which occurred when the earth and moon formed from the solar nebula were similar, and, tentatively, might point in the direction of a genetic relationship between earth and moon.

(v) This suggestion is supported by the history of tidal evolution of the earth-moon system, which implies that the moon was once only 2·8 earth radii distant from earth (Gerstenkorn, 1955). This is almost identical with Roche's limit and it does not appear likely that the similarity between these distances is a mere coincidence as is implied by the capture hypothesis (Öpik, 1961). Additional reasons for rejecting the capture hypothesis are given in the next section. If capture is rejected, the tidal history indicates that the moon was probably born very close to the earth and, therefore, a close genetic relationship might be inferred (cf. Section 7).

(*b*) *Chemical Differences between Earth and Moon*

Superimposed on the general resemblances which exist between moon and earth (above), there are some very important specific differences:

(i) The moon is strongly depleted in iron relative to the earth. If a core is present, it cannot amount to more than a few per cent. of the mass.

(ii) Apollo 11 basalts are strongly depleted in many siderophile elements relative to terrestrial basalts (e.g. Ganapathy *et al.* 1970).

(iii) The moon is much more strongly depleted in volatile metals (e.g. Na, K, Rb, Cs, Pb, In, Tl, Zn, Hg, etc.) than the earth compared to primordial abundances (Section 2 (*d*)).

(iv) The $\frac{FeO}{FeO+MgO}$ molecular ratio in the source regions of Apollo 11 basalt is probably between 0·20 and 0·26, compared to a probable value for this ratio of 0·12 in the source regions of terrestrial basalts (Green and Ringwood, 1967; Ringwood, 1970*b*).

(v) The mineralogy of the lunar mantle is probably pyroxene-dominated as compared to a preponderance of olivine in the terrestrial mantle. The ratios of Al_2O_3 and CaO to total pyroxenes are smaller in the lunar mantle than in the terrestrial mantle. Thus, important differences exist in the relative abundances of the major components, SiO_2, MgO, FeO, Al_2O_3 and CaO, between the lunar interior and the earth's mantle (Ringwood and Essene, 1970*b*; Ringwood, 1970*b*).

(vi) Studies of the chemistry of rare earths in lunar and terrestrial basalts (Haskin *et al.*, 1970; Gast and Hubbard, 1970) indicate that calcium-rich clinopyroxene is a less abundant phase in the lunar mantle than in the terrestrial mantle.

(vii) Terrestrial basalts and their source regions are much more oxidized (oxygen fugacity of 10^{-8}–10^{-9} atm. at 1200° C.) than lunar basalts and their source regions ($fO_2=10^{-13\cdot5}$ atm. at 1200° C.) (Section 2 (*f*)).

(viii) As a consequence of the low oxygen fugacity in the moon, H_2O and CO_2 are unstable relative to H_2 and CO at magmatic temperatures. Water and carbon dioxide are, therefore, very rare in lunar rocks compared to terrestrial rocks.

5. Bearing of Apollo 11 Data on Theories of Lunar Origin

We will consider first the traditional hypotheses of lunar origin—Fission, Binary Planet and Capture. The conclusions relating to the similarities and differences between earth and moon, which were discussed in the previous section, have a vital bearing on these hypotheses. In all hypotheses the first-order problem is to explain the large difference in density of earth and moon, which implies a major fractionation of iron between the bodies.

(*a*) *The Fission Hypothesis*

Darwin (1880, 1912) developed a theory according to which the moon and earth were originally combined in a single body which rotated with a period of four hours, so that the solar sides were raised every two hours. He estimated that the fundamental mode of the earth's free oscillations was one hour, and suggested that a resonance effect was established between the solar tides and free oscillations, leading to the development of an enormous tidal bulge. This ultimately became unstable and the tidal bulge was thrown off from th eearth to form the moon. Darwin's theory provided an elegant explanation for the moon's density which is similar to the uncompressed density of the earth's outer mantle. However, a series of fatal objections to Darwin's original hypothesis was raised by Jeffreys (1930) and others, and it was generally discarded. See also MacDonald (1964).

Ringwood (1960) suggested a new variant of Darwin's hypothesis arising from a discussion of the formation of the earth by accretion, as in Section 6. It was argued that after accretion the extent of reduction, and consequently the amount of metal phase, increased from the centre of the earth towards its margins. This configuration is highly unstable and there is the possibility that segregation of metal into the core might have been catastrophic. If, towards the end of the primary accretion process, the rate of rotation of the earth was close to the instability limit, rapid segregation of the core might have decreased the earth's moment of inertia, and accordingly increased its angular velocity sufficiently to cause instability and fission. According to Ringwood's suggestion, the excess angular momentum of the earth-moon system was carried away by the large primitive atmosphere, which was also disrupted and escaped during the cataclysm. A similar hypothesis was subsequently suggested and developed in greater detail by Wise (1963). The modified fission hypothesis has since been considered favourably by O'Keefe (1966), Cameron (1966), and others. Although it is recognized by all concerned that this hypothesis requires a highly favourable and *ad hoc*, combination of initial conditions if it is to be applicable, and is therefore of low intrinsic probability, its ability to explain the density of the moon, and the difficulties faced by alternative hypothesis of lunar origin, have combined to keep the fission hypothesis alive.

What, then, is the bearing of the new data from Apollo 11 on the status of this hypothesis ? According to earlier versions, either *solid* or *liquid* material was thrown out of the earth's upper mantle after the core had formed, and the moon was formed from this condensed upper mantle material. It would therefore be anticipated that the compositions of lunar basalts and terrestrial basalts formed by the partial melting of similar source material in the earth's upper mantle and in the moon would be generally similar. The many important compositional differences between lunar and terrestrial basalts and between their respective source regions, as summarized in Section 4, effectively contradict this consequence. Particularly difficult to explain are the differences in abundances of volatile elements, siderophile trace elements, major elements (Si, Mg, Fe, Al, Ca) and oxidation states. These difficulties are sufficient in my opinion to dispose of the earlier versions of the fission hypothesis which require that the moon formed from *solid* or *liquid* material thrown off by the earth's outer mantle.

Recently, modifications of the fission theory have been suggested by Wise (1969) and O'Keefe (1969). Both point out that after fission a strong tidal interaction would ensue between earth and the newly formed moon. This would cause the transformation of rotational energy into thermal energy, resulting in the volatilization of the outer regions of the earth and moon and the formation of a massive primitive atmosphere, mainly of volatilized silicates, amounting to 4% (Wise) or 10–20% (O'Keefe) of the mass of the earth. Both authors are concerned primarily with explaining the discrepancy between the angular momentum needed for fission and the total angular momentum of the present earth-moon system. They suggest, following Ringwood (1960), that the excess angular momentum of the earth-moon system was carried out of the system by escape of this primitive atmosphere.

Wise suggests that " Roasting of a newly formed moon adjacent to a tidally heated incandescent earth may account for a lunar magmatic source depleted in volatile alkali elements and enriched in refractory elements as suggested by first analyses of Apollo 11 specimens ". O'Keefe also had something similar in mind, as indicated in his abstract.

In my opinion, the simple high-temperature roasting of a condensed moon would be insufficient to account for the strong selective depletions of volatile metals in the moon, which would require a much more intensive high-temperature processing than indicated. Furthermore, the roasting process does not readily account for the inferred differences in major elements and mineralogy between the moon and the earth's mantle.

Nevertheless, the model suggested by Wise and O'Keefe provides an environment in which the chemical fractionations might well be explained. Both authors advocate a primitive atmosphere of volatilized silicates from three to 20 times more massive than the present moon. If most of the material now in the moon had condensed from that atmosphere and had fractionated during the process, the observed composition of the moon might be explained. A modification of this kind leads to a hypothesis having many features in common with the precipitation hypothesis of Ringwood (1966*a*, 1970*a*), which maintains that the material now in the moon was precipitated from a massive, hot, primitive terrestrial atmosphere to form a swarm of fractionated moonlets and that the moon formed by the coagulation of this swarm. Perhaps one could go a step further than O'Keefe and Wise to suggest that rotational instability during core formation threw off the earth's massive, hot, primitive atmosphere (Ringwood, 1960), but did not affect the solid or liquid upper mantle. The moon then precipitated *in toto* from this primitive atmosphere.

Lead isotope data on Apollo 11 rocks (Gopalan *et al.*, 1970 ; Tatsumoto, 1970) show that if the material now in the moon was derived from the earth by fission or by a related process, the time of derivation must have been close to 4·6 billion years ago when the earth was formed. O'Keefe's (1969) suggestion of delayed fission some 3·5 billion years ago requires modification.

(*b*) *Binary Planet Hypothesis*

The mass of the moon is about $\frac{1}{80}$ of that of the earth and, moreover, the moon carries most of the angular momentum of the earth-moon system. These distributions are unlike those of all other planets and satellites in the solar system in which satellites account for a much smaller proportion of the total mass and angular momentum. The distribution of mass and angular momentum between earth and moon is not unlike those of binary star systems, and it has frequently been suggested (e.g. Latimer, 1950 ; Kuiper, 1954, 1963 ; Orowan, 1969) that the origin of the earth-moon system is analogous to that of a binary star system.

According to this theory, moon and earth formed in close proximity, but separately and independently, by direct accretion from similar parental material. Instead of becoming a separate planet, the moon orbited the earth. This immediately raises the problem of explaining the moon's low density. Earlier attempts (e.g. Ramsay, 1949) to provide an explanation in terms of a silicate-metal high pressure phase transformation at the core-mantle boundary in the earth have been reduced to a state of negligible probability by recent high pressure experimental data (e.g. Birch, 1960). It has been postulated that earth and moon accreted from a mixture of pre-existing silicate and metallic iron particles in the solar nebula, and that in some way the earth received a greater proportion of metal particles. Physical processes which have been invoked to cause this metal/silicate fractionation have been vague and implausible, depending heavily upon *ad hoc* assumptions. The latest is the suggestion by Ganapathy *et al.* (1970) that a magnetic interaction between iron particles in the nebula may have caused preferential accumulation of iron in the earth. This was based upon a physical mechanism proposed by Harris and Tozer (1967), which was, however, shown to be untenable by Banerjee (1967). Further difficulties for the binary planet hypotheses arise from geochemical considerations (Ringwood, 1966*a*, 1966*b*) which show that it is most unlikely that the earth accreted from a pre-existing mixture of metal and silicate particles in the solar nebula.

Results from the study of Apollo 11 basalts have a decisive bearing upon this hypothesis. Let us assume, despite the difficulties mentioned above, that the earth and moon accreted from a well-mixed reservoir of metal particles and silicate particles in the solar nebula, and that an unknown physical process caused metallic iron to accrete preferentially upon the earth, ultimately to segregate into the core. In this case the earth's mantle and the moon would have formed from the same reservoir of silicate particles in the nebula. We would expect on this hypothesis that the compositions of the earth's mantle and moon should be very similar and that lunar and terrestrial basalts formed by partial melting of these similar source regions should be generally similar. This consequence is directly contradicted by the several major chemical differences which have been inferred to exist between lunar and terrestrial basalts and between their respective source regions (Section 4). It does not appear possible to explain these on the basis of the binary planet hypothesis.

(*c*) *Capture*

The capture hypothesis has become popular during recent years. This maintains that the moon was formed as an independent body in some other region of the solar system and subsequently passed close to the earth in an orbit which permitted it to be captured. There are many versions, the most widely discussed being those of Gerstenkorn and Urey. For capture to occur, an extremely favourable and critical conjunction of orbits of earth and moon must be assumed. Regardless of details, all capture hypotheses invoke the occurrence of an event of extremely low intrinsic probability. Furthermore, the capture hypotheses offer no explanation of the deficiency of the moon in iron relative not only to the earth but also to the other terrestrial planets.

For capture to occur under the least unfavourable conditions, moon and earth should move in very similar orbits, implying that moon and earth were born in the same region of the solar system and, presumably, from the same parental material. Even if it is assumed that the moon was captured from a highly eccentric orbit, in which case the probabilities of capture are much lower, it is hard to avoid the conclusion that the moon was born among the terrestrial planets, in all of which the abundance of iron is much higher than in the moon. Indeed, Ringwood (1966*b*) and Ringwood and Clark (1970) have shown that the abundance of iron relative to silicon and magnesium is probably the same in Mars, Venus and earth, and similar to that in chondritic meteorites and in the sun. The relative deficiency of iron in the moon is thus a problem of the first order, not to be lightly resolved by postulating an origin for the moon in some other region of the inner solar system.

Clearly, if the capture hypothesis is to be taken seriously it must possess some singularly attractive advantages in other directions in order to offset these profound disadvantages.

(*i*) *Gerstenkorn Capture Hypothesis.* As a result of tidal friction between earth and moon, the earth is transferring angular momentum to the moon, which accordingly is speeding up and moving further away. At the same time the earth's rotation is slowing down, and the length of the day is increasing. The rate of increase in length of the day is known from astronomical observations, and establishes the present magnitude of tidal friction between moon and earth. Assuming that this was constant, Gerstenkorn (1955) calculated the position of the lunar orbit backwards in time and showed that about two billion years ago the moon was only 2·8 earth radii distant from the earth, which is almost identical with Roche's limit. As the moon closely approached the earth, the inclination of the lunar orbit increased sharply and, providing that it was not destroyed at Roche's limit, its orbit passed over the poles of the earth and became retrograde, rapidly moving away from the earth. Reversing the time sense, Gerstenkorn accordingly argued that the moon had been originally captured by the earth on a retrograde orbit, and its subsequent history followed (in reverse) the course of the previous discussion.

Subsequent more elaborate calculations (e.g. MacDonald, 1964) have generally confirmed Gerstenkorn's results, but have shortened the time of closest approach to a period between 1·8 and 1·2 billion years ago. MacDonald and others pointed out that the moon and earth would be strongly heated and extensively melted at the time of closest approach, and that surface features on the moon would be completely obliterated. It follows that the present topography of the moon must be younger than the time of closest approach. All conclusions of this type rest upon the assumption that the mechanism of tidal dissipation within the earth has not changed greatly with time. Although they would concede some modest variations, it is probable that most pre-Apollo 11 advocates of the capture hypothesis would have maintained that the time scale for closest approach of moon to earth was unlikely to be in error by more than a factor of two and that the moon's features must, therefore, be much younger than the age of the earth.

The Apollo 11 results have destroyed the entire basis of this class of hypotheses, including the MacDonald "many moon" hypothesis. The ancient ages of Apollo 11 rocks (3·7 billion years) and the fact that the highlands are much older than the maria, show that the inferred time-scales of evolution of the lunar orbit and close approach of moon to earth are seriously wrong, apparently because the present rate of tidal dissipation is atypical.

Alfven and Arrhenius (1969) have recently advocated a hypothesis based on postulated spin-orbit resonances according to which the moon was captured on a retrograde orbit and evolved into direct orbit without coming closer to the earth than eight earth radii. In principle, this would avoid the catastrophic effects of close approach as in Gerstenkorn's theory. However, their mechanism requires a number of highly speculative assumptions. Recalling that the original capture event is one of very low intrinsic probability, these additional necessary assumptions which are unsupported by direct evidence necessarily render this version of the capture hypothesis even more tenuous and speculative.

Singer (1968) has proposed an extension of tidal theory based upon the assumption of a frequency-dependent dissipation function.

His objective was to remove one of the difficulties of the Gerstenkorn theory—namely that the earth would be extensively melted during the time of closest approach. However, his model has the moon periodically penetrating inside Roche's limit, so that it would be strongly deformed, heated and perhaps destroyed during the interval of close approach. Singer (1969) recognizes that these consequences are tolerable only it the time of closest approach was at about 4·5 billion years ago. Accordingly, he abandons the Gerstenkorn-MacDonald time-scale for tidal evolution by assuming that the present rate of tidal dissipation in the earth is atypical and much higher than on the average occurred in the distant past.

As discussed earlier, the Apollo 11 rock ages imply that this latter assumption is almost certainly correct. Nevertheless, the primary reason for preferring the capture hypothesis in the first place was to live with the short time-scale of tidal evolution found by Gerstenkorn. Once this is abandoned the principal justification (small though it be) for the capture hypothesis disappears.

We have seen that the capture hypotheses so far discussed do not explain the low iron content of the moon compared to the other terrestrial planets, nor do they provide an explanation of the other characteristic chemical properties of the moon which were discussed in Section 4. Moreover, capture is a process of very low intrinsic probability. Finally, the short tidal evolution time-scale which provided the primary rationale for the capture hypothesis is almost certainly incorrect. Until these very serious drawbacks are overcome, the above capture hypotheses hardly warrant further serious consideration.

(*ii*) *Urey Capture Hypothesis*. Urey (1962, 1963, 1965) has attempted to explain the low iron content of the moon compared to the earth on the basis of capture of the moon by the earth during formation of the solar system about 4·7 billion years ago. Urey attempts to avoid the intrinsic improbability of a unique lunar capture by postulating that a generation of lunar sized "primary objects" were present in the solar system before the planets were formed and that a period of intense collisions occurred, causing disintegration of nearly all the primary objects into a mixture of generally small metal and silicate particles, which were subsequently subjected to some kind of physical fractionation in the solar nebula. The terrestrial planets are supposed to have formed by accretion from this fractionated debris. Urey suggested that a few (out of thousands) lunar sized objects survived these catastrophes and that the moon is one of these.

Urey's original evidence for the existence of an early generation of lunar sized objects was based upon conclusions (then shared by many, including the author) that some kinds of meteorites had formed at high pressures in the centres of lunar-sized objects. Subsequently, these conclusions were shown to be incorrect by Anders and co-workers and they have been almost universally abandoned.

A major aspect of Urey's hypothesis was his proposal, based upon then-existing measurements of the iron abundance in the sun, that the moon was a "primary object" possessing the solar abundance of iron (and other metals). The much higher abundance of iron in the other terrestrial planets was assumed to have occurred as a result of physical metal-silicate fractionations during the collisions and fragmentations of the primary lunar objects. Recently, new and improved determinations of the abundance of iron in the sun (e.g. Garz *et al.*, 1969) have shown that the solar iron abundance is in the same range (relative to silicates) as occurs in chondritic meteorites, the earth, Mars and Venus. This removes the basis of Urey's hypothesis. Furthermore, the strong depletion of volatile metals in the moon relative to the primordial and terrestrial abundances of these metals (Section 4) is hardly consistent with the assigned properties of the "primary objects".

6. Towards a New Hypothesis of Lunar Origin

One of the most important results arising from the study of Apollo 11 rocks has been that the "standard" theories of lunar origin—fission, binary planet and capture—are no longer tenable in the forms in which they were earlier stated. They must either be developed into new forms which are consistent with the Apollo 11 data, or else they must be totally abandoned. A start towards developing such a new form of the fission hypothesis has been made by Wise (1969) and O'Keefe (1969).

Alternatively, we must explore in a different direction for a new type of hypothesis. An acceptable working hypothesis must be capable of explaining the major chemical similarities between earth and moon and the tidal evidence both of which suggest the existence of some kind of genetic relationship between earth and moon (Section 4). At the same time, it must explain the fractionation of iron and the other important chemical differences between earth and moon which were outlined in Section 4. The "precipitation" hypothesis developed by Ringwood (1966*b*, 1970) may provide a possible framework for interpreting these relationships This maintains that during the later stages of accretion of the earth a massive primitive atmosphere developed which was hot enough to selectively evaporate a substantial proportion of the silicates which were accreting. Subsequently the atmosphere was driven away by particle radiation from the sun as it passed through the T-Tauri phase. The relatively non-volatile silicate components were precipitated close to the earth to form a swarm of planetesimals or moonlets as the atmosphere was dissipated, and the moon formed by accretion of these chemically fractionated planetesimals.

The details have been stated by Ringwood (1970), and a summary only is given here. It was proposed that the earth accreted directly in the solar nebula from planetesimals of primordial composition resembling the Type 1 carbonaceous chondrites. These contain completely oxidized iron together with large amounts of water, nitrogen, sulphur and carbonaceous compounds, and have retained the primordial abundances of most elements except for extremely volatile substances. It was assumed, furthermore, that accretion of the earth occurred over a period of the order of 10^6 years or less, and that accretion was completed just before the sun entered its T-Tauri phase characterized by rapid mass loss and the generation of a solar wind some 10^6 to 10^7 times more intense than the present solar wind.

Formation of the earth under these boundary conditions is strongly influenced by the gravitational potential energy dissipated during accretion, which in turn controls the chemical equilibria in the accreting material. The accretion energy per gramme is plotted against radius of the growing earth in Figure 5. It increases approximately as the square of the radius, reaching 15,000 cals./gm. during the final stages.

During the early stages of accretion, the energy evolved is small and accretion is relatively slow. The temperature is accordingly low and is buffered by the latent heat of evaporation of volatiles, e.g. H_2O, in the planetesimals. During this stage (Fig. 5, I) a cool, oxidized volatile-rich nucleus of primordial material, perhaps about 10% of the mass of the earth, is formed.

As the mass of the nucleus increases, the energy of infall of planetesimals becomes sufficient to cause strong heating on impact, leading to reduction of oxidized iron by carbon and formation of a metal phase. This is accompanied by degassing and the formation of a primitive atmosphere, mainly of CO and H_2 (Stage II, Figure 5). With further growth (Stage III) both the temperature and intensity of reduction increase and metals which are comparatively volatile under high temperature reducing conditions (e.g. Na, K, Rb, Pb, Zn, Hg, In, Tl) are volatilized into the primitive atmosphere. During Stage IV the surface temperatures exceed 1500° C. and the relevant equilibria (Ringwood, 1966*a*) show that silicate minerals are selectively reduced and evaporated into the primitive atmosphere, whilst metallic iron continues to accrete upon the earth. Finally, during Stage V, after segregation of the earth's core, which causes a further evolution of 400–600 cals./gm. of gravitational energy for the whole earth, silicates from the outer mantle are directly evaporated into the primitive atmosphere. The mass of the primitive atmosphere is about one-quarter of that of the earth and it is composed mainly of CO and H_2 with about 10% of volatilized silicates.

It is assumed that this primitive atmosphere was dissipated immediately after accretion or during the later stages of accretion by a combination of factors: (i) intense solar radiation as the sun passed through a T-Tauri phase, (ii) mixing of the rapidly spinning high-molecular-weight terrestrial atmosphere with the low-molecular-weight solar nebula in which it is immersed, (iii) magnetohydrodynamic coupling resulting in the transfer of angular momentum from the condensed earth to the primitive atmosphere, and more speculatively (iv) rotational instability of the atmosphere caused by formation of the core (modified fission hypothesis) (Ringwood, 1960; O'Keefe, 1969; Wise, 1969). The relative importances of these processes are not known, but it seems likely that the intense solar wind from the T-Tauri phase of the sun played a major role.

As the result of a combination of these processes, the massive primitive atmosphere was dissipated. On cooling, the silicate components were precipitated to form an assemblage of earth-orbiting planetesimals resembling Öpik's sediment ring. A further fractionation according to volatility occurred during the precipitation stage, since the less volatile components were precipitated first at relatively high temperatures and close to the earth, whereas the more volatile components were precipitated at lower temperatures and further from the earth. The silicates precipitating at relatively high temperatures would probably have grown into relatively large planetesimals (10^2–10^7 cm. diam.), which would tend to be left behind by the escaping terrestrial atmosphere. However, the more volatile components precipitating at relatively low temperatures were more likely to have formed fine, micron-sized particles or smoke, which would be carried away with the escaping atmosphere by viscous drag, and hence lost from the earth-moon system. The moon then accreted from the sediment-ring of earth-orbiting planetesimals.

Ringwood (1970) showed in greater detail that this " precipitation " hypothesis accounted for the fractionation of iron and silicates between earth and moon in the context of a close genetic relationship between earth and moon. Chemical fractionations within the cooling primitive atmosphere also provide a basis for interpreting the strong depletions of volatile metals in the moon, the fractionation of some major oxyphile elements between moon and earth, the relative depletion of siderophile elements in the moon and the different oxidation state of the moon, as compared to that of the earth's mantle.

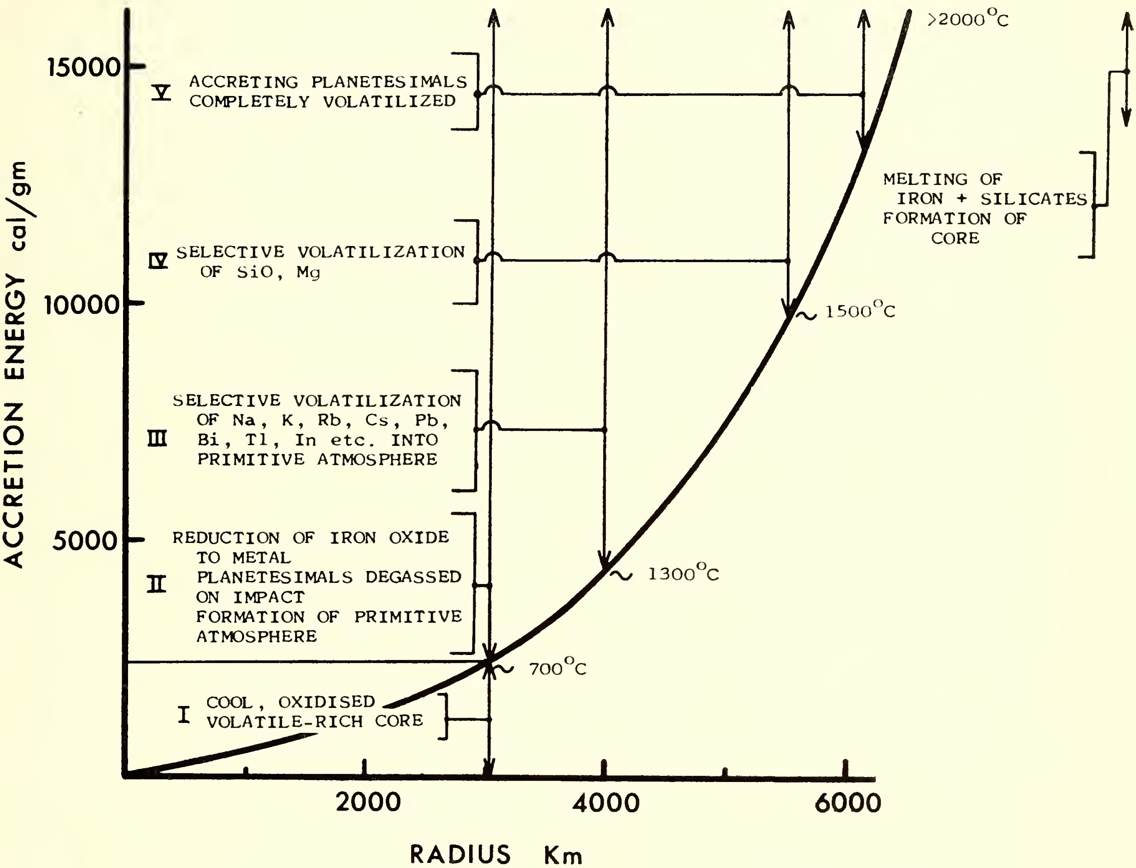

FIGURE 5.—Relationship between energy of accretion and radius of the growing earth. The principal stages of accretion are also shown in relation to the energy of accretion and approximate surface temperatures. (*After* Ringwood, 1970.)

Conclusion

The precipitation hypothesis complements the " sediment-ring " hypothesis of Öpik (1961, 1967), according to which the moon formed by the coagulation of a swarm or sediment ring of earth-orbiting planetesimals or moonlets. Öpik's hypothesis was proposed on the basis of his studies of lunar cratering and tidal evolution, and was not concerned with explaining the origin and composition of the planetesimals which is the principal contribution of the present hypothesis.

The precipitation and fission hypotheses are related, since according to the former the material now in the moon is regarded as having been derived ultimately from the earth—not from the solid mantle, but from the massive primitive terrestrial atmosphere. The latest versions of the fission hypothesis by O'Keefe (1969) and Wise (1969) maintain that fission was accompanied by the development of high temperatures and the formation of a massive primitive terrestrial atmosphere of volatilized silicates. This atmosphere was believed to be from three to 20 times more massive than the moon. These hypotheses, although developed from different premises to those of the precipitation hypothesis, clearly lead towards an environment of lunar origin which has important elements in common with that of the precipitation hypothesis. Cameron (1970), starting from yet another direction, finally derived a model according to which the earth develops a massive hot atmosphere containing volatilized silicates and the moon is ultimately formed from the atmosphere.

Although the hypotheses of Öpik, O'Keefe, Wise, Cameron and the author differ both in minor and major respects, and have been arrived at via different paths, it is tempting to see the beginning of a consensus. I am convinced that in one way or another the material now in the moon was ultimately derived from a massive hot primitive atmosphere which once surrounded the earth and that the chemical differences between earth and moon can be interpreted on this basis.

7. Acknowledgements

This paper was prepared at the Lunar Science Institute under the joint support of the Universities Space Research Association and the National Aeronautics and Space Administration Manned Spacecraft Center under Contract No. NSR 09-051-001.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 77–80, 1970

Gorceixite-Goyazite in Kaolinite Rocks of the Sydney Basin

F. C. Loughnan and C. R. Ward

Abstract—Occurrences of the phosphate mineral, gorceixite-goyazite $(Ba,Sr)Al_3(PO_4)_2(OH)_5$, in a claystone from the Illawarra Coal Measures and in two dyke clays from the southern part of the Sydney Basin are described. The phosphate mineral is associated with abundant well-ordered kaolinite and minor amounts of anatase. The concentration of the phosphate mineral in parts of the claystone could be attributed to its high specific gravity compared with that of the associated kaolinite. However, no explanation can be given for the origin of the mineral in the dyke clays.

Introduction

Renewed interest in the nature of soil phosphate minerals in recent years has shown that members of the plumbogummite group with the general formula $RAl_3(PO_4)_2(OH)_5$ (Palache *et al.*, 1951) including gorceixite (R=Ba), goyazite (R=Sr), crandallite (R=Ca) and florencite (R=Ce) have widespread distribution. Thus, Coetzee and Edwards (1959), Wolfenden (1965), Trueman (1965) and Schellmann (1966) have recorded the presence of these minerals in tropical soils, while Norrish (1957, 1968), who examined a range of soil types, concluded that they are common in the "less-weathered" terra rossas and rendzinas as well as the highly-leached laterites and krasnozens, and that in all these occurrences the associated clay mineral is kaolinite. Since both kaolinite and the phosphate minerals are resistant to chemical breakdown, it would be expected that their association would persist in detrital sediments derived from these soils. However, there has been only a limited number of references to the presence of plumbogummite minerals in kaolinite-rich rocks. In the occurrences of these minerals cited by Palache *et al.* (1951) no mention is made of their association with kaolinite, while according to Milton *et al.* (1959) the gorceixite nodules in the Bashi Marl, Alabama, are accompanied by glauconite. Nevertheless, Stadler and Werner (1962), Burger (1964) and Wilson *et al.* (1966) have described crandallite in kaolinite *tonsteins* of Carboniferous age from Germany and England, and Loughnan (1970) has recognized gorceixite-goyazite in the kaolinite-rich Garie member of the Narrabeen Group in the southern part of the Sydney Basin and in a kaolinite claystone (flint clay) of the basal Pennsylvanian at Olive Hill, Kentucky. The kaolinite in each of these deposits is particularly well-ordered.

Recently, gorceixite-goyazite has been found in relative abundance, associated with well-ordered kaolinite, in three separate deposits within the Sydney Basin. One of these is kaolinite claystone of Permian age that crops out at Fitzroy Falls, and the remaining two are completely kaolized igneous dykes that intersect Permian and Triassic strata at Fitzroy Falls and at Bullio, approximately 30 miles north-west of Fitzroy Falls.

Occurrence

At Fitzroy Falls toward the southern end of the Sydney Basin, an indurated claystone, approximately 4 ft. thick, forms the uppermost unit of the Permian Illawarra Coal Measures. The Narrabeen Group has been overlapped in this area, and the claystone is separated from the overlying Hawkesbury Sandstone by an eroded surface. Angular blocks of the claystone up to a foot across occur sporadically in the lower few feet of the sandstone. Below the claystone the succession is obscured by talus but, according to Shiels (private communication), coal occurs within 20 ft. of the base of the Hawkesbury sandstone in this area.

In structure, texture and mineralogy the claystone is similar to many of the *kaolin coal* tonsteins described by Burger *et al.* (1962) from the Westphalian Coal Measures of the Ruhr Basin and also to many of the flint clays of the Pennsylvanian of North America, particularly those occurring in the Olive Hill area, Kentucky (Patterson and Hosterman, 1958). The claystone is remarkably indurated, lacks bedding, and breaks with a pronounced conchoidal fracture. The texture of the rock varies from dense to brecciated and oolitic with the angular fragments and oolites ranging up to 1 mm. across. However, vermicular kaolinite crystals, a common feature of the European tonsteins and of similar kaolinite claystones observed elsewhere in the Sydney Basin

(Loughnan, 1962), are rare in the material from Fitzroy Falls.

Well-ordered kaolinite is the dominant constituent of all textural types of the Fitzroy Falls claystone and in some samples it comprises more than 90% of the mineral content. On the other hand, quartz rarely exceeds 10% and frequently is absent, while clay minerals other than kaolinite have not been detected. Siderite in the form of oolites or pseudoolites is abundant in some thin sections, and all samples examined by X-ray diffraction showed a reflection at 3·51Å attributable to anatase (Figure 1). Gorceixite-goyazite comprises as much as 15% of the claystone. The presence of the mineral was detected by X-ray diffraction and chemical analysis but, because of either a very fine particle size or the masking effect of the associated kaolinite, it was not recognizable in thin sections under the petrological microscope.

The dyke clay at Fitzroy Falls, where sampled, has a width of 18 in. and that at Bullio 2 ft. Although the parent material is not evident in either deposit, residual igneous textures can be observed in thin sections of these clays. Basalt and dolerite dykes are prevalent in the Sydney Basin, and where permeable sandstones form the host rocks they are generally completely altered down to the level of the water-table. Control of the depth of the clay by the level of the water-table suggests that the alteration of the igneous rocks is the result of low-temperature leaching

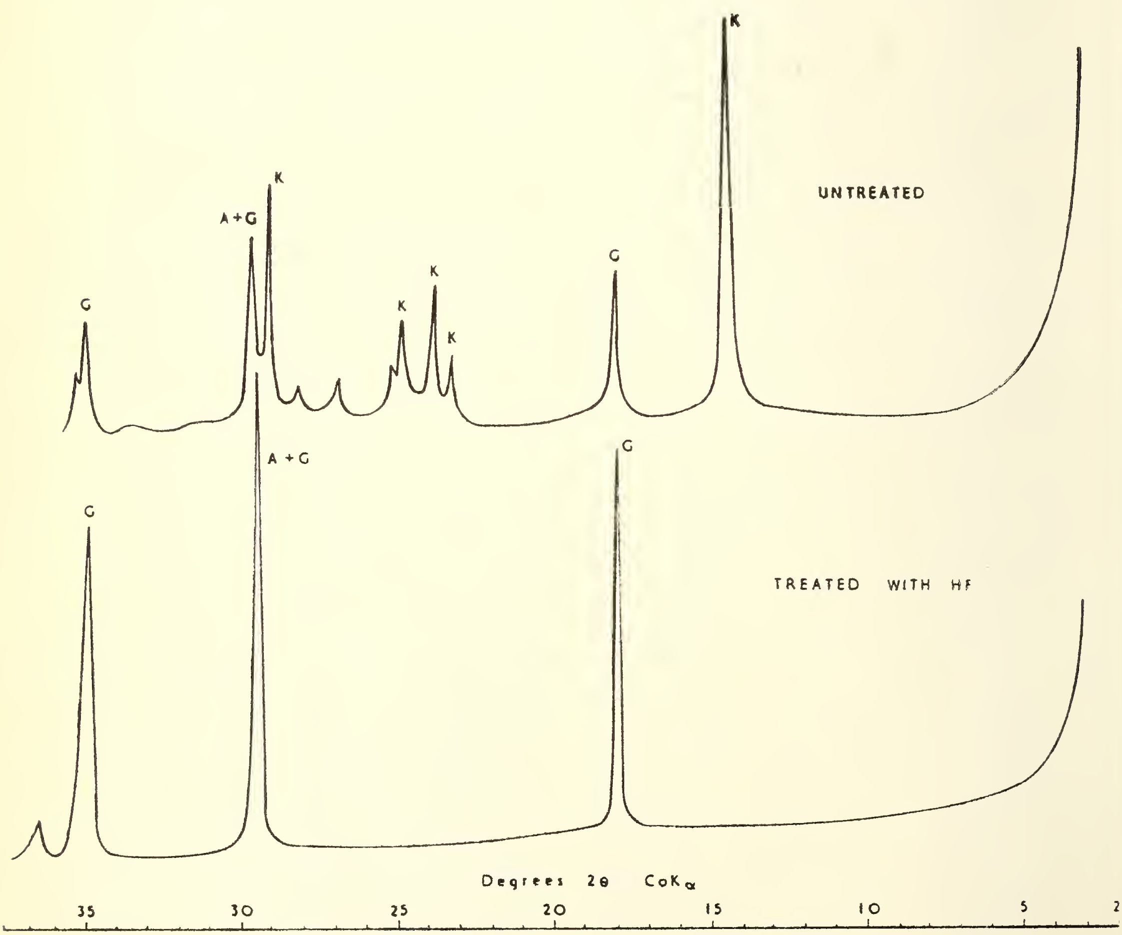
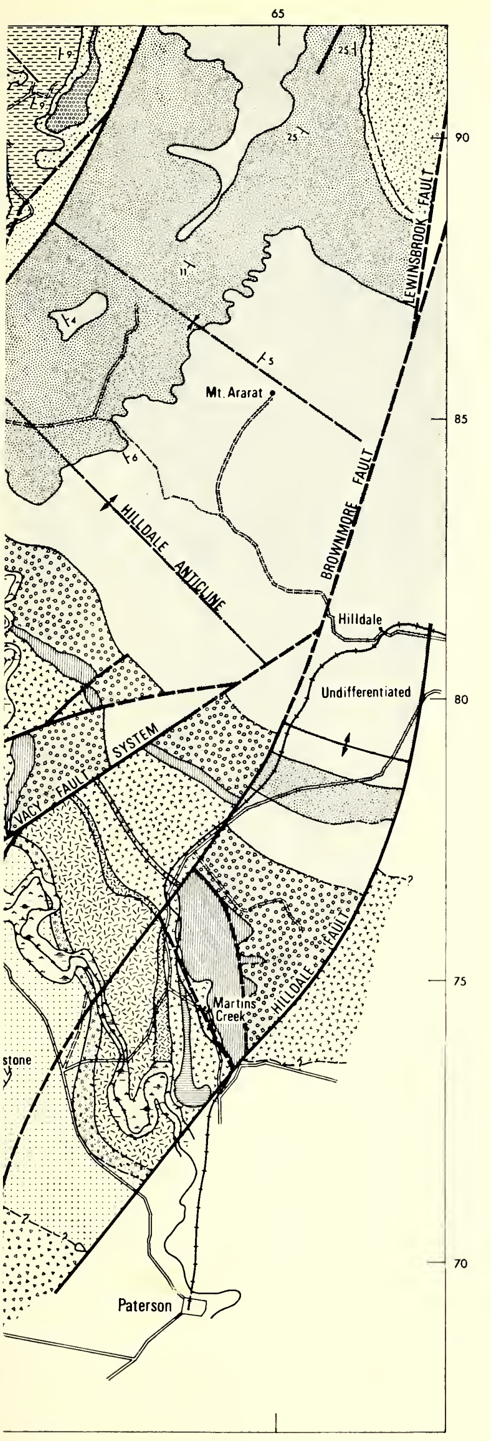


FIGURE 1.—X-ray diffraction traces from the Fitzroy Falls claystone before and after treatment with hydrofluoric acid.
K = reflections due to kaolinite.
G = reflections due to gorceixite-goyazite.
A = reflections due to anatase.



MAP 1
STRATIGRAPHIC MAP OF THE PATERSON-GRESFORD DISTRICT N.S.W.

SCALE 1 — 0 — 1 — 2 MILES

1 — 0 — 1 — 2 — 3 KILOMETRES

REFERENCE

QUATERNARY — *Unconsolidated sands and gravel*

CARBONIFEROUS

SEAHAM FORMATION — *Red lithic sandstone, pebble conglomerate, varve shale*

PATERSON VOLCANICS — *Toscanitic and dellenitic ignimbrite*

Sedimentary Lens — *Lensoidal lithic sandstone, conglomerate*

MT. JOHNSTONE FORMATION — *Yellow lithic sandstone, lithic tuff, conglomerate*

GILMORE VOLCANIC GROUP:

MOWBRAY FORMATION — *Red-purple lithic sandstone, lithic tuff, conglomerate*

Lambs Valley Ignimbrite Member — *Purple and white rhodacitic ignimbrite*

Breckin Ignimbrite Member — *Red and grey andesitic ignimbrite*

NEWTOWN FORMATION — *Purple lithic sandstone, conglomerate, siltstone*

Vocy Ignimbrite Member — *Red, white and grey rhyodacitic ignimbrite*

Mortins Creek Ignimbrite Member — *Grey andesitic ignimbrite*

Hypersthene Andesitic Pitchstone

WALLARINGA FORMATION — *Red lithic sandstone, conglomerate, lithic tuff and ignimbrite*

FLAGSTAFF SANDSTONE — *Yellow and green lithic sandstone, conglomerate, mudstone*

Mt. Rivers Ignimbrite Member — *Red-brown vitric ignimbrite*

Member A — *Bedded siltstone and lithic sandstone*

BONNINGTON SILTSTONE — *Blue-grey siltstone, minor limestone, mudstone and sandstone*

ARARAT SANDSTONE — *Yellow lithic sandstone and conglomerate, minor mudstone, oolitic limestone, ignimbrite*

Conglomerate bands

BINGLEBURRA MUDSTONE — *Green-brown friable mudstone, minor sandstone and limestone*

Geological Boundary Accurate — Approximate

Fault Accurate — Approximate

Anticline Accurate — Approximate

Syncline Accurate — Approximate

Strike and Dip of Bedding — Dip Slope

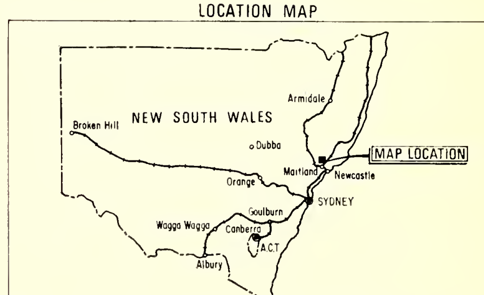
River — Creek

Road — Track

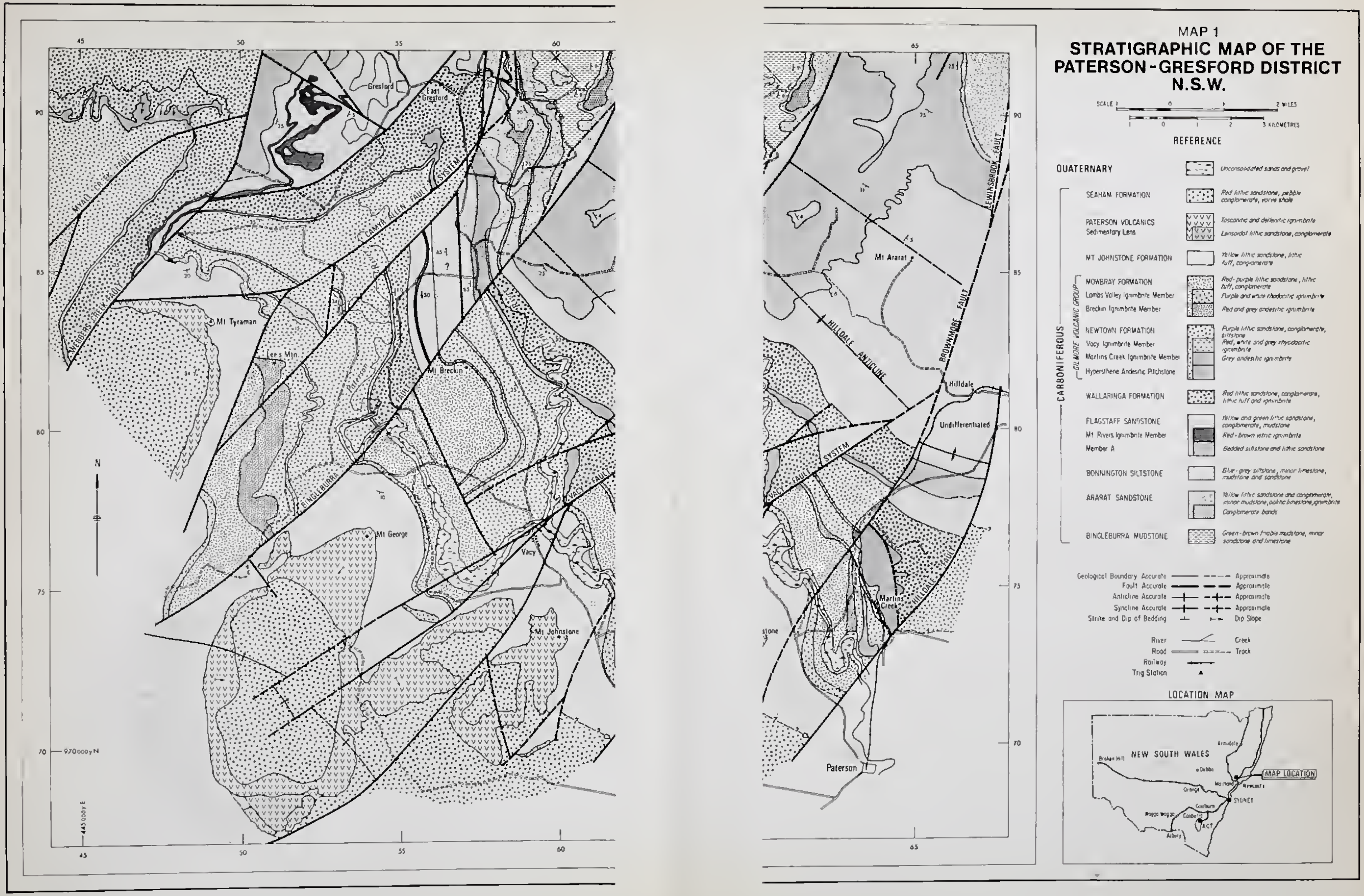
Railway

Trig Station

LOCATION MAP



This map was inadvertently omitted from the article by Hamilton, Hall and Roberts in Volume 107 (3/4) and should be inserted between pages 78 and 79 of that issue.



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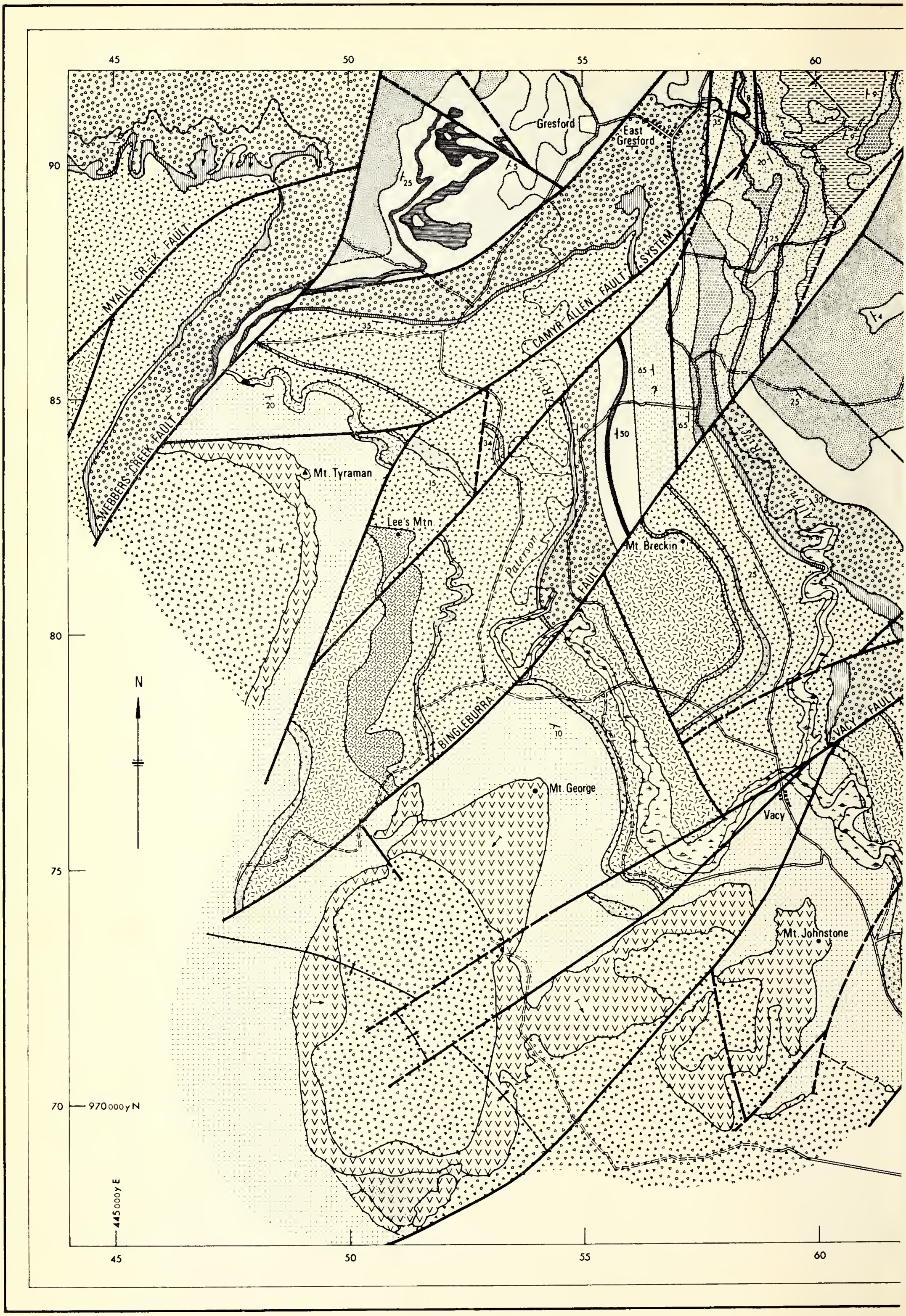

and not hydrothermal activity. As Loughnan and Golding (1957) have shown, kaolinite is the dominant alteration product in these dyke clays, but illite and/or mixed layer clay minerals may also be present. In the dyke clays at Fitzroy Falls and at Bullio well-ordered kaolinite was the only clay mineral detected, and gorceixite-goyazite is present to the extent of 10% and 15% respectively.

Composition of the Phosphate Minerals

For the specific identification of the phosphate mineral in the Fitzroy Falls claystone and the Bullio dyke clay, concentrates were obtained using the technique described by Norrish (1957, 1968). The rocks were treated with a 20% solution of hydrofluoric acid for two minutes and, after dilution and washing, the residue was neutralized with a normal solution of caustic soda. Examination of the residue by X-ray diffraction showed that the kaolinite had been completely destroyed and that gorceixite-goyazite and anatase (Figure 1) were the only minerals present. An elemental analysis of the residue was made by X-ray fluorescence through the courtesy of the Australian Atomic Energy Commission and the results converted to the oxide forms are given in Table 1. On the basis of these results, the phosphate mineral in the Fitzroy Falls claystone consists of approximately 60% gorceixite, 25% goyazite, 10% crandallite and 5% florencite, whereas that in the Bullio dyke clay is composed of 45% gorceixite, 40% goyazite, 10% crandallite and 5% florencite. Other metals detected in the residues of the clay rocks in amounts less than 1% are magnesium, lead, copper, zinc and, to a lesser extent, tin, chromium, manganese and boron. The residues also contained some free silica released from the kaolinite but not dissolved by the caustic soda.

Table 1

X-ray Fluorescence Analyses of the Phosphate Concentrates Expressed as Oxides

	Fitzroy Falls Claystone	Bullio Dyke Clay
SrO	2·09	5·20
CaO	0·58	0·62
BaO	7·37	8·37
CeO	0·50	1·06
TiO_2 (*a*) ..	8·47	23·27
Al_2O_3	11·22	30·03
P_2O_5	8·32	13·74
Fe_2O_3 (*b*) ..	19·81	0·21

Remainder undissolved silica.
(*a*) Present mostly as anatase.
(*b*) Present as free iron oxides.

Discussion

The origin of the gorceixite-goyazite in these clay rocks is not fully understood. From the study of their distribution in soils Norrish (1968) concluded that they do not represent residuals of the parent rock that have resisted chemical breakdown but rather, that they have formed during weathering. This would imply that the igneous rocks which formed the parent materials for the dyke clays at Bullio and at Fitzroy Falls contained appreciable quantities of phosphorus, barium and strontium, in addition to aluminium, and that these elements were concentrated through the loss of more mobile constituents such as the alkalis, magnesium and much of the calcium, iron and silicon. However, in published chemical analyses of igneous dyke rocks from the Sydney Basin (e.g. White and Mingaye, 1904) there is no suggestion of the presence of unusually high concentrations of phosphorus, barium or strontium. Moreover, since strontium and to a lesser degree barium behave in a manner similar to calcium and magnesium during weathering, it is difficult to understand the preferential retention of these ions in the resulting clay. Possibly the early release of aluminium and phosphorus during weathering initiated development of the gorceixite-goyazite structure and strontium and barium became entrapped or "fixed" within this structure.

The origin of the phosphate mineral in the Fitzroy Falls claystone does not present the difficulties encountered with the dyke clays. In the Sydney Basin there is much evidence to support a detrital origin for these claystones. The common occurrence of conglomeratic and brecciated textures, perfectly preserved fossil leaves and sharply defined lower boundaries in these claystones negates the possibility that they developed *in situ* through the intense leaching of a pre-existing rock. Presumably, they represent accumulations of detritus that were derived from highly-leached, kaolinite-rich soils which also contained gorceixite-goyazite. Local concentrations of the phosphate mineral in the sediment probably resulted from its greater specific gravity (3·1-3·3) compared with that of the accompanying kaolinite (2·6).

Acknowledgments

The spectrographic analyses were obtained through a grant from the Australian Research Grants Committee.

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(Received 29 September 1970)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 81–84, 1970

Internal Seiche Motions for One-dimensional Flow

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(Communicated by Professor A. Keane)

Abstract—The modes of oscillation for the internal waves at a density discontinuity in a fluid are examined for a variable shaped basin. The flow is considered as one-dimensional, the equations of motion are linearized, and the rotation of the earth is neglected.

1. Introduction

Internal oscillations in a basin are usually discussed by considering the basin shape to be rectangular in plan and the depth to be uniform. The early treatment (Lamb, 1932) assumed two separate layers of uniform densities ρ_1 and ρ_2. Later developments have attempted to account for the variation in density throughout the depth, and the motion of a stratified layer is summarized by Longuet-Higgins in an Appendix to Mortimer (1952).

The methods used to discuss surface seiches may probably be extended to treat the internal seiche. In particular, the Galerkin method as applied to the surface seiche in Clarke (1968) can be so used. In that article it was demonstrated that the Galerkin method is an easy-to-apply technique that is valid over a wide range of basin shapes. The form of the solution is ideal in that it gives both transport and wave height as well as the frequencies of various modes. The procedure used for examining the surface seiche consisted of transforming the linearized equations of motion for one-dimensional flow by defining two new variables, horizontal transport and surface area, and then solving these for the modes of oscillation as a sequence of approximations using Galerkin's method. A similar sequence of approximations may be determined for internal oscillations if new variables, horizontal transport and surface area, are defined for each layer. The flow is considered to be one-dimensional and transverse oscillations are neglected. The basin will be considered to be small enough so that the rotation of the earth can be neglected.

2. Equations of Motion

Choose the origin 0 in the free undisturbed surface at one end of the lake so that $0x$ is along the main axis of the lake and $0z$ vertically upward. The subscripts $j=1$ and $j=2$ will be used to denote variables in the upper and lower layers respectively. Then the linearized equations of motion, neglecting transverse motions, are

$$\dot{u}_j=-\frac{1}{\rho_j}\frac{\partial p_j}{\partial x}, \qquad j=1, 2, \qquad (1)$$

where u_j is the horizontal velocity in the x direction,
p_j is the pressure at the depth z,
and ρ_j is the density of the fluid, assumed constant in each layer.

If ζ_1 and ζ_2 are the wave heights at the surface and interface respectively, then the equations of continuity over a transverse section in each layer of the basin are

$$\frac{\partial}{\partial x}\{A_j(x)u_j\}=-\dot{\zeta}_j b_j(x)+\delta_{j1}\dot{\zeta}_2 b_2(x), \qquad j=1, 2, \qquad (2)$$

where δ_{j1} is the kronecker delta,
$A_j(x)$ is the area of the transverse section,
and $b_j(x)$ is the breadth at the surface of the section.

Assuming that the vertical accelerations are negligible the pressure in each layer is given by

$$\left.\begin{aligned} p_1&=\rho_1 g(\zeta_1-z), \\ \text{and} \quad p_2&=\rho_1 g(\zeta_1+h_1-\zeta_2)+\rho_2 g(\zeta_2-z-h_1) \end{aligned}\right\}, \qquad (3)$$

where h_1 is the depth of the upper layer assumed constant and g is the acceleration due to gravity.

Eliminating p_i from (1) and (3) gives

$$\dot{u}_j=-g\frac{\partial\zeta_j}{\partial x}-\delta_{j2}\frac{\rho_1 g}{\rho_2}\left(\frac{\partial\zeta_1}{\partial x}-\frac{\partial\zeta_2}{\partial x}\right). \qquad (4)$$

Transport variables, α_j, are introduced by

$$\alpha_j=A_j(x)\xi_j, \qquad j=1,2, \qquad (5)$$

where ξ_j is the horizontal displacement of a fluid particle from its mean position, and surface area variables, χ_j, by

$$\frac{1}{b_j(x)}\frac{\partial}{\partial x}\equiv\frac{\partial}{\partial\chi_j}, \qquad j=1,2. \qquad (6)$$

Thus equations (2) and (4) become

$$\frac{\partial\dot{\alpha}_j}{\partial\chi_j}=-\dot{\zeta}_j+\delta_{j1}\frac{b_2(x)}{b_1(x)}\dot{\zeta}_2,$$

i.e.,

$$\frac{\partial\alpha_j}{\partial\chi_j}=-\zeta_j+\delta_{j1}\frac{b_2(x)}{b_1(x)}\zeta_2, \qquad (7)$$

the constant of integration being taken as zero from initial conditions,

and

$$\ddot{\alpha}_j=-gf_j(\chi_j)\frac{\partial\zeta_j}{\partial\chi_j}-\delta_{2j}\frac{\rho_1}{\rho_2}gf_2(\chi_2)\left(\frac{\partial\zeta_1}{\partial\chi_2}-\frac{\partial\zeta_2}{\partial\chi_2}\right), \qquad (8)$$

where $f_j(\chi_j)=A_j(x)b_j(x)$. (9)

Eliminating ζ_j from (7) and (8) yields

$$\left.\begin{aligned} \ddot{\alpha}_1&=gf_1\left\{\frac{\partial^2\alpha_1}{\partial\chi_1^2}+\frac{\partial^2\alpha_2}{\partial\chi_2^2}\right\}, \\ \text{and} \quad \ddot{\alpha}_2&=gf_2\left\{\left(1-\frac{\rho_1}{\rho_2}\right)\frac{\partial^2\alpha_2}{\partial\chi_2^2}+\frac{\rho_1}{\rho_2}\frac{\partial^2}{\partial\chi_1\partial\chi_2}(\alpha_1+\alpha_2)\right\} \end{aligned}\right\}. \qquad (10)$$

To find the frequencies, σ, of normal modes of oscillation, put

$$\alpha_j=\alpha_j^* e^{i(\sigma t+\varepsilon)}, \qquad (11)$$

where

$$\alpha_j^*\equiv\alpha_j^*(x),$$

giving for (10) the transport equations

$$\left.\begin{aligned} &\frac{\partial^2}{\partial\chi_1^2}(\alpha_1^*+\alpha_2^*)+\frac{\sigma^2}{gf_1}\alpha_1^*=0, \\ \text{and} \quad &\left(1-\frac{\rho_1}{\rho_2}\right)\frac{\partial^2\alpha_2^*}{\partial\chi_2^2}+\frac{\rho_1}{\rho_2}\frac{\partial^2}{\partial\chi_1\partial\chi_2}(\alpha_1^*+\alpha_2^*)+\frac{\sigma^2}{gf_2}\alpha_2^*=0 \end{aligned}\right\}. \qquad (12)$$

The boundary conditions applicable to (12) are

$$\alpha_j^*=0 \text{ at } \chi_j=0 \text{ and } \chi_j=\chi_{jl}, \qquad (13)$$

where χ_{jl} is the total surface area of each layer.

3. Solution for Modes in a Basin with Vertical Sides

In many basins the sides are sufficiently steep for

$$\chi_1=\chi_2, \ =\chi, \text{ say.}$$

Eqs. (12) are then

$$\left.\begin{aligned}&\frac{d^2}{d\chi^2}(\alpha_1^*+\alpha_2^*)+\frac{\sigma^2}{gf_1}\alpha_1^*=0,\\ \text{and}\\ &\frac{d^2\alpha_2{}^*}{d\chi^2}+\frac{\rho_1}{\rho_2}\frac{d^2\alpha_1^*}{d\chi^2}+\frac{\sigma^2}{gf_2}\alpha_2^*=0\end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Eliminating α_1^* from the equations (14) gives

$$\frac{d^2}{d\chi^2}\left\{f_1\left(\frac{d^2\alpha_2^*}{d\chi^2}+\frac{\sigma^2}{gf_2}\alpha_2^*\right)\right\}-\frac{\rho_1}{\rho_2}\frac{d^2}{d\chi^2}\left\{f_1\frac{d^2\alpha_2^*}{d\chi^2}\right\}+\frac{\sigma^2}{g}\left(\frac{d^2\alpha_2^*}{d\chi^2}+\frac{\sigma^2}{gf_2}\alpha_2^*\right)=0, \quad \ldots\ldots (15)$$

i.e., $L(\alpha_2^*)=0$, say.

The boundary condition for this equation is now

$$\alpha_2^*=0, \ \chi=0, \ \chi_l. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

The Galerkin method (Kantorovich and Krylov, 1958 : 258–262) may be used to find a sequence of approximations to the solution of (15) subject to conditions (16). Let the n^{th} approximation to the transport α_2^* be

$$\begin{aligned}\alpha_n(\chi)&=\chi(\chi_l-\chi)(a_1+a_2\chi+\ldots+a_n\chi^{n-1})\\ &=\sum_n a_i\varphi_i, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)\end{aligned}$$

where each function φ satisfies (16), and are continuous over the domain $[0, \chi_l]$, with the orthogonality conditions

$$\int_0^{\chi_l} L(\alpha_n)\varphi_j d\chi=0, \qquad j=1, 2, \ldots, n. \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

The n orthogonality conditions (18) for the n^{th} approximation, $\alpha_n(\chi)$, yield n equations in the n unknowns a_i. The coefficients of the a_i in these equations are of the form

$$\mu_{ij}\lambda^2+\nu_{ij}\lambda+\tau_{ij},$$

where $\lambda=\sigma^2/g$.

Define square matrices of order n by $A=(\mu_{ij})$, $B=(\nu_{ij})$, $C=(\tau_{ij})$, then the integrated system of equations (18) is

$$(A\lambda^2+B\lambda+C)\mathbf{x}=0. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

The solutions λ of (19) determine frequency and the $\mathbf{x}$ determine transport. It should be noted that the matrices are of order n, hence there will be $2n$ values of λ and their corresponding $\mathbf{x}$, of which n are associated with a surface seiche and n are associated with an internal seiche.

To find the λ and $\mathbf{x}$ multiply (19) by A^{-1}, so that

$$(I\lambda^2+A^{-1}B\lambda+A^{-1}C)\mathbf{x}=0$$

from which a matrix D may be defined as

$$D=\begin{pmatrix}0_{n\times n} & -A^{-1}C\\ I_n & -A^{-1}B\end{pmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

Thus D is of order $2n$ and its eigen-values are the λ of (19).

If the eigen-vectors of D are denoted by $(\mathbf{x}_1'\mathbf{x}_2')'$ then it follows that

$$(I\lambda^2+A^{-1}B\lambda+A^{-1}C)\mathbf{x}_2=0,$$

i.e., $\mathbf{x}_2$, which is the latter n components of the eigen-vector $\mathbf{x}$ of D, is the solution $\mathbf{x}$ of (19).

4. Concluding Remarks

For many lakes and basins the shelving of the boundary will be sufficiently steep to allow the sides to be taken as vertical, and the theory here will apply. It is pointed out by Clarke (1968) that a seventh-degree approximation to the transport is sufficient in most cases to give high accuracy to the approximate solutions for the first few modes of oscillation. Here, the same degree of approximation will give a matrix D of order 10 and the eigen-value and vector reduction of D will be considerably longer. Nevertheless an execution time of one or two minutes should be sufficient on a computer of the speed of a CDC 3200 or IBM 360.

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(Received 22 June 1970)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 85–86, 1970

A New Species of Trilobite, *Cheirurus (Crotalocephalus) regius* n.sp. from the Early Devonian of Trundle District, Central N.S.W.

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Introduction

Devonian trilobites occurring further west than Parkes are a considerable rarity in New South Wales because of the geological, tectonic and palaeogeographic conditions. However, the main point of importance of the present material is the fact that this new species, described below, has been found in a new formation; stratigraphically it occurs just below the base of the Hervey Group, in the top portion of the "Trundle Group" (to be formally described elsewhere shortly) on the eastern side of the Tullamore Syncline, in strata which will be described as "Botfield Formation".

In 1898, W. S. Dun described "a pygidium of one of the Phacopidae, possibly *Coronura*" from a collection made by J. W. Watt from a point 7·5 miles north from Bogan Gate, on the Bogan Gate-Trundle road. The N.S.W. Department of Mines Annual Report (1909) on p. 190 mentions *Encrinurus* as occurring in Portions 3 and 8, Parish of Plevna, County of Cunningham, four miles north-east of Trundle. Raggatt (1937), in a list of fossils from this district, with determinations by W. S. Dun and F. W. Booker, mentions the genus *Proetus*. In more recent years, the author of this paper (during 1965–1968) found Devonian trilobites in several places around Trundle (Foldvary, 1969), but this specimen is the first from central N.S.W. that belongs to the subgenus *Cheirurus* (*Crotalocephalus*).

Systematic Palaeontology

Family CHEIRURIDAE Salter, 1864
Subfamily CHEIRURINAE Salter, 1864
Genus *Cheirurus* Beyrich, 1845
Subgenus *Cheirurus* (*Crotalocephalus*) Salter, 1953
Cheirurus (*Crotalocephalus*) *regius* n.sp.
Plate I, fig. 1

Type Specimen: Holotype (SUP 13925) from Por. 25, Par. Milpose, Co. Ashburnham, 15 miles east of Trundle, N.S.W., stratigraphically below the Hervey Group.

Diagnosis: Glabella with subparallel sides and bulbous frontal lobe; transglabellar furrows moderately V-shaped, curved towards the posterior end of the cranidium axially. Fixigenae rather large and deeply pitted. Tubercles well developed. The shape and large size of the cranidium is considered to be the distinctive characteristic of this species.

Description: The cranidium is unusually large in both dimensions: the length is 35·4 mm., the width 50·0 mm., therefore the width-to-length ratio is W/L=1·39. The glabella is distinctly non-parallel sided, the sides gently converging towards the posterior end of the cranidium; thus the greatest width of the glabella is midway on the frontal lobe (30 mm.). From the anterior end of the glabella, the first and second transglabellar furrows are continuous, crossing the axis, and they are curved moderately backwards axially; the distance between them is 5 mm. The third, preoccipital glabellar furrow is bent backwards in the axial region to the same extent as the occipital furrow is bent forwards, so as to join, and thereby forming a distinctive pattern, reminiscent of an hour-glass lying on its side. The occipital ring is rather wide (20 mm.) and its axial length is 6 mm., possibly wider than the fixigenae, which are large and have deeply pitted surfaces. The eyes are very close to the glabella (distance: 1·5–2 mm.), being in line with the second transglabellar furrow. The tubercles are unusually well developed, 0·5 mm. high and at the base 1 mm. wide, confined to the glabella, though they are absent in the axial region of the glabella, except in the most anterior part. The genal spines and the librigenae are not available.

Discussion: Though only a cranidium is available, the author decided to erect a new species for it, because of its unusually good preservation, its distinctness from other species in terms of size and proportions, and its excellent surface detail. These are also the reasons for the specific name given ("*regius*", Lat. "regal, splendid"). There is no difficulty in allocating this species to the subgenus *Cheirurus* (*Crotalocephalus*) as a result of the characteristics of the glabellar furrows described above, following G. Henningsmoen's taxonomic criteria (in R. C. Moore, 1959).

According to Strusz (1964), the two figures of Etheridge and Mitchell (1917, Pl. 25, fig. 8, and Pl. 26, fig. 11) depict two different species, one of which is *C.* (*Crotalocephalus*) *sculptus* (s.s.) of Etheridge and Mitchell, whereas the other one he considered sufficiently distinct from the former and, indeed, regarded it conspecific with his own *C.* (*Crotalocephalus*) *packhami* (holotype, SUP 6901). This is half the size of, and of different proportions from, the present species (W/L=1·21).

C. (*Crotalocephalus*) *silverdalensis* Etheridge and Mitchell (1917) is a different species again, with more V-shaped first and second transglabellar furrows; the sides of the glabella are more convergent posteriorly, not even subparallel as *C.* (*Crotalocephalus*) *regius*, or parallel as in the above species. *C.* (*Crotalocephalus*) sp. described by Talent (1963) from the Devonian of eastern Victoria on the basis of a juvenile specimen appears to be closest to *C.* (*Crotalocephalus*) *silverdalensis*.

Of the most closely related overseas species, *C.* (*Crotalocephalus*) *gibbus* (Beyrich, 1845), from the Branik beds of Bohemia is much narrower across the cranidium, only 32 mm., and W/L=1·08. *C.* (*Crotalocephalus*) *pauper* Barrande, 1852, also from Bohemia, is illustrated only by a pygidium and partial thorax (Barrande, 1852, Pl. 41, fig. 41). *C.* (*Crotalocephalus*) *pengellii* (Whidborne), from the Middle Devonian of Wolborough, South Devon, England, is different because of the much more forward position of the anterior lobe of the glabella, and because the preoccipital and occipital furrows do not seem to quite meet in the axial region.

Age: Because of the stratigraphical position of the locality, in the "Botfield Formation", where this specimen has been found, the age of *C.* (*Crotalocephalus*) *regius* is considered to be Lower Mid-Devonian. This is supported by the associated fauna, though in the very locality where this trilobite has been found there is only a meagre gastropod assemblage, consisting of *Loxonema* ? sp. and *Scalaetrochus* sp. with indeterminate brachiopod fragments; however, in the corresponding strata on the western limb of the Tullamore Syncline, near Botfield (N.W. corner of Por. 75, Par. Botfields, Co. Cunningham; grid ref. 582 918 on the Forbes 1 : 250,000 R502 series military map), there is the following assemblage in the same lithological facies:

Clathrodictyon sp.
Stromatopora sp.
Favosites sp.
Tryplasma sp., cf. *T. liliiformis.*
Leptaena sp.
Isorthis alpha.
Atrypa sp., cf. *A. reticularis.*
Buchanathyris ? sp.
Nicklesopora sp., cf. *N. geuriensis*
Scalaetrochus sp.
Loxonema sp.
Actinoceras ? sp.

This assemblage, as well as the one characterized by a somewhat different facies containing *Spinella pittmani*, four miles further south-west, suggests a late Lower Devonian to early Middle Devonian age, most probably Eifelian, both assemblages being high up in the local sequence.

The subgenus *Cheirurus* (*Crotalocephalus*) itself is restricted to Lower and Middle Devonian (Henningsmoen, 1959, 0431). This agrees with the age findings, on local material of allied species, by Strusz (1964), Etheridge and Mitchell (1917), and Talent (1963).

It is the presence of the rugose coral *Plasmophyllum* (*Mesophyllum*) with its well-established Middle Devonian age, in strata that are below those of the abovementioned localities, situated eight miles south of Trundle, that eliminates the possibility of Lower Devonian age and leaves us with Eifelian as the age for the trilobite presently described.

Acknowledgement

The author wishes to thank Professor K. S. W. Campbell (Australian National University, Canberra) for his kindness of reading the manuscript and offering valuable suggestions.

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(Received 20 October 1970)

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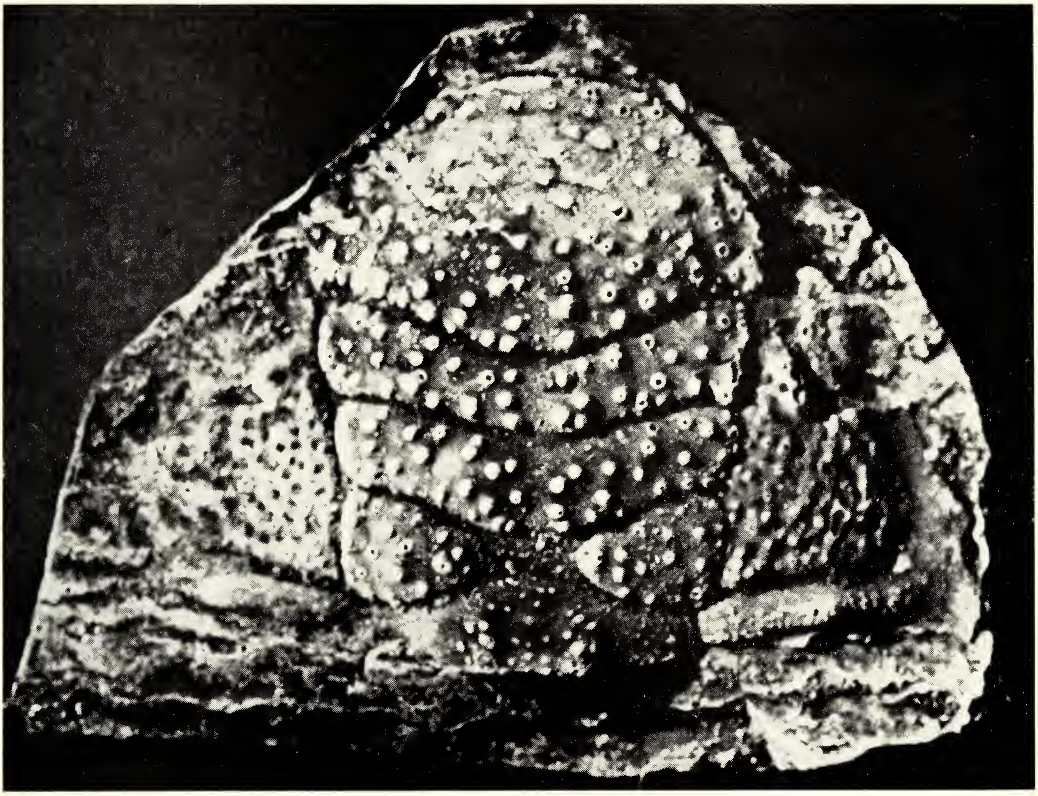

FIGURE 1.—Rubber mould of *Cheirurus* (*Crotalocephalus*) *regius* n. sp. 2× magnified.

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JOURNAL AND PROCEEDINGS OF THE ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 103. 1970 PARTS 3 and 4

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PUBLISHED BY THE SOCIETY
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

ISSUED DECEMBER 1, 1971

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Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 87–90, 1970

Light Tracks Near a Dense Charged Star

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Abstract—Integrals of the Einstein-Maxwell equations for static spherically symmetric situations in regions outside matter, with one of the functions in the metric left arbitrary, are used to investigate light tracks in the presence of a charged body. Conditions for the existence of circular photon orbits are obtained and non-circular paths are discussed.

1. Introduction

The general static spherically symmetric space-time metric can be written

$$-ds^2 = A(r)dr^2 + B(r)(d\theta^2 + \sin^2\theta d\varphi^2) - C(r)(dx^4)^2; \quad (1)$$

here ds is the space-time interval and the coordinates are $(r, \theta, \varphi, x^4)$, where (r, θ, φ) are spherical polars. Equation (1) corresponds to a fundamental tensor $(g_{\mu\nu})$ with non-zero covariant components given by

$$g_{11}, g_{22}, g_{33}, g_{44} = -A, -B, -B\sin^2\theta, C. \quad (2)$$

The field equations of general relativity give two relations between A, B and C, leaving one function arbitrary; various particular choices are listed by Synge (1960). For example, $B(r)$ is often taken to be r^2; then the empty space outside a static spherically symmetric uncharged body is described by the Schwarzschild metric in which $1/A = C = 1 - 2m/r$, where m is a constant. Atkinson (1965*a*) pointed out that it is sometimes useful to make no choice of the arbitrary function, and gave the appropriate integrals of Einstein's empty-space field equations; the integrals were then applied to the investigation of light tracks (Atkinson, 1965*b*).

Light and particle tracks in the presence of a static spherically symmetric uncharged body have been investigated by Darwin (1959, 1961).

The purpose of the present paper is to generalize results of Atkinson to the case in which the central object carries a spherically symmetric charge distribution. This topic is of interest in view of a number of investigations which have dealt with astronomical objects possessing net electric charges. In particular, Bailey (1960*a*, 1960*b*, 1960*c*, 1961, 1963*a*, 1963*b*, 1964*a*, 1965) gave explanations of a number of astrophysical and terrestrial phenomena by postulating the presence of net electric charges on the Sun, other stars, planets and galaxies. Two possible sources for such a charge were suggested, one of which involved a five-dimensional unified field theory (Bailey and Bondi, 1959; Taylor and Bailey, 1962). Criticisms of Bailey's suggestion of a net solar charge were expressed by Menzel (1964) and replied to by Bailey (1964*b*). Lyttleton and Bondi (1959) developed an electrodynamics, based on a generalization of Maxwell's equations, relating to stars and galaxies with net electric charges; they discussed the cosmological implications, as did Hoyle (1960). Charges on stars are also of interest in connection with the investigations of Bonnor (1960, 1964, 1965), who showed that an electric charge could prevent gravitational collapse from occurring.

2. Basic Theory

Using the metric (1) to describe the empty space outside a static spherically symmetric charge q, the Einstein-Maxwell equations are found to have the integrals

$$A = \frac{(B')^2}{4B}\left(1 - \frac{2m}{B^{\frac{1}{2}}} + \frac{\alpha q^2}{2B}\right)^{-1} \quad (3)$$

and

$$A = \frac{(B')^2}{4BC} \quad (4)$$

where a dash denotes differentiation with respect to r and α is a constant which depends on the units used; in (3) m is a constant of integration; the constant of integration in (4) has been set equal to unity, without loss of generality. Elimination of A between (3) and (4) shows that

$$C = 1 - \frac{2m}{B^{\frac{1}{2}}} + \frac{\alpha q^2}{2B}. \quad (5)$$

The integral (4) does not contain q explicitly and is the same (in different notation) as one given by Atkinson (1965*a*). When q vanishes, (5) becomes equivalent to Atkinson's other integral.

If B is put equal to r^2, (3) and (4) give

$$C = 1 - 2m/r + \alpha q^2/2r^2 = 1/A,$$

as for the Reissner-Nordström metric. The above integrals can be obtained by transforming the Reissner-Nordström solution.

A

The motion of an uncharged test particle, with co-ordinates x^μ, is described by

$$\frac{d}{ds}(g_{\mu\nu}\dot{x}^\mu)-\tfrac{1}{2}g_{\alpha\beta,\nu}\dot{x}^\alpha\dot{x}^\beta=0 \tag{6}$$

where a dot denotes differentiation with respect to s. For the metric (1), the fourth equation of the set (6) integrates to $C\dot{x}^4=\delta$ where δ is a constant. Suppose that initially $\theta=\pi/2$ and $\dot{\theta}=0$; the second equation of (6) shows that $\ddot{\theta}$ and all higher derivatives vanish initially, so the motion is confined to the $\theta=\pi/2$ plane. The third equation now integrates to $B\dot{\varphi}=h$, where h is a constant. Using these two integrals of (6), the first equation of (6) becomes

$$\frac{d}{ds}(A\dot{r})-\tfrac{1}{2}\left(A'\dot{r}^2+\frac{B'h^2}{B^2}-\frac{C'\delta^2}{C^2}\right)=0 \tag{7}$$

while the condition $\dot{x}_\mu\dot{x}^\mu=1$ becomes

$$A\dot{r}^2+\frac{h^2}{B}-\frac{\delta^2}{C}=-1, \tag{8a}$$

which leads, after writing

$$\dot{r}=(dr/d\varphi)\dot{\varphi}=(dr/d\varphi)(h/B),$$

to

$$\left(\frac{dr}{d\varphi}\right)^2+\frac{B}{A}=\frac{B^2}{ACh^2}(\delta^2-C). \tag{8b}$$

The time has been eliminated, so (8*b*) describes the geometry of the path.

Suppose that the moving particle is a photon, and let a dot now denote differentiation with respect to a scalar parameter p. Equation (7) still applies. The condition $\dot{x}_\mu\dot{x}^\mu=0$ leads to (8*a*), but with the right side zero, while

$$\left(\frac{dr}{d\varphi}\right)^2+\frac{B}{A}=\frac{B^2\delta^2}{ACh^2} \tag{9}$$

replaces (8*b*). Equation (9) describes the null geodesics of the static spherically symmetric metric (1) : it holds independently of any field equations.

In the next two sections, the integrals of the Einstein-Maxwell equations given above will be used to investigate light tracks. The photon, being uncharged, is not affected directly by the electric field of the central object, but the presence of the electric charge modifies the metric and thus the gravitational interaction.

3. Circular Light Tracks

Putting $\dot{r}=0=\ddot{r}$ in (7) and $\dot{r}=0$ in the equation for photons corresponding to (8*a*) shows that $B'/B=C'/C$. This condition for circular null geodesics of (1) was derived (in different notation) by Atkinson (1965*b*).

Differentiating (5) logarithmically gives

$$\frac{C'}{C}=\frac{m/B^{\frac{1}{2}}-\alpha q^2/2B}{1-2m/B^{\frac{1}{2}}+\alpha q^2/2B}\,\frac{B'}{B}. \tag{10}$$

Applying the condition $B'/B=C'/C$, (10) becomes

$$B-3mB^{\frac{1}{2}}+\alpha q^2=0, \tag{11}$$

so that

$$B^{\frac{1}{2}}=\frac{3m}{2}\pm\sqrt{\left(\frac{3m}{2}\right)^2-\alpha q^2} \tag{12}$$

holds on a photon circle ; when $q=0$, (12) reduces to $B^{\frac{1}{2}}=3m$, corresponding to $C=1/3$ (Atkinson, 1965*b*).

In what follows, B will be required to be real and positive ; m is real and positive and q is real. Further, B will be required to be a monotonically increasing function of the radial co-ordinate. It will be supposed that the central body has a radius less than that calculated for any photon circle.

Provided

$$\alpha q^2/m^2<9/4, \tag{13}$$

it appears from (12) that the effect of a non-zero value of q is to introduce a second photon circle, as well as to reduce the radius of the first ; both circles lie inside that which occurs when $q=0$. It will be seen later that there is also a lower limit on $\alpha q^2/m^2$, at which the inner circle ceases to exist. If (13) is violated, there are no photon circles. To first order in $\alpha q^2/m^2$, (12) gives

$$B^{\frac{1}{2}}\doteqdot 3m-\alpha q^2/3m \text{ or } \alpha q^2/3m. \tag{14}$$

When a co-ordinate system has been specified, (12) gives the co-ordinate radius r_0 of a photon circle. For example, with the Schwarzschild metric, $r_0=3m$ (Atkinson, 1965*b*) ; with the Reissner-Nordström metric, (14) becomes

$$r_0\doteqdot 3m-\alpha q^2/3m \text{ and } r_0\doteqdot\alpha q^2/3m.$$

The time t_0 taken for a photon to complete a circular orbit can be written $2\pi\dot{t}/\dot{\varphi}$, t being the time co-ordinate and a dot denoting differentiation with respect to p. Using the integrals $C\dot{x}^4=\delta$ and $B\dot{\varphi}=h$, and writing $x^4=ct$ where c is the speed of light in empty space, it follows that $t_0=(2\pi\delta/ch)B/C$. Putting $\dot{r}=0$ in the equation corresponding to (8*a*) for photons gives $h^2/B=\delta^2/C$; hence $t_0=(2\pi/c)(B/C)^{\frac{1}{2}}$ (Atkinson, 1965*b*). Substitution of the relativistic integral (5) gives t_0 expressed in terms of B :

$$t_0=\frac{2\pi}{c}\,\frac{B}{g^{\frac{1}{2}}} \tag{15}$$

where $g(B)\equiv B-2mB^{\frac{1}{2}}+\alpha q^2/2=CB$.

Using the quadratic (11) to simplify (15) leads to

$$t_0=\frac{2\pi}{c}\,\frac{B}{(mB^{\frac{1}{2}}-\alpha q^2/2)^{\frac{1}{2}}} \tag{16}$$

where $B^{\frac{1}{2}}$ is given by (12). So, to first order in $\alpha q^2/m^2$,

$$t_0\doteqdot 6\pi\sqrt{3}\frac{m}{c}\left(1-\frac{\alpha q^2}{12m^2}\right) \tag{17}$$

for one circle ; for the other, to lowest order in $\alpha q^2/m^2$, t_0 is imaginary.

From (15), g must be positive on a photon circle, Let g_- and g_+ denote the values of $g(B)$ on the inner and outer photon circles respectively. Substituting (12) into the definition of g shows that

$$\frac{1}{m^2}g_\pm = \tfrac{1}{2}\left(3-\frac{\alpha q^2}{m^2}\right) \pm \sqrt{\left(\frac{3}{2}\right)^2 - \frac{\alpha q^2}{m^2}}. \quad (18)$$

Hence, because of (13), $g_+>0$. Also g_- is positive or negative according as $\alpha q^2/m^2$ is greater or less than two. Thus (12) and (15) show that the inner circle exists only if

$$2<\alpha q^2/m^2<9/4. \quad (19)$$

4. Non-circular Light Tracks

Some information on non-circular light tracks can be obtained by investigating apses. Putting $\dot{r}=0$ in (7) and using the result $h^2/B=\delta^2/C$ mentioned in the last section, it follows that

$$\ddot{r}=\frac{\delta^2}{2AC}\left(\frac{B'}{B}-\frac{C'}{C}\right). \quad (20)$$

Substituting the relativistic result (10), and using $Cct=\delta$ to relate $\ddot{r}$ to d^2r/dt^2, (20) becomes

$$\frac{d^2r}{dt^2}=\frac{c^2C}{2A}\,\frac{B-3mB^{\frac{1}{2}}+\alpha q^2}{B-2mB^{\frac{1}{2}}+\alpha q^2/2}\,\frac{B'}{B}. \quad (21)$$

Using (4) and (5),

$$\frac{d^2r}{dt^2}=\frac{2c^2}{B^2B'}f(B)g(B) \quad (22)$$

where $f(B)$ denotes the left side of (11).

Equation (12) shows that on one photon circle $3m/2<B^{\frac{1}{2}}<3m$, while on the other, using (19), $m<B^{\frac{1}{2}}<3m/2$.

If the outer photon circle exists, then $f>0$ outside it. If the inner circle exists, $f>0$ inside it, with $f<0$ between the two circles. If there is only one photon circle, then inside it $f>0$ for $B<B_1$, while $f<0$ for $B>B_1$, B_1 being the inner zero of $f(B)$.

The derivative dg/dB is positive or negative according as $B^{\frac{1}{2}}>m$ or $B^{\frac{1}{2}}<m$. The minimum value of g, namely $\alpha q^2/2-m^2$, is by (19) positive or negative according as the inner circle exists or not. That is, if the inner circle exists, $g>0$ everywhere. If the inner circle does not exist, since g must be positive on the existing photon circle and this lies outside the position of the minimum of g, $g>0$ outside the circle. With only one circle, $g>0$ for $B<B_2$ and for $B>B_3$, while $g<0$ for $B_2<B<B_3$, B_2 and B_3 being points inside the photon circle.

When there is an outer but no inner photon circle, $\alpha q^2/m^2<2$; it is easily seen that $B_1>B_2$ and that $B_1<B_3$.

When there are no photon circles, (13) is violated and the minimum values of f and g are both positive ; $f>0$ and $g>0$ everywhere. Then, from (22) $d^2r/dt^2>0$ everywhere : apses can correspond to minimum values only of r, and there are thus no finite photon orbits of any kind.

If two photon circles exist, $d^2r/dt^2>0$ outside the outer one and inside the inner one. So in those regions, apses correspond to minimum values only of r, and there are no finite orbits there. A photon travelling on the outer circle will, if slightly perturbed outwards, move off to infinity. A photon travelling on the inner circle will, if slightly perturbed inwards, move further in at first. Between the circles, $d^2r/dt^2<0$, so apses correspond to maximum distances. Any photon reaching this region from outside of it will travel through it before reaching an apse. Finite non-circular orbits appear feasible, with a photon travelling between minimum values of r inside the inner circle and maxima between the two circles.

If only one photon circle exists, $d^2r/dt^2>0$ outside it. Inside, $d^2r/dt^2>0$ for $B<B_2$ and $B_1<B<B_3$, while $d^2r/dt^2<0$ for $B_2<B<B_1$ and $B_3<B$. Three types of finite orbits appear feasible, with a photon travelling between minimum values of r in $B<B_2$ and maxima in $B_2<B<B_1$, or minima in $B_1<B<B_3$ and maxima in $B>B_3$ (but still inside the photon circle) or minima in $B>B_2$ and maxima in $B>B_3$ (but still inside the photon circle).

The above calculations do not establish the existence of finite non-circular orbits. For such an orbit to exist, the time calculated for an arbitrary change to occur in the φ co-ordinate of a photon describing the orbit would have to be finite, real and positive. It should be noted that, for the case in which a single photon circle exists, all the finite non-circular orbits which seemed feasible above cross one or both of the apparent metric singularities at which C vanishes and hence, by (4), A is infinite. When two photon circles exist, C does not vanish.

The equation describing the geometry of a light path, namely (9), can be written

$$\left(\frac{du}{d\varphi}\right)^2+u^2=\left(1-\frac{Bu^2}{A}\right)u^2+\frac{B^2\delta^2u^4}{ACh^2} \quad (23)$$

where $u\equiv 1/r$. In Euclidean space, the right side of (23) is replaced by $1/p^2$, where p is the perpendicular from the origin to the tangent at the point (u,φ) of the path. If the geometry becomes Euclidean at large r, so that $A\to 1$, $B\to r^2$ and $C\to 1$, the right side of (23) approaches

δ^2/h^2: for a light path, the perpendicular p_∞ from the origin to the tangent at infinity is h/δ (Atkinson, 1965*b*).

For a photon initially describing a photon circle and then very slightly perturbed outwards, h can be replaced by its value h_0 on the photon circle, so $p_\infty = h_0/\delta$. Since $h^2/B=\delta^2/C$ holds on the photon circle, use of $C=g/B$ and (15) shows that $p_\infty = ct_0/2\pi$.

5. Concluding Remarks

In this paper, integrals of the Einstein-Maxwell equations for static spherically symmetric situations in regions outside matter have been applied to the investigation of light tracks in the presence of a charged body. Work of Atkinson (1965*a*, 1965*b*) has thus been extended to the case of a charged central object.

The coefficients in the Reissner-Nordström metric can be written (Jeffery, 1921) $B=r^2$ and

$$C=\frac{1}{A}=1-\frac{2G\mu/c^2}{r}+\frac{Gq^2/c^4}{r^2} \qquad (24)$$

in which G is the Newtonian gravitational constant and μ is the mass of the central body. Comparing (5) with (24), and following Bailey (1960*a*) by writing

$$q=\beta G^{\frac{1}{2}}\mu \qquad (25)$$

where β is a constant, it follows that

$$\frac{\alpha q^2}{2m^2}=\beta^2. \qquad (26)$$

In this notation, it was found in Section 3 that, if the central body is sufficiently small, the number of photon circles is 1, 2 or 0 according as $\beta^2<1$, $1<\beta^2<9/8$ or $9/8<\beta^2$ respectively. It was shown in Section 4 that when there are two photon circles, finite non-circular photon orbits are feasible.

It may be noted that Bailey (1960*a*, 1960*b*) took β for the Sun to be around 10^{-2}. Bonnor (1960, 1964, 1965) investigated a solution of the Einstein-Maxwell equations for a static spherically symmetric body with, in the above notation, $\beta=1$.

Another possible generalization of Atkinson's integrals would involve the space outside the central object being filled with matter. Such an investigation could be of interest in cosmology; also, a model of this kind has been used to investigate the perihelion motion of comets in the solar system (Aver'yanova and Stanyukovich, 1967).

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(Received 3 February 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 91-92, 1970

Occultations Observed at Sydney Observatory during 1970

K. P. Sims

The following observations of occultations were made at Sydney Observatory with the $11\frac{1}{2}$-inch telescope. A tapping key was used to record the times on a chronograph. The reduction elements were computed by the method given in the occultation Supplement to the *Nautical Almanac* for 1938 and the reduction completed by the method given there. Since the observed times were in terms of coordinated time (UTC), a correction which was derived from *Bureau International De L'Heure Circulaire D* was applied to the 1970 observations to convert them to UT2. In 1970 a correction of +0·01097 hour (=39·5 seconds) was applied to the time in UT2 to convert it to ephemeris time with which *The Astronomical Ephemeris for 1970* was entered to obtain the position and parallax of the Moon. The apparent places of the stars of the 1970 occultations were provided by H.M. Nautical Almanac Office.

Table I gives the observational material. The serial numbers follow on from those of the previous report (Sims, 1970). The observers were W. H. Robertson (R), K. P. Sims (S), and H. W. Wood (W). In all cases the phase observed was disappearance at the dark limb. Table II gives the results of the reductions which were carried out in duplicate. The Z.C. numbers given in Table I are from the *Catalog of 3539 Zodiacal Stars for Equinox 1950·0* (Robertson, 1940) and the *Smithsonian Astrophysical Observatory Star Catalog.*

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Table I

Serial No.	S.A.O. or Z.C. No.	Mag.	Date	U.T.2	UT2–UTC	Observer
561	1657	6·7	1970 Apr. 18	10 26 42·18	−0·02	W
562	1660	6·2	1970 Apr. 18	11 36 09·38	−0·02	W
563	118865	7·9	1970 Apr. 18	11 37 35·28	−0·02	W
564	1663	5·2	1970 Apr. 18	12 27 56·58	−0·02	W
565	1930	5·6	1970 May 18	12 28 20·75	−0·03	R
566	118546	8·6	1970 June 11	9 31 14·15	−0·03	R
567	1884	5·3	1970 June 14	12 55 13·47	−0·03	W
568	2505	5·4	1970 July 16	11 54 34·97	−0·03	W
569	184783	7·7	1970 Aug. 12	11 13 21·18	−0·03	S
570	2583	5·8	1970 Aug. 13	9 50 42·47	−0·03	W
571	2864	4·7	1970 Sep. 11	8 19 26·26	−0·04	S
572	186566	8·3	1970 Oct. 7	9 25 56·19	−0·04	S
573	2643	6·7	1970 Oct. 7	9 32 20·64	−0·04	S
574	186671	7·4	1970 Oct. 7	11 14 52·41	−0·04	S
575	187596	8·2	1970 Nov. 4	9 39 03·95	−0·05	S
576	2928	6·5	1970 Nov. 5	10 05 44·95	−0·05	W
577	188591	8·6	1970 Dec. 2	9 56 25·47	−0·05	S

TABLE II

Serial No.	Luna-tion No.	p	q	p^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of $\Delta\alpha$	Coefficient of $\Delta\delta$
561	585	+87	−49	76	−43	24	+2·4	+2·1	−1·2	+8·1	−0·84
562	585	+84	−55	70	−46	30	+1·0	+0·8	−0·6	+7·2	−0·88
563	585	+83	−56	69	−46	31	+2·3	+1·9	−1·3	+7·1	−0·88
564	585	+98	−22	95	−22	5	−2·1	−2·1	+0·5	+11·3	−0·65
565	586	+100	+8	99	+8	1	+0·9	+0·9	+0·1	+13·7	−0·36
566	587	+99	−12	99	−12	1	−1·0	−1·0	+0·1	+12·3	−0·56
567	587	+89	+45	80	+40	20	−0·1	−0·1	0·0	+14·7	+0·01
568	588	+87	−49	76	−43	24	+0·4	+0·3	−0·2	+11·2	−0·52
569	589	+97	−24	94	−23	6	−0·6	−0·6	+0·1	+12·5	−0·33
570	589	+99	+11	99	+11	1	+0·9	+0·9	+0·1	+13·1	+0·13
571	590	+86	+51	74	+44	26	0·0	0·0	0·0	+9·9	+0·69
572	591	+67	+74	45	+50	55	−0·3	−0·2	−0·2	+8·1	+0·79
573	591	+89	−45	80	−40	20	−1·5	−1·3	+0·7	+12·3	−0·38
574	591	+100	−6	100	−6	0	+2·0	+2·0	−0·1	+13·3	+0·02
575	592	+22	+98	5	+21	95	+0·4	+0·1	+0·4	+0·7	+1·00
576	592	+95	+31	90	+29	10	+0·3	+0·3	+0·1	+11·4	+0·56
577	593	+87	+49	76	+43	24	−0·7	−0·6	−0·3	+9·9	+0·70

(Received 18 June 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 93–102, 1970

Clarke Memorial Lecture for 1971

The Bearing of Some Upper Palaeozoic Reefs and Coral Faunas on the Hypothesis of Continental Drift

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Mr. Chairman, Ladies and Gentlemen,

I wish first to pay tribute to W. B. Clarke, to the honour of whose memory this lecture is given. Wherever he travelled, this pioneer in Australian geology constantly observed, analysed and synthesized all the geological data available; and he published his conclusions. His example we follow, each in his own way.

Interest in the hypothesis of continental drift has been enormously increased in recent years by geophysical observation and speculation. Palaeomagnetic and seismological observations, deductions and assumptions have led to the concept of "plate tectonics", which postulates physical conditions in the earth's crust and mantle such that very considerable movement of large or small segments of the earth's crust is possible. Segments that are relatively stable within themselves, such as continents, are thus assumed to have moved relative to one another.

The critical evaluation of their evidence, their assumptions and deductions, is best left to the geophysicists themselves. Geologists have a part to play, however, in looking to the tests their own accumulations of data may apply to the hypothesis.

Reefs and coral faunas are of use in testing the hypothesis of continental drift only in so far as they may be taken as indicators of palaeoclimates and palaeoclimatic zones.

The reef provinces of today are all located in the shallow sunlit waters of the tropics and near tropics. Reef growth in waters of average annual minimum temperature of less than 15° C. is greatly restricted or minimal, and so the present reef provinces tend to be bounded by this isotherm. Whether past shallow water reef growth was controlled by this temperature we still have to establish. Temperature is vital to our argument. If we can assume that the reef provinces of past eras were similarly located, we may use the known distribution of fossil reef provinces to deduce the position of tropical (and near-tropical) zones in past times. We may thus draw lines across the continents limiting the tropical zones for each geological age. It should then become apparent whether the continents have or have not always occupied their present position relative to the equator and the poles of rotation of this earth. If they have, the lines will be very roughly parallel to the present equator. If they have not, the lines will have an angular relation to the present equator, and this angle will vary from continent to continent according to the degree to which each continent has drifted.

There are two possibilities that may affect the width of the climatic zones. One is the surface temperature of the earth. If this rises, then the tropical, subtropical and warm temperate climatic zones may well widen, and the cold temperate and polar zones may narrow. The hypothesis that the earth's surface temperature has varied significantly in past times is widely accepted amongst earth scientists, but the assumed variations have not proved measurable, nor have their causes been established.

The second is a change in the circulation of ocean currents, particularly the warm surface currents, brought about by the submergence or emergence of greater or lesser areas of the continents as a result either of downwarp or uplift (which we know to have occurred), or of variations in the amount of water locked up in ice caps (which we also know have occurred). The northern and southern equatorial surface currents will always have been westward due to the rotation of the earth, but their deflection northwards by land masses would differ according to the shape and position and degree of submergence or emergence of the land against which they set. The Gulf Stream is an example. Such deflections cause the limiting line between subtropical and warm temperate zones, for example, to have tongue-like projections towards the pole. Similarly, the circulation of the cold bottom currents of the ocean will be affected by uplift or downwarp of sills or bars to the Arctic, for example.

So I accept that the width of the climatic zones may be expected to vary with time, and that their boundaries will not always be parallel to the equator. This means that a fossil reef found in a high latitude today does not necessarily imply that the continent on which it occurs has drifted away from the equator.

We now come to the sedimentological and palaeontological difficulties in the recognition of reefs in the sedimentary record, difficulties which must be disposed of or at least evaluated before we attempt to use reefs in palaeoclimatic zonation.

Reef construction on a regional scale takes place today in shallow, sunlit seas of normal salinity. A primary condition is a food supply adequate to maintain a profuse growth of calcareous algae and of algae that precipitate carbonates from seawater or entrap carbonate mud, as well as of animals that secrete skeletons of calcium carbonate. An adequate food supply is frequently made available where a change of slope causes nutrient-rich waters to well up from deeper levels. Thus barrier reefs may be developed at the top of a change of slope on shallow continental shelves or ridges, or around volcanic islands. Reefs today grow most profusely between low sea level and six fathoms, but a little less profusely down to 22 fathoms; they can still be constructed, though less strongly, down to 30 fathoms. Sunlight is necessary for the photosynthesis of reef plants, including the zooxanthellae, that are the symbionts of so many reef animals. Thus most reefs grow in shallow waters above wave-base, and wave or lateral current action tends to fill the interstices between their framework organisms with detritus from the reef and, more importantly perhaps, spreads reef detritus around the reef. The volume of reef actually growing at any one time in any shallow reef region commonly remains small compared with the volume of detritus derived from its organisms.

One of our difficulties derives from our definition of a reef. Many writers bring into the definition the criterion that the carbonate mass must grow by the action of its constructing organisms into the zone of wave action and maintain its growth against wave action. Others also insist that the constructing organisms form a framework that is rigid. But, of course, there are degrees of rigidity, and degrees of wave action, and the growth of a reef comprises both vertical and horizontal components.

What are we to term the bank- or ridge-like accumulations of coral skeletons and skeletal debris that are known to form today in dark or dimly lit waters, below wave base, and in temperatures between 15° C. and 4° C.? Such accumulations rise well above the level of the surrounding sea floor. They have no calcareous algal component. But in the fossil record they may well be termed either bioherms or fossil coral reefs, and we might make the false deduction that they were formed in tropical or near tropical latitudes. Clearly, all so-called fossil reefs must be sedimentologically evaluated, firstly to determine their depth of formation, and secondly, for any clues they might give on the temperature of formation.

Modern tropical reefs are mostly coral reefs, but always algae play an important part, as binders or trappers of debris as well as by providing much of the calcium carbonate of the reef. Many other animals are reef organisms—either contributing to the rigid or loose framework or dwelling in the interstices of the framework, and in some reefs they predominate over corals. Must corals therefore always be present in what we term a reef? It seems that we must give a negative answer to this question, though as a group the modern reef corals are perhaps the best indicators we have of the temperature of formation of a modern reef.

Coming now to the recognition of tropical and subtropical reefs in the stratigraphic record. We may interpret as reefs those carbonate bodies that not only rise up above their depositional surface, with or without encouragement by subsidence of the sea floor, but are sharply demarcated from their enclosing sediments and can be shown to be formed by organisms. Some writers, however, would withhold the name if the body did not project into the zone where it was attacked by wave action, i.e. when in its fossil form it is not surrounded by the detritus of wave action upon it. Laterally extensive carbonate bodies with parallel upper and lower surfaces, constructed by the same organisms that construct reefs, are commonly not accorded the name reef by stratigraphers, but are called "biostromes". Biostromes may, however, grow upwards at their outer edges as barrier reefs, and in this case are clearly back-reef beds. To some writers all vertically extensive organically formed carbonate bodies discordant with and of different textures from their enclosing sedimentary rocks are "bioherms". The root "herma" means a sunken rock or reef. But it is not at all sure that all such bodies are formed in warm waters. Other writers confine the name "bioherm" to similar rock bodies that are not surrounded by debris outwashed from them and thus did not rise into the zone of wave action. There is thus a dual and overlapping use of the two words " reef " and " bioherm ". Again, some authors use " bioherm " for a small discordant carbonate body formed by organisms, or presumably formed by organisms, and reserve " reef " for larger bodies. The usages given both words have wide spreads, and as always, where definitions imply degree, the degree involved in any one usage should be made clear. Some authors use the words " carbonate build-ups " for great masses of sedimentary carbonate rocks that may (or may not) include reefs.

A recent analysis of the " carbonate build-ups " of modern seas suggests that thick neritic carbonate sedimentation is zonal, more or less parallel to the equator, and concentrated between the latitutes of 5° and 30° north and south of the equator ; it has been suggested that the poor development observed in equatorial regions is due to the overwhelming quantity of terrigenous sediment deposited there. It is perhaps not without significance that the neritic carbonate sedimentary build-ups of today, like coral reefs, are almost co-extensive with the tropics.

All the abovementioned terms have an historical place, but because of the differing origins implied for the bodies so named one needs to examine each fossil example carefully and evaluate its particular environment of deposition. If the example is one of many in a reef-province, it can be far more safely used in the reconstruction of palaeoclimatic zones than if it is but a single, isolated example.

Carbonate sedimentology and petrography are today largely concerned with the recognition and description of the different lithological types and textures of living and fossil reefs and their associated sediments. All reefs that rise above wave-base have, on the side from which the waves attack (reef-front or fore-reef), an apron of coarse debris, roughly bedded, with the bedding planes sloping away from the upward-growing reef (reef-core or reef-wall) ; on the far side (back-reef) bedded sediments of distinctive character form ; reefs with lagoons have lagoonal sediments also of distinctive character. The microtextures and micro-structures of fossil carbonate build-ups and the diagenetic characters they show are extremely useful in the interpretation of the micro-environments of the reef facies.

Reefs have proved to be reservoirs for petroleum or natural gas, in many parts of the stratigraphic record, and the studies made on these subsurface bodies have greatly widened our knowledge of the distribution within them of the various orders of plants and animals. As examples of such studies we may cite the detailed work on the upper Devonian reefs of Alberta, Canada, and the complementary work on the Recent reefs of the Gulf of Mexico.

Fossil reefs are found to have grown on shallow, stable platforms, and particularly at the edges of such platforms ; they are also shown to arise from slightly deeper basins off the edges of platforms ; examples of fossil reefs on fossil submarine ridges and of fossil reefs and atolls on fossil volcanic islands are also known. The most magnificent fossil atoll so far described is that (of Akiyoshi) in the geosynclinal environment of the Carboniferous and Permian of Japan (Ota, 1968). Again, reefs growing in the more unstable parts of the Hercynian geosyncline of western Europe have different sedimentary structures from those of the more stable regions peripheral to or isolated in the unstable parts (Tsien, 1970).

The topographic and in many cases also the diastrophic environment of the formation of a fossil reef can now be fairly accurately deduced from the sedimentary characters of itself and its enclosing rocks. But the number of fossil reefs that have so far been adequately studied for such strict environmental interpretation is still infinitesimally small. With continuing sedimentological work of this precision we shall eventually know whether any particular fossil reef was formed below or above wave-base, in sunlight, on or at the edges of relatively stable platforms, or on ridges in regions of instability, or around volcanic islands. Already the general environment of major reef constructions is deducible in these terms. But certainty concerning the final physical condition, the one that alone is useful for reconstruction of the climatic zones of the past, is still eluding us. I refer to the temperature of the water in which the fossil reefs formed. If we could know that some, even if not all, of the carbonate mud of any fossil reef facies was physicochemically precipitated, then we might set limits on the temperature of formation. But at present certainty in this is not possible. There are three main variables : alkalinity, temperature, and the CO_2 pressure. If we could use isotopic methods of temperature evaluation for Palaeozoic reefs, as widely and as safely as we can for modern reefs, we would be in a far better position that we are today, but as yet we cannot.

If we wish to use fossil reefs as indicators of climatic zones, we must assume that major reef constructions indicate that they were formed in tropical or near tropical climatic zones. However, even today not all tropical and near tropical shallow waters sustain reefs, due perhaps to too great a contribution to a region of terrigenous sediment, or an insufficient primary food supply. Similar gaps must have existed in the past, and we cannot therefore say that absence of a reef province from a region implies a climatic belt too cold for its growth.

Another important additional assumption that we must make is that the profusely represented animals of the fossil reefs were subject to the same minimal temperature control as those of the living reefs ; that is, that stromatoporoids, fenestellid polyzoa, stalked echinoderms, tabulate corals and rugose corals grew profusely in a reef environment only above the same minimal temperatures as the animals dominant in present reefs ; that is, above 15° to 18° C.

I will now outline briefly the distribution of reefs or reef-building animals in the various periods of the Palaeozoic era, and will analyse in more detail those for two stages : the Frasnian stage of the upper Devonian and the Dinantian stage of the lower Carboniferous periods.

In palaeoclimatological work shore-lines are important because of their deflecting effect on surface currents. In drawing the boundaries between land and sea assumed for the different periods and stages of the Palaeozoic era I have taken the latest palaeogeographic reconstructions that I could find. This aspect of geological work is subject to rapid change as stratigraphic data accumulate.

In the Cambrian, marine animals with the ability to secrete skeletons of calcium carbonate first appeared and we find the sponge-like Archaeocyatha living in the reef environments but playing a subordinate part therein to algae. Cambrian reefs are small relative to those of the Middle Palaeozoic and later times. Archaeocyathan reefal limestones occur in a notably wide zone in the northern hemisphere (22·5° to 70° N.) and in high latitudes in South Australia and Antarctica (Hill, 1965). Similarly, in the Ordovician, the reefs are small. The main organisms found in them are algae, problematical soft-bodied organisms, sponges, stalked echinoderms, and the newly-evolved bryozoans, stromatoporoids, and corals. They are on the whole developed in carbonate provinces. Again we see a concentration of the reefs and corals in a wide belt in the northern hemisphere (22·5° to 75° N.) and in a high southern latitude in Tasmania (42° S.).

In the Silurian a major reef province existed in North America between 30° and 60° N. in terms of present geography (Lowenstam, 1957 ; Textoris and Carozzi, 1964) ; small reefs are recorded as far north as 75° N. (Fortier *et al.*, 1963) ; again England, Gotland (Hadding, 1950) and Estonia formed a reef province between 50° and 60° N., and in central Asia there is a reef province between 30° and 60° N. In the southern hemisphere there was a possible reef province (not adequately studied as yet) in Queensland, between 10° and 20° S. Stromatoporoids, tabulate and rugose corals are all very obvious in Silurian fossil reefs, but crinoids and bryozoa are also abundant in places ; algae have been recognized in those reefs subjected to detailed micropetrographic analysis. Silurian reefs on the whole are of small vertical extent.

Devonian reefs are a little better known than those of the Silurian. In the Lower Devonian thick (up to 300 and 400 metres) light-coloured and fine-grained limestones are in many places described as reefal (Deroo, Gauthier and Schmerber, 1967). They are common in Europe and North Africa between 20° and 50° N. A meridional chain of them is known along the Ural geosyncline (Nalivkin, 1967). In central Asia they are recorded from south of L. Balkash (45° N.) and in the Zaisan region (49° N.), near the U.S.S.R.-Mongolian border about 51° N. and in north-eastern U.S.S.R. between 65° and 70° N. The furthest north Lower Devonian reefs are probably those of Novaya Zemlya.

If we look at the palaeomagnetic latitudes of Eurasia, we see that the Lower Devonian reefs all fall between 30° S. and 55° N., which would give a slightly narrower (better ?) latitudinal spread for the reefs than with the continents in their present latitudes.

There are many Lower Devonian coralline limestones in eastern Australia, between 15° and 45° S., but strict sedimentological analysis must be made of them to indicate whether they are reefal.

In North America the Coblenzian Jeffersonville Limestone of Ohio and Kentucky is described as an organogenic bank of stromatoporoids, and tabulate and rugose corals. No Lower Devonian reefs are known in South America, southern Africa or Antarctica.

With the Middle Devonian we find in many places in Europe and north-west Africa a reversion more to the Silurian types of reef, rather small, discordant bodies not all of which suffered wave-action. Algae, problematical soft organisms, stromatoporoids, crinoids, tabulate corals, bryozoa and rugose corals all played a part in their construction. In the Dinant Basin of the Variscan geosyncline of western Europe, the reefs of the subsiding basinal areas are small in lateral extent but of considerable height; according to whether they originated below the zone of wave turbulence or not, they are free of or surrounded by talus broken from them by wave action. In the more stable shelf-like regions, the reefs are of considerable lateral extent, but their height is great only along the edge of the platforms where they grew upwards as barrier reefs. In those parts of reefs formed below the zone of wave turbulence, crinoids or lamellar tabulate corals and *Stromatactis* are characteristic; in the sub-turbulent zone, suffering little wave action, large lamellar stromatoporoids are dominant; in the zone of turbulence due to wave action, massive globular stromatopores are found. In the back-reef facies on stabler platforms or shelves behind the barrier, colonial Rugosa, *Thamnopora* and *Amphipora* are characteristic. In the fore-reef talus, brachiopods, solitary corals and conodonts abound. The general morphology of these Middle Devonian reefs of the Ardennes (Tsien, 1971) and the Eifel and the Slate Mts. (Krebs, 1967) is represented in the Upper Devonian of western Europe, as well as in other reef provinces of the Middle and Upper Devonian. Examples are the Middle Devonian reefs of north-west Africa, which compare closely with those of western Canada (Dumestre and Illing, 1967), the Middle and Upper Devonian reefs of central Europe (e.g. Holy Cross Mts., Poland (Pajchlova and Stasinska, 1967), and the atoll and barrier reefs of the Ural seaway (Nalivkin, 1967)). Furthest north of the Eurasian Middle Devonian reefs is one on Norvaya Zemlya at about 71° N. There are others in north-east Afghanistan, Ferghana and Zaisan (48° N.) and near the U.S.S.R. border on 52° N. and between 115° and 125° E. No modern sedimentological studies of the stromatopore and coral biostromes or reefs of Siberia, China or Indo-China, or of the coralline limestone of Japan, are known to me. So far as I am aware, reef-cores have not been described from the Middle Devonian of eastern Australia, but biostromal stromatoporoid back-reef types of coral limestones are common, as are sub-lagoonal *Amphipora* limestones. In the north-eastern part of Western Australia reefs began to develop in the late Middle Devonian, and are discussed below.

A splendid Middle Devonian reef province existed in western Canada between 50° and 68° N.; some of its reefs have proved to be reservoirs for petroleum or natural gas, and a great deal of sub-surface work has been carried out on them (Hriskevich, 1970). All of the micro-environments of a typical reef of today have been identified in them, and there can be no doubt that we are here dealing with a reef province like that of the Great Barrier Reef of today (10° to 25° S.). Algae and stromatoporoids are the dominant organisms of the reefs, but crinoids, bryozoa, brachiopods, tabulate and rugose corals also occur in back-reef or fore-reef or in perireefal environments. A Devonian reef on Ellesmere Island in the Canadian Arctic is either late Lower or early Middle Devonian (Fortier *et al.*, 1963).

No Devonian reef provinces or even single reefs are recorded from South America, central or southern Africa, or Antarctica.

I come now to the Frasnian stage of the Upper Devonian, which I wish to treat in a little more detail (Figure 1). Reef provinces are notable as follows: in western Canada between 50° and 68° N. (Klovan, 1964; Martin, 1967; Noble, 1970); in western Europe in Devon, Belgium (Tsien, 1971) and Germany (Krebs, 1967); in Poland at about 51° N. (Pajchlova and Stasinska, 1967); in the Carnic Alps (Deroo *et al.*, 1967); in the Urals between 56° and 60° N. (Nalivkin, 1967); in Asia between 45° and 57° N. and in the Kuznetsk Basin (Rzhonsnitskaya and Harin, 1967); and in Western Australia (Playford, 1967, 1969) between 15° and 20° S. In addition, there was possibly a reef province in China between 20° and 30° N.

In all these regions the reef province succeeded one established in the Middle Devonian, indicating some stability of climatic conditions. In yet two other areas, the Carnic Alps (Deroo *et al.*, 1967) and north-western Africa (Dumestre and Illing, 1967), small reefs persisted briefly from an earlier province. No Frasnian reef provinces are known in South America, Antarctica, central and southern Africa or India.

Thus the only known Frasnian reef province in the Southern Hemisphere (Western Australia) is well placed if no drift of Australia has occurred. However, it would be equally well placed for the palaeomagnetic latitudes deduced for Australia in the Devonian by Briden and Irving (1964); for the Western Australian reef province would lie between 0° and 10° S. palaeomagnetic latitudes.

The Frasnian shallow water reef provinces known in the Northern Hemisphere would be inconsistent with the present climatic zones and the present position of continents, unless we postulate that the earth's surface temperature was higher then, causing expansion of the warm climatic zones, or unless we postulate that the extinct invertebrate orders dominating the Frasnian reefs, the stromatoporoids, and the

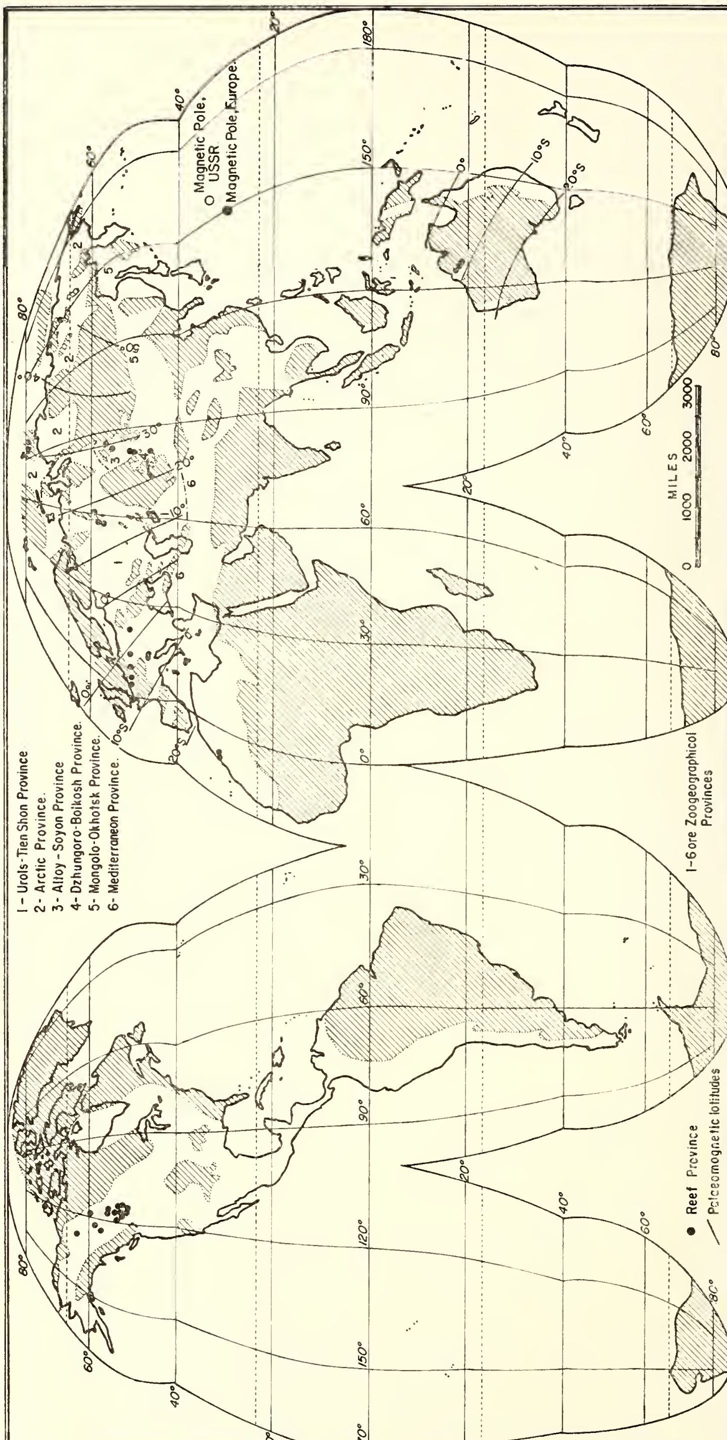
REEF PROVINCES OF FRASNIAN AGE
1 - Urals-Tien Shan Province
2 - Arctic Province.
3 - Altay-Sayan Province
4 - Dzhungaro-Balkash Province.
5 - Mongolo-Okhotsk Province.
6 - Mediterranean Province.
1-6 are Zoogeographical Provinces
● Reef Province
/ Paleomagnetic latitudes
O Magnetic Pole, USSR
● Magnetic Pole, Europe.
MILES
0 1000 2000 3000

FIGURE 1.

tabulate and rugose corals, proliferated in lower temperatures than the scleractinian reef-corals.

If we look at the Devonian palaeomagnetic latitudes deduced for Eurasia, one set for Europe (Briden and Irving, 1964) and the other for the U.S.S.R. (Vinogradov, 1969), the reef provinces including that of north-west Africa would lie between 30° S. and 30° N. This could perhaps be regarded as evidence of continental drift rather than as evidence that the continents in the Devonian lay in their present positions relative to the poles of rotation. This view would also involve the assumption that these Devonian reefs were tropical or near tropical. One exception, that of north-eastern Siberia (69° N., 150° E.), is mapped as a single reef, and no descriptions are available to me. It would be near the calculated 50° N. palaeomagnetic latitudes.

Next let us turn to the map for the Lower Carboniferous reef provinces (Figure 2). Here we find that reefs with cores (or walls), reef-fronts and back-reef deposits have been distinguished in north-western Europe, chiefly in Great Britain and north-western Africa, and we may speak of a small British reef province (Lees, 1964; Ramsbottom, 1969) between latitudes 50° and 56° N., and a north African province (Pareyn, 1961) between 30° and 35° N. Reef cores are aphanitic, with algae or fenestellids as framework or trapping organisms; fore-reef beds contain corals and trachiopods—back-reef beds may be coral (*Lithostrotion*) biostromes (Wolfenden, 1958). The great fossil atoll of Akiyoshi in Japan (Ota, 1968), comparable in size to the Cainozoic atolls in the Pacific, began its growth, it seems, at the end of Viséan time. Other similar limestone masses in Japan may well also prove to have been atolls. Groups of reefs have been plotted for Central Asia between 40° and 50° N. (Vinogradov, 1969), and two reefs are mentioned in the Russian literature for the Caucasus. *Lithostrotion* bioherms are mentioned for the northern Urals at about 62° N., and sub-surface reefs are mentioned in and near Bashkiria at about 55° N. Nalivkin (1967) has described the Urals reefs as coastal reefs. A single reef is reported in north-eastern Siberia at about 62° N.

In North America between 30° and 60° N. and even into north-western Alaska just within the Arctic Circle, there are great spreads of Lower Carboniferous carbonate sediments. In the U.S.A., among the many sub-environments in which these formed, there are banks variously called " knoll reefs " or " bioherms " or " Waulsortian knolls " of fine-grained carbonate of diverse origin. Some rose several hundred feet above the sea floor on which they formed. Some grew in water too deep or too tranquil for wave action to erode them; others grew into the turbulent zone and their tops are surrounded by their own detritus. Some are seen to have fenestellid bryozoa as one of the agents trapping carbonate mud and thus building a bank. In others, algae were trapping and binding or precipitating agents. Crinoids in some contributed volumes of detritus to the bank. Such banks seem to have grown on a shallow water shelf. In western North America, in places and at times *Lithostrotion* (or *Lithostrotionella*) " prairies " built extensive and sometimes thick (up to 100 ft.) biostromes; but no reef-cores to which these biostromes might be back-reef beds have been documented. How are we to interpret the temperature under which these North American " bioherms " and biostromes formed? Perhaps they formed only in response to the presence of nutrients—perhaps warmer temperatures assisted. Geophysical deductions for North America at present suggest that these " bioherms " formed between palaeomagnetic latitudes 20° S. and 40° N. (Briden and Irving, 1964).

The most interesting Lower Carboniferous reef is, however, that forming the base of the great Middle and Upper Carboniferous and Permian geosynclinal-type atoll of Akiyoshi, which is 8·1 by 3·8 nautical miles, about one-third the size of Bikini (Ota, 1968). This is in latitude 35° N. and compares well with the north-most Pacific atolls of today, Midway and Kure, in 28° N. latitude. The position of the Lower Carboniferous palaeomagnetic pole deduced for the U.S.S.R. (Vinogradov, 1969) and for Europe, however, would be quite close to Akiyoshi, at 44° N., 157° E., and if we accept this juxtaposition then we are placed in the same dilemma as we are when we look at fossil reefs in the present Arctic Circle. We are forced to admit that either polar waters were warmer then to support such reef growth, or that the invertebrates involved in reef formation could proliferate in colder waters than those of today. Thus we could not say that the palaeomagnetic latitudes deduced for the Lower Carboniferous give better palaeoclimatic zonal arrangements than would the undrifted continents. This does not, of course, prove that continental drift has not occurred.

The Viséan reef of Old Cannindah in Queensland (25° S.) is palaeoclimatically consistent with present climatic zones or with Australia drifted from palaeomagnetic latitudes (between 20° and 30° S.), assuming that the same temper-

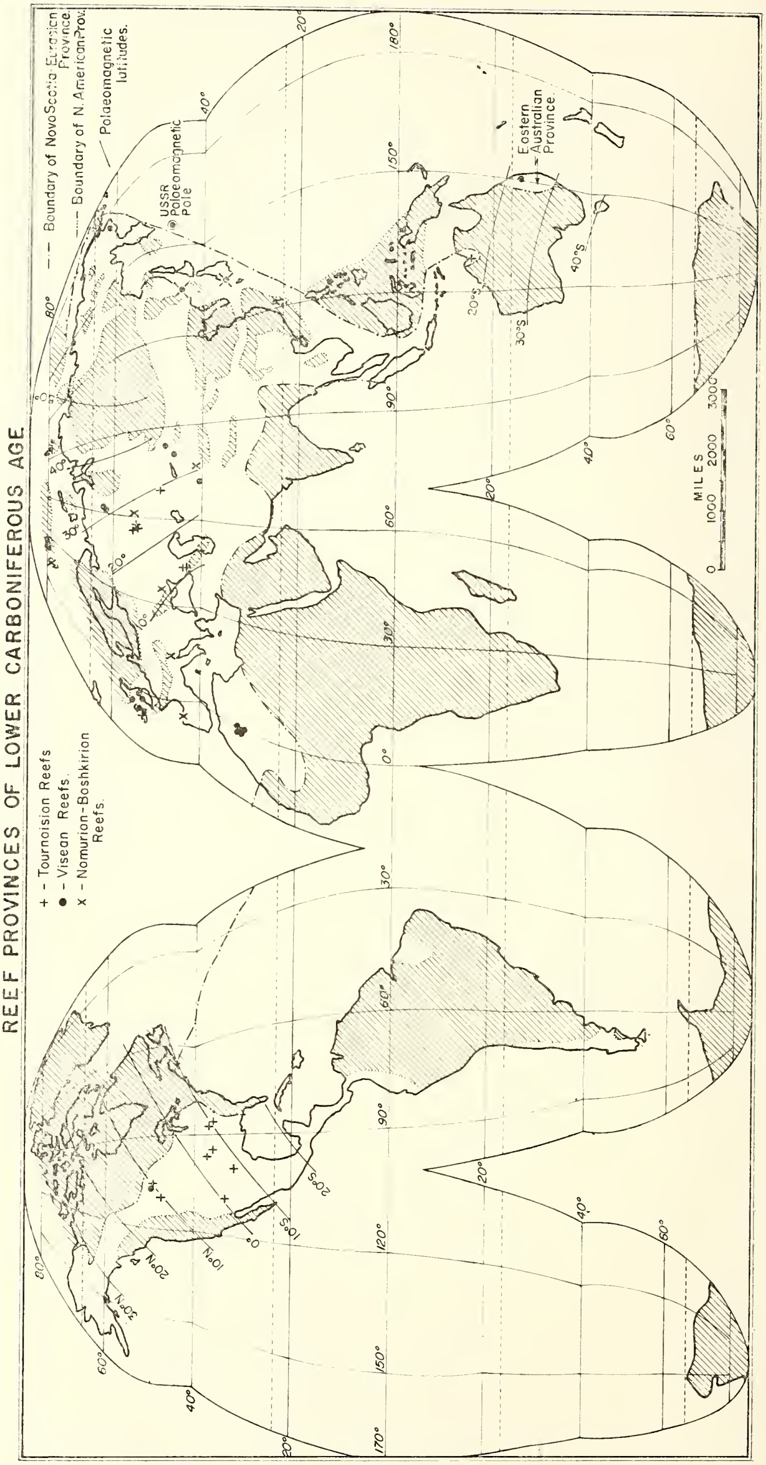
REEF PROVINCES OF LOWER CARBONIFEROUS AGE
+ - Tournaisian Reefs
● - Visean Reefs.
x - Namurian-Bashkirian Reefs.
– – Boundary of NovoScotia-Eurasian Province.
—— Boundary of N. American Prov.
Palaeomagnetic latitudes.
USSR Palaeomagnetic Pole
Eastern Australian Province.
MILES
0 1000 2000 3000

FIGURE 2.

ature controls over reef formation that exist today.

In the late Lower (or early Middle) Carboniferous reefs began to form in north-east Spain (de Groot, 1963) and in Spitzbergen (79° N.). The Spitzbergen reefs are described (Barbaroux, 1968) as small reefs somewhat like those of the Silurian of Gotland (58° N.). A reef province is reported near Vladivostok (64° N.) (Vinogradov, 1969), but no descriptions are available to me. The Akiyoshi and presumably the other Japanese atolls continue to grow through the Middle and Late Carboniferous and into the Permian. Spitzbergen reefs cease to be anomalous if we accept the palaeoclimatic implications usually predicated to palaeomagnetically deduced latitudes, but the reefs of Akiyoshi and of Vladivostok are anomalous.

Do the palaeocoral provinces fit palaeomagnetically deduced climatic zones better than they fit the present climatic pattern ? A careful study of the Lower Carboniferous coral faunas of the world shows that there are three major regions : (1) Nova Scotia, Eurasia, Western Australia ; (2) North America ; and (3) Eastern Australia (Hill, 1971 MS.). The North American province has a large number of endemic genera ; according to recent reports four Canadian genera of solitary Rugosa occur in the Taymyr region of Siberia, whilst three otherwise Russian genera of solitary Rugosa are reported to occur in the North American region. These reports still require detailed substantiation, but it is difficult to imagine that migration could have occurred except by way of Alaska and the Behring Sea ; if so, temperatures must have permitted this. The Nova Scotia-Eurasia-Western Australian province shows some endemic genera in western Europe and others in China ; and the ranges of these eastern and western endemic genera overlap in eastern Europe. Palaeocoral provinces can be distinguished in this great region and it is worthy of note that the Western Australian fauna, like the Indo-Chinese fauna, belongs to the Chinese province. Thus shallow water shelves presumably connected Western Australia to Indo-China and thence to China. Possibly eastern Australia received its *Lithostrotion* from Japan via a shelf east of the Philippines and New Guinea. So far as we know, no reefs were constructed in the Lower Carboniferous in those parts of Eurasia now in the Arctic Circle, except the small ones at the end of the epoch in Spitzbergen.

In later Carboniferous times (Middle and Upper Carboniferous) numerous reefs formed in the Urals, and there are many records of " bioherms " in the Pennsylvanian of North America : " bioherms " that on the whole are like those of the Mississippian. The Akiyoshi atoll continued to flourish. No Middle or Upper Carboniferous reefs are known in South America, Africa, Antarctica or Australia.

The Carboniferous reefs differ notably from those of the Silurian and Devonian in the relative unimportance of stromatoporoids and tabulate corals.

Permian reefs are known in western North America between 24° and 50° N. They differ from those of earlier periods, mainly in the absence of stromatoporoids and in the lesser importance of the tabulate corals. They are strongly developed in the Carnic Alps, in the Urals, and in Japan in the Akiyoshi limestone (and probably also in several limestone masses similar to that of the Akiyoshi fossil atoll). Permian reefs are not known in the Southern Hemisphere, though colonial Rugosa occur in northern New Zealand and in Timor.

Looking at the distribution of Palaeozoic reefs today, we see that in the Northern Hemisphere fossil reef provinces are clustered in the present temperate zones (between 22·5° and 67·5° N.). Thus, unless the warm climatic zones were wider in the Palaeozoic than now, or unless the stromatoporoids and Palaeozoic corals proliferated in reef profusion at lower temperatures than do the reef corals of today, the distribution of Palaeozoic fossil reefs is anomalous. Some of the anomalies appear to be lessened if we take the presently deduced palaeomagnetic latitudes to have had similar climatic significance to the corresponding latitudes of today and if we also assume continental drift. But other difficulties, such as the Japanese Carboniferous-Permian geosynclinal atoll of Akiyoshi, can then only be explained if we add to these two geophysical assumptions the assumption either that warm water penetrated into the palaeomagnetic high latitudes of Akiyoshi or that the Akiyoshi reef invertebrates proliferated in temperatures lower than those required by the reef animals of today. It is simplest to make one of the two latter assumptions only.

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(Received 20·8·71)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 103-107, 1970

Potassium-Argon Ages for Leucite-Bearing Rocks from New South Wales, Australia

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Abstract—The central New South Wales olivine leucitites have Miocene K-Ar ages (14–10 m.y.) that overlap with the ages of the eastern New South Wales volcanic rocks. The Murrumburrah leucite monchiquite has a minimum K-Ar age of Early Jurassic.

In this paper we present K-Ar ages on the two types of leucite-bearing volcanic rock in New South Wales: olivine leucitite and leucite monchiquite. These rocks were dated so as to define their ages more closely than can be done by stratigraphic geology.

The olivine leucitites have been described by Mingaye and White (1904) and Harvey and Joplin (1941); they occur in ten rather restricted areas in central New South Wales (Figure 1) as flows, minor pyroclastics and rare dykes (Browne, 1933). The lavas must be younger than the Lachlan Geosyncline rocks of Devonian and older age that they rest upon. They are generally regarded as Cenozoic because locally they overlie sediments that are thought to be Cenozoic in age (Branagan, 1969*b*), and because they are still extant even though they have never been protected from erosion by overlying sediments. The leucite monchiquite is found only as a small intrusive complex near Murrumburrah (Harvey and Joplin, 1941) in the eastern highlands of N.S.W. (Figure 1). Its age can only be defined as younger than the Devonian granite (Evernden and Richards, 1962) that it intrudes.

The K-Ar ages were determined on a 3–1 mm. fraction of the crushed whole rock, or, in the case of one sample, also on 0·25–0·125 mm. mineral concentrates. The method of potassium analysis used has been described by Cooper (1963), and the method of argon analysis by McDougall (1964, 1966). Analyses done in duplicate give a precision for potassium analyses of 0·5% (coefficient of variation) and for argon analyses of 5·7%.

The unusually poor precision of the argon analyses is most likely due not so much to poor precision of the argon analysis itself as the difficulty in obtaining representative splits from such impure mineral concentrates. Details of the localities of the dated samples are given in the Appendix.

The reliability of the K-Ar ages obtained depends both on the precision of the analytical techniques and on the argon retention properties of the main potassium-bearing phases in the rocks. For these samples of olivine leucitite it is estimated that the potassium is divided among the minerals approximately as follows: leucite 50–60%, nepheline and alkali feldspar combined 30%, phlogopite up to 30%, and clinopyroxene less than 1%. In flows and shallow intrusions elsewhere it has been found that nepheline, high temperature alkali feldspar and phlogopite are generally reliable minerals for K-Ar dating (Dalrymple and Lanphere, 1969), but virtually no data are available on the reliability of leucite. In olivine leucitites the whole rock age will be greatly influenced by the leucite age, as over one-half of the potassium resides in this mineral.

The K-Ar age of leucite in lava flows could be too low due to loss of argon by diffusion, or too high due to extraneous radiogenic argon included in the lattice of the mineral prior to and during eruption. The rate of argon diffusion from leucite is high at 500° C. (Evernden *et al.*, 1960), probably because of the inversion of leucite to cubic symmetry that is complete at 625° C., but direct measurement of argon diffusion from leucite at low temperatures has not been made. Also, leucite has never been tested for dating by comparing ages measured on it with ages of other co-existing minerals.

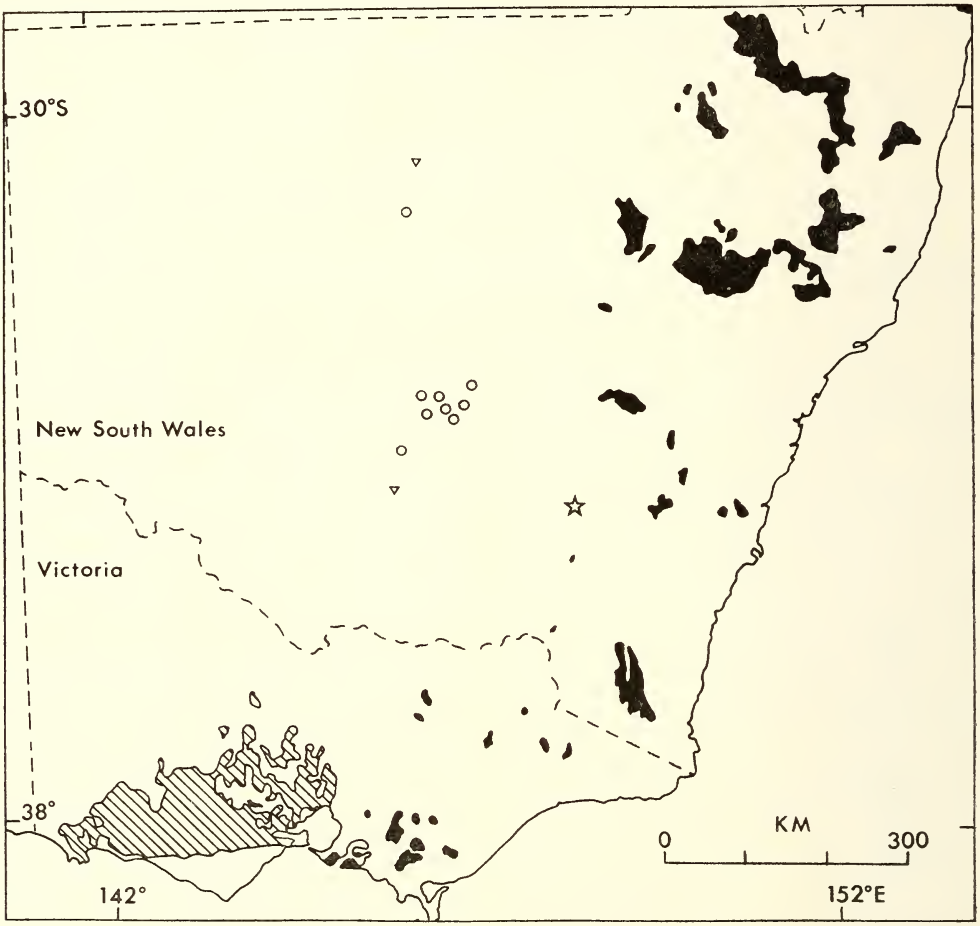

Figure 1.—Map of New South Wales and Victoria to show the distribution of the Miocene olivine leucitites that were dated (circles), not dated (triangles), pre-early Jurassic leucite monchiquite intrusion (star), the Palaeocene to Miocene volcanics of Victoria and New South Wales (black) and the Pliocene to Quaternary Newer Basalts of Victoria (shaded).

In this study both mineral and whole rock ages were determined on a sample (GA3470) of coarse grained olivine leucitite with subequigranular texture from a flow at Begargo Hill. The leucite concentrate obtained was about 99% pure. The phlogopite concentrate contained about 50% low potassium minerals (iddingsite, clinopyroxene and iron-titanium ore) which apart from introducing sampling difficulties should not unduly bias the phlogopite age. The clinopyroxene concentrate was 99% pure, but because it had a high potassium content the age may just be a reflection of the age of small amounts of leucite within the concentrate. The K-Ar results given in Table 1 show that the phlogopite concentrate age agrees with that of the leucite within experimental error at 13·8 (2×s.d.=0·8) m.y. The leucite and phlogopite ages both probably reflect the time of crystallization, as the sample is from a surface flow that is unlikely to have been heated after extrusion. The pyroxene concentrate and the whole rock ages are also concordant within

TABLE 1
K-Ar Ages

	K (%)	Rad. ^{40}Ar cc STP gm. 10^{-6}	Rad. ^{40}Ar (%)	Age (m.y.)	$2\times$s.d. (m.y.)	Mean Age (m.y.)	$2\times$s.d. (m.y.)
Olivine Leucitites :							
GA 3470 Begargo Hill WR	4·869, 4·893	2·673	84·9	13·6	±0·3	13·3	±0·6
		2·520	89·0	12·9	±0·3		
Pyroxene ..	0·118, 0·113	0·066	12·8	14·4	±0·7	14·4	±0·7
Leucite ..	16·10, 16·42	9·690	95·7	14·9	±0·6		
		8·766	96·0	13·4	±0·5	14·1	±1·4
		8·941	94·6	13·7	±0·5		
Phlogopite concentrate	3·389	1·715	9·9	12·6	±0·7	13·5	±2·2
		1·960	33·6	14·5	±0·5		
GA 3471 Begargo Hill WR	3·901, 3·913	1·708	74·0	10·9	±0·3		
		1·592	84·8	10·2	±0·2	10·6	±0·6
GA 3472 Bygalore WR	5·322, 5·318	2·070	53·2	9·8	±0·3		
GA 3473 Bygalore Trig WR	5·294, 5·270	2·592	49·1	12·3	±0·3		
GA 3474 Gorman Hills WR	4·558, 4·580	2·288	78·9	12·5	±0·3		
GA 3475 Tullibigeal WR	6·074, 6·082	2·437	74·2	10·1	±0·3		
GA 3476 Condobolin WR	4·364, 4·366	2·204	42·5	12·6	±0·4		
GA 3478 Lake Cargellico WR	4·575, 4·572	2·071	49·0	11·3	±0·2		
		2·326	48·0	12·7	±0·2		
GA 3479 El Capitan WR	5·871, 6·044	2·845	91·8	11·9	±0·3		
GA 3480 Burgooney WR	3·637, 3·638	1·984	73·1	13·6	±0·3		
GA 3481 Flagstaff H. WR	4·374, 4·366	1·758	82·3	10·1	±0·3		
Leucite Monchiquite :							
70–139 Murrumburrah WR	1·036, 1·031	8·404	92·1	194	±3		

$\lambda_\beta = 0{\cdot}472\ 10^{-9}$ yr.$^{-1}$; $\lambda_e = 0{\cdot}585\ 10^{-10}$ yr.$^{-1}$; ^{40}K/K$=0{\cdot}119\ 10^{-3}$; WR=whole rock.

experimental error. These limited data are consistent with the whole rock ages of olivine leucitite flows being unbiassed estimates of the time of their extrusion.

The olivine leucitites give whole rock ages that range from 14 to 10 m.y. (Table 1). The measured ages all fall within the Miocene (Harland *et al.*, 1964), and are consistent with the Cenozoic age suggested by the field evidence. The ages suggest that at both Bygalore and Begargo Hill eruptions of olivine leucitite may have occurred over periods of the order of 2 m.y. However, in both areas, because of discontinuous outcrop, the stratigraphic relations between the outcrops cannot be inferred. Hence we cannot tell whether these age differences truly represent prolonged periods of extrusion, or are merely a reflection of differing amounts of argon loss.

Lavas also of Late Cenozoic age cover large areas of the coastal highlands of south-eastern Australia. Those in western Victoria, the Newer Basalts, have a known age range of 4·5 to 0 m.y. (McDougall *et al.*, 1966) and hence are younger than the olivine leucitites, while those in north-east N.S.W. have a known time range of 24 to 13 m.y. (McDougall and Wilkinson, 1967; Webb *et al.*, 1967; Wellman *et al.*, 1969), so that they partly overlap the olivine leucitites in time. The olivine leucitites lie in a separate belt, are slightly younger in age, and have a strikingly different composition from these other volcanic rocks in N.S.W., so a separate origin for them is postulated. However, the outcrop pattern of olivine leucitites is approximately parallel to the main belt of outcrop of the other Cenozoic lavas of N.S.W., and to the coast of N.S.W., so that there is probably some important structural control of the location of the eruptive centres.

The Murrumburrah leucite monchiquite gives a minimum whole rock age of 194 ± 3 m.y., and is therefore earliest Jurassic or older in age (Harland, 1964). This is consistent with the post-Devonian age suggested by the geological control. The minimum age of earliest Jurassic is similar to the Early Jurassic age measured for many other small intrusions and flows in the south-eastern N.S.W. highlands (Evernden and Richards, 1962; Lovering and Richards, 1964; Dulhunty and McDougall, 1966; Branagan, 1969*a*). As the Murrumburrah leucite monchiquite is similar to these other intrusions in location, mode of occurrence, and age, it is probably part of this early Jurassic period of igneous activity.

The central N.S.W. olivine leucitites differ from the Murrumburrah leucite monchiquite in age, in chemical composition, and in location. The olivine leucitites are probably associated in some way with the Cenozoic volcanism in eastern N.S.W., while the leucite monchiquite is probably associated with the early Jurassic volcanism in eastern N.S.W.

Appendix

All specimens except No. 70–139 are olivine-leucitites composed essentially of leucite, clinopyroxene, olivine and iron-titanium ore. Biotite, nepheline, sanidine and amphibole in various proportions occur as accessories. The structures are generally microporphyritic with fully crystallized aphanitic groundmasses. Pertinent references are summarized by Vallance (1969).

GA 3470. Begargo Hill. Relatively coarse-grained (av. grain-size 1–2 mm.) lava with steeply-dipping jointing from small volcanic complex. Long. 146° 22′ E. Lat. 33° 31′ S. G.R., SI 55–6: 436857.

GA 3471. Begargo Hill. Fine-grained lava forming most of the volcano. Location references as above.

GA 3472. Bygalore. Low, dissected ridge probably relict of lava flow. Long. 146° 46′ E. Lat. 33° 30′ S. G.R., SI 55–6: 478861.

GA 3473. Mount Bygalore (The Monument). Steep-sided dyke structure with prominent vertical jointing. Long. 146° 45′ E. Lat. 33° 31′ S. G.R., SI 55–6: 477858.

GA 3474. Gorman Hills. Lava flow from small dissected volcanic complex. Long. 146° 47′ E. Lat. 33° 23′ S. G.R., SI 55–6: 480875.

GA 3475. Tullibigeal. Crescentic, dissected ridge, probably relict of a lava flow. Long. 146° 39′ E. Lat. 33° 27′ S. G.R., SI 55–6: 467865.

GA 3476. Condobolin (Weebar Hill). Crescentic ridge, probably remnant of a lava flow. Long. 147° 01′ E. Lat. 33° 10′ S. G.R., SI 55–7: 504900.

GA 3478. Lake Cargellico. Conspicuous, relatively large remnant of a lava flow forming a fingered outcrop. Long. 146° 20′ E. Lat. 33° 17′ S. G.R., SI 55–6: 434886.

GA 3479. El Capitan. Flow remnant of lava infilling along valleys (Cundari and Ollier, 1970). Long. 146° 12′ E. Lat. 31° 11′ S. G.R., SH 55–14: 420141.

GA 3480. Burgooney. Small, isolated flow remnant, probably related to the Tullibigeal complex. Long. 146° 37′ E. Lat. 33° 21′ S. G.R., SI 55–6: 464878.

GA 3481. Flagstaff Hill. Lava flow from small volcanic complex with well preserved scoria cone. Long. 146° 05′ E. Lat. 33° 47′ S. G.R., SI 55–6: 408826.

70–139. Murrumburrah. Leucite-monchiquite dyke described by Harvey and Joplin (1941). Long. 148° 21′ E. Lat. 34° 34′ S. G.R., SI 55–11: 636728.

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(Received 9. Feb. 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 109-118, 1970

Chemistry of Some Insect Secretions*

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Introduction

A number of the secretions used by insects and other arthropods for defensive purposes, as venoms, and as chemical messengers in their patterns of social organization have been characterized.[1, 2, 3] These secretions are produced by exocrine, that is ducted glands, which commonly open to the exterior, and vary in number, complexity and location. For example, Figure 1 illustrates the exocrine gland system of the primitive Australian ant, *Myrmecia gulosa*.[4]

Generally, defensive secretions are used by insects to prevent or discourage their enemies from interfering in their life patterns.[1] The venoms, communicated by biting or stinging, are used to kill or incapacitate the prey forming food for the insect or its young.[2] The exocrine secretions used as chemical messengers are termed pheromones.[3] They convey signals between individuals of the same or closely related species concerning, for example, food sources, mating or the presence of enemies. The broad categories—defensive secretions, venoms, pheromones — are not mutually exclusive, and a given secretion may have more than one function. The pheromones, as products of ducted endocrine glands, can be distinguished from hormones, which are products of ductless endocrine glands.

The chemistry of insect secretions has been studied, in detail, essentially in the last two decades. Whilst the work of pioneers such as Butenandt and his colleagues precedes this period, their structural studies on the sex pheromone, and the moulting hormone of *Bombyx mori* were not brought to fruition until the 1960's.[5] The earliest report of a chemical investigation on an insect secretion would appear to be one by the English botanist John Wray, who noted[6] in 1670 that Samuel Fisher had obtained an acid, formic, by dry distillation of wood ants. The chemical characterization of formic acid was undertaken by Berzelius[7] and Liebig[8] early in the nineteenth century. A number of biological observations on odoriferous insect secretions—some fragrant and others repugnant—have since been noted,[9] but these observations do not appear to have been followed up to any great extent by the chemist interested in natural products. Whilst the structure of cantharidin was investigated at the beginning of the twentieth century, this work does not appear to have been directed *per se* to an understanding of insect secretions.[10]

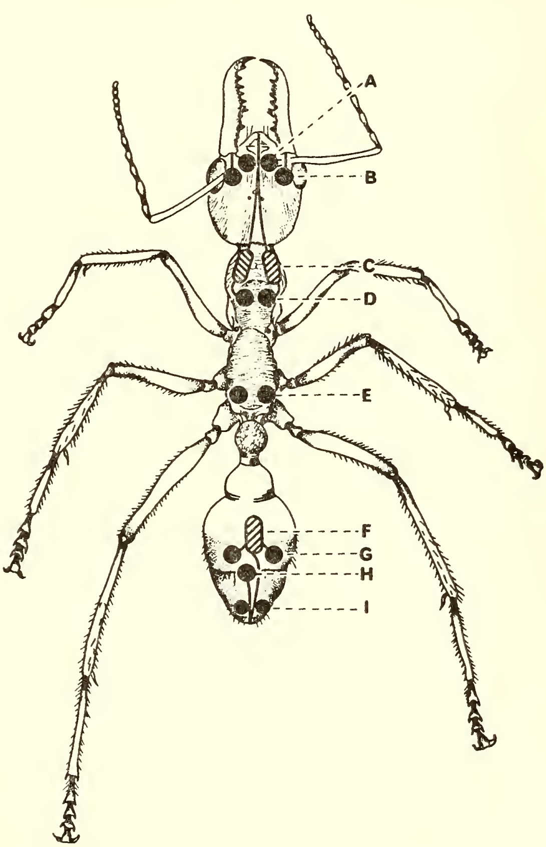


Figure 1.—Exocrine gland system of the bull ant, *Myrmecia gulosa*. (A) Pharyngeal glands ; (B) mandibular glands ; (C) salivary reservoirs ; (D) salivary glands ; (E) metasternal glands ; (F) venom reservoir ; (G) venom glands ; (H) accessory gland ; (I) dorsal abdominal glands (Cavill and Robertson[4]).

* The Liversidge Research Lecture, delivered before the Royal Society of New South Wales, 22nd October, 1970.

In the present lecture emphasis is placed on aspects of the chemistry of insect secretions that have interested us since 1952.*

Defensive Secretions, Venoms and Pheromones

In 1949, in the course of a search for antibiotics of animal origin, the Italian entomologist Pavan isolated iridomyrmecin (*3*) from anal glands of the Argentine ant, *Iridomyrmex humilis*.[11] In 1952 he reported to the Ninth International Congress of Entomology that Total extraction of the common Australian "meat" ant, *Iridomyrmex detectus*, with light petroleum gave 2-methylhept-2-en-6-one (*1*) and iridodial (*2*),[13, 14] the then novel 1,5-dialdehyde corresponding to iridomyrmecin. These anal gland constituents represented approximately 4% and 1% of body weight, respectively. Methylheptenone is now known to function as an alarm pheromone[15] as well as being a defensive secretion. A number of simple carbonyl compounds have been characterized from Dolichoderine ants and other

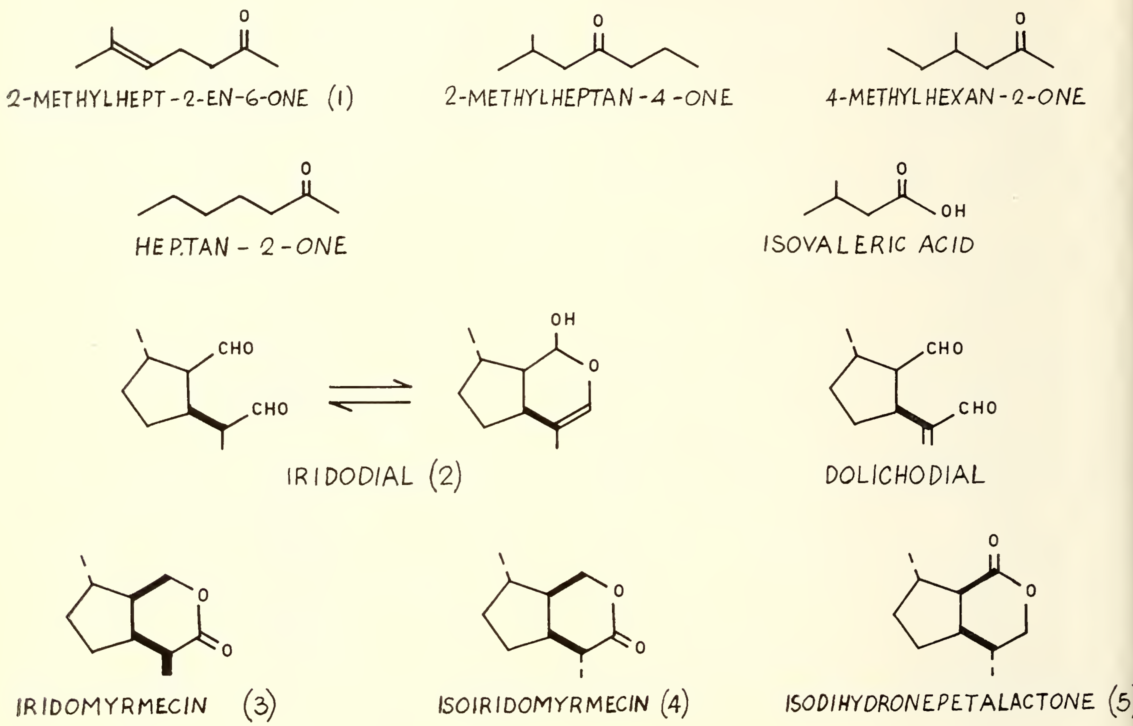


FIGURE 2.—Dolichoderine ant extractives.

iridomyrmecin was insecticidal.[12] This observation has prompted much of the interest since shown in defensive secretions.

A defensive secretion, often present in a relatively large amount, may be isolated as a major component by total extraction of the insects. The source of the material has then to be determined, odour and abundance enabling the rapid location of its glandular origin.

insects (see Figure 2). These saturated and unsaturated ketones have "knockdown" insecticidal activity (see Table 1).[16] The activity of these ketones, on the basis of EC_{50} values, compares quite favourably with that of some well-known fumigants, but their volatility renders their contact toxicity slight when compared with, for example, that of the pyrethrins.

The cyclopentanoid monoterpenes (see Figure 2) are also major constituents of the anal gland secretion of various species of Dolichoderine ants. The structure and stereochemistry of the iridolactones, iridomyrmecin (*3*) and isoiridomyrmecin (*4*), and of iridodial (*2*),

* Studies on insect chemistry in the University of New South Wales have received generous financial support from the Commonwealth Bank of Australia Rural Credits Development Fund, from the U.S. Public Health Service, and from the Australian Research Grants Committee.

TABLE 1
" Knockdown " Effect of the Vapour of Some Aliphatic Ketones and Other Fumigants[16]

Compound	EC_{50}*
2-Methylhept-2-en-6-one (1) . .	1·33
6-methylheptan-2-one . .	2·1
6-methylhept-3-en-2-one . .	1·17
4-methylpent-3-en-2-one . .	2·6
ethylene dichloride	5
ethyl formate	6
ethyl acetate	16

* EC_{50} is the vapour concentration in µl./l. required to give 50% knockdown of female houseflies in 2·5 hr.

were established in the mid 1950's.[17] More recently a re-investigation of the anal gland secretion of *Iridomyrmex nitidus* gave isodihydronepetalactone (*5*) in addition to isoiridomyrmecin.[18] These defensive substances of insect origin are structurally related to nepetalactone (*6*), the physiologically active principle of the catmint plant, *Nepeta cataria*, through the nepetalinic acids.[19] For example, oxidation of iridomyrmecin with aqueous potassium permanganate solution gave the nepetalinic acid (*7*),[14, 20] which is one of the two acids (*7*) and (*8*) originally isolated on hydrolysis and oxidation of nepetalactone (see Figure 3).

The suggested formation of iridodial in nature from citronellal by a terminal oxidation of the isopropylidene group, and then cyclization of the intermediate unsaturated dialdehyde (*11*) was simulated in the first synthesis of iridodial by Sir Robert Robinson and his co-workers (see Figure 4).[21] Citronellal (*9*), as its ethylene acetal (*10*) was oxidized with selenium dioxide in ethanol, and the product, on treatment with aqueous acetic acid, gave iridodial (*12*) together with the acyclic dialdehyde (*11*). A likely mechanism for the cyclization involves an enolic intermediate of type (*13*), and hence a *trans*-relationship of the adjacent 1- and 2-substituents would be expected in the resultant iridodials. Additionally, equilibration of the centres α to the two formyl groups could occur, so that the iridodial should contain the *trans,trans*-, *trans,cis*- and *cis,trans*-isomers.*

Iridodial from the " meat " ant *I. detectus* was considered to be a mixture of the *cis,trans*- and *trans,cis*-isomers, with the former predominating.[22] However, the *trans,cis*-isomers may have resulted from a partial equilibration of the *cis,trans*-iridodial during isolation and purification. A stereospecific synthesis of the *cis,trans*-iridodial (*20*), that is, the enantiomer of the *cis,trans*-irododial related to iridomyrmecin, was undertaken[23] so that an iridodial

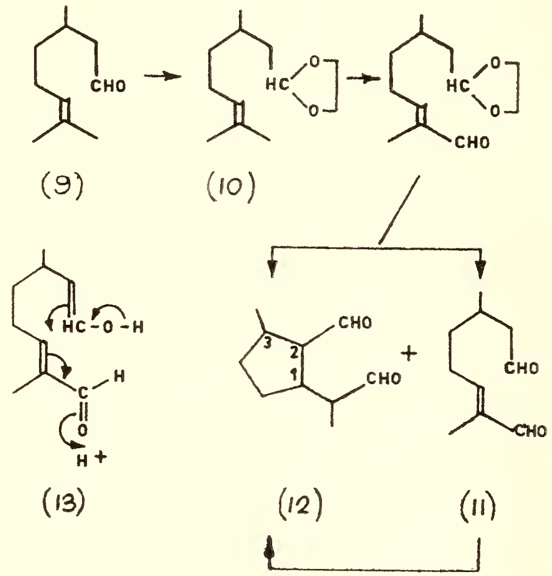


FIGURE 4.—Synthesis of iridodial from citronellal (Sir Robert Robinson and co-workers[21]).

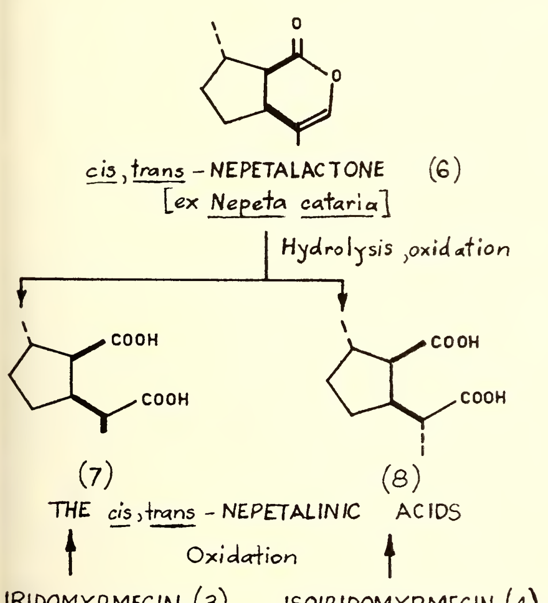


FIGURE 3.—Interrelation of *cis,trans*-nepetalactone and the iridolactones.

* In the designation of configuration, the relationship of the substituents at C1 and C2 is given first, and that at C2 and C3 second. For example, formula (20) is a *cis,trans*-iridodial.

of established configuration at each of the four optically active centres, would be available for comparative gas chromatography and, moreover, would provide a reference point for the determination of the stereochemistry of iridodials, and related enol-lactol tautomers, of insect and plant origin.

acid. A likely mechanism for this conversion is given in Figure 6 (cf. [23]).

Epoxidation of the conjugated double bond with alkaline hydrogen peroxide solution, thence fission of the epoxide (*17*), and loss of a molecule of water in the presence of mineral acid, gave the hydroxybicyclo-octenone (*18a*) as a

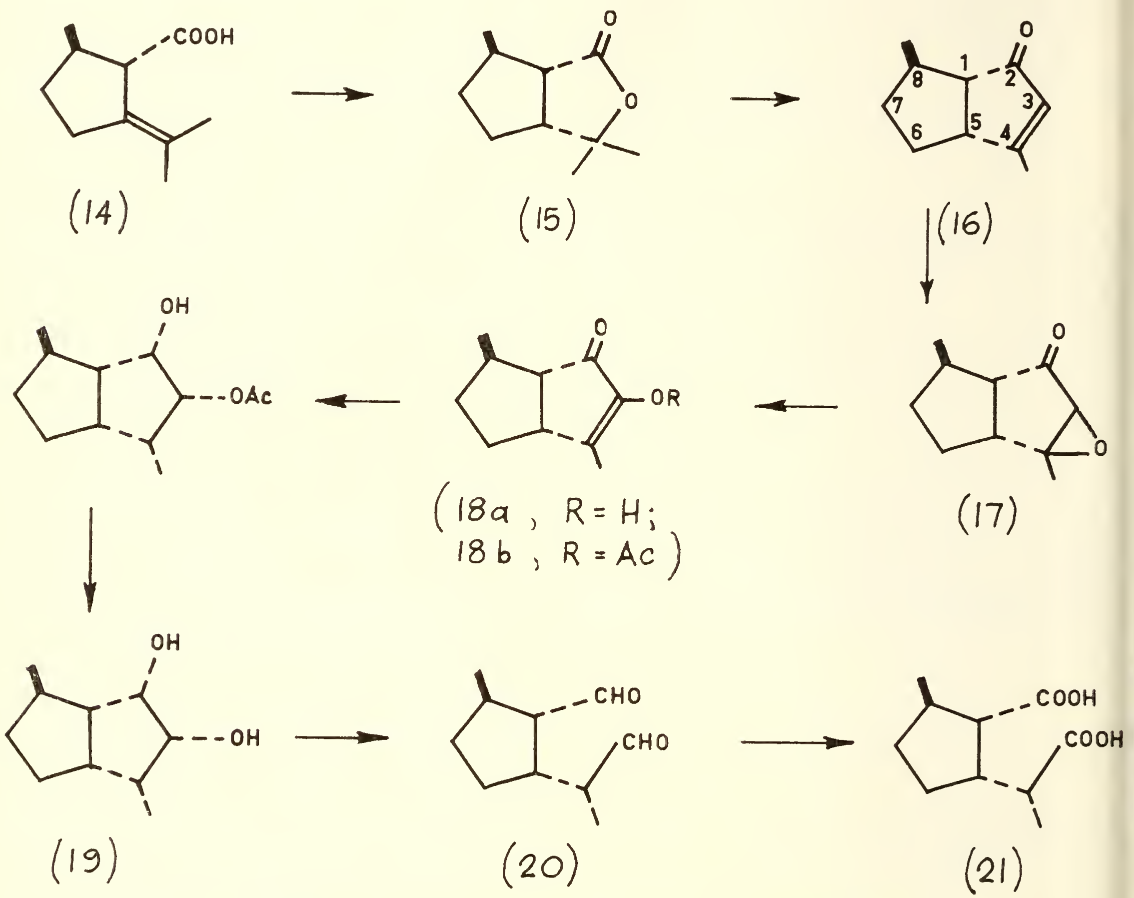


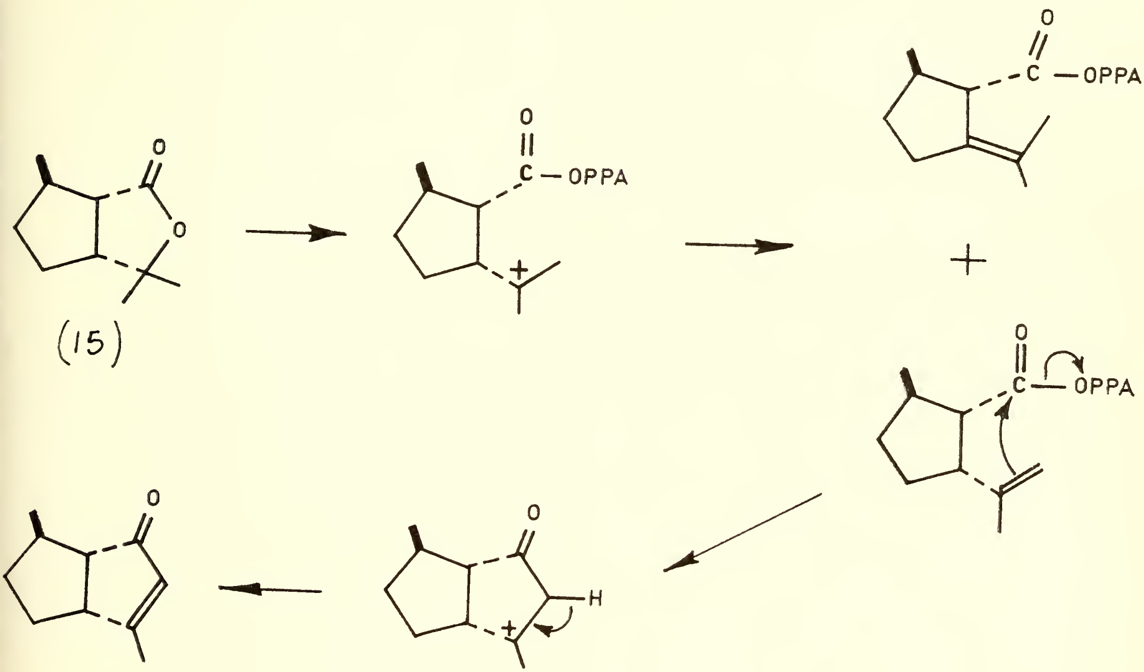
FIGURE 5.—A stereospecific synthesis of iridodial (Achmad and Cavill[23]).

This synthesis depended on the availability of (+)-*trans*-pulegenic acid (*14*) which was obtained from D-(+)-pulegone by a Favorskii rearrangement of the freshly prepared dibromide with sodium ethoxide in ethanol.

Treatment of the (+)-pulegenic acid (*14*) with hydrochloric acid in methanol gave the γ-lactone (*15*) in good yield. The more stable *cis*-fused structure was assigned to this lactone, whilst the *cis,trans*-configuration at the cyclopentane ring is that required in the final product. The key step in the synthesis was the conversion of this γ-lactone into the corresponding bicyclo-octenone (*16*) by the action of polyphosphoric

crystalline solid. Hydrogenation of the acetoxy-bicyclo-octenone, thence hydrolysis of the acetoxy group with alkali, yielded the intermediate glycol. On the basis that hydrogen had been added from the least hindered side of (*18b*), the glycol was assigned structure (*19*). The final stop was fission of this bicyclic diol with sodium metaperiodate, yielding the *cis,trans*-iridodial (*20*). The stereochemical assignments were confirmed by oxidation of the synthetic iridodial (*20*) with zine permanganate. The expected nepetalinic acid (*21*), that is the enantiomer of (*7*), was isolated, and identified by a gas chromatographic comparison of its methyl ester with that of the dimethyl nepetalinate obtained *via* the oxidation of iridomyrmecin.[23]

Further gas chromatographic studies using the freshly prepared synthetic iridodial (*20*), and natural iridodial from *I. detectus*, showed that the natural product is a mixture consisting predominantly of the *cis,trans*-isomers corresponding to isoiridomyrmecin and iridomyrmecin.



(15) (16)

FIGURE 6.—Conversion of the γ-lactone (*15*) into the bicyclo-octenone (*16*). (PPA = polyphosphoric acid.)

Iridodial does not show a " knockdown " insecticidal effect comparable with that established for the iridolactones. It was suggested[24] that iridodial may function as a fixative for the more volatile carbonyl compounds with which it is usually associated; in this case it is the ketones that have the " knockdown " action. More recently, in a study of the anal gland secretion of *Iridomyrmex nitidiceps*, which comprises iridodial and isovaleric acid, it was noted that iridodial could be contributing to the alarm pheromonal pattern for this insect.[25]

The venoms of the stinging Hymenoptera, especially of the bees and wasps, have been studied in detail in recent years.[26] However, until the recent work in Australia on the venom of the " bull-dog " ants, knowledge of proteinaceous ant venoms was sparse. In particular, the venom of the primitive red " bull-dog " ant, *Myrmecia gulosa*, well known for its aggressive behaviour and painful sting, has been characterized.[27] The venom is synthesized in the free gland filaments, stored in the venom sac or reservoir, then delivered by the duct to the sting barb. The Dufour's (accessory venom) gland secretion would also be delivered *via* the sting barb. The venom was isolated after individual collection of these ants, and dissection of the reservoirs, the yield on a dry weight basis being 0·5 mg./ant.

The venom is a proteinaceous one, and acid hydrolysis showed the presence of at least 19 aminoacids.[28] The crude venom was resolved into eight fractions by paper electrophoresis (see Figure 7). Fraction I was identified as histamine; it comprises 2% of the venom.[27] A histamine-releaser was also identified in the whole venom of bull-dog ants.[29] Fractions II to VIII were stained by the protein dyes bromophenol blue and Amidoschwarz 10B. Of these proteinaceous fractions, IV and V showed a sustained kinin-like activity,[30] whilst fraction VII contained a direct, heat labile haemolytic factor,[27] this activity being used in bioassay. Further, the venom contains a small protein molecule not associated with a single electrophoretic fraction, which is an inhibitor of insect mitochondrial respiration.[28, 31] Fractions IV and V also showed hyaluronidase activity,[27, 28] while phospholipase C activity was associated with fraction VI.[28] Thus the venom of *M. gulosa*, and also that of related "bull-dog" ants, is typical of the hymenopterous proteinaceous venoms: it contains a low

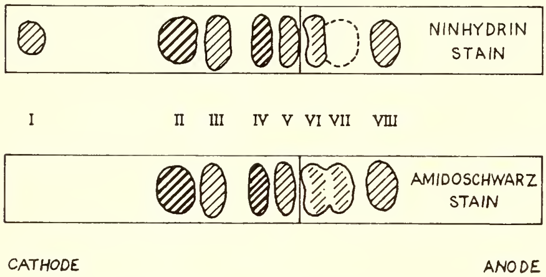


FIGURE 7.—Electrophoretic separation of *M. gulosa* venom. (*After* Cavill, Robertson and Whitfield.[27])

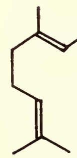
molecular weight physiologically active amine, biogenic peptides, proteins and toxins, and enzymes (cf. [32]). The "bull-dog" ant venoms are effective in killing their insect and other prey, also they are capable of inflicting pain on predators, including man, and hence are highly efficient in defence. Injection of saline extracts of the crude venom of *Myrmecia pyriformis* into mice shows that this venom is quite toxic; the LD_{50} was estimated to be 2–10 mg./kg. body weight.[30] The LD_{50} for *M. gulosa* venom injected into the house fly, *Musca domestica*, was ~10 μg./g.[33]

Recently, a study of the glandular origin and pattern of pheromonal activity involved in aggression in the "bull-dog" ant, *M. gulosa*, was undertaken.[34] The presence of at least three pheromones, a minor alarm pheromone in the rectal secretion which alerts the ant, a major alarm pheromone in Dufour's gland which activates the ant, and an attack pheromone in the mandibular glands, are involved in the pattern which results in stinging by these insects. No pheromonal activity was noted for the venom.

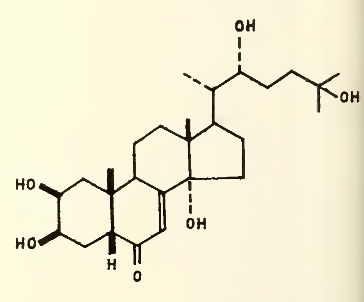
Some twelve hydrocarbons were reported[35] from the Dufour's gland, these components comprising 0·06% of the body weight of the insect. The major constituents were pentadecane (17%), *cis*-heptadec-8-ene (62%), and heptadecane (4%). In passing, it is noted that these hydrocarbons correspond in structure and proportion to the major free fatty acids isolated from *M. gulosa*, that is, palmitic, oleic and stearic.[36] The Dufour's gland hydrocarbons, whilst having a minor alarm effect, do not represent the alarm pheromone.[34] Thus a complex pattern of pheromonal activity has been established, but the chemical problem has yet to be solved.

The characterization of Dufour's gland constituents has also been achieved in more highly evolved ant species. Thus α-farnesene (*22*) was isolated from this gland in the Myrmicine ant *Aphaenogaster longiceps*.[37] This single constituent represents some 4% of the body weight of the insect. Current work on the Dufour's gland secretion of the Formicine ant, *Camponotus intrepidus*, again shows the presence of aliphatic hydrocarbons, within the range C_{10} to C_{17}. The normal alkanes are the major constituents (81%), together with a series of 3-methyl (16%) and 5-methylalkanes (2·3%). Alk-1-enes are minor constituents (~0·2%).[38]

There has been, and still is, conjecture as to the function of the above hydrocarbons. Their presence in the sting-bearing Myrmeciinae is not inconsistent with one of the earlier proposals that Dufour's gland secretion may function in the Hymenoptera, in general, as a sting lubricant. However, a remarkably wide range of feeding, foraging and nesting habits is displayed within the Formicidae and it is considered likely that the function of Dufour's gland secretion in relation to these habits could have undergone considerable change from the more primitive Myrmeciinae to the more advanced Myrmicinae and Formicinae (cf. [4]).



α-FARNESENE (22)



ECDYSONE (23)

Hormones

Whereas pheromones are products of the exocrine system and convey chemical signals between members of the same or closely related species, hormones are products of the endocrine system and convey signals between tissues within an individual of the species.

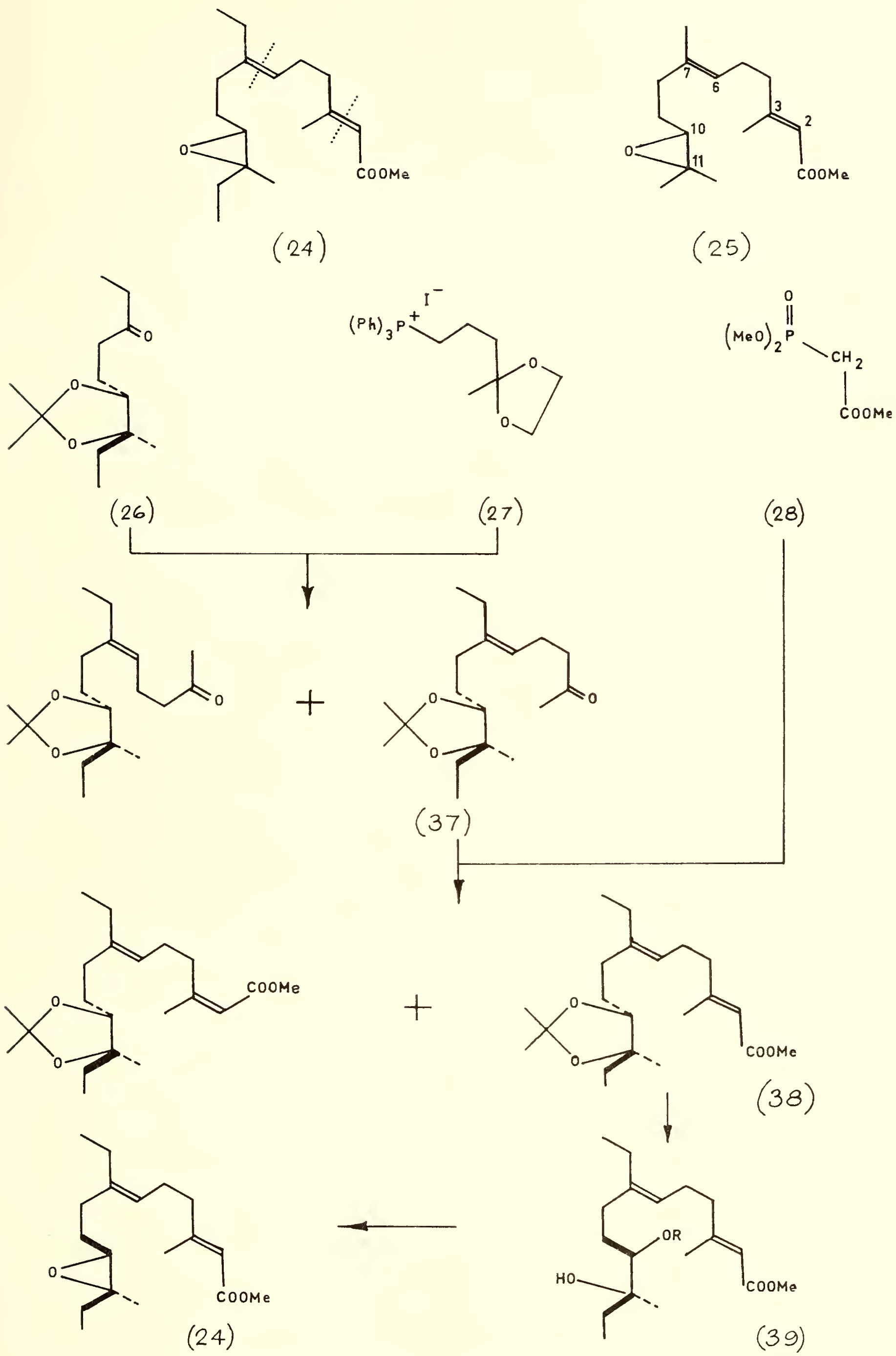


FIGURE 8.—Synthesis of the juvenile hormone (Cavill, Laing and Williams[43]).

Present knowledge of the hormonal control of insect development stems largely from the pioneering studies of Sir Vincent Wigglesworth.[39] At least three hormones, one originating in the brain, the juvenile hormone, and the moulting hormone, are involved in the regulation of post-embryonic development in insects which is characterized by moulting and metamorphosis. The structure of the brain hormone is unknown. The moulting hormone, ecdysone (*23*), isolated from the pupae of the silkworm, *Bombyx mori*, is steroidal.[5]

applicable to the synthesis of homologues and analogues.

The structure was built up from three units, of which the key C_{10} unit was the *trans*-acetonide of 7 - oxo - 3 - methylnonane - 3,4 - diol (*26*). Sequential Wittig reactions were used to add the C_5 unit (*27*) and the C_3 unit (*28*). These steps were modelled in a synthesis of the bisnor-hormone (*25*).[45] The chain-extending steps introduced the two olefinic bonds of (*24*), and at each step the required *trans*-isomer was separated by preparative gas chromatography.

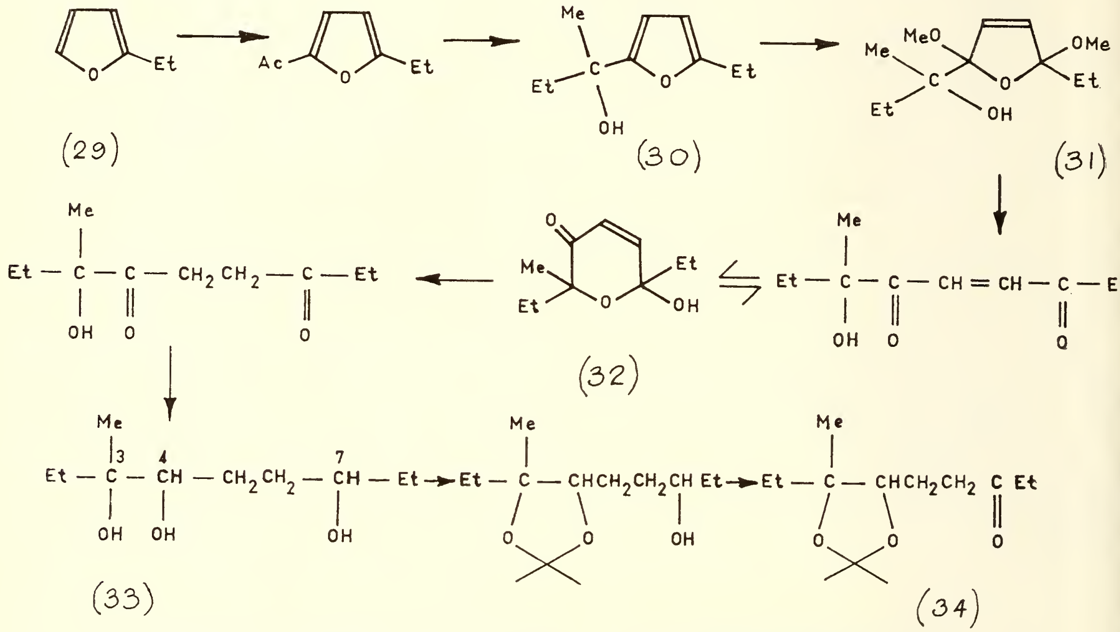


FIGURE 9.—Synthesis of the acetonide of 7-oxo-3-methylnonane-3,4-diol (*34*).

In 1967 the juvenile hormone from the giant silkworm moth, *Hyalophora cecropia*, was shown to have a modified sesquiterpenoid structure (*24*).[40] Currently this hormone is attracting much attention as its action in preventing maturation to the adult form renders it of potential value in insect control.[41] Not unexpectedly, a number of juvenile hormone syntheses have now been reported.[42] The synthesis, presently described,[43] follows our earlier work on α-farnesene (cf. [37]).

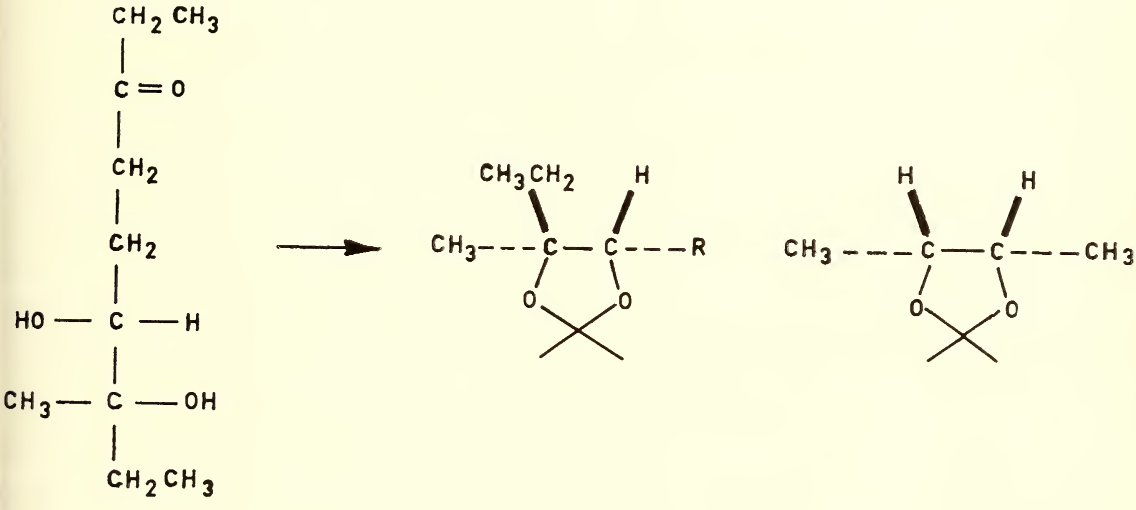
Structurally, the hormone may be considered as a bishomologue of the known sesquiterpenoid, methyl 10,11 - epoxy - 3,7,11 - trimethyl - dodeca-2,6-dienoate (*25*) which shows high juvenile hormone activity.[44] That is, in the hormone (*24*) two ethyl substituents replace the methyl groups at C7 and C11 in (*25*). The method of synthesis is a general one, being

Finally, the intermediate ester (*38*) was converted into the *cis*-10,11-epoxide structure of (*24*) *via* the 10,11-diol monomesylate (*39*).

The C_{10} unit was synthesized from 2-ethylfuran (*29*). The appropriate substituents were introduced into the furanoid intermediates, and importantly the furan (*30*), provides the genesis of the oxygen functions for the keto-acetonide (*26*). The furan (*30*), on treatment with bromine in methanol, gave the dihydrofuran derivative (*31*). Hydrolysis of this cyclic acetal with dilute hydrochloric acid yielded the dihydropyranone (*32*). Hydrogenation of (*32*) and reduction of the intermediate hydroxydiketone with sodium borohydride gave the triol (*33*). From the mode of synthesis of this acyclic triol (*33*), the centres at C3 and C4 are racemic, and the derived ketoacetonide (*34*) would be a mixture of enantiomeric pairs of *cis*- and *trans*-isomers about the 1,3-dioxalan ring. The *threo*-form of the triol (*35*) would give the *trans*-ketoacetonide (*26*), and thence the *cis*-expoide (*24*) (see Figure 10). Separation of the *threo*- and *erythro*-forms of the triol was achieved using an alumina column impregnated with boric acid for elution chromatography. At this stage configuration was assigned to the *trans*-ketoacetonide (*26*) on the basis of comparative n.m.r. data (see reference 43). The chemical shift value (δ) of the singlet for the protons (3H) of the methyl group situated *trans* to the hydrogen atom on the dioxalan ring in *26*, was compared with that for the equivalent methyl group in the known[46] *cis*-tetramethyl dioxalan (*36*). The methyl and hydrogen substituents at C4 and C5 in this model dioxalan (*36*) are, of course, *trans*. The signal for the protons of the tertiary methyl group appears at approximately 0·1 p.p.m. upfield from the *trans*-ketoacetonide and related compounds, compared with the equivalent *cis*-isomers.

Reaction of the *trans*-ketoacetonide (*26*) with the Wittig reagent prepared from (*27*) gave a mixture of the *cis*- and *trans*-isomers of the bisacetal. Selective hydrolysis of the ethylene acetal was achieved using toluene-*p*-sulphonic acid in the presence of a large excess of acetone (cf. [45]). The required *trans,trans*-dodecenone (*37*) having the longer retention time was separated from the *trans,cis*-isomer by preparative gas chromatography, and subjected to the second Wittig reaction with the sodium salt of trimethylphosphonoacetate (*28*). The required *trans,trans,trans*-product (*38*)* of longer retention time was separated from the *trans,cis,trans*-isomer. Finally, an acid hydrolysis of the isopropylidene group, and conversion of the diol into its monomesylate (*39*, R=Ms), then treatment with sodium methoxide in methanol, gave the required *cis*-epoxide (*24*).[43]

Whether the natural product is one of the optical antipodes, or the racemate, has yet to be determined, also resolution of the racemic hormone, as synthesized, has yet to be reported.



(35, threo) (26, R=$CH_2CH_2COCH_2CH_3$) (36)

FIGURE 10.—Stereochemistry of the acetonide (*26*). (*After* Cavill, Laing and Williams.[43])

Conclusion

In summary, I would refer to more general aspects of the chemistry and biology of insect secretions.

The defensive secretions that have been characterized are broadly grouped as (*a*) terpenoids and steroids, (*b*) aliphatics, primarily simple oxygenated alcohols, carbonyl compounds, acids and their derivatives, and (*c*) aromatics, including 1,4-benzoquinones, mandelonitrile derivatives and phenolics (cf. [1]). Many of these secretions, whilst fulfilling the defensive needs of the insects which produce

* In the *trans,trans,trans*-isomer the first *trans* refers to the isopropylidenedioxy group, the second to the 2,3 double bond, and the third to the 6,7 double bond.

them, are not necessarily adaptable for other insecticidal purposes. Studies on insect venoms, and especially on the proteinaceous venoms of the Hymenoptera, have a more biochemical and pharmacological bias. Apart from formic acid, little is known of the non-proteinaceous insect venoms. Work on insect pheromones and hormones is likely to be pursued with increasing vigour, and it is in this area that the major problems of isolation, prior to structure elucidation, have been noted. The need for satisfactory bioassay procedures is clear.

In studies on chemical communication in insects, the overall problem is very much an interdisciplinary one. The chemist is contributing to the solution of a problem in insect behaviour in which, say, the use of a given pheromone is but part of a complex behaviour pattern. The close collaboration of chemists and biologists is essential. The recent and intense synthetic studies[42] in relation to the juvenile hormone are prompted by potential applications of the ensuing compounds for insect control.

The advances of the last two decades have been considerable, and in turn they have relied on major advances in spectroscopic and chromatographic techniques. Yet, our total knowledge of insect secretions is meagre.

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(Received 15 December 1970)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 119–122, 1970

Relativistic Motion in Two Space-like Dimensions

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Abstract—In relativity theory a set of co-ordinate transformations suitable for investigating conditions experienced directly by an accelerated observer can be found. These transformations simplify the discussion of topics such as uniform rotation and the Thomas precession.

1. Introduction

In special relativity, any motion other than a rectilinear one must, as in classical physics, be accelerated. Any discussion of the kinematics of reference systems moving in a plane or in space must therefore take account of the fact that such systems do not hold the privileged position of inertial frames in the special theory. In particular, care must be taken in interpreting measurements made in an accelerated framework since co-ordinate measurements and physical measurements will in general be different.

One of the simplest classical accelerated co-planar motions is uniform rotation, and this is discussed in some detail below. It is kinematically one of the most intriguing types of motion because it seems at first sight that a velocity greater than light may be obtained by moving far enough away from the axis of rotation, no matter how slow this rotation may be.

Before proceeding to the subject of special relativistic motion in two space-like dimensions, we consider a transformation valid for any motion in a general co-ordinate framework in special or general relativity.

2. A General Transformation

Consider an initial framework with the metric

$$ds^2 = g'_{ij} dx'^i dx'^j$$

and take

$$x'^i = (x'^\alpha, t'), \qquad \alpha = 1, 2, 3.$$

Make the transformation

$$x'^i = x^\alpha \varphi^i_\alpha(t) + \psi^i(t) \qquad \ldots\ldots (1)$$

where $\varphi^i_\alpha(t)$ and $\psi^i(t)$ are functions of t (or x^4) only. This is an extension of the type of transformation considered by Marsh (1965). If the original framework is an inertial system, the new system will in general be accelerated, the motion of the space origin being specified by the functions $\psi^\alpha(t)$.

From (1),

$$dx'^i = \varphi^i_\alpha dx^\alpha + (x^\alpha \dot{\varphi}^i_\alpha + \dot{\psi}^i) dt \qquad \ldots. (2)$$

and the metric in the new co-ordinate system is

$$\begin{aligned} ds^2 = {} & g'_{ij} \varphi^i_\alpha \varphi^j_\beta dx^\alpha dx^\beta \\ & + 2 g'_{ij} \varphi^i_\alpha (x^\beta \dot{\varphi}^j_\beta + \dot{\psi}^j) dx^\alpha dt \\ & + g'_{ij} (x^\alpha \dot{\varphi}^i_\alpha + \dot{\psi}^i)(x^\beta \dot{\varphi}^j_\beta + \dot{\psi}^j)(dt)^2. \ldots (3) \end{aligned}$$

This metric might be required to take some special form at the space origin, $x^\alpha = 0$. Suppose the fundamental tensor at the origin is to be $g_{ij}(0,t)$. At that point also,

$$g'_{ij}(x'^i) = g'_{ij}(\psi^i).$$

Hence, for all t,

$$g'_{ij}(\psi^i) \varphi^i_\alpha \varphi^j_\beta = g_{\alpha\beta}(0,t)$$

$$g'_{ij}(\psi^i) \varphi^i_\alpha \dot{\psi}^j = g_{\alpha 4}(0,t)$$

$$g'_{ij}(\psi^i) \dot{\psi}^i \dot{\psi}^j = g_{44}(0,t).$$

If the motion of the origin is specified by $\psi^\alpha(t)$ there are ten equations to be satisfied by the other thirteen functions, $\varphi^i_\alpha(t)$ and $\psi^4(t)$. Hence there remains some arbitrariness allowing further specification of the new co-ordinate system.

The sections that follow are concerned with special relativistic motions in two dimensions. It is convenient to choose as the initial system the inertial framework with Lorentz metric

$$g'_{ij} = \eta_{ij} \equiv \begin{pmatrix} \delta_{\alpha\beta} & 0 \\ 0 & -c^2 \end{pmatrix}.$$

It is also convenient to have the fundamental tensor in the transformed system reduce to the Lorentz form at the space origin, so that (x^α, t) should have direct physical significance there. Hence the equations to be satisfied by the $\varphi^i_\alpha(t)$ and $\psi^4(t)$ reduce to

$$\left.\begin{aligned} \eta_{ij}\varphi^i_\alpha\varphi^j_\beta &= \delta_{\alpha\beta} \\ \eta_{ij}\varphi^i_\alpha\dot{\psi}^j &= 0 \\ \eta_{ij}\dot{\psi}^i\dot{\psi}^j &= -c^2 \end{aligned}\right\} \quad \ldots\ldots (4)$$

where, for two-dimensional motion, Latin indices range over 1, 2, 4 and Greek indices over 1, 2. There are then six equations to be satisfied by seven functions.

The transformation given by the equations (1) and (4) will now be used to discuss some topics usually treated by means of a continuous system of Lorentz transformations.

3. Rotational Motion

Consider a rotation without a translation of the observer's origin. If this origin is taken at the origin of the inertial system, then $x'^\alpha=0$ when $x^\alpha=0$. Hence, from (1),

$$\psi^\alpha=0 \quad \ldots\ldots\ldots\ldots \quad (5a)$$

and the second and third of (4) give

$$\varphi^4_\alpha=0 \quad \ldots\ldots\ldots\ldots \quad (5b)$$
$$\dot{\psi}^4=1$$

where the positive root has been chosen in the latter equation since t' increases when t increases. The equations (4) then reduce to

$$\varphi^\mu_\alpha\varphi^\mu_\beta=\delta_{\alpha\beta} \quad \ldots\ldots\ldots\ldots \quad (5c)$$
$$\psi^4=t. \quad \ldots\ldots\ldots\ldots \quad (5d)$$

A solution to (5c) is

$$\varphi^\mu_\alpha=\begin{pmatrix} \cos\omega t & -\sin\omega t \\ \sin\omega t & \cos\omega t \end{pmatrix}.$$

If the functions φ^i_α, ψ^i obtained here are substituted in (1), the classical transformation between an inertial system and one moving about a common origin with angular velocity ω is obtained:

$$\left.\begin{aligned} x'^1 &= x^1\cos\omega t - x^2\sin\omega t \\ x'^2 &= x^1\sin\omega t + x^2\cos\omega t \\ t' &= t. \end{aligned}\right\} \quad \ldots (6)$$

Although the validity of equations (6) may seem strange in the context of special relativity, it must be remembered that they represent a *co-ordinate* transformation. The co-ordinates (x^1, x^2, t) have direct physical significance only at the space origin of the rotating system, and since the two origins are at relative rest the transformation $t'=t$ is not surprising. Also, the apparent possibility of velocities greater than that of light relates to co-ordinate velocities only.

In order to investigate the relation between physical measurements made in the two frames at points other than the axis of rotation, consider a rotation in which an observer O in the accelerated frame does not remain at the axis of rotation but, in the estimation of an inertial observer O', moves in a circle of radius a at uniform speed. Hence try a transformation such that

$$x'^\alpha=(a\cos\omega t,\ a\sin\omega t) \text{ when } x^\alpha=0.$$

ω is related to the angular velocity in a way which will be found later (in equation (15)). From (1)

$$\psi^\alpha=(a\cos\omega t,\ a\sin\omega t) \quad \ldots\ldots \quad (7a)$$

and so the third of equations (4) gives

$$\psi^4=t(1+(a\omega/c)^2)^{\frac{1}{2}}. \quad \ldots\ldots \quad (7b)$$

The six functions φ^i_α must satisfy the remaining five of equations (4):

$$\left.\begin{aligned} \eta_{ij}\varphi^i_\alpha\varphi^j_\beta &= \delta_{\alpha\beta} \\ -\varphi^1_\alpha\sin\omega t+\varphi^2_\alpha\cos\omega t & \\ -\varphi^4_\alpha(1+(a\omega/c)^2)^{\frac{1}{2}}c^2/a\omega &= 0. \end{aligned}\right\} \quad \ldots (8)$$

Thus there is some freedom of choice for the rotating co-ordinate framework. For example, in classical kinematics one convenient set of moving axes could be those which remain parallel to the inertial axes. Another set could be taken in the radial and transverse directions to the circular path. This latter transformation would be

$$x'^1=(x^1+a)\cos\omega t-x^2\sin\omega t$$
$$x'^2=(x^1+a)\sin\omega t+x^2\cos\omega t.$$

Hence, for the corresponding relativistic case, choose

$$\varphi^1_1=\beta(t)\cos\omega t,\quad \varphi^2_1=\beta(t)\sin\omega t.$$

The five equations (8) then determine the five functions β, φ^α_2, φ^4_α. The solution is

$$\beta=1,$$
$$\varphi^i_\alpha=\begin{pmatrix} \cos\omega t & -(1+(a\omega/c)^2)^{\frac{1}{2}}\sin\omega t \\ \sin\omega t & (1+(a\omega/c)^2)^{\frac{1}{2}}\cos\omega t \\ 0 & a\omega/c^2 \end{pmatrix} \quad \ldots (9)$$

and the corresponding transformation (1) is (after writing $x^\alpha=x,y$)

$$\left.\begin{aligned} x' &= (x+a)\cos\omega t-y(1+(a\omega/c)^2)^{\frac{1}{2}}\sin\omega t \\ y' &= (x+a)\sin\omega t+y(1+(a\omega/c)^2)^{\frac{1}{2}}\cos\omega t \\ t' &= ya\omega/c^2 + t(1+(a\omega/c)^2)^{\frac{1}{2}} \end{aligned}\right\}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

From equation (3) with $g'_{ij}=\eta_{ij}$, the metric in the accelerated system is

$$ds^2=dx^2+dy^2-2\omega y(1+(a\omega/c)^2)^{\frac{1}{2}}dxdt +2\omega x(1+(a\omega/c)^2)^{\frac{1}{2}}dydt -c^2\{1+(\omega/c)^2[a^2-(x+a)^2 -y^2(1+(a\omega/c)^2)]\}dt^2. \quad \ldots\ldots\ldots\ldots (11)$$

4. Physical Velocities

The transformation equations (10) enable the physical measurements made by observers at the origin in each frame to be investigated. The velocity of the accelerated observer relative to the inertial frame is a particularly interesting quantity, since classically this becomes greater than c when a is greater than c/ω.

Since measurements made at the accelerated origin have direct physical significance, the velocity of any point in the inertial system in the path of the accelerated observer may be easily evaluated. Consider the motion of the point $x'=a, y'=0$ as seen by O:

$$\left.\begin{aligned} x&=a\,(\cos\omega t-1),\\ y&=-a(1+(a\omega/c)^2)^{-\frac{1}{2}}\sin\omega t, \end{aligned}\right\}\ldots\ldots (12)$$

giving

$$\left.\begin{aligned} \dot{x}&=-a\omega\sin\omega t,\\ \dot{y}&=-a\omega(1+(a\omega/c)^2)^{-\frac{1}{2}}\cos\omega t. \end{aligned}\right\}\ldots (13)$$

The quantities (13) may be interpreted as physical velocities if they are measured at $x=0$, $y=0$, i.e., as the accelerated origin passes the point $x'=a$, $y'=0$. Hence the components of the physical velocity of this point in the inertial system as measured by O are

$$\dot{x}=0,\ \dot{y}=-a\omega(1+(a\omega/c)^2)^{-\frac{1}{2}}.$$

Thus the speed of an inertial point as measured by the rotating observer as he passes it is $v=a\omega(1+(a\omega/c)^2)^{-\frac{1}{2}}$, which, for given ω, tends to the velocity of light as a tends to infinity.

Similarly, for an observer fixed in the inertial system the motion of the accelerated origin is given by

$$\left.\begin{aligned} x'&=a\cos\omega t,\\ y'&=a\sin\omega t,\\ t'&=t(1+(a\omega/c)^2)^{\frac{1}{2}}, \end{aligned}\right\}\ldots\ldots (14)$$

so that

$$dx'/dt'=-a\omega\sin\omega t\ .\ (1+(a\omega/c)^2)^{-\frac{1}{2}},$$
$$dy'/dt'=a\omega\cos\omega t\ .\ (1+(a\omega/c)^2)^{-\frac{1}{2}}.$$

Thus the measured speed is again

$$v=a\omega(1+(a\omega/c)^2)^{-\frac{1}{2}}$$

as must be expected.

If this expression for v is substituted in the third of equations (14), the usual time dilatation formula is obtained:

$$t'=t(1-(v/c)^2)^{-\frac{1}{2}}.$$

Also from equations (14), O' sees the angular velocity of the moving system to be

$$\Omega=\omega(1+(a\omega/c)^2)^{-\frac{1}{2}}. \quad \ldots\ldots (15)$$

From (12), the path of the point moving in O''s framework initially coincident with O's origin appears to O to move in an ellipse in the

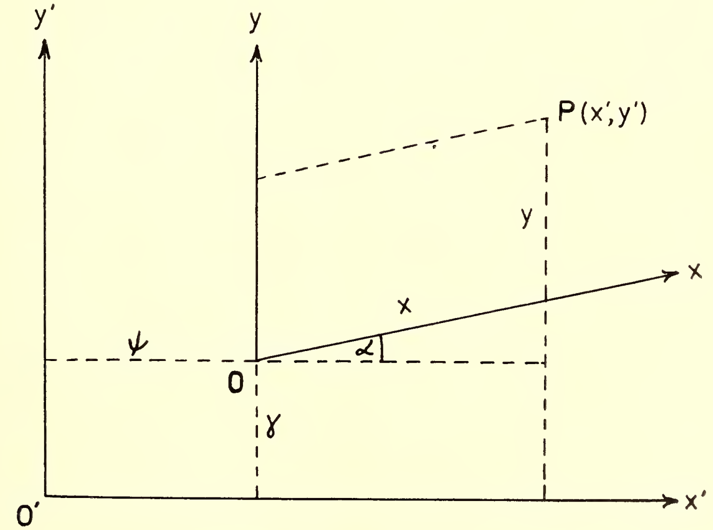

FIGURE 1.—Diagrammatic representation of a locally Lorentz accelerated framework Ox,y with the axis Oy parallel to the axis $O'y'$ of an inertial system.

(x,y) plane. The length of the path for one complete cycle as measured by O is

$$s=\int_{t=0}^{2\pi/\omega}(\mathrm{d}x^2+\mathrm{d}y^2)^{\frac{1}{2}}$$

$$=a\Omega\int_{0}^{2\pi/\omega}(1+(a\omega/c)^2\sin^2\omega t)^{\frac{1}{2}}\mathrm{d}t$$

$$\cong 2\pi a(1-\tfrac{1}{4}v^2/c^2) \qquad \text{to } o(v^2/c^2).$$

The proper time for one cycle as calculated by O is given by substituting from (12) into (11), and is found to be $2\pi/\Omega$, agreeing with O''s direct estimate of the time.

5. The Thomas Precession

In the general transformation (1), the motion of the accelerated origin as seen by the inertial observer depends on the functions $\psi^{\alpha}(t)$. There remain seven functions to be determined and six equations (4) to be satisfied by them. As in Section 3, an additional condition may be obtained by specifying the orientation of the axes of the accelerated system. For example, in classical mechanics the accelerated axes could be chosen parallel to the inertial set. In the present case, however, this would give two conditions, $\varphi_1^2=\varphi_2^1=0$. It is convenient to choose one of these, say $\varphi_2^1=0$, so that $O'x'^2$ remains parallel to Ox^2. The equations may then be solved to give all the other functions in terms of the $\psi^{\alpha}(t)$ which specify the motion. For convenience write $\psi^{\alpha}=\psi,\gamma$ and $x^{\alpha}=x,y$. In all cases ψ^4 is the same,

$$\psi^4=\int_{to}^{t}(1+(\dot{\psi}^2+\dot{\gamma}^2)/c^2)^{\frac{1}{2}}\mathrm{d}t.$$

Then, after some calculation,

$$\varphi_1^2=(\dot{\psi}\dot{\gamma}/c^2)(1+(\dot{\psi}/c)^2)^{-\frac{1}{2}}.$$

In a Euclidean space (see Figure 1)

$$x'=x\cos\alpha+\psi$$
$$y'=x\sin\alpha+y+\gamma.$$

If these are compared with the equations (1) it is seen that, when α is small, $\alpha\approx\varphi_1^2$. Hence, the average rotation in the x,y plane is approximately $\frac{1}{2}\dot{\psi}\dot{\gamma}/c^2$, which depends only on the velocity and not the acceleration of the origin O.

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(Received 25 February 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 123–126, 1970

The Nature of Time and Its Measurement

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Abstract—Einstein's new approach to space and time stimulated a complete re-evaluation of these concepts. In particular, his notion of time-dilatation, with its promise of journeys into the future (and also into the past ?), stirred the imagination of philosophers and writers of fiction. In the wake of Minkowski, time became merely a fourth dimension and scientists are still arguing about the "arrow of time" and the possibility of its reversal.

It is suggested that neither Special Relativity (nor any other physical theory) provides support to most of these speculations. Indeed Einstein's approach affirms that time is not an absolute concept apart from nature, but that it is a property of nature and can only be measured in terms of natural processes. Some implications of this viewpoint are outlined, and mention is made of a cosmological interpretation of the Special Theory which provides a universal measure of time through the concept of "cosmic time".

Man's attitudes to time had already passed through many phases before Newton. An outline of these attitudes both before and after Newton is given in Whitrow's monumental work "The Natural Philosophy of Time" (Whitrow, 1961). Whitrow also discusses the modern tendency to treat time as merely a fourth dimension whose direction is arguable (cf. Earman, 1967 ; Narliker, 1965). It would therefore appear useful to reaffirm and clarify certain basic propositions, and to examine the basis for the various views emanating from our present understanding of nature.

Newton was the first to give time an important and systematic role in describing the physical world. He considered phenomena as taking place on a background of space and time and in terms of space and time. He assumed these concepts to be independent and absolute. The employment of a co-ordinate reference frame, a device invented by Descartes, appeared to give to Newton's interpretation a geometric and mathematically useful significance.

Leibniz and other philosophers of science (Locke, Hume, Berkeley, etc.) modified and refined Newton's approach. Time (and also space) came to be seen as a property of nature, of natural phenomena, rather than the background to natural phenomena.

For Leibniz, space was the order of co-existences, time the order of succession of phenomena. Time was associated with the succession of ideas in the mind as well as with the succession of observation of phenomena in the world, and the direction of time was automatically defined by the direction of these successions.

This view, with certain refinements, was the one generally accepted at the end of the nineteenth century. However, in practice, many physical scientists still treated space and time as independent variables having a universal significance ; the problem of their measurement was considered a subsidiary problem of methodology.

Einstein (1905) challenged this still basically Newtonian approach, and proposed a physical theory based on two empirical assumptions (the Relativity and Light Principles) and resting entirely on quantities obtainable by defined measurements. Time and space as absolute or universal concepts had no place in his theory. Instead, he defined conventions (consistent with his Principles) for obtaining measures of the time and position* of an event in terms of clocks, rigid rods and a light-signal procedure.

Einstein showed that the assumption of his principles led to the result that observers associated with different inertial reference systems (and hence in relative uniform motion) would, in general, obtain different measures (as evaluated according to his conventions) of the time as well as of the space co-ordinates of a given event. This result was at variance with all previous notions of simultaneity and appeared to suggest that clocks in relative motion ran at different rates.

And indeed the theory does imply that an observer-cum-clock making an out-and-return journey from the earth would find that "time"

* His definitions of relative velocity, etc., derive from those of time and position relative to the observer.

(according to his clocks and all other physical and biological manifestations) has passed more slowly for him than for those who had remained on earth.

Einstein's theory was further interpreted by Minkowski (1908) as signifying that space and time no longer had any independent existence and that " only a kind of union of the two will preserve an independent reality ". Minkowski displayed the theory geometrically on a space-time diagram in which time appears as a fourth dimension whose direction is arbitrary.

The remarkable consequences of Einstein's approach have encouraged many different and contradictory interpretations of the nature of time. It has been suggested that the theory implies that space and time are purely subjective concepts—that each observer has his own private time-scale. Another school of thought takes the line that both space and time are fictions associated with our movement along the " world-lines " in space-time. The apparent multiplicity of time-scales has brought forth the concept of serial time (Dunne, 1927) in which one time-scale is measured in terms of another, *ad infinitum.*

The Minkowski approach has brought the direction of time under close scrutiny and encouraged serious speculation about the possibility of travelling in time—as we do in space ! Analysis of " the arrow of time " and the implications of time-reversal have occupied the attention of many scientists and philosophers, whilst the prospect of travelling into the future and/or back into the past has inspired a considerable literary output.

Without wishing to imply that speculation of this sort should be discouraged,* I feel that it is important to recognize that such fanciful notions about time have no basis in our view of the world, in Special Relativity or in any other well-founded theory of nature.

It is true that Einstein appeared to dispense with the concepts of both absolute time and of universal time. (The latter implies the existence of a common measure of time for all observers, and is a concept quite distinct from the former). However, Einstein did not treat time as a subjective concept, but rather as a property of natural phenomena which could be measured in terms of natural processes. Events at a certain locality might appear to occur at different rates according to different observers, but the order of these events is invariant for all observers ; alteration or reversal of this order is as contrary to the assumptions or results of Special Relativity as is the possibility of a local velocity greater than that of light. Indeed, the very manner proposed by Einstein to measure the time of a distant event, employing light-signals and clocks, implies unambiguously that time has a single direction—that the return of a reflected light signal at t_2 is later than its transmission at t_1, so that the difference, t_2-t_1, of the corresponding clock-readings is always positive.

* The science fiction, in particular, resulting from such unfettered speculation, is a very valuable addition to our literature.

The interpretation of " time-dilatation " has been the most contentious issue arising out of Special Relativity. The claim that it is an absolute phenomenon, as manifested in an out-and-return journey, appears to contradict the relativity principle assumption that uniform motion has no absolute connotation.

The late Geoffrey Builder (1958) pressed the logical significance of this issue, observing that " the relative retardation of clocks . . . demands our recognition of the causal significance of absolute velocities ". This challenging argument has been increasingly accepted in recent years ; Whitrow (1961), Schwartz (1968), Keswani (1966) and others now consider the universe as providing a fundamental unique reference frame, or basic substratum, with respect to which motion has an absolute significance and gives rise to absolute effects. Furthermore, it has been shown by the author (Prokhovnik, 1967) that this approach can be given a credible quantitative significance.

Astronomical advances in the last few decades suggest that our observable universe has a definite though dynamic structure associated with a set of fundamental particles, these being the galaxies and clusters of galaxies. Observation also supports the assumption, known as the Cosmological Principle, that the appearance of the universe and the laws of nature are the same from the viewpoint of any galaxy.

The universe appears to be expanding in so far as its fundamental particles appear to be receding from one another. To a first approximation, for a region of space and time limited by the scope of our observations, this mutual recession appears to obey the simple Hubble law

$$w=Hr=r/T,$$

where r is the distance, as measured by astronomical data, between a pair of typical galaxies receding with velocity w deduced from Doppler effect observations. H is called the Hubble constant, and its reciprocal, T, has the dimensions of time ; the present estimated value of T is about 13×10^9 years.

The Cosmological Principle implies that this expansion would be evident to any observer in the universe, and hence that the observed rate of the expansion provides a universal measure of time (as well as, for most cosmological models, a common " zero-time "), to which we can relate other measures of time. This relation may not be a simple one ; it will depend on the choice of cosmological model and on the associated scale-factor $R(t)$ by which we describe the expansion (Bondi, 1961). For instance, if the expansion is assumed to be strictly uniform in all respects, as in a Milne-type model, then $R(t) \propto t$, and T can be considered as the age of the universe in its present expansionist state. However, if we accept the Einstein-de Sitter model with $R(t) \propto t^{2/3}$, then the age of the universe is less than T ; on the basis of the Lemaitre model it is greater than T ; and for the Steady State model $R(t) \propto \exp(Ht)$, and here only the rate of expansion, associated with the value of H, assumes a universal significance for the purpose of measuring time.

The set of galaxies constitutes a fundamental reference frame, and it may be shown (Prokhovnik, 1967) that the movement of a system relative to this frame results in a slowing down of all physical and organic phenomena, and hence of all clocks which measure the rate of these phenomena. Thus, as Builder insisted, it is not time, but rather its measurement, which is affected by such motion. In terms of this cosmological viewpoint the relativistic principles and results emerge on a background of a universal reference frame and a universal basis for measuring time.

Landsberg (1970) remarks on the coincidence that the several arrows of time manifested by biological, thermodynamic and cosmological phenomena all point in the same direction. There exists a good case, therefore, that neither Special Relativity (whether in the form presented by Einstein or otherwise) nor any other modern theory of natural phenomena supports any esoteric concept of time. Rather do they confirm the standpoint of Whitrow (1961) and others that time is a property of our universe associated with the movement and change which is a feature of it. Without movement and change time would have no meaning, and only movement and change provide a basis for its measurement. The basic fallacy of Dunne's hypothesis (1927) of " serial time " is that time is not measured in terms of some abstract " time-scale ", but in fact is measured always in terms of natural phenomena—preferably recurring—manifesting change and movement. Most useful for this purpose are the apparently regularly recurring (i.e. periodic) phenomena such as the swings of a pendulum, the phases of the moon, the occurrence of the seasons, etc. Any more or less periodic phenomenon can be employed as a more or less accurate clock ; the degree of its accuracy may be estimated by comparison with other clocks.

This approach to the measurement of time is also consistent with that of Ellis (1966). Thus a space-interval has no absolute measure, but can only be measured in terms of another given space-interval. In the same way, thinking of time as duration (the manifestation of our consciousness of time), such duration, whether associated with change or movement *or not*, can only be measured in terms of the duration of a given phenomenon which can be employed to function as a clock. Thus there is no basis for treating time as an absolute concept ; it is rather, following Janet (1928), an intellectual construction which has evolved with man's perception of the universe and which he employs to describe a world in flux.

The nature of time is inseparable from man's recognition and consciousness of it. Man is never merely the neutral observer or economic unit postulated by scientific or social theories. For him " time " has a much richer meaning than the time of physical science. He carries a " consciousness " of time in terms of the many built-in clocks associated with his physiological and mental activity. Among the most obvious of these are the pulse-beat, the heart-beat and recently-discovered alpha rhythm of the cerebral cortex ; but he has less obvious clocks which feed his consciousness of time perhaps even more strongly, for example, the rhythm of taking meals, of sleeping and waking, and of many other routine activities. And ever present is the most inexorable clock of all—the life-span and its phases.

Thus even when there is no activity around him man retains a consciousness of time and a practical capacity for measuring it. This might easily tempt him to imagine that time is something independent of the outside world, and that the world exists in absolute time—in his time. However, such conviction is a result of man's capacity to observe (experience) the natural rhythms and changes within him as well as without. Such experience does not invalidate the thesis that time is a property of a changing world and would be meaningless and measureless in the absence of such a world.

This thesis is incompatible with the concept of time-reversal. Even if the universe were to change character (e.g. started contracting instead of expanding) and exhibited a reversal in the direction of familiar phenomena, this could in no sense constitute a reversal of the direction of time. Phenomena would still have duration which could be measured by clocks, and events would still occur in succession the order of which would define the direction of time. Only in its geometric representation does time assume more than one direction. In reality we can only travel into the future, not into the past. The past may (more or less) repeat itself, but such repetition does not constitute a reversal of time; we do not go back to the original event, we go forward to its repetition.

Only in regard to journeys into the future does Einstein's theory provide a glimmer of encouragement. It suggests that motion relative to the universal substratum is associated with a slowing down of all natural phenomena including the process of aging. Thus by undergoing rapid space trips to ward off old age, we might conceivably achieve survival into the future beyond our present dreams. Not that this would mean a longer biological life for the speeding traveller; his built-in clocks, his metabolism and the tempo of his activities and of his immediate environment would all slow down at the same rate. He would not experience a longer life than he might normally expect; his lifetime would merely be "dilated" relative to those staying on earth. However, the practical difficulties of this form of time (and space) travelling serve as a formidable barrier to its effective realization. Even if we could achieve and survive velocities half the speed of light, our aging rate would only slow down by about 13%! So it may be more practical to concentrate on diet.

Einstein's theory does not, after all, hold out much hope to the purveyors of the fantastic. However, his contribution has immeasurably enriched our view of the world and, in particular, our understanding of time. As a result of his approach we now appreciate more fully the role of measurement in the description of nature, and also the significance of natural properties in terms of their measurement. Note that Einstein's convention for measuring the time of an event precludes negative times. The existence of different measures of the time of an event does not mean that time has no objective significance, nor need it mean that the measures refer to a multitude of "times". Ellis (1966) recognizes the manifold character of natural properties and employs the term "cluster concept" to the set of measurements associated with a quantity. Einstein's approach shows how we can relate these different measures and that they manifest different facets of one of nature's most important properties.

Acknowledgement

I wish to thank the referee of this paper for his valuable comments, which served to clarify and strengthen a number of arguments in the article.

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(Received 25 March 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 103, pp. 127, 1970

Book Review

The Impact of Civilisation on the Biology of Man. S. V. Boyden (Editor). Australian National University Press. Pp. 233. August, 1970.

This book, which deals with how man has endured and adapted to changing conditions, originated in the proceedings of a two-day symposium held at the Australian Academy of Science, Canberra, in 1968. Many of Australia's leading biological scientists contributed in carefully prepared papers, or in discussion. Professor R. J. Dubos, of the Rockefeller University, New York, also attended, and very ably summed-up in the final session. The opening address was delivered by Sir Macfarlane Burnet.

Before 10,000 years ago, our ancestors had been hunter-gatherers for at least 2,000,000 years, moving over much of the earth's surface as nomadic bands. Then, relatively settled villages began to appear with a form of agriculture and the domestication of animals. About 5,500 years ago came irrigated agriculture and the growth of a few cities, but with most people still living in small villages. With the invention of steam power 250 years ago there developed some cities of 500,000, many of 100,000, and many villages of 1,000 persons. Thus the major changes in the social organization of man and his environment (which includes man) have occurred in recent times—the last few hundred years.

Infectious diseases such as malaria, tuberculosis, cholera, smallpox, measles and those caused by respiratory and enteric microbes increased in severity with urbanization. In affluent societies all the important infectious diseases of man have responded to improved hygiene, anti-bacterial chemotherapy and medical care, but are still important in the urban slums of developing countries.

Improvements in environmental hygiene and nutrition which followed in the wake of the industrial revolution have led to the attainment of reproductive age by an increasing number of children, with consequent rapid growth of population. In communities with advancing technology there has also been an increased expectation of life and a change in the main causes of death from infectious diseases to non-infectious disorders, e.g. coronary heart disease, cancer of the lung, bronchitis and external violence, particularly in males. Mortality records from South Australia reveal that in 1845 few more than 5% of all deaths were in persons over 50 years of age ; at the turn of the century this proportion had risen to 40% for both sexes, while in 1963, 80% of all deaths in males and 86% of all deaths in females occurred in the over-50 age group. Today, cardiovascular disease and cancer account for two-thirds of the total mortality in both sexes. Lung cancer accounts in general for between 20% and 40% of deaths from malignant disease ; the highest rate is in Britain, while low rates are found in Norway, Sweden and Japan.

Only 300 or 400 generations have passed since all mankind led a nomadic life. In as small a number of generations as this, little genetic change could have occurred in the human species in response to the new conditions. It is therefore proposed that man's relatively successful adaption to the ever-changing conditions associated with civilization has depended on learning, and in particular on cultural processes.

Homo sapiens' body and brain were shaped by the environmental influences that prevailed during his evolutionary development, and his genetic endowment will remain the same during the foreseeable future. He has now to live under the conditions created by social and technological forces which differ profoundly from those under which he evolved and to which he became genetically adapted. Since his surroundings and ways of life are forever changing, man can hardly ever achieve a true state of adaptedness to his environment.

This intensely interesting book is recommended for reading by all who meditate on the future, so that they may be aware of the trends.

C. J. Magee.

Report of the Council for the Year Ended 31st March, 1970

Presented at the Annual General Meeting of the Society held 1st April, 1970, in accordance with Rule 18 (*a*).

At the end of the period under review the composition of the membership was 354 members, 12 associate members and 9 honorary members; 12 new members were elected. Eight members and 1 associate member resigned; 3 names were removed from the list of members in accordance with Rule 5 (*b*).

Two new honorary members were elected during the year:

Dr. William R. Browne, F.A.A.
Sir Ronald Nyholm, F.R.S.

It is with extreme regret that we announce the loss by death of:

Dr. Ronald Leslie Aston (elected 1930).
Mr. Walter George Stone (elected 1916).

Nine monthly meetings were held. The abstracts of all addresses have been printed on the notice papers. The proceedings of these will appear later in the issue of the *Journal and Proceedings*. The members of Council wish to express their sincere thanks and appreciation to the eight speakers who contributed to the success of these meetings, the average attendance being 50.

The Council would like to draw attention to the poor attendances at many of the general monthly meetings, and in particular to one held on 5th November when only 42 members and visitors were present to hear a most excellent address by Dr. E. G. Bowen, C.B.E., F.A.A., entitled "The Anglo-Australian 150-inch Telescope".

The Annual Social Function was held at the University of New South Wales Union and was attended by 44 members and guests.

The Council has approved the following awards:

Clarke Medal for 1970: Mr. Gilbert P. Whitley, F.R.Z.S.

James Cook Medal for 1969: Lord Casey of Berwick and Westminster.

The Society's Medal for 1969: Professor R. J. W. Le Fevre, D.Sc., F.R.S., F.A.A., Professor and Head of the School of Chemistry, University of Sydney.

The Edgeworth David Medal for 1969: Professor B. W. Ninham.

The *Archibald Ollé Prize* was not awarded.

The Clarke Memorial Lecture was delivered by Professor A. E. Ringwood of the Australian National University, entitled "The Origin of the Moon". Two hundred and ninety members and visitors were present.

The Pollock Memorial Lecture was held at the University of Sydney on 1st May, 1969. The Lecture was entitled "Quasars, Exploding Galaxies and Cosmology", delivered by Dr. A. Sandage.

The Society has again received a grant from the Government of New South Wales, the amount being $1,500. The Government's continued interest in the work of the Society is much appreciated.

The Society's financial statement shows a deficit of $209.01.

The New England Branch of the Society's meetings will be included in the Proceedings of the Branch, which follow.

The first meeting of the newly formed South Coast Branch of the Society was on 20th June, 1969, held at Wollongong University College. A report on the proceedings of the Branch will follow.

The Section of Geology continued to hold regular meetings, and the Annual Report is tabled.

Subscription.—During the year the Council decided to raise the annual subscription from $6.30 to $10.00, except for residents outside of New South Wales and A.C.T., in which case the subscription was fixed at $7.00. Associate members, $1.05 to $2.00.

The annual subscription for the *Journal and Proceedings* to non-members to be raised from $10.00 to $12.00.

The President represented the Society at a garden party held at Government House in honour of Her Majesty the Queen; a reception to meet delegates to the 22nd International Congress of Pure and Applied Chemistry and the 12th International Conference of Co-ordination Chemistry; the commemoration of the 199th anniversary of the landing of Captain Cook at the landing place, Kurnell, and the placing of a wreath on the Banks Memorial; Cook Bicentenary Symposium of the Australian Academy of Science, Canberra; meeting of the Citizens' Council of the Captain Cook Bi-centenary Celebration.

Professor J. L. Griffith, member of Council, represented the Society at the annual dinner of the Chamber of Manufacturers of New South Wales.

Mr. M. J. Puttock, member of Council, represented the Society at the official opening of the 1969 Jubilee Engineering Conference and the annual dinner of the Sydney Division of The Institution of Engineers, Australia.

The Hon. Secretary, Mr. J. C. Cameron, represented the Society to meet the Managing Director of Mullard Ltd., London.

Two parts of the *Journal and Proceedings* were published during the year: Volume 101, Parts 3–4, and Volume 102, Part 1. Volume 102, Part 2, is to be issued before the end of April.

His Excellency the Governor-General, Sir Paul Hasluck, has accepted the office of Patron of the Society.

Council sent a message of congratulation to N.A.S.A. on 21st July, 1969, on the occasion of man's first landing on the moon.

Council held 11 ordinary meetings, and attendance was as follows: Mr. Neuhaus, 11; Prof. Smith, 11; Mr. Cameron, 9; Prof. Le Fevre, 4; Mr. Clancy, 6; Mr. Pollard, 7; Mrs. Krysko v. Tryst, 9; Mr. Poggendorff, 10; Mr. Puttock, 10; Mr. Kitamura, 9; Mr. Robertson, 9; Dr. Stanton, 0; Mr. Burg, 7; Dr. Pickett, 7; Prof. Griffith, 8; Prof. Keane, 9; Dr. Day, 1; Dr. Reichel, 4; Prof. Low, 5.

The Library.—Periodicals were received by exchange from 395 societies and institutions. In addition the amount of $140.05 was expended on the purchase of periodicals.

Among the institutions which made use of the Library through the inter-library loan scheme were :

N.S.W. State Government : Geological Survey of N.S.W. ; Division of Wood Technology ; Electricity Commission of N.S.W. ; State Office Block Library ; Water Conservation Commission ; Institute of Dental Research ; Soil Conservation ; M.W.S. and D. Board ; Department of Education ; State Parliament ; Department of Health.

Other State Governments : Department of Mines, South Australia ; State Library, South Australia ; Geological Survey of W.A. ; Department of Forestry, Queensland ; Department of Primary Industry, Queensland ; Geological Survey of Queensland.

Commonwealth Government : Australian Atomic Energy Commission ; Defence Standards Laboratory ; Bureau of Mineral Resources ; Joint Coal Board ; P.M.G. ; Experimental Building Station.

C.S.I.R.O. : Coal Research, Prospect, Cronulla ; Radio Physics ; Chemistry (Melbourne) ; Statistics ; Wool Research ; National Standards Laboratory.

Universities and Colleges : Sydney ; New South Wales ; Macquarie ; Newcastle ; Broken Hill ; Wollongong ; Australian National University ; La Trobe ; Monash ; Queensland ; Townsville ; Auckland (photostat sent) ; Otago (N.Z.).

Companies : C.S.R. Research ; C.S.R. Head Office ; B.H.P., Shortland ; Australian Iron and Steel ; Australian Consolidated Industries ; Imperial Chemical Industries ; Mount Isa Mines ; Peko-Wallsend ; Rikers Laboratories (almost weekly borrowing in 1968, which ceased when we suggested company membership) ; A.W.A.

Museums : The Australian Museum.

Miscellaneous : The Institution of Engineers ; N.Z. Trade Commissioner ; Bread Research Institute.

Total borrowings for the year 1969/1970 : 333.

It must be recorded that, following the illness of Miss Ogle, who had served the Society so well over a long period of time, the Executive experienced considerable difficulty in the day-to-day management of affairs from September, 1969, to January, 1970. In this regard I would like to pay a tribute to the loyal help given by Mr. Day during the difficult period.

We are fortunate now in having the services of Mrs. M. A. Collier as Secretary, and feel sure that the Society's business is in good hands.

J. C. Cameron,
Honorary Secretary.

1st April, 1970.

Honorary Treasurer's Report

A ratio of subscriptions to expenses (not including *Journal* printing) and a separate statement of *Journal* printing costs shows the necessity for increasing subscriptions in relation to expenditure.

Ratio of subscriptions to expenses :

	1966	1967	1968	1969	1970
Subscriptions	1,920	1,949	1,973	2,267	2,084
Expenses (not including *Journal* printing) ..	7,261	8,336	8,205	10,139	9,514
	1 : 3·78	1 : 4·28	1 : 4·16	1 : 4·47	1 : 4·56

Statement of " Journal " printing costs :

Vol. 101, Part 1	Vol. 101, Part 2	Vol. 101, Parts 3–4	Vol. 102, Part 1
(60 pp.)	(56 pp.)	(94 pp.)	(108 pp.)
$1,011	$1,088	$1,951	$2,177

Vol. 101, Parts 1–2 taken to account year ending 28th February, 1969 : $2,099.

Vol. 101, Parts 3–4, and Vol. 102, Part 1, taken to account year ending 28th February, 1970 : $4,128.

W. E. Smith,
Honorary Treasurer.

Abstract of Proceedings

2nd April, 1969

The one hundred and second Annual Meeting of the Society was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Prof. A. Keane, was in the chair. There were present 37 members and visitors.

Ernest Kokot and Daryl John McCarthy were elected members of the Society.

The following awards of the Society were announced :

The Society's Medal for 1968 to Mr. H. H. G. McKern.

The Clarke Medal for 1969 to Prof. S. W. Carey.

The Walter Burfitt Prize for 1968 to Prof. L. E. Lyons.

The Edgeworth David Medal for 1968 to Dr. R. M. May.

Library Referendum. It was announced that the result of the ballot was :

In favour of retaining the library : Yes, 72 ; No, 80.

If the decision is to dispose of the Library, by Gift, 44 ; Sale, 94.

It was announced that because of the closeness of the vote no authority was given for the disposal of the Library.

The Annual Report of the Council and the Financial Statement were presented and adopted.

The report of the South Coast Branch was presented by Mr. P. O'Halloran.

Dr. William Rowan Browne, F.A.A., was elected an honorary member of the Society.

Messrs. Horley & Horley were re-elected Auditors to the Society for 1969–1970.

Office-bearers for 1969–1970 were elected as follows :

President : J. W. G. Neuhaus, M.Sc.

Vice-Presidents : A. A. Day, Ph.D. (Cantab.), A. Keane, Ph.D., T. E. Kitamura, B.A., R. J. W. Le Fevre, D.Sc., F.R.S., F.A.A., A. H. Low, Ph.D.

Honorary Treasurer : W. E. Smith, Ph.D.

Honorary Librarian : W. H. G. Poggendorff, B.Sc.Agr.

Honorary Secretaries : J. C. Cameron, M.A., B.Sc. (Edin.), D.I.C. (General), M. Krysko v. Tryst (Mrs.), B.Sc., Grad.Dip. (Editorial).

Members of Council : R. A. Burg, A.S.T.C., B. E. Clancy, M.Sc., J. L. Griffith, B.A., M.Sc., J. W. Pickett, M.Sc. (N.E.), Dr.phil.nat. (Frankfurt/M.), J. P. Pollard, M.Sc., Dip.App.Chem. (Swinburne), M. J. Puttock, B.Sc.(Eng.), A.Inst.P., A. Reichel, Ph.D., M.Sc., W. H. Robertson, B.Sc., and New England Branch representative R. L. Stanton, Ph.D.

The following papers were read by title only : " Geology of the Talbragar Fossil Fish Bed Area ", by J. A. Dulhunty and J. Eadie ; " Granitic Development and Emplacement in the Tumbarumba-Geehi District, N.S.W. (1) The Foliated Granites ", by B. B. Guy ; " The Nature and Occurrence of Heavy Mineral Concentrates in Three Coastal Areas of New South Wales ", by J. R. Hails.

It was announced that at the meeting of the Council held 26th November, 1968, it was decided that the following alteration be made to By-law 12, Publications (*g*) : " Except in special circumstances material from non-members will not be accepted for publication " should be deleted, and replaced by " Material from non-members will not be considered for publication unless communicated by a member of the Society ".

As no resolution to the contrary was forthcoming, the alteration was passed.

The address of the retiring President, Prof. A. Keane, entitled " The Art of Applied Mathematics ", was delivered.

The retiring President then welcomed Mr. Neuhaus to the Presidential Chair.

Paper.—The following paper will be read by title only : " Stratigraphy and Structure of the Palaeozoic Sediments of the Lower Macleay Region, North-eastern New South Wales ", by John F. Lindsay.

Special Notice to Members.—At the meeting of the Council held 1st April, 1969, Council approved the following addition to the By-laws : " 13 (*a*) shall become 13 (*a*) (*aa*). The following shall be inserted : 13 (*a*) (*aa*). There shall be a South Coast Branch of the Society whose region shall include the territory in New South Wales within thirty miles of the coast south of and including the City of Greater Wollongong."

7th May, 1969

The eight hundred and thirty-fifth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney, at 7.45 p.m.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 39 members and visitors.

Peter Gerald Flood and Derek K. Griffin were elected members of the Society.

The Clarke Medal for 1969 was presented to Prof. S. Warren Carey.

It was announced that at the meeting of the Council held 1st April, 1969, Council approved the following addition to the By-laws : " 13 (*a*) shall become 13 (*a*) (*ab*). The following shall be inserted : There shall be a South Coast Branch of the Society whose region shall include the territory in New South Wales within thirty miles of the coast south of and including the City of Greater Wollongong."

As no resolution to the contrary was forthcoming, this addition was passed.

The following paper was read by title only : " Stratigraphy and Structure of the Palaeozoic Sediments of the Lower Macleay Region, Northeastern New South Wales ", by John F. Lindsay.

An address entitled " Operations of the Government Analyst's Branch " was delivered by Mr. E. S. Ogg, recently retired Government Analyst.

4th June, 1969

The eight hundred and thirty-sixth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 55 members and visitors.

Bede Edward Murray was elected a member of the Society.

The following paper was read by title only : " Lower Devonian Conodonts from the Lick Hole Limestone, Southern New South Wales ", by P. G. Flood.

An address entitled " World Wide Comparisons of Geological Environments " was delivered by Dr. C. T. McElroy, Diiector, Geological Survey of New South Wales, Department of Mines, Sydney.

2nd July, 1969

The eight hundred and thirty-seventh General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 80 members and visitors.

The following papers were read by title only : " The First Commonwealth Statistician : Sir George Knibbs ", by Susan Bambrick ; " Triassic Stratigraphy—Blue Mountains, New South Wales ", by R. H. Goodwin.

An address entitled " Experiments on Bedding Genesis " was delivered by Professor A. V. Jopling, B.Sc., B.E.(Civil) (Sydney), A.M., Ph.D. (Harvard), Geography Department, University of Toronto, Ontario, Canada.

6th August, 1969

The eight hundred and thirty-eighth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 78 members and visitors.

Ronald Walter Wilcox was elected a member of the Society.

Sir Ronald S. Nyholm, F.R.S., was elected an honorary member.

It was announced that a cable of congratulations had been sent to N.A.S.A. on historic achievement of man's first landing on the moon.

Notice of motion regarding subscriptions as follows :

1. " The annual subscription for associate members shall be $2.00 for those not receiving the Journal, and $5.00 for those receiving the Journal."
2. " The annual subscription for ordinary members shall be $10.00 except in the case of members resident outside the State of New South Wales ; Canberra, A.C.T. ; or Jervis Bay, A.C.T. ; in which case the subscription shall be $7.00."

Address.—An address entitled " The Drift from Science in Schools—Reasons and Remedies " was delivered by Professor Sir Ronald S. Nyholm, F.R.S., Professor of Inorganic Chemistry, University College, London.

3rd September, 1969

The eight hundred and thirty-ninth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 42 members and visitors.

The death was announced of Walter George Stone, member since 1916.

The following were elected members of the Society :

John Percival Brown.
John Hardy Callender.
Robert John Butler Pearson.
Stephen James Riley.

It was announced that alteration to the By-laws had been made as follows :

1. " That the annual subscription for associate members shall be $2.00 for those not receiving the Journal, and $5.00 for those receiving the Journal."
2. " That the annual subscription for ordinary members shall be $10.00 except in the case of members resident outside the State of New South Wales ; Canberra, A.C.T. ; and Jervis Bay, A.C.T. ; in which case the subscription shall be $7.00."

As no resolution to the contrary was passed at the meeting, the abovementioned becomes operative from 1st April, 1970.

The Section of Geology will meet Friday, 19th September, 1969.

Address.—An address entitled " Sydney—Future Planning " was delivered by Professor J. H. Shaw of the Faculty of Architecture, University of New South Wales, Kensington.

1st October, 1969

The eight hundred and fortieth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 30 members and visitors.

The death was announced of Ronald Leslie Aston, member since 1930.

The following were elected as associate members :

Ada Marjory Brown.
Alan Maurice Puttock.

Address.—An address entitled " Modern Development in Meteorology ", by Mr. V. J. Baker, Regional Director, Commonwealth Bureau of Meteorology, Sydney.

5th November, 1969

The eight hundred and forty-first General Monthly Meeting of the Society was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 42 members and visitors.

The Section of Geology will meet Friday, 21st November, 1969.

Address.—An address entitled " The Anglo-Australian 150-inch Telescope " was delivered by Dr. E. G. Bowen, C.B.E., F.A.A., Chief of the Division of Radiophysics, C.S.I.R.O., Epping, N.S.W.

3rd December, 1969

The eight hundred and forty-second General Monthly Meeting of the Society was held in Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 38 members and visitors.

The following application for membership was read for the first time : Mr. A. R. Collins. Proposed from personal knowledge by B. B. Guy and A. A. Day.

An address entitled " A Practical Guide to Music Criticism " was delivered by Mr. F. R. Blanks, who is a contributing music critic for *The Sydney Morning Herald*, music critic for the *Australian Jewish Times*, and Australian correspondent for the British music journal *Musical Times*.

THE ROYAL SOCIETY OF NEW SOUTH WALES

BALANCE SHEET AS AT 28th FEBRUARY, 1970

LIABILITIES

1969 $		$	$
—	Accrued Expenses		323.60
61	Subscriptions Paid in Advance		32.75
116	Life Members' Subscriptions—Amount carried forward		102.90
	Trust Funds (detailed below) :		
4,444	Clarke Memorial	4,482.28	
2,591	Walter Burfitt Prize	2,547.18	
1,439	Liversidge Bequest	1,514.83	
630	Ollé Bequest	710.26	
			9,254.55
—	Miss Ogle Fund		245.13
60,011	Accumulated Funds		59,644.31
8,898	Library Reserve Account		9,417.83
	Contingent Liability (in connection with Perpetual Lease)		
$78,190			$79,021.07

ASSETS

1969 $		$	$
2,223	Cash at Bank and in Hand		3,763.13
	Investments—		
	Commonwealth Bonds and Inscribed Stock—At Face Value—held for :		
3,600	Clarke Memorial Fund	3,600.00	
2,000	Walter Burfitt Prize Fund	2,000.00	
1,400	Liversidge Bequest	1,400.00	
9,680	General Purposes	9,680.00	
			16,680.00
548	Fixed Deposit—Long Service Leave Fund		168.61
—	Debtors for Subscriptions	361.20	
	Less Reserve for Bad Debts	361.20	
			—
30,470	Science House—One-third Capital Cost		30,470.43
13,600	Library—At Valuation		13,600.00
9,600	Library Investments—Special Bonds		9,600.00
	Furniture and Office Equipment — At Cost, *less*		
1,591	Depreciation		1,714.79
21	Pictures—At Cost, *less* Depreciation		19.56
2	Lantern—At Cost, *less* Depreciation		2.00
	Centenary Volume :		
	Stock	2,700.52	
	Reprints	38.70	
3,455			2,739.22
—	Sundry Debtor—Other		263.33
$78,190			$79,021.07

TRUST FUNDS

	Clarke Memorial $	Walter Burfitt Prize $	Liversidge Bequest $	Ollé Bequest $
Capital at 28th February, 1970	3,600.00	2,000.00	1,400.00	—
Revenue—				
Balance at 28th February, 1969 ..	844.11	590.34	39.10	630.26
Income for Period	194.75	108.19	75.73	80.00
	1,038.86	698.53	114.83	710.26
Less Expenditure	156.58	151.35	—	—
	$882.28	$547.18	$114.83	$710.26

ACCUMULATED FUNDS

	$	$
Balance at 28th February, 1969		60,011.47
Less :		
Deficit for Period	209.01	
Transferred to Miss Ogle Fund	100.00	
Increase in Provision for Bad Debts	46.60	
Subscriptions Written Off..	11.55	
		367.16
		$59,644.31

Auditors' Report

The above Balance Sheet has been prepared from the Books of Account, Accounts and Vouchers of The Royal Society of New South Wales and is a correct statement of the position of the Society's affairs on 28th February, 1970, as disclosed thereby. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

HORLEY & HORLEY,
Chartered Accountants,
Registered under the Public Accountants
Registration Act 1945, as amended.

65 York Street,
Sydney.
20th March, 1970.

(Signed) W. E. SMITH,
Hon. Treasurer.
J. W. G. NEUHAUS,
President.

INCOME AND EXPENDITURE ACCOUNT

1st MARCH, 1969, TO 28th FEBRUARY, 1970

1969 $		$
2,267	Membership Subscriptions	2,084.25
12	Proportion of Life Members' Subscriptions	12.60
1,500	Government Subsidy	1,500.00
8,416	Science House Management—Share of Surplus	7,704.07
470	Interest on General Investments	539.43
6	Donations	46.40
357	Sale of Reprints	178.95
841	Subscriptions to Journal	762.04
1,299	Sale of Back Numbers	663.03
57	Refund—Postages..	25.08
15,225		13,515.85
—	Deficit for Period	209.01
$15,225		$13,724.86

1969 $			$
59	Advertising		86.80
59	Annual Social		45.64
100	Audit		100.00
50	Branches of the Society		150.75
301	Cleaning		171.50
85	Depreciation		89.90
72	Electricity		65.58
25	Entertainment		28.00
104	Insurance		121.91
555	Library Purchases		140.05
418	Miscellaneous		197.70
444	Postages and Telegrams		308.27
	Printing—Vol. 101, Parts 3–4, Vol. 102, Part 1	$4,060.67	
	Binding	70.00	
	Postages	80.72	
2,222			4,211.39
181	Printing—General and Stationery		126.73
4,159	Rent—Science House Management		4,108.50
41	Repairs		17.48
75	Restoration of Portraits		—
3,323	Salaries		3,649.12
88	Telephone		105.54
12,361			13,724.86
2,864	Surplus for Food		—
$15,225			$13,724.86

Section of Geology

Abstract of Proceedings, 1969

Five meetings were held during this year, the average attendance being about 12 members and visitors.

MARCH 21st (Annual Meeting) :

(1) Election of office-bearers : Chairman, Mr. E. K. Chaffer ; Hon. Secretary : Mr. C. R. Ward.

(2) Notes and exhibits accompanied by short addresses :

(i) Mrs. K. Sherrard : Exhibits from specimens collected on excursions in connection with 23rd Session of the International Geological Congress, 1968.

Monograptus dubius from a graptolite-bearing sequence through Upper Wenlock and Lower Ludlow exposed in Pragowice Gorge, Bardo, near Kielce, Poland.

Sulphur from Piaseczno, south-east Poland, from Miocene Chemical Series.

Salt crystal from salt mine of Miocene age at Wieliczka, Cracow, Poland.

Model of the Venus of Vestonica. The original was made 25,000 years ago by Palaeolithic man at Dolni Vestonice, Czechoslovakia.

(ii) Mr. L. H. Hamilton : A brief account of the discovery and exploration of a scheelite deposit near Attunga, N.S.W., was given. Mr. Hamilton carried out the geological investigation of the deposit from when it was discovered in July, 1968, by the Attunga Mining Corporation, to the end of the year. The scheelite occurs as disseminated grains in skarn at the contact of a marble lens with the Inlet Monzonite, and in disseminated grains in diopside monzonite. The scheelite is concentrated in some parts of the diopside monzonite but is absent from other parts. The diopside monzonite appears to be a lime-contaminated contact phase of the Inlet Monzonite. The occurrence of the scheelite in the skarn is similar to that in other localities (e.g. King Island), but the occurrence of the scheelite in the diopside monzonite is somewhat unusual.

(iii) Mr. G. S. Gibbons exhibited several specimens from the Gosford Formation at Long Reef, illustrating different types of replacement. Firstly, a type of sand rod consisting of sideritic reed casts preserved in shale was shown. The sand rods have an acid-insoluble rind at the outer surface which is phosphate-rich.

Another specimen was exhibited which consisted of Triassic plant remains, of which the carbonaceous material had been replaced by metallic native copper. These were from a newly discovered exposure and indicate reducing conditions of preservation.

(iv) Mr. R. Goldbery exhibited specimens of a number of primary and secondary minerals recently identified from the Berry Formation at several localities throughout the Sydney Basin. Dawsonite occurs as fibrous aggregates filling cavities in dolomite and ankerite lenses in the usually shaly formation, this being the fifth occurrence of this mineral in the world. Occasionally associated with the dawsonite is nordstrandite, of which there are only two previously reported natural occurrences.

Yellow coatings and bedding plane concentrations of jarosite occur in the siltstone of the Berry Formation. These may be primary or secondary in origin. Thin lenticles of gypsum are also present. Secondary salts are mainly sulphates, and include thenardite, hexahydrite, bloedite and pickeringite. The origin of this overall assemblage is thought to be in evaporitic conditions in a barred marine basin.

(v) Mr. M. Tuckson : The mechanism of formation of some types of Wildflysch. Coarse breccias have in the past been attributed to slides, fluxoturbidity currents, grain flow or inertia flow and turbidity currents. It is proposed that rock avalanching and fault scarp erosion may be other mechanisms. With an increase in clay the mechanisms would be mudflow.

Turbidity currents are likely only to support very fine grains (Bagnold, 1962) or at least have a predominance of fine grains. Grain flow or inertia flow (Bagnold, 1956) is probably the mechanism by which many so-called fluxoturbidities are formed, but experiments done by Bagnold were confined to sand grains. There is no certainty that this mechanism will apply to coarser particles, especially if not nearly equidimensional. Possibly with coarser grains, up to boulders, this mechanism is replaced by avalanching with a greater degree of individual block sliding or rolling. This is probably also the case when the sea floor slope and thickness of the flow are insufficient to maintain inertia flow.

The term " slide " should be confined to cohesive masses of rock and blocks that slide as a whole without internal movement that could either by described as mudflow or rock avalanche.

Fault scarp erosions partly by waves and traction currents may account for some deposits.

It is considered that there is a more basic change in flow type from a laminar to turbulent mudflow than from a turbulent mudflow to a turbidity current.

It is proposed that submarine block sliding would occur, without a highly slumped substratum, but with one having a top layer, above a viscosity disconformity, eroded.

Bagnold, R. A., 1954 : " Experiments on a Gravity-free Dispersion of Large Solid Spheres in a Newtonian Fluid under Shear." *Proc. Roy. Soc.*, Ser. A, Vol. 225, pp. 49–63.

Bagnold, R. A., 1962 : " Auto-suspension of Transported Sediment ; Turbidity Currents." *Proc. Roy. Soc.* (*London*), Ser. A, Vol. 265 (1322), pp. 315–19.

(vi) Mr. C. R. Ward : Photo slides were shown of features illustrating the sedimentary environment of several units of the Narrabeen Group on the south coast of N.S.W. The units are essentially of a fluvial origin, being made up of lens-shaped sand and conglomerate bodies having marked evidence of contemporaneous erosion at the base. Exposures of the Bulgo and Scarborough sandstones show "fining upwards" cycles described in the literature.

In the middle part of the Bulgo sandstone, south of Garie Beach, the unit is made up of green coloured sandstones and shales of the fluvial type interbedded with layers of coarse granule conglomerate and horizons of phosphorite nodules. These granule conglomerates appear to be the product of high energy or upper regime water flow, but their origin is still uncertain.

MAY 16th :

Address by Mr. R. O. Chalmers, "Recent Mineralogical Field Work in Australia and Overseas".

Mr. Chalmers' address consisted of two parts, the first section dealing with the occurrence and origin of tektites and the second part describing the occurrence of precious and common opal in rhyolitic spherulites in northern N.S.W.

Tektites are spherical to ellipsoidal pieces of black glassy rock with a sub-metallic lustre. They have been found in several parts of the world, mostly in America and Europe. Photographs were shown of these localities and of some of the tektites found. Those occurring in Australia are known as "Australites". They form the best preserved and the most widespread occurrence in the world, being found over a large part of central Australia. The occurrence and morphology of Australites was discussed in detail, and the various hypotheses for their origin were outlined. Evidence available to date seems to favour an extra-terrestrial origin for this material.

Varieties of both precious and common opal have been found within rhyolic spherulites at Mullumbimby and other areas in the Mt. Warning volcanic complex. These spherulites appear to be related to "thunder eggs", a spherulitic structure with infilled radial cracks a dominant feature. The origin of these cracks and of the opal itself was discussed, and slides illustrating the field occurrence of this material were shown.

JULY 18th :

Address by Mr. J. H. Bryan, "Some Unusual Sedimentary Features of the Beacon Group, Antarctica".

The Beacon Group crops out extensively in East Antarctica, where it attains a maximum thickness of about 8,000 feet. The essentially flat lying strata, which range in age from Devonian to Jurassic, have in general a continental to shallow marine aspect.

The excellent exposures of the Beacon Group in "dry valleys" such as Arena Valley, permit a detailed study of the sedimentary structures of these sediments.

Though fossils are rare, there is abundant evidence of organic life preserved in the sandstones and shales with worm burrows, tracks and trails preserved on many horizons. Unusual shaped concretions are particularly abundant on several horizons, some of these being up to 6 feet long and 15 inches in diameter.

All manner of planar and trough cross stratification, desiccation polygons, and cut and fill structures are evidence of the shallow water environment of deposition.

Within Arena Valley the strata are locally deformed into a series of moderately to tightly appressed folds. These folded strata pass laterally into undeformed strata and are underlain and overlain by undisturbed sediments. This unique occurrence of deformed Beacon Group strata is considered to be the result of penecontemporaneous slumping initiated either by some tectonic disturbance or by overloading on the depositional slope.

SEPTEMBER 19th :

Address by Assoc. Prof. L. J. Lawrence, "The 1969 Eruption of Kiluea".

Professor Lawrence outlined the geographical arrangement and early history of the Hawaiian eruptions leading up to the March, 1969, outpourings. The Island of Hawaii was then considered as a U.S. National Park and as a vulcanological research centre of the U.S.G.S. Some of the research work being carried out by the U.S.G.S. was outlined.

Professor Lawrence then gave an account of the 1969 eruption of Halamaumau and illustrated various aspects by means of colour slides which he took during the eruption.

NOVEMBER 21st :

Students' Symposium : Recent Field Work Done in the Broken Hill Area.

Mr. W. Lang, "The Low Grade Metamorphic Facies of the Willyama Complex".

Mr. P. Cooper, "The High Grade Metamorphic Facies of the Willyama Complex".

Mr. Cooper has studied the Willyama Complex in the Euriowie Inlier from Bijerkerno to Cooma in the Barrier Ranges north of Broken Hill, N.S.W.

In this area the Willyama Complex has undergone metamorphism *before* deformation. Metamorphism reached the sillimanite-muscovite-almandine subfacies of the amphibolite facies and maximum conditions of temperature and pressure were approximately 3·5 Kb and 650° C.

The metamorphic grade increases westward from Bijerkerno with chloritoid, andalusite and sillimanite being developed. No staurolite has been detected.

The structural interpretation of the Willyama Complex has been complicated by the presence of a foliation parallel to bedding. This foliation has been ascribed by different workers to transposition, concentric shear effects or load metamorphism. Depending on the interpretation of the bedding foliation, two or three periods of deformation have been involved. However, no satisfactory evidence has been presented to confirm which of the three interpretations is correct.

The structure and metamorphism can be traced from the Bijerkerno Beds, the low-grade equivalents of the Willyama Complex. No unconformity exists between the Bijerkerno Beds and the main Willyama Complex.

Mr. J. W. Woodhouse, "The Torrowangee Group".

Unconformably overlying the metamorphic rocks of the Willyama Complex in the northern Barrier Ranges is an Upper Proterozoic sequence of siltstones, boulder beds and carbonates known as the Torrowangee Group.

In the west, over the so-called "Willyawangees" (low-grade Willyama Complex) sandstone, chert, dolomite and epidotized basalt make up the base of the Torrowangee Group. On the east, over the Euriowie Inlier, a conglomerate and massive buff dolomite (neither being everywhere present) are the basal rocks.

Over these basal rocks—disconformably on the west and with an overlapping relationship on the east—are the Yancowinna Beds, Euriowie Beds, and Teamsters' Creek Beds. These units are predominantly siltstones with varying amounts of quartzites, boulder beds, and carbonate.

The environment envisaged is shallow to medium depth marine-glacial, that is essentially a marine environment with glacial ice rafts depositing additional sediment as they melt. Description of the Torrowangee Group sediments as " tillites ", as in much literature, is not satisfactory.

Deformation represents an east-west shortening in excess of 50%. The shortening has caused both homogeneous and heterogeneous (folding) strain to differing degrees in different parts of the sequence. Second generation structures in the siltstones are to be found near the Euriowie Inlier. These are thought to be related to movements of the inlier along basement faults.

The onlapping relationship between the massive dolomite and younger sediments, after deformation, has given an unusual geometric arrangement with younger beds striking at a high angle to their contact with older beds. In the past this has been misinterpreted as the Corona Fault of some 20,000 feet displacement. In fact, it is an unconformable depositional surface along which there has been a little movement.

Report of the South Coast Branch of the Royal Society of New South Wales

Two meetings were held during 1969. The inaugural meeting in June was attended by 57 members and friends and was devoted to a lecture by Mr. Neuhaus, the President of the Society, on " The Role of the Forensic Chemist " and a panel exposition of Lawrence Hargreaves' life and works. The second meeting took the form of a geological excursion, and included visits to Minnamurra Falls and the Kiama blowhole. Seventy-five members and friends attended.

The annual meeting was held on 20th March in the new Union dining hall. Twenty-seven members and friends attended the meeting, which was preceded by a dinner at 7 p.m. Dr. R. W. Upfold was elected Chairman, and Mr. R. A. Facer was elected Secretary-Treasurer.

Dr. J. L. Symonds, Research Establishment Assistant Co-ordinator of the Jervis Bay Nuclear Power Station project, addressed the meeting on various aspects of the Australian Atomic Energy Commission's activities at Jervis Bay.

Of the annual grant of $50 provided by the parent Society, a total of $27.40 was spent on catering at the inaugural and annual meetings. The balance of the account is $23.03, which includes 43 cents interest.

R. A. Facer,
Secretary-Treasurer.

Report of the New England Branch of the Royal Society of New South Wales

Officers.—Chairman : N. H. Fletcher ; Secretary-Treasurer : R. L. Stanton ; Committee : J. H. Priestly, D. H. Fayle, R. H. Stokes, N. T. M. Yeates, H. G. Royle ; Branch representative on Council : R. L. Stanton.

Meetings were held as follows :

10th April : Professor B. Y. Mills, F.R.S., Professor of Astrophysics at the University of Sydney and Director of the Molonglo Radio Observatory : " Pulsars and Supernovae ".

14th July : Professor L. Hamilton, Professor of Conservation at Cornell University, Ithaca, New York : " What is Conservation ? "

Unfortunately, as in 1968, several (three) other speakers were unable to fulfil arrangements to come to Armidale for Royal Society meetings. In this connection it may be mentioned that the Honorary Secretary receives very little help from members in obtaining speakers for the Branch. Such help has been frequently promised, but only occasionally given.

Financial Statement

Balance at University of New England Branch, C.B.C., Sydney, at 10th April, 1969	$295.34	
Credit :		
Remittance from Royal Society of N.S.W., 1969	$50.00	
Interest to 30th June, 1969 ..	5.16	
Interest to 31st December, 1969	6.12	
		$356.62
Debit :	Nil	
Balance, 2nd April, 1970 ..		$356.62

R. L. Stanton,
Secretary-Treasurer.

Obituaries

Ronald Leslie Aston

Ronald Leslie Aston, who died on 7th September, 1969, was born in Queensland in 1901. He was educated at Newington College, Sydney, and at the University of Sydney; later at Trinity College, Cambridge. He graduated at Sydney first in Science and then in Engineering (with first-class Honours). Subsequently he was awarded the degree of Master of Science at Cambridge for his work on the effect of boundaries on the deformation of single crystal of aluminium. In 1932 he was accorded the distinction of being one of the few people awarded the degree of Doctor of Philosophy by Cambridge University for work done outside the precincts of the university: his work as leader of the Imperial Geophysical Experimental Survey in Australia.

Dr. Aston had a long association with the University of Sydney, becoming a lecturer in surveying and civil engineering in 1930, and later became a Professor in the Department of Civil Engineering. He will be remembered with affection by the many students who were fortunate to study under him.

In 1930 Dr. Aston was elected a member of the Royal Society of New South Wales, and served as President in 1948–1949. He was a consultant on the Snowy Mountains Scheme and from 1948 to 1955 was Editor of the *Australian Journal of Science*.

Walter George Stone

Walter George Stone, F.S.T.C., A.A.C.I., who died on 28th July, 1969, was born in 1882. He was a life member of the Royal Society of New South Wales, and a member since 1916. On 1st January, 1899, he became assistant to the then Curator and Mineralogist of the Mining Museum, Geological Survey of N.S.W., G. W. Card, A.R.S.M., F.G.S., who was also a member of this Society. At that time the Museum was situated behind Sydney Hospital. After obtaining his diploma as Associate of the Sydney Technical College, Mr. Stone took a year's leave of absence without pay to gain experience in the mining fields of Australia. He transferred to the staff of the Chemical Laboratory as Assistant Analyst and Assayer of the Mines Department in 1911, when the laboratory was situated at and worked in conjunction with the State Metallurgical Works at Clyde. After the laboratory's transfer to its present site in George Street North, he collaborated as Chemist with the late member of the Royal Society C. A. Sussmilch, F.G.S., in a thesis on the geology and chemistry of the Jenolan Caves area which was published by the Society. For this work he was awarded one of the very few Fellowships of the Sydney Technical College in 1915. In a world-wide assessment of analytical ability conducted by Dr. Washington of U.S.A., an eminent authority, he was graded as an A1 analyst: "A combination of A and 1 might be called 'perfect', the word being used subject to human limitations." Mr. Stone served voluntarily as Chemist in explosive factories of the Munitions Department in Great Britain during the 1914–1918 war.

As a part-time teacher in mineralogy at the Sydney Technical College for 14 years, he saw a period of expanding interest in geology and mineralogy. In 1935 Mr. Stone became Chief Analyst of the Mines Department, a position he held during the difficult war years of 1939–1945. The Fuel Research Committee formed in 1937 entailed increase in staff, equipment, space and work for the Laboratory. Mr. Stone retired in December, 1945.

Medallists, 1969-70
Citations

The Society's Medal

The Society's Medal is awarded to a member of the Society for " meritorious contributions to the advancement of science. This may include administration and organization of scientific endeavour ; and for services to the Society."

Professor Raymond James Wood Le Fevre, D.Sc., F.R.S., F.A.A., was born in London on 1st April, 1905. He was educated at Isleworth School and Queen Mary College, London. His wartime activities were many and varied and included Assistant Director, Research and Development, Ministry of Aircraft Production, Head of Chemistry at the R.A.F. Establishment, Farnborough. He held the rank of Wing Commander.

Among his academic appointments have been Lecturer and Reader in Organic Chemistry, University College, London, and Professor of Chemistry, University of Sydney.

During a very distinguished career, he has found time to serve on the Developmental Council of New South Wales University of Technology, Trustee of Museum of Applied Arts and Sciences, and Foundation Fellow and Member of the first Council of the Australian Academy of Science (1954). He was President of the Royal Society of New South Wales in 1961–1962.

The Clarke Medal for 1969

The Clarke Medal is awarded for distinguished work in the Natural Sciences done in, or on, the Australian Commonwealth and its territories.

The award for 1969 is made to Professor Samuel Warren Carey of the Department of Geology, University of Tasmania, for distinguished contributions in the field of geology.

(For further details, see *J. Proc. Roy. Soc. N.S.W.*, Vol. 103.)

James Cook Medal for 1969

The James Cook Medal is awarded for outstanding contributions to science and human welfare in and for the Southern Hemisphere.

The award for 1969 is made to Lord Casey of Berwick and Westminster, P.C., G.C.M.G., C.H., D.S.O., M.C., M.A.

The Society was honoured by the presence of Lord and Lady Casey on 21st October, 1970, the occasion of the presentation of the James Cook Medal for 1969 to Lord Casey.

The following brief biographical sketch draws attention to some of the highlights in the life and career of this distinguished Australian.

Richard Gardiner Casey was born in Brisbane in 1890 and subsequently attended Melbourne University, where he studied mining engineering. Then followed studies at Cambridge, where he earned the degree of M.A. with Honours in Mechanical Science.

For a time before World War I he was associated with the mining industry, first at the Mount Morgan gold mine in Queensland and then the Laloki copper mine near Port Moresby, New Guinea.

R. G. Casey enlisted in 1914 and saw active service in Europe and Gallipoli. He had an eventful military career and was awarded the Distinguished Service Order and the Military Cross.

After the war he rejoined Mount Morgan and for a time was associated with Australian Fertilizers at Port Kembla.

In the early 1920's S. M. Bruce (later Lord Bruce of Melbourne) persuaded Casey to join the Public Service and later to enter politics. Here it is perhaps appropriate to note that it is one of Lord Casey's clearly expressed views that more men with scientific and engineering training should be prepared to enter politics and become involved in the important business of government.

Subsequent to his entry into Federal Parliament in 1931 Casey became intimately involved in the evolution of the modern Liberal Party, and at one stage of his political career was a rival to R. G. Menzies for the Prime Ministership of Australia.

Between 1940 and 1942 Casey was in Washington, D.C., fulfilling the role of the first Australian Minister to the United States during the critical early war years when America was gradually committing herself to the Allied cause.

In 1942 Casey was invited by Winston Churchill to serve as U.K. Minister of State for the Middle East at Cairo, at the same time becoming a member of the British War Cabinet. Lord Casey recalls that it was during this stage of his career that he met Field Marshal J. C. Smuts, himself a distinguished recipient of the James Cook Medal of the Society.

From 1944 to 1946 Casey was appointed Governor of Bengal during the final years of the arduous Burma campaign and the initial, difficult transition period before Indian Independence.

On his return to Australia, Casey actively involved himself in the Australian political scene for the second time in his career. In 1950, as the first Minister of National Development, he was associated with the establishment of the Bureau of Mineral Resources, under Dr. H. G. Raggatt as its first Director.

Between 1950 and 1960 Casey was Minister in charge of the C.S.I.R.O. and as Minister for External Affairs (1951–1960) was largely responsible for the initiation of Australia's scientific effort in the Antarctic.

Amongst Lord Casey's publications we may cite the following : *An Australian in India, Double or Quit* (1948), *Friends and Neighbours* (1954), and *The Future of the Commonwealth* (1963). These reflect his interest in the future status of the British Commonwealth and the increasing Australian orientation towards her neighbours in S.E. Asia.

Lord Casey's subsequent career, which includes the Governor-Generalship of Australia from 1965 to 1969, is well known to members of our Society and does not require elaboration in this brief review.

The Society is fortunate to have in the person of Lord Casey a man of stature and wealth of experience to be the very worthy recipient of the James Cook Medal for 1969.

Edgeworth David Medal for 1969

The Edgeworth David Medal is awarded to Australian research workers under the age of 35 years for work done, mainly in Australia or its territories, or contributing to the advancement of Australian science.

The award for 1969 is made to Associate Professor Barry W. Ninham, of the Department of Applied Mathematics, University of New South Wales, for his outstanding contributions to applied mathematics, theoretical physics and, more recently, biophysics.

Professor Ninham was born on 9th April, 1936, in Croydon, South Australia. He graduated in theoretical physics at the University of Western Australia, B.Sc. (first-class honours) (1957), M.Sc. (1958). He was awarded a C.S.I.R.O. Post-Graduate Studentship tenable at the University of Maryland, U.S.A., where he studied for his Ph.D. (theoretical physics and mathematics) (1962) under Professor Elliott W. Montroll. He was appointed lecturer at the University of New South Wales in May, 1962. From 1964 to 1966 he held a Queen Elizabeth II Post-Doctoral Fellowship at the University of New South Wales. In 1969 he was Visiting Scientist at the National Institute of Health, Washington, D.C. In 1970 he is to accept the position of Professor of Applied Mathematics at the Research School of Physical Sciences, Australian National University.

Professor Ninham has written two books and published extensively, making significant contributions to several fields of theoretical physics and applied mathematics. He has always had a strong interest in mathematical analysis, and some of his contributions have been directly in this field. He has been particularly successful in applying these techniques both to numerical analysis and to statistical mechanics, which have been his major area of research. His work here has been outstanding : always highly original and thorough. Recently he has shown the relevance of sophisticated quantum-mechanical and stochastic methods to challenging problems of cell structure and dynamics in biophysics. He has already made pioneering contributions to this further field.

Members of the Society, April, 1970

A list of members of the Society up to April, 1969, is included in Volume 102.

During the year ended 31st March, 1970, the following were elected to membership of the Society :

Brown, John Percival, Bank Manager, E. S. & A. Bank, Wollongong, N.S.W., 2500 (1969).

Callender, John Hardy, Schoolteacher, Lot 101, Dallas Street, Mount Ousley, N.S.W., 2519 (1969).

Flood, Peter Gerald, B.Sc.(Hons.), Geologist, Bureau of Mineral Resources, Canberra, A.C.T., 2600 (1969).

Griffin, Derek K., B.Sc., Geologist, Lot 435, McDougall Avenue, Baulkham Hills, N.S.W., 2153 (1969).

Kokot, Ernest, B.Sc., Ph.D. (N.S.W.), A.S.T.C., A.R.A.C.I., 4 Cosgrove Avenue, Keiraville, N.S.W., 2500 (1969).

McCarthy, Daryl John, F.R.M.S., 12 Farrow Street, Lane Cove, N.S.W., 2066 (1969).

Murray, Bede Edward, B.A., 18 Bulwarra Street, Keiraville, N.S.W., 2500 (1969).

Pearson, Robert John Butler, Metallurgist, 25 Burling Avenue, Fairy Meadow, N.S.W., 2519 (1969).

Riley, Steven James, B.Sc.(Hons.), Department of Geography, University of Sydney, N.S.W., 2006 (1969).

Wilcox, Ronald Walter, B.Sc., Dip.Ed., 9 Benney Avenue, Fig Tree, N.S.W., 2500 (1969).

During the same period resignations were received from the following :

Blunt, Michael H.
Bossom, Geoffrey.
Feather, Norman T.
Henderson, Roger J.
McClymont, Vivienne C. (Mrs.) (Associate).
Priddle, Raymond A.
Slade, George H.
Warris, Bevan J.

and the following names were removed from the list of members under Rule XVIII :

Essex, Elizabeth A.
Flood, Richard W.

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Royal Society of New South Wales

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NOTICE

The Royal Society of New South Wales originated in 1821 as the "Philosophical Society of Australasia"; after an interval of inactivity it was resuscitated in 1850 under the name of the "Australasian Philosophical Society", by which title it was known until 1856, when the name was changed to "Philosophical Society of New South Wales". In 1866, by the sanction of Her Most Gracious Majesty Queen Victoria, the Society assumed its present title, and was incorporated by Act of Parliament of New South Wales in 1881.

THE ROYAL SOCIETY OF NEW SOUTH WALES SYDNEY

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JOURNAL AND PROCEEDINGS

OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 104

PARTS 1-4

1971

PUBLISHED BY THE SOCIETY,
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

Royal Society of New South Wales

OFFICERS FOR 1971-1972

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JOURNAL AND PROCEEDINGS OF THE ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 104 1971 PARTS 1 and 2

CONTENTS

PUBLISHED BY THE SOCIETY
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

ISSUED JUNE 6, 1972

NOTICE TO AUTHORS

General. Manuscripts should be addressed to the Honorary Secretaries, Royal Society of New South Wales, 157 Gloucester Street, Sydney. Two copies of each manuscript are required: the original typescript and a carbon copy; together with two additional copies of the abstract typed on separate sheets.

Papers should be prepared according to the general style adopted in this Journal. They should be as concise as possible, consistent with adequate presentation. Particular attention should be given to clarity of expression and good prose style.

The typescript should be double-spaced, preferably on quarto paper, with generous side margins. Headings should be typed without underlining; if a paper is long, the headings should also be given in a table of contents typed on a separate sheet, for the guidance of the Editor.

The approximate positions of Figures, Plates and Tables should be indicated in the text between parallel ruled lines. Captions of Figures and Plates should be typed on a separate sheet.

The author's institutional or residential address should be given in the title of the paper, the relevant author's initials being attached in brackets to the appropriate address in cases of papers written jointly.

Abstract. An *informative* abstract should be provided at the commencement of each paper for the guidance of readers and for use in abstracting journals.

Tables. Tabular matter should be typewritten on separate sheets, arranged for the most economical presentation on the printed page. Column lines should *not* be ruled in. Units of measurement should always be indicated in the headings of the columns or rows to which they apply. Tables incorporating both text and line diagrams (including dotted lines and shading) should be submitted in a form suitable for direct reproduction by photographic line blocks.

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VICK, C. G., 1934. *Astr. Nach.*, **253**, 277.

The abbreviated form of the title of this journal is: *J. Proc. Roy. Soc. N.S.W.*

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Line Diagrams. Line diagrams, fully lettered, should be made with dense black ink on either white bristol board, blue linen or pale-blue ruled graph paper. Tracing paper is unsatisfactory because it is subject to attack by silverfish and also changes its shape in sympathy with the atmospheric humidity. The thickness of lines and the size of letters and numbers should be such as to permit photographic reduction without loss of detail.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 1–4, 1971

On the Metric of an Astronomical Object in the Lyttleton-Bondi Theory

R. Burman
Department of Physics, University of Western Australia

Abstract—Lyttleton and Bondi developed a cosmological model in which there is net imbalance of charge, with matter and hence charge being continuously created. Here, the equations of that theory, namely the Proca equations combined with Einstein's field equations of general relativity, are used to investigate the space-time outside a static spherically symmetric object, with a radial outflow sufficient to keep the matter and charge densities constant. The situation with zero electromagnetic fields but non-zero potentials is investigated. An expansion of the metric is obtained which shows that there is no detectable departure from the predictions of the Schwarzschild metric.

1. Introduction

Lyttleton and Bondi (1959, 1960), and also Hoyle (1960), investigated the effects of a possible general charge imbalance in the universe; the excess could arise from differing magnitudes of the proton and electron charges, or from different numbers of protons and electrons everywhere in the universe. The possibility of ascribing the expansion of the universe to electrical repulsion was discussed. In the Lyttleton-Bondi theory, creation of matter implies creation of charge; hence Maxwell's equations cannot be accurately valid and an appropriate modification, the Proca equations, was used. The postulate of the conservation of existing charge was retained: in any volume element, the total charge is the sum of the charges of all the enclosed elementary particles existing there at the instant concerned. Also, charge was regarded as indestructible once created.

Taking $-e$ to be the charge on the electron, that on the proton is written $(1+y)e$, or alternatively, the ratio of number of protons to number of electrons is $(1+y):1$.

Consider a distribution of non-ionized hydrogen atoms of uniform density, each atom having a net charge ye. By considering non-relativistically the balance of gravitational and electrostatic forces on any one atom, it easily follows that the system will expand if $y>G^{\frac{1}{2}}m_H/e$, G being the Newtonian gravitational constant and m_H being the mass of the hydrogen atom (Lyttleton and Bondi, 1959). The consequent reduction of density can be offset by continuous creation of matter and hence of charge; the ratio of rates of charge and matter creation is ye/m_H. The radial streaming constitutes an electric current, but this need not imply the existence of electric and magnetic fields, Maxwell's equations being inapplicable.

The Proca equations, in contrast to Maxwell's equations, are not gauge invariant: the scalar and vector potentials have direct physical significance. These equations were used by Lyttleton and Bondi to investigate, in Newtonian space-time, a system having spherical symmetry about some point specified to be the origin; they found a solution with non-zero charge and current densities and non-zero electromagnetic scalar and vector potentials, but with zero electric and magnetic fields. Then, using the generally covariant form of the Proca equations, Lyttleton and Bondi obtained a solution with zero electric and magnetic fields in a space-time having the de Sitter metric—the metric of the homogeneous stationary universe of the steady-state theory. In this case, the current density 3-vector vanishes because of the co-moving nature of the co-ordinates.

2. Basic Theory

The purpose of this section is to present some of the basic electrodynamical theory, as developed by Lyttleton and Bondi (1959).

2.1. *Non-covariant Formulation*

Let $\mathbf{E}$ and $\mathbf{H}$ represent the electric and magnetic fields, while φ and $\mathbf{A}$ denote the scalar and vector potentials, so that

$$\mathbf{B}=\nabla\times\mathbf{A} \text{ and } \mathbf{E}=-\nabla\varphi-\frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}, \qquad (1a,b)$$

c being the speed of light in empty space. The simplest generalization of Maxwell's equations is the set of Proca equations

$$\nabla\times\mathbf{E}=-\frac{1}{c}\frac{\partial\mathbf{H}}{\partial t}, \qquad \nabla\cdot\mathbf{H}=0, \qquad (2a,b)$$

$$\nabla\times\mathbf{H}=\frac{4\pi}{c}\mathbf{j}+\frac{1}{c}\frac{\partial\mathbf{E}}{\partial t}-\lambda\mathbf{A}, \quad \nabla\cdot\mathbf{E}=4\pi\rho-\lambda\varphi \qquad (3a,b)$$

in which $\mathbf{j}$ and ρ are the current and charge densities; Maxwell's equations are obtained when the constant λ vanishes; $\lambda^{-\frac{1}{2}}$ has the dimensions of length, and Lyttleton and Bondi suggested that it might have the same order of magnitude as the radius of the observable universe. In another interpretation of (2) and (3), λ is related to a possible rest mass of the photon (Schrödinger, 1943; McConnell and Schrödinger, 1944; Bass and Schrödinger, 1955; Gintsburg, 1964; Patel, 1965; Kozarev and Okun', 1968; Goldhaber and Nieto, 1968). Equations (2) and (3) are Lorentz invariant, but not gauge invariant: φ and $\mathbf{A}$ have direct physical significance.

In a situation with continuous creation of charge, of amount q e.s.u. per unit proper volume per unit time, the equation of continuity of charge is replaced by

$$\nabla\cdot\mathbf{j}+\frac{\partial\rho}{\partial t}=q. \tag{4}$$

Taking the divergence of ($3a$) and using ($3b$), it follows that

$$\frac{4\pi}{c}\left(\nabla\cdot\mathbf{j}+\frac{\partial\rho}{\partial t}\right)=\lambda\left(\nabla\cdot\mathbf{A}+\frac{1}{c}\,\frac{\partial\varphi}{\partial t}\right); \tag{5}$$

so the Lorentz condition of conventional electrodynamics is replaced by

$$\nabla\cdot\mathbf{A}+\frac{1}{c}\,\frac{\partial\varphi}{\partial t}=\frac{4\pi q}{c\lambda}. \tag{6}$$

2.2. *Covariant Formulation*

Equations (2) and (3) are Lorentz invariant, but are not in covariant form. Let (A^{μ}) and (J^{μ}) denote the 4-potential $(\mathbf{A},\varphi)$ and the current density 4-vector $(\mathbf{j},\rho c)$ respectively; q has the same meaning as above. Partial and covariant differentiation will be denoted by a comma and a semicolon, respectively. The electromagnetic field tensor $(F_{\mu\nu})$ is defined by

$$F_{\mu\nu}=A_{\mu,\nu}-A_{\nu,\mu}. \tag{7}$$

The Proca equations (2) and (3) are, respectively,

$$F_{\mu\nu,\rho}+F_{\rho\mu,\nu}+F_{\nu\rho,\mu}=0 \tag{8}$$

which is equivalent to (7), and

$$F^{\nu}_{\mu;\nu}=\frac{4\pi}{c}J_{\mu}-\lambda A_{\mu}. \tag{9}$$

Equation (6) can be expressed as

$$A^{\mu}_{;\mu}=\frac{4\pi q}{c\lambda}. \tag{10}$$

Equations (9) and (10) can be written

$$\frac{1}{\sqrt{-g}}(\sqrt{-g}F^{\mu\nu})_{,\nu}=\frac{4\pi}{c}J_{\mu}-\lambda A_{\mu} \tag{11}$$

and

$$\frac{1}{\sqrt{-g}}(\sqrt{-g}A^{\mu})_{,\mu}=\frac{4\pi q}{c\lambda} \tag{12}$$

where g is the determinant of the metric tensor $(g_{\mu\nu})$.

In this modified electrodynamics, the energy-momentum tensor has the components

$$T^{\nu}_{\mu}=\frac{1}{4\pi}[F_{\mu\alpha}F^{\alpha\nu}+\tfrac{1}{4}\delta^{\nu}_{\mu}F_{\sigma\tau}F^{\sigma\tau}+\lambda(A_{\mu}A^{\nu}-\tfrac{1}{2}\delta^{\nu}_{\mu}A_{\alpha}A^{\alpha})]. \tag{13}$$

2.3. *Solutions with Zero Electromagnetic Fields*

When $F_{\mu\nu}=0$, (9) becomes

$$J_{\mu}=\frac{c\lambda}{4\pi}A_{\mu}. \tag{14}$$

Also, (7) then shows that

$$A_{\mu}=U_{,\mu}, \tag{15}$$

U being a scalar function; so (12) can be written

$$\frac{1}{\sqrt{-g}}(\sqrt{-g}U^{,\mu})_{,\mu}=\frac{4\pi q}{c\lambda}. \tag{16}$$

3. Space-time Outside a Spherically Symmetric Object

This section and the next deal with the space-time outside a static spherically symmetric central object, with a radial outflow sufficient to keep the matter and charge densities constant in spite of the continuous creation. It is assumed that the matter outside the central object is sufficiently tenuous to have no dynamical effect on the metric; in particular, the line element will be taken to be static, not merely stationary.

The static spherically symmetric space-time metric can be written

$$-ds^2=A(r)dr^2+r^2(d\theta^2+\sin^2\theta d\varphi^2)-C(r)c^2dt^2; \tag{17}$$

ds is the space-time interval, (r,θ,φ) are spherical polar co-ordinates, and t is the time co-ordinate. Equation (17) corresponds to a metric tensor $(g_{\mu\nu})$ with non-zero covariant components given by

$$g_{11}, g_{22}, g_{33}, g_{44}=-A,\ -r^2,\ -r^2\sin^2\theta,\ C \tag{18}$$

so that

$$g^{11}, g^{22}, g^{33}, g^{44}=-A^{-1},\ -r^{-2},\ -(r\sin\theta)^{-2},\ \rho^{-1}. \tag{19}$$

Also

$$\sqrt{-g}=(AC)^{1/2}\,r^2\sin\theta. \tag{20}$$

For the metric (17), the mixed components G^{ν}_{μ} of the Einstein tensor can be obtained from the book by Synge (1960, pp. 270-72): the only non-zero components are on the diagonal; it is found that

$$G^{4}_{4}=\frac{1}{r^2}\left[\frac{d}{dr}\left(\frac{r}{A}\right)-1\right] \tag{21}$$

and

$$G_1^1 - G_4^4 = \frac{1}{rA^2C}\frac{d}{dr}(AC), \tag{22}$$

which will be used soon.

In a static spherically symmetric situation, using the (r, θ, φ, ct) co-ordinate system, (A_μ) must have the form given by

$$(A_\mu) = (a, 0, 0, \varphi) \tag{23}$$

where a and φ are functions of r only; for the $F_{\mu\nu}$ to vanish, φ must be a constant. From (23),

$$(A^\mu) = (-a/A, 0, 0, \varphi/C), \tag{24}$$

so $A_\mu A^\mu = \varphi^2/C - a^2/A$. The only non-zero components T_μ^ν are diagonal ones. With $F_{\mu\nu}=0$,

$$T_1^1 = \frac{-\lambda}{8\pi}\left(\frac{a^2}{A} + \frac{\varphi^2}{C}\right), \tag{25}$$

$$T_2^2 = \frac{\lambda}{8\pi}\left(\frac{a^2}{A} - \frac{\varphi^2}{C}\right) = T_3^3 \tag{26}$$

and

$$T_4^4 = \frac{\lambda}{8\pi}\left(\frac{a^2}{A} + \frac{\varphi^2}{C}\right). \tag{27}$$

Hence

$$T_1^1 - T_4^4 = \frac{-\lambda}{4\pi}\left(\frac{a^2}{A} + \frac{\varphi^2}{C}\right). \tag{28}$$

As mentioned before, the dynamical effects on the metric of the outflowing matter will be neglected—that is, its mechanical contribution to the total energy-momentum tensor is disregarded. So, outside the central body, Einstein's field equations of general relativity are

$$G_\mu^\nu = -4\pi\alpha T_\mu^\nu \tag{29}$$

where α is a constant and the components T_μ^ν are given by (25) to (27). It follows from (21), (22), (27), (28) and (29) that

$$\frac{1}{r^2}\left[\frac{d}{dr}\left(\frac{r}{A}\right) - 1\right] = -\frac{\alpha\lambda}{2}\left(\frac{a^2}{A} + \frac{\varphi^2}{C}\right) \tag{30}$$

and

$$\frac{1}{rA^2C}\frac{d}{dr}(AC) = \alpha\lambda\left(\frac{a^2}{A} + \frac{\varphi^2}{C}\right). \tag{31}$$

Multiplying (30) through by r^2 and then integrating gives

$$\frac{1}{A} = 1 - \frac{\alpha\lambda}{2r}\int r^2\left(\frac{a^2}{A} + \frac{\varphi^2}{C}\right)dr. \tag{32}$$

Multiplying (31) through by rA and then integrating results in

$$\ln(AC) = \alpha\lambda\int rA\left(\frac{a^2}{A} + \frac{\varphi^2}{C}\right)dr. \tag{33}$$

Using (20) and (24), (12) becomes

$$\frac{1}{(AC)^{\frac{1}{2}}r^2}\frac{d}{dr}\left[\left(\frac{C}{A}\right)^{\frac{1}{2}} r^2 a\right] = \frac{-4\pi q}{c\lambda} \tag{34}$$

which integrates to

$$a = \frac{-4\pi q/c\lambda}{(C/A)^{\frac{1}{2}}r^2}\int (AC)^{\frac{1}{2}}r^2 dr + \frac{\beta}{(C/A)^{\frac{1}{2}}r^2} \tag{35}$$

where β is a constant.

4. Expansion of the Metric

Starting with the metric (17), and following a suggestion of Eddington (1924, p. 105), A^{-1} and C can be expanded in powers of $1/r$. One coefficient in the expansion is determined by requiring the geodesics to approximately coincide with the Newtonian orbits. The remainder are determined by the field equations of general relativity; alternatively, the lowest order of them, at least for the solar metric, are obtainable from observations. Expansions of this kind, with the metric taken to be in isotropic form or in the form (17), have received considerable attention in recent years (Robertson, 1962; Schiff, 1960, 1962, 1964, 1967; Schild, 1960).

For a metric of the form (17), consider the expansions

$$A = 1 + \beta_1\frac{2m}{r} + \beta_2\left(\frac{2m}{r}\right)^2 + \ldots \tag{36}$$

and

$$C = 1 - \frac{2m}{r} + \alpha_2\left(\frac{2m}{r}\right)^2 + \ldots, \tag{37}$$

m being a constant. The Newtonian orbits are obtained to a first approximation, provided m is identified with $G\mu/c^2$ where G is the Newtonian gravitational constant and μ is the mass of the central body. Any other non-zero choice of the coefficient of $2m/r$ in C would result in m being proportional, rather than equal, to $G\mu/c^2$ (Schild, 1962). The resulting formula gives, to first order, the same gravitational red-shift as general relativity. The rate of perihelion rotation of an orbiting particle, which is assumed to follow a geodesic, is approximately proportional to $(2+\beta_1-2\alpha_2)$, while the angle of deflection of light, which is assumed to follow a null geodesic, is approximately proportional to $(1+\beta_1)$ (Schild, 1962). The Schwarzschild metric can be expanded in the above way; the α's vanish and the β's are unity.

Equation (35) gives

$$a = \frac{-4\pi qr}{3c\lambda}\left[1 + 0\left(\frac{2m}{r}\right)\right] + \frac{\beta}{r^2}\left[1 + 0\left(\frac{2m}{r}\right)\right] \tag{38}$$

which reduces to the flat space result when terms involving m are neglected. The first term dominates at large (i.e., cosmological) distances. Near the body, the other term dominates; neglecting the first term and remembering that φ is independent of r, it is found from (32) and (33) that

$$\frac{1}{A}=1-\frac{2m}{r}+\frac{\alpha\lambda}{2}\left\{\frac{\beta^2}{r^2}\left[1+0\left(\frac{2m}{r}\right)\right]-\frac{\varphi^2 r^2}{3}\left[1+0\left(\frac{2m}{r}\right)\right]\right\} \quad (39)$$

and, with suitable choice of the constant of integration,

$$\ln(AC)=\frac{-\alpha\lambda}{2}\left\{\frac{\beta^2}{r^2}\left[1+0\left(\frac{2m}{r}\right)\right]-\varphi^2 r^2\left[1+0\left(\frac{2m}{r}\right)\right]\right\}. \quad (40)$$

Since the expansions are to hold near the central body, the terms in φ^2 will be neglected; thus

$$\frac{1}{A}=1-\frac{2m}{r}+\frac{\alpha\lambda\beta^2}{2r^2}+0\left(\frac{1}{r^3}\right) \quad (41)$$

and

$$AC=\exp\left\{-\frac{\alpha\lambda\beta^2}{2r^2}\left[1+0\left(\frac{2m}{r}\right)\right]\right\} \quad (42)$$

$$=1-\frac{\alpha\lambda\beta^2}{2r^2}+0\left(\frac{1}{r^3}\right). \quad (43)$$

Using (41), (43) gives

$$C=1-\frac{2m}{r}+0\left(\frac{1}{r^3}\right). \quad (44)$$

So the metric can be written in the form given by (36) and (37), with $\beta_1=1$ and $\alpha_2=0$; that is, the coefficients β_1 and α_2, which are the only ones affecting the standard observational tests of general relativity, have the same values as in the case of the Schwarzschild metric.

5. Concluding Remarks

This paper has dealt with the space-time metric outside a static spherically symmetric body in the presence of continuous creation of matter and charge, with a radial outflow sufficient to keep the matter and charge densities constant. The system has been described by the Lyttleton-Bondi theory in which there is a net imbalance of charge. The basic equations are Einstein's field equations of general relativity together with the Proca equations; it has been assumed that the outflowing matter is sufficiently tenuous as to have negligible dynamical effect on the metric, its mechanical contribution to the total energy-momentum tensor being neglected. The case of zero electromagnetic fields but non-zero vector and scalar potentials has been investigated. An expansion of the metric, applicable near the central body, has been obtained; this shows that there is no detectable departure from the predictions of the Schwarzschild metric.

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(Received 21st May, 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 5–10, 1971

Precise Observations of Minor Planets at Sydney Observatory during 1969 and 1970

W. H. Robertson

Abstract—Positions of 1 Ceres, 3 Juno, 11 Parthenope, 18 Melpomene, 39 Laetitia, 40 Harmonia and 433 Eros obtained with the 23 cm. camera are given.

The programme of precise observations of selected minor planets which was begun in 1955 is being continued and the results for 1969 and 1970 are given here. The methods of observation and reduction were described in the first paper (Robertson, 1958). All the plates were taken with the 23 cm. camera (scale 116″ to the millimetre). Four exposures were made on each plate except for the one for 433 Eros, which had two.

In Table I are given the means for all four images for the separate groups of stars at the mean of the times. The differences between the results average $0^s\cdot024 \sec\delta$ in right ascension and $0''\cdot44$ in declination. This corresponds to probable errors for the mean of the two results from one plate of $0^s\cdot010 \sec\delta$ and $0''\cdot19$. The result from the first two exposures was compared with that from the last two by adding the movement computed from the ephemeris. The means of the differences were $0^s\cdot012 \sec\delta$ in right ascension and $0''\cdot19$ in declination. It is expected that the two results from each plate will be combined into one when they are used. However, they are published in the present form so that any alteration of the positions of the reference stars can be conveniently applied by using the dependences from Table II. No correction has been applied for aberration, light time or parallax, but the factors give the parallax correction when divided by the distance. The observers at the telescope were W. H. Robertson (R), K. P. Sims (S) and Harley Wood (W).

In accordance with the recommendation of Commission 20 of the International Astronomical Union, Table II gives for each observation the positions of the reference stars and the dependences. The columns headed " R.A." and " Dec." give the seconds of time and arc with proper motion correction applied to bring the catalogue position to the epoch of the plate. The column headed " Star " gives the number from the Yale Catalogue (Vols. 11, 12, 13, 14, 16, 17, 20, 21, 22, 28). The plates were measured by Miss R. Bleakley, Miss A. Davis, Mrs. B. McLear, Miss R. Stanfield and Miss E. Wiegold, who have also assisted with the reductions.

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Table I

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		1 Ceres									
		1969 U.T.									
995	May	29·77177	21	03	54·490	−24	21	52·43	−0·001	−1·44	S
996	May	29·77177	21	03	54·495	−24	21	52·70			
997	June	12·73643	21	05	10·006	−25	23	34·87	+0·006	−1·28	W
998	June	12·73643	21	05	09·896	−25	23	34·16			
999	June	26·70698	21	01	33·601	−26	45	09·45	+0·045	−1·08	S
1000	June	26·70698	21	01	33·630	−26	45	09·88			
1001	July	08·66439	20	54	46·886	−28	04	03·84	+0·027	−0·87	W
1002	July	08·66439	20	54	46·958	−28	04	03·66			

Table I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		1 Ceres—*continued*									
1003	Aug.	05·56870	20	30	43·820	−30	46	34·52	+0·025	−0·46	S
1004	Aug.	05·56870	20	30	43·847	−30	46	34·22			
1005	Aug.	11·54097	20	25	26·330	−31	09	21·16	−0·009	−0·40	W
1006	Aug.	11·54097	20	25	26·298	−31	09	21·78			
1007	Aug.	18·52066	20	19	47·977	−31	28	47·33	+0·001	−0·35	R
1008	Aug.	18·52066	20	19	48·012	−31	28	47·68			
1009	Sept.	10·44386	20	08	20·128	−31	40	44·92	−0·021	−0·32	S
1010	Sept.	10·44386	20	08	20·132	−31	40	44·86			
1011	Sept.	16·43393	20	07	31·396	−31	32	42·22	+0·004	−0·34	R
1012	Sept.	16·43393	20	07	31·383	−31	32	42·60			
1013	Sept.	24·40770	20	07	54·926	−31	16	22·04	−0·013	−0·38	R
1014	Sept.	24·40770	20	07	54·964	−31	16	22·88			
1015	Oct.	03·40737	20	10	16·689	−20	51	23·43	+0·068	−0·47	S
1016	Oct.	03·40737	20	10	16·718	−30	51	23·24			
		3 Juno 1969 U.T.									
1017	May	15·72721	19	01	11·262	−06	03	50·00	+0·006	−4·08	W
1018	May	15·72721	19	01	11·288	−06	03	48·76			
1019	May	29·68784	18	56	20·390	−05	18	25·74	+0·013	−4·18	S
1020	May	29·68784	18	56	20·420	−05	18	26·26			
1021	July	10·56104	18	23	59·856	−05	17	20·86	+0·044	−4·18	W
1022	July	10·56104	18	23	59·863	−05	17	20·72			
1023	July	16·53889	18	19	01·412	−05	36	12·60	+0·038	−4·14	R
1024	July	16·53889	18	19	01·428	−05	36	12·94			
1025	Aug.	05·46910	18	06	08·898	−07	04	54·97	+0·018	−3·94	W
1026	Aug.	05·46910	18	06	08·862	−07	04	55·70			
1027	Aug.	11·45861	18	03	48·364	−07	36	55·68	+0·041	−3·87	S
1028	Aug.	11·45861	18	03	48·353	−07	36	55·26			
1029	Aug.	18·45296	18	02	07·406	−08	15	59·47	+0·086	−3·79	S
1030	Aug.	18·45296	18	02	07·411	−08	15	59·58			
1031	Sept.	12·37307	18	05	31·028	−10	36	29·16	+0·044	−3·45	S
1032	Sept.	12·37307	18	05	30·994	−10	36	29·71			
		11 Parthenope 1969 U.T.									
1033	Mar.	19·73638	15	19	59·526	−11	35	27·54	+0·027	−3·30	W
1034	Mar.	19·73638	15	19	59·485	−11	35	28·20			
1035	April	16·65229	15	10	35·208	−09	56	32·52	+0·024	−3·53	W
1036	April	16·65229	15	10	35·189	−09	56	32·40			
1037	April	28·61714	15	00	53·402	−09	02	51·04	+0·037	−3·66	S
1038	April	28·61714	15	00	53·372	−09	02	50·36			
1039	May	15·55632	14	45	09·568	−07	56	55·40	+0·026	−3·81	W
1040	May	15·55632	14	45	09·544	−07	56	54·70			
1041	May	21·53436	14	39	57·448	−07	40	40·02	+0·020	−3·84	R
1042	May	21·53436	14	39	57·436	−07	40	39·82			
1043	June	11·47405	14	27	12·222	−07	26	54·53	+0·038	−3·88	S
1044	June	11·47405	14	27	12·216	−07	26	54·03			
1045	July	08·40328	14	27	51·094	−08	49	51·62	+0·046	−3·69	R
1046	July	08·40328	14	27	51·106	−08	49	51·69			
		39 Laetitia 1969 U.T.									
1047	Sept.	16·77437	03	59	50·903	+08	31	01·04	+0·045	−5·91	W
1048	Sept.	16·77437	03	59	50·898	+08	31	00·26			
1049	Oct.	14·69986	04	02	01·602	+05	50	06·82	+0·046	−5·60	W
1050	Oct.	14·69986	04	02	01·605	+05	50	07·38			
1051	Oct.	20·66764	03	59	40·360	+05	11	13·51	+0·003	−5·52	R
1052	Oct.	20·66764	03	59	40·360	+05	11	13·80			
1053	Nov.	03·63497	03	50	54·433	+03	45	01·33	+0·038	−5·35	S
1054	Nov.	03·63497	03	50	54·405	+03	45	01·63			
		40 Harmonia 1969 U.T.									
1055	April	16·69772	16	31	27·058	−17	22	54·31	−0·010	−2·46	W
1056	April	16·69772	16	31	27·050	−17	22	53·92			

TABLE I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		40 Harmonia—*continued*									
1057	May	15·61004	16	11	25·076	−16	49	37·63	+0·007	−2·54	W
1058	May	15·61004	16	11	25·097	−16	49	37·65			
1059	May	19·59624	16	07	16·517	−16	44	13·90	+0·005	−2·56	R
1060	May	19·59624	16	07	16·460	−16	44	13·83			
1061	June	12·51997	15	43	07·379	−16	23	14·12	+0·026	−2·61	W
1062	June	12·51997	15	43	07·382	−16	23	14·41			
1063	July	08·44313	15	30	50·467	−16	51	27·82	+0·035	−2·54	R
1064	July	08·44313	15	30	50·540	−16	51	27·28			
1065	Aug.	05·37274	15	40	30·498	−18	30	12·09	+0·033	−2·31	W
1066	Aug.	05·37274	15	40	30·506	−18	30	11·83			
		1 Ceres 1970 U.T.									
1067	Nov.	04·55704	02	00	40·772	−00	25	48·58	+0·040	−4·83	R
1068	Nov.	04·55704	02	00	40·786	−00	25	48·44			
1069	Nov.	27·45974	01	44	20·424	−00	12	16·20	−0·032	−4·86	S
1070	Nov.	27·45974	01	44	20·406	−00	12	16·64			
1071	Dec.	17·42366	01	39	04·242	+01	06	09·02	+0·037	−5·03	W
1072	Dec.	17·42366	01	39	04·270	+01	06	08·88			
		3 Juno 1970 U.T.									
1073	Oct.	27·65034	03	47	43·122	−00	39	53·48	+0·032	−4·80	W
1074	Oct.	27·65034	03	47	43·088	−00	39	53·30			
1075	Dec.	17·47781	03	18	00·648	−04	26	10·45	−0·008	−4·30	W
1076	Dec.	17·47781	03	18	00·686	−04	26	10·06			
		11 Parthenope 1970 U.T.									
1077	Oct.	07·60135	01	34	14·456	+01	29	47·20	−0·003	−5·08	R
1078	Oct.	07·60135	01	34	14·493	+01	29	46·74			
1079	Nov.	16·46861	01	04	41·305	−00	55	52·35	−0·012	−4·77	R
1080	Nov.	16·46861	01	04	41·330	−00	55	51·84			
1081	Nov.	27·44020	01	02	25·830	−00	41	42·16	−0·002	−4·80	S
1082	Nov.	27·44020	01	02	25·858	−00	41	42·54			
		18 Melpomene 1970 U.T.									
1083	Mar.	18·77517	16	35	35·896	−09	47	35·20	−0·026	−3·56	R
1084	Mar.	18·77517	16	35	35·892	−09	47	36·38			
1085	May	04·67124	16	29	18·539	−05	45	53·24	+0·063	−4·13	S
1086	May	04·67124	16	29	18·504	−05	45	52·03			
1087	June	04·55190	16	00	18·486	−03	53	15·96	+0·018	−4·36	S
1088	June	04·55190	16	00	18·497	−03	53	16·31			
1089	June	25·48967	15	43	11·117	−04	06	22·27	+0·039	−4·33	R
1090	June	25·48967	15	43	11·074	−04	06	22·50			
1091	June	29·47042	15	40	58·884	−04	17	41·84	+0·018	−4·30	S
1092	June	29·47042	15	40	58·888	−04	17	41·86			
1093	July	06·44245	15	38	07·792	−04	43	35·84	−0·003	−4·25	R
1094	July	06·44245	15	38	07·806	−04	43	35·27			
1095	July	24·40418	15	36	58·492	−06	19	04·66	+0·033	−4·03	S
1096	July	24·40418	15	36	58·484	−06	19	03·55			
		433 Eros 1970 U.T.									
1097	July	02·60653	18	53	53·457	−33	11	58·49	+0·061	−0·10	R
1098	July	02·60653	18	53	53·437	−33	11	58·98			

Table II

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
995	14564	0·374015	53·330	16·98	1017	6508	0·299358	23·679	20·76
	14590	0·258250	56·933	24·22		6571	0·257466	54·713	27·55
	14611	0·367736	57·139	17·00		6448	0·443176	54·710	46·50
996	14548	0·281278	06·932	15·84	1018	6516	0·230180	03·769	10·27
	14600	0·314820	11·168	42·10		6562	0·358568	41·927	08·41
	14607	0·403903	15·177	12·79		6441	0·411251	11·299	32·79
997	14578	0·204604	16·180	31·56	1019	6459	0·323544	42·846	52·09
	14589	0·495382	57·534	14·01		6403	0·377194	32·304	26·86
	14639	0·300014	08·118	07·36		6441	0·299262	11·299	32·79
998	14569	0·339497	30·824	30·50	1020	6388	0·379892	42·213	36·98
	14602	0·326420	37·599	29·26		6448	0·284840	54·710	46·50
	14632	0·334083	25·449	40·63		6475	0·335268	26·757	46·46
999	13833	0·368586	54·243	37·88	1021	6162	0·442554	51·475	21·93
	13910	0·302196	04·132	37·09		6182	0·358580	29·759	20·99
	14569	0·329219	30·824	30·50		6193	0·198866	15·308	16·96
1000	14539	0·298209	56·352	52·36	1022	6148	0·378934	54·487	50·67
	13838	0·238984	22·190	15·16		6192	0·259696	10·129	16·75
	13903	0·462807	32·865	35·59		6199	0·361371	17·381	09·43
1001	13756	0·356666	36·138	17·84	1023	6118	0·336908	27·192	40·39
	13791	0·245235	34·016	11·54		6148	0·309062	54·487	50·67
	13828	0·398099	46·436	01·66		6160	0·354030	38·868	48·85
1002	13753	0·337810	20·184	50·06	1024	6125	0·367491	00·424	58·99
	13810	0·372436	33·077	04·66		6166	0·288220	21·698	24·82
	13826	0·289754	41·582	52·76		6162	0·344289	26·975	02·95
1003	11189	0·219445	01·189	39·64	1025	6091	0·301898	21·958	46·85
	11211	0·446896	32·798	19·60		6095	0·357820	18·977	36·26
	11238	0·333658	46·126	15·61		6121	0·340282	32·238	35·80
1004	11179	0·264796	24·708	46·00	1026	6096	0·246418	38·842	04·49
	11227	0·400678	03·698	16·39		6105	0·490070	21·637	07·68
	11237	0·334525	34·215	53·26		6109	0·263513	09·311	26·68
1005	11136	0·352008	32·449	08·86	1027	6083	0·356236	31·950	06·24
	11179	0·316408	24·707	46·00		6091	0·354764	21·958	46·85
	11188	0·331583	24·794	23·73		6109	0·289000	09·311	26·68
1006	11131	0·338958	11·860	24·66	1028	6079	0·338689	08·583	26·13
	11169	0·258732	40·213	15·30		6094	0·358241	53·797	06·77
	11189	0·402310	01·189	39·64		6107	0·303070	40·598	38·72
1007	11083	0·305236	22·552	28·62	1029	6079	0·373619	08·583	26·13
	11105	0·379652	45·145	52·83		6086	0·366203	14·485	36·51
	11131	0·315112	11·860	24·65		6091	0·260178	21·958	46·85
1008	11075	0·371921	39·698	46·80	1030	6071	0·386776	56·019	14·85
	11125	0·294868	37·172	43·60		6077	0·341556	58·833	38·76
	11127	0·333210	41·096	02·97		6107	0·271668	40·598	38·72
1009	10967	0·292881	47·655	28·11	1031	6172	0·368442	51·809	27·82
	10996	0·277950	22·243	50·60		6181	0·426933	46·690	55·44
	11030	0·429170	22·324	30·08		6102	0·204625	51·777	38·15
1010	10988	0·286381	16·462	27·75	1032	6171	0·396462	47·824	47·27
	11000	0·353834	42·166	40·66		6173	0·266924	58·381	17·22
	11022	0·359785	36·329	35·05		6189	0·336614	45·647	34·20
1011	10973	0·267082	09·798	03·39	1033	5359	0·172162	37·445	35·83
	11007	0·288736	17·337	52·53		5371	0·604755	21·795	37·63
	11009	0·444182	26·852	55·43		5375	0·223083	48·671	04·45
1012	10962	0·280020	34·284	06·10	1034	5353	0·483527	55·719	24·87
	10988	0·381236	16·462	27·75		5383	0·269561	48·755	59·68
	11030	0·338774	22·324	30·08		5394	0·246912	59·868	20·81
1013	10964	0·273288	37·951	51·50	1035	5307	0·278631	03·710	49·14
	11009	0·376223	26·852	55·43		5315	0·474574	31·499	17·84
	11015	0·350488	54·244	18·08		5325	0·246795	25·706	47·07
1014	10958	0·414380	25·277	17·28	1036	5306	0·322570	58·773	11·39
	11017	0·320457	12·132	13·52		5314	0·482958	22·244	28·72
	11022	0·265163	36·329	35·05		5333	0·194473	47·164	44·52
1015	11007	0·178876	17·337	52·53	1037	5256	0·290680	41·909	16·85
	11021	0·370740	35·711	15·34		5278	0·400143	10·208	19·44
	11026	0·450384	48·409	17·34		5279	0·309177	14·135	59·70
1016	10975	0·329941	18·650	05·60	1038	5254	0·307797	55·126	25·92
	11028	0·320620	07·110	54·40		5273	0·325592	37·996	24·18
	11049	0·349439	11·339	58·30		5286	0·366611	33·492	54·45

TABLE II—*continued*

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
1039	5164	0·348064	21·776	42·90	1061	5745	0·266856	19·576	58·97
	5200	0·297330	23·506	42·79		5760	0·457108	15·677	11·27
	5208	0·354607	59·475	08·52		5790	0·276037	13·324	01·52
1040	5180	0·279450	45·739	30·76	1062	5758	0·539288	08·040	40·40
	5190	0·247398	05·182	05·04		5764	0·275864	34·203	23·48
	5197	0·473152	36·731	02·87		5774	0·184848	20·289	49·83
1041	5153	0·308526	33·901	07·16	1063	5673	0·228890	55·073	50·24
	5164	0·522049	21·776	42·90		5706	0·370721	28·314	59·03
	5181	0·169425	03·863	08·41		5714	0·400389	38·947	52·57
1042	5142	0·191024	33·397	59·49	1064	5682	0·249556	47·349	57·25
	5162	0·347734	18·161	16·81		5707	0·316758	30·815	47·17
	5178	0·461242	41·416	07·33		5711	0·433686	41·408	28·17
1043	5099	0·259396	42·241	09·63	1065	5737	0·285978	31·277	46·84
	5102	0·277064	30·246	01·65		5762	0·357858	11·843	58·34
	5120	0·463540	10·443	31·30		6502	0·356164	12·104	38·48
1044	5096	0·293264	07·474	37·97	1066	5735	0·420764	39·355	50·75
	5114	0·389346	10·514	22·45		5763	0·273150	28·890	13·92
	5121	0·317389	42·455	59·26		6516	0·306085	10·035	04·90
1045	5102	0·456935	30·246	01·65	1067	401	0·332910	48·191	33·30
	5117	0·192322	42·754	50·46		402	0·353923	53·884	06·90
	5118	0·350743	53·714	14·14		429	0·313167	41·228	32·83
1046	5103	0·325927	41·324	33·53	1068	394	0·229158	54·235	40·10
	5111	0·420490	49·501	45·53		414	0·468904	58·568	10·36
	5126	0·253583	20·268	57·52		423	0·301938	05·132	58·80
1047	1474	0·241873	52·367	56·38	1069	347	0·435936	23·188	34·83
	1481	0·396990	16·739	38·81		349	0·378618	56·725	29·31
	1505	0·361137	54·173	04·70		364	0·185446	23·351	21·86
1048	1459	0·258617	21·720	31·40	1070	342	0·295676	26·223	10·66
	1483	0·372030	38·153	40·98		352	0·297586	47·449	46·95
	1511	0·369354	12·340	30·73		358	0·406738	07·247	36·13
1049	1480	0·234461	09·907	31·13	1071	462	0·256316	48·054	15·48
	1503	0·384944	14·867	32·35		496	0·312156	00·799	22·80
	1514	0·380595	11·598	41·11		330	0·431528	17·432	26·96
1050	1475	0·288546	47·147	02·00	1072	321	0·292418	57·325	42·25
	1498	0·283250	58·308	23·05		341	0·271852	12·692	06·17
	1517	0·428204	35·070	49·15		477	0·435730	09·338	25·37
1051	1175	0·343584	09·887	31·03	1073	813	0·340551	29·474	55·22
	1178	0·264260	34·314	44·96		821	0·481560	41·081	17·01
	1500	0·392156	03·740	47·80		835	0·177889	09·637	13·21
1052	1170	0·461346	47·101	01·87	1074	806	0·267192	35·826	31·50
	1189	0·359028	14·104	19·81		819	0·503225	13·574	35·03
	1490	0·179626	23·683	08·05		846	0·229583	25·708	34·56
1053	1114	0·268911	34·968	30·34	1075	778	0·339152	55·444	26·84
	1142	0·481052	05·164	53·41		798	0·278336	35·772	55·04
	1152	0·250037	22·420	00·98		824	0·382511	42·265	47·58
1054	1118	0·256418	06·246	05·04	1076	792	0·303834	22·483	36·91
	1130	0·328616	58·605	56·41		794	0·432633	29·511	40·31
	1153	0·414966	36·602	30·71		815	0·263533	23·795	14·82
1055	5962	0·408096	29·831	51·03	1077	431	0·428345	42·921	47·48
	5972	0·363720	43·761	54·20		462	0·270884	48·054	15·48
	5983	0·228184	29·388	36·40		321	0·300772	57·325	42·25
1056	5946	0·271454	51·458	04·30	1078	294	0·292348	25·272	53·43
	5973	0·318288	58·046	03·33		327	0·254141	51·963	10·51
	5986	0·410258	44·513	00·89		454	0·453511	40·417	41·69
1057	5886	0·312277	09·902	39·72	1079	203	0·382112	35·713	04·97
	5898	0·382100	19·795	30·80		225	0·242706	17·621	38·47
	5910	0·305623	49·554	49·46		248	0·375182	51·603	58·06
1058	5876	0·413516	31·499	07·44	1080	231	0·299182	52·483	48·52
	5889	0·162568	59·650	24·49		209	0·342750	16·712	35·40
	5921	0·423916	43·754	47·42		224	0·358067	13·542	58·63
1059	5867	0·278314	50·932	58·89	1081	198	0·298774	00·516	20·14
	5876	0·260597	31·499	07·44		209	0·254116	16·712	35·40
	5886	0·461089	09·902	39·72		214	0·447110	14·138	16·29
1060	5854	0·373228	52·218	54·77	1082	195	0·352826	16·210	27·68
	5889	0·322338	59·650	24·49		204	0·358212	43·680	50·60
	5895	0·304434	01·478	40·91		222	0·288961	22·958	33·81

TABLE II—*continued*

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
1083	5726	0·290234	23·050	40·62	1091	5471	0·287374	53·049	01·34
	5773	0·345074	31·715	50·31		5473	0·470799	47·973	52·99
	5741	0·364691	51·687	58·41		5481	0·241827	38·328	34·11
1084	5724	0·265600	05·758	09·74	1092	5460	0·250561	24·429	40·06
	5772	0·168868	49·712	59·30		5472	0·382150	28·971	06·67
	5751	0·565533	33·264	36·75		5489	0·367288	37·176	04·15
1085	5672	0·491657	40·090	34·89	1093	5453	0·352652	19·923	31·88
	5702	0·187266	05·146	06·10		5460	0·291052	24·429	40·06
	5738	0·321077	40·878	40·83		5480	0·356296	18·414	25·24
1086	5674	0·318686	08·997	10·42	1094	5445	0·417015	14·493	54·04
	5691	0·448379	55·228	25·00		5473	0·291265	47·973	52·99
	5728	0·232936	31·857	41·56		5474	0·291720	01·334	30·77
1087	5541	0·352608	26·804	03·00	1095	5452	0·272100	12·299	23·31
	5557	0·384825	33·926	56·26		5472	0·356943	49·290	28·05
	5578	0·262567	46·306	36·28		5465	0·370957	11·438	21·98
1088	5533	0·289235	59·138	16·17	1096	5449	0·229716	25·948	51·50
	5550	0·345087	29·362	12·14		5470	0·344804	39·146	23·88
	5585	0·365678	30·008	48·34		5466	0·425480	10·547	33·41
1089	5473	0·384198	47·972	52·99	1097	10247	0·283520	48·653	22·78
	5489	0·307772	37·176	04·15		10310	0·445704	15·011	09·05
	5491	0·308029	43·808	55·78		10314	0·270776	55·680	46·62
1090	5464	0·173958	01·561	07·08	1098	10264	0·243272	13·779	46·35
	5480	0·472167	18·414	25·23		10272	0·415182	50·171	04·89
	5500	0·353875	53·361	06·45		10336	0·341546	15·964	17·89

(Received 3. 9. 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 11–29, 1971

The Geology of the Coolac Serpentinite and Adjacent Rocks East of Tumut, New South Wales

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Abstract—The Coolac Serpentinite, east of Tumut in southern New South Wales, is a complex, steeply inclined ultrabasic belt 54 km. long and up to $3 \cdot 5$ km. wide occupying a tectonic zone between the Lower Devonian Burrinjuck Granite to the east and low-grade regionally metamorphosed sediments and volcanics of possible Ordovician to basal Devonian age to the west. The sedimentary-volcanic sequence and the Coolac Serpentinite are intruded by the Middle Devonian Bogong Granite and Killimicat Adamellite. (?) Middle Devonian rhyodacitic ignimbrites overlie the sedimentary-volcanic sequence in places, and areas of Tertiary sediments and basaltic rocks occur upon an erosional surface on the Coolac Serpentinite and Burrinjuck Granite.

New and revised data are presented on the stratigraphy and petrology of the area east of Tumut, emphasizing the ultrabasic belt, which comprises variably serpentinized ultrabasic rocks, numerous deformed and metasomatized tectonic inclusions of crustal rocks, and local occurrences of sulphide-rich rocks.

It is suggested that the process of serpentinization of the primary ultrabasic rocks has been concomitant with the metasomatic changes observed within the tectonic inclusions and at the margins of the belt, and has been characterized by a large relative loss of Ca from the ultrabasic rocks to the metasomatic products. Basic, ultrabasic and calc-silicate hornfelses within the aureole of the Bogong Granite are interpreted as being isochemically derived from rocks which had undergone prior metasomatic alteration within the serpentinite environment.

Introduction

This paper describes the geology of an area of approximately 460 km.^{2} in the Brungle-Adjungbilly—Goobarragandra district centred about 16 km. east-north-east of Tumut and 28 km. south-east of Gundagai in southern New South Wales. It is based on field and laboratory investigations undertaken by the authors while completing B.Sc. (Honours) degrees at the University of Sydney during 1967–68 and further studies by two of the authors (P.M.A. and A.J.I.) since 1967.

Early work in the area was confined to chromite, copper and other mineral prospects by officers of the New South Wales Geological Survey (Carne, 1896, 1908; Jaquet, 1917; Harper, 1917, 1920). Reconnaissance mapping of the southern part was carried out by Adamson (1960) and the northern part was studied by Veeraburus (1963). More detailed studies of the Coolac Serpentinite were made by Fraser (1961, 1967) and notably by Golding (1962, 1963, 1966, 1969*a*, 1969*b*) and by Golding and Bayliss (1968). The copper prospects of the area were investigated by Cochrane *et al.* (1967) and the McAlpine Mine in particular by Ashley (1969*b*) and by Lawrence and Golding (1969).

Stratigraphic Summary

Apart from several occurrences of high-grade metamorphic rocks of unknown age closely associated with the Coolac Serpentinite,[1] the oldest rocks in the sequence east of Tumut are the folded basic rocks of the Bullawyarra Schist[1] and metasediments of the Bumbolee Creek Beds.[1] The relationship between these two units is unknown but they are possible stratigraphic equivalents, both unconformably underlying the (?) Middle to Upper Silurian Blowering Beds,[2] an extensive unit of dacitic volcanics and fossiliferous quartzofeldspathic and calcareous sediments. Possibly overlying or contemporaneous with the Blowering Beds is the Honeysuckle Beds,[1] a discontinuous unit of altered basic volcanics and quartzofeldspathic sediments. The low-grade metamorphosed dacitic and basic volcanics and minor sediments of the (?) Middle to Upper Silurian Goobarragandra Beds[2] in the south of the area closely resemble rocks of the Blowering and Honeysuckle Beds. The unit cannot be traced to the north or west because of the intervening Bogong Granite and Coolac Serpentinite. Acidic volcanics of the (?) Lower to Middle Devonian Gatelee Ignimbrite[1] unconformably overlie the Bullawyarra Schist, Blowering and Honeysuckle Beds in places.

TABLE 1
Stratigraphic Column

Proposed Age	Unit Name and Rock Types
Quaternary ..	Alluvium
(?) Pliocene ..	Alkali dolerite, olivine basalt, analcime basanite, olivine nephelinite
(?) Eocene-Miocene	Sands, gravels, ferruginous sandstone, limonite
Middle Devonian (385 million years)	BOGONG GRANITE Biotite adamellite, biotite-hornblende micro-adamellite, adamellite aplite, leuco-adamellite, alaskite
	KILLIMICAT ADAMELLITE[1] Biotite adamellite, biotite granite, muscovite granite
	Muscovite granite
(?) Lower to Middle Devonian	GATELEE IGNIMBRITE[1] Banded rhyodacitic ignimbrite
	COOLAC SERPENTINITE[1] Schistose and massive serpentinite, partly serpentinized harzburgite, clinopyroxenite, wehrlite, lherzolite ; chromitite, rodingitic dykes. Tectonic inclusions of rodingitic rocks, chlorite-rich rocks, gabbro, metadolerite, metabasalt, amphibolitic rocks, deformed acidic igneous rocks, sedimentary rocks
(?)	High-grade foliated metamorphics closely associated with the Coolac Serpentinite : amphibolite, quartzite, schists, quartzofeldspathic gneiss
Lower Devonian (400 million years)	BURRINJUCK GRANITE Massive to foliated biotite granodiorite and adamellite. Quartz, microgranite, porphyritic microgranodiorite and microadamellite dykes. Intermediate and basic xenoliths. Mylonites and breccias
(?) Middle Silurian–basal Devonian	HONEYSUCKLE BEDS[1] Metabasalt, spilite, albite dolerite, porphyritic metadacite, slate, siliceous and quartzofeldspathic-lithic metasandstone. Calc-silicate-rich rocks ; basic, ultrabasic and calc-silicate hornfelses
	BLOWERING BEDS[2] Porphyritic dacite and rhyodacite, dacitic tuff, andesite, feldspathic subgreywacke, tuffaceous sandstone, siltstone, mudstone, conglomerate, lithic calcareous sandstone, limestone
	GOOBARRAGANDRA BEDS[2] Metadacite and metarhyodacite ; metabasalt, metadolerite and spilite ; slaty mudstone, metasiltstone, quartzofeldspathic metasandstone. Basic, ultrabasic, calc-silicate and pelitic hornfelses
(?) Pre-Middle Silurian	BUMBOLEE CREEK BEDS[1] Slaty shale, quartz-rich siltstone, quartzofeldspathiclithic sandstone
	BULLAWYARRA SCHIST[1] Slightly foliated metabasalt, greenschist, epidote amphibolite

[1] New name reserved by the Stratigraphic Nomenclature Committee, Bureau of Mineral Resources, Geology and Geophysics.
[2] Variation on previous name : Blowering Porphyry (Hall and Relph, 1956), Goobarragandra Porphyry (Adamson, 1960).

The Lower Devonian Burrinjuck Granite has intruded and metamorphosed rocks of the Goobarragandra Beds in the south of the area, and shows a faulted contact against the (?) Lower to Middle Devonian Coolac Serpentinite. The latter, a complex belt of variably serpentinized ultrabasic rocks associated with numerous deformed and metasomatized inclusions and several occurrences of sulphide-rich rocks, also shows faulted contacts with the Blowering and Honeysuckle Beds to the west and the Goobarragandra Beds to the south.

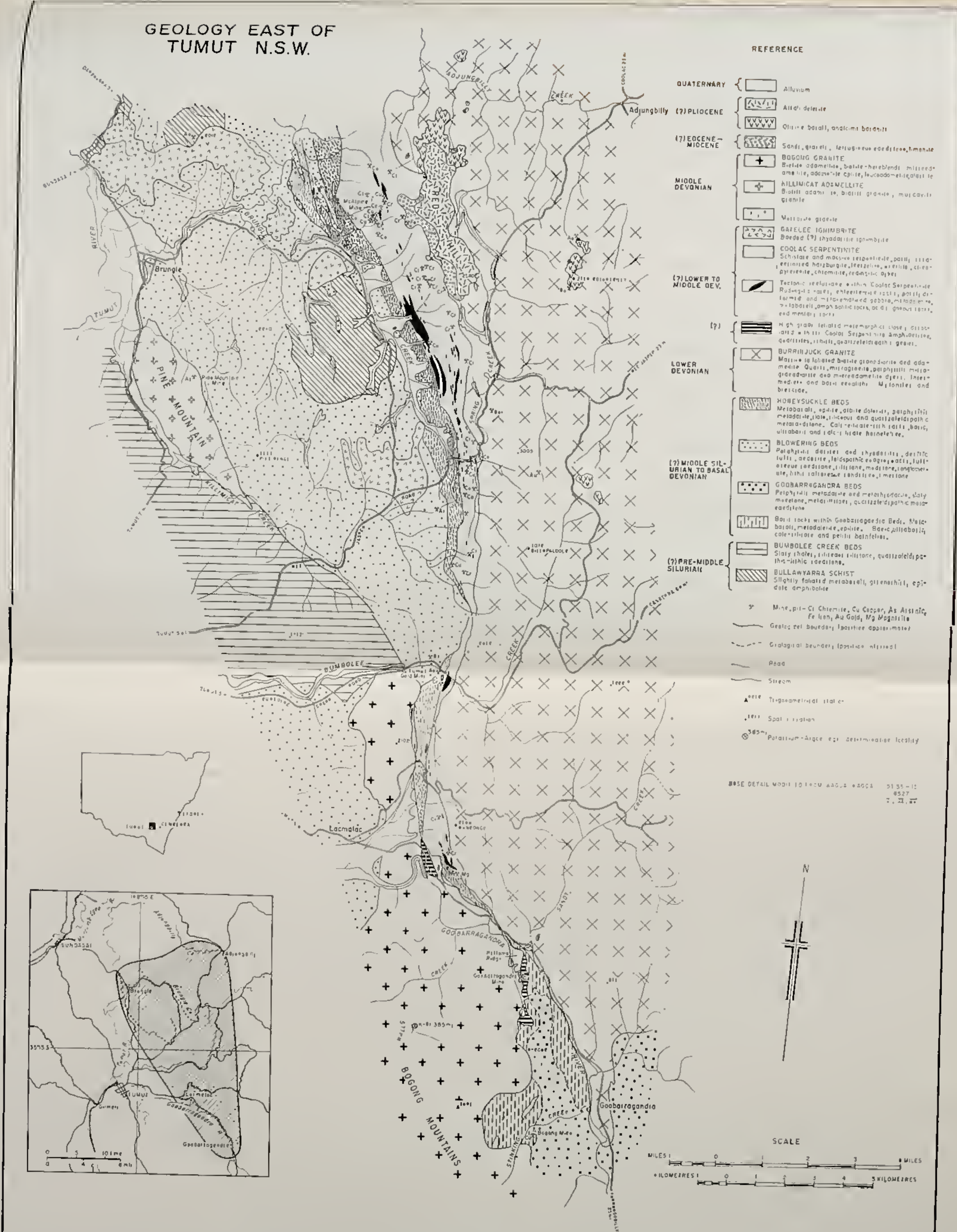
GEOLOGY EAST OF TUMUT N.S.W.
REFERENCE
QUATERNARY
Alluvium
(?) PLIOCENE
(?) EOCENE–MIOCENE
MIDDLE DEVONIAN
BOGONG GRANITE
KILLIMICAT ADAMELLITE
GATELEE IGNIMBRITE
COOLAC SERPENTINITE
(?) LOWER TO MIDDLE DEV.
(?)
BURRINJUCK GRANITE
LOWER DEVONIAN
HONEYSUCKLE BEDS
BLOWERING BEDS
(?) MIDDLE SILURIAN TO BASAL DEVONIAN
GOOBARRAGANDRA BEDS
BUMBOLEE CREEK BEDS
Slaty shales, siltstone, quartzofeldspathic-lithic sandstone.
(?) PRE-MIDDLE SILURIAN
BULLAWYARRA SCHIST
Road
Stream
Adjungbilly
Brungle
Lacmalac
Goobarragandra
PINE MOUNTAIN
BOGONG MOUNTAINS
BUMBOLEE
GOOBARRAGANDRA
SCALE
MILES
KILOMETRES
N

FIGURE 1.

The Middle Devonian Bogong Granite has intruded and metamorphosed the Bumbolee Creek, Blowering, Honeysuckle and Goobarragandra Beds, and the Coolac Serpentinite, while the apparently related Killimicat Adamellite[1] has intruded the Bumbolee Creek and Blowering Beds. Tertiary alkalic basaltic rocks associated with fluviatile sediments overlie the Coolac Serpentinite and Burrinjuck Granite at several places in the north of the area (Table 1).

Physiography

The west and north-west parts of the area, developed on the sedimentary-volcanic sequence, Killimicat Adamellite and the northern extension of the Bogong Granite, is undulating to hilly, but some of the larger streams have alluviated tracts up to 3 km. wide. Elevations in the far north-west are less than 250 m. above sea level and local relief attains 400–450 m. The eastern section (developed on the Burrinjuck Granite and Tertiary rocks) and southern section (on the Goobarragandra Beds and Bogong Granite) comprise a plateau region rising from 600 m. in the north-east to over 1,000 m. in the south. Parts of this region have been heavily dissected by the antecedent tributaries of the Tumut River (Adjungbilly, Spring, Brungle and Bumbolee Creeks, and the Goobarragandra River). North of the Goobarragandra River, the eastern plateau block is separated from the lower western zone by a prominent scarp (the Honeysuckle Range), which is primarily the topographic expression of the Coolac Serpentinite (Plate I–1).

Bullawyarra Schist

The Bullawyarra Schist occupies an area of about 10 km.^{2} centred 8 km. east of Brungle, and consists of slightly foliated metabasalt grading to highly deformed greenschist and epidote amphibolite (with fold axes plunging at 60° to 70° towards the south-east).

The slightly foliated metabasalt[3] contains fine-grained prismatic actinolite and epidote with minor albite, quartz, chlorite, sphene and magnetite, and contains amygdales of epidote + quartz($\pm$albite$\pm$calcite$\pm$chlorite). The greenschists are of two types: a minor variety containing fine-grained platy chlorite with quartz, calcite and epidote, and a more common type containing fine- to medium-grained, preferentially oriented prismatic actinolite with epidote and minor chlorite, albite, quartz, sphene and magnetite. The epidote amphibolite is slightly foliated and contains medium-grained epidote, actinolite and albite with accessory green biotite, chlorite, sphene, magnetite and haematite.

[3] The prefix meta- is used in this paper to denote a metamorphic rock in which the original microstructure is preserved.

Bumbolee Creek Beds

The Bumbolee Creek Beds is a sequence of tightly folded slaty shale, quartz-rich siltstone and sandstone of unknown thickness occupying at least 50 km.^{2} in the west of the mapped area. The orientation of bedding, mesoscopic fold axes and bedding-cleavage relationships indicates a large antiform structure plunging steeply to the south-east. Similarities in style and orientation of folding and the metamorphic grade suggest that the Bullawyarra Schist and Bumbolee Creek Beds are possible lateral stratigraphic equivalents.

Thinly bedded slaty shale and siltstone (comprising about 80% of the unit) form an alternating fine-coarse sequence characterized by cross-bedding, load casts, convolute lamination, slumping, worm burrows and a moderately well developed slaty cleavage. The siltstone contains sub-angular to sub-rounded detrital grains (0·01–0·06 mm.) of quartz (30–70%), albite (up to 10%), muscovite and partly chloritized biotite (up to 20%) in a matrix of very fine-grained quartz, chlorite, muscovite, tourmaline and iron oxide. Finer grained rocks have progressively less quartz and more mica and chlorite.

The sandstone displays a bedding thickness of 15–30 cm. (rarely up to 1 m.) and exhibits graded bedding, load casts and slumping. The sandstone contains subangular detrital fragments (0·1–1 mm. in size) of quartz (30–60%), albite (5–30%) and rock fragments (10–45%; comprising shale, quartzite, quartz-muscovite schist and fine-grained metabasalt), and epidote, sphene, calcite, muscovite, chlorite, tourmaline, apatite and iron oxide constitute a matrix of up to 15%.

Blowering Beds

The Blowering Beds is the most extensive unit in the mapped area and also crops out to the north-east and south of Tumut. The diverse rock types are intimately associated and the general lack of good outcrop precludes ready subdivision of the unit. The rocks are dominantly acidic volcanic in origin, comprising porphyritic dacite and rhyodacite, dacitic and rhyodacitic tuff and minor andesite, with interbedded sandstone (two distinct types), lithic calcareous sandstone, siltstone, mudstone, conglomerate and minor limestone.

Volcanic Rocks

The porphyritic dacite and rhyodacite are notable for their content of xenoliths and almandine garnet megacrysts. The rocks contain phenocrysts of quartz (15–25%), plagioclase (20–25%), and rarely K-feldspar, with xenoliths (8–10%) in a fine-grained groundmass (40–50%) of quartz, K-feldspar, plagioclase, biotite, chlorite, muscovite, epidote, iron oxide, sphene, zircon and apatite. The rounded xenoliths (up to 20 mm. across) comprise rhyodacite, spilite, quartzite, quartz-rich siltstone and minor muscovite-chlorite schist. The rounded quartz phenocrysts show embayments and undulose extinction. K-feldspar phenocrysts are clouded by fine sericitic mica, and tabular plagioclase phenocrysts exhibit normal progressive and oscillatory zoning from An_{21-27} to An_7, accentuated by fine inclusions of chlorite, sericitic mica, biotite, zircon, apatite, iron oxide, quartz and calcite.

Some of the dacitic volcanics are tuffaceous, characterized by phenocrystal fragments and reconstituted glass shards in a matrix rich in chlorite and greenish-brown biotite. The former glass shards are represented by elongated curved patches of fine-grained, polygonal quartz accompanied by anastomosing trains of iron oxide, chlorite and biotite. The apparently massive dacite and rhyodacite may also be welded tuffs whose original eutaxitic textures have been obliterated by devitrification and recrystallization (cf. Branch, 1966).

About 10% of the dacitic rocks examined contain fragmental crystals (up to 6 mm. across) of pink almandine-rich garnet ($n=1\cdot784\pm0\cdot005$, $a=11\cdot54$Å$\pm0\cdot01$Å), some of which contain large subhedral quartz grains. Such garnet megacrysts are not rare in rhyodacitic rocks (e.g. Edwards, 1936; Ryall, 1965; Taylor *et al.*, 1969), and with the embayed quartz phenocrysts characteristic of these rocks have been postulated by Green and Ringwood (1968) to represent possible liquidus phases of their host rhyodacite precipitated at depth. An analysis of a porphyritic garnet-bearing rhyodacite is presented in Appendix II.

Porphyritic andesitic rocks occur sporadically within the Blowering Beds, and contain phenocrysts (2–6 mm. across) of greenish-brown biotite, green hornblende and plagioclase (An_{25}) in a fine-grained groundmass of plagioclase, (?) K-feldspar, biotite, chlorite and a little quartz and epidote.

Sedimentary Rocks

The sandstone intercalated with the volcanics is dark greyish-green in colour and moderately well sorted (average detrital grainsize 0·1–1 mm.), forming beds up to 15 m. thick, and is composed of subrounded to subangular detrital quartz (12–65%), lithic fragments (15–55%), partly albitized plagioclase and microcline (7–30%) and minor sphene, biotite, iron oxide, tourmaline, zircon and chlorite in a matrix (1–3%) of chlorite and iron oxide with rare cement of microcrystalline quartz or calcite. The lithic fragments are dominantly igneous (spilite and rhyodacite) with minor siltstone, mudstone and muscovite-rich schist. According to the classification of Folk (1954), which is used throughout the paper, these rocks range from feldspathic subgreywacke through impure tuffaceous sandstone to tuffaceous sandstone.

In the north-western part of the mapped area, where acidic volcanics are rare, the sandstone of the unit differs, although it is also an impure tuffaceous type. The sandstone is thinly interbedded with mudstone and the sequences display graded and convolute bedding, lamination, slumping, washouts, load casts and brecciation. The sandstone contains partly albitized plagioclase (originally An_{40-50}; 20–50%), angular lithic fragments (metabasalt, granitic rocks, mudstone and (?) actinolite-chlorite schist; up to 20%), hornblende and augite (up to 15%) and minor quartz (up to 2%) in a matrix (15–50%) of very fine-grained chlorite, sericite, epidote and minor calcite and quartz. Lithic calcareous sandstone from the same area contains fragments of calcareous fossil material, mudstone and metabasalt, partly altered plagioclase and quartz in a very fine-grained matrix of chlorite, sericite, calcite and rare quartz.

Siltstone and mudstone are closely associated with, but subordinate to the sandstone. The dark green to dark greyish-purple siltstone contains subangular quartz with minor albite, iron oxide, green hornblende, tourmaline, biotite, muscovite, chlorite and epidote in a very fine-grained matrix of quartz and chlorite, and exhibits lamination, convolute bedding and slumping; some fine-grained quartz-rich examples resemble chert. The dark purple, greenish-brown and black mudstone contains fine-grained subangular quartz and muscovite in a very fine chloritic and micaceous matrix and displays a weak slaty cleavage.

Lenticular conglomerate beds are associated with the sandstone accompanying the dacitic volcanics, especially in an area 1–2 km. north of Bumbolee Creek. These rocks contain subangular boulders of rhyodacite, spilite, quartz-mica schist, siltstone and mudstone in a shaly matrix. A bed of conglomeratic limestone up to 170 m. thick, displaying an erosional lower contact with mudstone, contains fragmental fossiliferous limestone in a lithic calcarenite matrix. A small body of massive fossiliferous limestone occurs within sandstone and conglomerate about 1 km. north of Brungle Creek and 5·5 km. east-north-east of Brungle.

The Blowering Beds is the only recognized fossiliferous unit in the east Tumut sequence. Macrofossils are generally poorly preserved, however *Monograptus* sp. and small spiriferid brachiopods occur in mudstone exposed along a tributary of Bumbolee Creek, and the lithic calcareous sandstone, limestone and conglomeratic limestone contain *Heliolites* sp., *Acanthohalysites pycnoblastoides* Etheridge (1904) and unidentified crinoid stems and polyzoa. Conodonts including *Triconodella inconstans* Walliser (1964), *Ozarkadina* cf. *jaegeri* Walliser (1964) and *Belodina* sp. have been found in boulders of the conglomeratic limestone. A tentative Middle to Upper Silurian age for the unit is indicated.

Honeysuckle Beds

The term Honeysuckle Beds has been applied to a discontinuous unit (up to 900 m. wide) of low-grade metabasaltic and spilitic rocks with quartzofeldspathic metasediments and rare porphyritic metadacite that flanks much of the western margin of the Coolac Serpentinite within the area mapped. Relationships with the Blowering Beds are obscure owing to poor outcrop. However, the Honeysuckle Beds has been separated as a unit (possibly overlying or faulted against the Blowering Beds) on the basis of distinctive rock types and orientation of layering features (which parallel the serpentinite belt rather than bedding in the Blowering Beds).

Spilitic and Associated Rocks

The characteristic and dominant rock types of the Honeysuckle Beds, especially in the south, are low-grade metabasaltic and spilitic rocks (generally massive but in places brecciated or schistose) displaying relict intersertal, subtrachytic, porphyritic and rarely variolitic textures. Mineral assemblages are dominated by albite, chlorite, epidote-clinozoisite and tremolitic amphibole (each of which are locally enriched on a small but variable scale) with less common quartz and calcite, minor sphene, relict augite and disseminated haematite, pyrite, pyrrhotite, chalcopyrite and marcasite. Small bodies of medium-grained albite dolerite with subophitic textures also occur, and contain albite, augite, tremolite-actinolite, epidote, chlorite and minor sphene, " limonite ", calcite, ilmenite and leucoxene. Patches and monomineralic veins rich in prehnite, epidote, clinozoisite, garnet, diopside, tremolite, chlorite, calcite and albite are associated with the spilitic rocks, especially in the northern part of the unit close to the serpentinite belt, where there are also small areas of low-grade hornblende- and biotite-bearing porphyritic metadacite (essentially similar to rocks of the Blowering Beds).

Metasediments

The metasediments are subordinate except towards the north, where they comprise up to 60% of the unit. They range from fine-grained slate containing quartz$+$epidote$\pm$haematite$\pm$albite$\pm$sericite$\pm$chlorite$\pm$sphene to fine-grained quartz-rich sandstone (generally well sorted and weakly foliated) and medium- to coarse-grained quartzofeldspathic-lithic sandstone (displaying variable grainsize and graded bedding). The sandstone contains subangular grains of quartz and albite and in some cases subangular lithic fragments (quartz-rich siltstone) in a matrix (20–30%) containing variable quartz, epidote, albite, biotite, muscovite, tremolitic amphibole, garnet, chlorite and iron oxide. The metasediments, especially in the north, show similar calc-silicate veins and patches to the spilitic rocks and are also veined or replaced by quartz ($\pm$epidote).

The mineral assemblages in the basic rocks are of the type discussed by Vallance (1965, 1967) and Smith (1968). The calc-silicate veins and patches in both the spilitic and metasedimentary rocks also characterize the altered basic, rodingitic and other rocks occurring as tectonic inclusions in the Coolac Serpentinite and in other alpine ultrabasic bodies (e.g. Coleman, 1966, 1967). It is considered that the Honeysuckle Beds were originally submarine basaltic rocks and quartzofeldspathic sediments which have undergone low-grade metamorphism and metasomatism, the proximity of the serpentinite belt being an important factor in facilitating low-grade major element redistributions.

Goobarragandra Beds

In the Goobarragandra district, south-east of Tumut, a sequence of low-grade porphyritic metarhyodacite, metadacite, basic metavolcanics and minor arenaceous and pelitic metasediments (together with related higher grade hornfelses) has been termed the Goobarragandra Beds. The unit has not been subdivided, although it contains essentially similar rock types to the Honeysuckle and Blowering Beds combined, but with much less sedimentary material. To the east, the unit is continuous with the Peppercorn Beds (Walpole, 1952, 1964), which is best documented some 25 km. south-east of Goobarragandra (see also Legg, 1968).

The dacitic rocks are very similar to those of the Blowering Beds, although no garnetiferous or obviously tuffaceous examples have been noted. The rocks are strikingly porphyritic in quartz (embayed grains with undulose extinction), plagioclase (normally zoned from An_{32-47} to An_{16-18}), biotite (X=light yellowish-brown, Y=Z=deep red-brown) and very rarely K-feldspar, with a fine groundmass (45–60%) of quartz+K-feldspar with biotite, muscovite, plagioclase, apatite, zircon, chlorite, epidote and iron oxide. Those rocks occurring approximately east of the Yarrangobilly road are characterized by kinked biotite phenocrysts and a granophyric groundmass, whereas nearer the Bogong Granite the biotite occurs as aggregates (similar in shape to the phenocrysts) of small unstrained lath-like grains and the groundmass is microgranular (and contains albite+quartz patches). The latter features are interpreted as resulting from recrystallization, suggesting that the rocks experienced some strain (e.g. regional metamorphism) prior to thermal metamorphism by the Bogong Granite. An analysis of a porphyritic rhyodacite is presented in Appendix II.

The basic metavolcanics occur in a belt immediately south-west of the Goobarragandra River and also in the region west of the Bogong Copper Mine; they are intruded and metamorphosed by both the Burrinjuck and Bogong Granites. Low-grade metabasalt and metadolerite are the most widespread rock types, characterized by the mineral assemblage blue-green amphibole (mantling clinopyroxene)+albite (An_{7-9}) + ilmenite ± epidote ± green biotite±quartz. Of rare occurrence are: (*a*) volcanogenic breccias (composed of metabasaltic fragments in a fine matrix of volcanogenic detritus with patchy epidote, albite, chlorite and quartz), (*b*) pillows exhibiting epidote-rich selvedges surrounding a zone of albite varioles with interstitial amphibole and cores of lath-like albite, epidote and chlorite; Plate II–3), (*c*) variolites (containing albite varioles with amphibole and clinozoisite), and (*d*) amygdales (containing albite+tremolite-actinolite, epidote±albite and rarely quartz+chlorite+calcite).

The fine- to medium-grained, grey arenaceous metasediments (with rare graded bedding) contain detrital quartz, plagioclase (An_{31-40}), perthitic K-feldspar and minor zircon, apatite and iron oxide in a fine recrystallized matrix (20%) of quartz, feldspars and brown biotite aggregates, containing albite+quartz patches. Mica-rich pelitic rocks exhibit a crenulation cleavage.

Gatelee Ignimbrite

A distinctive purple banded rhyodacitic ignimbrite at least 100 m. thick occurring in four areas totalling about 10 km.^{2} to the north, east and south-east of Brungle has been termed the Gatelee Ignimbrite. The unit, gently folded about north-south axes, unconformably overlies the Bullawyarra Schist, Blowering and Honeysuckle Beds, and is tentatively correlated with similar rocks of the (?) Lower to Middle Devonian Boraig Group (Moye *et al.*, 1969) occurring near Talbingo about 55 km. south of Brungle.

The rocks tend to cap ridges and display subvertical columnar jointing normal to a prominent fine banding; they exhibit a hackly fracture and a dark brownish-purple colour, weathering to a pale mauve or cream. They contain 5–15% fragmental and rare partly resorbed phenocrysts (1–1·5 mm. across) of normally zoned plagioclase (An_{35-48} to An_{25-35}) and quartz in a finely laminated quartzofeldspathic groundmass showing oriented recrystallized flattened pumice lenticles and glassy shards. Fine-grained aggregates of iron oxide, sericite and epidote may be pseudomorphous after original mafic minerals. An analysis of a rhyodacitic ignimbrite is presented in Appendix II.

Burrinjuck Granite

The Burrinjuck Granite in the area studied represents the southernmost portion of a large batholith (190 km. long and up to 50 km. wide) extending north to Cowra (where it is termed the Young Granite). A K-Ar radiometric age determination (400 million years) at Micalong Creek 18 km. east of the mapped area (Evernden and Richards, 1962) tentatively places the age of the mass near the base of the Devonian. An age of 382 million years was obtained by the same authors on a small body allegedly of

Burrinjuck Granite about 5 km. south of Wee Jasper, but inspection of this mass reveals the rocks to be massive adamellites unlike the " normal " Burrinjuck Granite, but very similar to rocks of the Bogong Granite (385 million years). It is proposed that the Wee Jasper mass is a separate later intrusion.

The Burrinjuck Granite displays clear intrusive contacts (Plate II–4) with metabasaltic rocks of the Goobarragandra Beds (but limited contact metamorphism), and shows a faulted contact with the Coolac Serpentinite. The most common rock type is massive to foliated biotite granodiorite grading to adamellite, although xenoliths, veins and dykes of several types are widespread. Mylonites and breccias are well developed close to the serpentinite contact.

Granodiorite and Adamellite

The biotite granodiorite and adamellite (average grainsize 3–4 mm.) contain 30–40% quartz (anhedral grains with undulose extinction and deformation bands), 25–40% plagioclase (subhedral laths, some bent and microfaulted, with normal progressive and oscillatory zoning from An_{40-50} to An_{10-20}), 5–15% perthitic microcline, 20–25% biotite (deep red-brown, kinked or bent grains containing abundant oriented fine rutile needles), accessory ilmenite, apatite, zircon and secondary subradiating muscovite, very fine-grained sericitic mica, chlorite, clay minerals and epidote-clinozoisite. Foliation is defined by preferred orientation of lenticular quartz aggregates and biotite plates and aggregates. Incipient foliation is evident even in rocks remote from the serpentinite belt. Analyses 1–3 in Appendix II are of the " normal " massive granodiorite ; a mylonitic variety close to the contact with the serpentinite belt ; and a tectonic inclusion of Burrinjuck Granite within the belt.

Veins and Dykes

Quartz-rich veins (1–60 cm. wide) composed of strained quartz with minor chlorite, epidote-clinozoisite, pyrite or arsenopyrite are relatively common, as are narrow dykes of microgranite containing 40-50% quartz, 35–45% perthitic microcline (micrographic intergrowths with quartz are common), 5–10% plagioclase (An_{10-15}) and minor muscovite and biotite. Porphyritic microgranodiorite and micro-adamellite dykes up to 6 m. wide occur 4–6 km. north of Billapaloola T.S. and contain phenocrysts (up to 20 mm. across) of plagioclase (An_{19-33}), quartz and rare perthitic microcline in a finer-grained granular base of the same minerals with dark brown biotite, minor muscovite and iron oxide. All of the vein and dyke rocks exhibit identical deformation effects to the enclosing granodiorite.

Xenoliths

Small, generally ellipsoidal, biotite-rich xenoliths (rarely up to 60 cm. across) are common throughout the Burrinjuck Granite. Average grainsize is 0·5–1·5 mm., and they contain andesine, red-brown biotite and strained quartz with minor microcline, apatite and ilmenite. Of less common occurrence are large, irregular masses up to several hundred metres across of dioritic rocks intruded by partly contaminated granodiorite containing up to 20% green hornblende. The dioritic rocks (average grainsize 0·5–2 mm., with plagioclase and quartz phenocrysts up to 10 mm. in porphyritic examples), contain 30–50% andesine, up to 15% quartz, up to 5% microcline, 20–50% green and brown hornblende, up to 10% tremolite-actinolite, up to 10% red-brown biotite and minor apatite, zircon, sphene, chlorite and iron oxide. Rare metabasaltic xenoliths containing quartz ocelli occur near some contacts with the Goobarragandra Beds.

Mylonites and Breccias

Narrow, discontinuous zones (up to 100 m. wide) of mylonitic and brecciated granitic rocks occur in close proximity and parallel to the Coolac Serpentinite (although sporadic mylonite zones occur up to 2·5 km. east of the contact). The mylonites contain angular to rounded fragments of deformed quartz and plagioclase (1–2 mm. across) in a fine, laminated base of recrystallized quartz and feldspar with minor chlorite, epidote and muscovite. The breccias contain angular to rounded fragments of deformed granodiorite, plagioclase and quartz in a fine matrix of quartz and chlorite. A complete gradation exists from foliated granodiorite to these highly deformed rocks, which are considered to have been produced during the solid-state emplacement of the Coolac Serpentinite.

It is likely that the Burrinjuck-Young granitic mass is a large composite intrusion, with at least parts (east of Tumut, Coolac and Wallendbeen) exhibiting attributes of the " Murrumbidgee type " of plutonic rocks (cf. Vallance, 1969) : the presence of a foliation, association with a low-grade metamorphic environment, rather limited development of hornfelses, abundance of biotite and paucity of hornblende, and association with an ultrabasic belt.

Bogong Granite

The Bogong Granite occupies about 350 km.^{2} from Talbingo and Yarrangobilly through the Bogong Mountains to a point north of Lacmalac. Within the area mapped the mass has intruded the Coolac Serpentinite, Bumbolee Creek, Blowering, Honeysuckle and Goobarragandra Beds. In the Blowering-Talbingo area to the west, Hall and Relph (1956) report intrusive relations with the Blowering Beds and inconclusive contacts with the (?) Lower to Middle Devonian Boraig Group. A Middle Devonian age is suggested by a K-Ar radiometric age determination of 385 million years (J. R. Richards and I. McDougall, 1970, unpublished data) obtained on chlorite-free biotite from a coarse-grained adamellite (A.N.U. No. 69–924) from near Wall's Creek (S.M.H.E.A. grid reference 29222052).

The principal rock type is a slightly porphyritic adamellite (average grainsize 5 mm.) containing 38–45% anhedral quartz, about 25% each of plagioclase and perthitic orthoclase, 3–8% biotite and 1–3% accessory apatite, zircon, muscovite, epidote, iron oxide and allanite. Subhedral grains of plagioclase show normal zoning from An_{35} to An_{16} and some plagioclase-orthoclase interfaces are mantled by myrmekite. Tabular orthoclase grains exhibit coarse, well-developed vein perthite (An_3), and at many orthoclase grain interfaces there are small areas of intergranular albite (the albite in each orthoclase grain having the same optical orientation as the perthite of the adjacent grain). Biotite (X = yellowish brown, Y=Z=deep chestnut brown) occurs as short tabular grains with apatite and zircon inclusions. An analysis of a typical biotite adamellite from the Bogong Granite is presented in Appendix II.

Micro-adamellite (average grainsize 1·5 mm.) occurs near the margin of the mass in the Patton's Ridge region. Similar rocks have been described from the Blowering-Talbingo area (Hall and Relph, 1956). These rocks are veined by epidote and quartz near the serpentinite belt, and contain small amounts of hornblende near contacts with basic hornfelses. Adamellite containing about 25% quartz, up to 15% biotite, and up to 10% hornblende occurs in the Bogong Mountains west of the Bogong Mine. Veins and dykes of leuco-adamellite and micrographic quartz-microcline rocks occur in marginal parts of the mass and in adjacent hornfelses on Patton's Ridge. The variation in rock type indicates the Bogong Granite may be a composite mass.

Killimicat Adamellite

The Killimicat Adamellite, forming Pine Mountain to the south of Brungle, is a small granitic body 6·5 km. long and up to 1·6 km. wide which has intruded the Bumbolee Creek and Blowering Beds approximately along their mutual boundary. The dominant rock type is an unfoliated, even grained (rarely porphyritic) adamellite (grading to a granite) with an average grainsize of 1–3 mm. It contains quartz (40%), microperthitic orthoclase (35–40%; rarely as phenocrysts up to 20 mm. long) and plagioclase (15–20%; An_{21-25}) with slightly chloritized biotite (2–5%; X=pale straw, Y=Z=deep orange-brown) and rare muscovite and zircon. Micrographic quartz-K-feldspar intergrowths are common and rim myrmekite is developed at some plagioclase-quartz interfaces. An analysis of a typical granitic rock from the Killimicat Adamellite is presented in Appendix II. In some marginal areas there is a gradation to coarse-grained (4–5 mm.) muscovite granite containing quartz, K-feldspar and muscovite with minor sodic plagioclase, biotite and tourmaline and rare fluorite, molybdenite and arsenopyrite. Two small bodies of similar unfoliated, coarse-grained muscovite granite occur along the approximate boundary of the Blowering and Honeysuckle Beds 1·5 km. north of Brungle Creek and 5·5 km. east-north-east of Brungle.

The Killimicat Adamellite shows marked similarities to the Bogong Granite 8 km. to the south-east and possibly represents a cupola-like extension of the latter. Both of these masses differ from the Burrinjuck Granite as they comprise unfoliated rocks, show discordance with the strike of the enclosing rocks and produce moderate to high-grade contact metamorphic effects, and thus fall into the "Bathurst type" of plutonic rocks of Vallance (1969).

Hornfelses Adjacent to the Granitic Rocks

BURRINJUCK GRANITE

High-grade thermal effects are evident in metabasaltic rocks of the Goobarragandra Beds adjacent to the Burrinjuck Granite, but only within about 20 metres of the contacts and in xenoliths. The lower-grade parts of the aureole are indistinguishable from the low-grade regional metamorphism imposed on the rocks of the unit. The hornfelses preserve subophitic textures and contain brown hornblende, andesine and minor iron oxide. Small ovoid ocelli of quartz (±minor biotite) rimmed incompletely by green then brown hornblende are abundant in some examples.

Killimicat Adamellite

The small Killimicat Adamellite has produced only a limited contact aureole. The more pelitic rocks of the Blowering and Bumbolee Creek Beds show development of micaceous spots and close to the granitic body contain quartz+muscovite±biotite±cordierite. The porphyritic dacitic rocks of the Blowering Beds display recrystallized biotite phenocrysts and groundmasses, and a tuffaceous sandstone shows patchy development of diopside, garnet, green hornblende, epidote and chlorite.

Bogong Granite

In the region south of Lacmalac the Bogong Granite has produced extensive high-grade thermal metamorphism in rocks of the Coolac Serpentinite, Honeysuckle and Goobarragandra Beds. The narrow tongue of granitic rocks extending north from Lacmalac displays weak effects, possibly owing to its limited dimensions in this region.

The high-grade hornfelses of the Honeysuckle and Goobarragandra Beds display a large variety of mineral assemblages (see Table 2) which have extremely patchy development. The calc-silicate and ultrabasic hornfelses of the Goobarragandra Beds occur either adjacent to or within metaserpentinite, and in both units basic, ultrabasic and calc-silicate hornfelses may all occur within small outcrops or single thin sections.

Field relationships and bulk chemical compositions of the ultrabasic hornfelses indicate they are not metamorphosed serpentinites. Evidence suggests that the basic, ultrabasic and calc-silicate hornfelses have all been derived by essentially isochemical high-grade metamorphism of rocks which had previously undergone local low-grade metasomatic alteration in the serpentinite environment. Such metasomatic rocks are found in the Honeysuckle Beds away from the Bogong Granite and within the Coolac Serpentinite to the north, and similar low-grade major element redistribution has been observed elsewhere in basaltic rocks (e.g. Vallance, 1967; Smith, 1968). Likely parent materials for the calc-silicate and ultrabasic hornfelses are the variably rodingitized inclusions and chlorite-rich rocks associated with the serpentinite. Such assemblages were apparently present adjacent to the serpentinite belt in the Honeysuckle and Goobarragandra Beds prior to the intrusion of the Bogong Granite.

Table 2

High-grade Mineral Assemblages of the Honeysuckle Beds and Goobarragandra Beds Within the Bogong Granite Aureole

Type	Assemblage†	Occurrence†
Basic	Hb+Pl±Di(+Sph+Ap+Mt+Ep)	h, g
Calc-silicate*	Act+Cz+Di(±Musc)	g
	Act+Cz(+Di+Ga+Scap)	g
	Act+Pl+Cz(+Sph)	h, g
	Cz+Di(+Sph±Musc)	h, g
	Di+Act+Pl(+Sph)	h
	Di+Pl+Ep±Ga(+Sph)	h
	Di+Pl+Sp+Mt(±Chl)	g
	Cz	g
	Ep+Pl	h
	Ga	h, g
	Ga+Cz	h
	Ga+Pl	h
	Di(±Sp)	g
Ultrabasic	Act+Ol+Sp+Mt(±Chl)	h, g
	Anth+Ol+Sp+Mt(+Hy)	g
	Cum+Ol+Sp+Mt	g
	Hb+Cum(+Anth+Mt)	g
	Act+Sp+Mt	g
	Act+Pl+Di+Sp+Mt	h
	Anth+Hb+Di+Sp+Mt	h
	Di+Act+Sp+Mt	h
	Cord+Anth+Sp+Mt(+Hy++Phl)	g
	Cord+Anth(+Qtz+Pl+Phl)	g
	Act(±Scap±Cz)	g
	Ol+Hy+Sp+Mt	g
Pelitic	Qtz+Cord+Bi(+Musc)	g

* Many calc-silicate assemblages show extensive secondary replacement by prehnite.

† *Abbreviations :*

h =Honeysuckle Beds.
g =Goobarragandra Beds.
Hb =hornblende.
Pl =plagioclase.
Di =diopside.
Sph =sphene.
Ap =apatite.
Mt =magnetite.
Ep =epidote.
Act =tremolite-actinolite.
Cz =clinozoisite.
Musc=muscovite.
Ga =garnet.
Scap =scapolite.
Sp =green spinel.
Ol =olivine.
Chl =chlorite.
Anth=anthophyllite.
Hy =hypersthene.
Cum =cummingtonite.
Cord =cordierite.
Phl =phlogopite.
Qtz =quartz.
Bi =biotite.

Coolac Serpentinite

The Coolac Serpentinite, the southern half of which is described in this paper, represents a continuous outcrop of ultrabasic and associated rocks over a distance of 54 km., extending from a point 5 km. north-east of Coolac in the north to Patton's Ridge (4·5 km. north-west of Goobarragandra) in the south. The belt dips steeply (75°–90°) to the east with an average strike of 340°, and ranges in width from 3·5 km. at Red Hill to as narrow as 10 m. near the southern end. Lenticular satellitic bodies of serpentinite (Plate I–2) flank the main belt, and some occur beyond its northern and southern extremities. The Coolac belt is the largest of a series of discontinuous bodies of ultrabasic rocks trending west of north across south-eastern and central New South Wales from Cabramurra to Girilambone.

A problem of age arises with the Coolac Serpentinite (as with many other alpine-type ultrabasic masses) owing to possible repeated and incremental movements along the zone of emplacement (cf. Wilkinson, 1969). However, at least part of the Coolac Serpentinite must post-date the (?) Middle Silurian to basal Devonian sedimentary-volcanic sequence and the Lower Devonian Burrinjuck Granite, as fault-bounded satellitic serpentinite masses occur completely enclosed by both. Since the Bogong Granite shows intrusive relations with the serpentinite, at least part of the belt must pre-date this granitic body. Thus a tentative age between those of the Burrinjuck and Bogong Granites is envisaged (i.e., Lower to Middle Devonian), but it must not be overlooked that serpentinite emplacement could have occurred before or after this time in some sections of the belt. The Tertiary alkali dolerite at Red Hill, overlying the serpentinite-Burrinjuck Granite contact, shows no evidence of faulting, and it is assumed that this contact has been stable since the formation of the alkali dolerite.

In the mapped area, serpentinite and partly serpentinized harzburgite are the dominant rock types of the Coolac Serpentinite. There are also widespread small occurrences of wehrlite, lherzolite, clinopyroxenite and chromitite; narrow, discontinuous dykes of rodingitic rocks; and numerous tectonic inclusions of variably deformed and metasomatized basic, intermediate and acidic igneous and metamorphic rocks, and minor sedimentary material. Metamorphic mineral assemblages are developed in serpentinite in the Bogong Granite aureole and around some tectonic inclusions, and sulphide-rich rocks occur at several localities.

Serpentinite and Partly Serpentinized Harzburgite

Both massive and schistose serpentinite occur in the belt, and in places grade to almost unserpentinized harzburgite. North of Brungle Creek, a zone 100–800 m. wide of mostly schistose serpentinite occurs along the western margin of the belt, while the massive variety occupies a wider eastern zone. South of Brungle Creek this subdivision is not readily observable, and narrow zones of schistose serpentinite occur randomly through massive serpentinite.

The serpentinite contains lizardite with subordinate chrysotile (antigorite develops locally in proximity to inclusions and in the aureole of the Bogong Granite) with accessory magnetite and chromite and minor tremolite, talc, chlorite, magnesite or garnet.

Much of the massive serpentinite contains relict olivine (Fo_{91}), orthopyroxene (En_{90}; containing thin diopside lamellae) and diopsidic clinopyroxene. Serpentine minerals, fine-grained magnetite and tiny grains of heazlewoodite, millerite, pentlandite and awaruite replace the primary silicates, producing " mesh " textures after olivine and bastite pseudomorphs (composed of lizardite) after pyroxenes. Veining by chrysotile is common on a microscopic scale, but fibres exceeding 8 mm. in length have not been observed.

Most of the serpentinized rocks were derived from a coarse-grained (4–6 mm.) harzburgitic parent (approximately olivine 55–80%, orthopyroxene 10–35%, clinopyroxene up to 10% and chromite 1–2%), and were possibly emplaced as fault-bounded slices of partly serpentinized (or serpentinizing) material (cf. Hess, 1955; de Roever, 1957; Raleigh and Paterson, 1965; Hostetler *et al.*, 1966), although incremental movements and serpentinization have almost certainly continued since initial emplacement.

Metaserpentinite

Adjacent to the Bogong Granite thermally metamorphosed serpentinite shows patchy development of antigorite, talc, amphiboles (colourless clinoamphibole, anthophyllite and (?) gedrite) and olivine (Fo_{85}), but in contrast to analogous cases described by Durrell (1940), Taubeneck (1957) and Seki (1951), no green aluminous spinel (only minor magnetite) has been noted. Rocks composed largely of talc with clinoamphibole and/or anthophyllite (and magnetite) are also present. Elsewhere in the Coolac Serpentinite, in close proximity to tectonic inclusions which have undergone mineralogical readjustment, it is found that the serpentinite contains the assemblages tremolite + talc ± serpentine ± chlorite ± calcite (+chromite); serpentine + chlorite ± garnet ± tremolite±clinozoisite (+chromite); chlorite+ garnet+vesuvianite (+chromite) and tremolite +chlorite (+chromite+magnetite). Some of the assemblages are "rodingitic", but the presence of relict chromite and rare chlorite or talc pseudomorphs after pyroxene demonstrates the original ultrabasic nature of the rocks. At localities about 3·5 km. east-south-east of Lacmalac and 1 km. west of the Bogong Mine, anthophyllite-bearing metaserpentinite is veined and partly replaced by magnesite (+chalcedony) rocks.

Clinopyroxenite, Wehrlite and Lherzolite

A series of discontinuous bodies (up to 30 m. wide) varying from clinopyroxenite through wehrlite to rare lherzolite, and in places associated with gabbro and diorite (described later), crop out within schistose serpentinite over a distance of at least 6 km. close to the western margin of the Coolac Serpentinite north of Brungle Creek. The rocks are equigranular or porphyritic (average grainsize 2–6 mm., rarely up to 30 mm. in some clinopyroxenites), and contain clinopyroxene (close to $Ca_{46}Mg_{47}Fe_7$; 40–90%) with variable olivine (Fo_{82}; 5–40%), orthopyroxene (En_{82}), brown hornblende and chromite. Secondary serpentine minerals, magnetite, tremolitic amphibole, chlorite and garnet are also present. These rocks are similar to the wehrlite associated with serpentinized dunite and gabbro in the North Mooney Complex near Coolac (Golding, 1966, 1969*b*).

Chromitite

Chromitite forms small, steeply-dipping, lenticular bodies subparallel to the strike of the Coolac Serpentinite. They contain 30% to nearly 100% chromite with interstitial serpentine minerals and chlorite, and minor chromian garnet, clinopyroxene, tremolite, magnesite, chalcedony, haematite, magnetite, awaruite, heazlewoodite, chalcopyrite and pentlandite. Primary layered and mosaic textures are displayed together with brecciation and slickensiding. Chromite from these rocks in the Red Hill-Brungle Creek area contains 38·7% to 60·1% Cr_2O_3 and about equal amounts of FeO and MgO (Golding, 1966). Partial alteration of chromite has produced dark, variable thickness rims, which Golding and Bayliss (1968) have shown to be richer in Cr_2O_3 and Fe_2O_3 and poorer in FeO, MgO and Al_2O_3 than the unaltered spinel; such partly altered chromite grains are usually surrounded by chlorite.

Subsidiary Rocks

Narrow rodingitic veins and dykes are common in the massive serpentinite and a variety of subsidiary rock types occur as tectonic inclusions throughout the belt (Plate II–1, II–2). The serpentinite in contact with inclusions is invariably schistose and commonly shows evidence of metasomatic readjustment.

Rodingitic and Chlorite-rich Rocks

The rodingite forming veins and dykes is medium- to very coarse-grained and contains garnet, relict clinopyroxene and pale green chlorite as essential minerals; minor vesuvianite, tremolitic amphibole and sphene are present in some examples (see Appendix I for determinative data on garnets).

Other rodingitic rocks occur as small tectonic inclusions and as marginal zones to larger inclusions of metabasic, amphibolitic and granitic material. Most are fine- to medium-grained, but mineral assemblages and microstructures are very variable. Some examples preserve parent rock microstructure (e.g. intersertal, ophitic, gabbroic, foliated, brecciated), whereas others are new grain aggregates. The most common mineral assemblage is garnet+pale green chlorite + vesuvianite + clinopyroxene, although rocks very rich in garnet or vesuvianite are widespread. Prehnite, clinozoisite, tremolitic amphibole and sphene are locally abundant and relict chromite, apatite, zircon as well as leucoxene, magnetite or (?) zeolites occur as accessories.

Intimately associated with and forming discontinuous marginal zones around some rodingitic bodies are rocks consisting of fine to medium-grained pale green chlorite, with accessory garnet, vesuvianite, diopside, tremolitic amphibole, clinozoisite, prehnite, sphene, chromite, magnetite and (?) zeolites.

Rodingitic rocks have been recorded in the northern part of the Coolac Serpentinite (Golding, 1962, 1966, 1969*b*) and are characteristic of most alpine-type ultrabasic belts (e.g. Coleman, 1966, 1967; Suzuki, 1953; Baker, 1958; Benson, 1913–18). The metasomatic alteration of basic to acidic igneous and sedimentary material within ultrabasic rocks has been discussed in detail by Coleman (1966, 1967), and the rodingitic rocks of the Coolac Serpentinite are readily interpreted as metasomatized basic dykes and tectonic inclusions of various types, while the less common but intimately associated chlorite-rich rocks may represent complementary products of this metasomatism, being transitional between the altered inclusions and enclosing serpentinite (cf. Thayer, 1966).

The much greater amount of rodingitic compared with that of chloritic rocks and the widespread occurrence of calc-silicate-rich secondary alteration and veins in the inclusions and in rocks bordering the serpentinite belt suggests a larger contribution and greater mobility of Ca over Mg in the metasomatic processes. This relationship can be logically linked with the process of serpentinization of ultrabasic rocks, which is characterized by a very large loss and migration of original Ca relative to Mg (Page, 1967 ; Barnes and O'Neil, 1969 ; Coleman and Keith, 1971).

Gabbro, Diorite, Trondhjemite, Albitite Complexes

Bodies containing some or all of these rock types occur at intervals along the western margin of and within the serpentinite belt. These bodies are up to 2 km. long and 500 m. wide ; a common field associate is wehrlite. Internal relations are complex, with gabbro pegmatite and the more silica-rich rocks apparently intruding the dominant gabbro. At a number of localities, gabbro and diorite are seen to invade spilitic rocks and metadolerite of the Honeysuckle Beds (similar to the relations in the North Mooney Complex ; Golding, 1966, 1969*b*). Small tectonic inclusions of variably metasomatized gabbro, diorite and albitite are of sporadic occurrence throughout the belt, except in the far south.

Gabbro contains brown hornblende, clinopyroxene and partly albitized plagioclase (originally An_{45-58}), with minor ilmenite, pyrrhotite and apatite. Diorite contains greenish-brown hornblende, plagioclase (An_{40-45}) and minor ilmenite and quartz. Pegmatoid gabbroic rocks intruding the above types contain brown hornblende (up to 15 cm.), plagioclase (An_{55}) and minor ilmenite. Trondhjemite is medium- to coarse-grained, containing partly albitized plagioclase (An_{30-35}), interstitial quartz and minor biotite, whereas the albitite displays an equigranular or porphyritic texture and contains albite (An_{5-7}) with minor green amphibole and quartz.

All these rock types show gradations with one another, especially gabbro to diorite to quartz-bearing albitite. They also display extensive metasomatic replacement by low temperature phases typified by clinozoisite, tremolitic amphibole, prehnite, albite, chlorite, diopside, sphene, microcline, garnet and sericite.

The albite-rich rocks do not appear to be soda-metasomatized basic inclusions (cf. Leonardos and Fyfe, 1967) but the association with the rocks of the complexes indicates they may be members of the " alpine mafic magma stem " of Thayer (1963).

Metabasic Inclusions

Small inclusions of metabasalt and metadolerite occur rarely as small inclusions in the serpentinite belt and close to contacts with the Honeysuckle and Goobarragandra Beds. Mineral assemblages and textures are the same as the metabasics in these units although variable alteration to rodingitic assemblages is prevalent.

Amphibolitic Inclusions

Numerous amphibolitic inclusions (up to 400 m. long and 100 m. wide) occur in the Coolac Serpentinite, especially in the Red Hill-Brungle Creek area. The rocks are medium- to coarse-grained, commonly foliated, and exhibit variable development of metasomatic assemblages. Two parental types can be recognized : (*a*) a greenish-brown hornblende+plagioclase (+quartz+K-feldspar) type and (*b*) a brown hornblende+plagioclase (+clinopyroxene) type. In both types the plagioclase compositions are An_{29-50} and accessory apatite, magnetite, ilmenite and pyrrhotite are present.

Deformed Acidic Igneous Inclusions

Tectonic inclusions of deformed acidic igneous rocks, some several hundred metres long, are common throughout the Coolac Serpentinite (Golding, 1962, 1966, 1969*b* ; Veeraburus, 1963). Within the area mapped these inclusions comprise deformed biotite granodiorite, " soda granite " and porphyritic metadacite. The rocks contain variable quartz, plagioclase (An_{30-35} and An_{5-9}), microcline and biotite, with accessory muscovite, apatite, zircon and rutile. Alteration to calc-silicate assemblages is not prevalent, but some inclusions show development of the assemblages tremolite+prehnite+sphene and clinozoisite+chlorite+sphene.

Inclusions of deformed biotite granodiorite tend to be located nearer the eastern contact of the belt and appear to be infaulted blocks of Burrinjuck Granite. The medium- to coarse-grained " soda granite " occurs as isolated inclusions across the width of the belt and also as dykes and masses in the Honeysuckle Beds immediately adjacent to the western contact. These rocks are probably related to the gabbro-diorite-trondhjemite-albitite complexes. Inclusions of porphyritic metadacite have probably been derived from the Blowering Beds.

Sedimentary Inclusions

Sedimentary inclusions are uncommon in the belt. Inclusions of slaty mudstone and quartz-rich siltstone (derived from the Honeysuckle Beds) display little metasomatism with only slight development of chlorite and epidote. Inclusions of conglomerate and tuffaceous sandstone (derived from the Blowering Beds) have undergone partial metasomatic replacement by epidote, tremolite-actinolite, calcite, chlorite, sericite, albite and sphene.

High-grade Foliated Metamorphics

Apparent high-grade regional metamorphic rocks comprising amphibolite, quartzite, gneiss and schist occur flanking the serpentinite belt in the Patton's Ridge area; at a locality immediately west of the belt about 2·5 km. east of Lacmalac; and in two very small bodies adjacent to the main serpentinite belt near the Wee Jasper road.

The amphibolite contains brown-green hornblende + plagioclase (An_{27-35}) + minor ilmenite, apatite and epidote, and in places is characterized by narrow pink bands (vesuvianite + garnet + diopside + sphene or zoisite+diopside+garnet) and green bands (diopside + plagioclase + epidote + sphene). Although these bands roughly parallel the amphibolite foliation, they are transgressive in detail and are believed to represent contact metamorphosed rodingitic veins. The foliated quartzites contain assemblages with dominant quartz (70–90%) and minor hornblende, garnet, apatite, plagioclase (An_{10-40}), K-feldspar, iron oxide, biotite and muscovite; and an unusual quartzite containing up to 15% graphite with minor pink (?) almandine garnet, chlorite, epidote, magnetite, pyrite and chalcopyrite comprises the Wee Jasper road occurrences and another on Patton's Ridge. At the locality about 2·5 km. east of Lacmalac, there is in addition to amphibolite, quartzofeldspathic gneiss (quartz + oligoclase + orthoclase + biotite + muscovite + (?) sillimanite + iron oxide) and mica-rich schist (biotite+muscovite+quartz+plagioclase+iron oxide). It appears possible these rocks represent wedges of an exotic basement terrain tectonically introduced during the serpentinite emplacement.

Sulphide-rich Rocks

Rocks rich in sulphides occur locally in the Coolac Serpentinite, Killimicat Adamellite, Honeysuckle and Blowering Beds. The occurrences are small, and production of ore, where recorded, has been minor.

COOLAC SERPENTINITE

McAlpine Copper Mine

The McAlpine Mine is situated in an altered serpentinite wedge within a large tectonic inclusion of " soda granite " and diorite. All the rocks show variable foliation, brecciation and metasomatic readjustment. The major sulphide assemblage is sphalerite + chalcopyrite + cubanite, accompanied by galena, niccolite, pyrrhotite, magnetite, chromite, pyrite, arsenopyrite, maucherite, native bismuth, tetrahedrite, covellite, chalcocite, marcasite, bismuthinite, breithauptite and mackinawite with malachite, azurite, smithsonite, goslarite and " limonite " as oxidation products. Lamellar chalcopyrite-cubanite intergrowths and cubanite breakdown to lamellar chalcopyrite+magnetite are characteristic. Mutual boundary relations occur between sphalerite, chalcopyrite, cubanite, niccolite, galena and some of the more minor constituents. Further details of mine geology and ore petrology are given by Ashley (1969*b*) and Lawrence and Golding (1969).

Copper Prospects South of Brungle Creek

Five small prospects occur in schistose serpentinite in the area south of Brungle Creek. They contain dominant magnetite, with minor chromite, haematite, ilmenite, chalcopyrite, pentlandite, violarite, chalcocite, covellite, cuprite, tenorite, native copper, malachite, azurite, chrysocolla and " limonite ".

Goobarragandra Copper Mine

Mineralization at the Goobarragandra Mine occurs within tremolite (+olivine+spinel+magnetite) hornfels enclosed by almost unmineralized metaserpentinite in contact with the Bogong Granite. The ore exhibits polygonal aggregates of pyrrhotite, pyrite, chalcopyrite and minor sphalerite. Traces of pentlandite, mackinawite and violarite occur in the more massive sulphides. Pyrrhotite breakdown to secondary pyrite and/or marcasite+" limonite " is characteristic.

Bogong Copper Mine

The Bogong Mine is situated in the most southerly isolated serpentinite body in the map area. Sulphides occur in a foliated metadacite inclusion in weakly mineralized metaserpentinite near the Bogong Granite. The inclusion contains plagioclase (An_{7-15}), chlorite and minor phlogopite, tremolitic amphibole, quartz and clinozoisite. Bornite, chalcopyrite, sphalerite, millerite, siegenite, (?) wittichenite and (?) galena with secondary chalcocite, covellite, cuprite, tenorite, malachite and azurite are also present. Stringers of chalcopyrite in bornite and coarse subgraphic or vermicular intergrowths of bornite in chalcopyrite are well developed. The meta-serpentinite contains disseminated chalcopyrite, magnetite, chromite, millerite and pentlandite. Ashley (1968) describes this mine and its ore in more detail.

Killimicat Adamellite

At the Pine Mountain Mine sulphides occur in a quartz-rich aplitic dyke in adamellite. Ashley (1969*a*) describes arsenopyrite, pyrite, chalcopyrite, covellite, digenite, (?) bismuthinite, galena, molybdenite and (?) native bismuth together with scorodite, " limonite ", malachite and azurite occurring in quartz with minor chlorite, muscovite and small greisen patches.

Honeysuckle and Blowering Beds

Sulphides occur at two localities each in the Honeysuckle and the Blowering Beds. Immediately west of the serpentinite belt, 1·2 km. south-west of McAlpine Mine, quartz veins in sericitized and chloritized metadacite of the Honeysuckle Beds carry sparsely disseminated pyrite and chalcopyrite with " limonite " and a little gold and galena. At the Tumut Gold Mine, on Bumbolee Creek, 13 km. east of Tumut, disseminated to massive pyrite and minor chalcopyrite, sphalerite, pyrrhotite, covellite and marcasite with " limonite ", malachite, azurite and chalcanthite occur within schistose metabasalt of the Honeysuckle Beds showing variable alteration to magnesite-pyrite rocks. A small working 500 m. to the north shows disseminated arsenopyrite, pyrite, chalcopyrite, sphalerite, marcasite and (?) electrum with chalcocite, digenite, covellite, " limonite " and malachite in quartz veins in fine-grained epidote-rich siltstone of the Blowering Beds. A prospect 1 km. south of the Wee Jasper road, 16 km. north-east of Tumut, contains disseminated to massive arsenopyrite and minor pyrite and chalcopyrite in tourmalinized dacite and quartz-tourmaline veins in the Blowering Beds.

Origin of the Sulphides

The sulphide assemblages of the region are of two main types : (*a*) As, Fe and Cu sulphides with minor gold, galena, molybdenite and Bi minerals occurring in a quartz-rich host, with sporadic tourmaline and muscovite ; (*b*) Cu, Zn and Fe sulphides with Ni minerals restricted to the Coolac Serpentinite (commonly associated with tectonic inclusions).

It is proposed that the former association is related to the intrusion of the Middle Devonian Bogong Granite and Killimicat Adamellite ; since the assemblages are suggestive of an acidic plutonic origin. The latter association displays distinctive features—the association of Cu-Fe sulphides and nickel minerals and the structure and composition of the host rocks (originally chlorite-rich rocks, schistose serpentinite and altered inclusions)—indicating a relationship to the metasomatic process of serpentinization of the ultrabasics of the Coolac Serpentinite.

Tertiary Rocks

Lying on top and to the east of the Honeysuckle Range scarp are (?) Tertiary terrestrial sediments overlain by alkalic basaltic rocks.

Sediments

Fluviatile sediments occur as a veneer (up to 30 m. thick) over a peneplain surface formed on the Coolac Serpentinite and Burrinjuck Granite. Poorly consolidated sandy silts, sands and gravels, ferruginous sandstone and pisolitic to massive laterite are most common ; quartzite has been produced locally through thermal metamorphism by overlying basaltic rocks.

The sandy sediments contain angular, strained quartz with a matrix of clay minerals, " limonite " and rare plant fragments ; in the quartzite, quartz overgrowths occur on original detrital grains. The gravels have a sandy matrix with subangular to rounded pebbles of quartz, deformed granitic rocks, serpentinite, chert, pink adamellite, hornblende andesite, pelitic hornfels, metadolerite and quartz sandstone, indicating an apparent provenance within 50 km. to the south and west.

Basaltic Rocks

Alkali Olivine Basalt-Analcime Basanite-Olivine Nephelinite

Erosional remnants (generally less than 30 m. thick) of alkali olivine basalt, analcime basanite and olivine nephelinite overlie the (?) Tertiary sediments and Burrinjuck Granite. The flows are best developed around Adjungbilly T.S. and the northern part of Red Hill (where thicknesses locally attain 80 m.). The alkali olivine basalt contains small phenocrysts of olivine and titaniferous clinopyroxene in a fine groundmass of plagioclase (An_{50-55}), titanaugite, titanomagnetite, alkali feldspar and apatite. It is associated with analcime basanite (containing minor plagioclase (An_{55}) and significant analcime) and olivine nepheline (containing abundant nepheline and lacking plagioclase). The analcime basanite and olivine nephelinite are very fine-grained, holocrystalline and contain slightly iddingsitized, euhedral to subhedral olivine phenocrysts up to 1·5 mm. in a groundmass of titaniferous clinopyroxene, titanomagnetite and apatite, with analcime and a little plagioclase in the former and nepheline in the latter. (See analyses 10–12, Appendix II.)

Alkali Dolerite

A mass about 5 km. long, up to 1·2 km. wide and 30–80 m. thick of alkali dolerite crops out on Red Hill overlying Tertiary sediments and basaltic flows (see above), the serpentinite belt and Burrinjuck Granite. The rocks have subophitic textures and are notably porphyritic (and glomeroporphyritic). The average grainsize is 1–2·5 mm. Phenocrysts of olivine, plagioclase and clinopyroxene average 2·5–4 mm., some clinopyroxenes attaining 9 mm. Finer-grained, slightly porphyritic dolerite with an average grainsize of 0·5 mm. occurs in some basal parts of the mass.

The alkali dolerite contains 22 to 9% olivine, 36 to 10% titaniferous clinopyroxene, 36 to 64% plagioclase, 2 to 5% analcime, 2 to 8% alkali feldspar, 4 to 7% titanomagnetite (and a little ilmenite) and 1 to 2% apatite. Modal and cryptic variation occurs from base to top within the mass : the olivine composition changes from about Fo_{85} near the base to about Fo_{75} near the top ; clinopyroxene changes from a pale brown variety to one heavily rimmed with a deep mauve variety ; plagioclase changes from An_{58} to An_{45} ; the alkali feldspar and primary analcime contents increase ; and very small amounts of aegirine-augite (in places rimming interstitial titanaugite), titaniferous biotite and (?) kaersutite appear. An analysis of a typical alkali dolerite from the Red Hill mass is presented in Appendix II.

The texture, grainsize, thickness, modal and cryptic variation, and the moderate differentiation with enrichment in Fe, Ti and alkalis in the higher level indicate the body is possibly an unroofed sill.

Geological Synthesis

The geological history revealed east of Tumut can be tentatively summarized as follows :

(1) Possibly in the Ordovician to Middle Silurian, deposition of sediments of the Bumbolee Creek Beds and extrusion of parent basaltic rocks of the Bullawyarra Schist took place. Burial, metamorphism and deformation were followed by uplift and erosion.

(2) In the Middle Silurian to basal Devonian a period of acidic to basic volcanism (at least partly submarine) was accompanied by deposition of marine sediments (chiefly deep water). The volcanism, recorded in the Blowering, Honeysuckle and Goobarragandra Beds, may be continuous with that northwards in the main part of the Cowra Trough (e.g. the Canowindra Porphyry of Ryall, 1965).

(3) Burial, folding and low-grade regional metamorphism of the sedimentary-volcanic sequence was followed by the intrusion of the Burrinjuck Granite at relatively low temperature about 400 million years B.P.

(4) In the lower to Middle Devonian fault-controlled emplacement of the Coolac Serpentinite as a partly serpentinized ultrabasic belt containing numerous tectonic inclusions of various crustal rocks (including large slices of high-grade foliated metamorphic rocks) occurred. Mylonites were produced in the adjacent Burrinjuck Granite. Serpentinization and metasomatism in the serpentinite environment affected both the tectonic inclusions and the immediately adjacent sedimentary-volcanic units.

(5) The Gatelee Ignimbrite was extruded in a possible terrestrial environment, then gently folded, just prior to or contemporaneous with the intrusion of the Bogong Granite and the Killimicat Adamellite about 385 million years B.P. These were emplaced as relatively high temperature, fluid magmas and produced thermal metamorphism of the Coolac Serpentinite and the sedimentary-volcanic sequence (including previously metasomatized rocks).

(6) Since the intrusion of these granitic masses there was apparently little deposition, igneous activity or deformation, with the development of a peneplain surface, until the Tertiary fluviatile sedimentation, basaltic volcanism and uplift.

(7) Continued erosion and fluviatile sedimentation gave rise to the present configuration.

Acknowledgements

The authors wish to express their gratitude to Associate Professor R. H. Vernon and Dr. R. H. Flood, of the School of Earth Sciences, Macquarie University, for critically reading the manuscript, and thank Associate Professor T. G. Vallance, of the Department of Geology and Geophysics, University of Sydney, and Mr. A. C. Offenberg, of McDonald Street, Harbord, for helpful discussions.

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Appendix I

Garnet Data

The mineral name "garnet" as used in this study implies a variety close to grossular, $Ca_3Al_2(SiO_4)_3$, in composition unless otherwise specified. Garnets occurring within the rodingites and other metasomatized tectonic inclusions rich in calc-silicate minerals have n from $1{\cdot}728$ to $1{\cdot}738 \pm 0{\cdot}003$ and a from $11{\cdot}86$Å to $11{\cdot}90\text{Å} \pm 0{\cdot}01$Å. Garnet in a calc-silicate hornfels from Patton's Ridge has $n = 1{\cdot}746 \pm 0{\cdot}003$ and $a = 11{\cdot}86\text{Å} \pm 0{\cdot}01$Å. According to data of Deer, Howie and Zussman (1962), the former garnets range from a slightly hydrated variety (containing up to 10% of the hibschite, $Ca_3Al_2(SiO_4)_2(OH)_4$, molecule) to almost pure grossular containing little andradite and uvarovite in solid solution. The latter garnet has a composition close to $Gro_{93}And_7$.

Appendix II

Chemical Analyses of Rocks from the Tumut Area

Twelve chemical analyses of rocks from the mapped area (except analysis 7) are tabulated below.

Analyses 1, 2 and 3 reveal little compositional variation in rocks of the Burrinjuck Granite from three different environments. The Burrinjuck Granite shows the attributes of the "Murrumbidgee type" of plutonic rocks of Vallance (1969) and is similar chemically to the massive and foliated granodiorites and adamellites described from the Snowy Mountains area of New South Wales by Kolbe and Taylor (1966). The rocks are characterized by a high Fe^{2+}/Fe^{3+} ratio. Analyses 2 and 3 show higher Fe_2O_3 and lower FeO than analysis 1, attributed to the slight alteration (weathering) observed in thin section. Marked chemical similarities exist between typical samples of the Bogong Granite and Killimicat Adamellite (analyses 4 and 5). These masses are characteristic of the "Bathurst type" of Vallance (1969). Chemically they are similar to the leucogranites from the Snowy Mountains described by Kolbe and Taylor (1966). Analysis 6 shows the Gatelee Ignimbrite to be rhyodacitic in composition and chemically similar to the Bogong Granite and Killimicat Adamellite, except for much higher Fe_2O_3 (probably a function of its pyroclastic origin). A garnetiferous porphyritic rhyodacite from the Blowering Beds compares closely with a porphyritic rhyodacite from the Goobarragandra Beds (analyses 7 and 8).

1. View to the east across the Blowering Beds and Honeysuckle Beds to the Honeysuckle Range, the topographic expression of the Coolac Serpentinite. The McAlpine Mine is situated at the top of the scarp near the centre of the photograph.

2. Satellitic serpentinite belt within slates and metabasalts of the Honeysuckle Beds : on the Wee Jasper Road, about 250 m. west of the main ultrabasic belt and 17 km. north-east of Tumut.

1. Partly serpentinized layered harzburgite with a thin transgressive rodingite vein : just west of Red Hill.

2. Small tectonic inclusion of hornblende-albite-clinozoisite rock in schistose serpentinite : beside Bumbolee Creek Road, about 14 km. east of Tumut.

3. Pillow structure in low-grade metabasalts of the Goobarragandra Beds exposed in vertical cliff section : about 1 km. north-west of Goobarragandra.

4. Intrusive contact between Burrinjuck Granite (light) and metabasalts of the Goobarragandra Beds : in Sandy Creek, about 250 m. from its junction with the Goobarragandra River.

Chemically the rocks show many similarities to the Burrinjuck Granite, and differ from the Gatelee Ignimbrite in containing lower SiO_2 and alkalis, and higher CaO, MgO and total Fe. Analyses 9 to 12 are of the Tertiary basaltic rocks. The alkali dolerite from Red Hill (analysis 9) is comparable with the alkali olivine basalt from near Adjungbilly T.S. (analysis 10). From the alkali olivine basalt there appears to be a trend to strong undersaturation, and to a moderately potassic nature, with high P_2O_5, through the analcime basanite (analysis 11) to the olivine nephelinite (analysis 12).

	1	2	3	4	5	6
SiO_2 ..	68·76	69·87	69·92	75·87	76·53	73·27
TiO_2 ..	0·63	0·56	0·59	0·19	0·15	0·35
Al_2O_3 ..	14·14	14·21	13·58	12·68	12·06	14·36
Fe_2O_3 ..	0·35	0·87	0·74	0·15	0·26	1·50
FeO ..	4·08	3·09	3·19	1·17	0·97	0·60
MnO ..	0·10	0·08	0·10	0·06	0·05	0·11
MgO ..	2·69	2·24	2·16	0·95	0·64	0·99
CaO ..	2·61	3·24	2·03	0·65	0·55	0·40
Na_2O ..	2·19	2·68	2·46	3·32	3·16	3·37
K_2O ..	3·03	2·33	3·70	4·35	4·73	4·14
P_2O_5 ..	0·21	0·19	0·18	0·11	0·08	0·13
H_2O^+ ..	0·97	0·68	0·75	0·70	0·33	1·12
H_2O^- ..	0·09	0·14	0·11	0·15	0·13	0·27
CO_2 ..	0·10	0·00	0·02	0·06	0·17	0·14
Total	99·95	100·18	99·53	100·41	99·81	100·75

C.I.P.W. Norms

	1	2	3	4	5	6
Q ..	32·81	33·73	32·43	36·76	37·98	36·26
Or ..	17·90	13·77	21·86	25·70	27·95	24·46
Ab ..	18·52	22·67	20·81	28·08	26·73	28·50
Ne ..	—	—	—	—	—	—
An ..	10·94	14·83	8·77	2·13	1·13	0·25
C ..	3·25	1·85	2·32	1·73	1·33	4·25
Di ..	—	—	—	—	—	—
Hy ..	13·04	9·76	9·84	4·19	3·00	2·46
Ol ..	—	—	—	—	—	—
Mt ..	0·51	1·26	1·07	0·22	0·38	1·28
Hm ..	—	—	—	—	—	0·62
Il ..	1·20	1·06	1·12	0·36	0·28	0·66
Ap ..	0·49	0·44	0·42	0·25	0·19	0·30
Cc ..	0·23	—	0·05	0·14	0·39	0·32
H_2O ..	1·06	0·82	0·86	0·85	0·46	1·39

	7	8	9	10	11	12
SiO_2 ..	67·36	69·82	46·27	45·70	42·94	40·64
TiO_2 ..	0·66	0·49	2·26	2·02	2·23	2·65
Al_2O_3 ..	14·38	13·94	13·30	14·42	14·09	13·98
Fe_2O_3 ..	0·67	0·69	3·02	2·35	5·25	4·94
FeO ..	3·74	3·03	6·91	8·72	7·04	7·46
MnO ..	0·07	0·07	0·20	0·21	0·23	0·22
MgO ..	2·23	1·49	10·50	11·14	10·81	8·15
CaO ..	1·86	2·53	11·88	9·83	9·47	10·89
Na_2O ..	3·23	2·96	2·68	2·60	3·12	4·80
K_2O ..	3·71	3·33	1·30	1·21	1·68	2·23
P_2O_5 ..	0·15	0·12	0·85	0·79	1·21	1·81
H_2O^+ ..	0·86	1·02	0·72	1·29	0·65	1·31
H_2O^- ..	0·12	0·12	0·26	0·51	1·05	0·57
CO_2 ..	0·34	0·12	0·00	0·02	0·08	0·87
Total	99·38	99·73	100·15	100·81	99·85	100·71

C.I.P.W. Norms

	7	8	9	10	11	12
Q ..	26·00	30·94	—	—	—	—
Or ..	21·92	19·67	7·68	7·15	9·93	13·29
Ab ..	27·32	25·03	15·97	18·60	14·42	4·40
Ne ..	—	—	3·73	1·84	6·48	19·61
An ..	6·10	11·01	20·42	24·11	19·48	10·18
C ..	2·82	1·43	—	—	—	—
Di ..	—	—	26·26	15·59	15·13	21·77
Hy ..	10·91	8·02	—	—	—	—
Ol ..	—	—	14·65	22·62	17·87	11·35
Mt ..	0·97	1·00	4·38	3·41	7·61	7·10
Hm ..	—	—	—	—	—	—
Il ..	1·25	0·93	4·29	3·84	4·24	4·98
Ap ..	0·35	0·28	1·97	1·83	2·80	4·17
Cc ..	0·77	0·27	—	0·05	0·18	1·98
H_2O ..	0·98	1·14	0·98	1·80	1·70	1·88

Analyst : P. M. Ashley.

Analyses by X-ray fluorescence spectrometry, flame photometry (Na_2O), titrimetry (FeO) and gravimetry (H_2O, CO_2).

1. Massive biotite granodiorite (Burrinjuck Granite) : 4·3 km. north-north-east of Billapaloola T.S.
2. Mylonitic biotite granodiorite (Burrinjuck Granite) : about 20 m. from contact with Coolac Serpentinite, 400 m. south-west of Mundongo T.S.
3. Partly recrystallized, foliated biotite adamellite : inclusion in Coolac Serpentinite, 4·8 km. west-south-west of Adjungbilly T.S.
4. Granite (Killimicat Adamellite) : western side of Pine Mountain, 5 km. south of Brungle.
5. Biotite adamellite (Bogong Granite) : Bogong Mountains, 5·6 km. west-south-west of Goobarragandra.
6. Rhyodacitic ignimbrite (Gatelee Ignimbrite) : 3·5 km. north-north-west of Brungle.
7. Garnetiferous porphyritic rhyodacite (from Blowering Beds) : Carey St., Tumut.
8. Porphyritic rhyodacite (from Goobarragandra Beds) : 2·5 km. south of Goobarragandra.
9. Porphyritic alkali dolerite : Red Hill, 2·2 km. east-south-east of McAlpine Mine.
10. Porphyritic alkali olivine basalt : about 300 m. east of Adjungbilly T.S.
11. Porphyritic analcime basanite : Adjungbilly T.S.
12. Olivine nephelinite : Red Hill, 2·8 km. north-east of McAlpine Mine.

(Received 29. 10. 1970)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 31–37, 1971

The Phytochemical History of Torbanites

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Abstract—Recently, considerable advances have been made to an understanding of the chemistry of torbanite kerogen. Phytochemical research has shown that the present-day equivalent of the algal source of torbanite produces, not fats, but hydrocarbons of peculiar structure. This paper discusses the nature and chemistry of this alga in relation to the inadequacies of previous hypotheses of the origin of torbanite kerogen.

Experimental work using coorongite and model compounds as kerogen precursors has demonstrated that the conception of an exclusively hydrocarbon source for kerogen is untenable, and that, after deposition, microbial action has had an important secondary effect on the character of the original deposit. The hypothesis is here put forward that coorongite, and hence torbanite, has had a dual origin. It is believed that the primary source was the botryococcenes, but that there has been considerable later modification, and additions, arising from microbiological action. High pressure experiments on coorongite and models have shown that overburden pressure has not been a major factor in the diagenesis of the polymeric material.

Introduction

The nature of oil shale kerogen, its origin and mode of deposition has long been a topic of scientific investigation; indeed, the subject can be said to date its published literature from 1693 with the issue of British Patent 330. In general terms, kerogen may be described as an heterogeneous organic rock-forming material, differing in composition from area to area, and originating in many instances in algal or similar residues.

Although it seems unlikely that an entirely satisfactory hypothesis will ever be forthcoming to explain the formation and nature of such complex organic matter as that of the Green River oil shale or Kukkersite kerogen, the particular problem of the genesis of torbanite now seems much nearer solution.

The structural complexity and polymeric stability of kerogen renders it intractable to chemical attack. Conventional analyses will show only average values for the multitude of micro-structures which must be present. Degradative methods such as pyrolysis or oxidation have similar inadequacies and may, in fact, be characteristic of only certain labile entities within the polymer matrix. Analyses based on kerogen extracts are also of limited usefulness as the soluble portion may be exogeneous, having no intimate relation to insoluble kerogen itself, but arising from extraneous non-kerogen matter associated with the sedimentation process.

Because of the inertness of algal kerogen (torbanite), it was believed rewarding to take " a step backwards in time " and search for a juvenile kerogen in the hope that, being immature, it might be more amenable to chemical examination. Under these circumstances, useful results might be obtained and then extrapolated in terms of the fully lithified material.

While this work was proceeding, important information became available on the phytochemistry of certain algae as well as an additional study on algal physiology. In view of the significance of all these findings to an understanding of the origin of torbanite, it would seem fitting at this time to present further information on this subject.

The Evolution of Torbanite

Compared with true oil shales, torbanite has inherent advantages in any study of kerogen diagenesis. Specimens may be selected nearly free from mineral matter, and biological evidence demonstrates that torbanite arose mainly from a single plant source uncontaminated by animal and other residues. From a study of the stratigraphy of the deposits and their lenticular section, it is apparent that the source organisms grew in quiet stratified shallow fresh-water lakes containing both aerobic and anaerobic aqueous zones. As " pure protokerogen " nearly certainly had a density less than that of water, from a study of the rock structure it must be assumed that either the lakes periodically dried up and the organic residue became mixed with silt or, alternatively, the floating algae became associated with adventitious mineral matter and was caused to sink to the lake's bottom, where it became mixed with further fine mineral detritus.

As a result of bacterial, chemical and geological action in an anaerobic environment, the organic matter was deprived of much oxygen content, while the less resistant components were removed altogether. Thereafter, the pressure of overburden and passage of time induced lithification of the residue to a tough polymeric rock of extraordinary chemical stability. As hand specimens, which have been slowly calcined often show a coarse large-celled alveolate structure, it appears that local concentrations of pure organic matter occur throughout the rock matrix. Chemical studies during the present work have shown that most of the active chemical changes took place within a few decades of deposition and the succeeding aeons served only to solidify and toughen the polymer matrix with little subsequent major chemical change.

Microscopic examination of torbanite sections show a heterogeneous brownish orange matrix, in which are countless irregular yellow areas of organized structure and definite boundaries. Although the source material for these " yellow bodies " of torbanite was a subject of considerable speculation for over a century, the exhaustive examinations by Thiessen (1925) and by Blackburn and Temperly (1936) convincingly demonstrated that torbanite contains recognizable remains of pre-existent algal organisms, virtually identifiable with the extant alga *Botryococcus braunii* (Kutzing). Later work by Dulhunty (1944) and by Cane (1967) left little doubt that the sequence alga→coorongite→torbanite are definable steps in the diagenesis of the rock. After deposition, the main chemical processes appear to be initial oxidation and then polymerization, but, until recently, workers have failed to identify the monomeric units or to explain the exact nature of the gelosic matter of the kerogen precursor. Recent research has clarified many obscure points, and it is now possible to provide information on most aspects of the overall transformation from alga to rock.

The Occurrence and Growth of B. braunii

The genus *Botryococcus* is of wide distribution, and although its taxonomy has been a subject of contention the genus has now been firmly placed in the Chlorophyceae by Belcher and Fogg (1955). The principal species in cool climates is *B. braunii*.

Like some other phytoplankton, *B. braunii* can exhibit more than one growth pattern and phytochemical make-up. In the initial fast-growing stage, the algal mass is green, while at a later stage of development growth becomes very slow. At this resting stage chlorophyll pigmentation decreases and the colony appears reddish from β-carotene. The transformation from the green fast-growth form to the rust-coloured resting stage is usually brought about by an unfavourable environment, such as desiccation or by an adverse nutrient supply. Sporadically and under restricted conditions in a few isolated places in the world, this species colonizes to form thick water blooms which give rise to extensive rubbery deposits on the edges of lagoons or on the beds of almost dry lakes.

The change in colour and growth pattern is accompanied by an extraordinary increase in lipid content, the extent of which has been commented upon by many observers. Until recently, it was believed that the lipids were essentially fatty ester and, although fats undoubtedly make some contribution, Maxwell *et al.* (1968) have shown that the algal " oil " is not ester, but nearly entirely a mixture of two isomeric hydrocarbons of novel structure. Although some algal mat communities are quite rich in fatty acids of high unsaturation, the production of such large amounts of hydrocarbons is quite exceptional. After the death of the plant, this hydrocarbon mixture resists decay and the residue remains floating on the water until it is blown to the shore or deposited by other agency.

The desiccated material is termed coorongite, and it seems very likely indeed that coorongite is a modern representative of the immature kerogen mentioned earlier. The discovery of the botryococcenes and the physiological studies of Belcher (1968) have radically altered previous thinking on the chemistry of coorongite and torbanite kerogen. The actual formation of coorongite has already been described by Broughton (1920), and reference should be made to papers by Thiessen (1925) and by Cane (1969) for further information on its mode of occurrence and the nature of the deposit.

Phytochemistry of B. braunii

As mentioned above, *B. braunii* is a strange alga and exhibits different physiological behaviours, depending on the environment and food reserves. There seems little doubt that the spectacular build-up of lipids is a defense mechanism, to provide a suitable energy source, as well as to act as a protection from desiccation. In the green exponential-growth form, Brown *et al.* (1969) have shown that the unsaponifiable lipids (up to 15% of dry weight, but usually much less), consist mainly of n-alkadienes and n-alkatrienes in the C_{27}–C_{31} range, together with lesser amounts of n-alkenes between C_{19} and C_{33}. Moreover, Knights *et al.* (1970) have demonstrated that the three predominant hydrocarbons correspond to one general formula :

$$CH_2{=}CH{-}(CH_2)_n{-}CH{=}CH{-}(CH_2)_5{-}CH_3$$

with n=17, 21, 19 in increasing order of abundance. The saponifiable lipids consist mainly of esters of oleic, palmitic and other alkanoic acids.

At the orange resting stage, the alga contains a small amount of saponifiable lipids of orthodox composition, consisting mainly of palmitic, oleic and a C_{28} ester, together with less quantities of esters of C_{14}–C_{30} straight chain acids. The unsaponifiable lipids, which may amount to nearly 90% of the algal dry weight, consist nearly entirely of two isomeric $C_{34}H_{58}$ hydrocarbons. These botryococcenes—so called by Maxwell (1968)—are believed to contain six double bonds, six methyl groups, four exo-methylenes and a vinyl side-chain per molecule.

The elemental composition of the botryococcenes corresponds exactly to the $C_{34}H_{58}$ dimeric alkyl residue of the model trienoic acid discussed by Cane (1967) and closely resembles Aarna's " kerogen unit " $C_{34}H_{57}$ (1956). Both Cane and Aarna arrived at their conclusions by investigating the chemistry of kerogen itself, and their postulates reasonably fitted the known facts at that time. If the botryococcenes are indeed the main final metabolite of *B. braunii*, then the conclusion seems inescapable that coorongite, and presumably torbanite, were formed by oxidation and polymerization of these hydrocarbons. However, certain experimental facts do not completely fit this hypothesis and the only explanation in accord with the observations is to conclude that coorongite has a dual origin. There is no doubt that the primary source is the botryococcene hydrocarbons, but it is equally certain that a secondary contribution comes from lipoid matter of more normal composition. Spectroscopic studies point very strongly to fatty esters originating, either directly or indirectly, from microbial activity.

Coorongite and the Botryococcenes

There is no doubt that coorongite has its botanical genesis in growths of *B. braunii*, and for many years it has been assumed that highly unsaturated acids played a major role in its formation. The original premise arose partially from the work of Stadnikov (1929), who believed that the " hydrocarbons " of torbanite and coorongite resulted from the transformation of unsaturated fatty acids. Stadnikov postulated an initial oxidation and polymerization followed by bacterial decarboxylation under anaerobic conditions. Stadnikov's hypothesis is still probably partially valid, as coorongite may contain up to 14% saponifiable matter, composed mostly of fatty ester.

In contradiction to Stadnikov's hypothesis, it has now been established that *B. braunii* secretes very little fatty acid, but produces two reactive hydrocarbons which readily polymerize. Furthermore, recent observations (personal communication, Dr. J. Maxwell, University of Bristol) have shown that *B. braunii* in laboratory cultures can give rise to a rubbery residue (hereafter designated " B.b. rubber ") having most of the physical properties of coorongite. It would be facile to believe that coorongite represents simply an aged " B.b. rubber " ; the extraordinary feature is that neither coorongite, " B.b. rubber " nor the total lipids of *B. braunii* are identical one with the others, and although all have some common chemical configurations, each has chemical features absent in the other two.

Because of similarities between the tentative structure of botryococcene and that of squalene (see Figure 1), the use of squalene as a model compound was explored. Polymerization and oxidation experiments with squalene were not particularly successful, and no rubbery product was produced, even after prolonged incubation. Trienoic fatty acids, on the other hand, produced " rubbers " very similar to coorongite, but with an infra-red spectrum somewhat different from it, and different again from the botryococcenes. Gentle pyrolysis of both types of synthetic polymeric models yielded oils similar to shale oil, the least akin being that from polysqualene.

Within the general biological background given above, assisted by infra-red and n.m.r. spectra, the tentative chemical evolution of torbanite can now be traced. An examination of " B.b. rubber " shows that the three-stage transformation mentioned earlier is not the full story, but rather five distinct steps can be isolated and defined. The stages are: alga→botryococcenes→" B.b. rubber "→coorongite→torbanite. At all stages, the following major i.r. absorption bands (cm.$^{-1}$) occur: 2850–2962 (ν C–H), 1647 (ν C=C), 1467 (δ CH_2, δ CH_3) and 917, 1002 (γ C–H vinyl). There are slight shifts in frequency and in the case of coorongite the 1467 cm.$^{-1}$ absorption peak is augmented by a multiple " square trough " (see Figure 2) in the 1350±40 cm.$^{-1}$ region. The interpretation to be applied throughout is that all compositions are essentially aliphatic unsaturated hydrocarbons containing many small side alkyl groups of various configurations, some of which are unsaturated. In the case of the botryococcenes and " B.b. rubber " the absorption at *ca.* 1376 is quite sharp, whereas in coorongite and torbanite there is a wide absorption band made up of four distinct peaks at 1310, 1349, 1367, 1377. This shows that the gem. dimethyl terminal configuration suggested for the botryococcenes is supported by a plurality of small alkyl groups of various types. The occurrence of the latter is interpreted as the result of microbiological agencies.

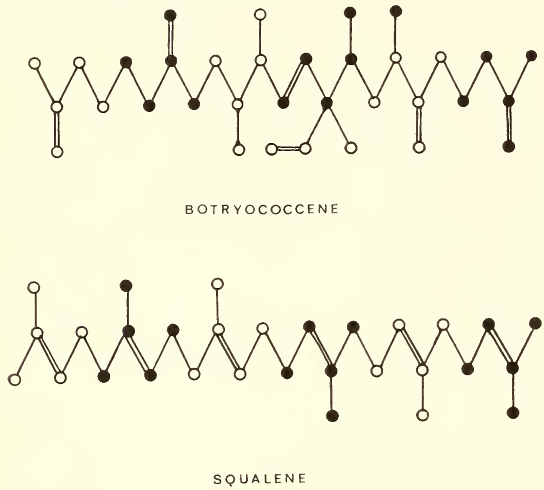

FIGURE 1.

Table 1 shows differences in chemical groupings which occur as the various stages develop, and Figure 2 illustrates the more important region of the infra-red spectra of each stage.

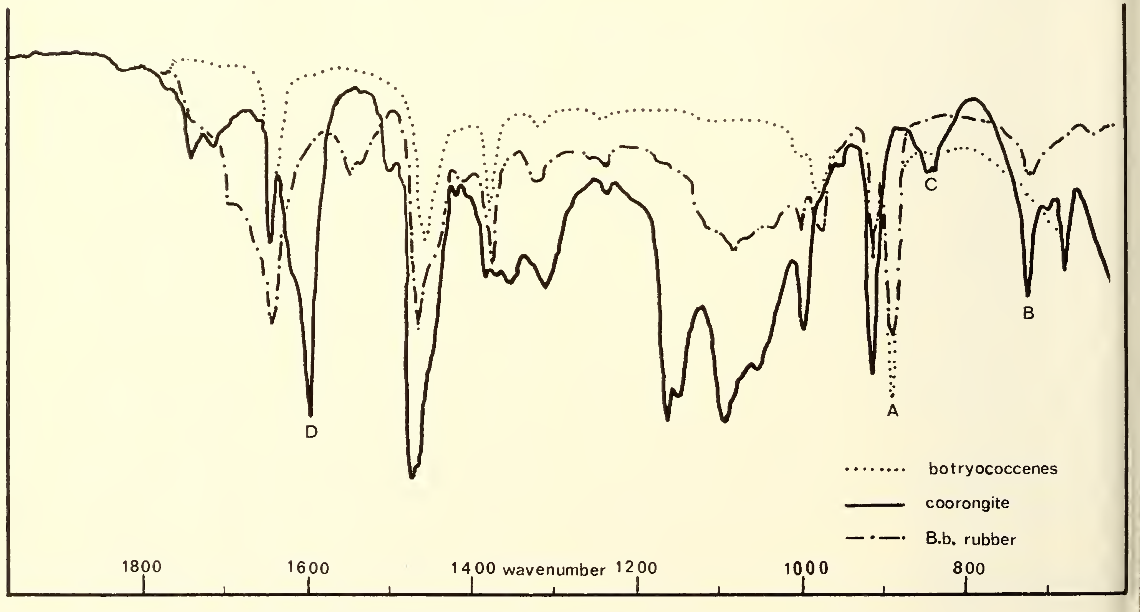

FIGURE 2.—Infra-red spectra of coorongite and precursors.

Three evolutionary trends can be clearly observed from the spectra :

(i) The progressive disappearance of the reactive disubstituted carbon-carbon double bonds and the exomethylene groups (A), although much general unsaturation still remains.

(ii) The appearance, after deposition, of oxygen linkages as hydroxyl and as carbonyl (fatty acids) as well as some clearly defined aromatic structures (C and D. Mass spectra indicate that these are probably alkyl benzenes). The presence of alkyl aromatics is strange, but they have already been noted by Douglas (1969). Their presence is supported by overlapping absorptions at *ca.* 1500 cm.$^{-1}$.

arise from chemical changes, and it must be accepted that these originate by means of biological processes.

N.m.r. studies (Figure 3) of the various stages in kerogen diagenesis support the infra-red evidence discussed above. Examinations by n.m.r. leave little doubt that the main contributors to " B.b. rubber " (n.m.r. trace A) are the botryococcenes, but these are not the sole progenitors. Differences are even more pronounced between coorongite and the botryococcenes. In coorongite (n.m.r. trace B) the bands between 4 and 5·5τ, arising from unsaturation, were barely developed (shown amplified in trace C), and there was virtually no resonances between 8·9 and 9·1τ arising from methyl groups attached to alkyl chains.

TABLE 1
Diagnostic Infra-red Absorptions

Wave Number	Assignment	Botryo-coccenes	Botryo-coccene Rubber	Coorongite	Kerogen
891 (A)	$=CH_2$	+	+	—	—
979	C=C	+	+	—	—
3310	O—H	—	+	+	+
725 (B)	$-(CH_2)_n-$	—	+	+	+
1745, 1710	C=O	—	—	+	+
1154, 1147, 1091 ..	—O—	—	—	+	+
1589, 1592 (D)	$C=C_{Ar}$	—	—	+	+
840 (C)	$C-C_{Ar}$	—	—	+	+

— = absent.
+ = present.

(iii) The development of substantial amounts of straight-chain methylene (B) as well as oxidation products (coorongite contains up to 15% oxygen). The relative ratio of 1376 : 1467 cm.$^{-1}$ bands also point to increased straight-chain structures in coorongite.

Some structural changes show up quite early in the transformation to " B.b. rubber ", for example, the development of $-(CH_2)_n-$ at 725 cm.$^{-1}$, completely absent in botryococcene. Also, the wide bands in the 1080–1160 region which correspond to oxygen-containing products arising probably from chemical oxidation as well as esters and alcohols of microbiological origin. The oxygen and straight-chain linkages are even more developed in coorongite.

In the later stages of transformation, the extent of the exomethylene structures (A) decreases and, spectrally, they are entirely absent in coorongite and kerogen (the spectrum of kerogen is not shown in Figure 2, but see Cane (1967)). Concomitant with the disappearance of the exomethylene groups, a pronounced aromatic component shows up. It does not seem feasible that such aromatics

The resonance at 8·7τ in the coorongite spectrum (B) is probably caused by the effect of oxygen on a neighbouring methyl group, possibly methoxy. Most n.m.r. features of coorongite show a general contribution from botryococcenes, but allow substantial additions from straight-chain and oxygen compounds.

The Origin of Torbanite

Although the evidence is conclusive that the prime source for coorongite is algal and it seems reasonable to extend the explanation to torbanite kerogen, one must not assume a single source material. Just as in some petroleums, it is now believed that both animal and plant debris contributed, the present study has shown that both straight-chain compounds (*ex* micro-organisms) and branched-chain hydrocarbons (*ex* alga) contribute to the chemistry of coorongite, and hence to the kerogen of torbanite itself.

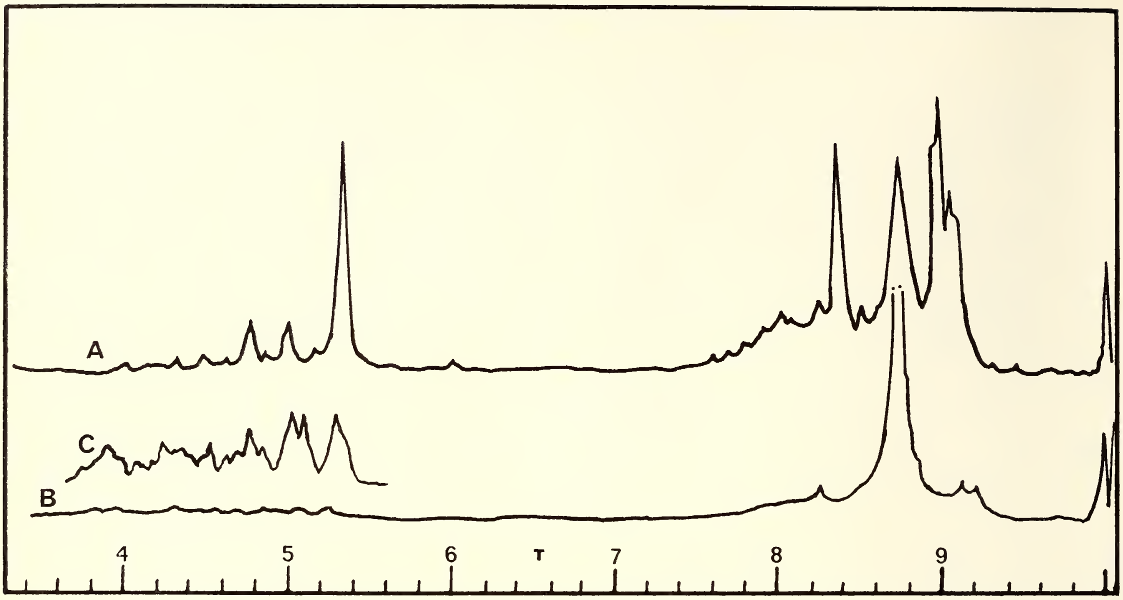

FIGURE 3.—N.m.r. spectra of coorongite and precursors.

There seems no doubt that micro-organisms play an important role after the " B.b. rubber " stage, and it seems equally likely that anaerobic bacteria cause the decrease in oxygen in the coorongite→kerogen transformation. Bacteria certainly can alter the composition of organic material and they are capable of preferentially attacking and removing specific chemical configurations. Undoubtedly, purely chemical reactions cause the initial oxidation and polymerization of the algal lipids, and one might surmize that " B.b. rubber " could be made under sterile conditions. One would expect, however, a somewhat different chemical composition from that occurring naturally.

By the very nature of the reactions leading to the fully polymerized substance, only traces of relatively unreactive residues are likely to be identified by solvent extraction and chemical analysis. The more characteristic reactants will have lost all identity by the complex hardening process, involving oxidation, polymerization and condensation, assisted and modified by bacterial attack. After the cessation of active chemical change, further transformation will have taken place under the overburden.

A study of models of the later stages in the coorongite→kerogen transformation has been of doubtful merit. Samples of polymers of trienoic acids and coorongite have been exposed to pressures up to 15,000 atms. without change to a rigid solid. There seems to be some evidence that pressures exceeding 22,000 atms. does induce solidification, but this so far exceeds any likely overburden pressure as to have little useful interpretation. Nevertheless, rigid solids similar to torbanite have been produced by maintaining coorongite and the acid gels under 28,000 atms. at 250° C. for 16 hours. There was no observable change under the same conditions at 30° C.

Although one can conjecture the likely final stages in the transformation to kerogen, all attempts so far to effect this change under laboratory conditions have been unsuccessful. As in many other similar processes, it would seem there is no substitute for geological time.

Acknowledgements

Acknowledgement is made to the donors of The Petroleum Research Fund, administered by the American Chemical Society, for partial support of this work. We also acknowledge the assistance of Professor G. R. Hill, of the University of Utah, for the high-pressure experiments.

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(Received 13 September 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 39–44, 1971

Potassium-Argon Basalt Dates and Their Significance in the Ilford-Mudgee-Gulgong Region

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Abstract—Three different topographical environments occur in separate areas of the Ilford-Mudgee-Gulgong Region. Tertiary basalts varying in mode of occurrence were selected from each area for potassium-argon (K-Ar) dating. Results revealed flows of upper Eocene-lower Oligocene and middle Miocene ages, resting on two different erosion surfaces regarded as Eocene and upper Miocene, respectively. An intermediate and prominent erosion level forming undissected upland surfaces along the Main Divide, and extending across deeply dissected country to the west, is believed to be of lower Miocene age. The auriferous gravels of the Gulgong deep leads were probably deposited between late-lower and early-middle Miocene time and buried beneath middle Miocene basalt flows.

Introduction

The purpose of this paper is to record K-Ar dates obtained for basalts at five places in the Ilford-Mudgee-Gulgong Region, and to consider the significance of results in relation to the age of auriferous deep leads at Gulgong and the geomorphology of the Cudgegong Valley and the areas through which the Cudgegong River passes.

Relations between different basalt occurrences and their topographical environments, and the geomorphological significance of the relations, have posed long-standing problems. The present investigation by K-Ar dating of selected basalts was undertaken with the object of throwing more light on such problems, as well as gaining more exact knowledge of the age of the Gulgong Gold Field.

The history and geology of the Gulgong Gold Field has been described by Jones (1940) ; the occurrence of Permian sediment in the Cudgegong Valley has been recorded by Dulhunty and Packham (1962) ; Mesozoic and Tertiary history of the region has been discussed by Dulhunty (1962) ; and the general geology has been summarized by Offenberg, Rose and Packham (1968). For geomorphology and Tertiary igneous history of central-eastern New South Wales bearing on the Mudgee-Gulgong Region, reference should be made to Browne, Wilkinson and others in Packham (1969).

All geological periods referred to in this paper, as equivalent to K-Ar dates in millions of years, are in accordance with the times scale by Funnell (1964).

Topographical Environments and Occurrence of Tertiary Basalt Flows

The Mudgee-Gulgong Region is situated on the Western Slopes of central-eastern New South Wales, to the west of the Main Divide. It includes three distinctly different topographical environments, which, for the purpose of the present paper, may be described as the Gulgong Surface, the Hargraves-Yarrabin Block and the Rylstone-Ilford Level, as illustrated in the locality map, Figure 1, and the topographical sections in Figure 2.

Tertiary basalt flows occur in all three topographical areas of the region. In each area the mode of occurrence is different.

The Gulgong Surface

A low undulating surface at about 1,500 to 1,750 feet above sea level, lying to the north of Mudgee. Basalt flows fill old valleys excavated in the general surface of the country. In places gold-bearing gravels occur beneath the basalt forming deep leads, as illustrated in Section C–D, Figure 1. In some cases the upper surfaces of the basalt flows now outcrop more or less level with the present surface, whilst in others the basalt is covered by up to 30 feet of alluvium.

The old deep lead valleys were excavated mainly in Middle Palaeozoic basement rocks, but in places along the Cudgegong Valley near Guntawong they cut through Permian sediments occurring on the valley floor and extending some depth beneath the present river bed. From sub-surface data (Jones, 1940) and surface elevation, it is evident that the deep-lead valleys were excavated to at least 70 feet below the

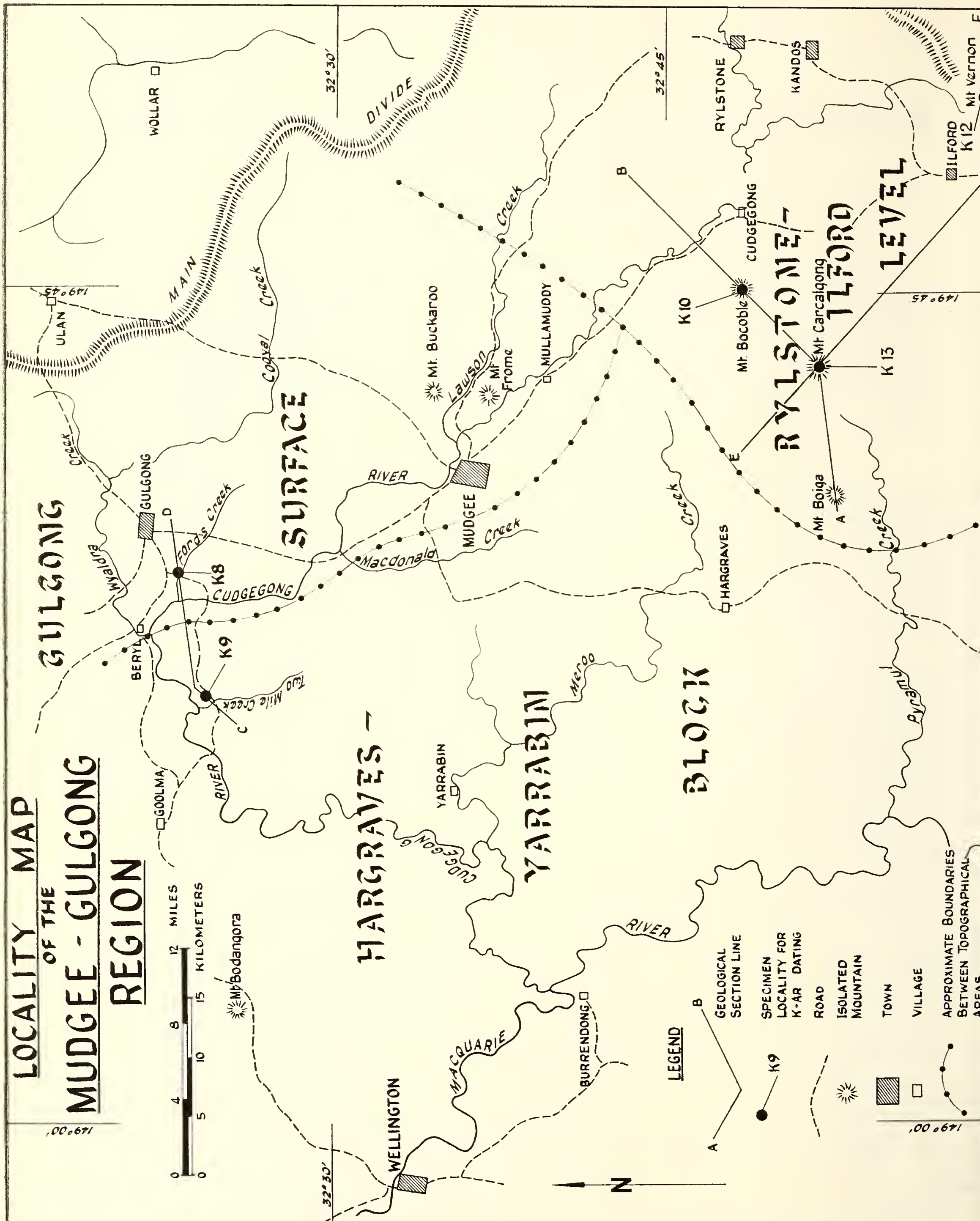

FIGURE 1.—Locality map showing topographical areas and location of basalts selected for potassium-argon dating.

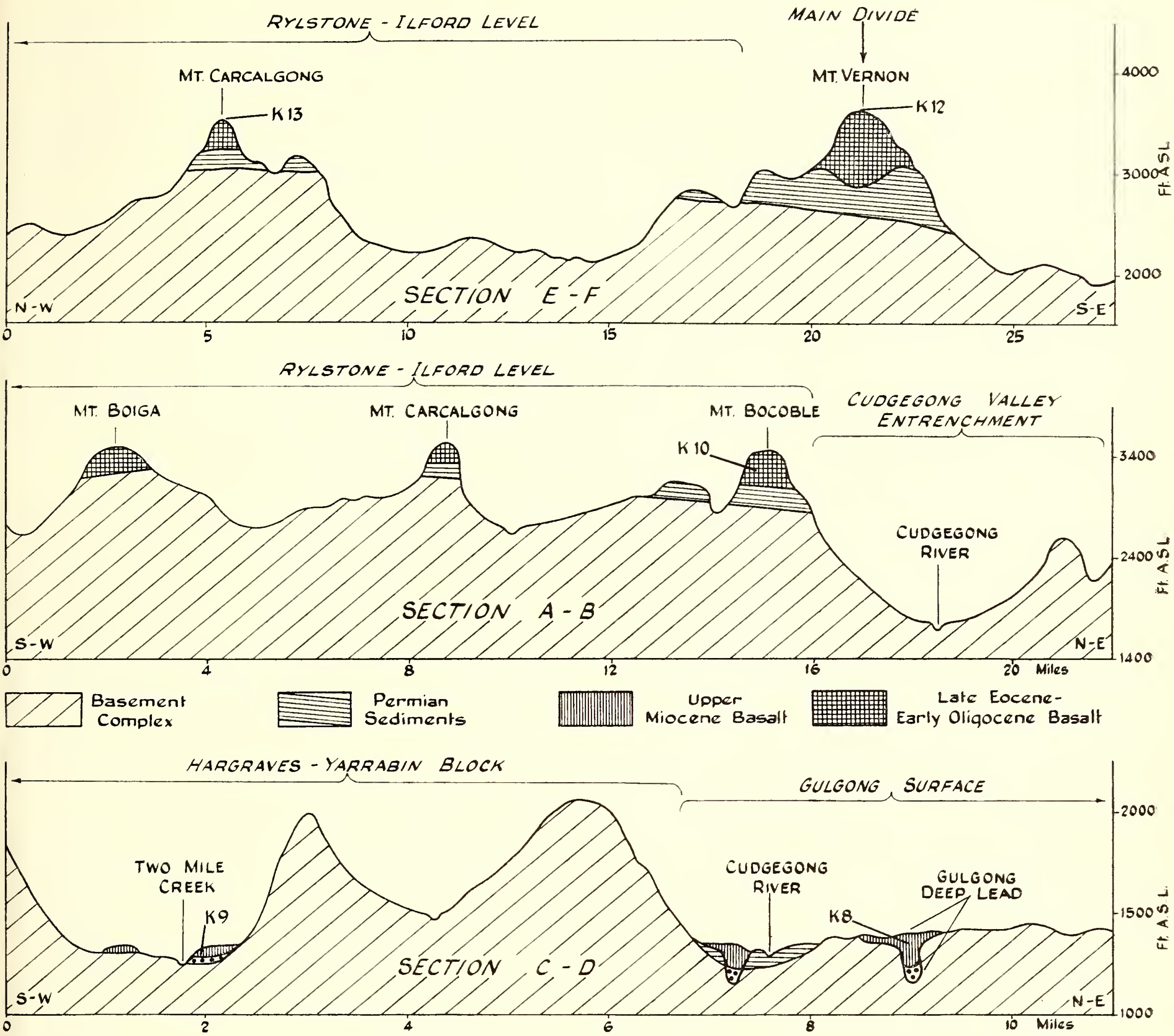

FIGURE 2.—Geological sections across topographical areas in the Mudgee-Gulgong-Ilford Region showing occurrence of basalts selected for potassium-argon dating.

present bed of the Cudgegong River, and that basalt flows, which filled the old valleys, now occur up to at least 50 feet below present river level.

The Hargraves-Yarrabin Block

An elevated area lying to the south and south-west of Mudgee at between 2,200 and 2,800 feet above sea level with erosional residuals to 3,200 feet. It is extensively and deeply dissected by streams flowing in valleys from 700 to 1,000 feet deep.

Basalt flows occur on the floors of valleys occupied by tributaries of the Cudgegong, and by the river itself downstream from Beryl. In the valley of Macdonald Creek, a small outlier of basalt 80 feet thick occurs on a rise of Permian sediments 150 feet above the valley floor, which is 500 to 700 feet below surrounding hills of basement rock (Dulhunty and Packham, 1962). Residuals of flow also occur on the floor of the valley of Two Mile Creek near the Gulgong-Wellington road crossing, one mile above its junction with the Cudgegong River, within the area of the Hargraves-Yarrabin Block. The valley which is carved entirely from basement rock is about 600 feet deep. Erosional residuals of basalt 10 to 30 feet thick lie on auriferous gravel level with the alluvium of the present valley floor, as illustrated in Section C–D, Figure 2. This represents a basalt flow across the valley floor at its present level, and subsequent removal of most of the basalt without further deepening of the valley.

The Rylstone-Ilford Level.

An upland surface at 2,500 to 3,000 feet with residuals rising to 3,600 feet, situated along the Main Divide and immediately to the west, between Rylstone and Ilford, as illustrated in Figure 1, and Sections A–B and E–F, Figure 2. This level is undissected by entrenchment due to late Tertiary elevation, as it is situated above the heads of rejuvenation in the valleys of the Cudgegong River and Pyramul Creek.

Flows of fine-grained olivine basalt, up to 500 feet thick covering Tertiary wash and soils, occur as erosional residuals at Mts. Boiga and Carcalgong on the western side of the Rylstone-Ilford Level, and at Cherry Tree Hill, Mt. Vernon and Kandos along the Main Divide. They rise to 3,600 feet and rest upon isolated pedestals of country rock standing some 300 to 500 feet above the average surface of the surrounding country. Such occurrences represent extrusion of basalt flows across an old erosion surface largely removed by subsequent erosion during the development of the present Rylstone-Ilford Level.

A coarser grained olivine basalt, or fine-grained dolerite, occurs on a pedestal of country rock at Mt. Bocoble, four miles west of Cudgegong Village. Its general mode of occurrence resembles that of the nearby basalt flows resting on pedestals, but it may be either a sill or a flow, as conclusive field evidence of its mode of origin is lacking. It is, however, not a plug.

The Cudgegong Valley

The Cudgegong River rises on the upland surface of the Rylstone-Ilford Level to the east of Rylstone. It flows west to its head of rejuvenation near its junction with Carwell Creek, midway between Rylstone and the village of Cudgegong. In this vicinity, at the upper limits of entrenchment due to late Tertiary elevation, the river descends into a deep, steep-sided valley carved out of the old upland surface (see Section A–B, Figure 2). It then flows north-west down through a deep, steep-sided valley to Mullamudy, where its valley floor widens and merges with the widespread valley alluvium extending along streams throughout the Gulgong Surface to the north and north-west.

Downstream from Mullamudy the receding valley wall on the north-eastern side of the Cudgegong River terminates in the isolated hills of Mt. Frome and Mt. Buckaroo. On the other side of the river the south-western valley wall continues to the south of Mudgee, and becomes the north-eastern escarpment to the Hargraves-Yarrabin Block separating it from the Gulgong Surface.

From Mudgee the Cudgegong River flows north-west through a wide valley, across the south-western side of the Gulgong Surface, parallel and close to the escarpment of the Hargraves-Yarrabin Block. At Beryl, near Gulgong, the river turns sharply to the south-west, flows into the Hargraves-Yarrabin Block through a deep, steep-sided valley, then south towards Burrendong Dam, where it joins the Macquarie River.

Selection of Basalts for Potassium-Argon Dating

Basalt specimens suitable for K-Ar dating (see Table 1), and typical in mode of occurrence for each of the three topographical areas, were collected at the localities shown on the map, Figure 1, and in the sections of Figure 2, as follows :

TABLE 1
Potassium-Argon Basalt Dates

Syd. Uni. Spec. No.	Geo-chron. Lab. No.	Locality	Calculated Age (m.y.)	Geol. Age (Funnell, 1964)
K 8	R1216	Ford's Creek, Gulgong	14·8±1·2	Middle Miocene
K 9	R1341	Two Mile Creek, Gulgong	13·8±1·1	Middle Miocene
K10	R1267	Mt. Bocoble, Cudgegong	35·6±2·1	Lower Oligocene
K12	R1676	Mt. Vernon, Ilford	33·7±2·1	Lower Oligocene
K13	R1745	Mt. Carcalgong, Pyramul	41·6±2·6	Upper Eocene

The Gulgong Surface

Specimen K8 was collected from the north bank of Ford's Creek, on the eastern side of the Gulgong-Wellington road, 3·2 miles from the Gulgong Post Office. Basalt at this point is portion of the flow which, in places, filled the valleys of the Main or Gulgong Deep Lead and its tributaries to depths of 130 feet below the present general erosion surface.

The Hargraves-Yarrabin Block

Specimen K9 was collected from an outcrop on the western side of the Gulgong-Wellington road, 0·35 mile north from the Two Mile Creek crossing, where basalt forms an erosional residual covering auriferous wash level with the upper surface of present-day alluvium on the floor of the valley.

The Rylstone-Ilford Level

Specimen K12 was collected on the eastern side of the road from Ilford to Running Stream via Mt. Vernon, at a point six miles from Ilford, where the basalt is approximately 500 feet thick. This flow and others in the vicinity of Mt. Vernon and Cherry Tree Hill rest on a pedestal of country rock standing 400 to 600 feet above the average surface of the adjacent surrounding country. The old erosion surface beneath the basalt exhibits some 200 feet of topographical relief, and carries auriferous Tertiary wash (Booker, 1938).

Specimen K13 was collected at the summit of Mt. Carcalgong from an outcrop 25 feet south-west of Carcalgong Trig. This occurrence probably consists of two flows amounting to about 300 feet of medium to fine-grained basalt resting upon what appears to be Tertiary soil overlying country rock.

Specimen K10 was collected from a level 200 feet above the base of coarse-grained basalt, or fine-grained dolerite, capping Mt. Bocoble at a point 0·2 mile west of Bocoble Trig. The erosional residual is about 400 feet thick and may represent either a flow or sill.

Results and Conclusions

K-Ar age determinations were carried out on the five selected specimens of basalt by Geochron Laboratories, Cambridge, U.S.A. Results are set out in Table 1.

After consideration of K-Ar dates in relation to mode of occurrence of basalts and topographical environments in which they occur, the following conclusions were drawn :

1. The high-level basalt flow residuals, such as Mt. Carcalgong and Mt. Vernon, set on pedestals of country rock above the general surface of the undissected Rylstone-Ilford Level, are late Eocene to early Oligocene in age, and very much older than the low-level " valley basalts " near Mudgee and Gulgong.

Similar occurrences of high-level basalts capping isolated pedestals of country rock, such as Mt. Bodangora on the western side of the Mudgee-Gulgong Region, and Nulla Mountain to the east of Rylstone, are almost certainly of similar history.

The pre-basalt erosion surface on which the " pedestal basalts " were extruded must have developed during Eocene time, and the early stages of its development may even date back to late Cretaceous.

The " pedestal basalts " would seem to have been extruded progressively at different times over a relatively long interval during late Eocene and early Oligocene, as suggested by results of Wellman, McElhinny and McDougall (1969) and McDougall and Wilkinson (1967) for basalts from the Liverpool and Barrington Ranges, and other occurrences in eastern New South Wales.

2. The K-Ar date obtained for the basalt, or fine-grained dolerite, at Mt. Bocoble suggests that it originated during the period of time in which nearby flows at Mt. Vernon and Mt. Carcalgong were extruded. It rests on country rock at about the level of the erosion surface on which the flows occur. If Mt. Bocoble is a flow, it belongs to the same general flow series as Mt. Carcalgong and Mt. Vernon. If it is a sill, it would appear to have been intruded between the surface of the pre-existing country rock and the base of earlier flows of the same series since removed by erosion in the immediate vicinity.

3. The upper surface of the dissected Hargraves-Yarrabin Block would appear to be continuous with, and a western extension of, the Rylstone-Ilford Level. The dissection of this block by the Cudgegong and Macquarie River systems must have taken place during lower Miocene time, as middle Miocene basalts lie upon the valley floors.

4. The widespread dominant surface of the Rylstone-Ilford Level must have developed during middle and upper Oligocene time, as remnants of the Eocene surface carry upper Eocene-lower Oligocene basalts, and the dissection of the Hargraves-Yarrabin Block occurred during lower Miocene time.

5. The basalt flows filling deep-lead valleys on the Gulgong Surface and those lying on valley floors in the adjoining Hargraves-Yarrabin Block are essentially the same age. They average 14·3 m.y.—equivalent to middle Miocene, and almost certainly belong to the same flow series.

6. The deep leads of the Gulgong Gold Fields occurring as auriferous gravel in relatively narrow entrenched valleys up to 250 feet deep

(Jones, 1940) were buried beneath basalt flows in middle Miocene time. The auriferous gravel was probably deposited between late-lower and early-middle Miocene time.

7. The removal of estuarine Permian sediments from their original basement valleys, during re-excavation, to form the present valleys of the Cudgegong River and some of its tributaries, such as Macdonald Creek and the Two Mile Creek (Dulhunty and Packham, 1962), must have been completed almost to its present stage by middle Miocene time.

Acknowledgements

In conclusion, the writer wishes to acknowledge the assistance of Associate Professor T. G. Vallance and Dr. E. A. K. Middlemost in petrological examination of basalts selected for K-Ar dating; helpful discussion with Dr. W. R. Browne; and also research facilities provided by the Department of Geology and Geophysics of the University of Sydney.

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(Received 24 August 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 45–61, 1971

Magnetic Properties of Rocks from the Giles Complex, Central Australia

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Abstract—The Giles Complex is a series of coarse-grained layered mafic and ultramafic intrusions about 1,100 m.y. old. Densities of the samples from the Complex ($2 \cdot 8$ gm. cm.$^{-3}$ to $3 \cdot 3$ gm. cm.$^{-3}$) span the range for rocks of this kindred.

The measured N.R.M. directions were widely scattered, and hence partial A.F. demagnetization was carried out. Since the magnetic susceptibility anisotropy ellipsoid was, on the average, triaxial, anisotropy effects on magnetization direction were ignored.

The partial A.F. demagnetization results correlated strongly with other stability tests such as the Koenigsberger ratio. After these stability tests 47% of the samples were shown to possess stable magnetization and gave a mean direction of magnetization which is statistically non-random at the 99% level, and which diverges from the present geomagnetic field direction. The results established that the Giles Complex was in its present position at the time of acquisition of its T.R.M. The magnetic properties tended to correlate with the state of exsolution and oxidation of the iron-titanium oxides.

Assuming the stable T.R.M. direction to correspond to that of a dipole, the position of the Earth's North Magnetic Pole 1,100 to 1,000 m.y. before the present, relative to Australia, was latitude 68° N., longitude 343° E. (semi-axes of the ellipse of 95% confidence: 23° and 29°).

1. Introduction

The Precambrian Giles Complex is a series of layered mafic and ultramafic intrusions extending over an area of at least 25,000 sq. km. of central Australia (Figure 1 and Nesbitt *et al.*, 1970). Palaeomagnetic data from the Precambrian is sparse, and hence the opportunity was taken to investigate the magnetic properties of the Giles Complex. In addition to filling a gap in the history of the geomagnetic field, it was expected that information could be added to the study of the structural relationships (and history) of the Complex. Further facets of the investigation include study of magnetic properties of the rocks and certain aspects of petrological/mineralogical properties. Preliminary studies (Facer, 1967) had indicated that detailed investigations were warranted.

In general, the Giles Complex intrusions, and many of the metamorphic rocks into which they were emplaced, have given rise to inselbergs and domed inselbergs which rise out of desert lowlands to form extensive arid upland regions. Mount Davies, the highest point shown in Figure 1, is, at 1,068 metres above sea level, about 500 metres above the lowland plain. These uplands are part of a series of mountain ranges extending in a broadly east-west direction through central Australia.

Present weathering of rock in the region is characteristic of arid regions, being mainly physical breakdown giving rise to boulder-strewn slopes and uplands, with some talus slopes (Plate I). However, there is some chemical weathering, which has emphasized the strongly-developed mineralogical layering of the Giles Complex (Plate I (2) and (3); and figures 3 and 4 in Nesbitt and Talbot, 1966). Because of these mainly physical weathering processes many of the Giles Complex rocks, especially the mafic portions, have only a thin weathering rind (at times less than a millimetre).

In 1963, the Department of Geology and Mineralogy, University of Adelaide, began the continuing Giles Project (Nesbitt and Kleeman, 1964). This is concerned mainly with a study of the " major intrusions of the Giles Complex " (Nesbitt and Talbot, 1966, p. 3), although at present most work is being carried out on the South Australian intrusive bodies. A similar programme is being conducted by the Geological Survey of Western Australia (the " Blackstone Project ") on the Western Australian intrusive bodies (Horwitz and Daniels, 1967; Horwitz *et al.*, 1967; Daniels, 1967).

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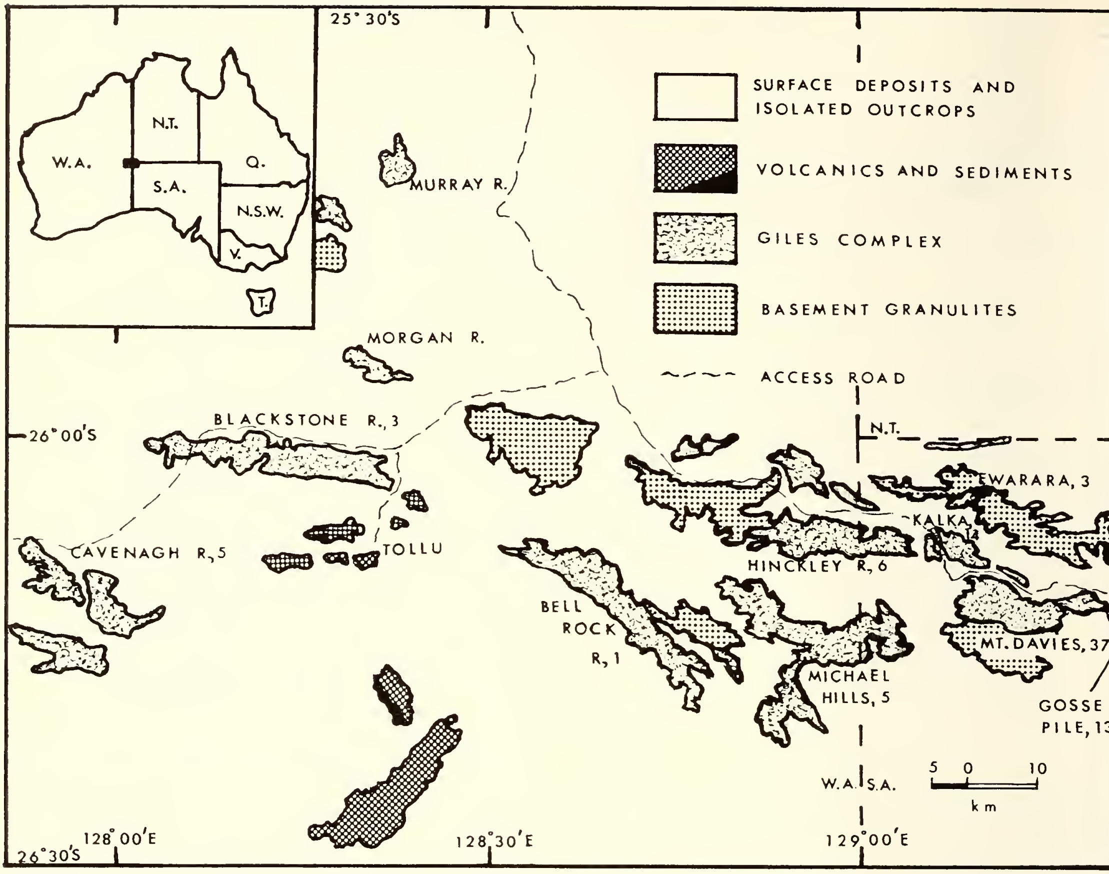


FIG. 1.—Simplified geological map of the part of the Giles Complex sampled, based on fig. 1 of Nesbitt and Talbot (1966) and on field observations. " *R* " is an abbreviation of " Range " and the number following the name indicates the number of oriented samples taken. The outcrops of the Giles Complex extend both to the east and to the west of the area shown here.

2. Geological Setting

The mafic and ultramafic rocks now known as the Giles Complex were first recorded by Streich (1893) and later by Basedow (1905). The area forms part of the Musgrave Block, and was briefly discussed in a regional interpretation of this Block by Sprigg and Wilson (1959), who considered the separate portions of the Complex to be parts of " a once continuous basic and ultrabasic (?) lopolith " (p. 536). Later work has modified this idea (Nesbitt *et al.*, 1970), the Complex now being considered as a series of separate, although related, intrusions.

2.1. *Regional Geology*

The only rocks from the area of Figure 1 for which radiometrically-determined ages have been published are the volcanics from Tollu. These volcanics have been dated at 1,060$\pm$140 m.y. (95% certainty limit) by Compston and Nesbitt (1967). South Australia Geological Survey geological map sheets for the area of Figure 1 show that apart from the intrusions no rocks were mapped with ages between Archaean and Tertiary. The Giles Complex and dolerite dykes were not dated on these maps. However, Nesbitt *et al.* (1970) considered the metamorphic terrane into which the Giles Complex has been emplaced to have an age of between 1,300 and 1,600 m.y. If this is the case, then the ages should be given as Proterozoic (Middle Proterozoic or Carpentarian) on the time-scale proposed by Dunn *et al.* (1966). Similarly, if the Giles Complex is related to the Tollu Volcanics (Nesbitt, 1966), then it too is Proterozoic (Upper Proterozoic or Adelaidean). In Figure 1 the lower three units of the legend may thus be considered

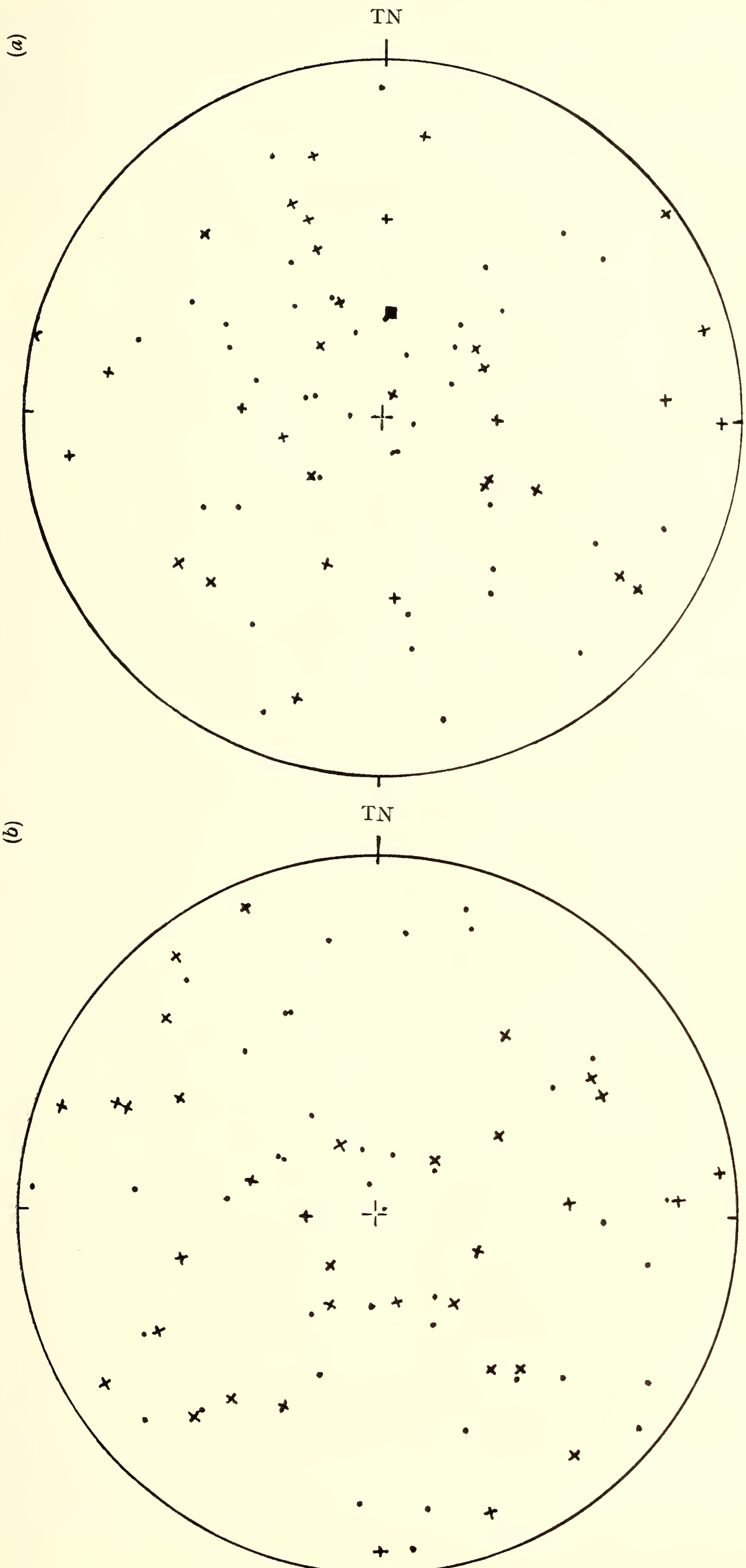


Fig. 2.

Explanation of Fig. 2.

Directions of N.R.M. magnetization, plotted on a stereographic equal-angle projection. The directions of the dolerite dykes and of the few sites at which no igneous layering was measurable have been omitted since they could not be plotted in part (*b*).

(*a*) Directions *before* rotating the layering to horizontal.

(*b*) Directions *after* rotating the layering to horizontal.

Dots indicate negative inclinations (Normal, plotted on to the upper hemisphere) and crosses positive inclinations (Reversed, lower hemisphere). The solid square indicates the direction of the earth's magnetic field for the collection area at Epoch 1966·5: declination 4° E. and inclination −58°.

Proterozoic. In the Western Australian portion of the area a similar situation obtains, although some rocks may extend in age to the Palaeozoic (Horwitz, 1967).

When visible, contacts of the Giles Complex with the metamorphic terrane are sharp. Tectonism had caused considerable deformation prior to intrusion, but post-intrusion tectonic processes appear to have been limited to broad warping with rotation of " blocks ", some of which are separated by shear zones up to half a kilometre in width and tens of kilometres in length. Despite these latter deformations, there has only been " granulation " or recrystal-

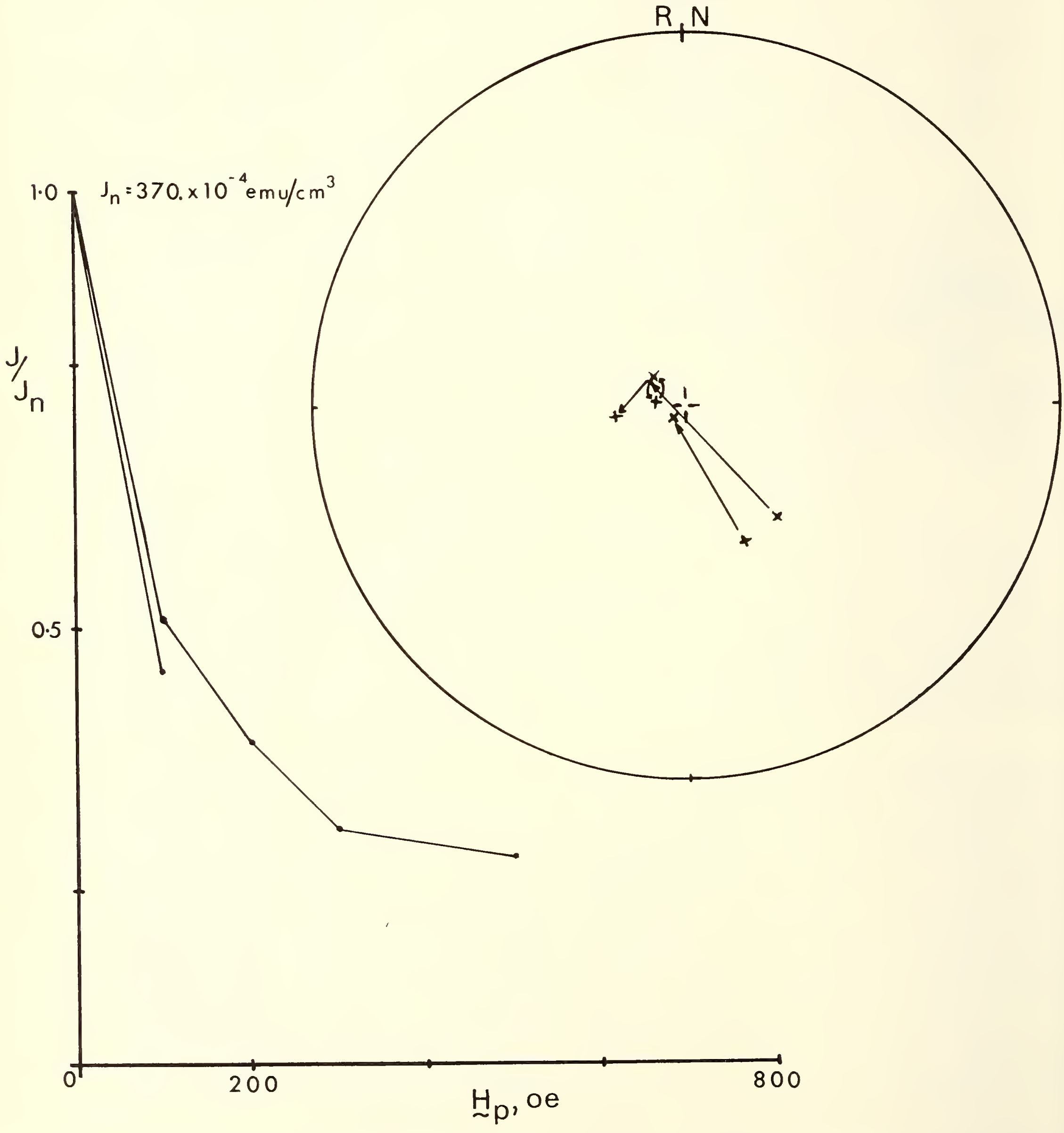


Fig. 3.—Partial A.F. demagnetization behaviour of the stable sample GCNF3B, with respect to variation in direction of, and intensity of, magnetization. The direction variations are relative to the sample orientation, and the intensity after each " A.F. step " has been normalized (to the N.R.M. intensity, which is shown). Direction symbols are as in Figure 2. The fuller results are for specimen 1C, and the abbreviated results are for the check specimen 4A.

lization, without any appreciable formation of *new* minerals, in the Giles Complex rocks.

Mafic and ultramafic intrusive rocks of the Giles Complex are mainly layered rocks, the main rock types being anorthosite, norite, gabbro and serpentinite. As well, there are olivine gabbros, troctolites, picrites and (olivine) pyroxenites (both clino- and ortho- varieties). The main characteristics of the separate isolated masses were summarized in Nesbitt and Talbot

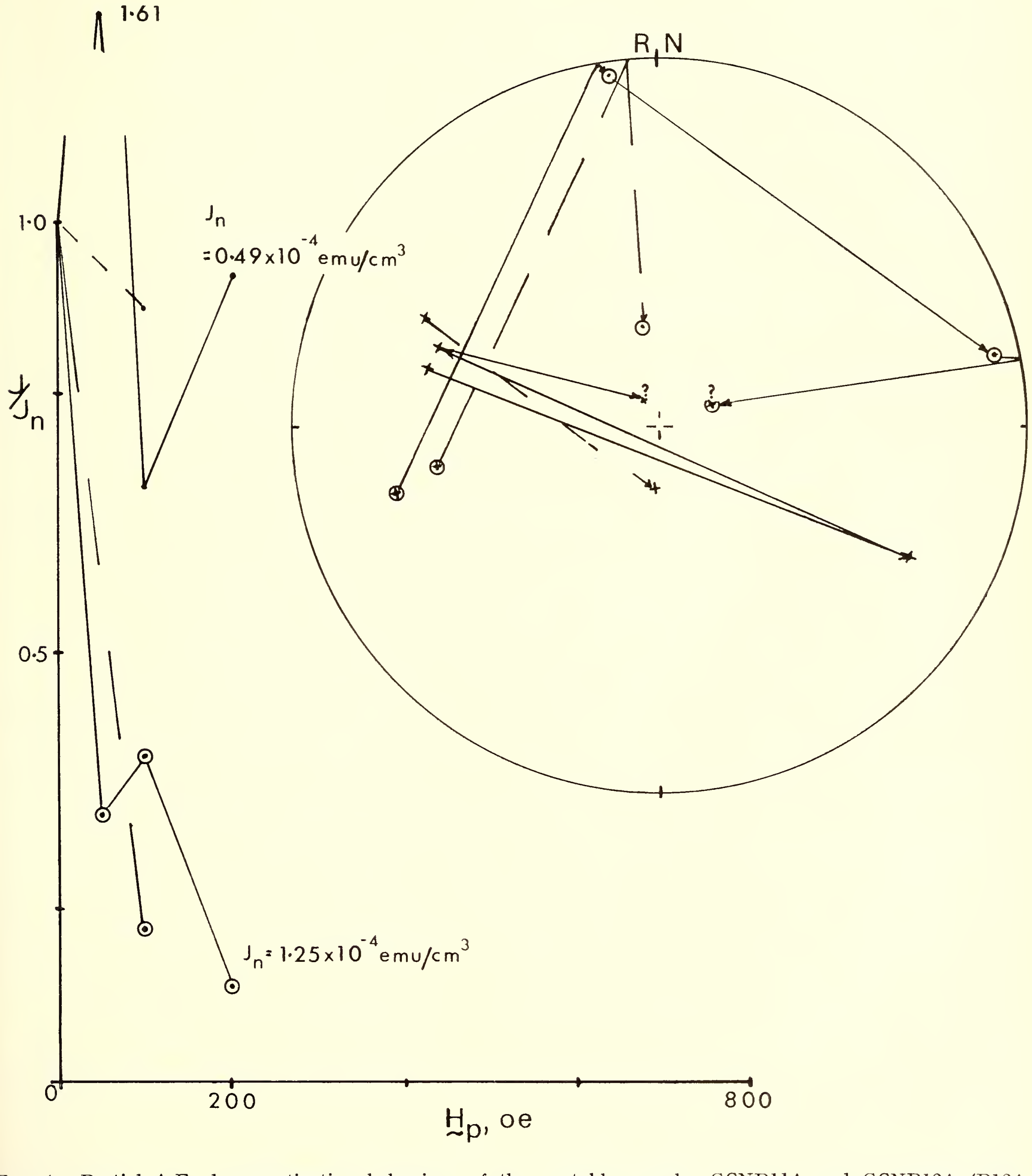
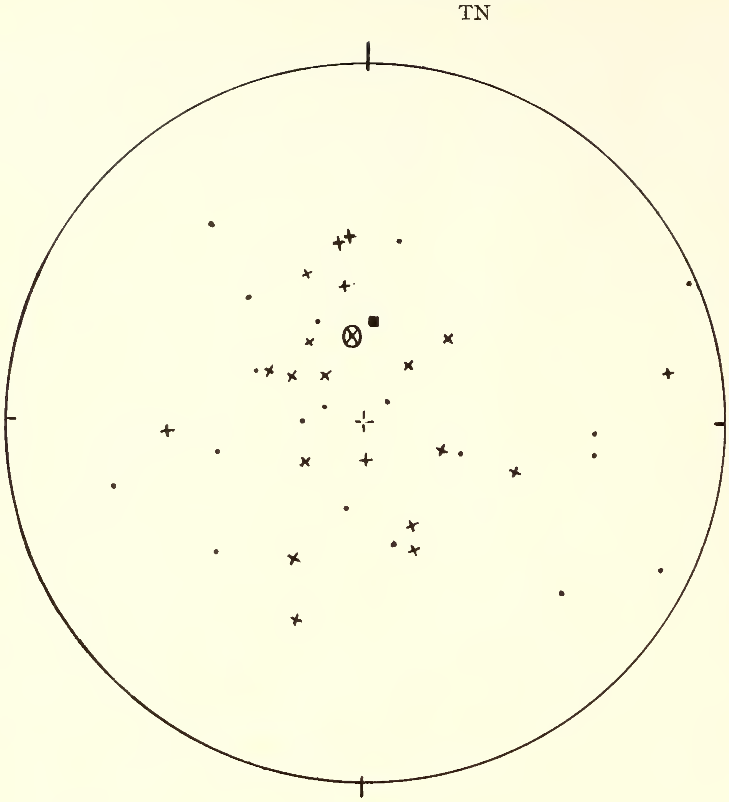


FIG. 4.—Partial A.F. demagnetization behaviour of the unstable samples GCNB11A and GCNB12A (B12A symbols circled), with respect to variations in direction of, and intensity of, magnetization. Symbols as in Figure 2, and explanation as in Figure 3. The fuller results are for specimens B11A4A and B12A1B, and the abbreviated results are for the check specimens B11A5A and B12A2A.

(a)



(b)

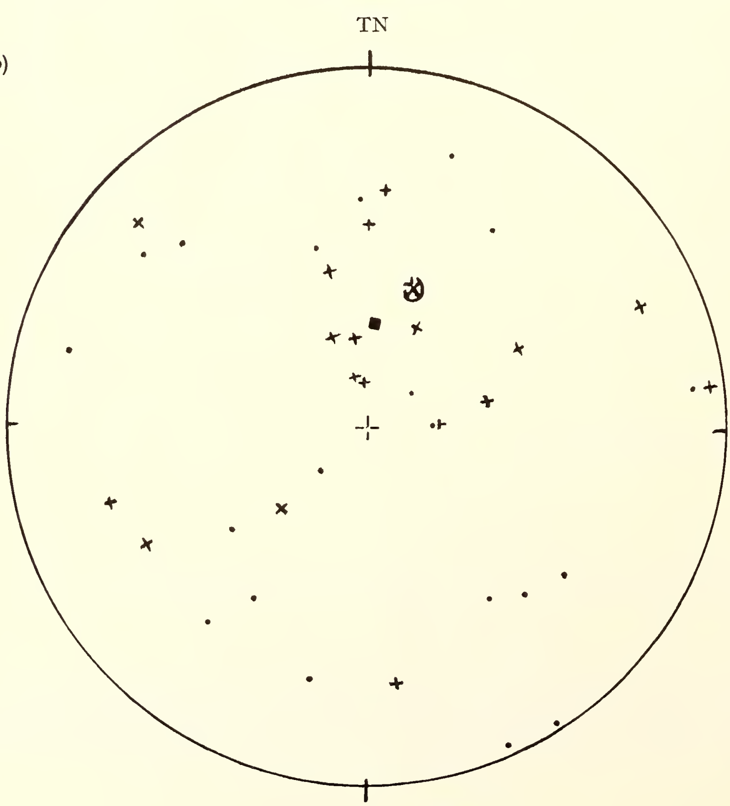


Fig. 5.

Explanation of Fig. 5.

Directions of magnetization after partial A.F. demagnetization. The mean direction is shown by a circled cross—it plots on to the *lower* hemisphere (i.e. opposite to that of the Geomagnetic field direction). This mean direction is plotted as the average of the similar mean sample- and mean specimen-direction. All symbols, and the "division" of the figure, are as in Figure 2.

(a) Mean direction, $D = 350°$ T., $I = +63°$.

(b) Mean direction, $D = 019°$ T., $I = +46°$.

(1966, table 1, p. 4). Nesbitt and Talbot (1966) noted that basic rocks make up approximately 90% of the Complex, and these have undergone least weathering.

The very noticeable development of layering in several of the intrusive bodies is on several scales. Large-scale mineralogical layering is very evident in the field (Plate I (2) and (3)). On the smaller scale (order of a few centimetres), layering is developed which shows distinct " sedimentary " structures such as graded bedding, cut and fill structures, ripple marks and slump structures. Nesbitt and Talbot (1966, p. 7) summarized the various types of layering thus : " The types of layering occurring in the Giles Complex include cryptic, rhythmic, phase and . . . igneous lamination."

Conflicting evidence exists concerning the depth of intrusion of the Giles Complex. Unfortunately only a few contacts are visible, but these generally indicate only slight metamorphic effects. Nesbitt (1966, p. 274) suggested a " shallow surface origin ". However, Goode and Krieg (1967) noted an aureole around Ewarara which is " physically visible over a width of the order of metres " (p. 187), and suggested a relatively deep intrusion. Moore (1968, p. 235) discussed his observation of rutile exsolution in orthopyroxene from Gosse Pile, and also suggested crystallization at depth.

2.2. *Densities of the Giles Complex Rocks*

The densities of the samples collected in this present investigation range from near 2·8 gm. cm.$^{-3}$ to 3·3 gm. cm.$^{-3}$, which almost completely spans the range of densities for basic and ultrabasic intrusive rocks given in Birch *et al.* (1942, p. 14).

This density range contrasts noticeably with the metamorphic terrane, and this has facilitated gravity studies of the contacts. Steele (1966) discussed results of gravity surveys across Mount Davies and Gosse Pile. The Geological Survey of South Australia has used gravity techniques as an aid to geological studies in the area.

3. Rock Magnetic Study

Rock magnetic study is here considered as a general concept covering palaeomagnetic and complementary studies, such as petrology (and mineralogy) of whole rocks. In a recent review article Wilson (1966) summarized advances in palaeomagnetism and rock magnetism, and this complementary nature of magnetic and petrological studies of rocks was used in this investigation.

Considerable data are presently being assembled on the possibility of correlation between the magnetic properties and the mineralogy and petrology of basalts. That it is still only a " possibility of correlation " is made evident by the still active discussion in the literature by those who have found correlation and those whose results are in less accord.

Further work on basalts and, perhaps even more importantly, other igneous rock types, is necessary. The correlations observed to date are far from conclusive, and further evidence may in fact show that there is no definite correlation. There are as yet few results from non-extrusive " basaltic " rocks, although recently Watkins and Haggerty (1968) studied some Icelandic dykes as well as basalts. An extension of such studies to other intrusive rocks such as the Giles Complex could therefore contribute significantly to a solution of this problem.

4. Field and Laboratory Preparation

4.1 *Field Procedures*

Information gained during the preliminary study (Facer, 1967) enabled a programme of sampling to be formulated, although minor modifications were made in the field. Where possible, sampling traverses were planned to be perpendicular to the strike of the layering of the Complex. Surface exposure was known to be good, although man-made exposures were negligible. Sampling procedures generally consisted of traversing on foot (although in a few cases four-wheel drive vehicle access was possible) to collect oriented samples. Lack of water prevented field-drilling.

Oriented samples were removed from outcrop after at least one face had been oriented. Since the Giles Complex rocks generally exhibit visible layering, the orientation of this layering was also noted at each sampling site—or in the case of a dyke sample, the orientation of the dyke was determined. Orientation was effected using a clinometer and a magnetic compass. The influence of the outcrop on the compass was estimated by a simple comparison of the declination of a line (e.g. layering) *at* the outcrop with its declination *one to two metres from* the outcrop. If the " line " measured was the layering, a further check could be made using aerial photographs and/or geological maps, if available. At the few " disturbed " sites an auxiliary method of orientation by sighting to distant objects beyond the zone of magnetic influence was used. The topography and the general lithology were noted in an attempt to avoid sites of lightning strokes and/or very rich magnetite concentrations.

The sampling information is summarized in Table 1 and Figure 1. Time limitations restricted the number of samples that could be collected from a site, hence many sites were represented by one sample only.

TABLE 1

Summary of Sampling

Range Name	Number of Sites	Number of Samples
Ewarara	2	3
Mount Davies	28	37
Kalka	11	14
Hinckley Range	4	6
Blackstone Range	3	3
Cavenagh Range	3	5
Michael Hills	2	5
Gosse Pile	9	13
Bell Rock Range	1	1

This table summarizes the sampling activity, and indicates the distribution of material collected for magnetic investigation.

The localities of these sampled intrusions are shown in Figure 1. The Morgan and Murray Ranges were visited, but outcrops were not found to be suitable for taking oriented samples.

The Bell Rock Range sample was collected by Dr. R. W. Nesbitt. Five hundred and forty specimens were prepared from the samples, being as evenly distributed as the sample shapes and sizes permitted.

At some sites dykes were sampled to provide control in the study of the reheating effects of the dykes. Samples of the dyke rock, the host rock at or very close to the contact, and the host rock a few metres from the dyke were collected.

4.2. *Laboratory Preparation*

Laboratory preparation procedures varied little from those in common use. Diamond-impregnated phosphor-bronze cutting tools were used throughout all stages in the preparation of the cylindrical specimens from the samples. Density determinations and thin and polished section studies have also been carried out for all samples.

Polished section studies of opaque oxides in whole rocks is a very important aspect of rock magnetic studies, as it provides a good indication of the carrier of the magnetism. Results of this study have been summarized in Facer (1971*b*).

5. Results

5.1. *N.R.M. Measurements*

All specimens were measured on an astatic magnetometer constructed by Kazmi (1960) and briefly mentioned by Manwaring (1963). The measurement procedures were those described by Kazmi (1960) and Manwaring (1960). Directions of magnetization could not be adequately measured when the intensity of magnetization was below about 10^{-5} e.m.u. cm.$^{-3}$

In addition to correcting for sample orientation, directions of magnetizations were adjusted for layering orientation because layering was the only common reference horizon within the Giles Complex. These direction changes were effected by construction using a stereographic equal-angle projection (" Wulff net "), or by using the computer programme DIRNCHANGE. written for this investigation.

Figure 2 shows the N.R.M. directions (north-seeking) both before rotating the layering to horizontal and after. Not all samples (especially

TABLE 2

Fisher Analysis of N.R.M. Directions

Group	Number of Units, N	R	Declination of R	Inclination of R	α_{95}	k
N.R.M. before	75	10·48	012° T.	−52°	42°	1·15
N.R.M. after	75	4·77	236° T.	−60°	67°	1·05

N.R.M. before : N.R.M. directions before rotation of the layering to horizontal.
N.R.M. after : N.R.M. directions with the layering horizontal.
N indicates a unit weight of a sample, including five samples which possessed two different directions.
R is the resultant vector, its direction representing the mean direction of the group.
α_{95} is the half-angle of the cone of 95% confidence.
k is Fisher's estimate of precision.

of the pyroxenites) possessed measurable directions. The distribution of directions in Figure 2 was assessed using the computer programme PALMAGFISHERANAL., based on Fisher's (1953) method. Table 2 contains the results of this analysis.

Fisher's (1953) k and α_{95} indicate that little significance can be attached to the mean direction of the N.R.M.'s. In addition, the length of R indicates a random distribution of directions at the 95% level according to Watson's (1956) criterion. Watson's (1956, p. 161) approximation gives a value for R_0 of 13·94 for $N=75$, which is well above the values of R in Table 2. However, the slight decrease in precision following adjustment of the layering could indicate that at least some of the N.R.M. was acquired with the layering in its present position.

It is quite possible that the N.R.M. includes a significant secondary component, perhaps directed along the Recent or present Geomagnetic field. At $D=004°$ T., $I=-58°$ for epoch **1966·5** the present field is rather close to the mean direction before rotation of layering, a good indication of secondary magnetization.

The N.R.M. directions of the dolerite dyke samples were too scattered for Fisher analysis, and did not show any direct relationship with dyke orientation. Nor is there any marked indication of significant dyke contact effects. These effects are probably restricted because of the narrow dyke widths (30 to 50 cm.).

Since the N.R.M. results appear to be of limited value for palaeomagnetic considerations, a variety of " stability tests " have been carried out.

5.2. *Stability Tests and Their Results*

It would be unusual if rocks of such age as the Giles Complex, collected at the surface, did not require some study to detect unwanted, perturbing magnetizations, and an attempt to remove these secondary magnetizations.

As a preliminary check on the stability of magnetization, shelf-tests were carried out on all samples. Apart from keeping all cylinder axes parallel and horizontal, storage of the specimens was random. They were measured over a period of up to two years, there being only small variations in N.R.M. intensity and direction. These variations were difficult to detect because of intra-sample scatter, but were more noticeable in samples of lower magnetic intensity. A check was made on inclinations as measured on the magnetometer. This showed that slightly more samples than would be expected had an inclination close to that of the present Geomagnetic field at Sydney, and thus appear to have acquired a small V.R.M. component in the laboratory. Many of these samples also have a low value of the Koenigsberger ratio.

A slightly better estimate of N.R.M. stability than the shelf-test is that afforded by the Koenigsberger ratio " Q ":

$$Q=\frac{J_n}{\varkappa F},$$

where J_n is the N.R.M. intensity and $\varkappa$ the magnetic susceptibility of the specimen measured, and F is the total intensity of the magnetic field. A similar ratio is that termed the " proportional Q value " by Zijderveld (1968, p. 3775) (here designated " QN " to avoid confusion with " Q ") :

$$QN=\frac{J_n}{\varkappa F+J_n},$$

where the symbols are as for Q. Using a simple computer programme, both Q and QN were computed for all samples for which J_n was not less than $0{\cdot}15\times10^{-4}$ e.m.u. cm.$^{-3}$ As would be expected in such a widespread sample population, both Q and QN show considerable variation. About 30% of the samples have Q-values less than unity and QN-values less than 0·5 (or 50%), this latter having been a minimum value indicative of stability in Zijderveld's (1968) study of Antarctic intrusions. Some samples have Q-values in excess of 100, and QN-values of up to 0·99 (99%). These indicate a high degree of stability.

Since many samples appeared to possess secondary magnetizations, the more rigorous stability test of partial demagnetization was employed. Partial A.F. demagnetization was used in this investigation, the instrumentation being that constructed by Chan (1963). Pilot specimens from each sample with J_n of not less than $0{\cdot}4\times10^{-4}$ e.m.u. cm.$^{-3}$ (46 samples) were partially demagnetized at various close steps, the maximum peak demagnetization field used being slightly in excess of 1,000 oersted.

The variation in intensity during A.F. demagnetization was graphed as normalized ratio J_{Hp}/J_n versus peak demagnetization field H_p, and the variation in direction was plotted on an equal-angle projection.

On the basis of intensity and direction changes separate estimates were made of the A.F. peak field most likely to indicate the T.R.M. direction. These two estimates, based on change of slope of the graph towards parallelism with the abscissa, a method considered by Creer and Valencio (1970), and on minimum direction change, showed good agreement. The necessary peak field to remove unstable components was generally 100 to 200 oersted.

A second set of specimens was then partially demagnetized at these selected fields. Figures 3 and 4 contain examples of stable and unstable demagnetization characteristics respectively.

The directions of magnetization after partial A.F. demagnetization of the samples for which stable magnetization directions were indicated have been plotted in Figure 5.

The values of Q and QN were compared with the partial A.F. demagnetization results. Arbitrary groupings of Q and QN indicative of stability were chosen, those for QN being chosen to provide a comparison with Zijderveld's (1968) observations. These results are summarized in Table 3.

TABLE 3

Comparison of Koenigsberger and "Proportional Koenigsberger" Ratios with Partial A.F. Demagnetization Results

Range	Percentage of Samples With Stable Directions (49 Samples)	Percentage of Samples Without Stable Directions (39 Samples)
$Q \leq 0{\cdot}50$	12	54 } 80
$0{\cdot}50 < Q \leq 1{\cdot}00$	4	26 } 80
$1{\cdot}00 < Q \leq 5{\cdot}00$	21 } 84	13
$Q > 5{\cdot}00$	63 } 84	7
$QN \leq 0{\cdot}50$	14	80
$0{\cdot}50 < QN \leq 0{\cdot}75$	14 } 86	10
$QN > 0{\cdot}75$	72 } 86	10

Notes:

Q and QN are the Koenigsberger ratio and the "proportional Q value" respectively.

One sample (GCNB6A) incorporated two rock types and so appears twice in this table.

It can be seen that there is very good agreement between indications of stability given by Q and QN as compared with partial A.F. demagnetization results. Of those samples for which apparently stable directions (A.F.) were found about 85% have Q-values and QN-values which indicated stability. The remaining 15% of samples have been omitted from subsequent palaeomagnetic analysis. Similarly, of those samples for which no directions could be listed following partial A.F. demagnetization, only 20% have Q- and QN-values which would otherwise suggest stability. In the former group several excluded samples showed slightly more weathering than normally acceptable in magnetic studies. In the latter group several samples in the 20% fraction were from sites whose topographic position could expose the outcrop to lightning strokes.

Very extensive Fisher analysis was carried out on the stable sample directions after partial A.F. demagnetization. Analyses assigning unit weight to specimens were also carried out. The results of the Fisher analysis of the entire population are shown in Table 4, in which six Giles Complex sample directions have been adjusted for probable reversals. Various combinations of groups (e.g. intrusive bodies) were also analysed for comparative studies.

The mean direction for the dolerite dykes is significant (Watson's, 1956, 95% level), using specimen unit weight, although barely so using sample units. It is probable, therefore, that this mean direction represents the Geomagnetic field direction at the time of the intrusion of these dolerite dykes, the spread perhaps reflecting slight time-intervals between intrusion of the separate dykes.

Means for the Giles Complex in Table 4, apart from sample units "after rotation", have values of R which indicate that "the null hypothesis of randomness" (Watson, 1956, p. 161) can be rejected at the 95% *and* 99% levels. The specimen unit weight means show tighter grouping than the sample unit means, although the directions are not dissimilar.

As a guide to the efficacy of the rotation of the layering to horizontal, comparisons were made of the Fisher parameters R, α_{95} and k of those groups for which mean directions before and after rotation could be computed. If R and k increased and α_{95} decreased after rotation, it was considered that Graham's fold-test was at least potentially significant—and *vice versa*. In most cases these parameters indicated an increase in scatter, and hence a rejection of the fold-test. Of the eight pairs which showed a slight reduction in scatter, not one pair could be considered to show significant reduction at the 95% level using the values given by McElhinny (1964). Graham's fold-test can therefore be rejected for rotation of the layering to a horizontal position.

Geographic groupings within the population (cf. Table 5) show good agreement between the South Australian and the Western Australian groups before rotation of the layering, this agreement being much reduced by rotation.

The computed means for which Watson's (1956) chi-squared test indicated non-randomness were used to calculate palaeo-pole positions. Because of their greater precision, specimen unit means were used to provide a basis for pole determination. The calculation of the position of the virtual palaeo-pole was facilitated by the computer programme S.PALPOLECALC. Table 5 contains a summary of the South palaeo-pole positions computed from mean directions of magnetization before rotation of the layering to horizontal.

anisotropy of magnetic susceptibility might reveal a magnetic foliation which could be related to either this primary layering or to that subsequently impressed on the rocks by tectonism. Such measurements were carried out at the Australian National University (with the kind permission of Professor J. C. Jaeger) on an instrument similar to that described by Granar (1958). The measurement procedure has been described by King and Rees (1962).

TABLE 4

Fisher Analysis of the Dolerite Dykes and the Entire Population

Group	Unit	Number of Units	Declination of R	Inclination of R	R	α_{95}	k	R_0
Dolerites . .	Sample	3	003° T.	+78°	2·51	71°	4·08	(~2·7)
Dolerites . .	Specimen	5	009° T.	+83°	4·03	43°	4·13	4·02
Giles Complex, before . .	Sample	39	346° T.	+61°	15·6	29°	1·63	13·27
Giles Complex, after . .	Sample	39	007° T.	+15°	11·8	36°	1·39	(10·04)
Giles Complex, before . .	Specimen	68	343° T.	+62°	30·8	19°	1·80	≮15·89
Giles Complex, after . .	Specimen	68	005° T.	+21°	20·6	26°	1·41	≮15·89

The Group indicates that part of the population which was used in the analysis. The dolerite group excludes one sample (GCNB6A) because it is weathered. The Giles Complex directions have been analysed both before and after rotation of the layering to horizontal.

R_0 is Watson's (1956) minimum value of R for rejection of the null hypothesis of randomness at the 99% level (and the 95% level).

Other symbols are as in Table 2.

5.3. *Magnetic Susceptibility Studies*

The magnetic susceptibility of each sample was measured using a commercial magnetic susceptibility bridge.

The wide range of magnetic susceptibility shown by the sample population reflects the variation in rock type. In general, susceptibilities show greater consistency within any rock type than do N.R.M. intensities—an indication of secondary magnetizations. The magnetic susceptibilities of some pyroxenites overlap the range of susceptibilities for pyroxenes summarized in Vernon (1961). Some rocks of gabbroic composition also possess magnetic susceptibilities of similar magnitude, reflecting the low opaque iron(-titanium)-oxide content of much of the Giles Complex. Except for sample GCND1B (from the Hinckley Range) the magnetic susceptibilities of the dolerite dyke samples are considerably higher than those of the Giles Complex host rocks.

Because the Giles Complex bodies are layered, it was thought that measurements of the

Distribution of the three axes of the magnetic susceptibility ellipsoid were investigated by Fisher analysis. This analysis was carried out using all measured specimens, apart from the dolerites and those Giles Complex rocks for which it was not possible to adjust for layering orientation. Results were non-random at the 95% level (Watson, 1956).

The directions of maximum and minimum magnetic susceptibility are the more tightly clustered. As Girdler (1961) and Khan (1962) found, the mean maximum principal direction lies along the strike of the layering and the mean intermediate principal direction is approximately at right angles to this. However, the mean minimum susceptibility is not near-vertical. This discrepancy is not likely to be a specimen shape effect, even though the specimens had not been prepared for these anisotropy studies and therefore did not have Porath *et al.*'s (1966) l/d ratio of 0·85.

The discrepancy may have arisen out of the influence of " secondary fabrics " (Stacey *et al.*, 1960, p. 40), impressed on the initial layering fabric by mild tectonic deformation. However, since it is possible that specimen shape, instrumental or data reduction effects are significant, this matter is receiving attention.

TABLE 5

Position of the South Palaeo-Pole

Group	Longitude ° E.	Latitude ° S.	δ°_p	δ°_m
Mount Davies	242	58	29	54
Kalka ..	133	27	Very large	
Blackstone Range ..	138	57	35	39
Cavenagh Range	192	71	9	14
South Australia	153	58	44	52
Western Australia ..	171	70	12	16
Ewarara, Kalka and Gosse Pile	118	24	53	53
Ewarara, Kalka Hinckley Range and Gosse Pile	108	33	50	52
Dolerites ..	126	40	Very large	
All	163	68	23	29

The group indicates that part of the population which was used in the computation—the dolerites were not included in " All ", the entire population.

δ_p and δ_m are the semi-axes of the elliptical error area around the pole (95% probability level).

The value for Mount Davies is included here for comparative purposes only, since the mean direction of magnetization cannot be considered non-random on Watson's (1956) criterion.

With this reservation, it was noted that of the 35 samples measured for magnetic susceptibility anisotropy nine are prolate, 14 triaxial and 12 oblate using Khan's (1962, p. 2879) convention. Khan (1962, p. 2882) found a similar variation in " oblateness " in the six gabbro samples that he studied. Girdler (1961) did not give " oblateness " values for the Skaergaard samples which he studied. However, a rough mean value (O=2·4) can be calculated using his mean values of magnetic susceptibility (Girdler, 1961, p. 200). This value is above the mean value (1·7) of the " oblateness " for the Giles Complex rocks (excluding sample GCNB25A, which had been strongly crushed by a shear zone). Because the magnetic susceptibility ellipsoid is triaxial, the direction of magnetization was not adjusted for possible anisotropy effects.

6. Discussion

6.1. *Stability and Acquisition of the T.R.M.*

The agreement of the Koenigsberger ratio, Q, and the proportional Q-value, QN, with their partial A.F. demagnetization characteristics, shows that about 47% of the samples are stable. This percentage is not too low, since many of the samples are pyroxenites containing negligible primary iron-titanium oxides and hence are of little value for magnetic studies. Additionally, since the Giles Complex is Precambrian in age, it is likely that some of the rocks have had their original T.R.M. destroyed. For example, Zijderveld (1968) found 31% of the 500 m.y.-old samples that he studied possessed stable T.R.M.'s.

The stability index, S.I., of Tarling and Symons (1967, p. 446) was determined for several samples to check other stability tests. For example, the partial A.F. demagnetization results for samples GCNF3B and GCNB11A and GCNB12A (Figures 3 and 4) were used to determine the S.I. for each possible sequence of demagnetization steps. The computer programme PALMAGFISHERANAL. was used for these determinations. Samples GCNB11A and GCNB12A did not give any values of S.I. above 0·5, and therefore possessed unstable remanence using the criterion of Tarling and Symons (1967). Of all possible sets of steps for sample GCNF3B, only one (incorporating N.R.M. directions) indicated instability. The most stable set (after the 100, 200 and 300 oersted steps) gave a stable S.I. of 3·8. This range of steps fits in with the fields considered most useful in this investigation, and also found to give the best indication of stable directions in the preliminary investigation (Facer, 1967). There is thus good agreement between the results of Figures 3 and 4 and S.I. values.

The mean direction of magnetization is divergent from that of the present Earth's field at the sampling region, the mean direction of magnetization (based on specimen unit mean) being D=343° T., I=+62°, and the present Geomagnetic direction D=004° T., I=−58° (for epoch 1966·5). The angular difference between these directions is 121° (they are in opposite hemispheres). This large divergence suggests that the mean direction is that of a stable magnetization (following Strangway, 1967, p. 209). Also, another test proposed by Strangway (1967, p. 210)—called by him *Separation of sampling sites*—depends on a wide areal distribution of sample sites. In this investigation the non-random mean direction of apparently stable magnetization of the population represents samples distributed over an area of 8,000 sq. km., and this indicates stable magnetization in the Giles Complex.

Of the six sites which were rejected on the basis of their A.F. demagnetization characteristics, but which would have been accepted on the basis of their Q- and QN-values, four could be sites of lightning strokes. Strangway (1967) noted that high Q-values could indicate lightning re-magnetization. However, since many stable samples (e.g., those from the Cavenagh Range) have very high Q-values, it seems that A.F. demagnetization properties (rapid decrease in magnetic intensity) give better indications of lightning stroke re-magnetization.

Fisher analysis of the entire population (Table 4) and of various groups within the population showed that a more precisely defined mean direction is achieved by assigning unit weight to specimens rather than to samples. Little difference exists between samples and sites as units since, by coincidence, most of the multi-sample sites were rejected following partial A.F. demagnetization. This disagrees with previously reported observations (Roy, 1966), and is possibly due to the scatter of directions, which requires a greater number of units to increase population density. Such a possibility is also suggested since Fisher analysis using igneous bodies as units showed negligible significance. This is why the specimen unit mean direction (for the entire population) was used as a basis for the calculation of the palaeo-pole position.

It is possible that the mean direction of magnetization just referred to is that of a moderate temperature V.R.M., which would be expected to be stable (Irving, 1964, pp. 33–34). This would fit with Storetvedt's (1968) opinion that remagnetization by V.R.M. is more important than T.R.M., which it can replace. However, for the Giles Complex it is more likely that the stable magnetization is a T.R.M., since it does not agree with the present Geomagnetic field direction for Australia as would be expected if magnetization was caused by viscous build-up. Another alternative to T.R.M. is C.R.M. Apart from minor weathering effects, however, no evidence of chemical alteration of opaque grains was observed in the rocks post-dating the high-temperature oxidation. The stable magnetization of the Giles Complex is thus considered to be a T.R.M.

6.2. *Correlation of Petrology/Mineralogy with Magnetic Properties*

Correlation of petrology and mineralogy with magnetic properties is not as good as has been observed by others (e.g. Wilson and Watkins, 1967). Using the "*magnetite oxidation number, M*" of Ade-Hall *et al.* (1968, p. 377), the state of oxidation of the iron-titanium oxides was considered in this study as "high" if M was two or larger, and "low" if M was below two. M was compared with the partial A.F. demagnetization results, considering sites as units rather than samples to avoid possible bias of multi-sample sites. Some sites were omitted since no definite indication of stability was given. There is a tendency for stable sites to correspond to high values of M. Of 34 stable sites, 19 have high M values, and similarly, of 22 unstable sites 12 have low M values. Of the 18 stable sites with a "Normal" sense of magnetization direction (using Irving's (1964) convention), 11 have low values of M and of 16 stable "Reversed" sites, 11 have high values of M. Although these correlations are not strong, they do agree with previous studies of Wilson and Watkins (1967) and Wilson *et al.* (1968). In this investigation no obvious correlation was apparent between magnetic parameters and the weathering of the silicate minerals. Obviously, much more work on coarse-grained mafic intrusive rocks is necessary, but there is at least an indication of some correlation of petrology with magnetic properties similar to that observed for fine-grained mafic extrusive rocks.

6.3. *Structural Implications*

Implications concerning the time of acquisition of magnetization of the Giles Complex have been summarized (Facer, 1971*a*). The preliminary results (Facer, 1967) had indicated slightly better grouping after rotation of the layering to horizontal. However, since only seven samples of the preliminary study possessed stable magnetization, this small population apparently gave misleading results.

Although no heating experiments were carried out, the generally low titanium content of the rocks suggests that the Curie temperature is probably in excess of 300° C. Nesbitt (1966, table 1) gave the average Mount Davies TiO_2 content as 0·18%, and the titanomagnetite grains do not show a high TiO_2 content. Since the Giles Complex was apparently intruded at depth (Goode and Krieg, 1967 ; Moore, 1968), and the gravitational layering would probably have been approximately horizontal, it is likely that tilting and uplift occurred soon after intrusion and consolidation, but *before* final cooling of the bodies. The Tollu Volcanics of Western Australia are thought to be related to the Giles Complex (Nesbitt, 1966), and they may have found their way to the surface during this period of uplift.

The post-tilting acquisition of magnetization prevents any conclusions being drawn about the relationships between the igneous bodies. It can be seen that, since the overall mean direction of magnetization for all Giles Complex bodies (excluding the unstable samples from Michael Hills) is non-random (Table 4), all Giles Complex intrusions were probably emplaced and uplifted at about the same time. The scatter in directions could indicate a time lag of several million years in cooling across the Complex as a whole.

6.4. *Aspects of Australian Precambrian Palaeomagnetism*

Reheating of the intrusions following T.R.M. acquisition would probably affect both isotopic dating and palaeomagnetic observations in a similar manner. The palaeomagnetic directions thus indicate the direction of the Geomagnetic field at the time indicated by the radiometric dating techniques. Compston and Nesbitt (1967) dated the Tollu Volcanics of Western Australia at 1,060±140 m.y. Since Nesbitt (1966) noted that these are probably related to the Giles Complex, its age is about 1,100 to 1,000 m.y.

Assuming that the stable T.R.M. was acquired in an axial dipole field, the position of the South magnetic pole at the time of cooling of

TABLE 6
Australian Precambrian Palaeomagnetically-determined Pole Positions

Rock Unit	Age (1)	Pole Position (2) (3)			References
		Latitude °N.	Longitude °E.	δp δm (α_{95})	
Edith River volcanics	Lower $\underline{P}_u$	6	014	15 24	Irving and Green (1958), p. 66
Nullagine lavas ..	$\underline{P}_u$	51	342	10 13	,, ,, ,,
Buldiva quartzite ..	Top of $\underline{P}_u$	30	239	8 14	,, ,, ,,
Lower Marinoan sandstones	Adelaidean	49	149	—	Briden (1967), p. 18 (see note 4)
Upper Marinoan sandstones	,,	74	178	—	,, ,, ,,
Iron Monarch I.F. ..	<1,800 m.y.	15	272	(12)	Chamalaun and Porath (1968), p. 455
,, ,, ,,	,,	64	267	(9)	,, ,, ,,
Iron Prince I.F. ..	,,	39	247	(9½)	,, ,, ,,
Widgiemooltha dykes	2420±30 m.y.	8	337	7½ 9	Evans (1968), p. 3269
Mt. Goldsworthy lode ore G1	Pre-$\underline{P}$	19½	084	(6)	Porath and Chamalaun (1968), p. 256
Mt. Goldsworthy lode ore G3	,,	30½	329½	(12½)	,, ,, ,,
Mt. Goldsworthy crust ore G2	Younger than lode ore	21½	259	(19)	,, ,, ,,
Mt. Goldsworthy B.I.F.	Pre-$\underline{P}$	—	—	—	,, ,, ,,
Dowd's Hill ore body, Koolyanobbing	——	43	356	(8½)	Porath and Chamalaun (1968), p. 257
Mt. Tom Price ore body	2100 m.y. (?)	22	057	(12)	Porath and Chamalaun (1968), p. 261
Mt. Newman ore body	,, ,,	17	066	(9½)	,, ,, ,,
Giles Complex ..	~1100 m.y.	68	343	23 29	This study

Notes : As much as possible the list is in order of publication.

(1) The age is that given in the reference noted, standard stratigraphic symbols being used here. In general, this age has not been checked with more recent data. In the case of the iron formations (" I.F.") the " ages " were determined from palaeomagnetic results (Porath, 1967).

(2) In all but the results of Irving and Green (1958) and Briden's (1967) Lower Marinoan results, partial demagnetization (with or without various additional tests) has been used to establish stability of remanence.

(3) δp and δm are the radii of the ellipse of 95% confidence (Irving, 1964, pp. 69–70), and α_{95} is the radius of the circle of 95% confidence.

(4) The pole positions were taken from McElhinny (1968) since Briden (1967) gave mean remanence directions only. The Lower Marinoan results are for natural remanence directions.

the Giles Complex was latitude 68° S., longitude 163° E. This is the pole calculated using the overall population, and agrees with the pole corresponding to the South Australian and Western Australian groups when calculated separately. The magnetization direction is thus negative, or Normal, using Irving's (1964, p. 71) convention.

The pole position calculated here is close to two other Precambrian palaeo-poles for Australia. Table 6 summarizes palaeomagnetically-determined pole positions for the Australian Precambrian, being based on all data known to the author.

The size of the ellipse for the Giles Complex probably results from slight scatter caused by time lags in cooling across the Complex and possibly to minor anisotropy effects associated with the several convection cells within the Giles Complex (Daniels, 1967, p. 59).

It can be seen in Table 6 that three pole positions are in close agreement (with overlapping ellipses of 95% confidence)—the Nullagine lavas, the Koolyanobbing hematite ore body, and the Giles Complex. Irving and Green (1958) did not carry out partial demagnetization of the Nullagine lavas, and so it is possible that the Nullagine results are in error. These three palaeo-poles represent Precambrian field directions, but the age of the magnetizations warrants clarification.

Recent mapping and stratigraphic studies of the area of sampling of the Nullagine lavas have resulted in some adjustments to earlier ideas on the stratigraphy, and in re-naming of units. The lavas sampled may in fact belong to the Wyloo Group, or perhaps the Bangemall Group. Horwitz (1967) gave a provisional subdivision of the Precambrian of Western Australia, and considered the base of the Bangemall Group to be at 1,000 m.y. This age corresponds well with that indicated for the Giles Complex. However, even if the samples of Irving and Green (1958) were " Nullagine " (current nomenclature " Fortescue Group "), it is possible that subsequent extrusion of lavas (e.g. of the Bangemall Group) could have re-magnetized the older, buried Nullagine lavas. Porath and Chamalaun (1968) did not ascribe an age to the Koolyanobbing hematite, but tentatively correlated its magnetization with the results given for the Nullagine lavas. Porath (1967, p. 409) noted that hydrothermal activity formed hematite in the ore and " has been responsible for the remanent magnetization ". If such is the case, then this early Precambrian rock could have been re-magnetized.

It was noted previously that the radiometrically-dated Tollu Volcanics could represent the final stage of igneous activity in the Giles Complex area. Since the Giles Complex cooled slowly, the age of the T.R.M. is likely to be no more than about 1,100 m.y., and with the error in the date for the Tollu Volcanics (±140 m.y., Compston and Nesbitt, 1967), may be about 1,000 m.y.—which is the age ascribed to the base of the Bangemall Group (Horwitz, 1967).

In summary, therefore, it is considered that the palaeo-pole position determined for the Giles Complex corresponds to a T.R.M. direction acquired about 1,100 to 1,000 m.y. ago. This palaeo-pole is not dissimilar from two other Australian Precambrian poles for which less definite ages are known.

7. Concluding Remarks

During this investigation it has been possible to establish that the layered mafic and ultramafic intrusive Giles Complex acquired a stable T.R.M. about 1,100 to 1,000 m.y. before the present. The stability of the magnetization was established from a variety of tests which gave consistent results. It has been shown that the Giles Complex acquired its T.R.M. after consolidation, tilting and probable uplift of the intrusions, and that most, if not all, bodies were magnetized over the same period of time (which is likely to be of the order of several million years). The Complex has undergone tectonic deformation, but as this is localized, it is possible to detect those parts of the Complex that have had their T.R.M. adversely affected. Post-tilting (?) intrusion of dolerite dykes has apparently had no effect on the magnetic properties of the Giles Complex as a whole.

The ancillary petrological and mineralogical study of the Giles Complex rocks has established a tendency for correlation of the state of exsolution/high-temperature oxidation of the iron-titanium oxides with the magnetic properties. Such a correlation in coarse-grained mafic and ultramafic rocks complements the correlation already observed by others in the magmatically equivalent fine-grained rocks. However, further results from other coarse-grained intrusions are required to confirm the general validity of the correlation in such rocks.

The palaeo-pole corresponding to the magnetization of the Giles Complex (latitude 68° N., longitude 343° E. or 17° W., with semi-axes of the 95% confidence ellipse of 23° and 29°) provides a useful control on other similar Australian Precambrian poles which are less precisely dated.

8. Acknowledgements

The assistance of Professor C. E. Marshall, Dr. A. A. Day and Dr. K. M. Chan of the Department of Geology and Geophysics of the University of Sydney is gratefully acknowledged. Dr. R. W. Nesbitt of the Department of Geology and Mineralogy, the University of Adelaide, has graciously assisted this investigation, both in the field and at Adelaide. Professor R. L. Wilson of the University of Liverpool has been most helpful in discussion of procedures and results. The measurement of the anisotropy of magnetic susceptibility was carried out at the Australian National University with the permission of Professor J. C. Jaeger, and the assistance of Drs. H. Porath, F. H. Chamalaun, M. E. Evans and M. W. McElhinny.

Financial assistance provided by the University of Sydney and the tenure of a Commonwealth Post-graduate Research Studentship have materially assisted this investigation, as has the indirect assistance of the Nuffield Foundation through its support of the "Giles Project" of the University of Adelaide. The extensive use of facilities provided by the Wollongong University College is gratefully acknowledged.

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(Received 12 May 1971)

EXPLANATION OF PLATE I.

1. View of the north side of the Blackstone Range at its western end. The metastable rock mantles (outlined) cover much of the very steep slopes, which in this photograph rise 50 to 70 metres above the level of the sandy pediment of the foreground.
2. Photograph showing the layering (layering orientation : strike 125° M., dip 86° N.E.) in north Mount Davies from just west of site GCNB2. The view is to the north-west, with Kalka on the right horizon. The surface cover consists mainly of spinifex (*Triodia* sp.) and loose boulders.
3. View to the south-west in south Mount Davies, site GCNB9 being in the shadow, left centre. The approximate orientation of the layering is strike 110° M., dip 70° N. to 75° N. The bluffs in the centre rise some 15 metres above the general slope. In the foreground can be seen the rough surface cover of loose blocks of rock.

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 63–75, 1971

Palaeozoic Sedimentology and Igneous Geology of the Woolgoolga District, North Coast, New South Wales

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Abstract—The sedimentary rock units in the Woolgoolga District are the Coffs Harbour Beds, probably upper Palaeozoic in age, and the Redbank River Beds, possibly Silurian in age.

The Redbank River Beds consist of cherts, jaspers with some biogenic contribution of radiolaria, and a submarine basic lava flow.

The Coffs Harbour Beds are a thick sequence of turbidites. Greywackes consist of lithic fragments, quartz, feldspar, opaques and secondary minerals such as chlorite, epidote and carbonate. Younger rocks of the northern half of the sequence are hornblende-bearing lithofeldspathic greywackes. In the lower half of the sequence hornblende detritus is lacking. A megabreccia occurs in the sequence at Mullaway. The geometrical style of slump folds as a facing indicator, and stratal thicknesses to determine source direction have been used.

A stock of leuco-adamellite occurs to the north of Signal Hill, where the quickly cooled comparatively low-temperature magma was intruded into the highest levels of the crust by permitted emplacement. Orientation of the xenoliths indicates a vertical flow direction. Metamorphic grade in the contact aureole of the stock only reached the albite-epidote-hornfels facies.

Introduction

The area studied covers a 32-kilometre strip of the coastline of northern New South Wales just south of Grafton (Figure 1). Although Mesozoic and Quaternary sediments occur, only the Palaeozoic rocks were examined, and they occur as part of one of the upthrust blocks described by Voisey (1959). The purpose of this paper is to describe and discuss the sedimentological features of a geosynclinal suite of greywackes and argillites, and also the geology of a leuco-adamellite stock and its contact aureole. Localities to which reference is made are shown on Figure 1.

The Palaeozoic sediments have been divided into two units: the Redbank River Beds and the Coffs Harbour Beds. These units are bounded in the south by the Cross Maglen Fault (Leitch *et al.*, 1969), and in the north and west by the Mesozoic Clarence Basin (McElroy, 1962).

No detailed description of the geology of this area has been published. Pittman (1880), Wilkinson and Slee (1889) and Carne (1895) briefly mentioned the area and attempted to assign an age to the beds. Other workers to discuss the area include Denmead (1928), Voisey (1934, 1959), Kenny (1936) and McElroy (1962). Recent reconnaissance work by the Geological Survey of New South Wales has been published in three maps (Rose, 1968; Leitch *et al.*, 1969; Brunker *et al.*, 1969).

Subdivision of the Palaeozoic Sediments

Jaspers and altered basic lavas at Red Rock have been separated from the more widespread Coffs Harbour Beds on the basis of distinctive lithology and different structural pattern. Other jaspers from northern New South Wales (i.e. in the Woolomin Beds—Chappell, 1961) are thought to be Silurian in age, and this may be the case of the Redbank River Beds at Red Rock. Similar rocks occur at Jackadgery (north of Grafton), where Whiting (1950) reported a Silurian limestone interbedded with sandstone, quartzites and silicified claystones. McElroy (1962) assigned the rocks south of the Mesozoic Clarence Basin to the Silurian, but the writer envisages a similar situation to that in New England, where two geosynclinal sequences have been recognized (Binns and others, 1967). The older sequence is more complexly deformed, contains prominent bars of jasper with laminated cherts, horizons of altered basic lava and minor Silurian limestones. The second sequence lacks jaspers and laminated cherts and contains only rare basic lavas. These rocks appear to be structurally less complex than those of the first sequence and contain Permian marine fossils at several localities (Binns and others, 1967), and a Carboniferous *Lepidodendron* (Crook, 1958).

The Coffs Harbour Beds are comparable with the Upper Palaeozoic sequence of New

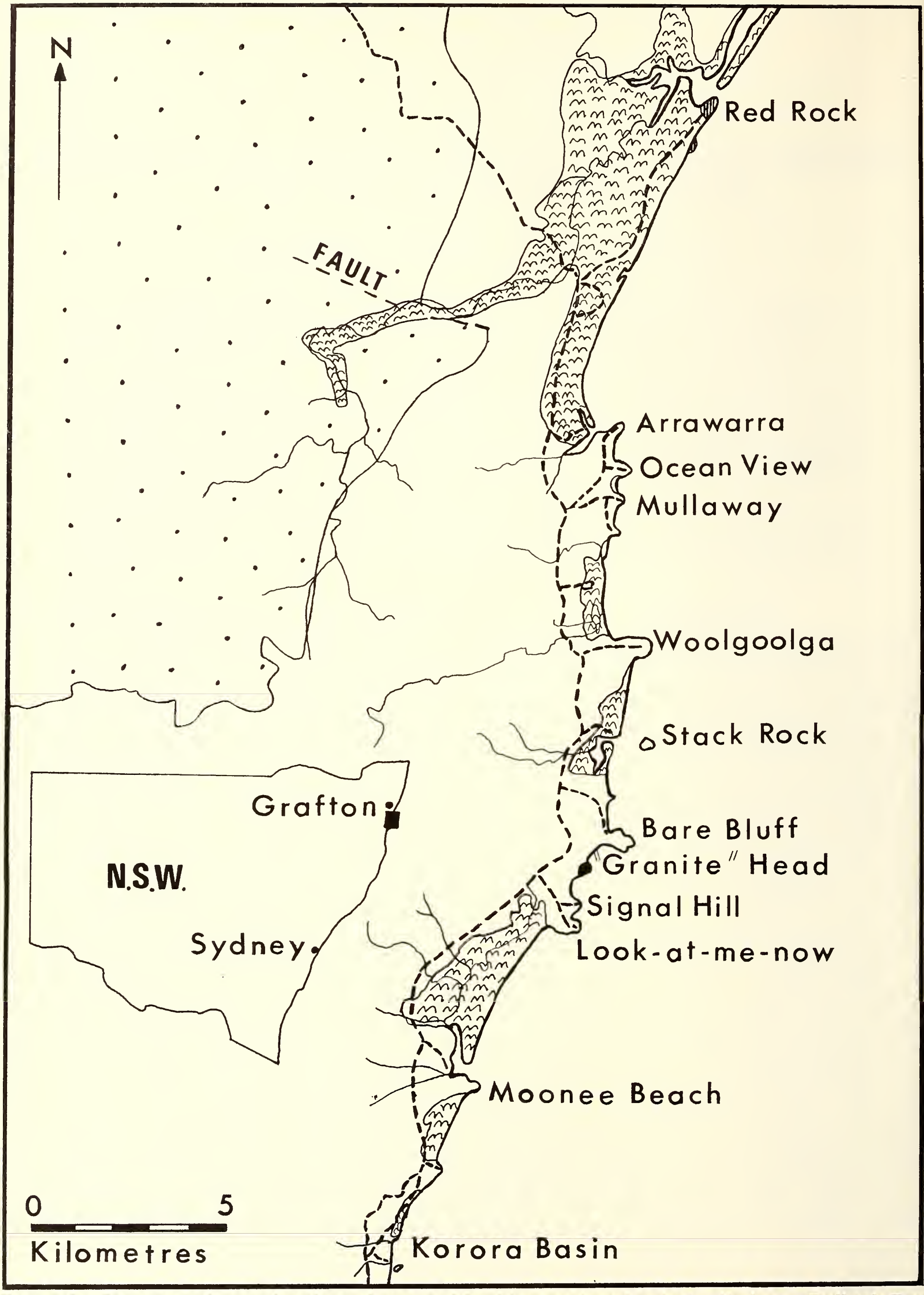

FIGURE 1.—Location and general geology of area, and localities mentioned in text. Geology : Redbank River Beds (stripes) ; Coffs Harbour Beds (blank) ; leuco-adamellite stock (black) ; Mesozoic Clarence Basin (stippled) ; and Quaternary alluvium (*m*).

England in that no jaspers or altered basic lavas have been found, and these rocks are structurally less complex than the cherts and jaspers at Red Rock (Korsch, in preparation). The field evidence is inconclusive but suggests that the Coffs Harbour Beds are younger than the rocks at Red Rock and that they might be Upper Palaeozoic in age.

Redbank River Beds

Synonymy : New name, derived from the Redbank River, near Red Rock village.

Type Locality : The headland at the south side of the mouth of the Redbank River.

Lithology : Red to white well bedded jaspers and cherts, with an interbedded altered basaltic lava.

Thickness : Not determined, owing to intense folding.

Age and Structural Relations : Silurian (?). These beds appear to be the oldest exposed rocks in the Woolgoolga district, and are possible equivalents of the jaspers of the Woolomin Beds (Chappell, 1961). Regional considerations suggest an unconformity or fault between these beds and the Coffs Harbour Beds, but in the absence of direct evidence other structural possibilities are conceivable, such as Red Rock headland being a giant breccia block, or the Redbank River Beds being a diaper piercing the Coffs Harbour Beds.

Sedimentation : The origin of cryptocrystalline cherts and jaspers is problematical. Davis (1918), Bryan and Jones (1962) and Jones (1963) believe cherts are formed from silica derived from hot springs in the ocean floor and that radiolaria flourished in this siliceous environment.

Dewey and Flett (1911) invoke actual submarine eruptions, especially of spilitic extrusions. This hypothesis is preferred for the Redbank River Beds because of the altered basaltic lava present. Hence cherts and jaspers of the Redbank River Beds formed by the precipitation of silica accompanying submarine vulcanism of a basic nature. The silica provided an opportunity for the growth of radiolaria, and thus their inclusion in the sediment.

Coffs Harbour Beds

Synonymy : Coffs Harbour schists (Denmead, 1928) ; Coffs Harbour Series (Voisey, 1934) ; Fitzroy Series (Kenny, 1936) ; Fitzroy Beds (McElroy, 1962) ; Coffs Harbour Beds (Voisey, 1969).

Type Section : Denmead (*op. cit.*) mentioned a type section in the Coffs Harbour " schists " but stated no location. Therefore, by tautonomy it is the cliffs and quarry on the south side of Coffs Harbour (*sensu stricto*).

Members : No members could be differentiated in the field, but in thin section two distinct greywacke types were recognized. Volcanic lithic greywackes occur in the southern part of the area and underlie hornblende-bearing greywackes to the north.

Lithology : Dark grey volcanic greywackes with interbedded mudstones, siltstones and some siliceous units.

Thickness : Unknown, but thought to be very thick (? 3,000 metres).

Age : Upper Palaeozoic (?). No fossils were found, but the Coffs Harbour Beds are of similar lithology to the Upper Carboniferous rocks at Halliday's Point (Leitch and Mayer, 1969). The east-west strike, if projected inland, could suggest that the beds are part of the same Upper Palaeozoic geosynclinal pile as the Carboniferous and Permian meta-sediments of New England (Binns, 1966).

Sedimentation

The Coffs Harbour Beds consist of interbedded units of two types :

(1) Well bedded units of fine sandstones, siltstones and mudstones, with the beds ranging in thickness from less than 25 mm. to about 75 cm.

(2) Massive units of greywackes and finer grained sediments occasionally containing imperfect graded bedding or traces of bedding.

Sedimentary Structures

Graded beds in the massive units are common, with an average thickness of 60 cm., but occasionally up to 300 cm. Delayed grading (Ta and Ta-b of Bouma, 1962) is very common.

Convolute laminations occur abundantly at Signal Hill and Look-at-me-now, but not at other localities. Figure 2 (*a*), (*b*), (*c*) illustrates the styles of the convolute folds seen. Cross-bedding occurs, but is not common and exists only on a small scale (i.e. less than 50 mm. thick).

Sedimentary boudins are common and are usually highly siliceous in nature. At Stack

Rock thick siliceous beds (100–130 cm.) have been boudined and in places even fractured and pulled apart.

Slumping is extremely common with good examples at Mullaway, Moonee Beach and Korora Basin. The beds are, in places, very intensely folded, but gentle folds also occur.

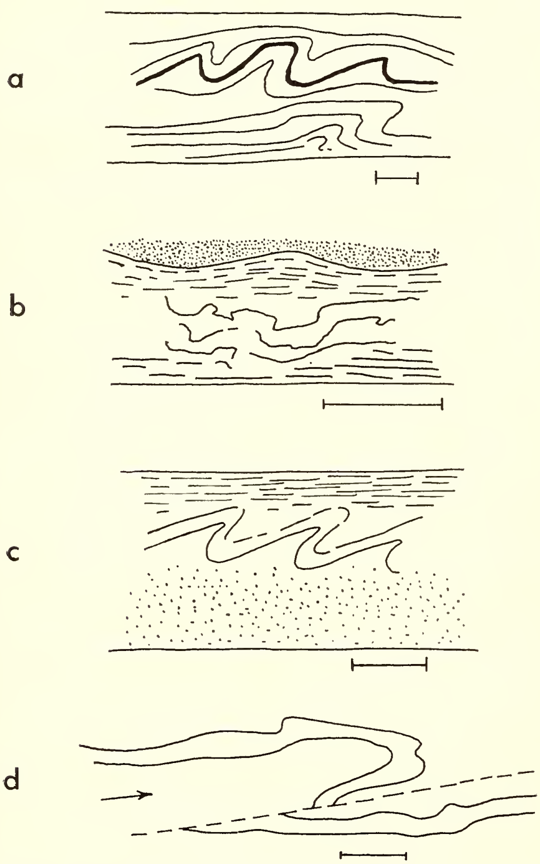

Figure 2.—Styles of convolute laminations at Signal Hill (*a*) and Look-at-me-now (*b*), (*c*). In each case the scale is 10 cm. (*d*) Style of a slump fold, at Korora Basin, used as a facing indicator. Scale is 20 cm.

Style of Slump Folds

There appears to be a dearth of literature considering specifically the style of slump folds and their use to determine facing direction. A typical style is one where a rounded anticline has been forced over the sediments in which a narrow syncline was forming (Figure 2 (*d*)). A shear or thrust often develops along the axial plane of the syncline (the " slip plane " of Fairbridge, 1947). At Korora Basin slump folds are exposed in a sequence of siliceous sandy beds and thinner cherty beds all with a vertical dip and strike of approximately 130°. No primary facing structures were visible but the style and attitude of the slump folds are interpreted to mean they face to the north-east.

Thickness of Individual Beds, and Direction of Transport

For headlands where well bedded sediments occur, sections of at least 3 m. were measured noting the thickness and lithology of each individual bed and apparent thicknesses recalculated to true thicknesses. The average thickness of individual beds was used to determine the transportation direction, assuming that down-current there is a decrease in the thickness of individual beds (cf. Pettijohn, 1962). The thickness diminishes towards the south after attaining a maximum thickness at Mullaway (Figure 3), and thus it may be concluded that the current flowed from a " northerly quadrant " toward a " southerly quadrant ".

Other Directional Indicators

At Signal Hill and Look-at-me-now several orientations of the fold axes of convolute folds were measured. Such fold axes are approximately normal to the current flow (Crowell, 1955). Potter and Pettijohn (1963) believe that anticlinal convolutions exhibit down-current overturning. Hence the convolutions, after " unfolding ", indicate a current direction from the west because the orientations are consistently around 268° ±5°. This result differs from that obtained by the measurement of stratal thicknesses.

The slump folding at Korora Basin indicates a movement direction from the north-west, i.e. about 330°. The slump megabreccia at Mullaway indicates movement from a northerly direction.

Because of the absence of good directional indicators such as flute or groove casts, the palaeogeography during deposition of the Coffs Harbour Beds is imperfectly known, but it may be tentatively concluded that the current flowed from a north-west quadrant to a south-east quanrant.

Mullaway Slump Megabreccia

Two lithological types were seen at the headland of Mullaway :

(*a*) Well bedded units of alternating fine sandstones and mudstones, the products of turbidity currents.

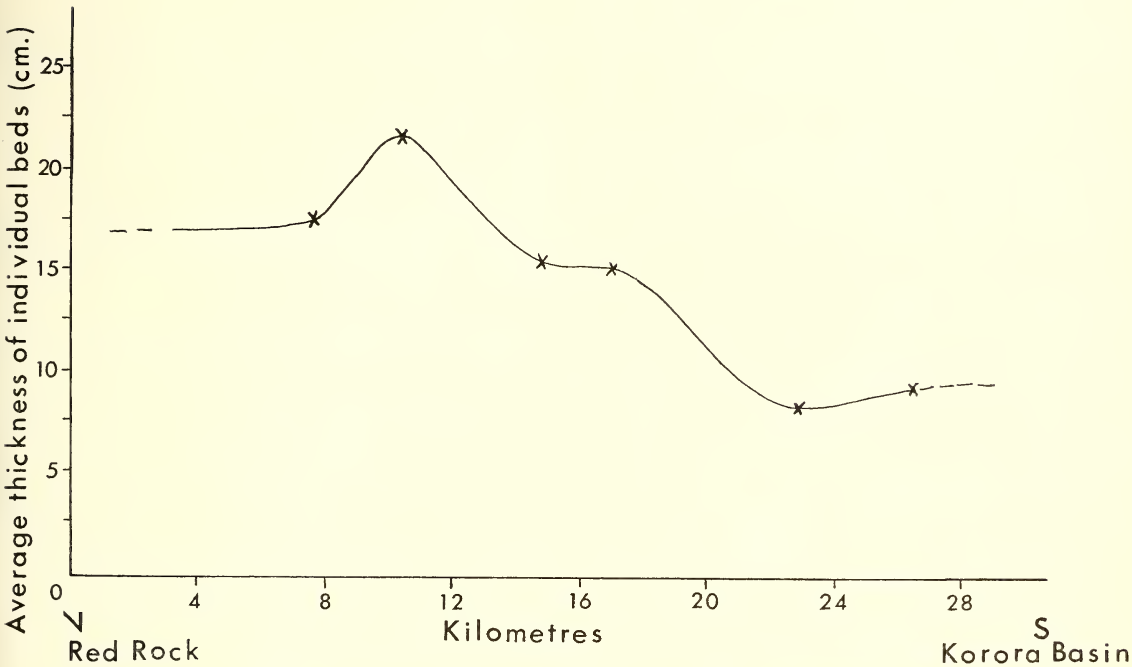

FIGURE 3.—Graph showing average thickness of individual beds from the Coffs Harbour Beds versus distance from Red Rock.

(*b*) Similar units containing large blocks of sedimentary material.

These units represent second-cycle mass-movement deposits resulting from the mobilization of the turbidites. They are megabreccias formed by submarine slumping of the open-face type. The matrix of the slump breccias consists of medium- to fine-grained sandstones, and contains blocks of massive, muddy cherts. These muddy cherts also form part of the bedded sequence at the southern side of the headland.

The blocks and matrix existed together as interbedded units prior to movement and the megabreccias resulted from gravitational instability and mass-movement of the pile of stratified rocks. The mechanisms by which a stack of soft wet sediments may be brought into a condition of instability are numerous, but tectonic steepening of the sea floor (Waterhouse and Bradley, 1957 ; Grant-Mackie and Lowry, 1964 ; Leitch and Mayer, 1969), increase of excess fluid pressure in the sediments (Carey, 1963) and oversteepening as a result of differential compaction (Snyder and Odell, 1958) are thought to be common.

The movements giving rise to the slump breccias appear to have occurred in rocks possessing little if any cover. The strata above the breccias are not disrupted, and the slight folding now seen is the result of a period of tectonism post-dating their deposition and diagenesis.

The slump breccias are the result of movements within a stratified mass in which certain horizons acted as viscous fluids while others remained rigid and fractured, or " pulled apart ", or deformed plastically to a limited extent. In the remobilized horizons the matrix material is silty, siliceous sandstone, and the blocks are very fine-grained cherty rocks. This contrasts with most previously described products of subaqueous mass-movement where the fine-grained material is considered to have failed first, to form the matrix of the resultant deposits. However, Carey (1963) postulated failure of coarse material first, due to increased water pressure in the sediments. At Mullaway (Figure 4) the coarser material in the matrix is similar to that of Leitch and Mayer (1969) at Halliday's Point, where the matrix is a coarse-medium grained greywacke.

The thick siliceous siltstones and sandstones (15–45 cm.) are crumpled and contorted and show pull-apart structures. The chert beds, 6 m. or more thick, are pulled apart into big blocks, with contorted beds in between. Very little transportation of the blocks has occurred. The formation of the blocks could have occurred during soft-sediment deformation or could be a result of a tectonic disturbance while the beds were still in a wet soft state. The transportation has been from a position somewhere to the north.

Gentle folding occurring on either side of the slump megabreccia may have formed during gravity sliding, but the writer believes these folds are products of the period of tectonism that also produced a syncline at the eastern end of this headland. Evidence for the deformation being tectonic is seen in the cleavage. The fracture cleavage, which is axial plane in other localities in the Woolgoolga district, is also in the axial plane of the gentle folds at Mullaway.

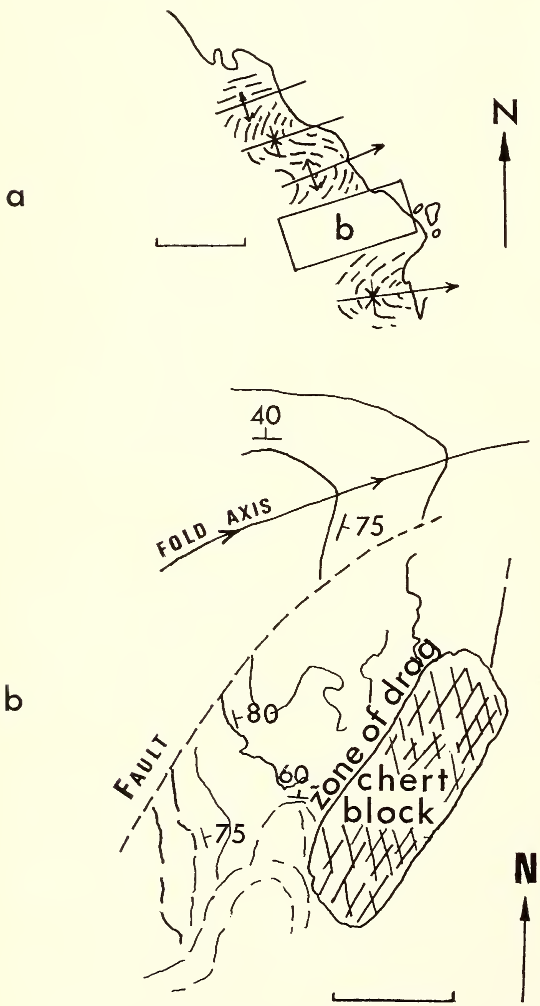

Figure 4.—Mullaway slump megabreccia.

(*a*) General setting showing tectonic folds to either side of the megabreccia. Scale is 50 metres.

(*b*) Detailed sketch showing a tectonic fold and the megabreccia. In the megabreccia crumpled and contorted siltstones and sandstones end to the north at a fault zone, and abut a massive chert block to the south. Movement of the chert block has been from a northerly direction. Scale is 10 metres. (Sketch after Dr. H. J. Harrington.)

Turbidite Origin of the Coffs Harbour Beds

Turbidites are commonly deep-water deposits, transported into bathyal depths away from the influence of bottom traction currents. A comparison of turbidites described in the literature (particularly Kuenen and Carozzi, 1953) with the sediments of the Coffs Harbour Beds shows that the latter are also turbidites.

The graded bed is considered to be a fundamental sedimentary unit, being deposited by a single turbidity current, and each graded bed may contain one to five layers (Ta-e of Bouma, 1962). In the Woolgoolga district complete graded beds along with truncated and base-cut-out sequences occur, indicating that there was a high degree of turbidite activity during the formation of the sediments. Because of the presence of repeated graded bedding and other features characteristic of turbidites, it is concluded that the Coffs Harbour Beds are ancient turbidite deposits.

Sedimentary Petrology

Modal analyses (volume per cent.) of 12 representative thin sections of the Coffs Harbour Beds have been determined using a Swift Automatic Point-counter, following the method of Bayly (1960). All detritus smaller than 0·05 mm. was counted as matrix. Refractive indices for several plagioclases were determined using conventional oil immersion techniques and an Abbe refractometer, and the refractive indices are considered correct to $\pm 0{\cdot}002$.

The classification of Pettijohn (1957) has been used to distinguish the sediments according to grainsize. Sandstones are further classified using the scheme of Dott (1964), the term " greywacke " being substituted for " wacke ".

Mudstones and siltstones, although common, have not been examined in detail. Two petrographic types of greywacke have been noted and are characterized by an abundance of lithic fragments and the presence of hornblende. These are here referred to as lithic greywackes and hornblende-bearing litho-feldspathic greywackes respectively. Both greywacke types will be described together.

(Figure 5 (*a*)) shows that the greywackes of the Coffs Harbour Beds fall in a restricted composition field. The hornblende-bearing litho-feldspathic greywackes contain more plagioclase and fewer volcanic lithic fragments than the lithic greywackes and hence occur closer to the feldspar apex in the QFR diagram (Figure 5 (*b*)).

TABLE 1

Modal Analyses of Greywackes from the Coffs Harbour Beds

Specimen number	8920[1]	8924	8932	8927	8936	8943	8949	8950	8955	8958	8963	8967
Grid reference[2]	756326	745326	744328	742329	727324	692333	635326	634324	618311	617311	611309	608307
Plagioclase	23·3	60·0	30·0	29·2	17·1	28·6	14·4	7·0	9·7	16·4	14·7	13·3
K-feldspar	0·3	0·1	—	—	—	0·4	0·3	—	—	0·2	0·5	0·1
Quartz	16·9	8·1	10·1	6·9	13·5	12·9	10·2	4·5	7·5	9·9	8·8	10·6
Hornblende	1·2	11·0	6·0	4·4	0·4	3·9	—	—	—	tr	—	—
Volcanic lithic fragments	25·4	5·2	17·9	23·9	30·7	30·2	39·9	52·7	50·3	45·9	41·9	44·9
Other lithic fragments	2·2	—	1·1	3·0	2·8	0·9	2·2	4·2	5·1	1·9	2·4	2·3
Matrix	24·3	8·8	23·1	26·1	19·9	6·7	27·8	27·1	19·8	16·6	22·5	18·8
Cement	1·7	3·6	4·9	1·6	6·7	12·5	2·4	2·7	5·6	4·4	4·2	3·2
Chlorite	0·3	2·3	3·5	2·0	5·1	1·7	0·6	0·8	0·3	1·3	1·6	3·8
Epidote	0·8	0·2	2·0	0·4	1·1	0·1	0·8	0·2	0·1	1·3	1·2	0·3
Opaques	2·1	0·7	1·4	1·0	2·2	1·7	1·3	0·8	1·3	1·9	2·0	2·7
Biotite	0·4	—	—	1·2	0·5	—	—	—	0·3	0·2	0·2	—
Prehnite	0·3	—	—	—	—	—	0·1	—	—	—	—	—
Carbonate	0·8	—	—	0·3	—	0·4	—	—	—	—	—	—
Percentage intraformational mudstone chips	1	3	3	15	10	1	5	5	1	4	2	5

[1] Numbers refer to thin sections housed in the U.N.E., Geology Department Collection.
[2] Grid references refer to the 1 : 63,360 series "Woolgoolga" Zone 8, Sheet No. 296.

The hornblende-bearing litho-feldspathic greywackes occur in the northern half of the area from Arrawarra to Woolgoolga, while the lithic greywackes occur to the south from Bare Bluff to Korora Basin. Both rock types occur mainly as massive units exhibiting poor grading and almost no bedding traces. This contrasts with the well bedded nature of the finer grained siltstones and mudstones.

In hand specimen the rocks are hard, compact and non-porous. They occur as unsorted dark grey sediments with fragments of lithic debris, mudstone and quartz up to 5 mm. in size. In thin section the rocks contain lithic fragments which are mainly acid to intermediate volcanics, and occasionally metasediments and cherts occur. Mudstone fragments, which are thought to be intraformational in origin, have not been included in the modal analyses, but have been estimated visually (Table 1). The mudstone chips have been elongated, indicating deformation during compaction.

Detrital minerals include quartz, plagioclase, minor K-feldspar and hornblende. Secondary minerals include chlorite, epidote, opaques (sometimes sulphides such as pyrite), prehnite and carbonate (rare). MLQ and QFR diagrams were constructed for the modes (Figure 5 (*a*) and (*b*)). Inspection of the MLQ diagram

LITHIC FRAGMENTS

(*a*) *Volcanics*

The majority of lithic fragments indicate derivation from one parent rock type—an acid to intermediate volcanic rock. The relatively few phenocrysts present in some lithic fragments are quartz, feldspar and rarely hornblende and biotite. The volcanic fragments are very angular to sub-angular in outline, are porphyritic andesite in composition, and occur as phenocrysts set in a devitrified groundmass occasionally exhibiting a plumose texture. The fragments are fine-grained holo- to hemi-hyaline rocks, now devitrified, commonly showing flow texture. Pyroclastic fragments also occur, but are less common. They are welded tuffs with an almost eutaxitic texture, and the secondary minerals having a pectinate texture.

(*b*) *Others*

Lithic fragments other than volcanics comprise only a small amount of the total volume of the rock (less than 5%). These are fragments of sedimentary and low-grade metamorphic rocks. Fragments of radiolarian chert occur.

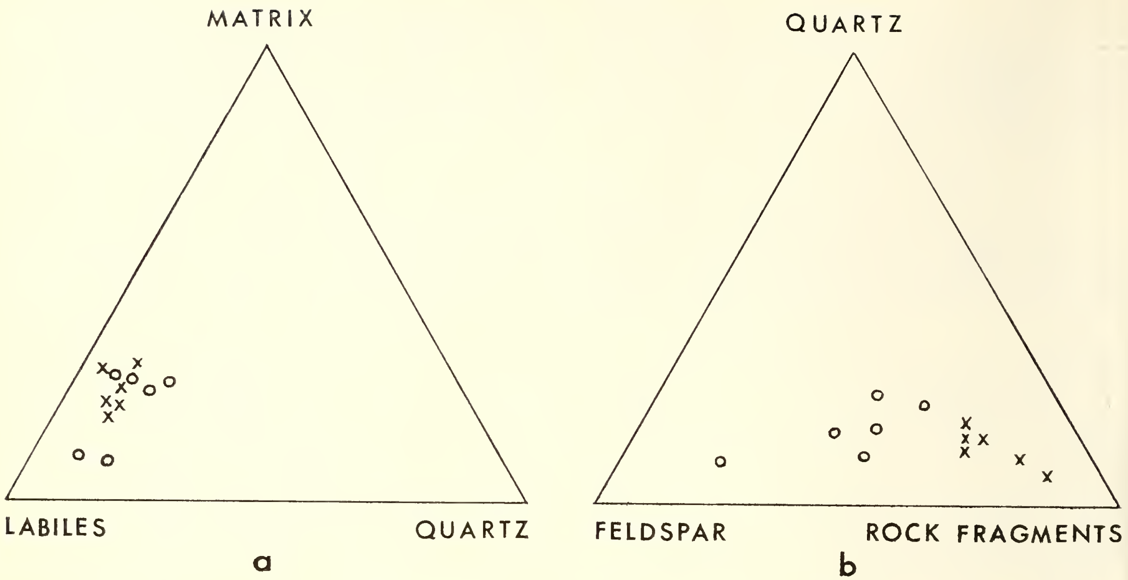

FIGURE 5.—MLQ diagram (*a*) and QFR diagram (*b*) for hornblende-bearing litho-feldspathic greywackes (o) and lithic greywackes (x) from the Coffs Harbour Beds.

QUARTZ

Quartz is fairly common, averaging around 10%, and varies in size from greater than 2 mm. to less than 0·05 mm. Single equant grains are dominant but occasionally composite grains occur. The grains are generally unclouded in appearance, sub-angular to angular, with minor subrounding. Extinction is uniform with the occasional undulose grain occurring. Quartz with β-outlines (resorbed pyramidal) commonly occur, indicating an acid volcanic source. Rarely, a well-rounded grain of detrital quartz is seen, and this may indicate that at least some of the detritus was derived from older sedimentary material (cf. Chappell, 1968).

FELDSPAR

Detrital feldspar is a very common constituent in both the lithic and hornblende-bearing greywackes. Plagioclase is the dominant feldspar present but K-feldspar occurs as orthoclase and to a lesser extent as microperthite and microcline. Myrmekite occurs in minor quantities, indicating some contribution from an acid plutonic source. The feldspars vary in size from 2 mm. to less than 0·05 mm. and vary from euhedral and subhedral crystals to the occasional anhedral grain.

Most grains have a cloudy appearance and have been partially replaced by flakes of sericite, chlorite, carbonate and epidote. (Epidote occurs as single grains or as a composite group up to 1 mm. wide.) Zoning is common and there is some evidence of deformation in the form of bent lamellae and rare fractured grains. Inclusions frequently occur aligned along cleavage planes. In zoned feldspars the zones are marked by rings of chlorite and epidote inclusions. This is similar to that found by Mayer (1969).

Refractive indices (β=1·552 to 1·555) indicate a composition of about $Ab_{58}An_{42}$, i.e. andesine. This is consistent with derivation from andesite.

HORNBLENDE

Hornblende is very common in the northern half of the district. It occurs up to 11%. The mineral occurs as both euhedral and anhedral grains up to 2 mm. long with the average size being less than 0·5 mm., and as very small flakes in the matrix. The grains are fresh and also partially or completely altered to chlorite and epidote (minor). The hornblendes, with extinction angles varying from 14° to 24°, are frequently twinned, very highly cleaved, and strongly pleochroic from pale yellow to green. A yellow to brown variety occurs only rarely.

Matrix

The matrix abundances range from 7% to 28%, and is composed of very fine (less than 0·05 mm.) chips of quartz and feldspar. There has been some recrystallization to produce chlorite, epidote and (rarely) calcite and biotite.

Cement

The cement comprises a mixture of the secondary minerals calcite, chlorite, epidote, albite and quartz, and in most cases is too fine grained to allow identification of the individual mineral components.

Mudstone Fragments

These fragments are thought to be intraformational, and with occasional silt-sized particles of quartz occurring, are less well sorted than the bedded mudstones.

Accessories

Opaques are a fairly common constituent and are detrital in origin, but rare grains appear to have formed by secondary processes. Biotite is rarely developed and appears as phenocrysts in the volcanic lithic fragments. Zircon is very minor in occurrence.

Secondary Minerals

Chlorite is formed by the alteration of hornblende and glassy volcanic fragments. Epidote is produced by the alteration of plagioclase. Feldspar is formed in association with quartz as a product of devitrification of the volcanic rock fragments. These minerals have been counted as volcanic lithic fragments in the modal analyses. Prehnite is rarely developed and occurs mainly in veins with quartz or calcite. Carbonate is common.

Siltstones

The siltstones and fine-grained sandstones (average grain size less than 0·2 mm.) have a composition of quartz, feldspar and volcanic lithic fragments set in a fine-grained matrix and cement. Small detrital fragments of opaque minerals are present and in the northern part of the area occasional small crystals of hornblende occur.

Mudstones

These were not examined in detail in thin section but are faintly laminated and more well sorted than the intraformational mudstone chips which occur in the greywackes.

Siliceous Sediments

These rare silica-rich rocks appear to be almost cherts and occur interbedded with the well-bedded sandstones, siltstones and mudstones. They consist of fine grains of quartz set in a groundmass of cryptocrystalline quartz. Occasionally mud and small clasts of feldspar occur. Veins of later quartz and prehnite are common.

Provenance

Volcanic detritus is the most important constituent of the greywackes. The abundance of hornblende, andesine-plagioclase and quartz as detrital grains suggests that the volcanic source is intermediate to acid, probably an andesite. The volcanic lithic fragments are almost entirely intermediate in composition. The presence of hornblende in the younger sediments indicates that there has been a slight change in composition of the source area during deposition. However, vulcanism has had a continuous influence on sedimentation throughout the period of deposition.

The abundance of euhedral and subhedral detrital feldspars and hornblendes indicates that the grains have suffered very little abrasion during transportation. Some rocks (e.g. T.S. 8924) could possibly be slightly reworked tuffs which have not been transported far from their original site of deposition. The composition now is probably very close to the composition of the original igneous rocks from which these sediments were derived.

There is a very minor amount of pyroclastic rock fragments in the form of welded tuffs (e.g. T.S. 8950), indicating a minor contribution from an ash fall source. However, the dominant provenance is that of an andesitic terrain.

A contribution from metasedimentary, plutonic, low-grade metamorphic, acid hypabyssal and chert basement sources persists throughout the sequence, but is of minor importance.

Burial Metamorphism

Common mineralogical reconstitution of the lithic and mineral detritus occurs throughout the Coffs Harbour Beds. This formation of secondary minerals is considered to be due to burial metamorphism as defined by Coombs (1961). In the sedimentary rocks of the area the burial metamorphic assemblages are :

(1) Quartz-albite-chlorite-epidote.

(2) Quartz-albite-chlorite-epidote-prehnite.

(3) Quartz-albite-chlorite-epidote-carbonate.
(4) Quartz-albite-chlorite-epidote-carbonate-prehnite.

These mineral assemblages are similar to the mineral facies assemblages described by Packham and Crook (1960) from the Parry Group, south of Tamworth.

Igneous Geology

An acid stock crops out at the headland between Bare Bluff and Signal Hill, its contacts with the Coffs Harbour Beds being knife-sharp and almost vertical.

In hand specimen the rock has no obvious lineation or foliation. Most specimens exhibit a slight porphyritic texture which is more strongly developed near the northern margin of the intrusion, and this could be due to one of two factors: there is a chilled zone at the margin of the intrusion; or, a later phase of magma has been intruded along the contact. A very distinct boundary parallel to the intrusion-sediment contact separates the porphyritic from the more massive rock.

Petrography

Quartz is common (up to 20%) and normally occurs as equant grains. Micrographic texture, undulose extinction and granophyric quartz occur, but in minor amounts.

Feldspar is the dominant mineral and occurs as large phenocrysts up to 5 mm. long, and as a very common constituent of the finer-grained material. Most of the feldspar occurs as randomly oriented laths exhibiting a well-developed xenomorphic-granular texture. The composition cannot easily be determined because of alteration to sericite and kaolinite. Several extinction angles of the poorly developed multiple twinning in the feldspars were measured, indicating a composition of oligoclase.

Biotite is a common constituent and most has been altered to penninite, frequently with a pseudomorphous ragged outline. Accessories include apatite and opaque oxides, presumably magnetite and ilmenite. Epidote, probably a breakdown product of biotite and plagioclase, is also present in small amounts.

This acidic intrusion exhibits a noticeable textural variation from medium grain size with occasional porphyritic feldspars to a porphyritic texture.

The sericitization and kaolinization makes it exceedingly difficult to determine relative amounts of plagioclase to alkali-feldspar but judging from the number of crystals showing poorly developed multiple twinning (approximately half the total feldspar) the rock approaches a leuco-adamellite in composition.

Xenoliths

The xenoliths occur as elongate to lens-shaped bodies and are more abundant near the margins of the intrusion. They are much more melanocratic than their acidic host but in thin section appear to be fine-grained equivalents of the coarser host rock. They are composed of laths of feldspar with intergranular quartz, and penninite after biotite. These xenoliths are cognate and were probably formed at an early stage of crystallization. Xenoliths of country rock such as mudstone are also present in the intrusion as accidental xenoliths, and they formed by fracturing at the contact during emplacement of the intrusion.

A detailed study was made of the orientation of the xenoliths. This was done by measuring the pitch, in the plane of exposure, of the longest axis of the xenolith. These lineations (Figure 6 (*a*)) indicate a strongly preferred orientation to the south-east of 77° to 156°. The section in which the intermediate and least axes should occur would be nearly horizontal and several measurements of the longer axis in these horizontal sections were recorded and plotted as a rose diagram (Figure 6 (*b*)). This figure exhibits a dominant orientation of north-west to south-east.

Because both the longest and intermediate axes lie in the north-west to south-east vertical plane, there exists a real preferred direction of the xenoliths in the rock. The preferred planar and linear orientation of xenoliths can be taken to indicate that there is a kinematic ac or ab plane, and the possible existence of a cryptic ac or ab fabric plane in the intrusion, that is, a primary flow plane (Balk, 1937). The fabric plane is not defined by the lineation and will only be found by microfabric work.

Sills

To the north of the intrusion there are several very narrow sills 5–60 cm. wide intruded along bedding planes in the country rock. To the south only one sill was noticed. The sills appear to be slightly more mafic than the main stock, but contain xenoliths.

Joints

The orientations of joints in the intrusion are plotted on an equal area projection (Figure 6 (*c*))

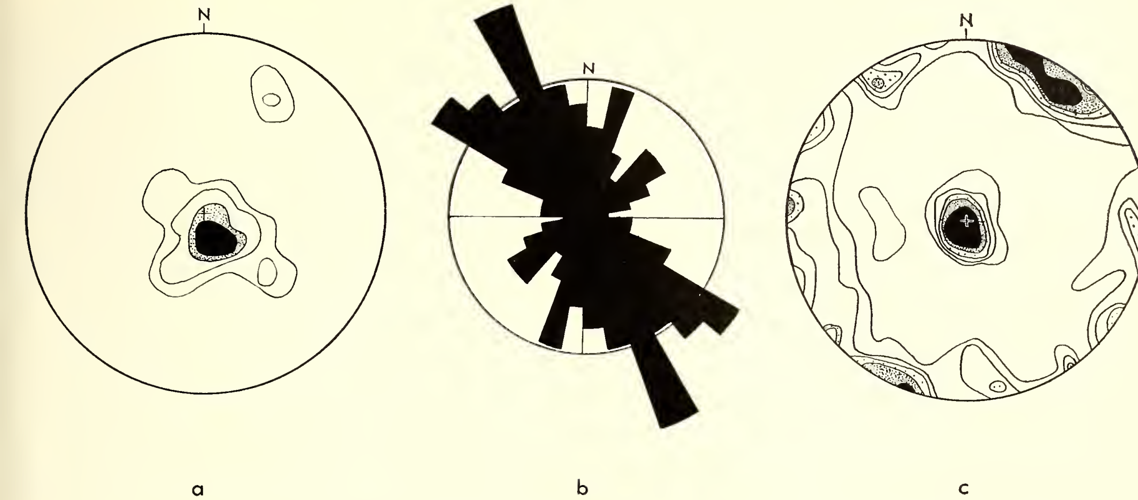

FIGURE 6.
(*a*) Poles to the long axes of 28 xenoliths from the leuco-adamellite stock at " Granite Head ". Contours 0, 4, 8, 12% per 1% area.
(*b*) Rose diagram showing strikes of the intermediate axis of 79 xenoliths, measured in horizontal planes.
(*c*) Poles to 102 joints from the leuco-adamellite stock at " Granite Head ". Contours 0, 1, 2, 3, 5% per 1% area.

where two dominant orientations occur. These are a sub-horizontal jointing and a near vertical joint system.

The joint pattern found in the intrusion can be compared with the joint pattern in the sediments of the whole district (Korsch, in preparation) and the two patterns are very dissimilar. Hence it is inferred that the joints of the sediments were not formed at the same time as those in the intrusion. Possibly the joints in the sediments were produced before the emplacement of the intrusion.

Because the xenoliths have an almost vertical orientation, it follows that the cross joints are nearly horizontal. These cross joints are among the earliest fractures to develop in a cooling mass and are thought to be tension fractures (Price, 1966).

EMPLACEMENT

The principal characters of the intrusion are: the general massive nature of the material, with a slight porphyritic texture and a preferred alignment of xenoliths; the discordant contacts with the surrounding country rocks; the presence of thin sills in the country rock, as offshoots from the main stock; and a poorly developed thermal aureole in which the degree of metamorphism only reached the albite-epidote-hornfels facies. These features indicate that the intrusion is an epizonal pluton (Buddington, 1959).

The intrusion appears to have had a permitted emplacement (Pitcher and Read, 1963) because the emplacement has produced no structural effect on its envelope; knife-sharp contacts cut across the metasediments; and the metamorphic aureole is very poorly developed, indicating that little heat was available during the emplacement. The low-grade metamorphic aureole could also be a result of the small size of the intrusion.

In conclusion, it is thought that this small leuco-adamellite stock formed from a relatively quickly cooled comparatively low-temperature magma emplaced in the highest levels of the crust by permitted emplacement.

Contact Metamorphism

The narrow-contact metamorphic aureole surrounding the leuco-adamellite stock consists of moderately baked greywackes, siltstones and mudstones. Traces of bedding are still visible in the field.

Biotite is ubiquitous in every thin section. Forty-five metres from the contact alteration is limited to reconstitution of the cement and parts of the matrix to biotite. Recrystallization of quartz and feldspar also occur. Closer to the contact (30 m.) biotite is extensively developed and muscovite is a minor constituent.

There appears to be less biotite developed nearer the contact (150 cm.), possibly because the parent sediments were better sorted and hence possessed a lower percentage of matrix and cement. In these rocks the matrix appears to have been more quartzose, and has been recrystallized to fine-grained granoblastic aggregates. Fragments of detrital quartz have been recrystallized to finer-grained granoblastic aggregates also, but these are coarser grained than those formed by recrystallization of the matrix.

Epidote occurs throughout the aureole but is most abundant close to the contact. It has a slightly pleochroic green colour, which is in contrast to the almost colourless variety developed in unmetamorphosed sediments elsewhere in the area. Feldspar also occurs throughout the aureole and is thought to be albite because of its biaxial positive interference figure.

In all thin sections there still remains a visible relict texture indicative of a very low grade of metamorphism. The assemblage is quartz-albite-epidote-biotite-opaques-muscovite-sphene. It is difficult to assign the aureole to any particular metamorphic facies because no diagnostic minerals formed. However, the co-existence of albite and epidote rather than the stability of calcic plagioclase suggests a tentative classification within the albite-epidote-hornfels facies (Turner, 1968) and is placed in the No. 1 assemblage.

No contact metamorphic effects were detected in specimens collected from neighbouring headlands, and hence the contact metamorphic aureole is very limited in extent.

Acknowledgements

The author is indebted to Dr. H. J. Harrington for his supervision of the project. The work for this paper was undertaken for an honours thesis during the tenure of a New South Wales Department of Education Teachers' College Scholarship at the University of New England, Armidale.

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(Received 23 August 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 77-88, 1971

Mineralogical Changes as Marker Horizons for Stratigraphic Correlation in the Narrabeen Group of the Sydney Basin, N.S.W.

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ABSTRACT—Detailed petrological analysis of arenites and lutites of the Lower Triassic Narrabeen Group in the southern part of the Sydney Basin has provided additional marker horizons for stratigraphic correlation. Up to three such horizons can be recognized in various parts of the basin, corresponding to short stratigraphic intervals over which the composition of the sediments undergoes a sudden and significant change. These changes are best illustrated by following the variation, throughout the vertical succession, of the ratio between quartz grains and rock fragments in the sandstones, so that borehole and outcrop sections can be represented diagrammatically by petrological profiles. Comparison of such profiles for sections across the basin suggests a number of modifications to previously published correlation schemes, particularly those put forward for the coastal regions.

Introduction

The Narrabeen Group is the lowermost of three Triassic rock units in the Sydney Basin, lying more or less conformably between the Permian Illawarra Coal Measures and the locally distinctive Hawkesbury Sandstone. The sequence has been subdivided into formations in three separate areas, the Illawarra or South Coast district, the Grose Valley or Western Margin district, and the Narrabeen-Wyong or North Coast district, but because these areas are separated from each other by either extensive cover of overlying strata or by poorly accessible mountainous country, correlations between them are largely tentative, aided only by the results of petroleum and coal drilling in the central part of the basin.

Stratigraphic Subdivisions

Formal stratigraphic nomenclature for the subdivisions of the Narrabeen Group in the coastal districts was introduced by Hanlon, Osborne and Raggatt (1953), and an independently based subdivision for the western districts was laid down by Crook in 1956. Crook's subdivision, in which three formations were recognized, has since been applied over an area extending from the Burragorang Valley (Helby, 1961) to the Glen Davis district (Goldbery, 1970) and the Upper Colo-St. Albans region (Galloway, 1968), but in the north and south coast districts, particularly the former, the original proposals of Hanlon *et al.* (1953) have been modified as a result of further studies (Stuntz, 1961; Bradley, 1964). These changes in nomenclature are summarized by Herbert (1970) and are embodied in a tabulation of currently accepted rock unit names in Table 1.

In the Illawarra district, the subdivision of Hanlon (1952) has been retained for the present study, although the original "Gosford Formation" has been replaced by the term "Newport Formation", following the work of Bradley (1964). Detailed study of the Bulgo Sandstone in the coastal exposures between Werrong and Garie North has shown the possible need for a further subdivision of this unit (Ward, 1971), but because these subdivisions cannot be carried very far to the west, formal stratigraphic names have not been applied. Instead, the Bulgo Sandstone has been broken up into three distinctive facies, details of which are given below.

The lower or pebbly facies contains a high proportion of rudaceous material and consists mainly of pebbly sandstone. The beds closely resemble the underlying Scarborough Sandstone, with a wide variety of pebble types including red, green, black, and grey siliceous materials loosely referred to by previous workers as "chert". A few thin beds of grey shale are also present, while at the base of the pebbly facies a distinctive dark green coloration of the sandstones is apparent. The pebbly facies crops out on the coast between Werrong and Era Beach and is 216′ 9″ thick in the nearby bore, Coal Cliff D.D.H. 17.

The middle facies of the Bulgo Sandstone, by virtue of its composition and distinctive colour in the field, is also known as the " green facies " or " volcanic facies ". It consists mainly of medium grained, dark green sandstone, with a number of beds of friable granule conglomerate and a few grey-green lutites.

Table 1
Rock Units of the Narrabeen Group
Showing lithological correlation

<table>
<tr><th>North Coast
(Bradley, 1964)</th><th colspan="2">South Coast and
Collaroy–Palm Beach</th><th colspan="2">Western District
(Goldbery, 1966)</th></tr>
<tr><td rowspan="2">Gosford Formation</td><td colspan="2">Newport Formation</td><td colspan="2" rowspan="2">Burralow Formation</td></tr>
<tr><td colspan="2">Bald Hill Claystone</td></tr>
<tr><td>Patonga Claystone</td><td>Shaley facies</td><td rowspan="4">Bulgo Sandstone</td><td rowspan="6">Grose Sandstone</td><td rowspan="2">Banks Walls Sandstone Member</td></tr>
<tr><td rowspan="2">Tuggerah Formation</td><td>Volcanic facies</td></tr>
<tr><td>Menai Claystone Member</td><td>Mt. York Claystone Member</td></tr>
<tr><td rowspan="8">Munmorah Conglomerate</td><td>Pebbly facies</td><td rowspan="3">Burra Moko Head Sandstone Member</td></tr>
<tr><td colspan="2">Stanwell Park Claystone</td></tr>
<tr><td colspan="2">Scarborough Sandstone</td></tr>
<tr><td colspan="2" rowspan="4">Wombarra Shale</td><td rowspan="5">Caley Formation</td><td>Hartley Vale Claystone Member</td></tr>
<tr><td>Govett's Leap Sandstone Member</td></tr>
<tr><td>Victoria Pass Claystone Member</td></tr>
<tr><td>Clywdd Sandstone Member</td></tr>
<tr><td colspan="2">Coal Cliff Sandstone</td><td>Beauchamp Falls Shale Member</td></tr>
<tr><td>Newcastle Coal Measures</td><td colspan="4">Illawarra Coal Measures</td></tr>
</table>

The facies attains an overall thickness of 165′ 4″ and crops out on the headlands between Era and Garie Beaches. The sandstones and granule conglomerates consist chiefly of intermediate to basic volcanic rock fragments, and owe their distinctive colour to alteration of this material to chlorite, mixed layer clay, and iron oxide minerals.

The sandstones of the upper facies are medium to fine grained, and mainly light grey-brown colour. They occur in fairly thin and frequently lenticular beds separated from each other by a considerable proportion of shaley material. Near the top of this facies the shales contain numerous red-brown laminae as the sequence passes up into the Bald Hill Claystone. The upper facies of the Bulgo Sandstone, also known as the shaley facies, is 147′ 11″ thick in Coal Cliff D.D.H. 17 and crops out on the headland north of Garie Beach.

In areas away from the coast, the volcanic facies gradually degenerates into a number of scattered beds, and finally, the Woronora district, disappears from the sequence. However, the pebbly facies can be recognized over much of the southern part of the basin and in the Liverpool-Heathcote district the top of this facies is marked by a very persistent bed of grey-green siltstone and claystone named herein the Menai Claystone Member. The type section of the Menai Claystone Member is taken from D.M. Port Hacking D.D.H. 92, sunk near Lucas Heights, where the unit was intersected at depths between 1759′ 1″ and 1776′ 0″. The complete log of this bore, giving details of the section, is available from the N.S.W. Department of Mines.

Lithological Correlation

Almost all the published correlations of the Narrabeen Group have used the prominent, but not always persistent red-beds of the sequence as marker horizons. Hanlon, Osborne and Raggatt (1953) considered from such a criterion that the Bald Hill, Collaroy and Patonga Claystones were stratigraphically equivalent, while Herbert (1970) suggests that the Mount York and Stanwell Park Claystones are equivalent and that the latter can be correlated with the Tuggerah Formation in the north. However, the work of Stuntz (1961) and Bradley (1964) indicates that the correlation put forward by Hanlon *et al.* (1953) was not valid, while the results of the present study suggest that the Stanwell Park Claystone occurs at a lower level in the sequence than do the Mt. York and Tuggerah units.

The Bald Hill Claystone has a unique mineralogy, consisting almost entirely of haematite and well-ordered kaolinite (Loughnan, 1963). It thus differs markedly from the other red-beds of the sequence, which contain quartz, illite and mixed layer clays, as well as haematite and a less well-ordered kaolinite (Loughnan, Ko Ko and Bayliss, 1964). The kaolinite-haematite rock crops out in the Illawarra district and in the area between Port Jackson and Broken Bay, thus providing further confirmation that these exposures represent the same unit, but in the area north of the Hawkesbury River no material of this type has yet been identified. The Patonga Claystone consists of quartz, feldspar, haematite, kaolinite, well-ordered and degraded illite, and appears both from its composition and stratigraphic relationships to represent a completely different horizon, while red-beds in the Gosford Formation at Bouddi Head, although situated at approximately the same horizon as the Bald Hill (300′ below the base of the Hawkesbury Sandstone), consist of quartz, illite, kaolinite and haematite, resembling, except for their red pigment, the other lutites in that part of the sequence.

Although the unit cannot adequately be identified in the North Coast district, the unique composition of the Bald Hill Claystone enables it to be traced westwards from the Illawarra type area to Brimstone Gully, in the Burragorang Valley, where a thin kaolinite-haematite claystone bed can be seen in the Burralow Formation immediately overlying the Grose Sandstone. However, investigations further to the north near Warragamba Dam (Loughnan *et al.*, 1964) failed to reveal a continuation of this horizon, and the only red-beds in the sequence here contain quartz and illite in relative abundance as well.

The Stanwell Park Claystone, although also somewhat different in composition from the associated lutites, does not persist over as large an area as the Bald Hill, and is thus of limited value in correlation. However, the top of the pebbly facies of the overlying Bulgo Sandstone can clearly be recognized in outcrop and subsurface data, since it represents in most areas the topmost occurrence of rudaceous sediment in the Narrabeen Group and is frequently marked by the Menai Claystone Member. The top of this conglomeratic succession can be traced northwards using borehole data, and it appears to correlate with the top of the Munmorah Conglomerate (Figure 3). In addition it can be traced westwards to the Kurrajong Heights bore, from which it can be correlated with the top of the Burra Moko Head Member of the Grose Sandstone (Goldbery, 1966).

Thus it appears from lithological correlation that the Mt. York Claystone Member is equivalent to the Menai Claystone Member of the Bulgo Sandstone rather than to the Stanwell Park Claystone and that the Menai Member can be correlated with the lowermost shales of the Tuggerah Formation. The Stanwell Park Claystone becomes interbedded with polymictic conglomerates in the Woronora district and merges with the Scarborough and lower Bulgo Sandstones to form a thick succession of rudites and coloured claystones in the Port Hacking and Sydney areas.

Lateral facies changes of this type, combined with the wide spacing of boreholes in the central regions, renders a detailed lithological correlation of the Narrabeen Group extremely difficult. Except for the Bald Hill Claystone, with its unique composition, the red-beds of the sequence are of limited value as stratigraphic markers, but the topmost occurrence of pebbly material appears to constitute a useful reference horizon. Thus a marker is available within the lower part of the sequence, the use of which necessitates some modification to inter-regional correlations proposed previously. Detailed study of the petrology of the sediments themselves, especially of the sandstones, provides a means of recognition of this marker and suggests the presence of two additional markers as well.

Petrological Correlation

The composition and texture of the sediments of the Narrabeen Group were first studied in a systematic manner by McElroy (1954). This study, as well as that of Loughnan (1963), indicated that a progressive change in sandstone composition took place throughout the succession as lithic sandstones in the lowermost beds gave way to quartzose sandstones at the top of the sequence, which were in turn overlain by the extremely quartzose Hawkesbury Sandstone. However, a more detailed investigation of Narrabeen Group petrology by Ward (1971) has shown that this change does not proceed at a more or less uniform rate, as had previously been supposed, but that it consists of a number of sudden changes at well-defined horizons, with the sediments between these horizons maintaining a fairly constant composition. It appears from comparison between adjacent boreholes and outcrop sections that the levels in the sequence where these changes take place may be used as marker horizons for stratigraphic correlation.

Method of Investigation

Petrological samples have been taken from a total of 17 localities in the southern and central parts of the basin, mostly from fully cored diamond drill holes, but including outcrop sections and the cored intervals of petroleum exploration wells. Although samples in the fully cored holes were taken from every significant change of lithology, the sandstones and shales were studied using samples spaced at approximately 50′ intervals except where more detailed information was required, so that the considerable time involved in thin section preparation and examination could be reduced.

The sandstones were examined under the microscope and a quantitative evaluation of their composition carried out using a Swift Automatic Point Counter with a spacing of 0·3 mm. and counting 500 points per slide. A study of the dependence of composition on grainsize was not carried out, but the effect of any such relationship was kept to a minimum by using, as far as possible, only sandstones of medium grainsize (approximately 0·25 mm.) in point counting.

A semi-quantitative estimate of the composition of the lutites of the sequence was obtained with the aid of X-ray diffractograms, chiefly of powdered samples, using cobalt $K\alpha$ radiation. Although these results are not as amenable to detailed study as the point count data, they provide valuable supporting evidence for a number of conclusions.

The conglomerates and pebbly sandstones of the sequence were not studied quantitatively, although thin sections of a number of individual pebbles were examined. However, the results of this investigation, as well as the data obtained from a study of heavy minerals in the sandstones, are of limited value in assisting stratigraphic correlation.

General Features of Narrabeen Group Sandstones

The sandstones of the Narrabeen Group consist chiefly of quartz grains, rock fragments of various types and interstitial clay, both detrital and authigenic in origin. Small amounts of mica, siderite and feldspar are also present, the latter being particularly common in the North Coast district. Ward (1971) has recognized three separate suites or natural associations of sediments within the Narrabeen Group, each with distinctive compositional properties.

The sandstones were studied quantitatively by determination of the ratio between quartz grains and rock fragments from point count data. In the western part of the basin the Narrabeen

Group sandstones are mostly quartzose in composition and the value of this ratio is high, usually exceeding 10 : 1. However, in the coastal districts sandstones from the middle part of the sequence have ratios between 1 and 3, dropping to less than 0·5 in the lowermost units. This lateral variation in composition appears to be related to the provenance of the sediments (Ward, 1971), so that the gradation across the basin represents mixing of up to three different kinds of clastic debris.

A study of the vertical variation in the value of this ratio provides an opportunity to examine in detail the nature of the upward transition in the Narrabeen Group from lithic to quartzose sediments encountered throughout the Sydney Basin, particularly in the coastal districts. In the discussion below, the ratio is designated by the symbol R.

Vertical Variation of Sandstone Composition

Table 2 shows the R values or quartz : rock fragments ratios for sandstones in the fully cored boreholes and well exposed outcrop sections of the area studied. In all sections and bores examined the R values are considerably lower at the bottom than at the top of the sampled interval, with the greatest variation being encountered in Elecom Ourimbah Creek D.D.H. 5, where the value ranges from approximately 0·3 to 67·0 over 2,000′ of strata.

Table 2

Vertical Variation in Sandstone Composition

Abbreviations for Rock Units:

Np = Newport Formation
BH = Bald Hill Claystone
Bg = Bulgo Sandstone
SP = Stanwell Park Claystone
Sc = Scarborough Sandstone
Wo = Wombarra Shale
CC = Coal Cliff Sandstone
Bu = Burralow Formation
Gr = Grose Sandstone
Ca = Caley Formation
Go = Gosford Formation
Pt = Patonga Claystone
Tu = Tuggerah Formation
Mu = Munmorah Conglomerate

D.M. Wollongong D.D.H. 44

Depth (ft.)	R Value	Rock Unit	Remarks
648	2·31	530– 560 Np	
704	2·37	560– 625 BH	
756	1·24		
780	2·80		
837	1·91	625–1085 Bg	
908	2·38		
980	2·88		980–1066
1066	0·76	1085–1130 SP	" Step " B
1162	0·45	1130–1230 Sc	
1249	0·75	1230–1390 Ca	
1388	0·53		

D.M. Wollongong D.D.H. 35

746	3·46	610– 640 Np	
811	4·50	640– 723 BH	
880	4·00		
923	4·14		
971	2·65	723–1290 Gr	
1025	4·45		
1080	3·56		1080–1135
1135	2·00		" Step " B
1190	0·65		
1281	0·30		
1335	1·85	1290–1470 Ca	
1395	0·86		

D.M. Wollongong D.D.H. 31

631	30·0	575– 623 BH	
665	14·0		
719	10·4		
773	9·6		
823	10·2		
872	6·3		
900	11·4	623–1149 Gr	900–965
965	3·6		" Step " B
1000	4·0		
1065	1·95		
1096	2·85		
1221	1·85	1149–1289 Ca	
1305	0·41		

D.M. Wollongong D.D.H. 6

550	3·75	490–535 BH	
590	11·8		
641	9·50		
690	9·33	535–836 Gr	690–795
745	2·87		" Step " B
795	0·87		
840	0·64	836–962 Ca	
891	1·54		

Coal Cliff D.D.H. 17

399	3·64	275– 322 Np	
428	2·08	322– 395 BH	
466	1·09	395– 932 Bg	
498	2·56		
535	1·44		
577	0·97		Volcanic sediments
624	0·42		between 500–750
692	0·59		and at approx.
742	1·43		900 ft.
774	1·80		774–832
832	0·67		" Step " B
866	0·42		
912	0·22		
1040	0·18	932–1091 SP	
1114	0·32	1091–1195 Sc	
1183	0·35	1195–1288 Wo	
1224	0·22		
1303	0·47	1288–1364 CC	
1351	0·57		

Ourimbah Creek D.D.H. 5

8 (+500)	67·0		Top of exposed Section 525 ft.
7 (+400)	12·2	+500–122 Gos.	a.s.l.
6 (+275)	3·9		
5 (+220)	3·2		
2 (+180)	11·9		Bore Collar 28 ft. a.s.l.
1 (+140)	3·2		
80	2·1		80–146
146	1·05		" Step " C
244	1·00		
317	1·45		
410	0·55	122–579 Pt.	
447	1·73		
504	0·76		
595	0·68		
646	0·94		
705	1·30		
738	0·45	579–945 Tu	
804	0·61		
859	1·44		
886	0·74		
944	2·2		
990	0·87		
1050	1·55		
1094	1·21		1094–1161
1161	0·42		" Step " B
1229	0·48		
1272	0·51	945–1619 Mu	
1339	0·33		
1421	0·34		
1492	0·91		
1568	0·36		
1612	1·4		

A.I.S. Metropolitan D.D.H. 6
(Data from Loughnan, 1963)

453	44	426– 475 Np	
461	19	475– 537 BH	461–545
545	2·41		" Step " C
561	1·04		
575	0·86		
602	1·28		
633	2·50		
663	4·10		
673	1·60		
712	1·85		
741	1·53		
754	0·26		
760	1·53	537–1094 Bg	
762	1·09		
785	1·10		
814	1·66		
830	0·82		
855	0·63		
880	0·92		
900	1·50		
925	0·73		900–945
945	0·35		" Step " B
1010	0·36		
1078	0·49		
1177	0·18	1094–1247 SP	
1203	0·23		
1226	0·29		
1257	0·28		
1295	0·12	1247–1356 Sc	
1325	0·17		
1374	0·15		
1390	0·17		
1400	0·10	1356–1470 Wo	
1423	0·12		
1459	0·32	1470–1514 CC	
1488	0·36		

Brimstone Gully–Burragorang Valley

27 (40)	21·7	0– 22 Bu	Top of Narrabeen Group at 0 ft.
25 (100)	29·5		Sample depths shown in brackets
23 (170)	23·5		
19 (230)	19·3		230–280
17 (280)	11·3	22–445 Gr.	? " Step " B
13 (375)	5·8		
11 (398)	10·4		
5 (445)	2·81		398–475
3 (475)	0·76	445–535 Ca	" Step " A

D.M. Port Hacking D.D.H. 92

750	4·68	724– 884 Np	
790	3·70		
850	5·25	884–1107 BH	850–1265
1119	2·88		? " Step " C
1265	1·83		
1378	1·61		
1485	2·24		
1556	2·30	1107–1935 Bg	
1700	2·22		
1803	2·71		1803–1971
1900	1·07		" Step " B
1971	0·75		
2023	0·41	1935–2474	
2136	0·51	Other units—	
2219	1·38	exact correla-	
2329	0·30	tion uncertain	
2451	0·50		

Jamberoo Pass—Stratigraphic Section

25	1·75	0– 10 Np	
35	2·32	10– 25 BH	
135	0·46	25–165 Gr	
160	0·86		

D.M. Huntley D.D.H. 5

533	3·20	493–511 BH	
567	3·25		567–604
604	0·93		" Step " B
646	0·68	511–718 Gr	
696	0·65		

A.O.G. Cecil Park No. 2

1105	13·5		
1168	7·7		
1201	8·1	1127–1310 Np	
1267	3·28		
1308	10·0		
1435	∞	1310–1460 BH	
1506	∞		
1556	36·5		1556–1606
1606	5·36		" Step " C
1655	3·16		
1703	5·45		
1751	5·10		
1805	4·16		
1853	4·40		
1887	2·48	1460+ Gr	
1925	4·36		
1966	5·79		
2005	3·75		
2062	2·68		
2090	3·12		
2160	4·07		
2219	2·70		Basal portion of
2254	2·58		Narrabeen Group
			not sampled

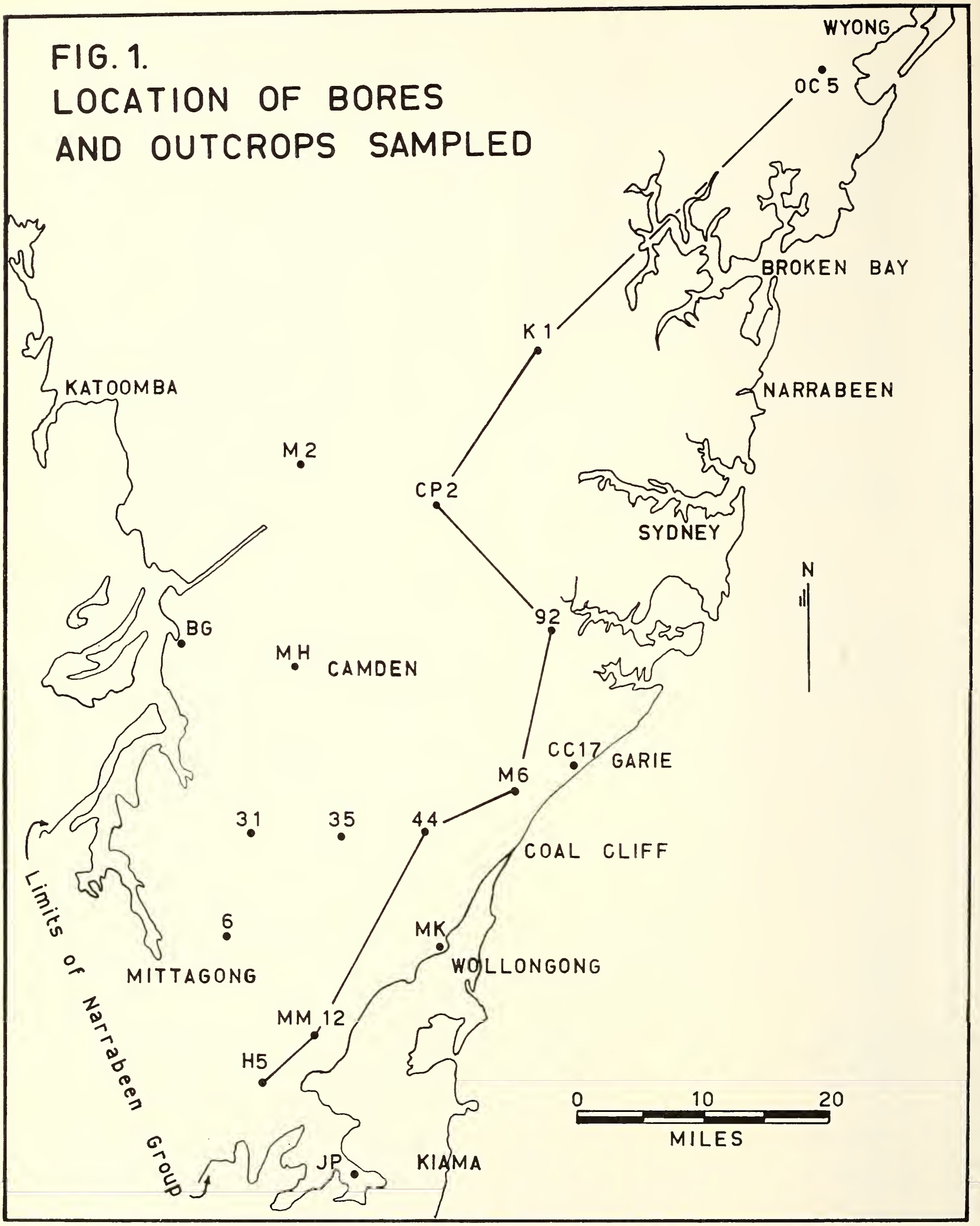
Because the R value is a numerical ratio, changes in sandstone composition do not produce a uniform change in R values. Thus sandstones in which the percentage of quartz is greater than that of rock fragments have R values between 1 and ∞, but for those in which rock fragments are in excess of quartz the R values vary between 0 and 1 only. Experience with Sydney Basin sediments has shown that the sandstones cover the whole possible range of compositions, from nearly pure quartz sandstone to extremely lithic varieties, and hence the R value only changes slowly if the sediments are of lithic composition but may fluctuate very sharply with small changes in quartz-rich sediments.

Graphic representations of the vertical variations in R value for typical borehole sections are given in Figure 2. In these plots the depth or stratigraphic position of each sample is plotted on a uniform linear scale, while the value of R for each sample is plotted on a non-linear scale similar in part to a logarithmic scale, which has been constructed by a graphic technique (Ward, 1971). The line joining the representations of the samples may be considered as a " petrological profile " of the Narrabeen Group at each locality.

Study of such profiles shows that the upward increase in R value for the Narrabeen Group sandstones does not take place at a uniform rate, but is in fact brought about by sudden changes in composition which occur at certain levels in the sequence, and that the sediments between these horizons are of relatively constant composition. For example, data from D.M. Port Hacking D.D.H. 92 (Table 2) show that a depth of approximately 1,800′, just below the Menai Claystone Member, the composition of the sandstones changes from lithic material with R values between 0·3 and 0·5 to significantly more quartzose sediment with the average R value of approximately 2·0. Such a sudden change is herein referred to as a " step " in the sandstone composition profile for the bore or section in question. Similar " steps " can be recognized from X-ray diffraction data of the lutites in the sequence, but although they appear to be at approximately the same levels as those in the sandstone profiles they cannot be fixed with the same degree of precision.

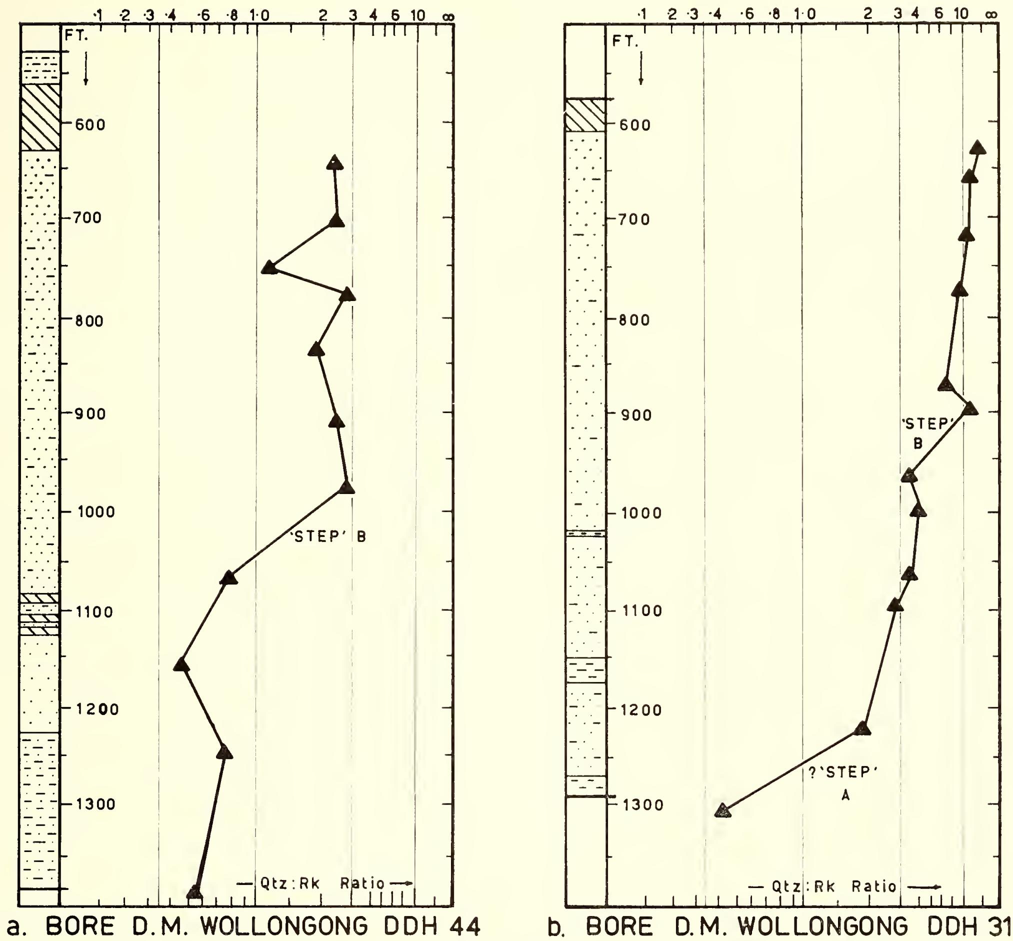
Three such " steps " have been recognized in the Narrabeen Group from modal analysis data of the arenites, but not all of these " steps " are necessarily present in any one profile. They are designated, from the base upwards, by the letters A, B and C, and the approximate position of each is given.

The lowermost of these, " step " A, can only be recognized in the western part of the basin. It is situated at or very near the top of the Caley



OC5	Elecom Ourimbah Creek D.D.H. 5	M6	A.I.S. Metropolitan D.D.H. 6
K1	A.O.G. Kenthurst No. 1	MM12	Mt. Murray D.D.H. 12
CP2	A.O.G. Cecil Park No. 2	H5	D.M. Huntley D.D.H. 5
M2	A.O.G. Mulgoa No. 2	6	D.M. Wollongong D.D.H. 6
MH	A.O.G. Mt. Hunter No. 1	31	D.M. Wollongong D.D.H. 31
B.G.	Brimstone Gully Stratigraphic Section	35	D.M. Wollongong D.D.H. 35
M.K.	Mt. Keira Stratigraphic Section	44	D.M. Wollongong D.D.H. 44
J.P.	Jamberoo Pass Stratigraphic Section	92	D.M. Port Hacking D.D.H. 92
CC17	Coal Cliff D.D.H. 17		

FIG. 2 SANDSTONE COMPOSITION PROFILES FOR TYPICAL SECTIONS THROUGH THE NARRABEEN GROUP.



FOR KEY TO LITHOLOGY SYMBOLS SEE FIG. 3

C.R.W. 1971

Formation, and although not called by that name has been traced by Goldbery (1970) as far as the Glen Davis district.

" Step " A is present in the section studied at Brimstone Gully, in the Burragorang Valley, where it occurs at a level somewhat above the base of the Grose Sandstone. This apparently anomalous position may indicate that the basal beds of the Grose Sandstone are, in fact, to be correlated with the Govett's Leap Sandstone Member of the Caley Formation, a situation brought about by the disappearance of the Hartley Vale Claystone Member. Such lensing out is common in marginal areas of the basin (Goldbery, 1966) and appears to be supported in this case by correlation with borehole data to the east.

" Step " B can be recognized over a large part of the basin, extending from Wyong to the Huntley and Mittagong districts and possibly as far west as the Burragorang Valley. It occurs at or near the top of the pebbly facies of the Bulgo Sandstone and can still be recognized at approximately the middle of the Grose Sandstone where the Stanwell Park Claystone pinches out in the southern and

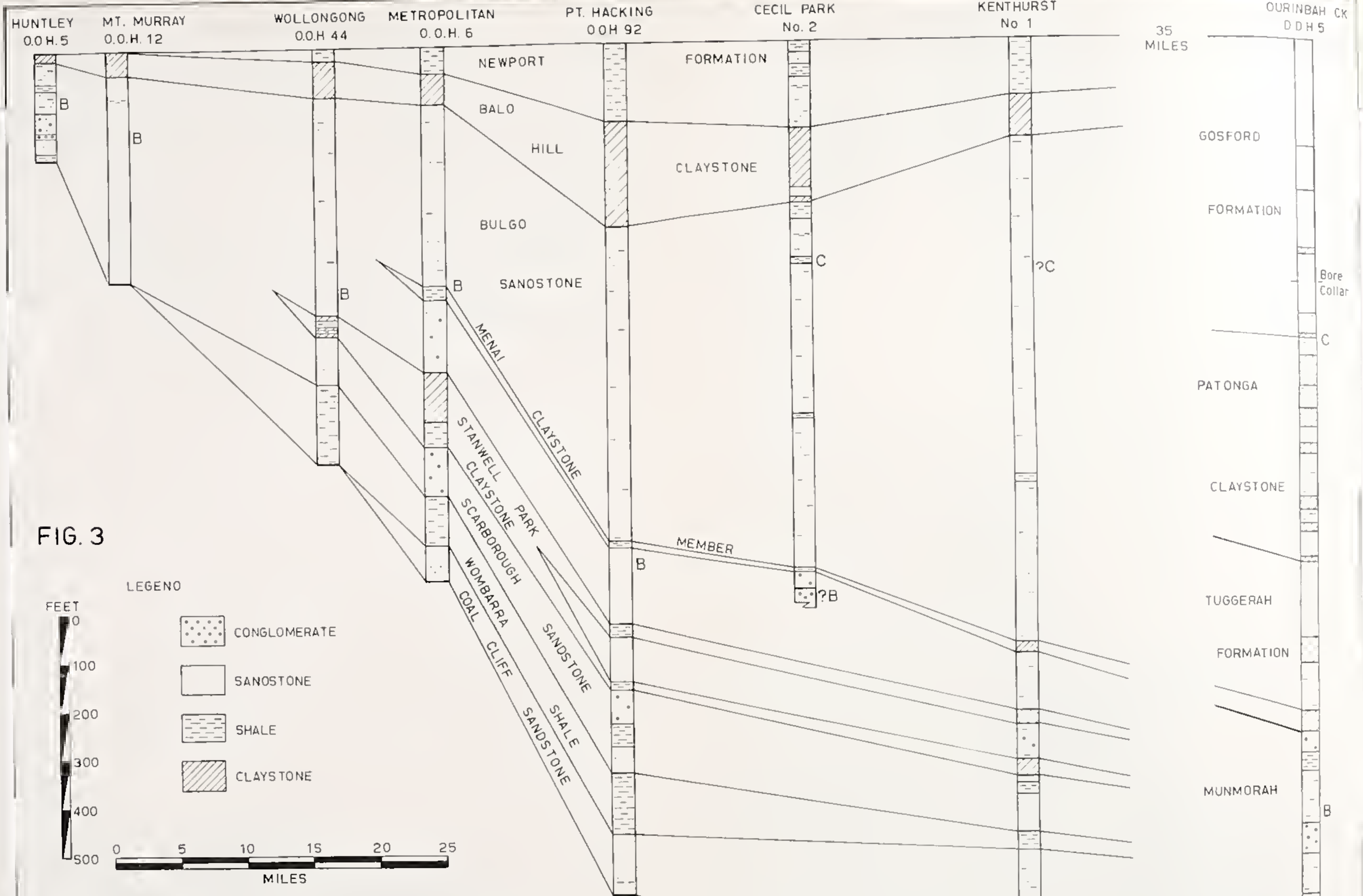
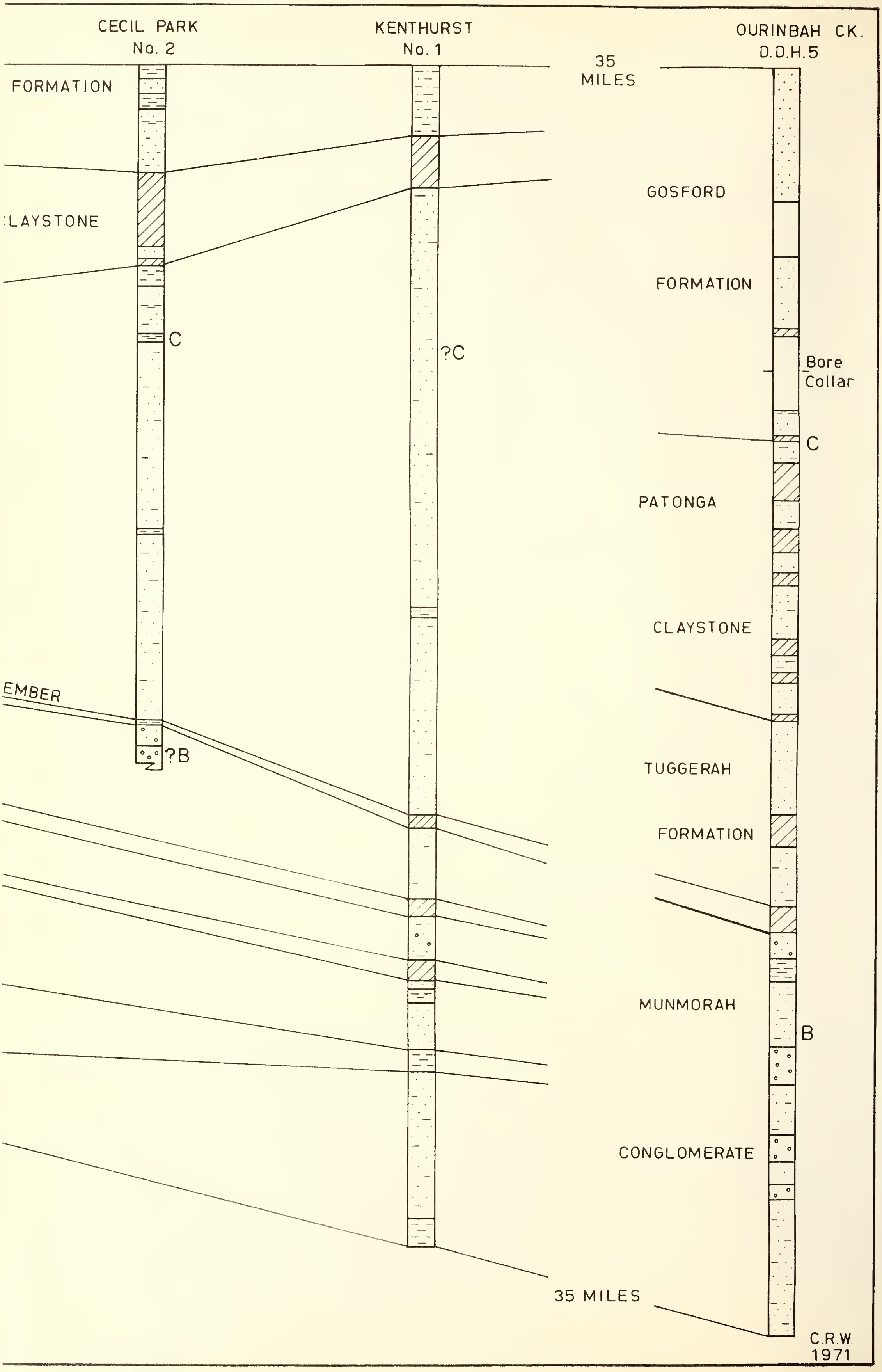


FIG. 3

NARRABEEN GROUP CROSS SECTION
DAPTO TO WYONG
SHOWING MINERALOGICAL MARKERS

DATUM BASE OF HAWKESBURY SANDSTONE


CECIL PARK
No. 2
KENTHURST
No. 1
OURINBAH CK.
D.D.H.5
35
MILES
FORMATION
:LAYSTONE
EMBER
C
?C
?B
GOSFORD
FORMATION
Bore
Collar
C
PATONGA
CLAYSTONE
TUGGERAH
FORMATION
MUNMORAH
B
CONGLOMERATE
35 MILES
C.R.W.
1971

south-western portions of the basin, but it becomes indistinct in the extremely quartzose sandstones of the western districts. Although insufficient data are available from the central districts, the " step " appears to persist to the North Coast area, where it occurs at approximately the top of the Munmorah Conglomerate in Ourimbah Creek D.D.H. 5.

Although the occurrence of a " step " at the top of the conglomeratic lower section of the Narrabeen Group in both the northern and southern parts of the basin suggests that a significant petrological charge occurs at this level across the basin, insufficient samples are available from the intervening area to confirm this correlation. A.O.G. Cecil Park No. 2 bore did not penetrate the whole of the Narrabeen Group, but only reached the top of this conglomeratic succession. As a result too few samples are available from the lower beds to indicate the existence of a " step ". Other bores in the central part of the basin have either been cored at intervals too widely separated for adequate study or else the core is no longer available.

" Step " C is situated very near the collar level of Elecom Ourimbah Creek D.D.H. 5, where it corresponds closely with the top of the Patonga Claystone or the base of the Gosford Formation. In A.O.G. Cecil Park No. 2 a " step " can be recognized at a depth of 1,600′, approximately 200′ below the base of the Bald Hill Claystone, but data from the intervening area is not yet available to substantiate correlation of these " steps ". However, the persistence of " step " B in the underlying succession further south suggests that such continuity is possible. Samples from A.O.G. Kenthurst No. 1, situated between these two bores, indicate that a substantial thickness of quartzose sediment underlies the Bald Hill Claystone and suggests that the profile would be similar to that of the Cecil Park bore, if sufficient closely spaced samples were available.

Some difficulty is encountered in recognition of " steps " in the petrological profile in areas where the " green sandstone " or volcanic facies is present in the Bulgo Sandstone. The arenites of this facies are extremely lithic in composition, so that their presence in any quantity interferes with the systematic upward transition towards more quartzose detritus.

Thus in Coal Cliff D.D.H. 17 the samples taken from above the projected level of " step " B are considerably more lithic in composition than those of bores only a short distance to the west, and " step " B is largely unrecognizable. However, these locally anomalous sandstones can readily be recognized both in hand specimen and under the microscope by their abundant content of trachytic volcanic grains and the intense alteration of such material to green chloritic clay. In addition to disrupting the profile of Coal Cliff D.D.H. 17, these volcanic sandstones are responsible for minor anomalies in the profiles of several other bores in the coastal regions, especially A.I.S. Metropolitan D.D.H. 6, D.M. Wollongong D.D.H. 44, and Mount Murray D.D.H. 12.

Conclusions

At the present time it is not possible to obtain a sufficient number of subsurface samples from the central part of the basin, so that any conclusions on north-south correlation drawn from the petrological data presented above are advanced on a tentative basis only. It is apparent that a " step " in the petrological profile, once recognized, can be traced from bore to bore over many miles, providing an additional aid to lithological correlation in doubtful areas. An extension of this concept may also be applied to inter-regional correlation, for example that between the Illawarra and North Coast districts of the Sydney Basin, and may also hold true for units other than the Narrabeen Group.

Lithological correlation of the Narrabeen Group across the basin indicated firstly that the Grose (Colo Vale) Sandstone in the west is equivalent to the Bulgo and Scarborough Sandstone on the coast, which merge as the Stanwell Park Claystone pinches out (Dickson, 1967). Tracing the top of the conglomeratic sequence further indicates that the Burra Moko Head Sandstone Member is the lateral equivalent not only of the Scarborough Sandstone, as suggested by Herbert (1970), but of also the lower or pebbly facies of the Bulgo Sandstone, thus implying that the Mount York and Menai Claystone Members occur at the same general stratigraphic horizon. The Munmorah Conglomerate of the North Coast district may also be correlated with these units, so that the Menai Member is probably equivalent to the thick shaley succession at the base of the Tuggerah Formation.

A " step " in the petrological profiles (" step " B) occurs at the top of the Munmorah Conglomerate in the north, the top of the pebbly facies of the Bulgo Sandstone in the south, and possibly, although this is uncertain, at the middle of the Grose Sandstone in the west. The presence of a major " step " at each of these horizons appears to support the lithological correlation described above.

The suggestions of Stuntz (1961) and Bradley (1964) that the Bald Hill and Patonga Claystones are not equivalent is further supported by the clay mineralogy of the respective units (Loughnan *et al.*, 1964) and by the position of " steps " in the sandstone composition profile of the sequence. A " step " occurs at the top of the Patonga Claystone at Ourimbah Creek, but 200′ below the Bald Hill Claystone in the Cecil Park bore. If these two " steps " are equivalent, as appears to be the case, the Bald Hill Claystone, with its distinctive mineralogical composition (Loughnan, 1963) is situated some distance above the Patonga, and thus further negates the correlation of Hanlon *et al.* (1953), which indicates physical continuity.

The origin of such " steps " in the petrological profiles, corresponding to sudden changes in the composition of the sediments being deposited at a particular point, appears due to fluctuations in the debris coming from the principal source areas. Regional studies suggest that the transition from lithic to quartzose sediments in the Narrabeen Group is the result of a shift in the source of the material from the north, the recently folded New England Geosyncline to the west, where the older Lachlan Geosyncline was exposed. The sudden changes in sediment composition suggest that this shift in source areas took place in a number of separate stages, probably in response to tectonic movements, and thus the effect of a " step " was felt over a large part of the basin more or less simultaneously or at least as soon as the sediment was dispersed.

Acknowledgements

The work described in this paper forms part of the author's Ph.D. thesis submitted to the University of N.S.W. in 1971. Core samples were made available by the N.S.W. Department of Mines, Australian Oil and Gas Corporation Limited, Kembla Coal and Coke Proprietary Limited, and the Joint Coal Board, to whom the author would like to record his thanks. Particular thanks are also due to Associate Professor F. C. Loughnan, who acted as supervisor for the doctoral study, and to Mrs. K. M. Ward for the typing of the manuscript.

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(Received 15 November 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 89–93, 1971

Longitudinal Free Oscillations in Jervis Bay, New South Wales

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Abstract—The longitudinal free oscillations in Jervis Bay are calculated theoretically by the Galerkin method applied to a one-dimensional flow model. The periods of the first six modes of the model are given together with the corresponding horizontal transports. Two power spectra of wave heights measured at one end of the Bay during southerly storms have been compared with the theory. Excellent agreement is obtained for the fundamental mode with a theoretical period of 33·6 minutes. The possible existence of transverse oscillations in the Bay during the time of measuring the wave height obscures the matching of other theoretical harmonics, but, since the excitation is caused by strong winds along the main axis of the Bay, some comparisons are speculated.

1. Introduction

Not many lakes or bays in Australia have been analysed for their free oscillations. Model studies of harbours have been carried out, e.g., Port Kembla harbour by the Public Works Department (1962), and both theoretical and experimental studies have been made on The Coorong, South Australia, by Clarke (1965*b*) and Noye (1967). A theoretical and experimental study of Jervis Bay has been undertaken and will now be described.

The methods of theoretical analysis of longitudinal oscillations in lakes and bays are mostly summarized by Defant (1961). Some variations of these have been made recently by Bottomley (1956), Darbyshire and Darbyshire (1957) and Raichlen (1965). Bottomley examined the free oscillations in Lake Wakatipu, New Zealand, from the behaviour of a laboratory model of the lake, while Darbyshire and Darbyshire applied the method of Chrystal (1906) to Lough Neagh by representing the lake as a series of coupled rectangles and matching boundary conditions at the junctions of the rectangles. They also used an interesting impedance approach with reasonable results. Raichlen transformed the shallow-water wave equations into a set of difference equations which were then solved numerically to obtain the periods and modes of oscillation.

Another method was given by Clarke (1968), who applied the Galerkin method (Kantorovich and Krylov, 1958) to the boundary value problem posed by the longitudinal oscillations of a lake or bay, and showed that it is an easy-to-apply technique which is valid over a wide range of basin shapes provided the flow in the transverse direction is negligible. The nature of the solution is a feature of the method in that it gives both transport and wave height as well as the frequencies of various modes. It is this method which is applied to Jervis Bay.

2. Application of the Galerkin Method to Jervis Bay

Jervis Bay (Figure 1) is about 100 miles south of Sydney and is on the New South Wales coastline. It is somewhat oval in shape and measures 9 miles along the longitudinal axis and $4\frac{1}{2}$ miles in the transverse direction.

The Bay is open to the sea, but the oscillations through the entrance were omitted from consideration by assuming a closed entrance from Bowen Island to Longnose Point. In terms of longitudinal oscillations along the main axis it is hence assumed that the loss in energy through the entrance is small over the time cycle of an oscillation. The Bay was divided into 44 stations along the main axis and transversals drawn for each station. The area of cross-section and the breadth in the surface for each station were then calculated.

If the origin O is chosen at the southern end of the Bay and the axis Ox along the main axis, which is almost due north, then the area of cross-section and the breadth at a station distant x from O is $A(x)$ and $b(x)$ respectively. The linear equations of motion are transformed by introducing a horizontal transport variable, α, and a surface area variable, χ, where

$$\alpha = A(x)u, \quad \dots\dots\dots\dots \quad (1)$$

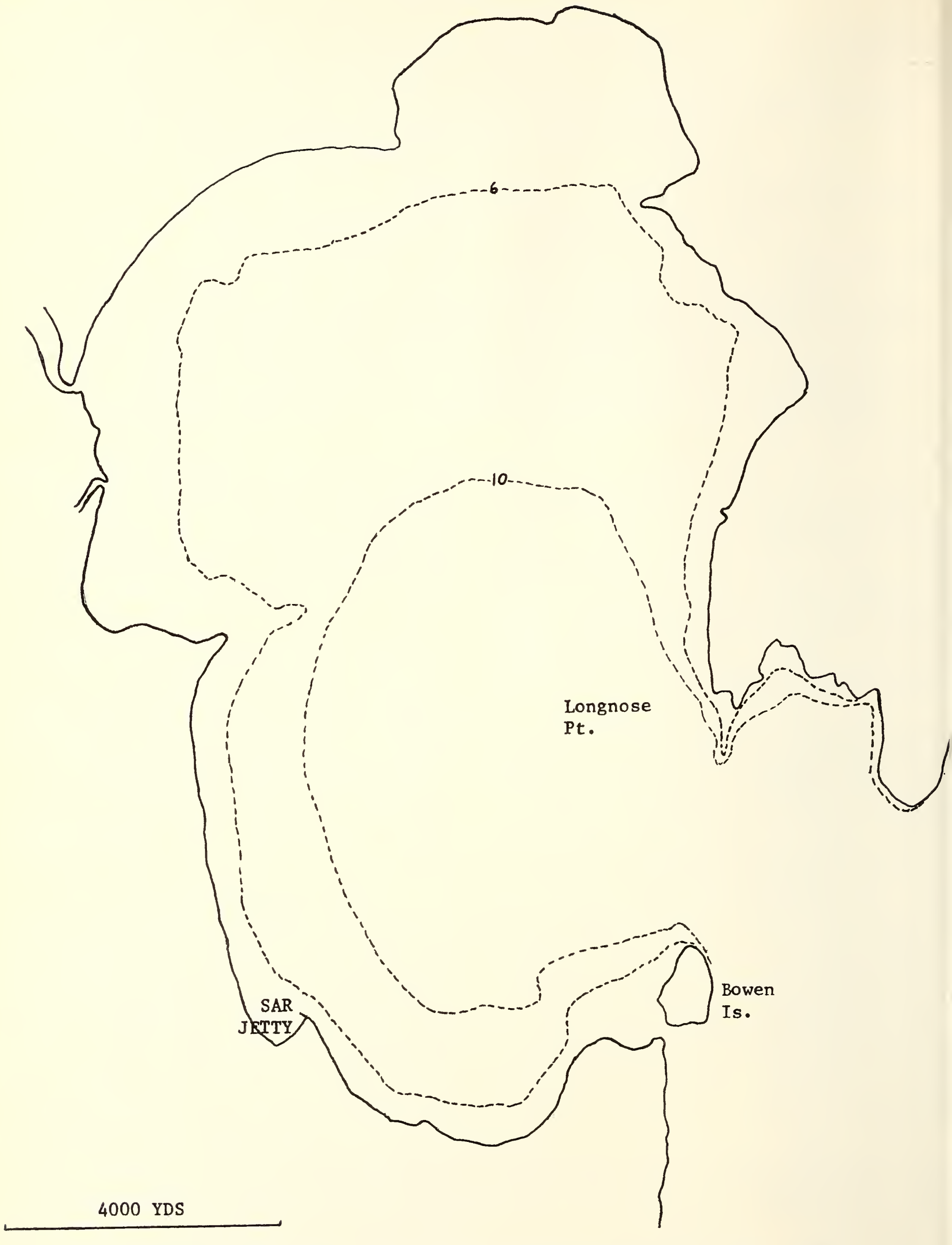

Figure 1.—Jervis Bay, with dotted lines indicating the 10- and 6-fathom lines.

with u being the horizontal velocity in the x direction, and

$$\chi=\int_0^x b(x')\mathrm{d}x'. \quad \ldots\ldots \quad (2)$$

By assuming periodic oscillations,

$$\alpha=\alpha^* e^{i(\sigma t+\varepsilon)}, \quad \ldots\ldots\ldots \quad (3)$$

the transformed equations become

$$\frac{\mathrm{d}^2\alpha^*}{\mathrm{d}\chi^2}+\frac{\sigma^2}{gf(\chi)}\alpha^*=0, \quad \ldots\ldots \quad (4)$$

where

$$f(\chi)=A(x)b(x). \quad \ldots\ldots \quad (5)$$

At the north end of the bay, $x=l$, say, the variable χ has the value χ_l. The boundary conditions are then

$$\alpha^*=0,\ \chi=0 \text{ and } \chi=\chi_l, \quad \ldots\ldots \quad (6)$$

i.e., there is no transport across the ends.

The approximate solution of the problem (4) and (6) is based on the Galerkin method, where the transport, α^*, is approximated as a polynomial satisfying the boundary conditions, i.e.,

$$\alpha^* \doteqdot \alpha_n(\chi)= \chi(\chi_l-\chi)(a_1+a_2\chi+a_3\chi^2+\ldots+a_n\chi^{n-1}) = \sum_{i=1}^{n} a_i\varphi_i. \quad \ldots\ldots \quad (7)$$

The functions φ_i must then satisfy orthogonality conditions

$$\int_0^{\chi_l}\left(\frac{\mathrm{d}^2\alpha_n}{\mathrm{d}\chi^2}+\frac{\sigma^2}{gf(\chi)}\alpha_n\right)\varphi_j\mathrm{d}\chi=0, \quad j=1,2,\ldots,n. \quad \ldots\ldots \quad (8)$$

The coefficients of the a_i are computed for each j value and are of the form $-\mu_{ij}+\lambda\nu_{ij}$, where $\lambda=\sigma^2/g$. Thus if $A=(\mu_{ij})$ and $B=(\nu_{ij})$ then the integrated system (8) is $(A-\lambda B)\mathbf{x}=0$, where $\mathbf{x}$ is the column vector of the a_1. Hence λ and $\mathbf{x}$ are the eigen-values and eigen-vectors of $B^{-1}A$.

In the analysis of Jervis Bay sufficient accuracy was obtained for the first six eigen-values λ when n was equal to 8, i.e., the approximation for the transport was a polynomial of degree 10. The periods of the first six harmonics were then calculated and are given in Table 1, together with the coefficients, a_i, of the corresponding transports. These coefficients have not been normalized in any way and lead directly to wave height, for

$$\frac{\mathrm{d}\alpha}{\mathrm{d}\chi}=-\zeta, \quad \ldots\ldots\ldots\ldots \quad (9)$$

where ζ is the wave-height.

3. Comparison of Theoretical Results with Experimental Evidence

Wave height recordings were obtained from Jervis Bay over a period of several months in 1968. Two of these records were chosen for analysis as they measured the effects of strong southerly winds along the Bay. One of these records was taken on 15th May and has been published by Clarke, Keane and O'Halloran (1968), the other was taken on 19th April. The recording instrument was situated on the Royal Australian Naval College SAR wharf at the southern end of the Bay.

The duration of the records chosen for analysis was five hours on 19th April and nine hours on 15th May. The data were read manually at intervals of three minutes and processed by the Time Series Analysis Program FSAPS of the User Group G6 CSIR (Clarke, 1965*a*). This programme computes either a Fourier series spectrum by the algorithm in A. P. Clarke (1964) or a Power spectrum by the method of Blackman and Tukey (1958). The Fourier series spectrum was computed for both of the records and is shown in Figure 2.

In this Figure the periods corresponding to local maximum energy have been marked and are expressed in minutes. The two spectra

TABLE 1

The Periods and the Coefficients, a_i, of the Approximate Transport, Eqn. (7), for the First Six Longitudinal Harmonics of Jervis Bay

Harmonic	Period (mins.)	Transport Coefficients							
		a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
1	33·6	−0·1786	0·0002	−0·0099	0·0047	−0·0011	0·0002	0·0000	0·0000
2	20·0	0·1445	−0·0015	−0·0252	0·0179	−0·0069	0·0013	−0·0001	0·0000
3	14·2	−0·1472	0·0560	−0·0088	0·0029	0·0003	−0·0003	0·0001	0·0000
4	10·8	0·1808	−0·1435	0·0643	−0·0417	0·0172	−0·0035	0·0003	0·0000
5	8·7	−0·3959	0·3449	0·0371	−0·0876	0·0278	−0·0045	0·0004	0·0000
6	7·2	−0·2017	0·3205	−0·1175	−0·0035	0·0067	−0·0005	−0·0001	0·0000

show close agreement with each other for these period times except for the periods 24·0, 20·0 and 17·4 minutes on 15th May spectrum and the period 15·8 minutes on the 19th April spectrum, which will now be discussed. The possibility of finding a maximum energy peak

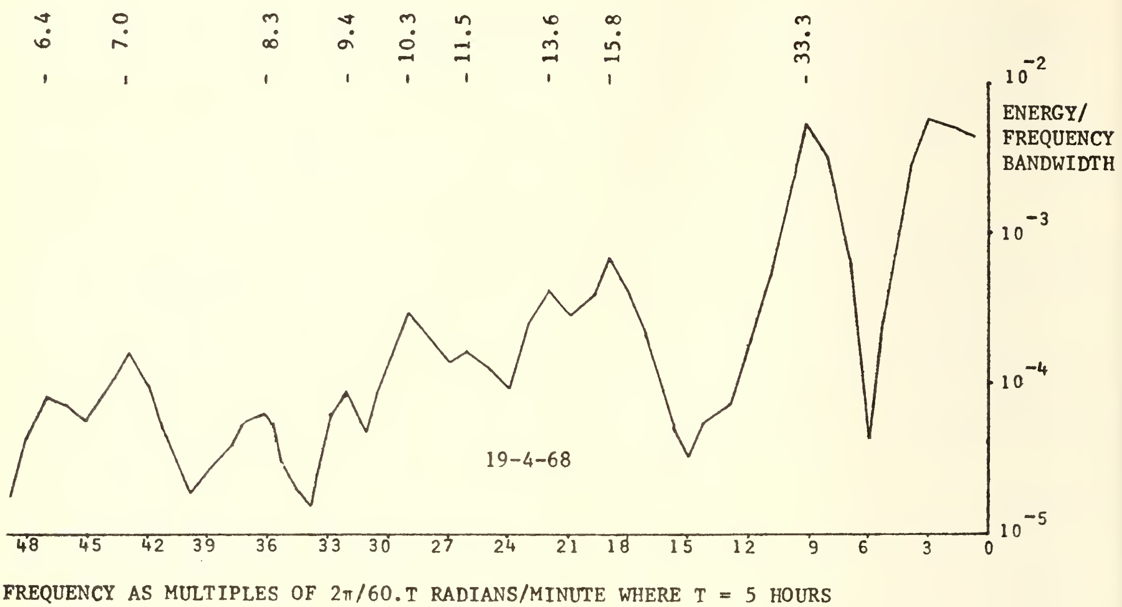

Fig. 2.—Fourier series energy spectrum for Jervis Bay, with maximum energy peaks marked to show the period in minutes.

near 24·0 minutes on the 19th April record is eliminated by the large density at the 33·3 minute period. The energy peak corresponding to 20·0 minutes on the record is plainly absent, which suggests that the conditions over the Bay were not conducive to an excitation of this harmonic, while the energy peak at 17·4 minutes for the 15th May spectrum is a broad peak and may well represent a peak nearer 16·0 minutes. Further experimental data are required in order to ratify the discrepancies.

When the theoretical periods are compared with the spectra it is clear that the peaks at 33·3 and 33·75 minutes correspond to the model's fundamental period of 33·6 minutes and that this figure is within the resolution factor for each spectrum.

Further comparisons are purely speculative, but it may be possible to match the model's second harmonic period of 20·0 minutes with the energy peak at 20·0 minutes on the 15th May. This would assume that the peak corresponds to a longitudinal oscillation and not to a transverse one. Other comparisons are obscured by the probable existence of resonant oscillations having a node at the entrance. More investigation is necessary to resolve these points.

Concluding Remarks

The free oscillations in Jervis Bay have been calculated theoretically by the Galerkin method applied to a one-dimensional flow model. The periods obtained were 33·6 20·0, 14·2, 10·8, 8·7 and 7·2 minutes and correspond to the first six longitudinal harmonics of the Bay, where it is assumed that no motion takes place through the entrance. Two power spectra obtained from wave records for the 19th April and 15th May, 1968, show energy peaks which are in close agreement with each other. Peaks at 33·3 and 33·75 minutes are in close agreement with the theoretical fundamental period of 33·6 minutes. The matching of other energy peaks with the theoretical model would be only tentative, and subject to further investigation.

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(Received 14 July 1971)

Report of the Council for the Year Ended 31st March, 1971.

Presented at the Annual General Meeting of the Society held on 7th April, 1971, in accordance with Rule 18 (*a*).

At the end of the period under review the composition of the membership was 346 members, 12 associate members, and 10 honorary members.

During the year 13 new members, two associate members and one honorary member were elected. One associate transferred to full membership. Fifteen members and one associate member resigned.

Honorary member elected : Dr. Thomas Iredale.

It is with regret that we announce the loss by death of :

Professor Albert E. Alexander (elected 1950).

Mr. Arthur J. Lambeth (elected 1939).

Miss Joan A. Marsden (elected 1954).

Dr. Henry S. H. Wardlaw (elected 1913).

Professor W. L. Waterhouse (elected 1919).

Nine monthly meetings were held. The abstracts of all addresses have been printed on the notice papers. The proceedings of these will appear later in the issue of the *Journal and Proceedings*. The members of Council wish to express their sincere thanks and appreciation to the nine speakers who contributed to the success of these meetings, the average attendance being 36.

The Annual Social Function was held at the University of New South Wales Union, and was attended by 53 members and guests.

Clarke Medal for 1971 : Dr. Nancy T. Burbidge, D.Sc.

The Society's Medal for 1970 : Dr. J. A. Dulhunty, D.Sc.

The Edgeworth David Medal for 1970 : Dr. D. A. Buckingham, Ph.D., M.Sc., B.Sc.

The Archibald Ollé Prize for Vol. 102 : Dr. B. B. Guy, B.Sc., Ph.D.

The Liversidge Research Lecture for 1970, entitled " Chemistry of Some Insect Secretions ", was delivered by Professor G. W. K. Cavill, of the School of Chemistry, University of New South Wales.

At the General Monthly Meeting on 6th June, 1970, a lecture entitled " James Cook and the Transit of Venus " was delivered by Mr. W. H. Robertson of the Sydney Observatory. Acknowledgement is given to the Captain Cook Bi-centenary Committee for their support of this lecture and for a grant towards printing.

In conjunction with the Australian Institute of Physics, a special lecture was held at the University of Sydney, entitled " The Scientific Experiments Planned for Apollo 14 on 31st January, 1971 ". The lecture was delivered by Dr. P. K. Chapman, N.A.S.A. Astronaut.

The Society has again received a grant from the Government of New South Wales of $1,500. The Government's continued interest in the work of the Society is much appreciated.

A sub-committee was set up during the year to look into the " Role of the Society for the future ". A report from this committee follows.

A most successful Summer School, " Mathematics Alive ", was run by the Society in January, 1971. It has been recommended that the Summer School become an annual event.

The Society's financial statement shows a surplus of $3,550.44.

The New England Branch of the Society's meeting will be included in the Proceedings of the Branch to follow.

A report of the Proceedings of the South Coast Branch will also follow.

The Section of Geology continued to hold regular meetings, and the Annual Report is tabled.

The President represented the Society at the Bi-centenary Celebrations of the Captain Cook Landing at Kurnell, and placed a wreath on the Banks Memorial. The celebration was held in the presence of Her Majesty the Queen.

Mr. J. W. G. Neuhaus, Vice-President, represented the Society at the Sydney Harbour Carnival and Fireworks Display arranged by the Citizens' Committee of the Captain Cook Bi-centenary Celebrations Committee.

Mr. M. J. Puttock, member of Council, represented the Council at the Annual Dinner of the Institution of Engineers, Australia, Sydney Division, and Annual Dinner of the Chamber of Manufactures of New South Wales.

Four parts of the *Journal and Proceedings* were published during the year : Volume 102, Parts 2, 3/4, and Volume 103, Part 1.

At a special meeting of Council Lord Casey of Berwick, accompanied by Lady Casey, received the James Cook Medal for 1969 and was entertained at a reception in the Society's rooms, where he inspected the library and viewed early records and documents from the archives of the Society.

Council held 11 ordinary meetings, and attendances were as follows : Professor Smith, 11 ; Dr. Pickett, 10 ; Mr. Chaffer, 11 ; Mrs. Krysko v. Tryst, 11 ; Mr. Puttock, 11 ; Mr. Humphries, 6 ; Mr. Poggendorff, 11 ; Mr. Robertson, 7 ; Mr. Clancy, 10 ; Professor Le Fevre, 6 ; Mr. Neuhaus, 7 ; Professor Griffith, 7 ; Mr. Pollard, 9 ; Mr. Kitamura, 10 ; Dr. Day, 3 ; Mr. Cameron, 6 ; Dr. Reichel, 1 ; Dr. Watton (leave of absence), 3 ; Professor Stanton, nil.

The Library.—Periodicals were received by exchange from 395 societies and institutions. In addition the amount of $156.68 was expended on the purchase of periodicals.

Among the institutions which made use of the Library through the inter-library loan scheme were :

New South Wales State Government : Geological Survey of New South Wales ; Department of Agriculture; Electricity Commission; M.W.S. and D. Board; Water Conservation and Irrigation Board; Department of Health; Department of Conservation; Department of Mines.

Other State Governments: Northern Territory Administration; Animal Industry and Agriculture Branch; Department of Forestry, Queensland; Geological Survey of Queensland; Department of Primary Industry, Brisbane; Queensland Herbarium; Department of Mines, Hobart.

Commonwealth Government: Atomic Energy Commission; Department of National Development; Joint Coal Board; Royal Military College, Duntroon; C.S.I.R.O.: Mineral Chemistry, Coal Research, Prospect, Cronulla, Textile Physics, National Standards Library.

Universities and Colleges: Sydney Technical College; Universities of Sydney, New South Wales, Newcastle, New England, James Cook of Northern Queensland, Melbourne, Flinders, Macquarie, Australian National University, Queensland, Adelaide, Wollongong University College, La Trobe, Tasmania. Universities of Auckland, Wellington, Canterbury and Otago supplied with Xerox copies.

Companies: C.S.R. Research; C.S.R. Head Office; B.H.P., Shortland; B.H.P., Newcastle; B.H.P. Oil and Gas, Melbourne; Australian Iron and Steel; Blue Metal and Gravel Co. Pty. Ltd.; Peko-Wallsend; Arnotts Biscuits; Union Carbide; Australian Consolidated Industries; Cyprus Mines Corp.; Eastern Nitrogen Ltd.; I.C.I.; Bonds Industries; James Hardie & Co.

Museums: Western Australian Museum; Australian Museum.

Miscellaneous: Institution of Engineers; Linnean Society of New South Wales; St. Vincent's Hospital; Royal North Shore Hospital; National Library of Australia.

Borrowings for the year 1970/71: members, 79; others, 439; total, 518.

Our Assistant Librarian, Mr. A. F. Day, retired in November. Mr. Day had the Society's well-being very much at heart, and he rendered many extra services. One area in particular where this was evident was the very efficient manner in which he reorganized the Society's library during his period of service.

It is with pleasure that we are able to report the appointment of Mrs. G. Procter as the new Assistant Librarian.

The Council also wish to extend their thanks to Mrs. Collier, our Assistant Secretary, who has, under difficult circumstances, so efficiently conducted the daily affairs of the Society.

In the period under review we were informed that Science House was to be resumed by the Sydney Cove Redevelopment Authority. This was officially gazetted on 18th December, 1970. Your Council has been most active in taking all possible measures to oppose resumption, and later in seeking professional advice in the compiling and lodging of the claim for compensation with the Authority.

It may well be that this enforced change is the most important event in the Society's long history, and provided we work together in the course of improving our illustrious Society it could lead to the brightest possible future.

E. K. CHAFFER,
Hon. Secretary.

7th April, 1971.

Summer School, 1971

"Mathematics Alive"

A four-day Summer School, "Mathematics Alive", was organized by Council members for sixth form high school students and a few first year university students to give the coming generation of scientists some insight into the way mathematics and computers are used in scientific research work. The School was held from Monday, 18th January, to Thursday, 21st January, in Science House. On the last day the students used computers at the I.B.M. Centre, Sydney, and they visited the Australian Atomic Energy Commission Research Establishment, Lucas Heights.

About 400 students sought admission to the School following distribution of application forms through the principals of metropolitan high schools. A selection of 95 students was made on the basis of advice from the school mathematics masters and 92 finally attended the School.

The subject-matter for the School was chosen to show the students the way computers are used in mathematical problem solving and the need for solidly based mathematical theory was emphasized. The lectures covered such subjects as abstract spaces, matrices, numerical analysis and FORTRAN coding and were given by Council members as well as staff from the A.A.E.C. Research Establishment and the I.B.M. Centre. (Thanks have already been expressed to these establishments for their generous help.)

One theme developed throughout the School concerned whether fuel in a nuclear reactor would melt, and centred around a study of the time-dependent (t) first-order non-linear differential equation

$$\dot{p}=[p-1-b\exp(-t)]p, \quad p(0)=1,$$

which approximately describes the influence on reactor power (p) of a disturbance b to the steady state ($p(t)=1$). We sought numerical solution of the given equation so that we could calculate the maximum power surge

$$h(b)=\max p(t).$$

The solution process involved the students in mathematics, numerical analysis as well as FORTRAN computer programming. Almost all the students were able to show from their computer results that the fuel melting condition

$$h(b)\geqslant 1\cdot 2$$

was not achieved when $b=0\cdot 5$.

From comments received from the students they really enjoyed the School. Many of the students have shown an interest in our Society. The Council suggest that it is up to the Society to maintain this interest with activities which show the coming generation the vital role of Science in our community—Science the servant of man.

JOHN POLLARD,
Director,
Summer School.

Role of the Society

Report Presented at the Annual General Meeting of the Royal Society of New South Wales on 7th April, 1971

During 1970 the Council agreed to consider the role and activities of the Society in the past and for the future.

The present activities of the Society include :

(i) Organization of occasional specialist lectures.
  (*a*) Clarke Memorial Lecture (Geology).
  (*b*) Liversidge Research Lecture (Chemistry).
  (*c*) Pollock Memorial Lecture (Mathematics and Physics).

(ii) Organization of the programme of monthly lectures on a variety of scientific topics.

(iii) Maintenance of the Society's library.

(iv) Publication of the *Journal and Proceedings*.

(v) Recognition of the merit of outstanding scientists by the award of medals and prizes:
  (*a*) The Society's Medal.
  (*b*) The Clarke Medal.
  (*c*) The James Cook Medal.
  (*d*) The Edgeworth David Medal.
  (*e*) The Walter Burfitt Prize.
  (*f*) The Archibald D. Ollé Prize.

(vi) Organization of symposia, summer schools and conferences.

The Council believes that these activities are of value to the scientific community in New South Wales and believes that they must be continued.

At the same time the Council feels that the Society should—where the state of its finances allows—do more to serve the members, and to this end it is investigating the possibility of undertaking additional activities.

Now that Science House has been resumed, the Society has the task of finding a new home. The type of activity which the Society is to pursue in the future must in part determine the sort of premises best suited for our new home, and the new Council will have to consider the two matters together.

All members will be affected in some measure by the decisions to be arrived at by the Council, and in its deliberations any opinions transmitted to it by members will be most useful.

Honorary Treasurer's Report

There was a surplus for the period of $3,550, as against a deficit for the previous year of $209, resulting in a total increase of $3,759, made up as follows :

		$
Increase in Subscriptions received ..		1,130
Increase in General Interest* ..		529
Increase in Donations received ..		353
Increase in Sale of Reprints ..		401
Increase in Subscriptions to Journal		360
Increase in Sale of Back Numbers ..		538
Surplus from Summer School ..		17
Reduction in Printing Costs ..		692
Reduction in Salary Costs		544
		4,564
Less :		
Reduction in Science House Surplus	$488	
Increase in Rental Paid	16	
Increase in General Expenses	301	
		805
Total increase		$3,759

* The increase in general interest is largely a result of the Council's decision that the interest on library investments be credited to the General Interest Account.

In the light of the recent increase in members' subscriptions, a sounder position is reflected in the following table.

Ratio of Subscriptions to Expenses

	1967	1968	1969	1970	1971
Subscriptions ..	1,949	1,973	2,267	2,084	3,222
Expenses (not including Journal printing) ..	8,336	8,205	10,139	9,514	9,427
	1 to 4·28	1 to 4·16	1 to 4·47	1 to 4·56	1 to 2·93

J. W. Pickett,
Hon. Treasurer.

Abstract of Proceedings

1st April, 1970

The one hundred and third Annual Meeting of the Society was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. W. G. Neuhaus, was in the chair. There were present 34 members and visitors.

Angus Robert Collins was elected a member of the Society.

The following awards of the Society were announced :

The Society's Medal for 1969 to Professor R. J. W. Le Fevre.

The Clarke Medal for 1970 to G. P. Whitley, F.R.Z.S.

The James Cook Medal for 1969 to Lord Casey of Berwick and Westminster.

The Edgeworth David Medal for 1969 to Professor B. W. Ninham.

The Annual Report of the Council and the Financial Statement were presented and adopted.

Messrs. Horley & Horley were re-elected Auditors for the Society for 1970–1971.

Office-bearers for 1970–1971 were elected as follows :

President : W. E. Smith, Ph.D.

Vice-Presidents : J. W. G. Neuhaus, M.Sc., A. A. Day, Ph.D. (Cantab.), R. J. W. Le Fevre, D.Sc., F.R.S., F.A.A., T. E. Kitamura, B.A., W. H. Robertson, B.Sc.

Hon. Secretaries : E. K. Chaffer (General), (Mrs.) M. Krysko v. Tryst., B.Sc., Grad.Dip. (Editorial).

Hon. Treasurer : J. W. Pickett, M.Sc. (N.E.), Dr.phil.nat. (Frankfurt/M).

Hon. Librarian : W. H. G. Poggendorff, B.Sc.Agr.

Members of Council : J. C. Cameron, M.A., B.Sc. (Edin.), D.I.C., B. E. Clancy, M.Sc., J. L. Griffith, B.A., M.Sc., M. J. Puttock, B.Sc.(Eng.), A.Inst.P., A. Reichel, Ph.D., M.Sc., J. P. Pollard, M.Sc., Dip.App.Chem., J. W. Humphries, B.Sc., E. C. Watton, Ph.D., B.Sc.(Hons.), A.S.T.C.

The following papers were read by title only :

" Radio-Carbon Datings of Ancestral River Sediments on the Riverine Plain of South-eastern Australia and Their Interpretation ", by Simon Pels.

" The Occurrence and Significance of Triassic Coal in the Volcanic Necks near Sydney ", L. H. Hamilton, R. Helby and G. H. Taylor.

The address of the retiring President, Mr. J. W. G. Neuhaus, entitled " Chemicals in Food ", was delivered.

The retiring President then welcomed W. E. Smith, Ph.D., to the Presidential Chair.

6th May, 1970

The eight hundred and forty-third General Monthly Meeting of the Society was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 33 members and visitors.

The following were elected as members : Jeannette Adrian, Helen Elizabeth Andrews, Paul Michael Ashley, Helena Basden, Keith Phillip Tognetti.

The following papers were read by title only :

" A Solar Charge and the Perihelion Motion of Mercury ", by R. Burman.

" The Distribution of Eupatorium adenophorum Speng. on the Far North Coast of New South Wales ", by Bruce A. Auld.

Address.—An address entitled " This Man-Made World " was delivered by Dr. G. C. Lowenthal, Tutor in Science, the Department of Adult Education, at the University of Sydney.

3rd June, 1970

The eight hundred and forty-fourth General Meeting of the Society was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 57 members and visitors.

The Chairman announced the deaths of Professor A. E. Alexander and Professor W. L. Waterhouse.

The following members were elected : Anthony John Irving, Kathleen Harvison Barwick, Viera Scheibner.

The Chairman announced the election of honorary member Thomas Iredale, B.Sc. (Syd.), D.Sc. (Lond.), F.R.I.C., F.R.A.C.I.

The following papers were read by title only :

" Meson Field Potential in Fundamental Theory ", by A. H. Klotz. (Communicated by Dr. A. Reichel.)

" The Coolac-Goobarragandra Ultramafic Belt, N.S.W.", by H. G. Golding.

Address.—An address entitled " The Transit of Venus " was delivered by Mr. W. H. Robertson of the Sydney Observatory. The evening was arranged in co-operation with the Captain Cook Bi-centenary Committee (Arts and Historical Committee), and is to be published.

1st July, 1970

The eight hundred and forty-fifth General Monthly Meeting of the Society was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 23 members and visitors.

The Chairman announced the death of Dr. Henry S. H. Wardlaw.

A letter was tabled from Miss M. Ogle thanking all for the presentation and good wishes.

Announcement of the Nuffield Foundation Australian Advisory Committee that the 1971 award Nuffield Commonwealth Travelling Fellowship in Medical

Sciences was awarded to Anthony R. Mocre, M.B., B.S., F.R.C.S., of the University of Melbourne at the Royal Melbourne Hospital.

Applications requested for next award in the fields of Natural Sciences and the Humanities and Social Sciences to Australian university graduates between the ages of 25 and 35 years.

Section of Geology to meet 17th July, 1970.

Address.—An address entitled " Chemical Education—Problems of Innovation and Change " was delivered by Professor H. F. Halliwell, Professor of Chemical Education in the School of Chemical Science, University of East Anglia, Norwich, England, who is visiting Australia under the Commonwealth Scheme.

5th August, 1970

The eight hundred and forty-sixth General Monthly Meeting of the Society was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 51 members and visitors.

No meeting of the Section of Geology for the month of August.

The following paper was read by title only :

" Devonian Stromatoporoids from the Broken River Formation, North Queensland ", by C. W. Mallett.

Address.—An address entitled " Drift Theory and Fossil Non-marine Evidence from Antarctic and Neighbouring Continents and Islands " was delivered by Professor P. Tasch, Professor of Geology at Wichita State University in Kansas, U.S.A.

2nd September, 1970

The eight hundred and forty-seventh General Monthly Meeting of the Society was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 11 members and visitors.

The following members were elected : Stephen Sydney Sampson, Bruce Runnegar.

The Edgeworth David Medal for 1969 was presented to Professor B. W. Ninham.

The next meeting of the Section of Geology will be 18th Deptember, 1970.

The following paper was read by title only :

" The Lower-Middle Palaeozoic Stratigraphy of the Bowan Park Area, Central Western New South Wales ", by V. Semeniuk.

Address.—An address entitled " Dynamic Aspects of Plant Breeding " was delivered by Dr. K. S. McWhirter, Senior Lecturer in Genetics and Plant Breeding at the University of Sydney.

7th October, 1970

The eight hundred and forty-eighth General Monthly Meeting of the Society was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 28 members and visitors.

The Chairman announced with regret the death of Joan Audrey Marsden, member since 1954.

The following member was elected : Ronald Rion Burman.

There will be no meeting of the Section of Geology in October.

The following papers were read by title only :

" A Solar Charge and the Perihelion Motion of 1566 Icarus ", by R. Burman.

" On a Classical Pair of Equations ", by J. L. Griffith.

Address.—An address entitled " Blood Transfusion " was delivered by Dr. G. T. Archer of the Red Cross Blood Transfusion Service, York Street, Sydney.

4th November, 1970

The eight hundred and forty-ninth General Monthly Meeting of the Society was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 31 members and visitors.

The Chairman announced with regret the death of Arthur James Lambeth, member since 1939.

Barry William Ninham was elected a member.

David Alastair Wadley was elected an associate member.

The Section of Geology will meet on Friday, 20th November, 1970.

The following papers were read by title only :

" A Note on Some Non-calcareous Stalactites from the Sandstones of the Sydney Basin, N.S.W.", by E. V. Lassak.

" Occultations Observed at Sydney Observatory during 1969 ", by K. P. Sims.

" James Cook and the Transit of Venus ", by W. H. Robertson.

" Origin of the Moon ", Clarke Memorial Lecture, 1969, by A. E. Ringwood.

Address.—An address entitled " Metric Conversion in Australia " was delivered by Mr. A. F. A. Harper, Executive Member, Metric Conversion Board.

2nd December, 1970

The eight hundred and fiftieth General Monthly Meeting was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 52 members and visitors.

Archivedes Kalokerinos was elected a member.

It was reported that Council had informed members of notice of resumption of Science House by the Sydney Cove Redevelopment Authority.

Action had been taken in a letter of objection to the resumption addressed to the Minister for Local Government based on three points :

(1) Financial hardship by loss of income and low rental cost of Society's rooms.

(2) The acknowledged architectural merit of the building.

(3) The contribution of members of the Society to the progress of the State.

A copy of this letter was sent to the Premier, the Minister for Education and Science, and the Member for King, Mr. A. R. Sloss.

Notice was given of a lecture by Dr. P. K. Chapman, N.A.S.A. Astronaut, to be held in conjunction with the Australian Institute of Physics, on Tuesday, 8th December, 1970, at 7.45 p.m., entitled " The Scientific Experiments Planned for Apollo 14 on 31st January, 1971 ", to be held in the Stephen Roberts Theatre, University of Sydney, preceded by a dinner, to which all members were invited, in the Staff Club of Sydney University, at 6 p.m.

It was announced that the next meeting of the Section of Geology would be the Annual Meeting, to be held on 19th March, 1971, at 7.15 p.m., in the Small Hall of Science House.

An address entitled " Before Captain Cook : Some Recent Results of Archaeology on the Coast of South-eastern Australia " was delivered by Mr. J. V. S. Megaw of the Department of Archaeology, University of Sydney.

THE ROYAL SOCIETY OF NEW SOUTH WALES

BALANCE SHEET AS AT 28th FEBRUARY, 1971

LIABILITIES

1970 $		$	$
324	Accrued Expenses		326.96
33	Subscriptions Paid in Advance		59.80
103	Life Members' Subscriptions—Amount carried forward		98.70
	Trust Funds (detailed below) :		
4,482	Clarke Memorial	4,669.12	
2,547	Walter Burfitt Prize	2,650.98	
1,515	Liversidge Bequest	1,523.33	
710	Ollé Bequest	810.26	
			9,653.69
245	Miss Ogle Fund		—
59,644	Accumulated Funds		63,361.59
9,418	Library Reserve Account		8,898.49
	Contingent Liability (in connection with Perpetual Lease)		
$79,021			$82,399.23

ASSETS

1970 $		$	$
3,763	Cash at Bank and in Hand		107.52
	Investments :		
	Commonwealth Bonds and Inscribed Stock—At Face Value—held for :		
3,600	Clarke Memorial Fund	3,600.00	
2,000	Walter Burfitt Prize Fund	2,000.00	
1,400	Liversidge Bequest	1,400.00	
9,680	General Purposes	9,680.00	
9,600	Library Fund	9,600.00	
			26,280.00
169	Fixed Deposit		—
	Deposits at Call—held for :		
—	Trust Funds Revenue	2,653.69	
—	Long Service Leave Fund	630.96	
—	General Purposes	4,082.22	
			7,366.87
30,470	Science House—One-third Capital Cost (one-third 1968 V.G. $100,000)		30,470.43
13,600	Library—At 1936 Valuation		13,600.00
1,715	Furniture and Office Equipment—At Cost, *less* Depreciation		1,660.40
20	Pictures—At Cost, *less* Depreciation		18.58
2	Lantern—At Cost, *less* Depreciation		2.00
2,739	Centenary Volume :		
	Stock	2,480.85	
	Reprints	38.70	
			2,519.55
	Debtors for Subscriptions	699.80	
	Less Reserve for Bad Debts	699.80	
—			—
	Sundry Debtors :		
—	Reprints	283.35	
263	Other	90.53	
			373.88
$79,021			$82,399.23

TRUST FUNDS

	Clarke Memorial $	Walter Burfitt Prize $	Liversidge Bequest $	Ollé Bequest $
Capital at 28th February, 1971 ..	3,600.00	2,000.00	1,400.00	—
Revenue :				
Balance at 28th February, 1970 ..	882.28	547.18	114.83	710.26
Income for Period	186.84	103.80	72.66	100.00
	1,069.12	650.98	187.49	810.26
Less Expenditure	—	—	64.16	—
	$1,069.12	$650.98	$123.33	$810.26

ACCUMULATED FUNDS

	$	$
Balance at 28th February, 1970		59,644.31
Add :		
Transferred from Library Reserve		519.34
Surplus for Period		3,550.44
		63,714.09
Less :		
Increase in Provision for Bad Debts	338.60	
Subscriptions Written Off	13.90	
		352.50
		$63,361.59

Auditors' Report

The above Balance Sheet has been prepared from the Books of Account, Accounts and Vouchers of the Royal Society of New South Wales and is a correct statement of the position of the Society's affairs on 28th February, 1971, as disclosed thereby. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

HORLEY & HORLEY,
Chartered Accountants.
Registered under the Public Accountants Registration Act 1945, as amended.

65 York Street,
Sydney.
24th March, 1971.

(Signed) J. W. PICKETT,
Hon. Treasurer.
W. E. SMITH,
President.

INCOME AND EXPENDITURE ACCOUNT

1st MARCH, 1970, TO 28th FEBRUARY, 1971

1970 $			$
2,084	Membership Subscriptions		3,222.00
12	Proportion of Life Members' Subscriptions		4.20
1,500	Government Subsidy		1,500.00
7,704	Science House Management—Share of Surplus		7,216.20
540	Interest on General Investments		1,068.74
47	Donations		400.00
179	Sale of Reprints		580.43
762	Subscriptions to Journal		1,121.55
663	Sale of Back Numbers		1,200.79
	Refund :		
25	Postages		136.92
—	Xerox Copying		29.30
—	Summer School Surplus		16.81
13,516			16,496.94
209	Deficit for Period		—
$13,725			$16,496.94

1970 $			$
—	Accountancy		285.00
87	Advertising		110.63
46	Annual Social		59.43
100	Audit		110.00
151	Branches of the Society		100.00
172	Cleaning		110.40
90	Depreciation		85.72
66	Electricity		62.67
28	Entertainment		15.40
122	Insurance		115.49
140	Library Purchases		156.68
198	Miscellaneous		232.40
308	Postages and Telegrams		416.86
	Printing—Vol. 102, Parts 2, 3 and 4; Vol. 103, Part 1	$3,287.55	
	Binding	—	
	Postages	231.88	
4,211			3,519.43
127	Printing—General and Stationery		204.03
4,108	Rent—Science House Management		4,124.00
17	Repairs		5.77
3,649	Salaries		3,105.44
105	Telephone		127.15
13,725			12,946.50
—	Surplus for Period		3,550.44
$13,725			$16,496.94

Section of Geology

Abstract of Proceedings, 1970

Five meetings were held during this year, the average attendance being about 10 members and visitors.

MARCH 20th (Annual Meeting) :

(1) Election of office-bearers : Chairman, Dr. B. B. Guy ; Hon. Secretary, Mr. E. V. Lassak.

(2) Address by Dr. P. R. Evans, " Late Mesozoic Geological History of Eastern Australia ".

It is possible to divide the Late Mesozoic into a series of zones based on the sequence of microfloral assemblages in the containing strata. Plots of the distribution, variations in thickness and sedimentary types associated with these zones express the progressive evolution of the area during Mesozoic times.

The Early Jurassic sequences appear to be the product of a large river system which crossed southern Queensland to debouche in an eastern sea located beyond the present continental margin. The blocks of Palaeozoic and Early Mesozoic rock which currently divide the Great Artesian Basin from the Clarence-Morton and Maryborough Basins had little influence on the deposition at the time. Uprising of the Nebine Ridge to divide the Eromanga from the Surat areas of sedimentation began in late Middle or Upper Jurassic time. Minor downwarping during early Middle Jurassic time developed into the Laura Basin in northern Queensland. A major transgression by marine environments moved southwards from the Papuan Basin during Early Cretaceous times. The transgression extended at least as far south as the centre of the Murray Basin in the Aptian. Foundering of the Gippsland-Otway lineament commenced in early Cretaceous time, but open marine conditions failed to enter the region. The late Albian-early Turonian was a period for regression of the sea to the north and for eventual break-through of marine conditions into the Otway Basin. From mid-Turonian time onward deposition was restricted to the continent's borders and sediments of this age are known only in the Gippsland Basin and Otway Basin. However, open marine conditions were never fully developed in those portions of the three basins which have so far been investigated.

MAY 15th :

Address by Mr. D. Taylor : " Tertiary History of the Southern Australian Continental Shelf ".

Foraminiferal studies on the Tertiary deposits of southern Australia (from Esperance to Melbourne) have revealed a developing series of environmental events. From late Cretaceous into early Tertiary times sedimentation was in estuarine, lagoonal and marsh situations with occasional ingressions of marine conditions marked by the presence of planktonic foraminifera. Even drilling offshore has not penetrated a continuous marine sequence. A southern Australian seaway was not established until the late Eocene, when carbonate deposition commenced with influxes of planktonic foraminifera. Carbonate sedimentation, rich in both foraminifera and bryozoa, persisted to the present day with occasional localized disruptions, especially during the Oligocene. Generally, the Tertiary seas were temperate and the prevailing hydrological system was apparently identical to that operating today, i.e. West Wind Drift. During the upper Eocene and lower Miocene there is faunal evidence of brief periods of oceanic warming which are more evident in the west than in the east. This series of environmental events and speculations on paleohydrology are consistent with current theories on the rifting of Australia from Antarctica. This rifting reached its zenith in late Eocene times and the dilation was apparently greater in the west than in the east.

JULY 17th :

Address by Dr. H. G. Golding : " Volcanics of Arran, Antrim, etc. (a Geological Travelogue) ".

Dr. Golding first illustrated features encountered mainly in Iran, Turkey and the Balkans. These included the Quaternary andesite peak of the Demavend, Elburz Mts., Iran ; the chromite workings at Guleman, Anatolia ; the Radusa chromite mine, Macedonia ; the magnesite deposits at Goleš, Serbia ; chrysotile asbestos in the Ozren herzolite, Bosnia ; the Karstic Dinarides, Herzegovina ; the Kassariani schists on Hymittos near Athens ; leucitite and piperino, near Rome ; the Barrandian limestone, Prague ; mixed granite-diorite of the Bohemian Massif ; and Carboniferous, Cretaceous and Tertiary beds in south and central England.

Dr. Golding then outlined aspects of the geology of Arran, where Dalradian schists are intruded by Tertiary granite, and flanked by Arenig pillow lavas and Devonian and Carboniferous beds ; while Tertiary pitchstones, crinanites and other rocks intrude Permian strata. Occurrences of these rocks, and views of Holy Island (riebeckite trachyte), Pladda Island (dolerite) and Ailsa Crag (riebeckite microgranite) were illustrated by slides.

In the north of Ireland the contact of the Mourne Granite with Palaeozoic sediments and the contact of a cone sheet with hornfelses near Carlingford were illustrated. Slides were shown of pipe and spike amygdules, vesicle cylindres, columnar and other structures in the Antrim basalts at Belfast, Island Magee and Giant's Causeway localities.

Specimens exhibited included leucite crystals from the Appian Way, chrome diopside from Dubostiča, Bosnia, elaterite from Derbyshire, pitchstones from Arran, plombierite from Scawt Hill, and perlitic obsidian from Sandy Braes, Antrim.

SEPTEMBER 18th :

Address by Mr. C. R. Ward : " Some Aspects of Narrabeen Group Sedimentation ".

The sediments of the Narrabeen Group were deposited principally by fluvial activity, although a lower deltaic plain environment appears to be represented in the topmost formations of the sequence. Studies of cross-bedding in the sandstones indicate a southerly to south-easterly direction of transport for most of the sequence, with significant departures from this trend at certain stratigraphic horizons.

In the south coast district, the middle part of the Bulgo Sandstone consists of very distinctive, dark green sediments made up of grains and granules of altered intermediate volcanic rock, together with a quartz-poor clay assemblage. Analysis of the cross-bedding in this part of the sequence shows that the material was derived from the east, beyond the present coastline. Geophysical data from this area, as well as the petrology of the sediments themselves, appear to indicate that the underlying Gerringong volcanics had been uplifted and were sufficiently exposed during the Lower Triassic to supply sediment to several parts of the Narrabeen Group. Information such as this is of great importance in palaeogeographical interpretations of the Sydney Basin.

NOVEMBER 20th :

Address by Dr. A. D. Albani : " A Study of the Bedrock in Jarvis Bay and Broken Bay ".

Dr. Albani discussed first his recently concluded work on the bedrock of Jarvis Bay. It shows the presence of two separate drainage systems. A major one including most of the central and southern portion and a minor one in the northern part of the bay.

Present work in the Broken Bay area shows that Pittwater is a separate drainage system. Anomalies in the bedrock levels in the northern area adjoining Brisbane Water are as yet unexplained.

Report of the South Coast Branch of the Royal Society of New South Wales

It is with pleasure that I report on the activities of the small South Coast Branch.

The Annual Dinner and Annual General Meeting was held in the Union, Wollongong University College, on 20th March, 1971. Twenty-seven members and their guests attended. The guest speaker was Dr. J. Symonds, who gave an address on the proposed nuclear power station development at Nowra. The address was well illustrated and most informative, as was shown by the keen interest of the members and guests.

Subsequent to this meeting two attempts to arrange a general meeting were not successful.

During the year potential members were introduced to the Society, and one member resigned due to a move interstate.

R. A. Facer was nominated as South Coast Branch representative on the Council early in 1971. The next meeting (Annual Dinner and Annual General Meeting) will be held on 23rd April, 1971.

The only changes in the financial position were the addition of the \$50.00 subsidy from the main branch and \$1.00 interest. However, expenses of the 1971 Annual General Meeting and Annual Dinner will have to come out of the current balance.

	$
Balance as in last report	23.03
Add—	
Subsidy	50.00
Interest	1.00
Balance as at 1st April, 1971 ..	\$74.03

Richard Facer,
Secretary-Treasurer.

Citations

The Society's Medal for 1970

The Royal Society of New South Wales' own medal for service to science and to the Society is awarded to Dr. John Allan Dulhunty.

Dr. Dulhunty's contributions to Australian geology are widely known and respected. His researches have dealt chiefly with coal and torbanite (the so-called "oil shale") and with the Permian and Mesozoic geology of the Mudgee-Gilgandra-Gunnedah region of northern New South Wales. He has also made significant contributions to the study of Coal Measures polynology, and the glacial geomorphology of the Snowy Mountains. The scope of his investigations may be illustrated by two widely differing examples: one, research into the causes of instantaneous outbursts of the working face in coal mines, and another, the plumbing of the depth of the Blue Lake in the Snowy Mountains, establishing its glacial origins.

For twelve months during the Second World War Dr. Dulhunty undertook special work for the Government on the technology of torbanites. For this period he was granted leave from his research position with the Linnean Society of New South Wales, which he held from 1940 to 1944. In 1946, a mere eight years after gaining his Bachelor's degree, he was awarded a Doctorate of Science by the University of Sydney for his thesis on "The Classification and Origin of the New South Wales Torbanites".

Dr. Dulhunty's diverse research has been recorded in 56 publications to date, in Australian and overseas journals. The importance of his work brought him this Society's recognition in 1961, when he was invited to deliver its Clarke Memorial Lecture, and in 1964, he was elected Federal President of the Geological Society of Australia for the customary one-year term.

After a period shortly after graduation as University Demonstrator, and a later period, 1951 to 1957, as Senior Lecturer in Geology, Dr. Dulhunty in 1957 was made Reader in Geology at the University of Sydney, a post which he still adorns. He has acted for three separate and none-too-easy years as acting head of his department. Known to generations of students by the acronym of his initials as "Jad", he is always a lucid and popular lecturer. For many years he has contributed substantially to the appreciation and understanding of geology in the community at large through his ever-popular Adult Education lectures. In the sphere of secondary education he was Chief Examiner in Geology in the old Leaving Certificate Examination for some ten years.

John Dulhunty's services to the Society have extended over a lengthy period. Following his election to membership in 1937, he became a member of Council in 1942, continuing to 1947, when he was elected President. He again served on the Council of the Society from 1956 to 1959, and has given much unrecorded help over the years in advice, and latterly in writing the Society's Centenary Volume.

It gives me and the Council great pleasure in conferring on Dr. John Dulhunty the Society's Medal for 1970.

The Clarke Medal for 1970

Gilbert Percy Whitley, F.R.Z.S., entered the service of the Australian Museum, Sydney, on 18th April, 1922. He was appointed as a cadet in the Department of Ichthyology. By 1925 he was Acting Ichthyologist during the extended absence on sick leave of his senior, A. R. McCulloch. McCulloch died at an early age, and by the end of 1926 the young Whitley was appointed Ichthyologist, a position he held until his retirement in August, 1964.

Whitley, while still in his teens, came with his family from England to Australia at the beginning of 1921. The first of many records of his activity as a collector is in Bombay and Ceylon on the outward voyage, where he collected shells. In 1923 he spent a holiday on Lord Howe Island, the first of many visits there to collect insects, with his friend and colleague the late Anthony Musgrave, for many years Entomologist at the Museum.

Space will not permit one to give a complete account of his field work. Up to April, 1971, he had undertaken 86 separate field trips. Some of these were short collecting trips in the Sydney district and elsewhere in New South Wales. In others he ranged much further afield. Whitley has visited the Great Barrier Reef eight times, including three months on Low Isles with the British Great Barrier Reef Expedition under the leadership of Professor C. M. (now Sir Maurice) Yonge, in 1928. A spectacular trip fraught with certain danger due to bad weather was in 1936 with Sydney yachtsmen who sailed from Sydney to Lord Howe Island and then 120 miles north to the little known Elizabeth and Middleton Reefs. There he gathered extensive collections, not only of fish but of many other types of marine life.

From 1942 to 1949 Whitley did a tremendous amount of marine biological work at sea with the C.S.I.R.

(now the C.S.I.R.O.). From 1942 to 1946 he was seconded to the C.S.I.R. on full-time service. In C.S.I.R. research vessels he sailed the coasts of Tasmania, Queensland, Western Australia, the Northern Territory and Papua-New Guinea. Numerous islands and reefs were visited, including many shoals in the Timor Sea.

He was a guest worker on two Danish research vessels, the *Dana* under the command of Professor Johannes Schmidt in 1929 and the *Galathea* under the command of Anton Bruun in 1951. In 1956 he was awarded a commemorative *Galathea* silver medal by the King of Denmark.

Whitley is an indefatigable traveller, mostly at his own expense and in his own time, be it noted. His travels are not mere sightseeing jaunts. Wherever there is collecting to be done and museums and other research institutes to be visited, these take prior place. Nonetheless he savours to the full the cultural stimulus of countries abroad. He is keenly interested and well versed in music and other arts.

A list of the places he has visited reads like a travel agency's guide book. He visited Europe, the U.K. and the U.S.A. for six months in 1938–1938. In 1958 he again visited the U.S.A., mainly to attend a conference in New Orleans on the shark menace, but he managed to see other parts of the U.S.A. and to collect shells at Canton Island on the way over. In the Pacific area he has made collections on the New Guinea mainland, on New Caledonia, the Solomons, New Hebrides, Tonga, Fiji, Rarotonga in the Cook Islands, Tahiti and other islands in French Polynesia and Hawaii. He has visited New Zealand several times and has collected there.

In 1962 he attended an ichthyological symposium in southern India, but managed also while away to spend some time in Ceylon, Singapore and Indonesia.

His attendances at various science congresses are too numerous to mention. Worthy of note was his attendance at the Pan-Indian Ocean Science Congress in Perth in 1954 and the Pacific Science Congress in Tokyo in 1966. He managed on this occasion to fit in some shell collecting at Guam and he also visited Taiwan, the Philippines, Thailand and Singapore.

The writer, not being a zoologist, cannot do full justice to his scientific publications. His entire publications number in all 519. This of course includes many articles in the Museum publication *Australian Natural History* (formerly *The Australian Museum Magazine*), encyclopaedia articles and letters to newspapers, including one about a ticket-of-leave man John Roach, employed from 1834 to 1841 at the Museum as "collector and bird stuffer". Although Roach had ability and skill, he was not very well liked by certain zoologists of the time, who referred to him as the "rascally bird stuffer". Whitley also wrote an excellent article on the history of the Museum in *Australian Natural History*, entitled "The First Hundred Years". He has also written a much more comprehensive history of the Museum, which unfortunately remains unpublished. For some time he occupied an additional unpaid post at the Museum, that of Archivist.

He has written several authoritative books, and his scientific papers in journals of learned societies must be numbered in the hundreds.

Another of Whitley's notable interests is reflected in his studies on the scientific work carried out by expeditions in Australia and the nearby Pacific Islands. One may cite as a few examples his scholarly, profusely documented articles on the scientific work of the very early Dutch explorers and those of Tasman, Dampier and de Vlamingh. His article "Naturalists of the First Fleet" was written in 1938 to commemorate the sesquicentenary of the founding of the colony of New South Wales. To commemorate the bicenternary of the discovery of the east coast of Australia by Cook in 1770, he wrote a comprehensive and authoritative handbook, *Early History of Australian Zoology*, published by the Royal Zoological Society of New South Wales, and a shorter article, "The Endeavour's Naturalists", in *Australian Natural History*.

Whitley shows the tenacity of a Sherlock Holmes unravelling the tangled skeins of crime in his seeking of information on little-known early naturalists. He literally haunts the Mitchell Library.

In one of his articles, Whitley gives an account of George Tobin, who is not at all well known. He was third lieutenant under Bligh on the voyage of the *Providence* (1791–1793) to Tahiti to collect breadfruit. On the way the *Providence* anchored in Adventure Bay, South Bruny Island, Tasmania, for a fortnight, where Tobin proved himself an able observer and a first-rate artist. He made fine paintings of the scenery, birds, fish and the rare monotreme the Porcupine Ant-eater, which are now in the Mitchell Library. Bligh himself also found time to make a drawing of the ant-eater. It is characteristic of Whitley that he visited Adventure Bay and collected one.

Another example of Whitley's combined historical and scientific researches was when he visited two of Cook's landing spots on the Queensland coast on the 1770 voyage. To quote his own words: "My late friend, the entomologist, Anthony Musgrave, and I, made a pilgrimage in May 1957, to Thirsty Sound and its environs, at the same time of the year as Cook's visit, 180 years previously." They collected ants from an ant tree identical with one described by Banks at this very spot. They also visited Seventeen Seventy, Bustard Bay, another of Cook's landing places. This was the first landing after Botany Bay, and the place where Cook and his men supplemented their dreadful shipboard diet with several fine big bustards. Bustard Bay is 40 miles south-east of Gladstone and Thirsty Sound is 80 miles south-east of Mackay.

For a total of 22 years in the period 1947–1971 Whitley edited the publications of the Royal Zoological Society of New South Wales and on two occasions was the President of the Society. He has also been President of the Linnean Society of New South Wales and has served on the Councils of the Royal Australian Historical Society and the Anthropological Society of New South Wales.

Since retirement, Gilbert Whitley has been an Honorary Associate of the Australian Museum. He works and publishes scientific papers probably at a greater pace than ever, since he is uninterrupted by the routine matters that plague the life of a scientist in a government position. He has also managed to fit in two or three periods of travel each year since retirement. As recently as April, 1971, he returned from an extensive four months trip to Europe, the U.K. and South Africa. Characteristically, on his way home he squeezed in enough time to collect shells at Mauritius.

Edgeworth David Medal for 1970

The Edgeworth David Medal is awarded for distinguished contributions by young scientists, under the age of 35, for work done mainly in Australia or its territories or contributing to the advancement of Australian science.

David Anson Buckingham was educated at the University of Canterbury, Christchurch, New Zealand, and the Australian National University, Canberra. He obtained his degree of Doctor of Philosophy from the A.N.U. in 1962, held a Post-doctoral Fellowship at the University of North Carolina in 1963, and became an Assistant Professor of Chemistry at Brown University in 1964. Subsequently he rejoined the Biological Inorganic Chemistry Unit in the John Curtin School of Medical Research, Canberra. Currently he is a member of the Research School of Chemistry in the Australian National University.

Dr. Buckingham has an established reputation as an inorganic chemist with specialized interests in the wide field of metal-containing co-ordination compounds. He is the author or part-author of more than 60 research papers.

In 1963 Dr. Buckingham discovered that a cobalt chelate could effect selective N-terminal hydrolysis of simple peptides. He has brilliantly investigated the scope and usefulness of this type of reaction. As a result, a new and valuable synthetic procedure, whereby glycine units can be added to the molecules of a variety of amino-acid and peptide esters, is now available to biological organic chemistry.

The implications of the full range of Dr. Buckingham's published works are far-reaching ; they extend beyond the traditional boundaries of inorganic chemistry, and touch many questions, concerning complex reaction mechanisms, enzymes, stereo-structures, ligand reactivities, etc., which are topically important.

Archibald D. Ollé Prize for 1970

This prize is awarded by the Council to a member of the Society who has submitted the best paper during the year.

Dr. Brian B. Guy receives this award for the papers entitled "Granitic Development and Emplacement in the Tumbarumba-Geehi District, N.S.W. : (i) The Foliated Granites ; (ii) The Massive Granites", published in Parts 1 and 2 of Volume 102 of the *Journal and Proceedings of the Royal Society of New South Wales*. The major section of the work for these papers was undertaken during the years 1961–1964, whilst Dr. Guy was enrolled for a Ph.D. degree at Sydney University. Additional investigations were carried out during 1967–1968.

Dr. Guy graduated B.Sc. with honours in 1961 and was awarded Ph.D. in 1964, both degrees from Sydney University.

From 1964–1965 he filled the post of Post-doctoral Research Associate, Crystallography Laboratory, University of Pittsburgh.

During the years 1966–1970 Dr. Guy was Senior Tutor in the Department of Geology and Geophysics at the University of Sydney.

Present research interests include the crystallography of phase transformations in silicates and sulphide minerals. Dr. Guy is now engaged as Research Petrologist with a private commercial venture.

Obituaries

Walter Lawry Waterhouse

Walter Lawry Waterhouse joined the Royal Society of New South Wales in 1919 and served as President in 1937. His distinguished career and service to the Society were recognized in the award of the Clarke Medal in 1943, the Society's Medal in 1948, and the James Cook Medal in 1952.

The following report on the life and work of Proiessor Waterhouse is published by kind permission of the Editor, *The Gazette, University of Sydney*, and of the writers of the obituary for the *Gazette*.

Walter Lawry Waterhouse, Emeritus Professor of Agriculture, died on the 9th December, 1969, at the age of eighty-two years. Professor Waterhouse, perhaps more than any other man, was responsible for the establishment of the Faculty of Agriculture of the University of Sydney as a recognized centre of teaching and research in agricultural science. He was one of its first eight graduates; he was the first recipient of the degree of Doctor of Science in Agriculture, and he was a member of its teaching staff from 1921 (when he was the third permanent appointment to the faculty) until his retirement in 1952.

In the eyes of almost two generations of students, Waterhouse epitomised the faculty. Without detracting in any way from the contribution of Sir Robert Watt, it can be said that "Wally", as he was affectionately known to these students, introduced them by precept and example to the essence of the scientific way of life. The fact that Sir Robert Watt, himself, acknowledged the key role which Waterhouse played in the development of the faculty is evidenced by the generous encomiums which he was wont to shower on Professor Waterhouse in the course of public addresses.

Waterhouse's primary teaching responsibility lay in three courses, plant pathology, genetics and plant breeding and agricultural botany, which formed part of the third-year curriculum in the faculty. Though scheduled as lectures at 11 a.m. Monday to Friday and two afternoons of practical work throughout the academic year, these courses tended to occupy the students' whole working hours, much to the great annoyance of other members of the teaching staff of the faculty. If the Monday lecture fell on a public holiday, it was invariably made up at some other time. Students could be found in the so-called "Plant Path. Laboratory" well before 9 a.m., at lunch-time, after 5 p.m., and at periods when they should have been attending other lectures or practical classes. Waterhouse's lectures were carefully and methodically prepared and delivered, but he firmly believed that scientists were made by doing things rather than by mere exposition. He set assignments for students which could never have been completed in the scheduled hours.

In the first term of the third year, for instance, students were required to prepare a set of permanently-mounted microscopic slides showing diseased plant tissue. Modern pedagogues are wont to dismiss such activity as just so much "busy work" that contributes little to scientific education, but the students who carried out Waterhouse's assignment learned a great deal not only about the techniques involved, but some of the older virtues of the pride of craftsmanship, the rewards of industry and the inadequacy of the second-best. Likewise, a significant component of second-term practical course consisted in inducing reluctant Drosophila flies to mate and in examining the genetic consequences.

Those were the days when members of the University were accustomed to seeing the wheat plot at the Ross Street entrance overrun each October with eager students learning from the master the art of crossing wheat; or Dr. Waterhouse leading the third-year class around the university grounds on a spring afternoon in search of the numerous pasture plants and weeds with which the grounds are still surprisingly well-endowed. With Black's *Flora of South Australia* under one arm and magnifying glass in his pocket, Wally would pause periodically to extol the characteristics of "little *Poa annua*" as he was wont to call it or some other plant which came to light in the course of these voyages of discovery. Alternatively, he would ask some student whose interest was waning under the influence of the afternoon sun to expound what he had been taught in the course of earlier perambulations.

Waterhouse was equally an exacting and yet inspiring task-master to those students who were fortunate enough to undertake specialised honours work with him in the final year. Whether it was the fact that for a long time in the faculty he had no rival as a research worker or because he selected his students carefully in the principle that investment of time and energy with the brighter students was likely to bring greater rewards, the fact is that many distinguished agricultural scientists, who have subsequently made their mark in the profession, passed through Waterhouse's hands and are the first to acknowledge his contribution to their subsequent success.

Waterhouse not only taught his students the virtues of industry; he practised them himself. What he accomplished in the way of teaching and research (with in many cases very primitive facilities), if reported on the A.U.C. forms, would bring cries of "impossible" from the administrators of today.

In his research activities, Professor Waterhouse made substantial contributions of both a fundamental and an applied nature. From the time of his appointment as Walter and Eliza Hall Agriculture Research Fllow in 1918 until his retirement in 1952, his research attention was focussed on wheat rust. In this he set the pattern for much of the work which is still going on in the faculty and which has over the years contributed so much to the reputation of the faculty as a research centre. At the time of his retirement the Research Committee of the University took the rather unusual step of writing to him and stating, " During the whole history of the University your work is considered by many to be one of its outstanding contributions ".

Waterhouse pioneered the assessment of annual changes in the pathogenic variability of the important cereal rusts. These studies, which are still being continued at this University, were, and are, of inestimable value to wheat breeders in planning programmes aimed at breeding varieties possessing resistance to stem and leaf rust. Perhaps Waterhouse's most notable original contribution was his demonstration that new races of wheat rust could arise on the alternate hosts of both stem and leaf rust of wheat—namely *Berberis vulgaris* and *Thalictrum sp.* respectively. The possibility of this phenomenon had earlier been hypothesised by E. C. Stakman at the University of Minnesota, but Stakman himself had been unable to demonstrate it. Waterhouse's investigation of the host range of the various sub-species of stem rust on Australian grasses indicated the importance of these hosts in the persistence over the summer of economically important rusts.

To the farmers of Australia, however, Waterhouse is chiefly remembered as a breeder of highly successful wheat varieties. In the late 1930's he released varieties such as Hofed and Fedweb, which rapidly gained acceptance among wheat-farmers. But it was the variety Gabo, released in 1945, which had the greatest impact on the wheat-growing industry both in Australia and abroad. It proved to be adaptable to a wide range of environmental conditions and possessed outstanding quality. At one period it was the leading variety grown in Australia and it also gave high yields in other parts of the world, including Mexico. Indeed, Dr. Borlaug, the Director of the Rockefeller wheat improvement programme in Mexico, records how, to his great embarrassment, he was given a new Chevrolet car by a grateful Mexican farmer to whom he had given some seed of the high-yielding Gabo. Though its popularity has now declined, Gabo has figured prominently in the pedigrees of wheat varieties more recently released on the local scene. Its broad adaptability has also resulted in its widespread use as a parent in the production of improved varieties in such countries as India and Mexico.

Walter Waterhouse was born in Maitland in 1887 and was educated at Sydney Boys' High School, of which his father was the first headmaster. He subsequently attended the Hawkesbury Agricultural College, and after spending two years in Fiji entered the Faculty of Agriculture in 1911. In 1914, on graduating with First-Class Honours and the University Medal, he was awarded the 1851 Science Exhibition, but he did not take it up, enlisting instead in the A.I.F. In 1916 he was awarded the Military Cross for conspicuous gallantry at Pozieres. He was seriously wounded in 1916 and invalided back to Australia. On his recovery he was awarded the Walter and Eliza Hall Agriculture Research Fellowship. During his tenure of this fellowship, he worked at the Imperial College of Science and Technology, from which he obtained the diploma, and at the University of Minnesota, where he established links with the American rust workers. On his return to Australia in 1921 he was appointed Lecturer and Demonstrator in the faculty. He was promoted to the grade of Reader in 1937 and to that of Research Professor in 1946.

In 1929 Waterhouse was awarded the degree of Doctor of Science in Agriculture for his work on wheat rust. He was the recipient of the Farrer Memorial Medal in 1938 and again in 1949, the Clarke Medal of the Royal Society in 1943, the medal of the Australian Institute of Agricultural Science in 1948, the James Cook Medal of the Royal Society in 1952 and the E. C. Stakman Medal from the University of Minnesota. On the establishment of the Australian Academy of Science, Waterhouse was elected a Fellow and in 1955 was made a Companion of St. Michael and St. George by Her Majesty the Queen. He retired from the service of the University in 1952 and subsequently became an emeritus professor.

As a person, Waterhouse was a dignified, self-effacing, extremely kind and devout man. In 1924 he married Dorothy Hazlewood, who with his three daughters survives him. His devotion to his family carried over to his relationships with his students. He had a tremendous personal interest in the subsequent careers of those students who passed through his hands, and was ever ready to give them the benefit of his advice when they requested it. He was the embodiment of courtesy and good manners. No man, so far as is known, ever succeeded in following Walter Waterhouse through a doorway, no matter how hard he tried. But despite his modesty and gentle manners, Waterhouse was a man of action when the occasion demanded it.

When future historians assess the contributions of scientists to the development of Australian agriculture in the twentieth century, there can be no doubt that the name of Waterhouse will be well to the fore. Indeed, it would not be surprising if he were given pride of place.

Albert Ernest Alexander

Albert Ernest Alexander was born at Ringwood, in Hampshire, England, on the 5th January, 1914. In 1934 he graduated B.Sc. with First-class Honours in Chemistry from the University of Reading and moved to the University of Cambridge, where, after taking his B.A. in 1935, he entered the research group headed by Professor (now Sir) Eric Rideal, F.R.S. His interests were already strongly directed toward colloid chemistry. The Ph.D. degree was awarded in 1938. For nine months he continued his Cambridge researches in the Department of Medical Chemistry of the University of Uppsala, in Sweden, but the outbreak of war made necessary a return to Britain. He became a Fellow of King's College in 1939, and in 1944 an Assistant Director of Research in the Department of Colloid Science.

During the war Alexander was a member of a Ministry of Supply " extra-mural " research team formed at Cambridge to consider problems associated with smoke-screening, incendiary devices, etc. ; most of such work was then classified as " secret ". He also managed to continue his own researches.

In 1947 the Chemical Society of London invited Alexander to give the annual Tilden Lecture. In this he surveyed the results of his years at Cambridge. The text of the lecture (" Some Applications of Surface Chemistry to Problems in Colloid Science ") reveals not only the experimental ingenuity of the author but also the wide usefulness of his techniques for the investigation of many biological and other systems in which proteins, enzymes, bile acids, soaps, etc., are present at air-water and oil-water interfaces.

In 1949, Alexander accepted the Foundation Professorship of Applied Chemistry in the New South Wales University of Technology (now the University of New South Wales) ; in 1956 he resigned and moved to the Chair of Physical Chemistry in the University of Sydney.

In both universities the departments formed around him gained international reputations for their activities in the general fields of surface chemistry and colloids. Alexander has been the author or part-author of more than 130 papers dealing directly or indirectly with chemical and physical phenomena and properties at surfaces and interfaces. He was the first to place the study of mono-layers at oil-water boundaries on a firm foundation, and to recognize the importance of hydrogen bonding as a factor often determining film stability.

Alexander had a conviction that knowledge should be fruitfully applicable to practical situations. This belief shows in the Liversidge Lecture (" Surface Chemistry in the Service of Man ") delivered to the 1954 meeting of A.N.Z.A.A.S., in his relations with C.S.I.R.O. and the industrial research associated concerned with bread and leather, and in many of the topics he chose for his own investigations (e.g. cattle dips, kidney stones, vegetable tanning, wool problems, etc.).

In 1960, Alexander was elected into the Fellowship of the Australian Academy of Science. He has loyally supported the Royal Australian Chemical Institute, being its N.S.W. President in 1955 and serving many years on its committees. He has been a member of the Royal Society of New South Wales since 1950.

In both the Australian universities where he was a Professor he conducted campaigns which drew public attention to situations which he thought were wrong or unwise. He spoke forthrightly—clearly, loudly, and often, with fear of no man. The first of these campaigns concerned the organization of the University of N.S.W., the last has concerned the Wyndham scheme for science teaching in schools. Alexander's 66-page booklet, " Education and Alchemy ", published in May, 1969, was to be his final contribution to an argument started back in 1966.

He had ideas, too, for the reforming of universities : they are set out in the A. D. Ross Lecture delivered at the University of Western Australia in March, 1965. Entitled " University Organization and Government : A Century Out-of-Date ? ", the case is developed for more democratic systems of control through elected representatives of the academic staff on all bodies involved in policy making, for more decentralized administrations, and for a scrapping of the present Faculty and Departmental divisions.

Yet behind and during all his public campaigning, Alexander remained a most agreeable colleague, never angry and never speaking in an unfairly critical way of another person. He had many friends in many countries.

He was amongst us in apparently normal health and vigour during August, 1969, when the I.U.P.A.C. Congress was meeting in Sydney. He became ill a few weeks later. Towards the end of the year a brain tumour was diagnosed, located, and operated upon, but without lasting success. He died peacefully in the evening of the 23rd May, 1970.

Joan Audrey Marsden

Joan Audrey Marsden was born in Sydney on 8th April, 1926, the oldest of seven children. She received her secondary education at St. Scholastica's College, Glebe, and gained a Diploma in Chemistry in 1957. Miss Marsden was elected a member of the Royal Society of New South Wales in 1954.

After 25 years' service with Dunlop Australia Ltd., Miss Marsden was presented with a gold watch and became a member of the exclusive " 25 Years and Over Club ". Joan Marsden had served 26 years with this firm at the time of her death on 5th August, 1970. Her hobbies were photography, learning of languages (in particular Japanese and Italian), also an interest in lapidary and travelling, the latter culminating in an extensive tour of the Pacific in 1969.

Members of the Society, April, 1971

The year of election to membership and the number of papers contributed to the Society's Journal are shown in brackets, thus : (1934 : P8). * indicates Life Membership.

Honorary Members

BLACKBURN, Sir Charles Bickerton, K.C.M.G., O.B.E., B.A., M.D., Ch.M., 152/177 Bellevue Road, Double Bay, 2028 (1960).

BRAGG, Sir Lawrence, O.B.E., F.R.S., The Royal Institution of Great Britain, 21 Albemarle Street, Piccadilly, London, W.1., England (1960).

BROWNE, William Rowan, D.Sc., F.A.A., 363 Edgecliff Road, Edgecliff, 2022 (1913 : P23 ; President 1932).

BURNET, Sir Frank Macfarlane, O.M., Kt., D.Sc., F.R.S., F.A.A., c/o Department of Microbiology, University of Melbourne, Parkville, Victoria, 3052 (1949).

FIRTH, Raymond William, D.Litt., M.A., Ph.D., Professor of Anthropology, University of London, 33 Southwood Avenue, London, N.6, 5.SA, England.

IREDALE, Thomas, D.Sc., 41 Addison Avenue, East Roseville, 2069 (1943).

NYHOLM, Sir Ronald Sydney, D.Sc., F.R.S., Professor of Inorganic Chemistry, University College, Gower Street, London, W.C.1, England (1940 : P26 ; President 1954).

O'CONNELL, Rev. Daniel J., S.J., D.Sc., Ph.D., F.R.A.S., Borgo S. Spirito 5, 00193 Rome, Italy (1953).

OLIPHANT, Sir Marcus L., K.B.E., Ph.D., B.Sc., F.R.S., F.A.A., Emeritus Professor, Research School of Physical Sciences, Australian National University, Canberra, A.C.T., 2600 (1948).

ROBINSON, Sir Robert, M.A., D.Sc., F.R.S., F.C.S., F.I.C., Professor of Chemistry, Oxford University, England (1948).

Members

ADAMSON, Colin Lachlan, B.Sc., 43 Holt Avenue, Cremorne, 2090 (1944).

ADKINS, George Earl, A.S.T.C., A.M.Aus.I.M.M., A.M.I.E.(Aust.), Dip.App.Sc., School of Mining Engineering, University of New South Wales, Kensington, 2033 (1960).

ADRIAN, Jeannette, B.Sc., Geological Survey of New South Wales, Box R216, P.O., Royal Exchange, N.S.W., 2000 (1970).

*ALBERT, Adrien, D.Sc., F.A.A., Professor of Medical Chemistry, Australian National University, Canberra, A.C.T., 2600 (1938 : P4).

ANDERSON, Geoffrey William, B.Sc., c/o Box 30, P.O Chatswood, 2067 (1948).

ANDREWS, Helen Elizabeth, B.Sc., 33 Hillcrest Avenue, Gladesville, 2111 (1970).

ANDREWS, Paul Burke, B.Sc., 50 Melbourne Road, East Lindfield, 2070 (1948 : P2).

ARNOT, Richard Hugh Macdonald, B.A., B.Sc.Agr., 3 Eleanor Court, Donvale, Victoria, 3111 (1963).

ASHLEY, Paul Michael, B.Sc., 2 Fernhill Avenue, Epping, 2121 (1970).

*AUROUSSEAU, Marcel, M.C., B.Sc., 229 Woodland Street, Balgowlah, 2093 (1919 : P2).

BADHAM, Charles David, M.B., B.S., D.R. (Syd.), M.C.R.A., " New Lodge ", 16 Ormonde Parade, Hurstville, 2220 (1962).

*BAKER, Stanley Charles, Ph.D., Department of Physics, University of Newcastle, 2300 (1934 : P4).

BANFIELD, James Edmund, M.Sc., Ph.D. (Melb.), Department of Organic Chemistry, University of New England, Armidale, 2350 (1963).

BANKS, Maxwell Robert, B.Sc., Department of Geology, University of Tasmania, Hobart, Tasmania, 7000 (1951).

BARWICK, Kathleen Harvison, 21 Lower Fort Street, Miller's Point, 2000 (1970).

BASDEN, Helena, B.Sc., Dip.Ed., 3 Norfolk Avenue, Collaroy Beach, 2097 (1970).

BASDEN, Kenneth Spencer, Ph.D., B.Sc., Department of Fuel, University of New South Wales, Kensington, 2033 (1951).

BAXTER, John Philip, K.B.E., C.M.G., O.B.E., Ph.D., F.A.A., Australian Atomic Energy Commission, 45 Beach Street, Coogee, 2034 (1950).

BEADLE, Noel Charles William, D.Sc., Professor of Botany, University of New England, Armidale, 2350 (1964).

BEALE, James Edgar Osborne, Solicitor, 166 Keira Street, Wollongong, 2500 (1968).

BEAVIS, Margaret, B.Sc., Dip.Ed., 3 Rosebank Avenue, Epping, 2121 (1961).

BELL, Alfred Denys Mervyn, B.Sc.(Hons.), School of Applied Geology, University of New South Wales, Kensington, 2033 (1960).

*BENTIVOGLIO, Sydney Ernest, B.Sc.Agr., 41 Telegraph Road, Pymble, 2073 (1926).

BINNS, Raymond Albert, B.Sc. (Syd.), Ph.D. (Cantab.), Professor of Geology, University of Western Australia, Nedlands, W.A., 6009 (1964 ; P1).

*BISHOP, Eldred George, Box 13, P.O. Mosman, 2088 (1920).

BLANKS, Fred Roy, B.Sc., 19 Innes Road, Greenwich, 2065 (1948).

BLAYDEN, Ian Douglas, B.Sc.(Hons.), 73 Abingdon Road, Roseville, 2069 (1966).

BOLT, Bruce Alan, Ph.D., Professor of Seismology, Department of Geology and Geophysics, University of California, Berkeley, U.S.A. (1956 : P3).

BOOKER, Frederick William, D.Sc., 11 Boundary Street, Roseville, 2069 (1951 : P1).

Booth, Robert Kerril, B.Sc., Dip.Ed. (Syd.), Science Teacher, 6 Jellicoe Street, Hurstville, 2220 (1964).

Bradley, Edgar David, M.B., B.S. (Syd.), D.O., Ophthalmologist, 107 Faulkner Street, Armidale, 2350 (1964).

Branagan, David Francis, M.Sc., Ph.D., Senior Lecturer, Department of Geology and Geophysics, University of Sydney, 2006 (1967 : P2).

Brennan, Edward, B.E.(App. Geology), P.O. Box 5, Mount Morgan, Queensland, 4714 (1962).

Bridges, David Somerset, 19 Mount Pleasant Avenue, Normanhurst, 2076 (1952).

*Briggs, George Henry, D.Sc., 13 Findlay Avenue, Roseville, 2069 (1919 : P1).

Brown, Desmond J., D.Sc., Ph.D., Department of Medical Chemistry, Australian National University, Canberra, A.C.T., 2600 (1942).

Brown, Kenneth John, A.S.T.C., A.R.A.C.I., 3 Karda Place, Gymea, 2227 (1963).

Brown, John Percival, 40 Woolgoolga Street, North Balgowlah, 2093 (1969).

Browne, Ida Alison, D.Sc., 363 Edgecliff Road, Edgecliff, 2227 (1935 : P12 ; President 1953).

Bruce, Colin Frank, D.Sc., Physicist, 17 Redan Street, Mosman, 2088 (1964).

Bryan, John Hamilton, B.Sc.(Hons.), Geologist, 9/90 Raglan Street, Mosman, 2088 (1968).

Buckley, Lindsay Arthur, B.Sc., 131 Laurel Avenue, Chelmer, Queensland, 4075 (1940).

Bullen, Keith Edward, D.Sc., F.R.S., F.A.A., Professor of Applied Mathematics, University of Sydney, 2006 (1946 : P3).

Burg, Raymond Augustine, Senior Analyst, Department of Mines, N.S.W. ; p.r. 17 Titania Street, Randwick, 2031 (1960).

Burman, Ronald Rion, M.Sc., Ph.D., Physics Department, University of Western Australia, Nedlands, W.A., 6009 (1970 : P2).

Burns, Bruce Bertram, D.D.S., Dental Surgeon, Suite 607, T. & G. Building, Park Street, Sydney, 2000 (1961).

Butland, Gilbert James, B.A., Ph.D., F.R.G.S., Professor of Geography, University of New England, Armidale, 2350 (1961).

Callender, John Hardy, Schoolteacher, Lot 101, Dallas Street, Mount Ousley, 2519 (1969).

Cameron, John Craig, M.A., B.Sc. (Edin.), D.I.C., 15 Monterey Street, Kogarah, 2217 (1957).

Campbell, Ian Gavan Stuart, B.Sc., c/o Barker College, Hornsby, 2077 (1955).

*Carey, Samuel Warren, D.Sc., Professor of Geology, University of Tasmania, Hobart, Tasmania, 7000 (1938 : P2).

Cavill, George William Kenneth, Ph.D., D.Sc., Professor of Organic Chemistry, University of New South Wales, Kensington, 2033 (1944).

*Chaffer, Edric Keith, 66 Victoria Avenue, Chatswood, 2067 (1954).

*Chalmers, Robert Oliver, Australian Museum, College Street, Sydney, 2000 (1933 : P1).

Chambers, Maxwell Clark, B.Sc., 58 Spencer Street, Killara, 2071 (1940).

Chiarella, Carl, M.Sc., 28 Curban Street, Balgowlah, 2093 (1967).

*Churchward, John Gordon, B.Sc.Agr., Ph.D., 12 Glen Shian Lane, Mount Eliza, Victoria, 3930 (1935 : P2).

Clancy, Brian Edward, M.Sc., Australian Atomic Energy Commission, Lucas Heights, 2232 (1957).

Coalstad, Stanton Ernest, B.Sc., Metallurgical Chemist, 16 Station Street, Marrickville, 2204 (1961).

Cohen, Samuel Bernard, M.Sc., 46 Wolseley Road, Point Piper, 2027 (1940).

Cole, Edward Ritchie, B.Sc., Associate Professor of Organic Chemistry, University of New South Wales, Kensington, 2033 (1940 : P2).

Cole, Joyce Marie (Mrs.), B.Sc., 7 Wolsten Avenue, Turramurra, 2074 (1940 : P1).

Collett, Gordon, B.Sc., 16 Day Road, Cheltenham, 2119 (1940).

Collins, Angus Robert, B.Sc., 16 Hull Road, Beecroft, 2119 (1969).

Conaghan, Hugh Francis, M.Sc., Chief Analyst, Department of Mines, N.S.W. ; p.r. 104 Lancaster Avenue, West Ryde, 2114 (1960).

Conolly, John Robert, B.Sc. (Syd.), Ph.D. (N.S.W.), Department of Geology, University of South Carolina, Columbia, South Carolina, 20908, U.S.A. (1963 : P4).

Cook, Alan Cecil, M.A. (Cantab.), Wollongong University College ; p.r. Lot 19, Dallas Street, Mt. Ousley, 2519 (1968 : P2).

Cook, Cyril Lloyd, Ph.D., c/o Propulsion Research Laboratories, Box 1424H, G.P.O., Adelaide, S.A., 5001 (1948).

Cortis–Jones, Beverley, M.Sc., 65 Peacock Street, Seaforth, 2092 (1940).

Coss, Paul, B.Sc., 2 Alarna Place, St. Ives, 2075 (1963).

Cox, Charles Dixon, B.Sc., 51 Darley Street, Forestville, 2087 (1964).

Crawford, Edwin John, B.E., 7a Battle Boulevarde, Seaforth, 2092 (1955).

*Cresswick, John Arthur, 101 Villiers Street, Rockdale, 2216 (1921 : P1).

Croft, James Bernard, B.E., Ph.D., Watts, Griffis and McQuat (Aust.) Pty. Ltd., 56 Pitt Street, Sydney, 2000 (1956).

Crook, Keith Alan Waterhouse, Ph.D., Geology Department, Australian National University, Canberra, A.C.T., 2600 (1954 : P9).

Cruikshank, Bruce Ian, B.Sc.(Hons.), 16 Arthur Street, Punchbowl, 2196 (1965).

Davies, George Frederick, 57 Eastern Avenue, Kingsford, 2032 (1952).

Davis, Gwenda Louise, B.Sc., Ph.D., Associate Professor, Department of Botany, University of New England, Armidale, 2350 (1961).

Day, Alan Arthur, Ph.D., F.R.A.S., Department of Geology and Geophysics, University of Sydney, 2006 (1952 : P1 ; President 1965).

Denton, Leslie A., Bunarba Road, Miranda, 2228 (1955).

Divnick, George, Engineer Agronom. (Yugoslavia), Engineering Analyst, 90 Highclere Avenue, Punchbowl, 2196 (1960).

Doherty, Gregory, B.Sc.(Hons.), Australian Atomic Energy Commission, Lucas Heights, 2232 (1963).

*Donegan, Henry Arthur James, M.Sc., F.R.A.C.I., F.R.I.C., 18 Hillview Street, Sans Souci, 2219 (1928 : P1 ; President 1960).

Drake, Lawrence Arthur, B.A.(Hons.), B.Sc., Director, Riverview College Observatory, Riverview, 2066 (1962 : P1).

Dulhunty, John Allan, D.Sc., Department of Geology and Geophysics, University of Sydney, 2006 (1937 : P22 ; President 1947).

Edgar, Joyce Enid (Mrs.), B.Sc., 12 Calvert Avenue, Killara, 2071 (1951).
*Elkin, Adolphus Peter, C.M.G., Ph.D., Emeritus Professor, 15 Norwood Avenue, Lindfield, 2070 (1934: P4; President 1940).
Ellison, Dorothy Jean, M.Sc., 45 Victoria Street, Roseville, 2069 (1949).
Emerson, Donald Westland, M.Sc., B.E.(App.Geo.), Department of Geology and Geophysics, University of Sydney, 2006 (1966: P1).
Emmerton, Henry James, B.Sc., 37 Wangoola Street, East Gordon, 2072 (1940).
Engel, Brian Adolph, M.Sc., Geology Department, University of Newcastle, 2308 (1961: P1).
Evans, Phillip Richard, B.A. (Oxon.), Ph.D. (Bristol), Esso Palynology Laboratory, School of Applied Geology, University of New South Wales, 2033 (1968).

Facer, Richard Andrew, B.Sc.(Hons.), Department of Geology, Wollongong University College, Wollongong, 2500 (1965: P1).
Fallon, Joseph James, Loch Maree Place, Vaucluse, 2030 (1950).
Fayle, Rex Dennes Harris, Pharmaceutical Chemist, 141 Jeffrey Street, Armidale, 2350 (1961).
Fisher, Robert, B.Sc., 3 Sackville Street, Maroubra, 2035 (1940).
Fleischmann, Arnold Walter, 5 Erang Street, Carss Park, 2221 (1956: P1).
*Fletcher, Harold Oswald, M.Sc., 131 Milson Road, Cremorne, 2090 (1933).
Fletcher, Neville Horner, B.Sc., M.A., Ph.D., Professor of Physics, University of New England, Armidale, 2350 (1961).
Flood, Peter Gerard, B.Sc.(Hons.), P.O. Box 52, Spit Junction, 2088 (1969).
Foldvary, Gabor Zoltan, B.Sc., 267 Beauchamp Road, Matraville, 2036 (1965).
French, Oswald Raymond, 6 Herberton Avenue, Hunters Hill, 2110 (1951).
Friend, James Alan, Ph.D., Professor of Chemistry, University of West Indies, St. Augustine, Trinidad, W.I. (1944: P2).

Galloway, Malcolm Charles, B.Sc., Geologist, c/o Department of Geology, University of South Carolina, Columbia, South Carolina, 29208, U.S.A. (1960: P1).
Garretty, Michael Duhan, D.Sc., Box 763, G.P.O., Melbourne, Victoria, 3001 (1935: P2).
Gascoigne, Robert Mortimer, Ph.D., Department of Philosophy, University of New South Wales, Kensington, 2033 (1939: P4).
Gellert, Emery, Dr.phil. (Basle), 38 Toorak Avenue, Wollongong, 2500 (1968).
Gibbons, George Studley, M.Sc., 8 Marsh Place, Lane Cove, 2066 (1966).
Gibson, Neville Allan, Ph.D., 103 Bland Street, Ashfield, 2131 (1942: P6).
*Gill, Stuart Frederic, 45 Neville Street, Marrickville, 2204 (1947).
Glasson, Kenneth Roderick, B.Sc., Ph.D., 70 Beecroft Road, Beecroft, 2119 (1948: P1).
Golding, Henry George, M.Sc., Ph.D., School of Applied Geology, University of New South Wales, Kensington, 2033 (1953: P5).
Goodwin, Robert Henry, B.Sc., M.Sc., Geologist, Department of Geology and Geophysics, University of Sydney, 2006 (1968: P1).
Gordijew, Gurij, Engineer Hydro Geology (Inst. Hydro Meteorology in Moscow, 1936), 41 Abbotsford Road, Homebush, 2140 (1962).
Gow, Neil Neville, B.Sc.(Hons.), 168 Mica Street, Broken Hill, 2880 (1966).
Grahame, Mervyn Ernest, B.A., Schoolteacher, 161 Parry Street, Hamilton, 2303 (1959).
Grant, John Guerrato, Dip.Eng., 37 Chalayer Street, Rose Bay, 2029 (1961).
Gray, Charles Alexander Menzies, B.E., M.E., Professor of Engineering, Wollongong University College, Wollongong, 2500 (1948: P1).
Gray, Noel Macintosh, B.Sc., 1 Centenary Avenue, Hunters Hill, 2110 (1952).
Griffin, Derek K., B.Sc., Lot 435, McDougall Avenue, Baulkham Hills, 2153 (1969).
Griffin, Russell John, B.Sc., Unit 3, 17–19 Grasmere Road, Cremorne, 2090 (1952).
Griffith, James Langford, B.A., M.Sc., Associate Professor of Mathematics, University of New South Wales, Kensington, 2033 (1952: P17; President 1958).
Groden, Charles Mark, M.Sc., c/o Department of Mathematics and Sciences, Florida Institute of Technology, Melbourne, Fla., 32901, U.S.A. (1957: P3).
Gutmann, Felix, Ph.D., 70a Victoria Road, West Pennant Hills, 2120 (1946: P1).
Gutsche, Herbert William, B.Sc., School of Earth Sciences, Macquarie University, North Ryde, 2133 (1961).
Guy, Brian Bertram, B.Sc. (Syd.), Ph.D. (Syd.), c/o Union Miniere Development and Mining Corporation, Golden Fleece House, 100 Pacific Highway, North Sydney, N.S.W., 2060 (1968: P2).

Hackett, Ian Harry, B.Sc.(Chem.Eng.), Research Chemist, 5 Wyralla Avenue, Epping, 2121 (1968).
Hall, Brian Keith, Ph.D. (U.N.E.), B.Sc.(Hons.), Assistant Professor of Biology, Dalhousie University, Halifax, Nova Scotia, Canada (1967).
Hall, Francis Michael, Ph.D., M.Sc., A.S.T.C., Chemistry Department, Wollongong University College, Wollongong, 2500 (1968).
*Hall, Norman Frederick Blake, M.Sc., 16a Wharf Road, Longueville, 2066 (1934).
Hamilton, Lloyd, B.E., c/o Mining Geology Department, Royal School of Mines, Imperial College, London, S.W.7 (1965: P1).
Hancock, Harry Sheffield, M.Sc., 16 Koora Avenue, Wahroonga, 2079 (1955).
Hanlon, Frederick Noel, B.Sc., 21/43 Musgrave Street, Mosman, 2088 (1940: P14; President 1957).
Hardwick, Reginald Leslie, B.Sc., 12/38–40 Meadow Crescent, Meadowbank, 2114 (1968).
Harper, Arthur Frederick Alan, M.Sc., National Standards Laboratory, University Grounds, City Road, Chippendale, 2008 (1936: P1; President 1959).
Harris, Clive Melville, Ph.D., Associate Professor of Chemistry, University of New South Wales, Kensington, 2033 (1948: P6).
Harrison, Ernest John Jasper, B.Sc., 8 Fernhurst Avenue, Cremorne, 2090 (1946).
Haydon, Sydney Charles, M.A., Ph.D., F.Inst.P., Professor of Physics, University of New England, Armidale, 2351 (1965).
*Hayes, Daphne (Mrs.), B.Sc., 412/108 Elizabeth Bay Road, Elizabeth Bay, 2001 (1943).

HELBY, Robin James, M.Sc., 344 Malton Road, North Epping, 2121 (1966 : P2).

HIGGS, Alan Charles, c/o Colonial Sugar Refining Co. Ltd., Building Material Division, 1–7 Bent Street, Sydney, 2000 (1945).

HILL, Dorothy, D.Sc., F.R.S., F.A.A., Professor of Geology and Mineralogy, University of Queensland, St. Lucia, Brisbane, 4067 (1938 : P6).

HILL, Helen Campbell (Mrs.), 14 Miowera Road, North Turramurra, 2074 (1951).

HODGINS, Reginald William, A.S.T.C., B.Sc., Engineering Analyst, Department of Main Roads, N.S.W. ; p.r. Lot 89, Savoy Street, Port Macquarie, 2444 (1967).

*HOGARTH, Julius William, B.Sc., 4 " Hillsmore ", 20 Joubert Street, Hunters Hill, 2110 (1948 : P6).

HORNE, Allan Richard, 149A Hawkesbury Road, North Springwood, 2777 (1960).

HOWE, Bernard Adrian, c/o Exploration Physics, 265 Old Canterbury Road, Dulwich Hill, 2203 (1963).

HUMPHRIES, John William, B.Sc., Physicist, National Standards Laboratory, University Grounds, City Road, Chippendale, 2008 (1959 : P1 ; President 1964).

*HYNES, Harold John, D.Sc.Agr., 7 Futuna Street, Hunters Hill, 2110 (1923 : P3).

IRVING, Anthony J., B.Sc.(Hons.) (Syd.), Department of Geophysics and Geochemistry, Australian National University, Canberra, 2600 (1970).

JAEGER, John Conrad, D.Sc., F.A.A., Geophysics Department, Australian National University, Canberra, A.C.T., 2600 (1942 : P1).

JENKINS, Thomas Benjamin Huw, Ph.D., Department of Geology and Geophysics, University of Sydney, 2006 (1956).

JONES, James Rhys, 25 Boundary Road, Mortdale, 2223 (1959).

*JOPLIN, Germain Anne, D.Sc., Geophysics Department, Australian National University, Canberra, A.C.T., 2600 (1935 : P10).

KALOKERINOS, Archivides, M.B., B.S., F.A.C.M.T., Walgett Street, Collarenebri, 2383 (1970).

KEANE, Austin, Ph.D., Professor of Mathematics, Wollongong University College, Wollongong, 2500 (1955 : P4 ; President 1968).

KIMBLE, Jean Annie, B.Sc., 2/163 Homer Street, Earlwood, 2206 (1943).

*KIRCHNER, William John, B.Sc., " Fairways ", Linkview Avenue, Blackheath, 2785 (1920).

KITAMURA, Torrence Edward, B.A., B.Sc.Agr., 18 Pullbrook Avenue, Hornsby, 2077 (1964).

KOCH, Leo E., D.Phil.Habil., School of Applied Geology, University of New South Wales, Kensington, 2033 (1948).

KOKOT, Ernest, B.Sc., Ph.D. (N.S.W.), A.S.T.C., A.R.A.C.I., 4 Cosgrove Avenue, Keiraville, 2500 (1969).

KORBER, Peter Henry Wilibald, B.Sc., Analytical Chemist, 7/24, Cammeray Road, Cammeray, 2062 (1968).

KRYSKO v. TRYST, Maren (Mrs.), B.Sc., Grad.Dip., School of Applied Geology, University of New South Wales, Kensington, 2033 (1959).

LACK, N. Edith (Mrs.), 471 Sailors Bay Road, Northbridge, 2063 (1968).

LANDECKER, Kurt, D.Ing. (Berlin), Department of Physics, University of New England, Armidale, 2351 (1961).

LASSAK, Erich Vincent, M.Sc. (N.S.W.), B.Sc.(Hons.), A.S.T.C., Research Chemist, 167 Berowra Waters Road, Berowra, 2081 (1964 : P2).

LAWRENCE, Laurence James, D.Sc., Ph.D., Associate Professor, School of Applied Geology, University of New South Wales, Kensington, 2033 (1951 : P4).

LEAVER, Gaynor Eiluned (Mrs.), B.Sc. (Wales), F.G.S. (Lond.), 30 Ingalara Avenue, Wahroonga, 2076 (1961).

LE FEVRE, Raymond James Wood, D.Sc., F.R.S., F.A.A., Professor of Chemistry ; p.r. 6 Aubrey Road, Northbridge, 2063 (1947 : P4 ; President 1961).

*LEMBERG, Max Rudolph, D.Phil., F.R.S., F.A.A., Assistant Director, Institute of Medical Research, Royal North Shore Hospital, St. Leonards, 2065 (1936 : P3 ; President 1955).

*LIONS, Francis, Ph.D., 93A Mona Vale Road, Pymble, 2073 (1929 : P56 ; President 1946).

LIONS, Jean Elizabeth (Mrs.), B.Sc., 93A Mona Vale Road, Pymble, 2073 (1940).

LLOYD, James Charles, B.Sc., 1 Spurwood Road, Turramurra, 2074 (1947).

LOCKWOOD, William Hutton, B.Sc., Institute of Medical Research, Royal North Shore Hospital, St. Leonards, 2065 (1940 : P1).

LOVERING, John Francis, Ph.D., Professor of Geology, University of Melbourne, Parkville, Victoria, 3052 (1951 : P4).

LOW, Angus Henry, Ph.D., Associate Professor, Department of Applied Mathematics, University of New South Wales, Kensington, 2033 (1950 : P4 ; President 1967).

LOWENTHAL, Gerhard C., Ph.D., M.Sc., 17 Gnarbo Avenue, Carss Park, 2221 (1959).

LYONS, Lawrence Ernest, Ph.D., Professor of Chemistry, University of Queensland, St. Lucia, Brisbane, 4067 (1948 : P3).

MACCOLL, Allan, M.Sc., Department of Chemistry, University College, Gower Street, London, W.C.1, England (1939 : P4).

McCARTHY, Daryl John, F.R.M.S., 29 Johnson Street, Chatswood, 2067 (1969).

McCARTHY, Frederick David, Dip.Anthr., Principal, Australian Institute of Aboriginal Studies, Box 553, City P.O., Canberra, A.C.T., 2600 (1949 : P1 ; President 1956).

McCOY, William Kevin, 86 Ave Da Republica, Macao, via Hong Kong (1943).

McCULLAGH, Morris Behan (1950).

McELROY, Clifford Turner, Ph.D., M.Sc., 6 Boyne Place, Killarney Heights, Forestville, 2087 (1949 : P2).

McGREGOR, Gordon Howard, 4 Maple Avenue, Pennant Hills, 2120 (1940).

McKAY, Maxwell Herbert, M.A., Ph.D., Professor of Mathematics, University of Papua and New Guinea, Boroko, T.P.N.G. (1956 : P1).

McKERN, Howard Hamlet Gordon, M.Sc., F.R.A.C.I., Museum of Applied Arts and Sciences, Harris Street, Broadway, 2007 (1943 : P12 ; President 1963).

McMAHON, Barry Keys, B.Sc., 58 Bent Street, Lindfield, 2070 (1961).

McMAHON, Patrick Reginald, Ph.D., Professor of Wool Technology, University of New South Wales, Kensington, 2033 (1947).

McNAMARA, Barbara Joyce (Mrs.), M.B., B.S., c/o Dr. B. Burfitt, Callan Park Hospital, Rozelle, 2039 (1943).

MacKellar, Michael John Randal, B.Sc.Agr. (Syd.), B.A.(Hons.) (Oxon.), 21 Mulgowrie Crescent, Balgowlah Heights, 2093 (1968).

Magee, Charles Joseph, D.Sc.Agr., 57 Florida Road, Palm Beach, 2108 (1947 : P2 ; President 1952).

Majstrenko, Petro, M.Sc. (Copenhagen), Lecturer in Mathematics, University of New England, Armidale, 2351 (1966).

Males, Pamela Ann, 13 Gelding Street, Dulwich Hill, 2203 (1951).

Manser, Warren, B.Sc. (Syd.), Department of Earth Sciences, University of Papua and New Guinea, Boroko, T.P.N.G. (1964).

Marshall, Charles Edward, D.Sc., Professor of Geology and Geophysics, University of Sydney, 2006 (1949 : P1).

Martin, Peter Marcus, M.Sc.Agr., Dip.Ed., Lecturer, Botany Department, University of Sydney, 2006 (1968).

Meares, Harry John Devenish, 9 Raymond Road, Neutral Bay, 2089 (1949).

*Mellor, David Paver, Professor of Inorganic Chemistry, University of New South Wales, Kensington, 2033 (1929 : P25 ; President 1941).

Millership, William, M.Sc., 18 Courallie Avenue, Pymble, 2073 (1940).

Minty, Edward James, M.Sc., B.Sc., Dip.Ed., 155 Willoughby Road, Naremburn, 2065 (1951 : P2).

Moelle, Konrad Heinrich Richard, Absolutorium (Innsbruck), Ph.D. (Innsbruck), Lecturer in Geology, University of Newcastle ; p.r. 2 Hillcrest Road, Merewether, 2308 (1967).

Moore, Laurence Frederick, B.A. (N.E.), Teacher, 21 Cavendish Avenue, Blacktown, 2148 (1967).

Morrissey, Matthew John, M.B., B.S., 152 Marsden Street, Parramatta, 2150 (1941).

Mort, Francis George Arnot, 29 Preston Avenue, Fivedock, 2046 (1934).

Mosher, Kenneth George, B.Sc., 9 Yirgella Avenue, Killara, 2071 (1948).

Moye, Daniel George, B.Sc., 36 Sylvander Street, North Balwyn, Victoria, 3104 (1944).

*Murphy, Robert Kenneth, Dr.Ing.Chem., 68 Pindari Avenue, North Mosman, 2088 (1915).

Murray, Bede Edward, B.A., Lecturer in Mathematics, Wollongong Teachers' College, Wollongong ; p.r. 18 Bulwarra Street, Keiraville, 2500 (1969).

Murray, Jascha Ann (Mrs.), M.Sc., 42 Sherlock Close, Cambridge, England (1961).

Nasher, Beryl, Ph.D., Professor of Geology, University of Newcastle, 2308 ; p.r. 15 Princeton Avenue, Adamstown Heights, 2289 (1946 : P2).

*Naylor, George Francis King, Ph.D., Department of Psychology and Philosophy, University of Queensland, St. Lucia, Brisbane, 4067 (1930 : P7).

*Neuhaus, John William George, M.Sc., 32 Bolton Street, Guildford, 2161 (1943 : P1 ; President 1969).

*Newman, Ivor Vickery, Ph.D., 1 Stuart Street, Wahroonga, 2076 (1932).

Ninham, Barry William, Ph.D., M.Sc., Department of Mathematics, Research School of Physical Sciences, Australian National University, Canberra, A.C.T., 2600 (1970).

Noakes, Lyndon Charles, B.A., Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T., 2601 (1945 : P1).

*Noble, Robert Jackson, Ph.D., 32a Middle Harbour Road, Lindfield, 2070 (1920 : P4 ; President 1934).

O'Farrell, Antony Frederic Louis, A.R.C.Sc., B.Sc., Professor of Zoology, University of New England, Armidale, 2351 (1961).

O'Halloran, Peter Joseph, B.Sc., Dip.Ed., M.Sc., 52 Bindaga Street, Aranda, A.C.T., 2614 (1968).

Old, Adrian Noel, B.A., B.Sc.Agr., Senior Chemist, N.S.W. Department of Agriculture ; p.r. 13 Fallon Street, Rydalmere, 2116 (1947).

Oxenford, Reginald Augustus, B.Sc., 10 Greaves Street, Grafton, 2460 (1950).

Packham, Gordon Howard, Ph.D., Department of Geology and Geophysics, University of Sydney, 2006 (1951 : P4).

Pearce, Marcelle Gordon Ivy, M.Sc. (Melb.), Experimental Officer, C.S.I.R.O., Division of Applied Physics ; p.r. 108 Burns Road, Wahroonga, 2076 (1967).

Pearson, Robert John Butler, Metallurgist, 25 Burling Avenue, Fairy Meadow, 2519 (1969).

*Penfold, Arthur Ramon, Flat 516, Baroda Hall, 6a Birtley Place, Elizabeth Bay, 2011 (1920 : P82 ; President 1935).

Perry, Hubert Roy, B.Sc., 74 Woodbine Street, Bowral, 2576 (1948).

Peterson, George Arthur, B.Sc., B.E., 55 Roseville Avenue, Roseville, 2069 (1966).

Philip, Graeme Maxwell, M.Sc. (Melb.), Ph.D. (Cantab.), F.G.S., Professor of Geology, University of New England, Armidale, 2351 (1964 : P1).

Phillips, Marie Elizabeth, Ph.D., 16 Lawley Place, Deakin, A.C.T., 2600 (1938).

Phipps, Charles Verling Gayer, Ph.D., Department of Geology and Geophysics, University of Sydney, 2006 (1960).

Pickett, John William, M.Sc. (N.E.), Dr.phil.nat. (Frankfurt/M), Palaeontologist, N.S.W. Geological Survey, Mining Museum, 28 George Street, North, Sydney ; p.r. 112 Blues Point Road, McMahons Point, 2060 (1965).

Pinwill, Norman, B.A., The Scots College, Victoria Road, Bellevue Hill, 2023 (1946).

Poggendorff, Walter Hans George, B.Sc.Agr., 85 Beaconsfield Road, Chatswood, 2067 (1949).

Pollard, John Percival, M.Sc. (N.S.W.), Dip.App.Chem. (Swinburne), Mathematician, Australian Atomic Energy Commission ; p.r. 25 Nabiac Avenue, Gymea, 2227 (1963).

Pratt, Boyd Thomas, B.Sc.(Hons.) (N.S.W.), 11 Harbourne Road, Kingsford, 2032 (1967).

Priestley, John Henry, M.B., B.S., B.Sc., Medical Practitioner, 137 Dangar Street, Armidale, 2350 (1961).

Prokhovnik, Simon Jacques, M.A., B.Sc., School of Mathematics, University of New South Wales, Kensington, 2033 (1956 : P3).

*Proud, John Seymour, B.E., Finlay Road, Turramurra, 2074 (1945).

Puttock, Maurice James, B.Sc.(Eng.), M.Inst.P., C.S.I.R.O. National Standards Laboratory, University Grounds, City Road, Chippendale ; p.r. 2 Montreal Avenue, Killara, 2071 (1960).

*Quodling, Florrie Mable, Ph.D., B.Sc., 145 Midson Road, Epping, 2121 (1935 : P5).

Rade, Janis, M.Sc., Box 28A, 601 St. Kilda Road, Melbourne, 3004 (1953 : P6).

Ramm, Eric John, Experimental Officer, Australian Atomic Energy Commission, Lucas Heights, 2232 (1959).

Rattigan, John Herbert, Ph.D., M.Sc., Geophoto Resources Consultant, 30 Herschel Street, Brisbane, Queensland, 4000 (1966 : P2).

*Rayner, Jack Maxwell, O.B.E., B.Sc., 5 Tennyson Crescent, Forrest, Canberra, A.C.T., 2603 (1931 : P1).

Read, Harold Walter, B.Sc. (1962 : P1).

Reichel, Alex, Ph.D., M.Sc., Department of Applied Mathematics, University of Sydney (1957 : P4).

Rice, Thomas Denis, B.Sc., 5 Harden Road, Artarmon, 2064 (1964).

Rigby, John Francis, B.Sc. (Melb.), Geological Survey of Queensland, 2 Edward Street, Brisbane, Queensland, 4000 (1963).

Riggs, Noel Victor, B.Sc. (Adel.), Ph.D. (Cantab.), F.R.A.C.I., Associate Professor of Organic Chemistry, University of New England, Armidale, 2350 (1961).

Riley, Steven James, B.Sc.(Hons.), Department of Geography, University of Sydney, N.S.W., 2006 (1969).

Ritchie, Arthur Sinclair, M.Sc., Associate Professor of Geology, University of Newcastle, 2308 (1947 : P2).

Ritchie, Ernest, D.Sc., F.A.A., Professor of Chemistry, Chemistry Department, University of Sydney, 2006 (1939 : P19).

Robbins, Elizabeth Marie (Mrs.), M.Sc., 21 Palm Street, St. Ives, 2075 (1939 : P3).

Roberts, Herbert Gordon, B.Sc., Anaconda Aust., Inc., 34 Hunter Street, Sydney, 2000 (1957).

Roberts, John, Ph.D., School of Applied Geclogy, University of New South Wales, Kensington, N.S.W., 2033 (1961 ; P3).

Robertson, William Humphrey, B.Sc., c/o Sydney Observatory, Sydney, 2000 (1949 : P30).

Robinson, David Hugh, A.S.T.C., Chemist, 12 Robert Road, West Pennant Hills, 2120 (1951).

Rod, E.

Rosenbaum, Sidney, 5 Eton Road, Lindfield, 2070 (1940).

Rosenthal-Schneider, Ilse, Ph.D., 48 Cambridge Avenue, Vaucluse, 2030 (1948).

Ross, Victoria (Mrs.), M.Sc., B.Sc.(Hons.), " Meroo ", Mill Road, Kurrajong, 2758 (1960).

Rountree, Phyllis Margaret, D.Sc., 7 Windsor Street, Paddington, 2021 (1945).

Royle, Harold George, M.B., B.S. (Syd.), 161 Rusden Street, Armidale, 2350 (1961).

Runnegar, Bruce, B.Sc., Ph.D., Department of Geology, University of New England, Armidale, 2351 (1970).

Sampson, Stephen Sydney, 16 Amelia Place, North Narrabeen, 2101 (1970).

Sappal, Krishna Kumar, M.Sc., Geologist, c/o Department of Geology, Nagpur University, Nagpur, India (1966).

*Scammell, Rupert Boswood, B.Sc., 10 Buena Vista Avenue, Clifton Gardens, 2088 (1920).

Scheibner, Viera, Dr.Nat.Rer., Geologist, 10 Landy Place, Beacon Hill, 2100 (1970).

Scholer, Harry Albert Theodore, M.Eng., Civil Engineer, c/o Harbours and Rivers Branch, Public Works Department, N.S.W., Phillip Street, Sydney, 2000 (1960).

See, Graeme Thomas, B.Sc., School of Nuclear Chemistry, University of New South Wales, Kensington, 2033 (1949).

Selby, Edmond Jacob, P.O. Box 121, North Ryde, 2113 (1933).

*Sharp, Kenneth Raeburn, B.Sc., Engineering Geology Branch, Snowy Mountains Authority, North Cooma, 2629 (1948).

Shaw, Stirling Edward, B.Sc.(Hons.), Ph.D., F.G.A.A., School of Earth Sciences, Macquarie University, North Ryde, 2113 (1966).

Sherrard, Kathleen Margaret (Mrs.), M.Sc., 43 Robertson Road, Centennial Park, 2021 (1936 : P6).

Sherwin, Lawrence, B.Sc.(Hons.) (Syd.), 186 Sylvania Road, Miranda, 2228 (1967).

Simmons, Lewis Michael, Ph.D., The Scots College, Victoria Road, Bellevue Hill, 2023 (1945 : P3).

Sims, Kenneth Patrick, B.Sc., 25 Fitzpatrick Avenue East, French's Forest, 2086 (1950 : P15).

Slade, Milton John, B.Sc., Dip.Ed. (Syd.), M.Sc. (N.E.), Armidale Teachers' College, Armidale, 2350 (1952).

Smith, Ann Ruth (Mrs.), B.Sc.(Hons.), Box 134, P.O., Queenstown, Tasmania, 7467 (1959).

Smith, Glennie Forbes, B.Sc. (Syd.), Box 134, P.O., Queenstown, Tasmania, 7467 (1962).

Smith, William Eric, Ph.D. (N.S.W.), M.Sc. (Syd.), B.Sc. (Oxon.), Associate Professor of Applied Mathematics, University of New South Wales, Kensington, 2033 (1963 : P2 ; President, 1970).

Smith-White, William Broderick, M.A., Associate Professor of Mathematics, University of Sydney, 2006 (1947 : P4 ; President, 1962).

South, Stanley Arthur, B.Sc., Geologist, 47 Miowera Road, Turramurra, 2074 (1967).

Stanton, Richard Limon, Ph.D., Associate Professor of Geology, University of New England, Armidale, 2351 (1949 : P2).

Stephens, James Norrington, M.A. (Cantab.), Ph.D., 170 Brokers Road, Mt. Pleasant, Wollongong, 2519 (1959).

Stevens, Eric Leslie, B.Sc., Senior Analyst, Department of Mines, N.S.W., 20 Myra Street, French's Forest, 2086 (1963).

Stevenson, Barrie Stirling, B.E.(Mech. and Elec.) (Syd.), 21 Glendower Street, Eastwood, 2122 (1964).

Stock, Alexander, D.Phil., Ph.D., Professor of Zoology, University of New England, Armidale, 2351 (1961).

Stokes, Robert Harold, Ph.D., D.Sc., F.A.A., 45 Garibaldi Street, Armidale, 2351 (1961).

Strusz, Desmond Leslie, Ph.D., B.Sc., Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T., 2601 (1960 : P3).

Stuntz, John, B.Sc., 11 Jackson Crescent, Pennant Hills, 2120 (1951).

Surry, Charles (1961).

Suters, Ralph William, B.Sc. (N.S.W.), Science Master, Berkeley High School ; p.r. 49 Walang Avenue, Figtree, 2500 (1968).

Swanson, Thomas Baikie, M.Sc., Flat 4, 112 Walsh Street, South Yarra, Victoria, 3141 (1941 : P2).

Swinbourne, Ellice Simmons, Ph.D., 30 Ellalong Road, Cremorne, 2090 (1948).

Taylor, Nathaniel Wesley, M.Sc. (Syd.), Ph.D. (N.E.), Department of Mathematics, University of New England, Armidale, 2351 (1961).

THEW, Raymond Farly, 88 Braeside Street, Wahroonga, 2035 (1955).
THOMAS, Penrhyn Francis, A.S.T.C., Optometrist, Suite 22, 3rd Floor, 29 Market Street, Sydney, 2000 (1952).
THOMPSON, Don Gregory, B.Sc., Dip.Ed., Master, R.A.N. College, Jervis Bay, 2540 (1967).
THOMSON, David John, B.Sc., Geologist, 61 The Bulwark, Castlecrag, 2068 (1956).
THOMSON, Vivian Endel, B.Sc., 1/171–177 Rokeby Road, Howrah, Tasmania, 7018 (1960).
THWAITE, Eric Graham, B.Sc., 8 Allars Street, West Ryde, 2112 (1962).
TICHAUER, Erwin R., D.Sc.(Tech.), Dipl.Ing., Research Professor of Biomechanics ; p.r. Apt. 12J, Kips Bay Plaza, 330 East 33rd Street, New York, N.Y., 10016, U.S.A. (1960).
TILLEY, Philip Damien, B.A., Dr.Phil., Department of Geography, University of Sydney, 2006 (1967).
TOMPKINS, Denis Keith, Ph.D., M.Sc., 14 Warrowa Road, Pymble, 2073 (1954 : P1).

UPFOLD, Robert William, B.E., M.E., Department of Engineering, Wollongong University College, Wollongong, 2500 (1968).

VALLANCE, Thomas George, Ph.D., Associate Professor, Department of Geology and Geophysics, University of Sydney, 2006 (1949 : P3).
VAN BRAKEL, Albertus Theodorus, B.Sc.(Hons.), Geologist, 7 Bruce Street, Glendale, 2285 (1968).
VAN DIJK, Dirk Cornelius, D.Sc.Agr., c/o C.S.I.R.O., Division of Soils, Cunningham Laboratory, St. Lucia, Queensland, 4067 (1958).
VEEVERS, John James, Ph.D., School of Earth Sciences, Macquarie University, North Ryde, 2113 (1953).
VERNON, Ronald Holden, Ph.D., M.Sc., School of Earth Sciences, Macquarie University, North Ryde, 2113 (1958 : P1).
VICKERY, Joyce Winifred, M.B.E., D.Sc., 15 The Promenade, Cheltenham, 2119 (1935).
VOISEY, Alan Heywood, D.Sc. ; p.r. 9 Milton Street, Carlingford, 2118 (1933 : P13 ; President 1966).
*VONWILLER, Oscar U., B.Sc., F.Inst.P., F.A.I.P., Emeritus Professor, "Rathkells", Kangaroo Valley, 2577 (1903 : P10 ; President 1940).

WALKER, Donald Francis, Surveyor, 13 Beauchamp Avenue, Chatswood, 2067 (1948).
*WALKOM, Arthur Bache, D.Sc., 5/521 Pacific Highway, Killara (1919 and previous membership 1910–1913 : P2 ; President 1943).
WARD, Colin Rex, Ph.D., B.Sc.(Hons.), Geologist, School of Physical Sciences, N.S.W. Institute of Technology, Broadway, 2007 (1968).
WARD, Judith (Mrs.), B.Sc., 16 Mortimer Avenue, Newtown, Hobart, Tasmania, 7008 (1948).
WASS, Robin Edgar, Ph.D. (Syd.), B.Sc.(Hons.) (Qld.), Department of Geology and Geophysics, University of Sydney (1965 : P1).
*WATERHOUSE, Lionel Lawry, B.E. (Syd.), 112 Brown's Road, Wahroonga, 2076 (1919 : P1).
WATTON, Edward Charlton, Ph.D., B.Sc.(Hons.), A.S.T.C., Associate Professor of Chemistry ; p.r. 17 Malory Avenue, West Pymble, 2073 (1963).
WEBBY, Barry Deane, Ph.D., M.Sc., Department of Geology and Geophysics, University of Sydney, 2006 (1966).
WEST, Norman William, B.Sc., c/o Department of Main Roads, Sydney, 2000 ; p.r. 9/62 Murdock Street, Cremorne, 2090 (1954).
WESTHEIMER, Gerald, B.Sc. (Syd.), Ph.D., F.S.T.C., Professor of Physiology, University of California, 2575 Life Sciences Building, Berkeley, California, 94720, U.S.A. (1949).
WHEELHOUSE, Frances, Senior Laboratory Technician, School of Biological Sciences, University of New South Wales, Kensington, 2033 (1968).
WHITLEY, Alice, M.B.E., Ph.D., 39 Belmore Road, Burwood, 2134 (1951).
WHITLEY, Gilbert Percy, F.R.Z.S., Honorary Associate of the Australian Museum, College Street, Sydney, 2000 (1963).
WHITWORTH, Horace Francis, M.Sc., 31 Sunnyside Crescent, Castlecrag, 2068 (1951 : P4).
WILCOX, Ronald Walter, B.Sc., Dip.Ed., Lecturer, Wollongong Teachers' College, Wollongong, 2500, p.r. 9 Benney Avenue, Fig Tree, 2500 (1969).
WILKINSON, John Frederick George, M.Sc. (Qld.), Ph.D. (Cantab.), Professor of Geology, School of Earth Sciences, Macquarie University, North Ryde, 2113 (1961 : P1).
WILLIAMS, Benjamin, 30 Croft Road, Eleebena, 2280 (1949).
WILLIAMSON, William Harold, M.Sc., 6 Hughes Avenue, Ermington, 2033 (1949 : P1).
WILSON, Christopher John Lascelles, B.Sc., c/o Geologisch en Mineralogical Instituut, Garenmarkt 16, Leiden, Netherlands (1967 : P1).
WINCH, Denis Edwin, Ph.D., M.Sc., Senior Lecturer in Applied Mathematics, University of Sydney, 2006 (1968).
WOOD, Clive Charles, Ph.D., B.Sc. (1954).
WOOD, Harley Weston, D.Sc., M.Sc., Government Astronomer, Sydney Observatory, Sydney, 2000 (1936 : P16 ; President 1949).
WRIGHT, Anthony James, Ph.D., B.Sc., Department of Geology, Wollongong University College, Wollongong, 2500 (1961).
WYLIE, Russell George, Ph.D., M.Sc., Physicist, National Standards Laboratory, University Grounds, City Road, Chippendale, 2008 (1960).

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Associates

BROWN, Ada Marjory (Mrs.), 40 Woolgoolga Street, North Balgowlah, 2093 (1969).

DENTON, Norma (Mrs.), Bunarba Road, Miranda, 2228 (1959).
DONEGAN, Elizabeth (Mrs.), 18 Hillview Street, Sans Souci, 2219 (1956).

EMERY, Hilary May Myvanwy (Mrs.), c/o Dr. F. W. Clutterbuck, 234 Bay Terrace, Wynnum, Queensland, 4178 (1965).

GRIFFITH, Elsie A. (Mrs.), 9 Kanoona Street, Caringbah, 2229 (1956).

GUNTHORPE, Robert John, B.Sc.(Hons.), Department of Geology, University of New England, Armidale, 2350 (1965).

LEAVER, Harry, B.A., B.Sc., M.B., Ch.M., M.R.C.O.G., F.G.S., 30 Ingalara Avenue, Wahroonga, 2076 (1962).

LE FEVRE, Catherine Gunn, D.Sc. (Lond.), 6 Aubrey Road, Northbridge, 2063 (1961).

PUTTOCK, Alan Maurice, 5/52, Martin Street, Harbord, 2096 (1969).

STANTON, Alison Amalie (Mrs.), B.A., 35 Faulkner Street, Armidale, 2350 (1961).

STOKES, Jean Mary (Mrs.), M.Sc., 45 Garibaldi Street, Armidale, 2350 (1961).

WADLEY, David Alastair, Department of Human Geography, Research School of Pacific Studies, Australian National University, Canberra, A.C.T., 2600 (1970).

Obituary

1968-1969

William Lindsay PRICE (1927).
Sir Harold George RAGGATT (1922).
Ethelbert Ambrook SOUTHEE (1919).
Frederick G. N. STEPHENS (1914).
Andrew UNGAR (1952).
Hans Samuel Arthur ROSENTHAL (Associate 1961).

1969-1970

Walter George STONE (1915).
Ronald Leslie ASTON (1930).

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Royal Society of New South Wales

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JOURNAL AND PROCEEDINGS OF THE ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 104 1971 PARTS 3 and 4

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PUBLISHED BY THE SOCIETY
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

ISSUED JANUARY 10, 1973

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VICK, C. G., 1934. *Astr. Nach.*, **253**, 277.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 121–122, 1972

On Hoyle's Electrodynamic Version of the Steady-State Cosmology

R. R. Burman

Abstract—Hoyle once published a version of the steady-state cosmology, based on Proca's equations, in which separation of matter and anti-matter produces an intergalactic magnetic field. Here, the constants in that theory are evaluated by using recent results on intergalactic Faraday rotation.

1. Introduction

Lyttleton and Bondi (1959) investigated the effects of a possible general charge imbalance in the universe; the excess could arise from differing magnitudes of the proton and electron charges or from a difference in the numbers of the two particles. In their theory, continuous creation of matter and charge occurs; hence Maxwell's equations cannot be valid and an appropriate modification, the Proca equations, was used. The postulate of the conservation of existing charge was made: in any volume element, the total charge is the sum of the charges of all the enclosed elementary particles existing there at the instant concerned. Also, charge was regarded as indestructible once created. Taking $-e$ to be the charge on the electron, that on the proton is written $(1+y)e$; alternatively, the ratio of number of protons to number of electrons is $(1+y):1$.

Hoyle corrected and modified Lyttleton and Bondi's calculations (Hoyle, 1960; Lyttleton and Bondi, 1960; Bondi, 1961) and obtained a version of the steady-state theory based on the Proca equations and the field equations of general relativity with no cosmological term. In Hoyle's electrodynamics, electrical forces reverse direction when charges are sufficiently far apart, and he suggested that electrical forces might bring about separation of matter and anti-matter; matter and anti-matter are created in pairs, and the process of separation generates a magnetic field.

2. Some Equations of the Theory

In Hoyle's theory, the strength B of the cosmic magnetic field is estimated by

$$B \sim \frac{4\pi e}{c} \frac{H}{M} \frac{|y|}{(-\lambda)}\rho \quad \ldots\ldots\ldots \quad (1)$$

where c is the speed of light in vacuum, H is Hubble's constant, ρ is the average proper density of matter in the universe, M is the proton mass, and λ is a negative constant; $(-\lambda)^{-\frac{1}{2}}$ has the dimensions of length and the scale of the separation between matter and anti-matter is $\gtrsim(-\lambda)^{-\frac{1}{2}}$. The proper mass density ρ of cosmological matter is given by

$$\rho = \frac{3H^2}{4\pi G}, \quad \ldots\ldots\ldots\ldots \quad (2)$$

G being the Newtonian gravitational constant. The relations (1) and (2) give

$$B \sim \frac{3eH^3}{McG} \frac{|y|}{(-\lambda)}. \quad \ldots\ldots\ldots\ldots \quad (3)$$

The theory involves an equation which can be written

$$\frac{|y|}{(-\lambda)^{\frac{1}{2}}} = \left(\frac{G}{3}\right)^{\frac{1}{2}} \frac{Mc}{feH} \quad \ldots\ldots \quad (4)$$

in which f is the fraction of the cosmological material separated. The relations (3) and (4) give

$$(-\lambda)^{-\frac{1}{2}} \sim \left(\frac{G}{3}\right)^{\frac{1}{2}} \frac{fB}{H^2} \quad \ldots\ldots\ldots \quad (5)$$

and

$$|y| \sim \frac{Mc}{e} \frac{H}{f^2 B}. \quad \ldots\ldots\ldots \quad (6)$$

Hoyle mentioned that the theory could be freed from (4) by introducing the C-field; then λ and y would be independent.

With $H^{-1}=3\times10^{17}$ sec., corresponding to $H=100$ km. sec.$^{-1}$ Mpc.$^{-1}$, (3) becomes

$$B \sim 10^{-41}\frac{|y|}{(-\lambda)} \quad \ldots\ldots \quad (7)$$

while (2) shows that $\rho=4\times10^{-29}$ gm. cm.$^{-3}$; (5) and (6) become

$$(-\lambda)^{-\frac{1}{2}} \sim 10^{31} fB \quad \ldots\ldots\ldots \quad (8)$$

and

$$|y| \sim \frac{3\times10^{-22}}{f^2 B}. \quad \ldots\ldots \quad (9)$$

3. Use of Observations

Sofue *et al.* (1968), Kawabata *et al.* (1969) and Reinhardt and Thiel (1970) have presented evidence that Faraday rotation occurs in extragalactic space. Kawabata *et al.* took H to be 100 km. sec.$^{-1}$ Mpc.$^{-1}$, and deduced that $N_e B = 2 \times 10^{-14}$ gauss cm.$^{-3}$, N_e being the electron density. If the cosmological medium is fully ionized, then the value of ρ calculated above implies that $N_e = 2 \times 10^{-5}$ cm.$^{-3}$. With $B = 1 \times 10^{-9}$ gauss and $f = 1$, the relations (7), (8) and (9) give

$$\frac{|y|}{(-\lambda)} \sim 10^{32} \text{ cm.}^2, \quad \ldots\ldots\ldots\ldots \quad (10)$$

$$(-\lambda)^{-\frac{1}{2}} \sim 10^{22} \text{ cm.} \sim 3 \text{ kpc} \ldots\ldots \quad (11)$$

and

$$|y| \sim 3 \times 10^{-13}. \quad \ldots\ldots\ldots\ldots \quad (12)$$

This value of $|y|$ is far too large for the charge imbalance to arise from a discrepancy between the magnitudes of the proton and electron charges.

Arp (1971) has re-analysed the Faraday rotation data using his interpretation of quasar red shifts in which they do not entirely owe to the cosmological expansion. He found $N_e B$ to be $\sim 10^{-13}$ to 10^{-12} gauss cm.$^{-3}$; this means that, with $N_e \sim 10^{-5}$ cm.$^{-3}$, $B \sim 10^{-8}$ to 10^{-7} gauss, and so, with $f = 1$, (7), (8) and (9) give

$$\frac{|y|}{(-\lambda)} \sim 10^{33} \text{ to } 10^{34} \text{ cm.}^2, \quad .. \quad (13)$$

$$(-\lambda)^{-\frac{1}{2}} \sim 10^{23} \text{ to } 10^{24} \text{ cm.} \quad \ldots\ldots \quad (14a)$$

$$\sim 30 \text{ to } 300 \text{ kpc.} \quad \ldots\ldots \quad (14b)$$

and

$$|y| \sim 3 \times 10^{-14} \text{ to } 3 \times 10^{-15}. \quad (15)$$

4. Concluding Remarks

In this note, some recent information on the intergalactic magnetic field has been used to evaluate constants which occur in an electrodynamic version of the steady-state cosmology. The scale of the separation between matter and anti-matter has been found to be several kiloparsecs or greater. The magnitude of the charge imbalance has been found to be far too large to be explicable in terms of a discrepancy between the magnitudes of the proton and electron charges.

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(Received 13 December 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 123–141, 1972

Words, Actions, People: 150 Years of the Scientific Societies in Australia*

D. F. Branagan

" Upwards of thirty years have now elapsed, since the colony of New South Wales was established in one of the most interesting parts of the world—interesting as well from the novel and endless variety of its animal and vegetable productions, as from the wide and extending range for observation and experiment, which its soil and climate offer to the agriculturist. Yet little has been done to awaken a spirit of research or excite a thirst for information amongst the Colonists . . . It is therefore proposed to form a Society, for the purpose of collecting information with respect to the Natural State, capabilities, productions, and resources of Australasia and the adjacent regions, and for the purpose of publishing, from time to time, such information as may be likely to benefit the world at large.

The undersigned individuals therefore subscribe their names as original Members of a Society, to be called The Philosophical Society of Australasia." Thus on the 4th July, 1821, James Bowman, Henry Grattan Douglass, Barron Field, Frederick Goulburn, Francis Irvine, John Oxley and Edward Wollstonecraft set in motion the first of our scientific societies, with Dr. Douglass named as Secretary. (Philosophical Society's Minute Book.)†

The regulations drawn up by the seven pioneers in 1821 were challenging indeed. Each member in rotation was to produce a monthly paper on some subject connected with the objects of the Society under penalty of ten pounds! This was perhaps the beginning of our present " publish or perish " syndrome.

" Polemical divinity and party politics shall be excluded from such papers."

" No paper shall be printed without the authour's (*sic*) permission. The selection of papers for publication shall be determined by ballot—two black balls to exclude "—perhaps as satisfactory a way to referee papers as any presently in operation!

" No refreshment to be introduced, except tea and coffee, under penalty of Five Pounds."

" The Society was to meet every Wednesday at each other's Houses in Sydney, alphabetically, at 7 o'clock in the evening. Fine for non-attendance at a quarter of an hour after that time, five shillings. No excuse to be allowed but sickness, public business, or non-residence in Sydney." Major Goulburn seems to have been the chief offender as a late-comer, being fined no less than thirteen times, and Dr. Douglass was not far behind during the period till August, 1822! Mr. Wollstonecraft was excused from one meeting because " he was called upon to attend the funeral of a friend in the country ", but on another occasion when he was " engaged to dine at Government House " it was " resolved, that such excuse is not sufficient "!

Each member paid in five pounds to help set up a Museum, purchase a few books of reference and other incidental expenses, and Major Goulburn offered the use of a room in the Colonial Secretary's Office for the proposed Museum and Library.

* Address given in commemoration of the sesquicentenary of the foundation of the Philosophical Society of Australasia.

† According to Phillips (1909), an earlier attempt was made in 1818 to set up an Agricultural Society; this failed because of Governor Macquarie's opposition to Judge Advocate Wylde's idea of balloting for membership. Macquarie wished emancipists to be freely admitted.

In the next few months Mr. Patrick Hill (Surgeon of the Royal Navy), Reverend Samuel Marsden, William Howe, Esq., Lt. Phillip Parker King, R.N., and Alexander Berry, Esq., were proposed as new members, all but Marsden accepting; while on 24th October, 1821, Mr. Bowman resigned.

There was no meeting on the 7th November, the day of Governor Major-General Sir Thomas Brisbane's arrival in the colony, but on the following Wednesday (14th November) the Society approved a letter prepared earlier by the secretary, Dr. Douglass, to be sent to Governor Brisbane together with the minutes of the Society.

> " Sir
>
> . . . a few individuals of the Colony, anxious to obtain information, in the several branches of science and natural history, which this extensive and interesting quarter of the globe offers to industry and research, agreed to meet and form a Society . . . .
>
> I . . . express the anxious wish of this Society, that you would accept the Presidency of their infant body . . . ."

Brisbane's letter of acceptance is dated 16th November. He attended his first meeting on 2nd January, 1822.

Up to August, 1822, when detailed records of the Society cease, three other members were gained, viz. M. C. Rumker, Esq. (as listed in the minutes of the Society—this is of course Charles Stargard Rumker), Donald Macleod, Esq., Staff Surgeon to Brisbane and his family, and Robert Townson, LL.D. (the latter was nominated in August and his final acceptance is not known).

The cessation of the minutes in August, 1822, is almost certainly due to Douglass's clash with other Magistrates and with Dr. James Hall over the convict girl Ann Rumsby (*Aust. Dict. of Biography*, Vol. 1, p. 314) which started a long chain of litigation and other events. During all of this Governor Brisbane and Dr. Douglass remained friendly, as did Douglass and Goulburn, but relations between Brisbane and Goulburn became strained and Field and Douglass fell out. Evidence of at least one later meeting is given by Barron Field in his *Geographical Memoirs* (1825), where the paper by P. P. King " on the Maritime Geography of Australia " is labelled " Read 2nd October 1822 " before the Society.

Whether the Society continued to be active beyond this date I have not yet found out, but it is listed among the Institutions of Sydney in the *Australasian Almanac* for 1825 and not afterwards. Field's preface to his *Geographical Memoirs*, dated 28th February, 1825, sets out the oft-quoted " that infant society soon expired in the baneful atmosphere of distracted politics ".

Achievements of the Society

So far I have dealt with the personalities involved in this first society. Those interested in these quite fascinating characters can find further details in the notes by Cambage (1922) and in the *Australian Dictionary of Biography* (Vols. 1 and 2).

Just what scientific work did the Society try to do? The letter to Brisbane, quoted above, indicates that the Society was concerned to gather facts and carry out original work rather than just discuss already known material. At one of its early meetings it set out to make contact with many overseas societies. Apart from those to be expected in Europe and the United States of America, societies in India (Calcutta, Madras, Bombay), Ceylon and Java were to be approached asking for their co-operation in various ways. In particular, the Society would offer to exchange duplicate materials from its Museum as " it would be desirable to compare these specimens with others resulting from the same natural kingdoms in different parts of the world ".

When, and even if, the circular letter was sent I cannot ascertain. The " draught of a circular letter to the several scientific Societies of the different quarters of the globe " was presented to the meeting of 26th September, 1821, and adopted. However, on the 10th October it was " Resolved, That the first sentence of the Society's Letter to the various Philosophical Institutions of the Globe, be altered . . . ", and on 2nd January, 1822, it was " resolved, That the following paragraph be added to the Society's intended circular Letter to the different Scientific Institutions, throughout the world: ' I am desired to add, that quarterly meteorological tables, together with astronomical observations, will be regularly transmitted to you '." This last addition is clearly the work of Governor Brisbane.

During the first year of the Society material for the Museum was obtained from various sources—the major emphasis being geological.

A collection of minerals, fossils and petrifications came from Rev. Mr. Youl at Port Dalrymple (now Launceston, Tasmania), " specimens of the different stratifications of coal " from Major Morisset, Commandant at Port Hunter (Newcastle), and mineral specimens were brought from Port Macquarie by Mr. Oxley. Furthermore, members were requested " to transmit to the Museum, specimens of the different soils in their respective districts of the country, noting the depth at which each specimen was taken, and such other particulars as they may deem proper ". Contacts likely to obtain suitable articles for the Museum were eagerly sought. Captain Raine of the *Surry*, sailing for Macquarie Island, and Mr. Kent, bound for the Sandwich Islands (Hawaii), were given written Instructions and Queries, and Raine's report* proved particularly interesting. Assistant Surgeon Fenton at Port Macquarie was requested to obtain " specimens of the timber and natural history of that port " which were apparently later transmitted through Captain Allman, the Commandant there. In April, 1822, Mr. Field presented " two Peruvian bottles of great rarity and antiquity ". The hand of Douglass, of Irish origin and a graduate of Trinity College, Dublin, can be seen in the request to the Museum Committee " to report what specimens of natural history the Society can spare to the Museum of Trinity College, Dublin ". The Museum also housed a Catalogue prepared by Field, " digested into one volume " of the respective libraries of eight of the members.

Perhaps of most interest is a specimen the Society *did not* obtain. At the meeting of 19th December, 1821, " Mr. Wollstonecraft informed the Society, that Mr. [Hamilton] Hume reported the existence in Lake Bathurst, of an animal supposed from his description to be the manatee or hippopotamus ". Consequently it was " Resolved, that Mr. Wollstonecraft be authorized to reimburse Mr. Hume any expense he may incur, on the part of himself or any black natives, in food or labour, for the purpose of procuring a specimen of the head, skin or bones of this animal ; and that the Treasurer do make good the same ".

Papers of the 1821 Philosophical Society

How effective was the resolution of the first meeting concerning monthly papers and fines ?

* See J. S. Cumpston (1968), MacQuarie Island Antarctic Division, Department of External Affairs, Melbourne, pp. 50-53.

The records give the answer. At this first meeting Dr. Douglass was at the head of the list to give a paper, but this seems to have been forgotten later in the year when after the period devoted to organizing the Society it was resolved (14th November, 1821) " that the first peremptory paper be produced and read, on the first Wednesday in January next ". In the January minutes we find " Mr. Berry, who stood first in order of the Society's Rules to furnish a paper to be read before the Society, not being prepared to do so, Mr. Field read a paper on the Aborigines of New Holland and Van Diemen's Land, and it was consented that Mr. Berry's turn should be postponed till the first Wednesday in next month ".

Field's paper was preceded at the December, 1821, meetings of 19th and 26th by two from non-members. On the 19th was " Read the Journal of an Expedition from Lake Bathurst to the Pigeon House, on this Coast, performed last month by an European Native of the Colony, Mr. Hamilton Hume ", while on the 26th " Read the Journal of a Tour to Jervis's Bay from the County of Argyle, performed by Charles Throsby, Esqr. in November last and December instant ".

At the 7th February, 1822, meeting when Berry was due to speak we find in the minutes " Mr. Berry, whose turn it was to read a paper before the Society, was reported as unaccountably detained on an exploratory voyage to Bateman's Bay, the result of which he intended to make the subject of his paper ". However, at the 13th February meeting " Mr. Berry read a Narrative of his late Voyage of Discovery to Jervis's and Bateman's Bays ". It was " resolved, that by reason of Mr. Berry's detention from the last meeting by the perils of the seas, his paper be now accepted as a satisfaction for his fine ". On 6th March Berry followed this up with a second paper on the Geology of the Coastline between Newcastle and Bateman's Bay.

At the 13th March meeting Mr. Rumker read a paper on the importance of astronomical observations in the southern hemisphere, and some weeks later the President (Governor Brisbane) " presented to the Society various Memoirs and Tables of astronomical and other calculations " for its use.

McLeod was apparently next on the list, but at the 10th April meeting " Mr. Macleod not having laid before the Society a paper, according to the laws of rotation, and having, by this default, incurred a fine of Ten pounds, Resolved, That, for special reasons, the said fine be remitted upon the production of the paper on the first Wednesday in the next month ". The question of Mr. McLeod's paper was adjourned at subsequent meetings and on 5th June, 1822, we find a new resolution on the books " that the Society's Rule making it compulsary (*sic*) upon each Member in his turn to write a monthly paper, be suspended for the next six months ; and that it be left to the interest and zeal which it is hoped each Member has in the objects of the Society, to lay before them a paper at such time as he may think proper, without any penalty for default. At the same meeting it was decided that the first meeting of each month should be held at the Secretary's house at Paramatta (*sic*) and that 'henceforth all Members absent from such meetings be fined ten shillings '." However, for the July meeting " His Excellency the President requested the favour of the Society's company at a dinner . . . being the anniversary of the institution of the Society ".

Although much of this is amusing, we must acknowledge that at least 30% of the Society's members contributed papers in a period just over a year—a figure certainly not approached by our present societies !

What was the quality of these papers ? Rumker's paper setting out the work which could be done in astronomy was the first product of the group setting up Brisbane's observatory at Parramatta. The three workers involved, Brisbane, Rumker and James Dunlop, in a few years carried out an extraordinary amount of important work. Regular observations began in May, 1822, but some observations were made soon after the arrival of Brisbane in November, 1821 (Wood, 1966). Berry's geology paper (1825) contains some very perceptive material indeed. He recognized the unconformity between the rocks of the Sydney Basin and the older rocks in the Bateman's Bay area ; he had more than an inkling of the significance of the Lapstone Monocline, and described in some detail the character of the Hawkesbury Sandstone. Field's paper, as Hedley (1921) says, " did not appreciate that the ragged and despised black-fellow at his kitchen door was a treasury of ethnological information ", but Hedley's comment that Field " produced a trashy and pedantic memoir " is rather unkind at this early attempt at ethnology when one considers the general attitude of Europeans to natives in the early 19th century. Governor Brisbane was appreciative and moved at the 6th March, 1822, meeting " that the thanks of the Society be given to Mr. Field for his valuable paper on the Aborigines of New Holland ". King's paper (King, 1825), as one would expect, is a competent one which describes many features of Australia's coastline.

As a final note to the papers presented, it is apparent that they all deal with rather broad topics. This may have been caused by an early resolution of the Society " That every experiment, related in any paper laid before the Society, shall (if possible) be performed and verified at the reading of the paper, or if not possible at the time, that the Society shall take the best means to determine the truth and value of such experiment, and that the means and result of such verification be deposited in the Society's Museum ". Perhaps there would be some merit in introducing a similar resolution today !

The Commemorative Tablet at Kurnell

One other activity of the Society still remains to be mentioned. This is the setting up of a memorial tablet at Kurnell to commemorate the landing of Cook and Banks.

Barron Field first brought up the matter at the 18th July, 1821, meeting when he " laid before the Society a Latin Inscription by a friend, commemorating the landing of Capt. Cook and Sir Joseph Banks, K.B. on this coast, for the purpose of being engraved on brass and erected on the spot, by this Society ". Captain Irvine took up the proposal but suggested some amendments, and on 8th August, 1821, it was resolved " that an English Inscription . . . would be preferable ". Major Goulburn is next on the scene, and his inscription, presented 15th August, was adopted. However, there were second thoughts on the inscription, which were finally thrashed out at the 29th August meeting, and " the language of the Inscription was finally settled ".

Messrs. Field and Oxley were deputed to " form a Committee to procure the Inscription to be engraven on brass, with a view to its erection by the Society, against a rock, on the south shore of Botany Bay ".

On 23rd January, 1822,

> " The Inscription Committee reported that the Tablet was now ready, and that they had ascertained a proper place, for its

erection ; and they therefore requested the honour of the Company of the President and Members to a little collation on the spot, upon the affixing of the Inscription, on such day as the President and Members shall appoint."

The meeting of 6th March announces that " the day for affixing the tablet . . . was appointed " but gives no details. However, the *Sydney Gazette* of Friday, 15th March, 1822, has the following—

" On Wednesday morning his Excellency the Governor came to town for the purpose of accompanying the Philosophical Society to the south head of Botany Bay to erect an inscription to commemorate the first landing of Captain Cook and Sir Joseph Banks ; but when the party arrived at the north shore, the state of the wind forbade their crossing the bay. The excursion was therefore postponed till the following Wednesday, and the President and members dined where they were, and were honoured by the company of the principal officers of the ' Dauntless ', together with Captain Elliott and Captain Piper."

The minute book gives no mention of this activity, but records a meeting at Major Goulburn's that evening at which Rumker's paper was read. There is a hint of some changes in organization, however, in the statement " The Minute Book being accidentally left at Parramatta the proceedings of the last Meeting were not read ".

The rough weather had abated the following week and the Society was successful in its efforts. The *Sydney Gazette* (Friday, 22nd March) once again records the activity—

" His Excellency the Governor-in-Chief came to town on Tuesday last, and returned to Parramatta yesterday. On Wednesday last his Excellency the President and members of the Philosophical Society of Australasia, made an excursion to the south head of Botany Bay, for the purpose of affixing a brazen tablet, with the following inscription, against the rock on which Captain Cook and Sir Joseph Banks first landed.

A.D.—MDCCLXX.

" Under the auspices of British science, these shores were discovered by JAMES COOK and JOSEPH BANKS, the Columbus and Mæcenas of their time. This spot once saw them ardent in the pursuit of knowledge. Now, to their memory, this tablet is inscribed, in the first year of the Philosophical Society of Australasia.

" Sir THOMAS BRISBANE, K.C.B. and F.R.S.L. and E., (Corresponding Member of the Institute of France),

President.

A.D.—MDCCCXXI.

" On this interesting occasion the Society had the good fortune to be assisted by Captain Gambier and several of the officers of His Majesty's ship ' Dauntless ' ; and after dining together in a natural arbour on the shore, they all repaired to the rocks, against which they saw the tablet soldered, about twenty-five feet above the level of the sea, and they there drank to the immortal fame of the illustrious men whose discoveries they were then met to commemorate."

The Society's minutes (27th March, 1822) record the matter more formally—

" The Inscription Committee reported that the President and Members were engaged all day on Wednesday last, in affixing the tablet to the memory of Cook and Banks, at the South head of Botany Bay, and that the Society had the honour to be assisted in that duty by Captain Gambier, and several of the Officers of His Majesty's Ship Dauntless, now refreshing at this port, on her way from South America to India, with specie. They reported the tablet to be pinned and soldered into a beetling rock, twenty-five feet above the level of the sea, and to bear from Cape Banks, . . ., and from the Barrack Tower on the north shore, . . ."

[Apparently the compass bearings were not made available to the Secretary.] Barron Field was moved by the occasion to write several sonnets, which he later published (1825).

On the 15th May, 1822, the Treasurer was " authorized to pay five guineas to Stewart, the Engraver of the Inscription-plate ". But the matter was not quite closed then because at the same meeting it was

" Resolved, That it be referred to Capt. King and Mr. Wollstonecraft, to enquire into the state of the Inscription-plate and to consider whether, with the assistance of public subscription, a pillar might not be erected for the reception of it, out of the reach of the sea-spray."

There is no further reference to the plate in the minutes.

Apparently it was not moved, and its existence was only periodically noted by the scientific societies (e.g. in 1862, 1880, 1921), while there was no comment about it during the Bicentenary Celebrations held at Kurnell in 1970.

An interesting sidelight on the preparation of the plaque is that the earlier versions each made provision for insertion of the name of the President, although none had been elected. It seems likely that the Society had made up its mind quite early to ask Brisbane to become President, despite the absence of any comment in the minutes.

Final Comments on the 1821 Philosophical Society

A Museum created, papers given and published, a monument erected, and even an anniversary dinner—these are solid achievements for a society which operated for somewhat less than two years.

In a sense, the Society probably started too early. Just a few years later and there might have been a stronger body of more active scientists ready to keep things going—Alexander Macleay, John Busby, Archdeacon Scott, Rev. C. P. N. Wilton, Thomas Mitchell to name but a few.

Even at the time of formation there are obvious gaps in the potential membership. Why did not James Dunlop become a member ? Did Brisbane keep him out of the way ? Was Allan Cunningham away too much ? What about Hamilton Hume and Charles Throsby (related to Surgeon Hill by marriage)—did they live too far out of town ? Why did not Townson come in at the start—did the Society not know of him ? And what about John Dickson the engineer ?

Douglass did not arrive in Sydney until May, 1821, and Goulburn less than a year earlier, and these were undoubtedly the prime movers in getting the Society going. Perhaps Douglass wanted to build up a good image quickly in the colony following his rather ? irregular departure from England. All in all there is no doubt the Society started very rapidly before Douglass and Goulburn could have been acquainted with a wide circle of people.

Perhaps I have dwelt too long with the infant Society, but I feel that in many senses its affairs have been rather poorly treated by earlier writers, many of whom lacked the Society's records. On the other hand, despite our commemoration this year, I feel, like J. H. Maiden (1918), that its links with our present society are tenuous indeed, despite the re-appearance in Sydney of a widely-travelled Dr. Douglass early in 1848.

Other New South Wales Activities, 1822-1850

Whereas philosophical affairs in New South Wales quickly declined, earthier matters were surer of attention, and a series of agricultural and horticultural societies was established with gay abandon between 1822 and 1856. Maiden (*op. cit.*) has dealt with these societies in some detail. Suffice it to say that Governor Brisbane, Frederick Goulburn, Barron Field, Robert Townson, Alexander Berry, Edward Wollstonecraft, H. G. Douglass, Captain King and William Howe appear in the list of officers of the first Agricultural Society, which first met on 5th July, 1822, and followed up with an inaugural dinner on 16th July. This society seems to have had its demise in 1836, as did the semi-rival Australian Society formed in 1830.

Smith (1881) believed that the Australian Society was " An attempted revival " of the Philosophical Society, but there is no evidence to support this view.

These societies were followed by the Australian Floral and Horticultural Society (sometimes called the Sydney Horticultural Society 1836–1848) supported apparently by professional gardeners, and the " Australasian Botanic and Horticultural Society 1848–1856 ", which joined with the " Horticultural Improvement Society of New South Wales " to form the " Australian Horticultural and Agricultural Society " in the latter year. The 1848 society had amongst its officers E. Deas-Thomson, Alexander Macleay, Charles Nicholson, George Bennett, Rev. W. B. Clarke, William Macleay, Charles Moore and Thomas S. Mort. The Horticultural Improvement Society had an independent life only from late 1854 to December, 1856, under its President Sir William Denison and Vice-Presidents Sir Charles Nicholson and Sir Thomas Livingstone Mitchell.

The Australian Horticultural and Agricultural Society, formed on 8th December, 1856, was the precursor of the present separate Horticultural and Agricultural Societies of N.S.W., and its President Sir William Denison. Its meetings were regular and covered a wide variety of topics, mainly concerned with plant varieties useful for cultivation and properties of soils.

Scientific Activities in Tasmania, 1821-1855

Mention of Sir William Denison provides a link with the distant scientific societies of Tasmania.

Scientific societies in Tasmania can also be dated from 1821 (Piesse, 1914). In that year The Van Diemen's Land Agricultural Society first saw the light in Hobart under the Presidency of Governor Sorell. The major object of the Society seems to have been to put down sheep-stealing! but it was also concerned with improvements in husbandry. The Society prospered at least till 1829, when the Van Diemen's Land Scientific Society was formed " constituted . . . in imitation of the Royal & other literary & scientific societies of Europe & India ". Among the Society's objects was to be a museum of natural history and an " Economic or Experimental Garden . . . a piece of ground set apart for eliciting and discovering the properties and uses to which the vegetable productions of the island may be applied and to ascertain the improvements which may be adopted in their cultivation ". In this Society the Governor (Colonel Arthur) was Patron and its first President Dr. John Henderson. This gentleman, in his inaugural address, " proceeded to remark on the present state of the natural sciences, particularly as regards their nomenclature " and suggested in place of the existing nomenclature the substitution of certain syllables and letters, of which might be " compounded names expressive of the diagnostic marks of each particular plant ". This seems to have been an attempt to introduce the then recently developed chemical formulae technique into botany (but see Hoare, 1968). Henderson's remarks did not go unchallenged at the time, Dr. James Ross, defending the " excellent classification which learned men had adopted in the old world ". Henderson seems to have had a penchant for the unorthodox in science as witness his ideas about the Canobolas Mountains made during his trip in search of the inland sea in 1831 (Henderson, 1832).

On the same evening, 16th January, 1830, the Society entertained its Patron at dinner, where the chef " had done his best to cover the table of our philosophers with the first specimens of our fish, flesh & fowl ".

The Society met monthly, discussed many matters and established a museum, but did not last.

In 1837 Sir John Franklin came to Hobart and the following year created the Tasmanian Society, which published an excellent journal largely on natural science. Rev. John Lillie was its first Secretary. The setting up of the Franklin Museum at Ancanthe, Kangaroo Valley, in 1842 was closely associated with this Society. Franklin was still in Tasmania when his successor, Sir Eardly Wilmot, arrived in 1843. Wilmot wished to reconstitute the Society and put the Colonial (botanical) Gardens in its care. Consequently, on 14th October, 1843, he formed " The Botanical & Horticultural Society of Van Diemen's Land ", which in 1844 became " The Royal Society of Van Diemen's Land for Horticulture, Botany and Advanced Science ". Eardly Wilmot as Governor was still technically President of the older " Tasmanian Society ". In November, 1843, he resigned from this Presidency, thinking perhaps that the Society would fold, but it turned and re-elected Franklin, who must have been rather embarrassed.

However, Franklin soon departed and the Tasmanian Society, in the guise of its most active member, R. C. Gunn, retired to Launceston.

[Fuller details of these early societies are given in Piesse (*op. cit.*) and Morton (1901).]

Eardly Wilmot was followed as Governor in 1847 by Sir William Thomas Denison.

There is no doubt that Sir William Denison (1804–71) deserves more than a passing mention in the history of science in Australia. He was trained as an army engineer at the Royal Military Academy (1819–23) and was employed in Canada between 1827 and 1831 on the construction of the Rideau Canal. In February, 1833, he became instructor of engineer cadets at Chatham, where he established an observatory, and in 1836 he was employed as an observer at the Greenwich Observatory. In 1837 he was in charge of works at Woolwich Dockyard, and remained with the Admiralty till June, 1846. During this period he was made a Fellow of the Royal Society (*Aust. Encycl.*, Vol. 3, p. 232). He was appointed Governor of Tasmania early in 1847.

Soon after his arrival, he interested himself in the affairs of the Royal Society of Van Diemen's Land. (The Society had obtained royal consent in 1844. In 1855, when the name of the colony was changed, it became the Royal Society of Tasmania.) In February, 1849, Denison wrote to Admiral Beaufort " I have set on foot a scientific society ; that is, I have succeeded in making a society, which had been nominally established several years, perform some work, and I hope to be able to forward home a specimen of its labours shortly ".

Early in 1848, Dr. Joseph Milligan was appointed paid Secretary of the Royal Society " in its proper and originally intended character of a Scientific Society ", in succession to Dr. Lillie. Sir William Denison made it possible for the Society to secure Dr. Milligan's services by giving him at the same time an appointment under the Government.

The Society prospered under Milligan's secretaryship and Denison's patronage. Volume 1, Part 1, of *Papers and Proceedings* appeared in May, 1849, printed at the Government Printing Office, and similar volumes appeared in following years.

In September, 1853, a northern branch was set up at Launceston and fluorished till about 1860. A collection of rocks and minerals was gathered by the northern members. These afterwards went to the Mechanics' Institute of Launceston and formed the nucleus of collections in the Victoria Museum and Art Gallery about 1880.

In June, 1848, Denison gave permission for the Society to use free of charge " the large Committee Room at the Legislative Council Chamber " in Hobart as a museum, library and society meeting room. This arrangement continued till 1852.

During his time in Tasmania Denison read papers to the Society on a wide variety of topics.

Denison in New South Wales

In 1855 Denison went to Sydney as Governor of New South Wales. On 30th July that year Sir William presided when members of the " Australian Society " met with a view to reactivating that Society, which had been formed in 1850 (largely as a result of Dr. Douglass's activities). Some information about this Australian Society is given in Clarke (1867) and Maiden (*op. cit.*). On 9th May, 1856, the newly constituted Philosophical Society of New South Wales, which included many members of the Australian Society, had its first meeting, at which Denison presided and read a paper on " The development of the railway system in England, with suggestions as to its application to the colony of New South Wales ".

Writing to Colonel Harness in February, 1857, Denison said " The work of the Government is taken out of my hands . . . [a local legislative body now governed] but I manage to make work for myself. I am President of a Philosophical Society, and I have succeeded in organising an Agricultural Society. For both of these I have to write."

In a letter to Sir Roderick Murchison, 25th June, 1856, Denison wrote :

> " I have got my Philosophical Society to work at last . . . I determined I would not be President of an effete body, so I called the members together, read a paper on Railroads, got them to agree to meet regularly once a month for eight months in the year, and shall now, by the help of occasional papers from myself, and of suggestions to others, manage, I dare say, to generate, first an appetite for writing, and then a taste for observation, in order to have something to write about."

Denison's next paper, " On the Moon's Rotation ", was read on 8th July, 1857, together with a paper " On a New Sun Gauge or New Actinometer " by Mr. (W. S.) Jevons and " On Sanitary Reform of Towns and Cities " by Dr. Bland. On 12th August, 1857. Denison continued his earlier topic " On Railways ". He mentions this paper in a letter from Braidwood to Sir Roderick Murchison, in which he notes that his practical knowledge of the colony, gained in the past two years, has given him a clearer understanding of the best type of railway for the colony. [He proposed wooden rails and horse-drawn carriages initially.] On 8th December, 1858, his subject was " On the Filtration of Water through Sand ". This is only a short time after the important work of Henri Darcy on water movement was carried out and published in France. At the Council meeting, 16th September, 1859, there is mention of Sir William Denison's paper " On the Dental System of Mollusca " (see *Siphonaria* etc. below) being published in the *Empire*. At the 19th September, 1860, meeting his topic was " Bridge

Building ", " which he illustrated by numerous drawings and plans of bridges ". The last meeting of the Society he attended was on 19th December, 1860, when he was presented with a farewell address in which, among other things, it is stated . . . " We are indebted for the reorganisation of the Society on a satisfactory basis, also . . . particularly for the valuable papers treating of the special capabilities and requirements of the Colony, which you have contributed from time to time . . . ." Denison capped this address by reading two communications he had received from Mr. Thomas Hale of Bellambi, giving particulars of the horse tramway he had constructed from the coal-mine to the harbour.

The construction of Sydney Observatory in 1857 followed Denison's work in the Executive Council two years earlier. Writing to Murchison on 21st May, 1855, he said, " I am going to try to persuade the Council to vote a sufficient sum to re-establish the observatory here, and I have written to Airy to ascertain whether he can find me a competent observer ". He ensured that the activities of the Observatory " would extend beyond the work connected with the running of a time ball for purposes of Navigation " (Wood, 1967). He maintained a close association with the Rev. William Scott, first astronomer, who contributed a number of papers to the Philosophical Society.

In May, 1859, Sir William suggested that a Microscopical Committee be elected. This soon took the form of a special section of the Society, but it was active only till September the following year. His Excellency exhibited various features at meetings, and at the September, 1859, meeting read a paper " explanatory of the microscopic objects he had mounted and laid before the meeting, viz :— Tongues of two *Siphonaria*, *Chiton*, *Chitonellus*, *Risella*, *Turbo*, *Radius*, *Nerita*, and two *Patellas*."

This is an appropriate point in the history of the New South Wales societies to deal briefly with some developments in Victoria.

Victorian Societies

The formation of the Philosophical Institute of Victoria (later the Royal Society of Victoria) out of the two societies " The Victorian Institute for the Advancement of Science " and " The Philosophical Society of Victoria " has an fnteresting link with the Tasmanian societies, as its first president was Andrew (later Sir Andrew) Clarke (1824–1902).

Clarke was a military engineer who had the good fortune to be sent to Hobart with Sir William Denison in 1847. He later (1849) became Denison's private secretary and was always appreciative of Denison's help and friendship. He was an active member of the Royal Society in Tasmania, but in May, 1853, moved to Melbourne as Surveyor-General. Denison's influence may be discerned in Clarke's planning of Victoria's first railways, installation of the electric telegraph, and initiation of the Museum of Natural History. Clarke held office in both of the foundation societies (President of the Philosophical Society in 1855) and became President when they amalgamated in July, 1855. He left the colony in 1858.

From the outset, the Victorian society took an interest in sponsoring exploration, the first expedition being that of Burke and Wills.

The Royal Society of Victoria (as it became in 1859) was lucky to have the patronage of Sir Henry Barkly, Governor of Victoria from 1856 to 1863. Barkly, who also helped to found the Acclimatisation Society and the " National Observatory " (in Melbourne), was by no means a figurehead.

An important feature of the Society's early years was the fairly regular appearance of its transactions. In 1860 a very interesting (and geologically quite important) controversy was commenced in the Transactions. This was the long-continued verbal battle between Rev. W. B. Clarke and Professor Frederick McCoy on " the Question of the Age of Australian Coal Beds ". Four exchanges of opinion and information occur in the 1860 volume alone, following McCoy's original description of a fossil fern found by Richard Daintree as *Taeniopteris* and of Mesozoic age. Clarke maintained that the Australian coal measures were Palaeozoic. Although Clarke's opinion proved generally correct, this controversy was not really solved till much later. Aspects of the later history of the Royal Society of Victoria are discussed by Prescott (1961) and will not be repeated here.

I will now move on to the important year 1874, passing without comment over the period when the Philosophical Society of New South Wales changed its name (1866) and became the Royal Society of New South Wales. This period has been adequately treated by others, particularly Rev. W. B. Clarke in his inaugural address of 1866 and by Smith (*op. cit.*).

1874—The " Challenger " Expedition, William Macleay and the Linnean Society

1874 was an important year for Australian science, not least because of the visit of the famous " Challenger " expedition which set the science of oceanography on a firm footing. The scientific part of the expedition was under the charge of Professor (later Sir) Wyville Thomson. The *Challenger* reached Sydney somewhat earlier than expected on 6th April, and remained till 8th June. Several long articles in *The Sydney Morning Herald* describe the results of the Expedition's work up to its arrival in Australia. Before coming to Sydney, *Challenger* spent two weeks in Melbourne, where it was well received.

Magnetic observations were also carried out at the Melbourne Observatory. Thomson wrote that their " stay was greatly enlivened by the receptions and excursions arranged for the members of the Expedition by the inhabitants of Victoria ".

In Sydney, Thomson, and other scientists were made welcome at Elizabeth Bay House by William Macleay and at other houses, both in Sydney and the surrounding country, and the local zoologists organized an enjoyable collecting " picnic " around the shores of Port Jackson on 23rd April. This was reciprocated by the *Challenger*, which took invited guests out to sea to show off its dredging equipment on 3rd June. *The Empire* (4th June, 1874) gives an excellent account of this excursion.

Discussions with Sydney scientists influenced Thomson's activities. He wrote, " it seemed to us from what we heard in Sydney there was a chance of making valuable additions to the natural history of north east Australia, by examining carefully the faunae of some of the rivers. Those in which *Ceratodus* had lately been discovered had the greatest interest." Thomson thought it possible that other forms of Dipnoi might be found. Consequently Thomson, Lt. Aldrich, John Murray, Mr. Pearcey and others, armed with information and introductions, went by ship to Brisbane and thence to Maryborough, reaching there on 11th May. The party, with the help of Mr. Sheridan, the customs officer, an enthusiastic and knowledgeable amateur naturalist, camped some miles up the Mary River, where " *Barramunda* " (as the natives called the lung-fish) had been caught before.

Orthodox line fishing, netting, and even dynamiting (!) produced a considerable variety of specimens, but it was not till the tenth day, just before the party was due to return, that three specimens of the lung fish were caught on lines.

During the absence of Thomson and party in Queensland, H. N. Moseley made two excursions to " Browera Ck." (i.e. Berowra Ck.), where he observed in detail the physical character of the valley, the complex nature of the water environment varying from fresh to salt with its great variety of fauna, and the extensive kitchen middens which stretch for some miles along the banks.

The ageing Rev. W. B. Clarke, senior Vice-President of the Royal Society, had been ill and unable to prepare an Anniversary Address for the annual meeting of the Society on 20th May, so following a short introductory paper the *Challenger* officers exhibited some of their sampling apparatus and discussed their expedition in an informal conversazione which attracted a big audience. The Council of the Society was embarrassed to hear indirectly at its 27th May meeting that a bale of 40 yards of canvas belonging to the Expedition had " gone off " at the conversazione ! The Council meeting of 24th June records that 40 yards of canvas had been purchased and sent to catch H.M.S. *Challenger* at New Zealand.

Clarke met Thomson on his return from the successful trip to Queensland and discussed some of the results of the expedition, at that time known in detail only for the Atlantic and Indian Ocean sections. Clarke's Anniversary Address of May, 1875, and his additional paper given in December, 1875, is an excellent summary of the Expedition's work. Macleay also met Thomson at the end of May and discussed his Queensland work.

Earlier in the year (28th March) Sydney University announced the acceptance of William Macleay's offer to bequeath the Macleay collections and library to the University. In view of the long association of the Macleay family with the Australian Museum (Alexander, William Sharp and William were all at some time Trustees), it may seem curious that the bequest was not offered to the Museum. Many years before (about 1852) the University had put out feelers to have the Australian Museum transferred to its charge, but this move was rejected (Etheridge, 1916).

Probably the main factor in the bequest going to the University was the friendship between William Macleay and his father-in-law, Sir Edward Deas-Thomson, at that time Chancellor of the University. Deas-Thomson believed that the announcement of the bequest at this time would be a stimulus to the formation of a medical school at the University, and the setting up of a hospital (Prince Alfred) adjacent to the University.

Macleay was keen to spend more time on his scientific work, particularly his collections, but his seat in Parliament prevented him. He had intended to resign at the end of the session, but the sudden resignation of the Government in November, 1874, gave him the opportunity to leave earlier than he had expected. He began immediately to devote himself full time to the pursuit of " Natural Science ".

In 1862 William Macleay, with the support and approval of W. S. Macleay, had commenced one of Australia's earliest specialist societies—the Entomological Society. Like most groups, it started enthusiastically, but attendances waned and it seems that no meetings were held from May, 1865, to December, 1866, or in 1871 or 1872, while only one or two were held in other years. Despite William Macleay's own statement that the Society closed in 1869, the minutes of several later meetings are available and indicate that sporadic meetings were held until 1874 (Fletcher, 1893).

Although very small, the Entomological Society was important (1) because it focussed some attention on biology, a topic generally neglected by the Philosophical Society in the 1860's ; (2) because it issued its own publications, the first issued by a specialist scientific society in New South Wales ; and (3) because it almost certainly helped to stimulate workers like Gerard Krefft, E. P. Ramsay, Dr. J. C. Cox and Count Castelnau, all of whom expanded their work into other biological fields. It should be noted that of the 24 members only six offered papers to the Society.

There is no doubt that the *Challenger* visit stimulated considerable activity among the " Natural Scientists " residing in Sydney. The original idea of forming a wider-ranging natural science society than the defunct Entomological Society seems to have been due to Commander Stackhouse, R.N., and Dr. Alleyne, then the Health Officer, but known around the town as " the curious old gentleman with the shocking hat who used to frequent the Australian Club ". Alleyne had in 1852 been the first medico to administer chloroform in the colony. Of Stackhouse I know little, but he is probably commemorated in the genus *Stackhousia* (which includes about 16 species of herbs with rather woody rhizomes).

During October, 1874, Stackhouse and Alleyne " sounded out " the opinions of persons likely to be interested and then, in association with Macleay and W. J. Stephens, they proceeded to draw up a constitution. Macleay, in fact, missed the vital meeting on Thursday, 24th October, because of the threat of rain and some indisposition, but despite this was informed next day that the members wanted him for President. The name chosen for the new society was the " Linnean Society of New South Wales ", proposed by W. J. Stephens, while Stackhouse proposed " The Banksian Society ". The first activities of the Society were Linnean " picnics " or field days on the harbour (similar to the *Challenger* picnic) on 21st November and 19th December, when a good time was had by all—some samples were obtained for collections, others were capably cooked by W. B. Dalley to provide a pleasant repast, and all returned suitably sunburnt.

In his Chairman's Address to the Linnean Society (31st January, 1876) outlining the first year of its activity, Macleay, while speaking kindly of the Royal Society, justifies the formation of the new body " . . . I allude particularly to the Royal Society of Sydney (*sic*) . . . a number of valuable papers have been read at its meetings. But mingled with those scientific papers have been others not of a scientific character, and possessing certainly no interest except of the most local kind. The publications of its proceedings also have not been conducted with the celerity and regularity to be expected from a society not deficient in point of means, and it is that irregularity and uncertainty in publication which makes it as a society useless as a record of zoological, botanical or geological discovery. Concerning the Linnean Society Macleay went on to say, " The proceedings of the monthly meetings, with the papers read, have been printed as soon as the matter in hand was sufficient for an octavo sheet. And the only regret I have to express, is, that the numbers of those contributing papers are not greater, and that Zoology seems to turn the scale upon Botany and Geology ".

I have not found any comment about the formation of the Linnean Society in the records of the Royal Society at the same time. Despite the *Challenger* visit, the Royal Society was not very lively. Rev. W. B. Clarke was in rather poor health, and Professor Liversidge, relatively new to the colony, was no doubt a little hesitant to start things moving. Two general meetings late in 1874 lapsed for want of papers, and the 30th September Council meeting lapsed for want of a quorum. However, the Council sent out letters asking for papers to be offered and shortly after decided that regular meetings would be held whether or not papers had been offered and that notes and exhibits would be welcomed.

Despite the shortage of papers, the Society still had standards to maintain. At the 27th June, 1874, Council meeting a letter from Mr. Martin Gardiner was received offering to read a paper on " Geodesic Investigations ". However, Council refused to entertain his paper when " Hon. Treasurer informed Council Mr. Gardiner had not paid any subscription to the Society for the last eleven years ! "

Comparison of the membership lists of the Royal and Linnean Societies in 1875 shows 49 members common to both, including Stackhouse, the first Secretary of the Linnean Society, W. J. Stephens, Liversidge, James Cox and E. P. Ramsay. Although Macleay was elected a member of the Philosophical Society of New South Wales in August, 1856, he did not continue into the Royal Society in the 1860's. E. C. Merewether, Deas-Thomson and Sir William MacArthur belonged only to the Linnean Society in 1875, although the last-named was in the Royal Society in 1872. The Royal Society had an additional 106 members, the Linnean Society a separate 75.

Both societies began to develop rapidly, whether under the stimulus of competition as well as changing social conditions I cannot be positive. There was generally a separation into topics of Natural Science on the one hand (Linnean Society) and Physical Sciences on the other (Royal Society), although some overlap is apparent.

The organizing abilities of Liversidge, backed by his sustained efforts, were most important to the Royal Society, while there is no doubt Macleay's personal backing of the Linnean Society both with energy and cash helped it to consolidate.

The importance of regular printing of the Royal Society's journal by the Government Printer should also not be overlooked. This commenced in 1873 but needed Liversidge's editorial capabilities to give the journal a new format.

A further stimulus for science occurred late in 1874, when a number of observation stations were set up in New South Wales to observe the transit of Venus. Details of this highly successful activity are given by Russell (1892).

The Garden Palace Fire

One of the tragedies for the historians of Australian Science occurred on 22nd September, 1882. This was the destruction of the Garden Palace by fire. The building had been used for the very successful International Exhibition of 1879–80 and must be considered one of the most remarkable achievements of James Barnet, the Colonial Architect. It certainly is an indication of the level which technology had achieved in the colony at that time. Barnet was given his first instructions for preparation of plans about the middle of December, 1878, building commenced on 13th January, 1879, " yet on the 17th September, exactly eight months afterwards, the building was finished, and the Exhibition was opened . . . ". " To accomplish the work . . . much of it had to be done at night, with the aid of the electric light." It covered a site of more than five acres, was 800 ft. north to south, 500 ft. east to west: the main dome 100 ft. in diameter reached a height of 210 ft. above the ground. In addition there were four entrance towers and 10 minor towers. Construction was largely of brick and timber, and the cost a little over £198,000.

Following the highly successful Exhibition, the building was converted for use by various Government departments and societies. On the ground floor was the new Technological and Sanitary Museum, office of the Mining Department, the office and museum of the Linnean Society, and " a very extensive museum of Geological specimens arranged by the officers of the Department of Mines ". The fire destroyed many precious documents and specimens. " It is estimated by Mr. Moore, the Curator of the Botanic Gardens, that about 20,000 or 30,000 plants are nearly all destroyed ". Along with all the fossils, minerals and rocks collected by the Mining Department was " the collection of the late Rev. W. B. Clarke, which, with Mr. Clarke's maps and library, cost the Government £7,000." The whole collection had an estimated value of £50,000.

The Linnean Society suffered to the extent of over £2,500. It lost the whole of its library, comprising donations and exchanges and about £1,200 worth of books recently purchased by William Macleay, together with its collection of plants and all its publications, while the Rev. Tenison-Woods lost books worth £1,500. Along with many works of art, the results of the 1881 census were also lost ; *The Sydney Morning Herald* wrote caustically " there can be no doubt that a feeling of the utmost indignation will pervade all classes of the community when it is realized that that information which has cost so much to collect . . . is now irreparably lost ".

The Council of the Linnean Society met the same day as the fire to consider what action to take, and a general meeting of members was called to discuss the Society's situation. In the event the Society decided on a policy of " business as usual ".

The Geographical Society of Australasia— The First Australia-wide Society

It is not generally remembered that this Society was closely related to the Royal Society of New South Wales. One of Liversidge's changes introduced into the Royal Society was the provision of specialist sections. These first became active in 1876. [Similar specialist sections were introduced about the same time in the Royal Societies of Victoria and South Australia.] Initially, allowance was made for nine sections — Astronomy and Physics, Chemistry and Mineralogy, Geology and Palaeontology, Zoology and Botany (including Entomology), Microscopical Science, Geography and Ethnology, Literature and Fine Arts (including Architecture), Medical Science, and Sanitary Science (and Statistics). These had varying success, but by 1882 only two, the Microscopical and Medical sections, were active. There were, however, later section renewals and developments.

The Geographical section was one which had lapsed after some activity. However, on 2nd April, 1883, a meeting took place, at the home of Dr. Belgrave, " for the purpose of either reorganising the Geographical Section of the Royal Society, or forming a new and entirely independent organisation on a co-operative basis to apply to all the Australasian Colonies ". Among those present were Mr. Gerard and Mr. Du Faur, secretary and chairman respectively of the " defunct Geographical Section ". Du Faur " related in considerable detail the efforts made by the Council of the Royal Society for establishing a Geographical Section. In spite of every effort it lapsed, the Chairman and Secretary becoming ultimately the only attendants at meetings ". Du Faur was inclined to think the geographers should stick to the Royal Society largely because of its healthy bank balance.

However, the others at the meeting thought that the time had come for an Australia-wide society as they had received a favourable reaction from interested persons in other colonies.

The original name chosen was The Federal Geographical Society of Australasia, and (Professor) W. J. Stephens was careful to define Australasia : " the Australian region as defined by W. Wallace shall be recognised by this Society as the space within which the operations shall be concentrated ". The enthusiastic Frenchman E. Martin La Meslée was elected as Secretary, while Stephens became Vice-President. No President was named.

Political pressure existed even in those days, and Sir John Robertson's comment at the final organizational meeting that the word " Federal " in the Society's title could lose it many friends did not go unheeded : the title became merely " The Geographical Society of Australasia ".

The inaugural meeting of the Society was a " grand spectacular " held on 22nd June, 1883, at the Protestant Hall in Castlereagh Street. After an introduction by Professor Stephens, Meslée presented a long paper on the Exploration of New Guinea. Between 700 and 800 packed the hall to get the Society off to a good start.

However, the organizers were determined on a continent-wide society which could sponsor exploration—especially of the unknown parts of New Guinea. Interested persons in Melbourne met on 13th August, 1883, to discuss the formation of a Victorian branch. J. Cosmo Newbery. Director of the Victorian Museum, pointed out that the Royal Society of Victoria had a geographical section which it might be better to join while still maintaining affiliation with the Geographical Society of Australasia. A committee was appointed to confer with the Council of the Royal Society (of Victoria) " as to the practicability of amalgamation ". However, this does not seem to have eventuated and a separate organization, with Baron Von Mueller as Vice-President and A. C. MacDonald as Secretary, was created. Developments were slower in other States, but in July, 1885, both Queensland and South Australia set up branches.

Two " Federal Council " meetings were held. The first, called " The Australian Geographical Conference ", met at the Melbourne Town Hall between 17th and 23rd December, 1884. At this meeting Sir Edward Strickland (from the New South Wales branch) was named President and Baron Von Mueller Vice-President. The meeting also decided that similar conferences should be held by a combination of branches " for the purpose of discussing periodically important matters affecting the interests of geographical science in Australia ".

The second interstate meeting appears under the title " Second Interprovincial Geographical Conference ", held at the rooms of the South Australian branch of the Royal Geographical Society of Australasia in Adelaide during September, 1887. At this meeting, attended by delegates from New South Wales, Victoria and South Australia, there was considerable discussion on the need for incorporating the Society and for drawing up a satisfactory Federal constitution which had not yet been achieved. The general opinion of the meeting was that the Society needed to be kept united.

The New South Wales branch persisted at least till 1898. In 1893 we find its proceedings published as the *Journal and Proceedings of the Royal Geographical Society of Australasia*, and there is little or no mention of other branches. However, there was apparently still co-operation between the branches.

The Victorian branch persisted as an independent body till about 1918, after which it incorporated with the Victorian Historical Society. The Queensland and South Australian branches have continued to the present as an important heritage of this first attempt to link scientists in an Australia-wide scientific society.

Attempts to form a Geological Society of Australasia were less ambitious, but likewise aimed at a continent-wide representation (Branagan and Vallance, 1967).

The Geological Society might well have become Australia's first permanent professional specialist scientific body similar to those operating today. However, it was thwarted to some extent by the formation in Broken Hill in 1893 of the Australian Institute of Mining Engineers. Coinciding with the growth of mining, this institute grew rapidly and soon received company support.

When the institute moved to Melbourne it and the Geological Society had their offices in the same building. However, both retained their separate identities. While the Institute continued to grow, the Geological Society did not. The Society finally ceased to function in 1905.

Shortly after the formation of the Geographical and Geological Societies, a more successful Federal body came into being. This was the loosely-linked Australian Association for the Advancement of Science (A.A.A.S.—later A.N.Z.A.A.S.), the " brainchild " of Archibald Liversidge. The A.A.A.S., which first met in 1888, has proved surprisingly effective. Its formation has been adequately described by Russell (1888).

Professional Societies

(i) *The Engineers*

It is not possible to go into the development of these societies in any detail, but a few interesting aspects deserve mention. As we have shown earlier, engineers such as Denison and Clarke (as well as Professor William Henry Warren) contributed to the various learned societies during the 19th century, and in fact have continued to do so until the present.

The first separate engineering society was the " Engineering Association of New South Wales ", established in 1870 (Pugh, 1970). A separate similar society was established in 1883 in Melbourne.

The first moves for amalgamation of the various State bodies (which were many) were made in 1910, and final agreement was reached in 1917 (Corbett, 1957). One of the largest groups of engineers—the Northern Engineering Institute of New South Wales based in Newcastle—was hesitant about joining a federation, but finally decided to join.

The objectives of the Federal body were very different from those of the 19th century societies. First and foremost it was concerned with professional objectives, such as qualifications, ethics, conditions of work, and salaries. Technical and scientific matters, although not neglected, were subordinate.

(ii) *Organization of the Chemists*

The Australian Chemical Institute was formed in 1917 largely through the efforts of Sir David Orme Masson of Melbourne (Leighton, 1954). The co-operation of societies in other States was not won easily. Masson realized the need for winning over the New South Wales chemists, and spent considerable time in Sydney during 1916 and 1917 working with Professor Charles Fawsitt to build up support.

The Australian Chemical Institute achieved incorporation by Royal Charter in 1932. From 1917 to 1934 the headquarters of the Council were in Sydney, during which time the Institute grew to a membership of nearly 1,000. This contrasts with a total number of about 200 Australian chemists in 1904.

In 1934 the headquarters were moved to Melbourne with the idea that a periodic transfer of central responsibility from State to State would prove stimulating. At the same time publication of a journal was commenced to replace the earlier use of the pages of the *Australian Chemical and Mining Journal.*

From its inception, the Institute showed its concern for qualifications, professional conduct and service to the community. Likewise the Institution of Engineers and the Australasian Institute of Mining and Metallurgy (originally the Australian Institute of Mining Engineers—reorganized in 1918) directed their attention to these matters with subordinate interest in matters of research.

At this time the lot of the scientist, and particularly the chemist, was not good.

About 1917 the Victorian Department of Mines advertised for a B.Sc. graduate with a sound knowledge of chemical analysis for research on the distillation of brown coal. The salary offered was £72 per annum ! Willsmore (1921) remarks drily that the then Victorian Minister for Mines, in a lecture given to the Royal Society of Arts in London, claimed for his department great credit for its zeal in stimulating chemical research !

However, it must be sadly confessed that it was the Great War which proved the major stimulus to chemistry in this country. The drastic shortage of chemists in Britain at the beginning of the war in 1914 left the country far behind the German war effort. The result of this was a massive recruiting campaign in Australia and other parts of the Commonwealth.

There can be little doubt that the return of many of these chemists to Australia, aware of their capabilities and their usefulness in the developing economy, helped to create an efficient professional body out of the Australian Chemical Institute.

There is clearly a relation between the growth of a professional spirit amongst engineers and scientists and the development of the new universities of Queensland (1911) and Western Australia (1913). In both of these institutions Engineering and Chemistry and other science professorships were among those first created, taking precedence over more classical topics—something which would have been unthinkable 30 years earlier.

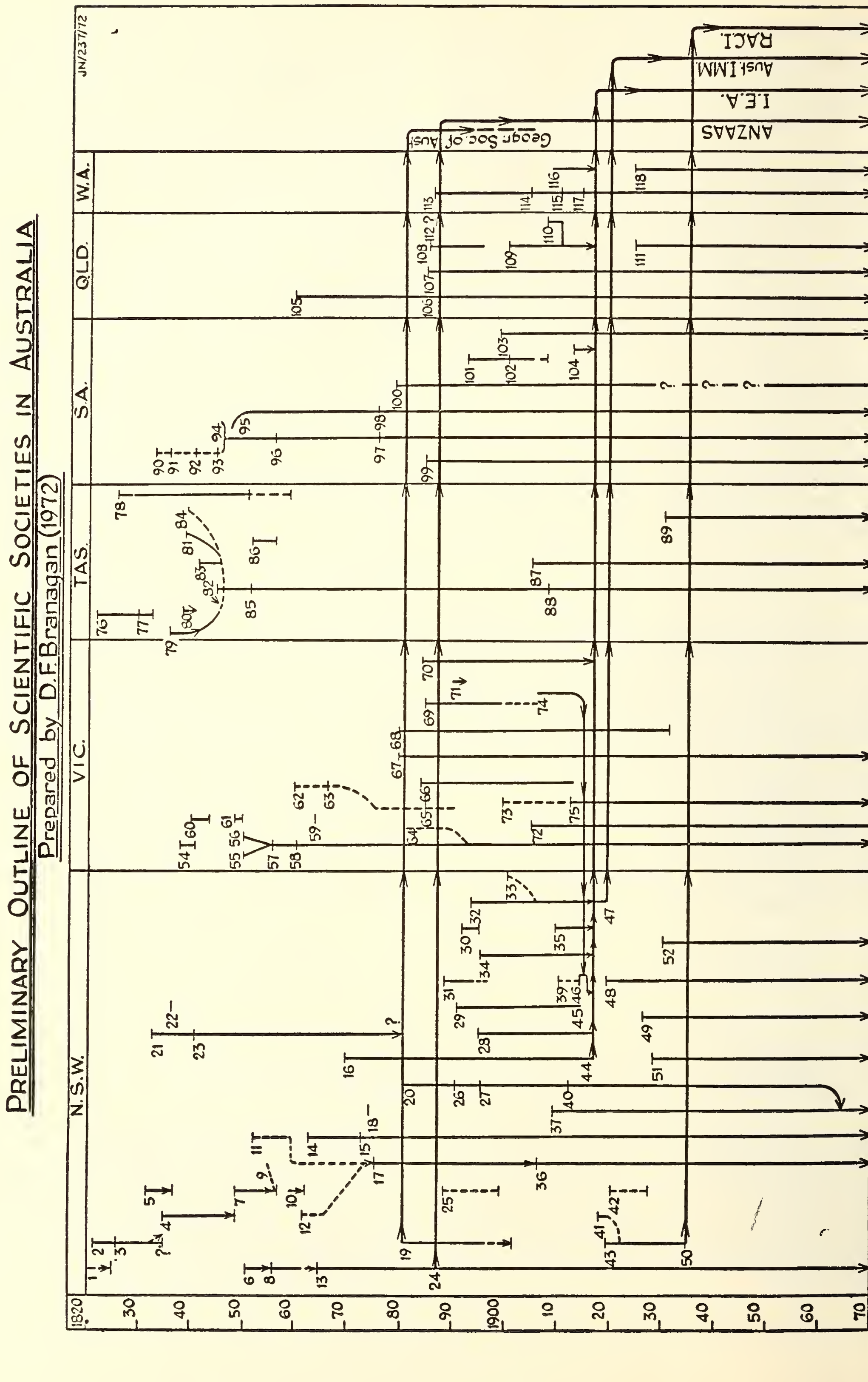
Something of the pattern of growth of Australian Science is shown in Table 1, which must still be regarded as a preliminary list of the scientific societies which have existed within Australia.

Key to Table

Note 1 : No attempt made to list Societies formed since 1950.
Note 2 : Societies 21, 22 and 23 have been studied up to the 1880's. The ? at the foot of this line refers to the continuation of 23. 23 did not join the Geographical Society of Australasia.

New South Wales Societies

1. Philosophical Society of Australasia.
2. Agricultural Society of New South Wales.
3. Agricultural and Horticultural Society of New South Wales.
4. Australian Floral and Horticultural Society.
5. The Australian Society to Promote the Growth and Consumption of Colonial Produce and Manufactures.
6. Australian Philosophical Society.
7. Australian Botanic and Horticultural Society.
8. Philosophical Society of New South Wales.
9. Horticultural Improvement Society of New South Wales.
10. Australian Horticultural and Agricultural Society.
11. Zoological Society of Sydney.
12. Acclimatisation Society.
13. Royal Society of New South Wales.


PRELIMINARY OUTLINE OF SCIENTIFIC SOCIETIES IN AUSTRALIA
Prepared by D.F.Branagan (1972)
JN/237/72
N.S.W.
VIC.
TAS.
S.A.
QLD.
W.A.
Geogr. Soc. of Aust.
ANZAAS
I.E.A.
Aust I.M.M.
RACI.

14. Entomological Society of New South Wales.
15. Linnean Society of New South Wales.
16. Engineering Association of New South Wales.
17. Zoological and Acclimatisation Society of New South Wales.
18. Botanic Society of Sydney.
19. Geographical Society of Australasia (New South Wales Branch).
20. Naturalists Society of New South Wales.
21. Mechanics Institute of Sydney.
22. Mechanics Institute of Newcastle.
23. Sydney Mechanics School of Arts.
24. Australasian Association for the Advancement of Science.
25. St. George's District Natural Science Society.
26. Naturalists Union of New South Wales.
27. New South Wales Naturalists Club.
28. Electrical Association of New South Wales.
29. Electrical Club of New South Wales.
30. Northern Engineering Institute of New South Wales.
31. Bathurst Scientific Society.
32. Australian Institute of Mining Engineers (Broken Hill).
33. Broken Hill Scientific Society.
34. Sydney University Engineering Society.
35. Northern Engineering Institute of New South Wales.
36. Royal Zoological Society of New South Wales.
37. Wild Life Preservation Society of New South Wales.
38. This number not used.
39. Maitland Scientific and Historical Research Society.
40. Naturalists Society of New South Wales.
41. Australian Chemical Association.
42. Microscopical Society of New South Wales.
43. Australian Chemical Institute.
44. Institute of Engineers, Australia.
45. Amalgamation of Electrical Club of New South Wales and Electrical Association of Victoria (74).
46. Electrical Association of Australia.
47. Australasian Institute of Mining and Metallurgy.
48. Barrier Field Naturalists Club.
49. Geographical Society of New South Wales.
50. Royal Australian Chemical Institute.
51. Anthropological Society (of New South Wales).
52. Royal Society of Australia (later of Canberra).
53. ——

Victorian Societies

54. Mechanics Institute of Melbourne.
55. Victorian Institute for Advancement of Science.
56. Philosophical Society of Victoria.
57. Philosophical Institute of Victoria.
58. Royal Society of Victoria.
59. Brunswick Ornithological Society.
60. Mechanics Institute (? of Victoria).
61. Geological Society of Victoria.
62. Zoological Society of Victoria.
63. Zoological and Acclimatisation Society of Victoria.
64. Microscopical Society (of Victoria).
65. Zoological Acclimatisation Society.
66. Geographical Society of Australasia (Victorian Branch).
67. Field Naturalists Club of Victoria (Melbourne).
68. Geelong Naturalists Club.
69. Geological Society of Australasia.
70. Victorian Institute of Engineers.
71. Melbourne University Engineering Society.
72. Bird Observers Club of Victoria.
73. Australasian Ornithologists' Union.
74. Electrical Association of Victoria.
75. Royal Australasian Ornithologists Union.

Tasmanian Societies

76. Van Diemen's Land Agricultural Society.
77. Van Diemen's Land Scientific Society.
78. Mechanics Institute of Hobart (? Van Diemen's Land Mechanics Institute).
79. The Tasmanian Society.
80. Franklin Museum (Arcanthe) Botanical and Horticultural Society of Van Diemen's Land.
81. Launceston Horticultural Society.
82. Royal Society of Van Diemen's Land for Horticulture, Botany and the Advancement of Science.
83. Hobart Town Agricultural Society.
84. The Midland Society.
85. Royal Society of Tasmania for Horticulture, Botany and the Advancement of Science.
86. Ornithological Society of Tasmania.
87. Tasmanian Field Naturalists' Club.
88. Royal Society of Tasmania.
89. Astronomical Society of Tasmania.

South Australian Societies

90. South Australian Literary and Scientific Association.
91. Adelaide Mechanics Institute.
92. South Australian Subscription Library.
93. South Australian Library and Mechanics Institute.
94. The Mechanics Institute (of Adelaide).
95. Adelaide Philosophical Society.
96. South Australian Institute.
97. Public Library and Museum of South Australia.
98. Royal Society of South Australia.
99. [Royal] Geographical Society of Australasia (South Australian Branch).
100. [Royal] Zoological Society of South Australia.
101. Astronomical Section (Royal Society of South Australia).
102. South Australian Astronomical Association.
103. South Australian Ornithological Association.
104. South Australian Institute of Engineers.

Queensland Societies

105. Queensland Philosophical Society.
106. Royal Society of Queensland.
107. [Royal] Geographical Society of Australasia (Queensland Branch).
108. [Queensland] Mechanical Engineering Association.
109. Queensland Institute of Engineers.
110. Queensland Electrical Association.
111. North Queensland Naturalists' Club.
112. Rockhampton Scientific Society.

Western Australian Societies

113. Mueller Botanical Society of Western Australia.
114. Western Australia Natural History Society.
115. Natural History and Scientific Society of Western Australia.
116. Engineering Institute of Western Australia.
117. Royal Society of Western Australia.
118. Western Australia Naturalists' Club.

My aim has been to show something of the growth of a community spirit among Australian scientists and to point to a few of the people who were responsible.

I have attempted only to give an inkling of the threads which can be traced through our history. We have seen some of the achievements of the infant societies, the effects of organization, wise Vice-regal patronage and Government assistance, the desire for and achievement of Australia-wide organizations, the successful linking of widely separate disciplines, and the professional organization of scientists both for their own benefit and the good of society.

Perhaps I have not shown the humanity of the people who make up this fascinating web. This topic must be left to another occasion.

Acknowledgements

The Council of the Royal Society of New South Wales kindly allowed me access to their archives. Mrs. Collier and Mrs. Proctor, of the Royal Society staff, helped me considerably in using the Society's library facilities.

I wish also to thank Miss Pam Green, Fisher Library Rare Books, the Librarian, Public Library of New South Wales, and the staff of the Mitchell Library and Professor T. G. Vallance and Mr. Gilbert Whitley. Funds from the University of Sydney Research Grant were used in the preparation of this paper.

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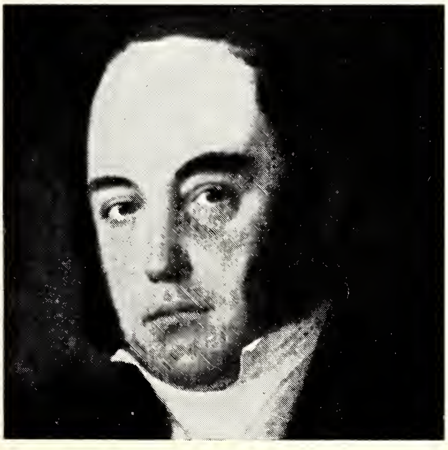
John Oxley.

Barron Field.

Patrick Hill.



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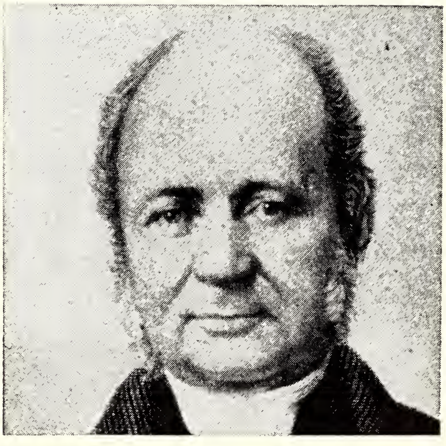

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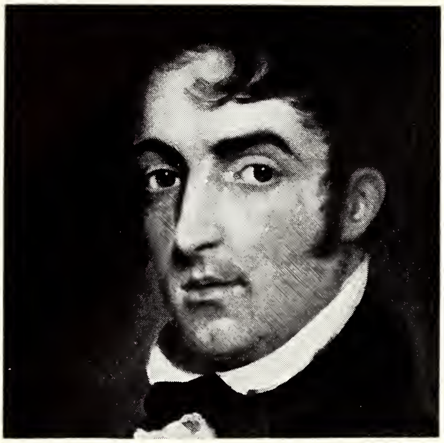

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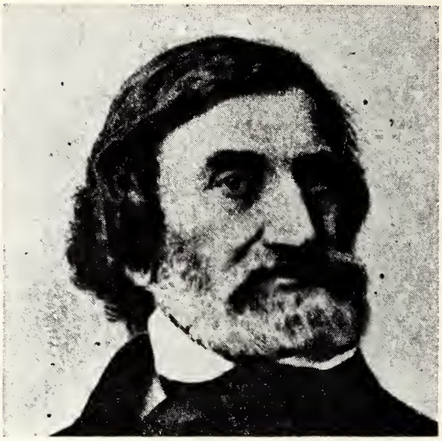
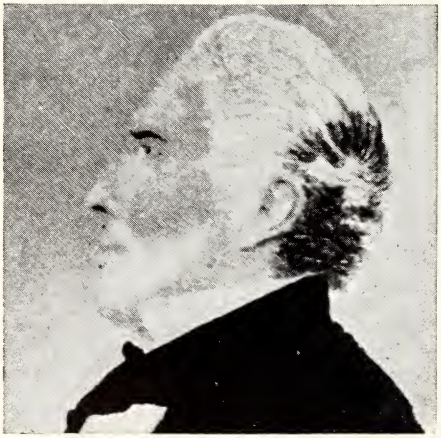


C. S. Rumker.

Governor Sir Thomas Brisbane.



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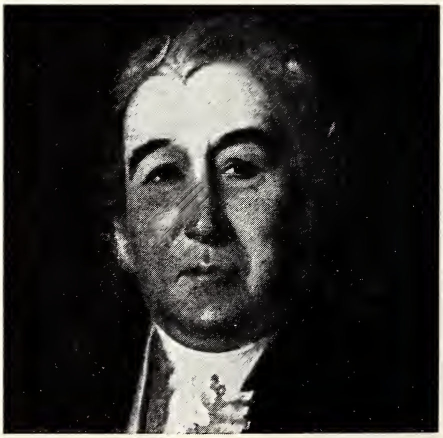

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(Received 16 October 1971)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, pp. 143–149, 1972

Radiation Pressure and Related Forces*

William E. Smith

Abstract—The phenomenon of radiation pressure is introduced and briefly surveyed. The Larmor theorem and the adiabatic theorem are used to deduce expressions for radiation pressure, and to show that radiation pressure is a normal concomitant of wave propagation.

Electromagnetic radiation pressure is discussed in some detail using the author's generalized steady force theory for arbitrary loss-free systems. This approach emphasizes the unity of radiation pressure, and quasi-stationary forces, regarded here as related forces. It is shown that the generalized adiabatic theorem includes the content of much previous theoretical work. Practical applications are also discussed.

A similar formulation is given for acoustics leading to a corresponding generalized adiabatic theorem. Radiation pressure effects in oceanography are mentioned briefly but not discussed in detail.

I. Introduction

When a wave is physically reflected or absorbed, a mean pressure is exerted on the reflector or absorber. This pressure is known as radiation pressure. For electromagnetic waves (e.g. light) it arises as a time average of the Maxwell stress tensor, while for acoustics (sound) or surface waves on fluids it is due to second order terms from the non-linear equations of hydrodynamics. The effects are intimately connected with the assignment of linear momentum to wave motion ; radiation pressure then being the result of reversal or absorption of the linear momentum of the radiation. We shall see from the Larmor and adiabatic theorems that radiation pressure is to be expected from waves of almost any kind, although detailed attention will be given only to electromagnetic and sound waves with a brief mention of surface waves on fluids.

We might ask for situations where radiation pressure is directly observable. Consider firstly electromagnetic radiation. Optometrists for many years displayed a device which was supposed to illustrate radiation pressure from sunlight. A set of paddles was delicately suspended in an evacuated glass container so that pressure on the paddles would cause the paddle wheel to rotate. One side of the paddles was shiny and reflecting and the other sides blackened and absorbing. Radiation pressure on the reflecting side would be approximately twice as great as on the absorbing side leading to a rotational torque when placed in sunlight. Unfortunately these devices rotate in the opposite direction from that first expected. The resolution is with the secondary effects due to residual gas molecules in the evacuated container. The blackened side becomes hotter than the reflecting side and the counter rotational torque is the result of recoil momentum from the heated gas molecules leaving the paddles. Another classic case can also be quoted. A comet's tail is deflected away from the sun on close approach. Radiation pressure from sunlight will contribute to this bending. However, the effect of radiation pressure is far outweighed by the solar wind. Several romantics in the early days of the space exploration era proposed the use of sail boats using radiation pressure rather than wind for voyages through space. (The parallel is not complete since the keel plays an essential rôle with conventional craft.) Presently, we shall see that under most circumstances radiation pressure for the wave regime is an exceedingly small effect.

Accurate measurements confirming the existence of radiation pressure were made for light by Lebedew (1901) and Nichols and Hull (1901, 1903). Beth (1936), in a set of classic

* Presidential Address delivered to the Royal Society of New South Wales at Science House, Gloucester Street, Sydney, on 7th April, 1971.

experiments, measured the angular momentum of suitably polarized light. Practical applications for electromagnetic radiation pressure effects have been found in the microwave part of the spectrum. Carrara and Lombardini first made microwave radiation pressure measurements in 1949. A whole series of microwave radiation pressure power meters resulted from the work of Cullen and his collaborators in the 1950's. In fact, many familiar measuring instruments (electrostatic voltmeters, moving-iron ammeters or current dynamometers) may be regarded as limiting cases of radiation pressure devices. The general theory for the production of steady forces in electromagnetic systems (Section IV) makes no sharp distinction between the quasi-static and wave regimes.

In acoustics, too, radiation pressure may be used for the absolute measurement of energy flux. A circular disc suspended by a fibre along a diameter as axis experiences a torque from radiation pressure when placed in a sound field. This device, known as the Rayleigh disc, and other devices based on radiation pressure, have been supplanted, except for ultrasonics, by the development of the reciprocity technique, largely because of their inconvenience, fragility and poor accuracy.

The above examples indicate that although radiation pressure is a widespread phenomenon, it usually gives rise only to small effects, and often very great care is required to detect it at all. There is no fear of being knocked over by the radiation pressure from sunlight or by the heat of radiation from a furnace. We shall see from Sections II and III that for a plane wave the radiation pressure P is of the order of the energy density U, allowing us to estimate magnitudes. The solar flux at the surface of the earth is about $1{\cdot}4\ \mathrm{kW/m^2}$. To obtain the corresponding energy density we must divide by the wave velocity c ($\doteqdot 3\times 10^8$ m/sec).

$$\therefore\ P \doteqdot 4{\cdot}7\times 10^{-6}\,\mathrm{Pa} \quad (1\ \mathrm{Pascal}=1\ \mathrm{N/m^2}).$$

On noting that atmospheric pressure is about 10^5 Pa, we see why radiation pressure is usually negligible. Even at the surface of the sun $P \doteqdot 0{\cdot}2$ Pa, while a powerful laser beam with a Poynting vector of $10^7\ \mathrm{kW/m^2}$ produces a pressure of only 33 Pa. However, when we regard quasi-stationary electric and magnetic forces as related forces, significant pressures arise from accessible fields. The magnetic pressure in vacuo from a magnetic induction of $0{\cdot}5$T (5,000 gauss) is about 10^5 Pa (≈ 1 atmosphere). For an electric field of 3×10^6 V/m the pressure is about 40 Pa.

Electromagnetic radiation pressure also arises in equilibrium thermodynamics from the presence of black body radiation. For isotropic radiation $P=U/3$, and classical thermodynamics leads to the form of the Steffan-Boltzmann law (the constant of proportionality requires quantum statistical mechanics). Equilibrium black-body radiation pressure is very small at ordinary temperatures (containment pressure $\approx 2\times 10^{-6}$ Pa at 300 K), but because of its proportionality to the fourth power of temperature it increases dramatically with temperature provided the hypothetical containment vessel provides a sufficient barrier to the increasingly shorter wavelengths constituting the radiation.

For sound, a given energy flux will produce a much larger radiation pressure because the velocity of propagation is so much smaller. Since $c\approx 330$ m/sec for sound, this factor is about 10^6, so that a flux of $1\ \mathrm{kW/m^2}$ gives $P \doteqdot 3$ Pa.

In Sections II and III the Larmor and adiabatic theorems are used to assess the magnitude of radiation pressure forces, and to show that radiation pressure is a natural concomitant of wave propagation. Section IV discusses electromagnetic radiation pressure forces in some detail and shows how radiation pressure and quasi-stationary electromagnetic forces can be integrated into a single generalized average force theory. Section V deals with a similar formulation for acoustics and Section VI briefly mentions the occurrence of radiation pressure effects in oceanography.

II. The Larmor Theorem on Radiation Pressure

An elementary energy conservation argument leads to the radiation pressure developed by reflection of a plane wave. Consider a plane wave travelling in the x direction incident normally on a reflector which itself is moving very slowly with velocity $-u$ in the x direction. The position of the reflector at time t is $x=-ut$.

Suppose the incident wave is represented by the wave amplitude

$$a_i \cos \omega_i(t-x/c) \quad \ldots\ldots\ldots\ (1)$$

where c is the phase velocity and ω_i the angular frequency of the incident wave. The reflected wave amplitude may be taken as

$$a_r \cos \omega_r(t+x/c) \quad \ldots\ldots\ldots\ (2)$$

with $\omega_r \neq \omega_i$ to account for the Doppler shift in frequency brought about by the moving reflector. The wave propagation is assumed non-dispersive in regarding c as unchanged, and in these circumstances no distinction need be made between group and phase velocities.

At the reflector surface ($x=-ut$) the total amplitude is zero for all t, i.e.

$$a_i \cos \omega_i(t+ut/c)+a_r \cos \omega_r(t-ut/c)=0 \qquad (3)$$

i.e. $a_i+a_r=0$ .... (4)

and $\omega_r/\omega_i=(c+u)/(c-u)$ (non-relativistic Doppler formula) .... (5)

Now suppose the radiation pressure exerted on the reflector is P. We consider the energy balance between the incident and reflected waves, and the rate of work done against the radiation pressure in moving the reflector. The reflected wave has a different energy flux from the incident wave because, although it has the same amplitude, it has a different frequency. We suppose as for mechanical waves (e.g. sound), that the energy density U is proportional to the square of the velocity of wave motion, i.e. ω^2. The rate at which energy hits the reflector/m² in a long train of the incident wave is

$$U(\omega_i)(c+u) \qquad (6)$$

The rate at which energy goes into the reflected wave is

$$U(\omega_r)(c-u) \qquad (7)$$

The difference in these two fluxes is maintained by the work done against the radiation pressure force.

I.e., $U(\omega_r)(c-u)-U(\omega_i)(c+u)$
=rate of work done against the radiation pressure
$=Pu$ (as $u\rightarrow 0$) .... (8)

But $U(\omega_r)/U(\omega_i)=\omega_r^2/\omega_i^2=(u+c)^2/(u-c)^2$
from (5) .... (9)

∴ from (8)

$$2uU(\omega_i)(c+u)/(c-u)=Pu \qquad (10)$$

and as $u\rightarrow 0$

$$P=U_i+U_r \qquad (11)$$

=total energy density (Larmor theorem).

For electromagnetic waves, modification is required since $U(\omega)$ is independent of frequency for constant field amplitude. Equation (4) must be modified in this case. The electric field E should be transformed to the moving frame of the reflector before setting the total amplitude zero.

c

The transformed fields (non-relativistic since $u\rightarrow 0$) are

$$E_i'=E_i(1+u/c) \qquad (12)$$
$$E_r'=E_r(1-u/c)$$

giving

$$-E_r/E_i=(c+u)/(c-u) \qquad (13)$$

after setting $E_i'+E_r'=0$.

Then

$$U_r/U_i=(c+u)^2/(c-u)^2 \qquad (14)$$

which is the same as equation (9) and the same radiation pressure is obtained.

It is clear that energy flux arguments of the above type could be applied to any wave motion, and unless very special conditions are fulfilled, radiation pressure will result. The limitation of the discussion to non-dispersive waves is not essential to this conclusion. However, the discussion is based on energy conservation, so the wave propagation must be sensibly loss-free. The same requirement appears in the other approaches to follow.

III. Radiation Pressure from the Adiabatic Theorem

Another general approach to the deduction of radiation pressures is provided by the adiabatic theorem (Brillouin, 1964). The adiabatic theorem, otherwise known as the Boltzmann-Ehrenfest theorem, or in electromagnetism as the resonator action theorem (Maclean, 1945), was obtained in mechanics by Boltzmann (1904). For our application to linear oscillatory systems it may be simplified to

$$\delta(W\tau)=0 \qquad (15)$$

where W is the energy and τ the period of some oscillatory mode, and δ denotes a small adiabatic variation generated by a slow change in some parameter of the system. A simple mechanical example illustrating the theorem is provided by a pendulum formed when a weight is suspended on a string from a fixed point. If a ring slipped over the string is held steady, and slowly (i.e. over many periods of the pendulum) moved vertically so as to alter the effective length of the pendulum, the period and energy of the motion of the pendulum will satisfy (15), i.e. $W\tau$=constant, for small amplitudes of vibration. The change of energy results because work is done in moving the ring, and this work is related by the adiabatic theorem to the change in period.

For our application to radiation pressure, we consider a resonator formed by the reflection of plane waves between two plane parallel reflectors separated by a distance l. The reflector separation is to be slightly changed very slowly to $(l+\delta x)$ (i.e. adiabatically). Suppose ω is the resonant angular frequency, λ the wavelength, and c_p, c_g the phase and group velocities of the waves. For resonance

$$l=n\lambda/2 \qquad (16)$$

where n is some integer,

i.e.
$$l=n\pi c_p/\omega \qquad (17)$$

When l is changed to $(l+\delta x)$ adiabatically, the frequency will change so that (17) is still satisfied with the same n. Allowing for the possibility of dependence of c_p on ω, we obtain from (17)

$$\delta x=n\pi\{c_p-\omega(dc_p/d\omega)\}\delta(1/\omega) \qquad (18)$$

However, equation (15) is equivalent to

$$\delta W+\omega W\delta(1/\omega)=0 \qquad (19)$$

Eliminating $\delta(1/\omega)$ from equations (18) and (19) gives

$$\delta W+\omega W\delta x/n\pi(c_p-\omega dc_p/d\omega)=0 \qquad (20)$$

In the adiabatic displacement, δW arises because of the work done by radiation pressure on the reflectors. If F_x is the total radiation pressure force on the reflectors

$$\delta W=-F_x\delta x \qquad (20)$$

Substitution in (20) gives

$$F_x=\omega W/n\pi(c_p-\omega dc_p/d\omega) \qquad (21)$$
$$=(W/l)(c_g/c_p) \qquad (22)$$

$\therefore$ Radiation pressure $P=U_t(c_g/c_p)$ (23)

where U_t is the total radiation density in accord with the result of Section II, but this time the possibility of dispersion has been allowed for. Because energy is transported at the group velocity, the linear momentum flux associated with an energy flux $\mathbf{N}$ is $\mathbf{N}/c_p$. A simple case of dispersive waves complying with this result occurs when electromagnetic waves travel along a waveguide. If a material medium is present, there are additional problems in applying the adiabatic theorem because of compression or displacement of the medium (Brillouin, 1964).

IV. Electromagnetic Radiation Pressure Forces

Having discussed radiation pressure in a general way from the Larmor theorem and the adiabatic theorem in the previous two sections, we return to the specific problem for electromagnetic radiation. It will be shown that an integrated formulation for the production of radiation pressure forces gives an expression valid for all regimes from free or confined wave propagation to the quasi-static forces more usually regarded as solely magnetic or electric in origin. In this formulation there is no sharp division between wave pressures and quasi-stationary magnetic or electric pressures. The results are summarized in the generalized adiabatic theorem.

In electromagnetic theory radiation pressure results from time averages of the Maxwell stress tensor (Panofsky and Phillips, 1962). Consequently, in the general case there is a tensor of radiation pressure which is not an isotropic pressure at all. This aspect of the misnomer " radiation pressure " has been consistently emphasized by L. Brillouin (1964). However, in simple contexts the companion concepts of linear or angular momentum of radiation (Panofsky and Phillips, 1962) may lead to simple physical derivations of radiation pressure produced forces. For example, if a plane wave impinges on a simple scatterer, conservation of the total linear wave momentum of the incident plane wave and the scattered waves leads to the average force exerted on the scatterer. A slightly more involved calculation (especially so because of the various possible polarizations) using the conservation of angular momentum would lead to the average torque exerted on the scatterer. This type of approach tends to be useful only for single scattering, although its application is not confined to free waves. It can be applied equally well to guided wave situations (Cullen, 1966, and accompanying papers).

Cullen (1952) considered another approach to a considerably more general system, where two wave guides (an input and an output) transmitted radiant energy through a general loss-free system in which some generalized mechanical co-ordinate x was a parameter. Cullen was able to apply the resonator action theorem (adiabatic theorem) (Maclean, 1945) to provide a means for deducing the average generalized force F_x corresponding to the parameter x. The formula obtained involved only variations in the behaviour of the total system as observed from the waves in the input and output wave guides, as the parameter x was varied. This work resulted in the development of a series of absolute microwave power meters (Cullen and Stephenson, 1952 ; Cullen, Rogal and Okamura, 1958 ; Cullen, 1966).

To generalize further, we consider an arbitrary loss-free electromagnetic system excited from the exterior. It has been shown (Smith, 1961) that the average generalized force F_x corresponding to a generalized co-ordinate x of the system can be expressed as

$$2i\omega F_x\delta x=\iint_S(\delta\mathbf{E}\times\mathbf{H}^*+\mathbf{E}^*\times\delta\mathbf{H})\,.\,d\mathbf{A}$$

(inward normal positive) .. (24)

where ω is the angular frequency of excitation (time dependence $\exp(i\omega t)$), **E** and **H** are complex r.m.s. electric and magnetic field vectors on a mathematical surface S enclosing the system, and δ denotes changes resulting from a small adiabatic variation of the parameter x. Equation (24) provides a general relationship between radiation pressure type forces and observable exterior behaviour for a general loss-free electromagnetic system. Appropriate specialization (Smith, 1964*a*) leads to Cullen's formula.

It is often convenient to describe an electromagnetic system by reactance **X**, susceptance **B**, or scattering **S**, parameter matrices (Montgomery, Dicke and Purcell, 1948) in which case equation (24) can be written in any of the forms

$$F_x=(1/2\omega)\mathbf{I}\dagger(\partial\mathbf{X}/\partial x)\mathbf{I} \quad \ldots\ldots (25)$$

$$F_x=(1/2\omega)\mathbf{V}\dagger(\partial\mathbf{B}/\partial x)\mathbf{V} \quad \ldots\ldots (26)$$

$$i\omega F_x=-\tfrac{1}{2}\mathbf{b}\dagger(\partial\mathbf{S}/\partial x)\mathbf{a} \quad \ldots\ldots\ldots\ldots (27)$$

where **I**, **V**, **a** and **b** are complex r.m.s. column vectors of current, voltage, incoming wave amplitudes and outgoing wave amplitudes respectively, and † denotes hermitian conjugates.

There are some very important features of equations (24) to (27). Firstly, only exterior behaviour and not internal details are required for their application. Secondly, by making use of suitable impedance, etc., standards, they may be used as the basis for an absolute calibration. Finally, from a theoretical point of view they make absolutely no distinction between wave and quasi-stationary force production. The one formulation gives results for both arbitrarily small and arbitrarily large frequencies. From this angle the family of radiation pressure and related forces is a very large one. Two simple limiting cases will show the correspondence between this general formulation and electrostatics or magnetostatics. If the system considered behaves as an inductor of inductance L excited by a current I, then equation (25) becomes the familiar magnetostatics formula

$$F_x=\tfrac{1}{2}I^2\partial L/\partial x \quad \ldots\ldots (28)$$

Similarly, for a capacitor C excited by a voltage V equation (26) reduces to the electrostatics formula

$$F_x=\tfrac{1}{2}V^2\partial C/\partial x \quad \ldots\ldots\ldots\ldots (29)$$

There is, in fact, an intimate connection between the adiabatic theorem of Section III and the force formulation giving equation (24). This interrelation can be expressed in the generalized adiabatic theorem (Smith, 1967)

$$\omega F_x dx+Wd\omega=\frac{1}{2i}\iint_S(d\mathbf{E}\times\mathbf{H}^*+\mathbf{E}^*\times d\mathbf{H})\,.\,d\mathbf{A}$$

$$\ldots\ldots\ldots\ldots (30)$$

where W is the average electromagnetic energy stored by the system. In addition to the adiabatic theorem and the steady force formula (eqn. (24)), this theorem also covers as special cases (i) the expression of energy storage W in terms of exterior behaviour and (ii) interconnections between forces and energy storage (Smith, 1966), e.g.,

$$F_x+\omega(\partial F_x/\partial\omega)_V=(\partial W/\partial x)_V \quad \ldots\ldots (31)$$

$$F_x+\omega(\partial F_x/\partial\omega)_I=(\partial W/\partial x)_I \quad \ldots\ldots (32)$$

Equations (31) and (32) reduce to well-known electrostatic and magnetostatic force/energy formulas if the second terms of the right-hand sides of equation (31) and (32) tend to zero as $\omega\to 0$. Equations (31) and (32) have been used to discuss the frequency dependence of some idealized measuring instruments (Smith, 1969).

To conclude this section, some incidental applications of steady forces in electromagnetic systems will be mentioned. As noted earlier, forces produced in this manner can be made the basis for the absolute calibration of electrical measuring instruments (e.g. microwave power meters in the wave regime). For many years low-frequency electrical standards have been based on the ampere derived from magnetostatic forces of the type described by equation (28). At the present time there are at least two standards laboratories (N.B.S. in U.S.A. and N.S.L. in Australia) working on the precision establishment of standards from electrostatic forces of the type described by equation (29).

Radiation containment of plasmas for fusion reactions has received some attention over the years of fusion device research. Proposals require enormous powers coupled with superconducting resonant cavities to reach the required magnetic inductions to give sufficient containment pressure. Why bother when static fields can be attained so much more easily?

The theoretical advantage of high-frequency fields is that the magnetostatic equation $\nabla \times \mathbf{B}=0$ in the containment region does not have to be satisfied. This opens the possibility of field configurations having a well of B which is desirable for containing a conducting plasma (Hatch, Hasan and Smith, 1969). There has been no thorough examination of the theoretical problems of radiation containment of dense plasmas and the technological problems are immense.

Eddy-current levitation forces (Okress *et al.*, 1952) where the levitation force is provided by average magnetic stresses are also related forces. In a loss-free idealization the generalized force theory is directly applicable. Unless the levitated body is superconducting, the loss-free idealization is unreasonable. Nevertheless the levitation force in the lossy case is still given by equation (28), where L is the effective inductance (Smith, 1965*a*, 1965*b*). This is an unexpectedly simple result in view of the problems connected with forces and radiation pressure when losses are not negligible. All of the previous theorems mentioned have required the loss-free condition somewhere in their derivations.

V. Acoustic Radiation Pressure

Much of what has been said for electromagnetic radiation pressure applies for acoustic radiation pressure. The problems are similar, but initially more complicated because of the non-linearities of the equations of hydrodynamics. A linear approximation is usually adequate in acoustics. Radiative pressure then arises as a second order non-linear correction. An enlightening way of looking at radiation pressure, which gives the appropriate tensor formulation and at the same time parallels the use of the Maxwell tensor in electromagnetism, is to consider the momentum flux density tensor (Landau and Lifshitz, 1959). The radiation pressure tensor is then obtained by time averaging this tensor using quantities derived from the linear approximation. In this way the tensor nature of radiation pressure follows directly.

Investigations of acoustic radiation pressure have centred around the average mechanical effects on a single scatterer. The historically important Rayleigh disc was treated by solving a hydrodynamical flow problem (Lord Rayleigh, 1945). The general form of the force exerted on a single scatterer is contained in Westervelt's (Westervelt, 1957) formula. Similarly, Maidanik (1958) has obtained an expression for the radiation pressure torque in terms of scattering amplitudes.

A generalized force theory (Smith, 1964*b*, 1965*c*) has been developed for arbitrary acoustic systems excited from the exterior in the same spirit as that in electromagnetism. Although the details of the derivation are naturally very different, the final result is very similar to equation (24).

$$\omega F_x \delta x = \tfrac{1}{2} i \iint_S (p \delta \mathbf{v}^* + \mathbf{v} \delta p^*) \cdot d\mathbf{A} \quad \ldots \quad (33)$$

(inward normal positive)

where p and $\mathbf{v}$ are the complex r.m.s. pressure and velocity fields on a mathematical surface enclosing the system and δ denotes an adiabatic variation of the generalized co-ordinate. When expressed in parameter matrix forms (Smith, 1964*b*, 1965*c*), equation (33) gives the same results as in electromagnetism (i.e. equations (25)–(27)). (There are some errors of detail in the cited references, but the results are nevertheless true). Equation (33) can be used as the starting point for alternative derivations of the formulas of Westervelt and Maidanik for single scattering (Smith, 1972).

A generalized adiabatic theorem for acoustics has also been propounded (Smith, 1971) :

$$\omega F_x dx + W d\omega = \tfrac{1}{2} i \iint_S (p d\mathbf{v}^* + \mathbf{v} dp^*) \cdot d\mathbf{A} \quad \ldots \ldots \ldots \ldots \quad (34)$$

Analogously to the corresponding electromagnetic theorem (equation (30)), this theorem includes the ordinary adiabatic theorem, the steady force theory above, the expression of the average energy storage W in terms of exterior behaviour and interrelations between force and energy storage.

$$F_x + \omega(\partial F_x/\partial x)_p = (\partial W/\partial x)_p \quad \ldots \quad (35)$$

$$F_x + \omega(\partial F_x/\partial x)_{v_n} = (\partial W/\partial x)_{v_n} \ldots \quad (36)$$

As in electromagnetism, the theory assumes loss-free conditions, but otherwise the system is arbitrary. There are severe difficulties in the way of extensions to dissipative systems.

VI. Radiation Pressures in Oceanography

Effects associated with radiation pressure also occur with ocean waves. Second-order terms in the non-linear equations of motion, which are ignored in the wave propagation, give changes in the mean level or lead to gross mass transport akin to streaming in acoustics. (For a discussion of these effects for gravity waves, see Longuet-Higgins and Stewart (1962), Whitham (1962).) We shall not attempt to discuss any details of such effects, but we note that here is yet a further example of the universality of radiation pressure.

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(Received 29 March 1972)

Journal and Proceedings, Royal Society of New South Wales, Vol. 104, 151–152, 1972

Note on Sandstone Dykes at Minchinbury, N.S.W.

G. S. Gibbons

(Communication to the Editor)

Abstract—The geometry and petrology of a sandstone dyke formerly exposed in a basalt-breccia pipe at Minchinbury (N.S.W.) indicate that a mass of sand behaved as a fluid shortly after the breccia was formed. If the breccia now exposed represents the vent of a volcano, it may be that similar flow processes occurred within the breccia itself.

Introduction

The nature of the breccia pipes around Sydney has aroused considerable controversy for many decades. Hamilton, Helby and Taylor (1969) have presented evidence that they are volcanic pipes, possibly representing a level a small distance below the vent itself. This differs from the interpretation of Wilshire (1961), who described them as layered diatremes.

In 1959, the writer was a student of Wilshire and made a number of observations in Minchinbury quarry which seemed consistent with Wilshire's concepts, and were in fact regarded by him as confirmatory evidence. In view of the newer concepts, the observations are somewhat anomalous, and it is for this reason that the present note has been prepared.

Description

Minchinbury neck is situated 35 km. west of Sydney, grid reference 383824 on the Sydney 1 : 250,000 Military sheet. A large quarry has been opened in the neck, which consists essentially of a breccia of highly altered basaltic fragments, vesicular in part, generally with vaguely defined margins. The matrix is largely composed of clays and chlorites with some calcite ; in parts the matrix is very dark grey and contains 20–50% granular quartz. Scattered through the breccia are fragments, to boulder size, of sandstone, coal, and other rock types.

In 1959 a dyke-like sandstone body could be seen in the eastern wall of the quarry's upper bench. Three exposures of this feature were carefully sketched at the time, as shown in Fig. 1. It is estimated that these vertical exposures were about 2 m. apart—i.e. the three exposures cover about 4 m. along strike.

The dyke material consists mainly of angular fragments of quartz (75%) and fine-grained, rounded rock fragments (15%) in a matrix of crystalline calcite. Many quartz grains are fractured in place ; there is no significant parallelism of long axes, and no grains show overgrowth effects. Broken feldspar grains are present, and both albite and cross-hatch twin types can be seen. Some of the rock fragments appear to consist of chloritized, vesicular basic rock. Locally, fragments of coal and even of breccia are visible. A foliation was visible in the dyke, consisting of narrow carbonaceous zones parallel to the dyke wall.

Discussion

Reference to Figure 1 shows clear evidence of mobility of the dyke material, in the veinlets extending as tongues into the surrounding breccia, and in bifurcation of the dyke. Enclosure of coal and breccia fragments provides confirmatory evidence. That the dyke was formed shortly after deposition of the original breccia is strongly suggested by the off-sets and slickensides.

There is a problem in the very loose-packed nature of the sand grains ; unless the enclosing calcite was present as solid particles originally, it would appear that other minerals—perhaps clays—were formerly present. Associate Professor T. G. Vallance has suggested that such clays might well have been replaced by calcite, especially as carbonitization is very strong in the surrounding breccia.

Conclusion

If it be assumed that the breccia consists of ejectamenta which have fallen back into a volcanic vent, the tabular form and foliations of the dyke cannot be explained in terms of relict bedding, even assuming a high degree of plasticity. It must be accepted that the sand flowed into a vertical fissure, either from the wall of the pipe or from a particularly large block within the breccia. Some further movement occurred within the breccia, and then (or perhaps concurrently) the whole mass—basaltic breccia and sandstone dyke—was carbonitized.

The main problem with this explanation is the question : what will cause sandstone to flow? In the first place, the sandstone may have been only weakly compacted. Secondly, it was probably very argillaceous. Thirdly, it almost certainly had a high water content, and was heated to perhaps 200° C. under probably less than 100 m. of sediment cover. Water has a vapour pressure of 15 atmospheres at 200 °C., and even without vaporization expands by more than 10% from 20° C. to 200° C. under (say) 20 atmospheres pressure (Clark, 1966, pp. 374–376). Such expansions might well be adequate to convert a weakly cemented argillaceous sandstone to a thick slurry which would migrate readily towards a zone of lower pressure. Re-solidification might follow from loss of water, from decrease in temperature and resulting compaction, or even by recrystallization of clays initiated by the increased temperature.

The above discussion, necessarily speculative, considers the implications of the sandstone dyke described. The importance of this isolated feature is that the indicated mobility must also be possible within the breccia mass (or at least its fine-grained phases), where it would be far more difficult to recognize.

Acknowledgements

Among many discussions which the author has had on this subject, the most useful have been those with H. G. Wilshire, T. G. Vallance and L. H. Hamilton.

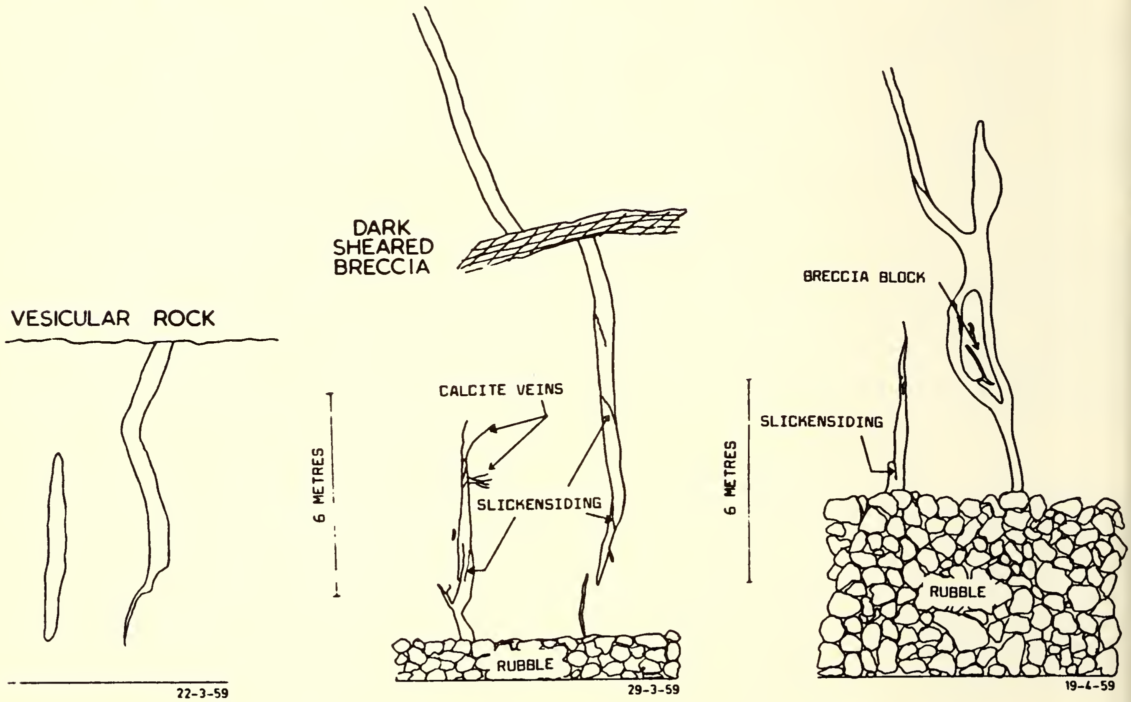

Fig. 1.—Sketches of successive exposures of sandstone dyke in Minchinbury quarry.

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(Received 23 March 1972)

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JOURNAL AND PROCEEDINGS

OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 105

PARTS 1 - 4

1972

PUBLISHED BY THE SOCIETY,
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

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Journal and Proceedings of the Royal Society of New South Wales

VOLUME 105 1972 PARTS 1 and 2

Published by the Society
Science House, Gloucester and Essex Streets, Sydney
Issued 16th April, 1973

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Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 1–2, 1972

On the Motion of Particles in Conformally Flat Space-Times

R. R. Burman

Abstract—The Papapetrou-Pirani equation of motion for a spinning particle is specialized to conformally flat space-times. In de Sitter space, this equation, and the DeWitt-Brehme-Hobbs equation of motion for a non-spinning charged particle in an electromagnetic field with radiation reaction allowed for, have the same forms as in special relativity.

Papapetrou (1951) investigated the motion of a spinning test particle in general relativity in the absence of non-gravitational fields. Equations of motion for its centre of mass and for its spin were obtained and expressed in covariant form. Since there are three equations for the six independent components of the skew-symmetric spin tensor ($S^{\alpha\beta}$), some conditions must be imposed. Pirani (1956) suggested requiring $u_\beta S^{\alpha\beta}$ to vanish.

Consider the four-dimensional Riemannian space-time of general relativity with coordinates x^α and interval ds; $ds^2=g_{\mu\nu}dx^\mu dx^\nu$, ($g_{\mu\nu}$) being the metric tensor. The speed of light in empty space will be put equal to unity. A particle with mass m is at (x^α) and has 4-velocity $(u^\mu)=(dx^\mu/ds)$. With the condition $u_\beta S^{\alpha\beta}=0$, Papapetrou's equations combine to show that m is a constant of the motion and to give

$$m\dot{u}^\mu=-(\ddot{S}^\mu{}_\nu+\tfrac{1}{2}R^\mu{}_{\nu\rho\sigma}S^{\rho\sigma})u^\nu \quad \ldots\ldots\ldots \quad (1)$$

where a dot denotes total covariant differentiation following the world-line of the particle and ($R^\alpha{}_{\beta\mu\nu}$) is the Riemann-Christoffel curvature tensor.

In a conformally flat space-time, $g_{\mu\nu}=e^\psi\eta_{\mu\nu}$ where ($\eta_{\mu\nu}$) is the flat space metric tensor and ψ is a function of the x^α; also (Petrov, 1969)

$$R^\alpha{}_{\beta\gamma\delta}=\delta^\alpha_{[\gamma}(\tfrac{1}{2}\psi_{,\delta]}\psi_{,\beta}-\psi_{,\delta],\beta}-\tfrac{1}{2}\eta_{\delta]\beta}\eta^{\sigma\tau}\psi_{,\sigma}\psi_{,\tau})$$
$$+\eta^{\alpha\sigma}\eta_{\beta[\gamma}(\psi_{,\delta],\sigma}-\tfrac{1}{2}\psi_{,\delta]}\psi_{,c}) \quad \ldots\ldots \quad (2)$$

where a comma denotes partial differentiation.

With (2), using the skew-symmetry of ($S^{\mu\nu}$) and the condition $u_\beta S^{\alpha\beta}=0$,

$$R_{\alpha\beta\gamma\delta}S^{\gamma\delta}u^\beta=(\tfrac{1}{2}\psi_{,\sigma}\psi_{,\beta}-\psi_{,\sigma,\beta})S_\alpha{}^\sigma u^\beta\,; \quad \ldots \quad (3)$$

hence (1) is specialized to conformally flat space-times. If

$$\psi_{,\alpha,\sigma}=\tfrac{1}{2}\psi_{,\alpha}\psi_{,\sigma}, \quad \ldots\ldots\ldots\ldots \quad (4)$$

then the part of the effective 4-force which depends explicitly on the Riemann-Christoffel tensor vanishes.

DeWitt and Brehme (1960) and Hobbs (1968*a*) investigated the motion of a non-spinning charged particle in an electromagnetic field in a Riemannian space of arbitrary hyperbolic metric, with the effect of electromagnetic radiation reaction included. The resulting equation of motion consists of the generally covariant form of the Lorentz-Dirac equation, together with extra force terms. The force term found by DeWitt and Brehme is non-local in time, but does not depend explicitly on the curvature tensor; the term found by Hobbs contains the Ricci tensor. The former term vanishes in conformally flat space-times; the latter vanishes in conformally flat space-times satisfying (4) (Hobbs, 1968*b*). So, in conformally flat space-times satisfying (4), the curvature tensor, in its full or contracted forms, does not explicitly enter either the DeWitt-Brehme-Hobbs or the Papapetrou-Pirani equations of motion: the equations have the same forms as in Minkowski space.

Conformally flat spaces which obey (4) have been discussed by Laugwitz (1965). When (4) is satisfied, (2) gives

$$R_{\alpha\beta\gamma\delta}=2Kg_{\alpha[\gamma}g_{\delta]\beta} \quad \ldots\ldots\ldots\ldots \quad (5)$$

where $K=-\tfrac{1}{4}g^{\sigma\tau}\psi_{,\sigma}\psi_{,\tau}$: (5) has the form for a space-time of constant Riemannian curvature K (Synge, 1960); in general relativity, the space-time must therefore be de Sitter space (Synge, 1960).

Acknowledgement

I thank the referee for pointing out that a conformally flat space-time which satisfies (4) must, in general relativity, be de Sitter space.

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(Received 27 March 1972)

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 3–8, 1972

Astronomical Objects Embedded in Matter

I. External Metrics

R. R. Burman

Abstract—This series deals with bodies, which may be charged, embedded in matter which has density varying with the radial coordinate. In this Part, the external material is represented by uncharged incoherent matter ; static spherically symmetric integrals of the Einstein-Maxwell equations are obtained with one of the functions in the metric left arbitrary. For the case of homogeneous external matter, one integral is obtained in closed form and expansions of the other integral are given which are valid near the central body, if it is uncharged, or well away from it ; for an uncharged central body, the second integral also is expressed in closed form.

1. Introduction

The general static spherically symmetric space-time metric can be expressed by

$$-ds^2=A(r)dr^2+B(r)(d\theta^2+\sin^2\theta d\varphi^2)-C(r)(dx^4)^2 \; ; \qquad (1)$$

here ds is the space-time interval and the co-ordinates are $(r, \theta, \varphi, x^4)$, where (r, θ, φ) are spherical polars. The field equations of general relativity give two relations between A, B and C, leaving one function arbitrary ; various particular choices have been listed by Synge (1960). For example $B(r)$ is often taken to be r^2 ; then the empty space outside a static spherically symmetric uncharged mass is described by the Schwarzschild metric in which $1/A=C=1-2m/r$, where m is a constant. Atkinson (1965*a*, 1965*b*) pointed out that it is sometimes useful to make no choice of the arbitrary function, and gave the appropriate integrals of Einstein's empty-space field equations. The integrals were then applied to the investigation of light tracks (Atkinson, 1965*b*). Corresponding results for the more general case in which the central object carries a static spherically symmetric charge distribution have been obtained (Burman, 1970).

The purpose of the present series is to generalize the work further by taking the charged central body to be surrounded by matter. In this Part, the external material is taken to be a static spherically symmetric distribution of uncharged incoherent matter ; the Einstein-Maxwell equations are integrated to give two relations between A, B and C : one function is left arbitrary. Particular attention is paid to the case in which the matter is homogeneous.

The model treated in this series could represent a star, or other astronomical object, together with matter surrounding it ; such a model has been used to investigate the perihelion motion of comets in the solar system (Aver'yanova and Stanyukovich, 1967). Models consisting of objects embedded in matter have been discussed in cosmological investigations, for both static (Horák, 1969 ; Eisenstaedt, 1970 ; Leibovitz, 1970) and expanding (McVittie, 1933 ; Gilbert, 1956 ; Pachner, 1961 ; Vaidya and Shah, 1967) distributions of the external matter ; Vaidya and Shah allowed for a charge on the central body.

2. Integrals of the Einstein-Maxwell Equations

If $(G_{\mu\nu})$ denotes the Einstein tensor, then, for the metric (1),

$$G_4^4=\frac{1}{2B'B^{\frac{1}{2}}}\frac{d}{dr}\left[\frac{(B')^2}{B^{\frac{1}{2}}}\frac{1}{A}\right]-\frac{1}{B} \qquad (2)$$

and

$$G_1^1-G_4^4=\frac{(B')^3}{2A^2B^2C}\frac{d}{dr}\left[\frac{ABC}{(B')^2}\right] \; ; \qquad (3)$$

a dash denotes differentiation with respect to r.

The electromagnetic field tensor is defined by $F_{\mu\nu}=\varphi_{\mu,\nu}-\varphi_{\nu,\mu}$ where (φ_μ) is the 4-potential and a comma denotes partial differentiation. The electromagnetic energy-momentum tensor has components E_μ^ν where (Eddington, 1924)

$$E_\mu^\nu=F_{\mu\alpha}F^{\alpha\nu}+\tfrac{1}{4}\delta_\mu^\nu F_{\sigma\tau}F^{\sigma\tau}. \qquad (4)$$

Outside regions containing current or charge, the Maxwell equation

$$(\sqrt{-g}F^{\beta\alpha})_{,\alpha}=0 \quad \ldots\ldots (5)$$

is applicable ; here $g\equiv\det(g_{\mu\nu})$ where $(g_{\mu\nu})$ denotes the fundamental tensor.

In static problems, only the fourth component φ_4 of the 4-potential is non-zero, and with spherical symmetry this is a function of r only. The only non-zero components $F_{\mu\nu}$ are then F_{41} and F_{14}, which equal φ_4' and $-\varphi_4'$ respectively. Hence $F^{14}=-F^{41}=\varphi_4'/AC$. Equation (5) integrates to

$$\varphi_4'=\frac{q}{B}(AC)^{\frac{1}{2}} \quad \ldots\ldots (6)$$

where q is a constant. The only non-zero components E_μ^ν are given by

$$E_1^1=-E_2^2=-E_3^3=E_4^4=q^2/2B^2. \quad \ldots\ldots (7)$$

Einstein's field equation is

$$G_\mu^\nu-\Lambda\delta_\mu^\nu=-kE_\mu^\nu-hM_\mu^\nu \quad \ldots\ldots (8)$$

where Λ is the cosmological constant, k and h are positive constants, and (M_μ^ν) is the matter tensor. For incoherent matter, $M_\mu^\nu=\rho u_\mu u^\nu$ where ρ is the proper density and $u^\alpha=cdx^\alpha/ds$ where c is the speed of light in empty space ; (u^μ) is the 4-velocity. For static incoherent matter, the only non-zero component of (M_μ^ν) is M_4^4, which equals $c^2\rho$.

It follows from (8), (7) and $M_4^4=c^2\rho$ that

$$G_4^4=\Lambda-hc^2\rho-kq^2/2B^2 \quad \ldots\ldots (9)$$

and

$$G_1^1-G_4^4=hc^2\rho. \quad \ldots\ldots (10)$$

With ρ a function of r only, (2) and (9) integrate to

$$A=\frac{(B')^2}{4B}\left(1+\frac{kq^2}{2B}+\frac{\Lambda}{3}B-\frac{hc^2}{2B^{\frac{1}{2}}}\int\rho B^{\frac{1}{2}}dB\right)^{-1}. \quad \ldots\ldots (11)$$

Substituting (3) into (10), and writing

$$f\equiv\frac{(B')^2}{4AB}, \quad \ldots\ldots (12)$$

results in

$$\frac{f^2}{C}\frac{d}{dB}\left(\frac{C}{f}\right)=\tfrac{1}{2}hc^2\rho \quad \ldots\ldots (13)$$

which integrates to

$$C=f\exp\left(\tfrac{1}{2}hc^2\int\rho f^{-1}dB\right). \quad \ldots\ldots (14)$$

If ρ is regarded as a function of B, then (11) gives A in terms of B ; then, from (12),

$$f=1+\frac{kq^2}{2B}+\frac{\Lambda}{3}B-\frac{hc^2}{2B^{\frac{1}{2}}}\int\rho B^{\frac{1}{2}}dB \quad \ldots\ldots (15)$$

which expresses f in terms of B, and so (14) gives C as a function of B.

3. Dust of Constant Density

If ρ is constant, (11) becomes

$$A=\frac{(B')^2}{4B}\left(1-\frac{2m}{B^{\frac{1}{2}}}+\frac{kq^2}{2B}-\alpha B\right)^{-1}, \quad \ldots\ldots (16)$$

where m is a constant of integration and

$$\alpha\equiv\tfrac{1}{3}(hc^2\rho-\Lambda), \quad \ldots\ldots (17)$$

while (14) becomes

$$C=f\exp\left(\tfrac{1}{2}hc^2\rho\int f^{-1}dB\right) \quad \ldots\ldots (18)$$

where now

$$f=1-\frac{2m}{B^{\frac{1}{2}}}+\frac{kq^2}{2B}-\alpha B. \quad \ldots\ldots (19)$$

The function B will henceforth be required to tend to zero as $r\rightarrow 0$.

If there is no central body, $m=0=q$ and

$$\int f^{-1}dB = -\frac{1}{\alpha}\ln(1-\alpha B)+\text{const.} \quad (20)$$

so (18) gives

$$C \propto (1-\alpha B)^{-(1+\Lambda/\alpha)/2}. \quad (21)$$

Also, (16) reduces to

$$A = \frac{(B')^2}{4B}(1-\alpha B)^{-1}. \quad (22)$$

Writing x for $B^{\frac{1}{2}}$, equation (16) becomes

$$A = (x')^2\left(1-\frac{2m}{x}+\frac{kq^2}{2x^2}-\alpha x^2\right)^{-1}, \quad (23)$$

and, if I denotes the integral in (18),

$$I = \int \frac{-2x^2dx}{\alpha x^3 - x + 2m - kq^2/2x}. \quad (24)$$

4. An Uncharged Central Body

When $q=0$,

$$C = \frac{-1}{x}(\alpha x^3 - x + 2m)^{-\Lambda/3\alpha}\exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right] \quad (25)$$

where

$$J \equiv \int \frac{dx}{\alpha x^3 - x + 2m}; \quad (26)$$

also,

$$A = (x')^2\left(1-\frac{2m}{x}-\alpha x^2\right)^{-1}. \quad (27)$$

Let x_1, x_2 and x_3 denote the roots of $\alpha x^3 - x + 2m$ and let D denote the discriminant $(27\alpha m^2-1)/(3\alpha)^3$.

If $0<27\alpha m^2<1$, corresponding to $\Lambda < hc^2\rho < \Lambda + 1/9m^2$, then $D<0$ and the roots are real and distinct, so

$$\exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right] \propto (x-x_1)^a(x-x_2)^b(x-x_3)^c \quad (28)$$

where

$$a \equiv \frac{1+\Lambda/3\alpha}{1-3\alpha x_1^2} \equiv \frac{1+\Lambda/3\alpha}{\alpha(x_2-x_1)(x_1-x_3)}, \quad (29a,\ b)$$

$$b \equiv \frac{1+\Lambda/3\alpha}{1-3\alpha x_2^2} \equiv \frac{1+\Lambda/3\alpha}{\alpha(x_1-x_2)(x_2-x_3)} \quad (29c,\ d)$$

and

$$c \equiv \frac{1+\Lambda/3\alpha}{1-3\alpha x_3^2} \equiv \frac{1+\Lambda/3\alpha}{\alpha(x_2-x_3)(x_3-x_1)}. \quad (29e,\ f)$$

If $\alpha<0$ or $>1/27m^2$, corresponding to $hc^2\rho<\Lambda$ or $hc^2\rho>\Lambda+1/9m^2$, respectively, then $D>0$ and there is one real root, say x_1, and two complex conjugate roots; writing x_2 as $d-ie$ and x_3 as $d-ie$, where d and e are real, it follows that

$$\exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right] \propto \{(x-x_1)[(x-d)^2+e^2]^{-\frac{1}{2}}\}^a$$

$$\times\exp\left[a\left(\frac{d-x_1}{e}\right)\arctan\left(\frac{x-d}{e}\right)\right]. \quad (30)$$

If $27\alpha m^2=1$, corresponding to $hc^2\rho=\Lambda+1/9m^2$, then $D=0$ and there are three real roots, one pair of which, say x_2 and x_3, are equal ; thus

$$\exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right]\propto\left(\frac{x-x_2}{x-x_1}\right)^p\exp\left(p\frac{x_2-x_1}{x-x_2}\right) \quad (31)$$

where

$$p\equiv\frac{1+\Lambda/3\alpha}{\alpha(x_1-x_2)^2}. \quad (32)$$

If $\alpha=0$, then

$$C\propto\left(1-\frac{2m}{x}\right)\exp\{\tfrac{1}{2}hc^2\rho[x^2+4mx+8m^2\ln(x-2m)]\}. \quad (33)$$

If the cosmological term is neglected, then

$$C=\frac{-1}{x}e^{-J}; \quad (34)$$

also, $\alpha=hc^2\rho/3$ so that $D<0$, >0 or $=0$ according as $9m^2hc^2\rho<1$, >1 or $=1$.

If $m=0$, then

$$C\propto(\alpha x^2-1)^{1-hc^2\rho/2\alpha}. \quad (35)$$

If $\Lambda<0$ and $hc^2\rho<2|\Lambda|$, then C vanishes on the circle $x=\alpha^{-\frac{1}{2}}$. If $hc^2\rho>\Lambda$ or $>2|\Lambda|$, according as $\Lambda>0$ or <0, then C is infinite on the circle $x=\alpha^{-\frac{1}{2}}$: for any non-zero co-ordinate time interval, the corresponding proper time interval on that circle is infinite.

5. Some Approximations

Sufficiently near the central body, the metric is dominated by the presence of that body : the metric is slightly disturbed from what it would be if ρ and Λ were zero. Hence it is to be expected that terms proportional to α can be treated as small perturbations about the case in which $\alpha=0$.

Sufficiently well away from the central body, the gravitational effect of the matter outside the body predominates over that of the body : the metric is slightly disturbed from what it would be if m were zero. Hence it is to be expected that terms proportional to m can be treated as small perturbations about the case in which $m=0$.

As illustrated by the Reissner-Nordström metric, the gravitational effect of charge falls off more rapidly with increasing distance than that of mass : sufficiently well away from the central object, the metric is slightly disturbed from what it would be if q were zero. Hence it is to be expected that terms proportional to q^2 can be treated as small perturbations about the case in which $q=0$, and that terms proportional to mq^2 will be small compared with those proportional to m or q^2.

5.1. Near an Uncharged Central Body

In this sub-section, an approximate closed-form expression for C will be obtained which is valid near the central object ; attention will be restricted to the case of an uncharged body.

Equation (26) can be written

$$-J=\int\left(1-\frac{\alpha x^3}{x-2m}\right)^{-1}\frac{dx}{x-2m}. \quad (36)$$

Sufficiently near the central body, the term in α should be of secondary importance. Expanding, integrating term by term and retaining terms to first order in α leads to

$$\exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right]\propto(x-2m)^{4m^2hc^2\rho+1+\Lambda/3\alpha}$$
$$\times\exp\left\{\tfrac{1}{3}hc^2\rho\left[\tfrac{1}{2}(x-2m)^2+6m(x-2m)-\frac{(2m)^3}{x-2m}\right]\right\}. \quad (37)$$

This expression is valid near the central body, with the proviso that, for a body inside the circle $x=2m$, it fails in the vicinity of that circle if $\rho\neq0$.

Near the central body, but well outside the circle $x=2m$, so that $\alpha x^3/(x-2m)$ is small, approximating the factors preceding the exponential in (25) and using (37) gives

$$C\propto\left(1-\frac{2m}{x}+\frac{\Lambda}{3}x^2\right)(x-2m)^{4m^2hc^2\rho}$$
$$\times\exp\left\{\tfrac{1}{3}hc^2\rho\left[\tfrac{1}{2}(x-2m)^2+6m(x-2m)-\frac{(2m)^3}{x-2m}\right]\right\}. \quad (38)$$

5.2. Well Away from an Uncharged Central Body

In this sub-section, an approximate closed-form expression for C will be obtained which is valid well away from the central body, which is taken to be uncharged.

Equation (26) can be written

$$-J=\int\left(1-\frac{2m/x}{1-\alpha x^2}\right)^{-1}\frac{dx}{x(1-\alpha x^2)}. \quad (39)$$

At sufficiently large distances from the central body, the term in m should be of secondary importance. Expanding, integrating term by term and retaining terms to first order in m leads to

$$\exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right]\propto\left[\frac{x^2}{1-\alpha x^2}\left(\frac{1+\alpha^{\frac{1}{2}}x}{1-\alpha^{\frac{1}{2}}x}\right)^{3\alpha^{\frac{1}{2}}m}\right]^{\frac{1}{2}(1+\Lambda/3\alpha)}$$
$$\times\left[1-\left(1+\frac{\Lambda}{3\alpha}\right)\frac{2m}{x}+\frac{mhc^2\rho x/3}{1-\alpha x^2}\right]. \quad (40)$$

This expression is valid well away from the central body, with the proviso that, if $\alpha>0$, then it will fail in the vicinity of the circle $x=\alpha^{-\frac{1}{2}}$.

Well away from the central body, but not near the circle $x=\alpha^{-\frac{1}{2}}$, so that $(2m/x)\div(1-\alpha x^2)$ is small, approximating the factors preceding the exponential in (25) and using (40) gives

$$C\propto(1-\alpha x^2)^{-\frac{1}{2}(1+\Lambda/\alpha)}\left(\frac{1+\alpha^{\frac{1}{2}}x}{1-\alpha^{\frac{1}{2}}x}\right)^{\frac{1}{2}(1+\Lambda/3\alpha)3\alpha^{\frac{1}{2}}m}$$
$$\times\left(1-\frac{2m}{x}+\frac{m(hc^2\rho+2\Lambda)x/3}{1-\alpha x^2}\right). \quad (41)$$

When $m=0$, expression (41) reduces to (35).

5.3. Well Away from a Charged Central Body

The effect on the metric of a charge on the central object decreases more rapidly with increasing distance than does the effect of the mass. Writing

$$I=\int\frac{-2x^3}{\alpha x^3-x+2m}\left(1-\frac{kq^2/2x}{\alpha x^3-x+2m}\right)^{-1}dx, \quad (42)$$

expanding, and integrating term by term, gives, to first order in $kq^2/2$, $I\doteqdot I_0-\frac{1}{2}kq^2K$ where I_0 denotes the value of I when $q=0$ and

$$K\equiv\int\frac{2x\,dx}{(\alpha x^3-x+2m)^2}. \quad (43)$$

Hence

$$C\doteqdot\left(1-\frac{2m}{x}+\frac{kq^2}{2x^2}-\alpha x^2\right)(\alpha x^3-x+2m)^{-(1+\Lambda/3\alpha)}$$
$$\times\exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right]\exp\left(-\tfrac{1}{4}kq^2hc^2\rho K\right). \quad (44)$$

Well away from the central body, but, if $\alpha>0$, then not near the circle $x=\alpha^{-\frac{1}{2}}$, so that $(2m/x)\doteq(1-\alpha x^2)$ and $(kq^2/2x^2)\doteq(1-\alpha x^2)$ are both small, approximating the factors preceding the exponentials in (44) and using (40) gives

$$C\propto(1-\alpha x^2)^{-\frac{1}{2}(1+\Lambda/\alpha)}\left(\frac{1+\alpha^{\frac{1}{2}}x}{1-\alpha^{\frac{1}{2}}x}\right)^{\frac{1}{2}(1+\Lambda/3\alpha)3\alpha^{\frac{1}{2}}m}$$
$$\times\left(1-\frac{2m}{x}+\frac{kq^2/2x^2}{1-\alpha x^2}+\frac{m(hc^2\rho+2\Lambda)x/3}{1-\alpha x^2}\right) \qquad (45)$$
$$\times\exp\left(-\tfrac{1}{4}kq^2hc^2\rho K\right).$$

Sufficiently well away from the central body

$$K\doteq\int\frac{2dx}{x(1-\alpha x^2)^2}, \qquad (46)$$

to which approximation products of m and kq^2 in I are neglected, and the last factor in (44) or (45) is approximately proportional to

$$\left(\frac{1-\alpha x^2}{x^2}\right)^{kq^2hc^2\rho/4}\exp\left(\frac{-kq^2hc^2\rho/4}{1-\alpha x^2}\right). \qquad (47)$$

Hence, on expanding the exponential in (47), expression (45) gives, using (17),

$$C\propto x^{-\frac{1}{2}kq^2hc^2\rho}(1-\alpha x^2)^{\frac{1}{2}(\frac{1}{2}kq^2hc^2\rho-1-\Lambda/\alpha)}$$
$$\times\left(\frac{1+\alpha^{\frac{1}{2}}x}{1-\alpha^{\frac{1}{2}}x}\right)^{\frac{1}{2}(1+\Lambda/3\alpha)3\alpha^{\frac{1}{2}}m}\left[1-\left(\frac{2m}{x}-\frac{kq^2}{2x^2}\right)\frac{1-hc^2\rho x^2/2}{1-\alpha x^2}\right]. \qquad (48)$$

If $\alpha>0$, then this approximation will fail in the vicinity of the circle $x=\alpha^{-\frac{1}{2}}$.

6. Concluding Remarks

This paper has been concerned with obtaining static spherically symmetric integrals of the Einstein-Maxwell equations for the metric outside a body which is embedded in matter. Some exact and some approximate solutions have been obtained. These results will be applied, in Parts II and III of this series, to the investigation of light tracks. One way of extending the work of this paper would be to allow the external matter to have non-zero pressure.

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(Received 31 May 1972)

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 9–14, 1972

Astronomical Objects Embedded in Matter

II. Light Tracks

R. R. Burman

Abstract—This paper deals with the space-time region, outside a static spherically symmetric object, occupied by a continuous distribution of matter. Integrals of the Einstein-Maxwell equations, with one of the functions in the metric left arbitrary, are used to investigate light tracks ; conditions for the existence of circular photon orbits are obtained. Particular attention is paid to the case in which the external matter is homogeneous and the central object is uncharged.

1. Introduction

Light and particle tracks in the presence of a static spherically symmetric uncharged body have been investigated by Darwin (1959, 1961). Light tracks were also investigated by Atkinson, who used integrals of Einstein's empty-space field equations obtained leaving one function in the metric arbitrary (Atkinson, 1965*a*, 1965*b*). His results have been generalized so as to apply for a central body with a static spherically symmetric charge distribution (Burman, 1970).

The purpose of this paper, and of a subsequent part of the series, is to extend the work further to include the effects of a continuous static spherically symmetric distribution of matter outside the object. Integrals of the Einstein-Maxwell equations obtained in Part I (Burman, 1972) will be used.

2. Basic Theory

The general static spherically symmetric space-time metric can be expressed by

$$-ds^2=A(r)dr^2+B(r)(d\theta^2+\sin^2\theta d\varphi^2)-C(r)c^2dt^2\,; \qquad (1)$$

here ds is the space-time interval, (r, θ, φ) are spherical polars, t is a time co-ordinate, and c is the speed of light in empty space. The null geodesics of (1) have been investigated (using different notation) by Atkinson (1965*b*). In particular, when $\dot{r}=0$, with a dot denoting differentiation with respect to t, it is found that

$$\ddot{r}=\frac{c^2C}{2A}\left(\frac{B'}{B}-\frac{C'}{C}\right) \qquad (2)$$

where a dash denotes differentiation with respect to r ; this equation describes the nature of apses. If $\dot{r}=0=\ddot{r}$, corresponding to a circular null geodesic, then

$$\frac{B'}{B}=\frac{C'}{C}. \qquad (3)$$

The time for a photon to describe such a circle is t_0 where

$$t_0=\frac{2\pi}{c}\left(\frac{B}{C}\right)^{\frac{1}{2}}. \qquad (4)$$

These results hold for all metrics of the form (1), independently of any field equations, if, in the case of (4), null geodesics can be interpreted as light tracks.

For the model treated previously (Burman, 1972) and described in the Introduction,

$$A=\frac{B'^2}{4B}\,\frac{1}{f} \qquad (5)$$

and

$$C=f\exp\left(\tfrac{1}{2}hc^2\textstyle\int\rho f^{-1}dB\right) \qquad (6)$$

where

$$f = 1 - \frac{2m}{B^{\frac{1}{2}}} + \frac{kq^2}{2B} + \frac{\Lambda B}{3} - \frac{hc^2}{2B^{\frac{1}{2}}} \int^B \rho B^{\frac{1}{2}} dB \; ; \qquad (7)$$

the notation of the previous paper has been used. The function B approaches zero as r does, but is otherwise an unspecified positive function of r.

3. Use of the Relativistic Integrals

In this section, the relativistic integrals will be substituted into (2), (3) and (4), and some special cases will be discussed.

3.1. The General Case

From (6),

$$\frac{C'}{C} = \frac{1}{f}(f' + \tfrac{1}{2}hc^2\rho B'),$$

and use of (7) results in

$$\frac{C'}{C} = \frac{1}{f}\left(\frac{m}{B^{\frac{1}{2}}} - \frac{kq^2}{2B} + \frac{\Lambda B}{3} + \frac{hc^2}{4B^{\frac{1}{2}}} \int^B \rho B^{\frac{1}{2}} dB\right)\frac{B'}{B}. \qquad (8)$$

Substituting the relativistic result (8), equation (2) becomes

$$\ddot{r} = \frac{c^2 C B'}{2AB}\left[1 - \frac{1}{f}\left(\frac{m}{B^{\frac{1}{2}}} - \frac{kq^2}{2B} + \frac{\Lambda B}{3} + \frac{hc^2}{4B^{\frac{1}{2}}} \int^B \rho B^{\frac{1}{2}} dB\right)\right]. \qquad (9)$$

Use of (5), (6) and (7) results in

$$\ddot{r} = \frac{2c^2 f}{B'}\left(1 - \frac{3m}{B^{\frac{1}{2}}} + \frac{kq^2}{B} - \frac{3hc^2}{4B^{\frac{1}{2}}} \int^B \rho B^{\frac{1}{2}} dB\right) \exp\left(\tfrac{1}{2}hc^2 \int \rho f^{-1} dB\right). \qquad (10)$$

The condition for a photon circle becomes

$$1 - \frac{3m}{B^{\frac{1}{2}}} + \frac{kq^2}{B} = \frac{3hc^2}{4B^{\frac{1}{2}}} \int^B \rho B^{\frac{1}{2}} dB. \qquad (11)$$

Substitution of the relativistic integral (6) into (4) gives the orbital time in terms of B:

$$t_0 = \frac{2\pi}{c}\left(\frac{B}{f}\right)^{\frac{1}{2}} \exp\left(-\frac{hc^2}{4} \int \rho f^{-1} dB\right); \qquad (12)$$

t_0 will be real provided $f > 0$ on the circle concerned. Use of the condition (11) in (7) shows that, on a photon circle,

$$f = \tfrac{1}{3}\left(1 + \Lambda B - \frac{kq^2}{2B}\right). \qquad (13)$$

3.2. Homogeneous External Matter

If ρ is constant, (11) becomes

$$B - 3mB^{\frac{1}{2}} + kq^2 = aB^2 \qquad (14)$$

where

$$a \equiv \tfrac{1}{2}hc^2\rho. \qquad (15)$$

Equation (12) becomes

$$t_0 = \frac{2\pi}{c}\left(\frac{B}{f}\right)^{\frac{1}{2}} \exp\left(-\frac{a}{2} \int f^{-1} dB\right) \qquad (16)$$

where f is evaluated on the photon circle and is given by (13). Equation (10) becomes

$$\ddot{r} = \frac{2c^2 f}{B'}\left(1 - \frac{3m}{B^{\frac{1}{2}}} + \frac{kq^2}{B} - aB\right) \exp\left(a \int f^{-1} dB\right). \qquad (17)$$

From (7),

$$f=1-\frac{2m}{B^{\frac{1}{2}}}+\frac{kq^2}{2B}+\tfrac{1}{3}(\Lambda-2a)B. \qquad (18)$$

In the following, B will be required to be real and positive ; hence m and q are real. Further, B will be required to be a monotonically increasing function of r. It will be supposed that the central body has a radius less than that calculated for any photon circle.

3.3 No External Matter

When there is no matter external to the central body, (14) reduces to a quadratic in $B^{\frac{1}{2}}$ with solutions

$$B^{\frac{1}{2}}=\frac{3m}{2}\pm\sqrt{\left(\frac{3m}{2}\right)^2-kq^2}. \qquad (19)$$

If $q=0$, then there is a single photon circle ; it is at $B^{\frac{1}{2}}=3m$, corresponding to $C=\frac{1}{3}+3\Lambda m^2$, as found previously (Burman, 1971). If $\Lambda=0$, then the effect of a non-zero q is, if $kq^2/m^2<(3/2)^2$, to introduce a second photon circle, and both circles lie inside that which occurs when $q=0$; there is a lower limit on kq^2/m^2, at which the inner photon circle ceases to exist, since the time taken for a photon to describe that circle is real only if $kq^2/m^2>2$ (Burman, 1970).

4. Circular Light Tracks about an Uncharged Body in Homogeneous Matter

This section will deal with photon circles for the case in which the external matter is homogeneous and the central body is uncharged.

4.1. The Basic Cubic

When $q=0$, (14) becomes a cubic in $B^{\frac{1}{2}}$:

$$aB^{3/2}-B^{\frac{1}{2}}+3m=0. \qquad (20)$$

For a photon circle occurring sufficiently near the central body, $B^{\frac{1}{2}}\doteqdot 3m$, or, to a higher approximation,

$$B^{\frac{1}{2}}\doteqdot 3m(1+9am^2). \qquad (21)$$

As is to be expected, (21) shows that the radius of the photon circle is increased by the presence of the matter external to the central body. Well away from the central body, (20) is satisfied by

$$B^{\frac{1}{2}}\doteqdot 1/a^{\frac{1}{2}}, \qquad (22)$$

which becomes exact when there is no central body ; to a higher approximation,

$$B^{\frac{1}{2}}\doteqdot\frac{1}{a^{\frac{1}{2}}}-\frac{3m}{2}; \qquad (23)$$

as is to be expected, the radius is reduced by the presence of the central body.

The discriminant Δ of the cubic (20) is

$$\frac{1}{(3a)^3}\left[3a\left(\frac{9m}{2}\right)^2-1\right]. \qquad (24)$$

According as $\Delta>0$, $=0$ or <0, corresponding to $(3a)^{\frac{1}{2}}9m/2>1$, $=1$ or <1, there are one real and a pair of complex conjugate roots, three real roots with at least two of them equal or three distinct real roots. So in these three cases there are at most one, two and three photon circles, respectively. For any of these possible photon circles to be realized, the root concerned must be positive and the time calculated for a photon to describe the orbit must be real.

4.2. The Roots of the Cubic

The quantities p_+ and p_- are defined by

$$p_{\pm}^{3}=\frac{3m}{2a}\pm\Delta^{\frac{1}{2}} \text{ and } p_+p_-=\frac{1}{3a}. \qquad (25a,\, b)$$

The three roots of (20) are given by

$$B_{\frac{1}{2}}^{\frac{1}{2}}=\tfrac{1}{2}(p_{+}+p_{-})\pm\frac{i\sqrt{3}}{2}(p_{+}-p_{-}) \qquad (26a)$$

$$B_{3}^{\frac{1}{2}}=-(p_{+}+p_{-}). \qquad (26b)$$

When $\Delta>0$, p_{+} and p_{-} are both real and positive; $B_3^{\frac{1}{2}}$ is the only real root and it is negative, so there are no photon circles.

When $\Delta=0$, p_{+} and p_{-} both equal $(3m/2a)^{\frac{1}{3}}$, which is equal to $9m/2$ or $(3a)^{-\frac{1}{2}}$, so

$$B_{1}^{\frac{1}{2}}=B_{2}^{\frac{1}{2}}=9m/2 \qquad (27a)$$

$$=(3a)^{-\frac{1}{2}}; \qquad (27b)$$

$B_3^{\frac{1}{2}}$ is negative. The double root could correspond to a photon circle.

When $\Delta<0$, p_{+} and p_{-} are complex and there are three distinct real roots; they are given by (26) but can also be written as

$$\frac{2}{(3a)^{\frac{1}{2}}}\cos\left(\frac{\varphi+2k\pi}{3}\right) \qquad k=0,\ 1,\ 2 \qquad (28a)$$

in some order, where

$$\cos\varphi=-(3a)^{\frac{1}{2}}\frac{9m}{2}. \qquad (28b)$$

Choosing φ to lie in the second quadrant, it follows that the argument of the cosine in (28*a*) lies in $(\pi/6,\ \pi/3)$ for $k=0$, in $(5\pi/6,\pi)$ for $k=1$ and in $(3\pi/2,\ 5\pi/3)$ for $k=2$. Hence

$$0<B^{\frac{1}{2}}<1/(3a)^{\frac{1}{2}} \qquad \text{for } k=2 \qquad (29)$$

and

$$1/(3a)^{\frac{1}{2}}<B^{\frac{1}{2}}<1/a^{\frac{1}{2}} \qquad \text{for } k=0; \qquad (30)$$

the root corresponding to $k=1$ is negative.

If $(3a)^{\frac{1}{2}}9m/2$ is small, then (25) gives

$$p_{\pm}^{3}\doteqdot\frac{\pm i}{(3a)^{3/2}}\left[1\mp i(3a)^{\frac{1}{2}}\frac{9m}{2}\right]$$

so that

$$p_{+}+p_{-}\doteqdot-3m \qquad (31a)$$

and

$$p_{+}-p_{-}\doteqdot\frac{-2i}{(3a)^{\frac{1}{2}}}. \qquad (31b)$$

Hence, from (26),

$$B_{3}^{\frac{1}{2}}\doteqdot 3m \qquad (32)$$

and

$$B_{1}^{\frac{1}{2}}\doteqdot\frac{1}{a^{\frac{1}{2}}}-\frac{3m}{2}, \qquad (33)$$

corresponding to possible photon circles close to the central body and well away from it, respectively; $B_2^{\frac{1}{2}}$ is negative.

If $(3a)^{\frac{1}{2}}9m/2=1-x$ where x is a small positive quantity, then

$$p_{\pm}^{3}\doteqdot\frac{1}{(3a)^{3/2}}[1\pm i(2x)^{\frac{1}{2}}]$$

so that

$$p_{+}+p_{-}\doteqdot\frac{2}{(3a)^{\frac{1}{2}}} \qquad (34a)$$

and

$$p_{+}-p_{-}\doteqdot\frac{2i}{3}\left(\frac{2x}{3a}\right)^{\frac{1}{2}}. \qquad (34b)$$

Hence, from (26),

$$B_{\frac{1}{2}}^{\frac{1}{2}} \doteqdot \frac{1}{(3a)^{\frac{1}{2}}}\left[1\mp\left(\frac{2x}{3}\right)^{\frac{1}{2}}\right] \; ; \qquad (35)$$

$B_3^{\frac{1}{2}}$ is negative.

4.3. Orbital Periods

With $q=0$, equation (11) shows that

$$f=\tfrac{1}{3}(1+\Lambda B) \qquad (36)$$

on a photon circle. Use of (36) in (16) gives

$$t_0=\frac{2\pi}{c}\left[\frac{3B}{(1+\Lambda B)^{1+3a/\Lambda}}\right]^{\frac{1}{2}} \qquad \text{(for } \Lambda\neq 0\text{)} \qquad (37)$$

or

$$t_0=\frac{2\pi}{c}(3B)^{\frac{1}{2}}\exp\left(-\frac{3a}{2}B\right) \qquad \text{(for } \Lambda=0\text{)}. \qquad (38)$$

If the cosmological term is neglected (so that $f=\frac{1}{3}$), then t_0 is real. If $\Lambda\neq 0$, then t_0 is real if $\Lambda>-1/B$ on the circle ; in particular, if $\Lambda>0$, then t_0 is real ; if $\Lambda<-1/B$, then t_0 will be real only if $3a/\Lambda$ is equal to an odd integer. For the solutions $B^{\frac{1}{2}}\doteqdot 3m$ and $B^{\frac{1}{2}}\doteqdot 1/a^{\frac{1}{2}}$, t_0 is real if $\Lambda\gtrsim -1/(3m)^2$ and if $\Lambda\gtrsim -a$, respectively.

To summarize, when $(3a)^{\frac{1}{2}}9m/2>1$, there are no photon circles. When $(3a)^{\frac{1}{2}}9m/2<1$, there are photon circles at $B_i^{\frac{1}{2}}$ and $B_o^{\frac{1}{2}}$, where $0<B_i^{\frac{1}{2}}<B_o^{\frac{1}{2}}<a^{-\frac{1}{2}}$, provided $\Lambda>-1/B$ on them ; in particular, if $(3a)^{\frac{1}{2}}9m/2\ll 1$, then $B_i^{\frac{1}{2}}\doteqdot 3m$ and $B_o^{\frac{1}{2}}\doteqdot 1/a^{\frac{1}{2}}$, with better approximations given by (21) and (33) respectively ; if $(3a)^{\frac{1}{2}}9m/2$ is near 1, but slightly less, then $B_o^{\frac{1}{2}}$ and $B_i^{\frac{1}{2}}$ are given by (35). When $(3a)^{\frac{1}{2}}9m/2=1$, there is a single photon circle at $B^{\frac{1}{2}}=(3a)^{-\frac{1}{2}}$, provided $\Lambda>-3a$.

5. Non-Circular Light Tracks

With $q=0$, equation (18) becomes

$$f=1-\frac{2m}{B^{\frac{1}{2}}}+\tfrac{1}{3}(\Lambda-2a)B. \qquad (39)$$

Hence, (17) becomes

$$\ddot{r}=\frac{2c^2}{BB'}\beta\gamma\exp\left(a\int f^{-1}dB\right) \qquad (40)$$

where

$$\beta\equiv aB^{3/2}-B^{\frac{1}{2}}+3m \qquad (41)$$

and

$$\gamma\equiv\tfrac{1}{3}(2a-\Lambda)B^{3/2}-B^{\frac{1}{2}}+2m\equiv -B^{\frac{1}{2}}f. \qquad (42)$$

The function β is the left side of (20) ; γ is the left side of the cubic equation (34) of the previous paper (Burman, 1972).

Let I denote the integral in (40) and let

$$\alpha\equiv\tfrac{1}{3}(2a-\Lambda). \qquad (43)$$

Writing x for $B^{\frac{1}{2}}$,

$$I=\int\frac{-2x^2dx}{\alpha x^3-x+2m}$$

$$=\frac{-2}{3\alpha}\left[\ln\left(\alpha x^3-x+2m\right)+J\right] \qquad (44)$$

where

$$J\equiv\int\frac{dx}{\alpha x^3-x+2m} \qquad (45)$$

which has been evaluated previously (Burman, 1972). The exponential factor in (40) becomes

$$(\alpha x^3 - x + 2m)^{-(1+\Lambda/3\alpha)} \exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right]. \quad \ldots\ldots\ldots\ldots\ldots (46)$$

So (40) can be written

$$\ddot{r} = \frac{2c^2}{BB'}\beta\gamma^{-\Lambda/3\alpha} \exp\left[-\left(1+\frac{\Lambda}{3\alpha}\right)J\right]. \quad \ldots\ldots\ldots\ldots\ldots (47)$$

If $\Lambda=0$, equation (47) reduces to

$$\ddot{r} = \frac{2c^2}{BB'}\beta \exp(-J) \quad \ldots\ldots\ldots\ldots\ldots (48)$$

where J is given by (45) with α now equal to $2a/3$.

An apse corresponds to a minimum or maximum in the co-ordinate distance from the central body according as $\ddot{r}>0$ or <0. The nature of apses, and hence the feasibility of finite non-circular orbits, could be studied with the above equations.

6. Concluding Remarks

In Part I (Burman, 1972) integrals of the Einstein-Maxwell equations were obtained for a static spherically symmetric situation consisting of a charged body embedded in a continuous distribution of uncharged incoherent matter. In the present paper the integrals have been applied to the study of light tracks ; particular attention has been paid to the case in which the external matter is homogeneous and the central body is uncharged. Let M and ρ denote the mass of the central object and the density of the external matter. It has been shown that if $M\rho^{\frac{1}{2}}$ exceeds a critical value, then there are no photon circles ; if $M\rho^{\frac{1}{2}}$ equals the critical value, then there is at most a single photon circle ; if $M\rho^{\frac{1}{2}}$ is less than the critical value, then there are at most two photon circles.

Part III will deal with light tracks about a charged central body embedded in homogeneous matter.

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(Received 23 June 1972)

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 15–18, 1972

Occultations Observed at Sydney Observatory during 1971

K. P. Sims

The following observations of occultations were made at Sydney Observatory with the 11½-inch telescope. A tapping key was used to record the times on a chronograph. The reduction elements were computed by the method given in the occultation Supplement to the *Nautical Almanac* for 1938 and the reduction completed by the method given there. Since the observed times were in terms of coordinated time (UTC), a correction for 1971·5 of +0·01155 hour (=41·6 seconds) was applied to these times to convert them to ephemeris time with which *The Astronomical Ephemeris for 1971* was entered to obtain the position and parallax of the Moon. The apparent places of the stars of the 1971 occultations were, except for numbers 631 and 641, extracted from occultation data issued by the U.S. Naval Observatory. For occultation No. 631 the apparent place of Z.C. 3198 was taken as $21^h\ 48^m\ 42^s{\cdot}021$ in R.A. and $-11°\ 28'\ 26''{\cdot}41$ in Dec. whilst for occultation No. 641 the apparent place of companion B to the star S.A.O. 187106 was taken as $18^h\ 38^m\ 07^s{\cdot}899$ in R.A. and $-25°\ 32'\ 03''{\cdot}31$ in Dec.

Table I gives the observational material. The serial numbers follow on from those of the previous report (Sims, 1970). The observers were W. H. Robertson (R), K. P. Sims (S), and H. W. Wood (W). For occultations 580, 632–640, and 647 the phase observed was reappearance at the dark limb. With the exception of occultation No. 579, which was a disappearance at the bright limb, the phase observed in the remaining cases was disappearance at the dark limb. Table II gives the results of the reductions which were carried out in duplicate. The Z.C. or S.A.O. numbers given in Table I are from the *Catalog of 3539 Zodiacal Stars for Equinox* 1950·0 (Robertson, 1940) and the *Smithsonian Astrophysical Observatory Star Catalog*.

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Sims, K. P., 1971. *J. Proc. Roy. Soc. N.S.W.*, **103**, 91 ; Sydney Observatory Papers No. 64.

Table I

Serial No.	S.A.O. or Z.C. No.	Mag.	Date	U.T.C.	Observer
578	0221	3·7	1971 Feb. 1	9 52 48·30	W
579	2366	1·2	1971 Mar. 18	12 33 21·75	R
580	2366	1·2	1971 Mar. 18	13 25 31·69	R
581	1635	5·4	1971 May 5	12 33 02·81	S
582	1637	6·0	1971 May 5	14 04 42·01	S
583	079688	7·8	1971 May 28	7 39 32·77	S
584	098020	8·3	1971 May 29	8 11 26·16	S
585	1298	6·5	1971 May 29	8 14 13·31	S
586	080351	8·6	1971 May 29	8 21 50·15	S
587	080352	8·9	1971 May 29	8 29 12·15	S
588	1299	6·3	1971 May 29	8 37 10·15	S
589	080353	8·7	1971 May 29	8 37 39·26	S
590	1303	6·8	1971 May 29	8 38 58·05	S
591	098018	7·4	1971 May 29	8 39 59·68	S
592	098043	8·4	1971 May 29	8 49 22·84	S
593	118218	8·3	1971 May 31	11 50 46·74	S
594	118221	8·4	1971 May 31	11 57 42·61	S
595	118219	8·2	1971 May 31	12 08 35·40	S

Table I—*Continued*

Serial No.	S.A.O. or Z.C. No.	Mag.	Date	U.T.C.	Observer
596	080094	8·4	1971 June 25	7 29 40·89	R
597	080099	7·9	1971 June 25	8 13 41·35	R
598	118460	9·0	1971 June 28	9 43 38·03	S
599	1845	6·5	1971 July 1	8 53 26·22	R
600	138862	8·7	1971 July 28	8 39 52·23	S
601	138888	9·0	1971 July 28	10 39 04·36	S
602	2558	6·2	1971 Aug. 3	11 02 16·89	R
603	138739	8·8	1971 Aug. 24	8 57 40·80	W
604	157707	8·8	1971 Aug. 25	8 20 18·22	R
605	182754	9·3	1971 Aug. 27	9 44 24·04	R
606	2098	8·5	1971 Aug. 27	11 07 17·92	R
607	2360	7·6	1971 Aug. 29	10 47 51·00	W
608	2366	1·2	1971 Aug. 29	11 59 59·30	W
609	2373	6·2	1971 Aug. 29	13 08 43·05	W
610	185295	7·6	1971 Aug. 30	8 44 24·52	S
611	186770	7·8	1971 Aug. 31	11 08 32·98	R
612	2823	7·0	1971 Sep. 1	9 23 51·11	S
613	158051	8·4	1971 Sep. 22	8 24 47·57	R
614	1958	7·5	1971 Sep. 22	9 22 57·41	R
615	158072	8·3	1971 Sep. 22	9 32 24·76	R
616	158540	9·0	1971 Sep. 23	8 22 42·00	W
617	158542	7·9	1971 Sep. 23	8 23 59·30	W
618	184935	8·3	1971 Sep. 26	8 32 06·56	W
619	184957	8·5	1971 Sep. 26	9 28 50·46	W
620	2449	7·5	1971 Sep. 26	9 38 45·86	W
621	184987	8·5	1971 Sep. 26	10 04 49·86	W
622	185021	8·8	1971 Sep. 26	11 09 52·46	W
623	185020	7·6	1971 Sep. 26	11 21 09·86	W
624	186029	8·6	1971 Sep. 27	8 34 35·96	S
625	187465	7·8	1971 Sep. 28	8 54 40·90	R
626	187490	8·5	1971 Sep. 28	9 02 29·70	R
627	187532	8·4	1971 Sep. 28	10 02 08·56	R
628	2761	6·6	1971 Sep. 28	10 17 39·97	R
629	2767	6·4	1971 Sep. 28	10 59 29·69	R
630	2771	5·7	1971 Sep. 28	12 06 45·84	W
631	3198	8·2	1971 Oct. 1	11 49 33·40	S
632	1292	6·7	1971 Oct. 12	18 21 39·70	R
633	1293	6·7	1971 Oct. 12	18 28 28·40	R
634	1294	6·9	1972 Oct. 12	18 34 17·00	R
635	098014	8·0	1971 Oct. 12	18 34 27·50	R
636	098018	7·4	1971 Oct. 12	18 50 39·50	R
637	098020	8·3	1971 Oct. 12	18 50 49·50	R
638	1298	6·5	1971 Oct. 12	18 52 36·30	R
639	1299	6·3	1971 Oct. 12	18 58 14·80	R
640	1302	6·7	1971 Oct. 12	19 01 23·50	R
641	—	8·5	1971 Oct. 25	8 52 11·69	S
642	187106	8·0	1971 Oct. 25	8 52 26·15	S
643	187130	9·3	1971 Oct. 25	9 42 40·09	S
644	188333	8·7	1971 Oct. 26	9 18 01·00	R
645	3017	5·3	1971 Oct. 27	14 13 31·45	W
646	3134	6·9	1971 Oct. 28	9 27 29·55	R
647	3134	6·9	1971 Oct. 28	9 44 16·61	R
648	3142	6·8	1971 Oct. 28	10 51 35·59	R
649	164408	8·2	1971 Oct. 28	11 07 48·56	R
650	188071	8·9	1971 Nov. 22	10 06 38·37	S
651	188083	9·1	1971 Nov. 22	10 15 48·00	S
652	188098	8·0	1971 Nov. 22	10 31 33·51	S
653	145823	8·9	1971 Nov. 25	10 05 06·41	R
654	146380	8·5	1971 Nov. 26	11 05 57·81	R
655	3501	5·3	1971 Nov. 27	11 20 03·58	W

TABLE II

Serial No.	Lunation No.	p	q	p^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of $\Delta\alpha$	Coefficient of $\Delta\delta$
578	595	+72	−69	52	−50	48	+1·2	+0·9	−0·8	+13·6	−0·34
579	596	+83	−56	69	−46	31	−0·2	−0·2	+0·1	+9·9	−0·67
580	596	−96	−27	93	+26	7	−2·1	+2·0	+0·6	−13·3	−0·13
581	598	+61	−79	37	−48	63	+0·8	+0·5	−0·6	+2·7	−0·98
582	598	+44	−90	19	−40	81	+0·4	+0·2	−0·4	−0·4	−1·00
583	599	+88	−47	78	−41	22	+1·4	+1·2	−0·7	+10·1	−0·68
584	599	+84	−54	71	−45	29	+2·9	+2·4	−1·6	+8·6	−0·80
585	599	+81	−58	66	−47	34	+1·9	+1·5	−1·1	+8·1	−0·82
586	599	+78	+62	61	+49	39	−1·0	−0·8	−0·6	+13·3	+0·32
587	599	+94	+35	88	+33	12	+1·3	+1·2	+0·5	+14·1	+0·02
588	599	+48	−88	23	−42	77	+1·8	+0·9	−1·6	+2·3	−0·99
589	599	+65	+76	42	+49	58	−1·1	−0·7	−0·8	+12·2	+0·50
590	599	+82	−58	67	−47	33	+1·7	+1·4	−1·0	+8·1	−0·82
591	599	+30	−95	9	−29	91	0·0	0·0	0·0	−0·5	−1·00
592	599	+100	−1	100	−1	0	+1·9	+1·9	0·0	+13·3	−0·35
593	599	+99	+17	97	+17	3	+0·8	+0·8	+0·1	+14·2	−0·28
594	599	+83	+56	69	+46	31	−0·4	−0·3	−0·2	+14·6	+0·14
595	599	+88	−48	77	−42	23	+1·7	+1·5	−0·8	+8·6	−0·82
596	600	+100	−1	100	−1	0	+0·8	+0·8	0·0	+13·2	−0·32
597	600	+42	−91	18	−38	82	−1·1	−0·5	+1·0	+1·5	−0·99
598	600	+98	+19	96	+19	4	+0·3	+0·3	+0·1	+14·4	−0·27
599	600	+57	−82	32	−47	68	+2·1	+1·2	−1·7	+2·4	−0·99
600	601	+79	−61	63	−48	37	+2·2	+1·7	−1·3	+6·6	−0·90
601	601	+86	+52	73	+44	27	+0·3	+0·3	+0·2	+14·8	+0·09
602	601	+47	+88	22	+41	78	−0·4	−0·2	−0·4	+5·8	+0·90
603	602	+71	−70	51	−50	49	−0·1	−0·1	+0·1	+4·8	−0·95
604	602	+90	+44	81	+40	19	−0·2	−0·2	−0·1	+14·7	+0·02
605	602	+80	+60	64	+48	36	−1·1	−0·9	−0·7	+13·2	+0·33
606	602	+96	−28	92	−27	8	−0·6	−0·6	+0·2	+11·6	−0·56
607	602	+78	+62	61	+49	39	+0·3	+0·2	+0·2	+11·5	+0·53
608	602	+100	−9	99	−9	1	+1·0	+1·0	−0·1	+13·2	−0·20
609	602	+77	−64	59	−49	41	+1·9	+1·5	−1·2	+9·3	−0·72
610	602	+81	−59	65	−48	35	+0·2	+0·2	−0·1	+10·6	−0·60
611	602	+99	+15	98	+15	2	+0·5	+0·5	+0·1	+13·0	+0·25
612	602	+73	+68	53	+50	47	−0·4	−0·3	−0·3	+7·7	+0·82
613	603	+98	+21	96	+21	4	+0·7	+0·7	+0·1	+14·3	−0·18
614	603	+31	+95	10	+29	90	−0·8	−0·2	−0·8	+9·4	+0·76
615	603	+85	−52	73	−44	27	−0·8	−0·7	+0·4	+8·5	−0·81
616	603	+77	−64	59	−49	41	+0·5	+0·4	−0·3	+7·4	−0·85
617	603	+96	−28	92	−27	8	−2·9	−2·8	+0·8	+11·4	−0·58
618	603	+100	−5	100	−5	0	+1·6	+1·6	−0·1	+13·3	−0·11
619	603	+99	−15	98	−15	2	+1·9	+1·9	−0·3	+13·1	−0·20
620	603	+64	−77	41	−49	59	+0·8	+0·5	−0·6	+8·0	−0·80
621	603	+99	−16	97	−16	3	+0·5	+0·5	−0·1	+13·1	−0·21
622	603	+88	−47	78	−41	22	−2·5	−2·2	+1·2	+11·5	−0·50
623	603	+44	+90	19	+40	81	+0·1	0·0	+0·1	+6·4	+0·88
624	603	+99	+12	99	+12	1	+1·1	+1·1	+0·1	+13·2	+0·18
625	603	+12	+99	1	+11	98	−1·2	−0·1	−1·2	−0·8	+1·00
626	603	+64	−77	41	−49	59	+0·6	+0·4	−0·5	+10·3	−0·65
627	603	+100	−3	100	−3	0	+1·4	+1·4	0·0	+13·4	+0·15
628	603	+31	+95	10	+29	90	−0·5	−0·2	−0·5	+1·8	+0·99
629	603	+98	+18	97	+18	3	−0·8	−0·8	−0·1	+12·7	+0·35
630	603	+99	−16	97	−16	3	+1·5	+1·5	−0·2	+13·6	+0·02
631	603	+84	+55	70	+46	30	−2·6	−2·2	−1·4	+7·8	+0·84
632	603	−99	+14	98	−14	2	−0·4	+0·4	−0·1	−12·5	+0·46
633	603	−72	−69	52	+50	48	−1·2	+0·9	+0·8	−12·9	−0·41
634	603	−79	−61	63	−48	37	−0·6	+0·5	+0·4	−13·4	−0·31
635	603	−76	−65	58	+49	42	−1·1	+0·8	+0·7	−13·2	−0·35
636	603	−83	−56	69	+46	31	+0·3	−0·2	−0·2	−13·7	−0·25
637	603	−100	+2	100	−2	0	0·0	0·0	0·0	−13·2	+0·36
638	603	−100	−3	100	+3	0	−0·3	+0·3	0·0	−13·4	+0·31
639	603	−89	−46	79	+41	21	+0·1	−0·1	0·0	−14·0	−0·13
640	603	−96	+28	92	−27	8	−0·4	+0·4	−0·1	−11·4	+0·59

Table II—*Continued*

Serial No.	Luna-tion No.	p	q	p^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of $\Delta\alpha$	Coefficient of $\Delta\delta$
641	604	+100	+9	99	+9	1	+0·7	+0·7	+0·1	+13·2	+0·23
642	604	+100	+10	99	+10	1	+0·7	+0·7	+0·1	+13·2	+0·24
643	604	+100	−7	100	−7	0	+0·6	+0·6	0·0	+13·5	+0·08
644	604	+92	+39	85	+36	15	−0·5	−0·5	−0·2	+11·0	+0·60
645	604	+40	−92	16	−37	84	+1·0	+0·4	−0·9	+9·9	−0·72
646	604	+43	−90	18	−39	82	+0·9	+0·4	−0·8	+10·9	−0·66
647	604	−2	−100	0	+2	100	−0·3	0·0	+0·3	+6·0	−0·91
648	604	+97	+25	94	+24	6	−0·5	−0·5	−0·1	+11·5	+0·61
649	604	+90	−44	81	−40	19	−1·4	−1·3	+0·6	+14·5	−0·05
650	605	+68	−73	47	−50	53	+1·5	+1·0	−1·1	+11·5	−0·56
651	605	+93	−36	87	−34	13	+0·8	+0·7	−0·3	+13·7	−0·14
652	605	+100	−6	100	−6	0	+2·5	+2·5	−0·2	+13·6	+0·17
653	605	+85	+53	72	+45	28	+0·1	+0·1	+0·1	+8·0	+0·84
654	605	+83	+56	69	+46	31	−0·4	−0·3	−0·2	+7·3	+0·87
655	605	+95	−30	91	−29	9	0·0	0·0	0·0	+14·8	+0·16

(Received 10 July 1972)

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 19–26, 1972

A Gabbro-Troctolite-Anorthosite Intrusion at Dirnaseer, near Temora, New South Wales

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Abstract—The Dirnaseer basic intrusion, consisting largely of crudely layered gabbroic, troctolitic and anorthositic rocks, is interpreted as representing the exposed portion of a high level, boat-shaped magma chamber. Marginal doleritic rocks are interpreted as a chilled facies of the intrusion, and xenoliths of granular plagioclase-olivine-clinopyroxene hornfels are considered to be recrystallized fragments of previously emplaced gabbros. The rocks display tholeiitic affinities, being relatively poor in Ti, P, K and Na and relatively rich in Mg. Apart from some chemical differences, the Dirnaseer intrusion shows particular similarity to the Somerset Dam Intrusion and Eulogie Park Gabbro in Queensland, and has many features in common with other basic intrusions. New data are also given for a quartz-bearing two-pyroxene gabbro from Wyalong and a metadolerite from Reefton, New South Wales.

Introduction

Several small bodies comprised of gabbroic, troctolitic and anorthositic rocks crop out near the village of Dirnaseer, about 25 km. south-east of Temora, New South Wales. The rocks, designated as late- or post-Devonian olivine dolerite on the first edition (1967) of the Cootamundra 1 : 250,000 Geological Sheet, appear to intrude (?) Silurian low grade quartz-rich metasediments and are partly mantled by Cainozoic alluvium. In the present work, field, petrographic and geochemical studies have been undertaken with the aim of explaining some features of the origin of these rocks and similar rocks elsewhere.

Geological Setting

The best exposed rocks of the intrusion occur on a low hill covering about 3 km.^{2} near the village of Dirnaseer. Several areas of poor outcrop occupy a similar area on a low rise about 5 km. to the west (see Fig. 1). The eastern, roughly crescentic mass is composed chiefly of plagioclase-rich olivine gabbro, with less abundant troctolite and olivine gabbro and rare anorthosite (some occurring as veins up to 2 cm. wide in troctolite). The gabbroic and troctolitic rocks locally exhibit layering defined by varying proportions of plagioclase and mafic minerals, although no regular, persistent layering is evident on a large scale. Dips on the layering are predominantly (but not exclusively) westerly and strikes are sub-parallel to the outline of the body (see Fig. 1). Finer grained, altered doleritic rocks (possibly representing a chilled facies of the intrusion) occur near one contact with recrystallized muscovite quartzite (which grades away from the intrusion into indurated micaceous sandstone).

The three areas of outcrops on the west possibly represent surface exposures of a mass similar in shape to, but a rough mirror-image of, the eastern body. The western rocks comprise olivine gabbros (some displaying easterly-dipping layering) together with minor plagioclase-rich gabbro (transitional to anorthosite), marginal altered dolerite and fine-grained plagioclase-olivine-clinopyroxene hornfelses. The granular hornfelses, which have not been observed among the eastern rocks, are found both as small, discrete xenoliths within the gabbros and also as larger bodies. The xenoliths (up to 1 m. in length) are lenticular and elongate parallel to the layering in the gabbros ; the larger hornfels bodies, which exhibit crude relict layering and variable grainsize, show all gradations to normal gabbroic rocks.

Petrography and Chemistry

The nomenclature adopted for the Dirnaseer rocks follows that of Jackson (1968, fig. 2), except that limiting boundaries have been set as 5% rather than 10% by volume. Qualifying terms such as olivine-rich and plagioclase-rich have been used where appropriate ; thus, the name plagioclase-rich olivine gabbro refers to olivine gabbros containing more than 75% plagioclase and encompasses rocks designated as "leucogabbro" by Mathison (1967) and Wilson and Mathison (1968).

The relative abundances and average primary modal compositions of the various rock types of the intrusion are summarized in Table 1. Major element chemical analyses, trace element data and C.I.P.W. norms for six rocks from the Dirnaseer intrusion, and for two rocks from basic masses near Reefton and near Wyalong (see location map in Fig. 1) are presented in Table 2.

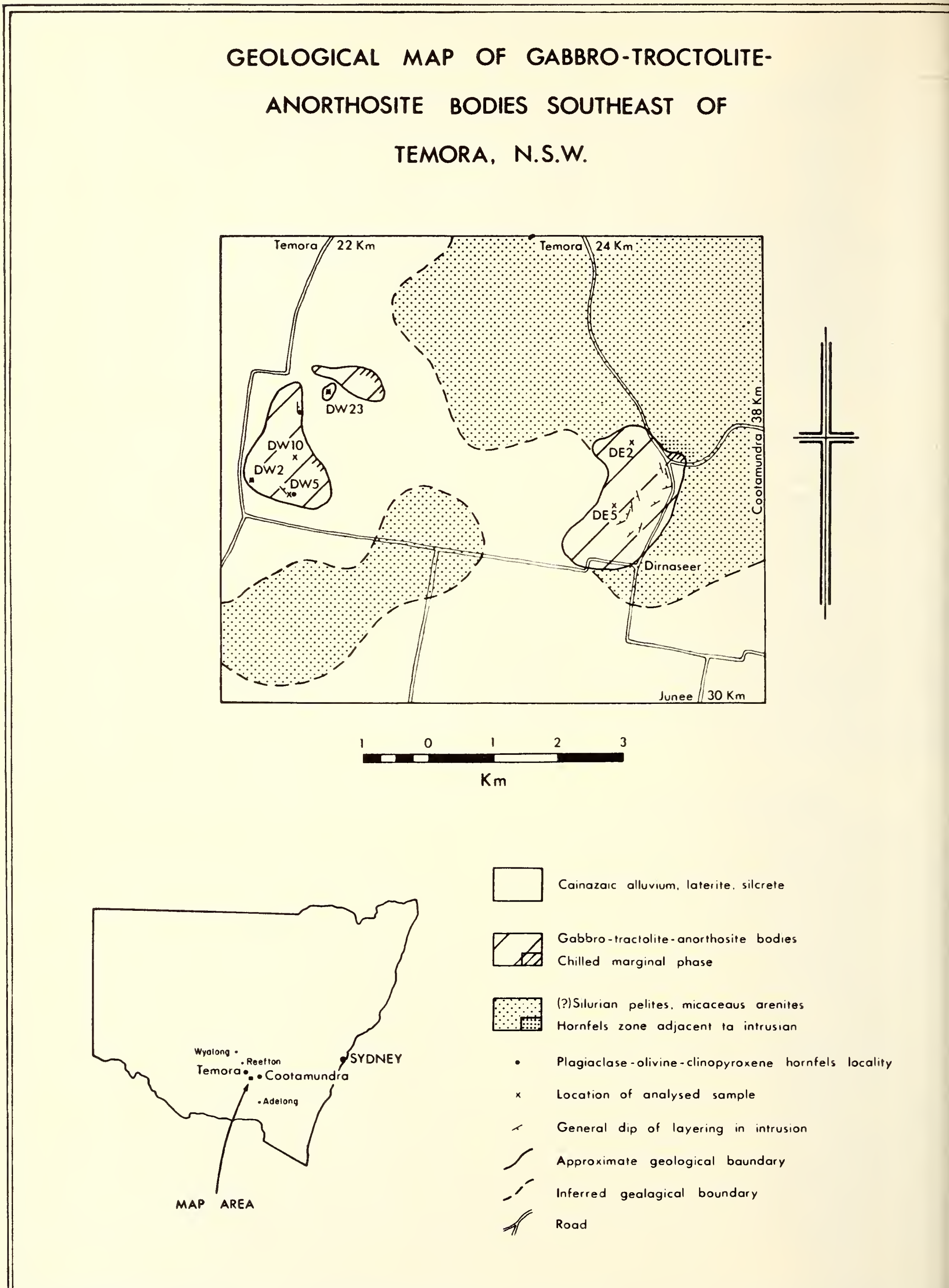

FIG. 1.—Geological map of gabbro-troctolite-anorthosite bodies south-east of Temora, N.S.W.

Primary minerals observed in the rocks are plagioclase, olivine, clinopyroxene, orthopyroxene, brown amphibole, biotite, sphene, iron oxides, and sulphides. The silicate minerals show variable but generally slight alteration to secondary hydrous phases.

Plagioclase is the dominant primary phase in all the rocks of the intrusion (ranging from about 50% to nearly 100% by volume). Grainsize ranges from an average of 0·5 mm. in the mafic hornfelses to 2–3 mm. in the troctolites, some elongate grains attaining 6 mm. in the latter. The grains are mostly subhedral, although those enclosed by clinopyroxene are commonly euhedral and lath-shaped. In the troctolites, a weak preferred orientation of plagioclase laths is apparent, and, in these rocks and the anorthosites, the grains display slight bending and there is some tendency for their boundaries to meet at interfacial angles of 120°. There is no marked difference in plagioclase composition among the various rock types, nor does the mineral show compositional zoning, except in the dolerites (where it is zoned from An_{30} to An_{65}, and averages An_{55}). In the plagioclase-rich olivine gabbros, the plagioclase composition ranges from An_{64} to An_{72}, whereas in the troctolitic rocks the range extends to An_{80}. Alteration of plagioclase to fine-grained prehnite, clinozoisite, albite, calcite and sericitic mica is minor, except in the dolerites.

Olivine occurs in all the rocks of the intrusion except the anorthosite veins in troctolite and in some of the dolerites, and constitutes up to 35% by volume of the more olivine-rich gabbros and troctolites. The olivine grains (0·2 mm. across in the mafic hornfelses and up to 3 mm. across in the troctolites) are usually subhedral and enclosed in clinopyroxene and plagioclase, although in some troctolites they are interstitial to plagioclase laths. A weak preferred dimensional orientation of olivine is present in some of the layered troctolites. The composition is $Fo_{75\pm5}$ for all rock types. Olivine has been partly to completely altered to secondary phases. The common secondary assemblage is lizardite + pale green (pleochroic) chlorite + magnetite, but minor talc, phlogopitic mica and pyrrhotite also occur. Plagioclase surrounding partly altered olivine shows radial cracking, probably caused by expansion during the alteration of the latter (Plate I).

Clinopyroxene is present in all the rocks of the intrusion except for anorthosite veins in troctolite and in some of the very altered dolerites. Only trace amounts occur in the troctolites, but some of the mafic hornfelses, gabbros and dolerites contain up to 40% by volume of clinopyroxene. In all rocks except the granular mafic hornfelses, clinopyroxene has an ophitic to poikilitic texture, enclosing both olivine and plagioclase, and some very poikilitic grains measure 6 mm. across. In the mafic

TABLE 1

Relative Abundances and Average Primary Modal Compositions of the Main Rock Types

Rock Type	Olivine Gabbro	Plagioclase-rich Olivine Gabbro	Troctolite	Anorthosite	Plagioclase-olivine-clino-pyroxene Hornfels	Dolerite (Chilled Margin)
Eastern Body	Common	Dominant	Common	Rare	Absent	Rare
Western Body	Dominant	Rare	Absent	Rare	Rare	Rare
Average Modal Proportions of Primary Minerals (Volume Per Cent.)[1]						
Plagioclase	65	85	70	97	55	55
Olivine	15	8	25	2	15	5
Clinopyroxene	17	6	3	1	29	39
Orthopyroxene	<0·5	<0·5	—	—	<0·5	—
Brown amphibole ..	1	<0·5	<0·5	—	<0·5	<0·5
Biotite	<0·5	<0·5	<0·5	—	—	—
Sphene	—	—	—	<0·5	—	—
Oxides	0·5	<0·5	0·5	<0·5	<0·5	1
Sulphides	0·5	<0·5	0·5	—	<0·5	<0·5

[1] Minor amounts of secondary alteration products have been assigned to the appropriate primary phases.

TABLE 2
Chemical Analyses

	1	2	3	4	5	6	7	8
SiO_2	42·88	43·79	45·94	45·40	46·24	46·94	51·36	48·88
TiO_2	0·09	0·13	0·20	0·18	0·20	0·40	1·54	2·29
Al_2O_3	22·99	22·77	22·26	27·35	29·01	15·28	17·19	14·77
Fe_2O_3 ..	1·43	1·22	0·79	0·72	0·52	1·20	2·28	3·98
FeO	4·89	5·10	3·38	2·70	1·58	6·71	6·82	7·53
MnO	0·10	0·10	0·08	0·06	0·04	0·16	0·19	0·24
MgO	13·23	10·83	9·13	5·59	3·08	12·61	5·18	5·28
CaO	11·89	12·26	15·19	15·11	15·68	15·08	9·45	9·28
Na_2O	1·03	1·47	1·16	1·44	1·84	0·97	3·07	4·42
K_2O	0·05	0·07	0·07	0·05	0·11	0·05	0·45	0·62
P_2O_5	0·02	0·00	0·02	0·02	0·04	0·02	0·32	0·29
H_2O^+	2·09	3·13	2·12	1·75	1·62	1·59	1·15	2·31
H_2O^-	0·11	0·07	0·09	0·17	0·02	0·11	0·01	0·14
CO_2	0·10	0·16	0·10	0·10	0·10	0·07	0·08	0·15
Total ..	100·90	101·10	100·53	100·64	100·08	101·19	99·09	100·18

Analyses by X.R.F. spectrometry (fused borate button technique), flame photometry (Na_2O) and classical methods (FeO, H_2O and CO_2)

Trace Elements (p.p.m.)

	1	2	3	4	5	6
Sc	41	42	56	50	49	74
V	8	21	59	30	27	106
Cr	165	118	776	143	113	451
Ni	123	139	73	71	33	57
Cu	44	26	44	43	35	85
Zn	50	50	32	28	18	51
S	53	254	444	21	21	938
Mn	774	766	573	416	300	1,074
Ti	436	779	1,236	1,085	1,043	2,237
K	—	—	576	453	848	—

Analyses by X.R.F. spectrometry (pressed powder technique)

C.I.P.W. Weight Per Cent. Norms

	1	2	3	4	5	6	7	8
Q	0·00	0·00	0·00	0·00	0·00	0·00	3·98	0·00
Or	0·30	0·41	0·41	0·30	0·65	0·30	2·68	3·67
Ab	8·61	11·72	9·81	12·18	15·14	8·20	26·00	35·60
Ne	0·06	0·38	0·00	0·00	0·23	0·00	0·00	0·97
An	57·96	55·32	55·32	68·01	70·57	37·19	31·82	18·64
Di	0·20	3·58	15·32	4·93	5·04	29·71	10·20	19·97
Hy	0·00	0·00	2·73	1·25	0·00	4·16	16·04	0·00
Ol	29·06	24·10	12·93	10·39	5·36	17·23	0·00	7·73
Mt	2·07	1·77	1·15	1·04	0·75	1·74	3·33	5·78
Il	0·17	0·25	0·38	0·34	0·38	0·76	2·93	4·36
Ap	0·05	0·00	0·05	0·05	0·09	0·05	0·77	0·67
Cc	0·23	0·36	0·23	0·23	0·23	0·16	0·18	0·34
H_2O	2·20	3·20	2·21	1·92	1·64	1·70	1·16	2·45
Percentage An (Plag) ..	87·1	82·5	84·9	84·8	82·3	81·9	55·0	34·4
Percentage Fo (Ol)	84·7	81·0	84·8	81·4	82·0	79·0	—	62·2

1. DE 5. Troctolite.
2. DW 5. Olivine gabbro (transitional to troctolite).
3. DW 2. Olivine gabbro.
4. DE 2. Plagioclase-rich olivine gabbro.
5. DW10. Plagioclase-rich gabbro (transitional to anorthosite).
6. DW23. Plagioclase-olivine-clinopyroxene hornfels xenolith.
7. Orthopyroxene-clinopyroxene-hornblende-biotite-quartz gabbro, 1 km. north of Wyalong ("norite-rock" locality of Watt (1899)).
8. Low grade metadolerite, 4 km. east of Reefton.

Sample localities for analyses 1–6 are indicated in Figure 1.

Samples are housed in the collection of the School of Earth Sciences, Macquarie University (catalogue numbers MU 2144–2151 inclusive).

hornfelses the clinopyroxene forms equant grains averaging 0·4 mm. across. It contains rare inclusions (some vermicular) of ilmenite and magnetite, and is commonly rimmed by brown amphibole and/or a green actinolitic amphibole with chlorite and sphene.

Orthopyroxene occurs as rare, small subhedral grains (up to 0·5 mm. across) in some of the olivine gabbros, closely associated with clinopyroxene and olivine. It is generally extensively altered to fine-grained aggregates of talc and chlorite.

Brown amphibole, besides rimming clinopyroxene, also forms discrete grains poikilitically enclosing plagioclase. It comprises up to 3% by volume of some olivine gabbros and is commonly fringed by (apparently altered to) pale green actinolitic amphibole.

Biotite is a rare accessory mineral in some olivine gabbros where it occurs as small plates usually associated with olivine, and as narrow rims on some ilmenite grains.

Sphene is a rare accessory phase in some anorthosites and transitional plagioclase-rich gabbros.

Ilmenite and *magnetite* amount to about 1% by volume of the more mafic gabbros and dolerites, but are very rare in plagioclase-rich rocks. Ilmenite, the dominant oxide mineral, occurs discretely, or in composite grains with magnetite, the grains showing irregular outlines (occurring interstitially to plagioclase, olivine and pyroxenes) and attaining a maximum grainsize of 1 mm. Ilmenite shows narrow rims of sphene in some of the more altered rocks. Magnetite has not been observed as independent primary grains but only in composites with ilmenite.

Sulphide minerals comprising pyrrhotite, chalcopyrite, pentlandite, sphalerite, marcasite and mackinawite, are sparsely distributed through the olivine gabbros and troctolites, forming up to 0·5% by volume of some mafic gabbros. Pyrrhotite is by far the most dominant sulphide mineral and occurs as droplike grains interstitial to the silicate minerals (Plates III and IV). Some pyrrhotite-rich aggregates measure 15 mm. across. Both monoclinic and hexagonal polymorphs of the mineral occur, the dominant monoclinic type containing exsolved lamellae of the hexagonal type. Pyrrhotite contains lamellae, " flames " and irregular grains of pentlandite, chalcopyrite and rare sphalerite, and in places displays slight alteration to marcasite. Pyrrhotite and less abundant chalcopyrite are intergrown locally with secondary actinolitic amphibole (Plate II), and the alteration of olivine has produced a little pyrrhotite associated with magnetite. Rare tiny wisps of mackinawite occur in some chalcopyrite grains.

Discussion

The rock types at Dirnaseer bear a striking resemblance to those described from two layered basic intrusions in Queensland—the Somerset Dam Intrusion (Mathison, 1967) and the Eulogie Park Gabbro (Wilson and Mathison, 1968). The only notable differences are the imperfect layering and apparent absence of " ferrigabbros " (magnetite-rich gabbros) in the Dirnaseer occurrence.

Mathison (1967, fig. 9) has interpreted the Somerset Dam Intrusion as representing the exposed portion of a high-level, dish-shaped magma chamber. The diversity of rock types is considered to be the result of crystallization of periodically renewed batches of basic magma, with factors such as the composition of the magma, the limited range of crystallization temperature, diffusion processes and the control of water vapour pressure playing important roles in the prevention of progressive differentiation by gravitational crystal settling. Despite its poor exposure, the Dirnaseer occurrence can also be interpreted to have formed in this way. Although the two separate areas of outcrop at Dirnaseer could conceivably represent independent intrusive bodies, it is suggested, in view of the complementary outcrop patterns and dips of layering in the two areas, that the rocks constitute a single, crudely layered, elongate saucer-shaped or boat-shaped intrusive unit, which is exposed only at each end.

Despite the probable close similarity in form and structure, the rocks of the Dirnaseer intrusion are systematically different in chemical composition from those in both of the Queensland occurrences. The troctolites, olivine gabbros, plagioclase-rich olivine gabbros, and xenoliths of plagioclase-olivine-clinopyroxene hornfels at Dirnaseer are all much poorer in Si, Ti, P, K and Na, but richer in Mg and Ca than their counterparts at Somerset Dam. The chemical composition of the doleritic chilled marginal phase of the Eulogie Park Gabbro is quite similar to the estimated bulk composition of the Somerset Dam Intrusion and again unlike that of the Dirnaseer intrusion. These chemical features, especially the poverty in Ti, P, K and Na, are consistent with the hypothesis that the Dirnaseer rocks have been derived from a magma even more tholeiitic in character than that which gave rise to the Queensland examples.

The closest rocks similar to the Dirnaseer gabbros, although characteristically richer in orthopyroxene, are those of the small, layered norite-gabbro body at Adelong, about 100 km. south-south-east of Dirnaseer (Vallance, 1954 ; Chaffer, 1957), and the noritic rocks associated with diorites around Wyalong, about 80 km. north-north-west of Dirnaseer (Watt, 1899). The analysed orthopyroxene-clinopyroxene-hornblende-biotite-quartz gabbro from Wyalong exhibits a plagioclase lineation and chemically (analysis 7, Table 2) is notably richer in Si, Ti, Na, K and P and poorer in Ca than the Dirnaseer gabbros. A small basic body located about 4 km. east of Reefton (40 km. north-north-west of Dirnaseer) contains low-grade metadolerite composed of albite, clinopyroxene and actinolitic amphibole, with minor chlorite, pumpellyite, clinozoisite, sphene, ilmenite and tourmaline. The metadolerite is chemically dissimilar to the Dirnaseer rocks in having higher Ti, Na, K, P and Fe and lower Ca and Al (analysis 8, Table 2).

The plagioclase-olivine-clinopyroxene hornfels xenoliths associated with the gabbros at Dirnaseer have been the subject of particular study in view of the differing interpretations placed on such rocks in gabbroic intrusions elsewhere. The terms beerbachite, gabbro-aplite, granulite, etc., have been used to describe some of these rocks ; however, Phillips (1969) recommends that the term beerbachite be reserved for rocks occurring as dykes rather than xenoliths. Basic granular hornfelses very similar to those at Dirnaseer are found as xenoliths and/or marginal zones in the Somerset Dam Intrusion, Eulogie Park Gabbro, Mt. Samson Complex (Phillips, 1959), Carlingford Complex (Harry, 1952 ; Le Bas, 1960), Girvan-Ballantrae mafic-ultramafic belt (Bloxam, 1955), Insch Gabbro (Sadashivaiah, 1950), Ardnamurchan Hypersthene-Gabbro (Wells, 1951, 1953 ; Brown, 1954), Ben Buie Gabbro-Complex (Bailey *et al.*, 1924 ; MacGregor, 1931), Skye Gabbro-Complex (Harker, 1904 ; MacGregor, 1931), Frankenstein Gabbro (Klemm, 1926 ; MacGregor, 1931), Duluth Gabbro (Grout, 1933) and Freetown Complex (Wells, 1962). Some authors (e.g. Grout, 1933 ; Sadashivaiah, 1950 ; Harry, 1952 ; Phillips, 1959) have interpreted these rocks as extensively metasomatized ("gabbroized") sedimentary country rocks, whereas others (e.g. Wells, 1962) have considered them to be recrystallized earlier gabbroic rocks. Wells (1953) has also noted two other hypotheses, viz. the xenoliths represent (1) thermally metamorphosed basaltic or doleritic rocks, or (2) fragmented basic dykes initially intruded into hot gabbro.

With regard to the hornfels xenoliths in both the Dirnaseer intrusion and the Somerset Dam Intrusion, their commonly tabular form and the crude layering shown by some examples are inconsistent with derivation from the largely massive country rocks. Furthermore, the occurrence in both intrusions of zones of rocks transitional between hornfelses and olivine gabbros (cf. Mathison, 1967, p. 60) is considered to be convincing evidence that the xenoliths hornfels are virtually isochemically recrystallized fragments of gabbroic rocks emplaced previously. The two analysed hornfels xenoliths from the Somerset Dam Intrusion are similar in chemical composition to the weighted average of the layers in Zone 4 of that mass. However, in contrast, the analysed Dirnaseer xenolith (analysis 6, Table 2) is chemically different from the associated coarse-grained rocks (e.g. poorer in Al, richer in Fe, Ti, Mn, Sc, V, Cu and S), although it is certainly of broadly gabbroic composition.

The proportion of secondary (alteration) minerals (such as actinolitic amphibole, chlorite, prehnite and clinozoisite) in the Dirnaseer and Queensland rocks reaches a maximum in the most leucocratic representatives, and, as pointed out by Mathison (1967), this consistent association suggests that a late magmatic or deuteric process, rather than a regional metamorphic one, has given rise to such phases in all the rocks. Nevertheless, in the Dirnaseer intrusion, which is probably older than the Queensland intrusions, part of the observed alteration, notably in the finer grained, marginal dolerites, can possibly be ascribed to low-grade regional metamorphism.

The status of the brown amphibole found in small amounts in most of the rocks is, however, ambiguous. By analogy with similar amphiboles in rocks of the Somerset Dam Intrusion, it is most likely to be a titaniferous hornblende. Mathison (1967, p. 70) deduces from textural relationships that the Somerset Dam amphibole (which is a kaersutite) has two distinct modes of origin : solid state replacement of augite (mainly in leucogabbros), and late magmatic crystallization from the intercumulus liquid (mainly in olivine gabbros). In the Dirnaseer rocks, this distinction also holds, in that brown amphibole forms both optically continuous overgrowths (commonly closely associated with actinolitic amphibole) on clinopyroxene in plagioclase-rich olivine gabbros, and also interstitial poikilitic grains in olivine gabbros and troctolites.

The sulphide minerals are, for the most part, interstitial to, and do not appear to replace the primary silicate minerals (Plates III and IV). It appears probable that they have segregated as an immiscible sulphide liquid phase within a crystallizing silicate magma. According to Naldrett (1969), the crystallization of Fe-Ni-Cu sulphides interstitial to plagioclase and unaltered pyroxene is indicative of a relatively low water content of the magma, under which conditions the silicate liquidus is reached before that of the sulphides.

At the time of initial crystallization of the sulphides, a homogeneous sulphide solid solution probably existed. Subsequent unmixing of minor chalcopyrite, pentlandite and sphalerite from a pyrrhotite host apparently then occurred with decreasing temperature. The occurrence of intergrowths of pyrrhotite and chalcopyrite with euhedral secondary actinolitic amphibole (Plate II), and of pyrrhotite as an alteration product of olivine, suggest both a recrystallization of some of the primary sulphides and a moderately high fugacity of sulphur during the relatively low temperature alteration of the primary minerals. The formation of mackinawite also may have occurred at temperatures comparable to the alteration of the primary silicates (cf. Chamberlain and Delabio, 1965; Clark, 1966; Genkin, 1971).

Acknowledgement

The authors wish to express their gratitude to Associate Professor R. H. Vernon of the School of Earth Sciences, Macquarie University, for his helpful comments.

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(Received 24 March 1972)

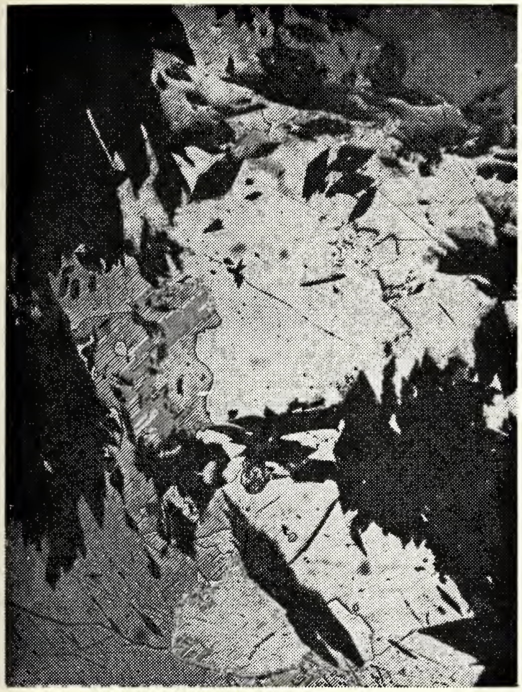
Explanation of Plates

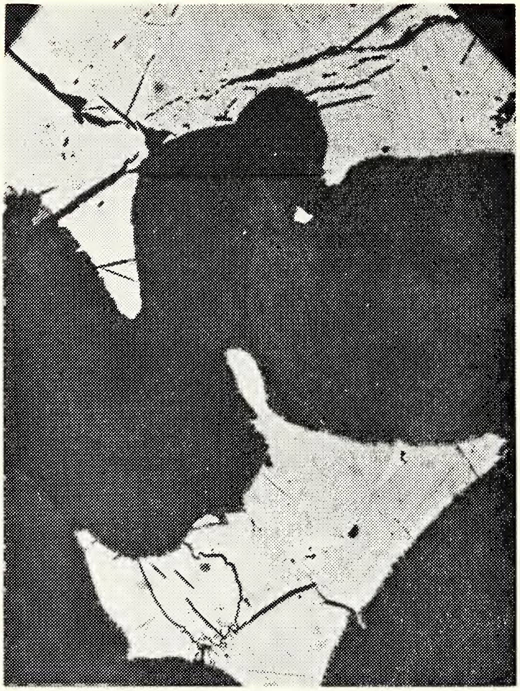
Plate I.—Olivine (pale grey, centre) partly altered to lizardite, chlorite (both dark grey) and magnetite (white) with radial cracking in surrounding plagioclase (medium grey) : troctolite. Reflected light. ×55. Sample DE5.

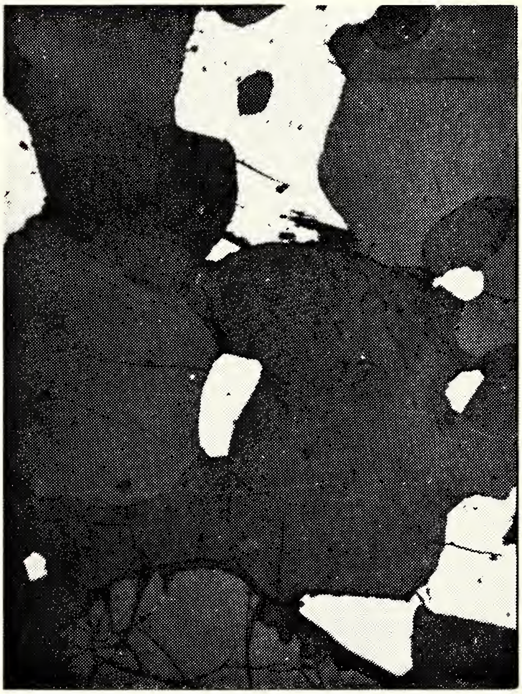
Plate II.—Secondary euhedral actinolitic amphibole (dark grey) enclosed by chalcopyrite (white) and pyrrhotite (pale grey) : olivine gabbro. Reflected light. ×150. Sample DW2.

Plate III.—Pyrrhotite (white) interstitial to plagioclase (darkest), clinopyroxene and olivine (medium grey) : olivine gabbro. Reflected light. ×75. Sample DW2.

Plate IV.—Pyrrhotite (almost white) interstitial to clinopyroxene (dark grey). Note minor wavy lamellae of hexagonal pyrrhotite (pale grey, right) and inclusions of pentlandite (white, lower left) within the dominant monoclinic pyrrhotite : olivine gabbro. Reflected light. ×75. Sample DW2.







Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 27–29, 1972

Ripple-Drift Cross-Lamination in the Hawkesbury Sandstone, New South Wales

Colin R. Ward

Abstract—Ripple-drift cross-lamination (climbing ripples) is present in the bottomset of a cross bed unit in the Hawkesbury Sandstone, west of Garie, N.S.W. The structure has been formed by a combination of vertical settling and traction transport of coarse grained sand in a manner similar to that described by Boersma (1967) for modern sediments of the Rhine delta in Holland. The direction of current flow was opposite to that of the adjacent cross bed unit because of the influence of a zone of reverse circulation in the bottomset area.

Introduction

Although cross bedding is a prominent feature of the Middle Triassic Hawkesbury Sandstone, other sedimentary structures are relatively rare. In a detailed survey, Standard (1969) recorded only six occurrences of ripple marks, with wavelengths of approximately 30 cm. and amplitudes slightly in excess of 2·5 cm. Branagan (1971), however, suggests that there may also be many poorly preserved mega-ripples or dune structures with wavelengths of more than 5 m. and amplitudes up to 1 m.

Ripple-drift cross-lamination, a structure known also as climbing ripples, has been described from a number of sedimentary environments, including the top of fluvial point bars (Visher, 1965), turbidites (Walker, 1963) and fluvioglacial deltas. It is common in fine-grained sediment, such as silt and fine sand, and is considered to be formed by a combination of traction transport and vertical settling from suspension (Jopling and Walker, 1968; Allen, 1970). Although this sedimentary structure has not previously been reported from the Hawkesbury Sandstone, an excellent exposure is preserved in a road cutting west of Garie Beach, within the Royal National Park, approximately 32 km. (20 miles) south of Sydney (Fig. 1).

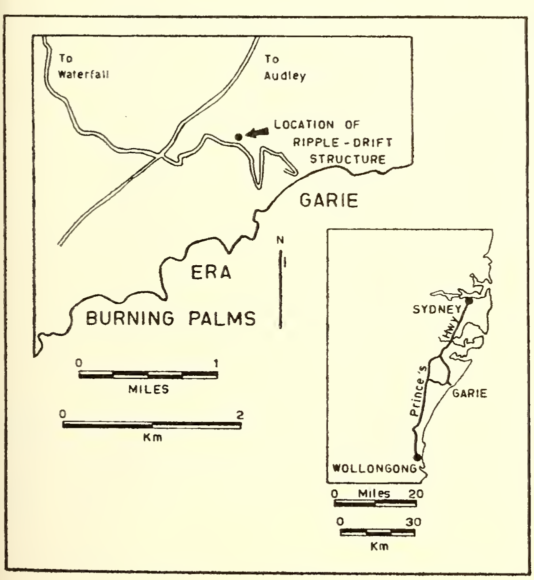


Fig. 1.—Locality map.

Description

The ripples are larger than those described by Standard (1969) and have an amplitude of approximately 5 cm.; their wavelength is difficult to estimate because of contemporaneous erosion (Plate I). Superposition of successive sets of ripples has been preceded by almost complete erosion of the stoss or upcurrent side, so that the structure corresponds closely to type A of Jopling and Walker (1968). A zone of smaller ripples, with a tendency towards development of sinusoidal ripple lamination (Jopling and Walker, *op. cit.*) is present as a minor feature.

The sediment which contains the ripple-drift structure is a medium- to coarse-grained sandstone, with sporadic pebbles of white vein quartz up to 1 cm. in diameter. The sandstone is fairly friable, and following soaking and gentle crushing can be subjected to sieve analysis. The results of such an analysis (Fig. 2) show a graphic mean grainsize (Folk, 1968) of $0{\cdot}83\varphi$ (0·56 mm.) and an inclusive graphic standard deviation of 0·89φ, indicating a moderate degree of sorting. The inclusive graphic skewness is +0·29, indicating an excess of fine material. Because many of the quartz grains have suffered secondary enlargement, and a certain amount of authigenic clay is present (Standard, 1969), these data should not be subjected to excessively detailed analysis. However, the sediment is unusually coarse-grained for one exhibiting ripple-drift cross-lamination, since the structure appears to be most common in silts and fine sands.

The horizon containing the ripple-drift cross-lamination is situated in the same bed as, and a few metres east of a prominent set of easterly dipping high angle cross beds. The ripple-drift horizon lies in front of and slightly below the toe of these cross beds, and rests upon a bed of similar pebbly sandstone containing very low angle cross stratification. Additional poorly exposed ripples, although not of the climbing type, are present towards the base of this bed (Plate II) and are in turn underlain, beneath a sharp contact, by a further high angle cross bed unit. The top of the ripple-drift horizon is covered by a thick accumulation of talus and weathered debris, and cannot be examined in detail.

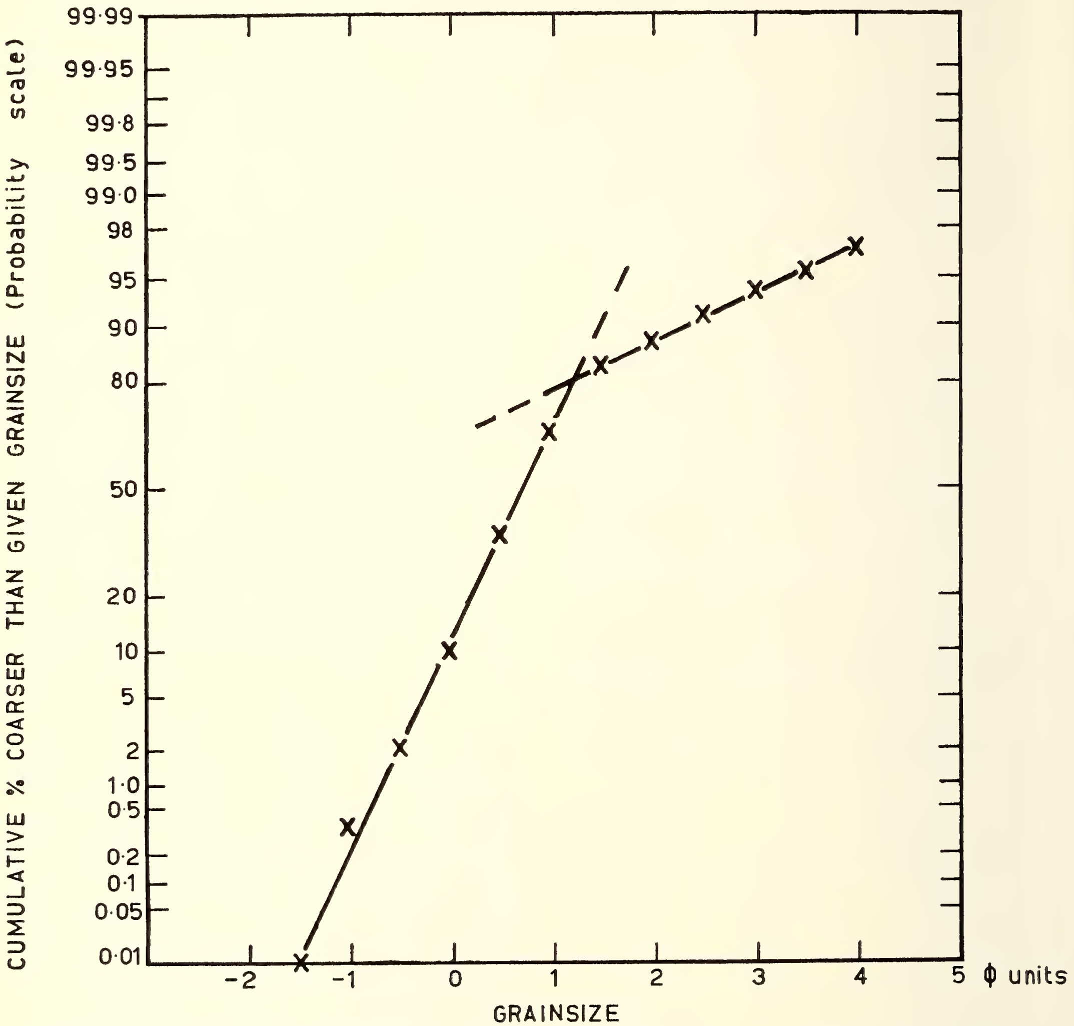


FIG. 2.—Cumulative grainsize distribution curve (probability ordinate) for ripple-drift sandstone.

Ripple-drift cross-lamination grading down into massive and horizontally bedded bottomset sediment.

General view of ripple-drift horizon and underlying sediment.

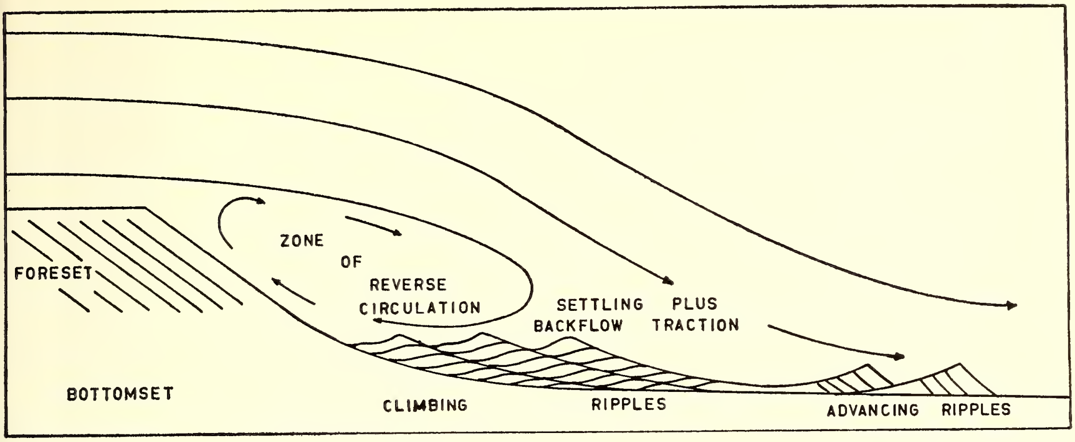


Fig. 3.—Mechanism of ripple-drift formation. (*After* Boersma, 1967.)

Origin

Similar climbing ripples and other sedimentary structures in Recent sediments of the upper Rhine delta in Holland are described by Boersma (1967). In this case the climbing ripples are thought to have formed in the lee of advancing mega-ripples or dunes in the river channel (Fig. 3). As the mega-ripple advances, it forms high angle cross beds. The finer sediment settles out from suspension, and at the same time is transported by a traction current flowing in the opposite direction to the main stream because of back flow in the lee of the advancing mega-ripple (Jopling, 1964).

The model described by Boersma (1967) appears to explain the ripple-drift cross-lamination, low angle cross bedding and other ripple marks in the Hawkesbury Sandstone at Garie ; it also accounts for the directions of sediment transport. The coarse grainsize of the ripple-drift sediment is probably a reflection of active flow conditions and an abundant supply of suspended sediment form avalanches on the foreset slope of the advancing mega-ripple.

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(Received 23 June 1972)

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 31–37, 1972

Late Devonian (Frasnian) Conodonts from Ettrema, New South Wales

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Abstract—Conodont faunas from two localities are discussed and illustrated. Their age is considered to be late Frasnian (toIδ). One new subspecies, *Polygnathus nodocostatus ettremae*, is described.

Introduction

During preparation of correlation tables for the Devonian System of Australia and New Zealand (Pickett, 1972), a number of units remained only doubtfully correlated, due to insufficient data regarding their precise age.

An occurrence of limestone near Ettrema Mine, on Jones Creek (GR 207780 Nerriga 1 : 31,680 sheet, 35 km. ESE of Nowra), one of these, had been reported initially as Silurian in age (Rose, 1966), then as mid-Devonian (Croft *et al.*, 1970). Because of its palaeographical implications, a mid-Devonian age seemed questionable. Accordingly, the locality, which is most difficult of access, was visited, and samples taken.

The most obvious elements of the macrofauna in the limestones in Jones Creek are large, inflated atrypid brachiopods, and rare plocoid phillipsastreid corals. The limestones themselves are well-bedded, with occasional interbeds of shale which may dominate the sequence over a vertical distance of up to 20 metres. The beds are strongly folded and in places much sheared. The area has not been mapped in any detail because of the rugged topography and the blanket of Permian sediments which obscure the older Palaeozoic rocks everywhere but in the gorges. The locality is important because it is the first limestone occurrence in New South Wales of proven Frasnian age. It is probable that the sediments will be referable to a horizon in the Merrimbula Group. Other fossil localities within the Merrimbula Group, notably locality UP. 4 of Wood (in McElroy and Rose, 1962), appear to be Frasnian also. Specimens from this locality in the Mining Museum collections contain abundant *Productella*, *Cyrtospirifer* and *Tentaculites*, with some *Tenticospirifer* and a large coarsely ribbed pectenoid. These are preserved in a well-washed orthoquartzite. The presence of the four named genera is good evidence for a Frasnian age for this fauna. In Ettrema Creek, on a horizon very close to that of conodont fauna 2, are occasional shale bands with abundant fossils, sheared to a varying extent. One of these contains a few specimens of *Productella ?* sp., another contains crowded *Cyrtospirifer* sp.

Nomenclature

Recent advances in conodont research have been towards description of conodont assemblages, " natural " genera, and species. While it is not the intention of the author to become involved in the current debate on nomenclatorial procedures, some justification for the procedure adopted is warranted. Polygnathids make up 39% of the present fauna. It is thus apparent that if a given conodont apparatus contains only two polygnathid elements and a number of others (as suggested by Klapper and Philip, 1971) there must have been some winnowing of the fauna, especially considering that a further 3% of other platform types occurs in the fauna, and that icriodids constitute another 7%. Apparently, therefore, the fauna contained a number of species of *Polygnathus* (*sensu* Klapper and Philip, 1971), i.e. of apparatuses of their type 1. The sorting of the fauna (and probably also the number of specimens available) precludes determination of which other elements belonged to the natural species. Hence, although it is possible to identify to " species " most of the discrete elements present, it is not possible to apply a specific name to the natural species, and only possible in two cases for the genera (and this with some doubt). Furthermore, since ranges of natural species are in general not established, these can only be determined from those of the discrete elements. The examination of the present fauna was undertaken for stratigraphic reasons rather than for information on the conodonts themselves. Thus I am in support of the standpoint clearly enunciated by Rhodes (1962), since the stratigraphical palaeontologist is in most cases forced to use a terminology for the discrete units. Until the natural taxonomy becomes refined to a point where the various elements can be confidently referred to their natural species, the present morphological taxonomy remains the most useful means of designation.

Table 1

Occurrences of Conodont Species

Locality 1

Bed of Jones Creek, ¼ mile upstream from Ettrema Mine. GR 207780 Nerriga 1 : 31,680 sheet :

Ancyrodella curvata (Branson and Mehl)
Ancyrognathus asymmetrica (Ulrich and Bassler)
Angulodus walrathi (Hibbard)
Apatognathus varians Branson and Mehl
Apatognathus sp. nov.
Bryantodus sp.
Hindeodella germana ? Holmes
Hindeodella subtilis Bassler
Icriodus brevis angustulus Seddon
Icriodus expansus Branson and Mehl
Ligonodina magnidens Ulrich and Bassler
Ligonodina sp.
Lonchodina robusta ? Branson and Mehl
Lonchodina typicalis Bassler
Ozarkodina elegans (Stauffer)
Ozarkodina immersa Hinde
Palmatolepis hassi Müller and Müller
Pelekysgnathus cf. *planus* Sannemann
Polygnathus nodocostata ettremae subsp. nov.
Polygnathus normalis Miller and Youngquist
Polygnathus xylus ? Stauffer
Roundya aurita Sannemann
Roundya sp.
Synprioniodina alternata Ulrich and Bassler

Locality 2

East bank of Ettrema Creek 1 mile upstream of junction with Jones Creek. GR 197798, Touga 1 : 31,680 sheet :

Hindeodella sp.
Icriodus cf. *expansus* Branson and Mehl
Polygnathus normalis Miller and Youngquist

Age of the Strata

The faunas from the two localities are given in Table 1. The fauna from Ettrema mine contains as important species *Ancyrodella curvata*, *Ancyrognathus asymmetrica*, *Palmatolepis hassi*, *Polygnathus normalis* and *Polygnathus nodocostatus ettremae*. The ranges of the first four species in Western Australia as given by Glenister and Klapper (1966) are conodont zones 5–11, 8–9, 5–11, 6–18, respectively. The best fit with the present samples is given by the range of *Ancyrognathus asymmetricus*, i.e. zones 8–9, upper *gigas*-zone, lower toIδ. Seddon (1970*a*) reports *Polygnathus normalis* and *Palmatolepis hassi-subrecta* occurring together in samples BC 23–3, for which he gives no age, and BC 25–5, for which he determines a toIγ age. *Ancyrodella curvata* he reports from the lower *gigas*-zone. The toIδ interval is poorly represented in Seddon's material, the only samples being BC 76–6 and BC 76–7. The species recorded by him are very different from those of the present samples, which according to Glenister and Klapper's ranges fit best into this interval. Ziegler (1962) indicates that *Ancyrognathus asymmetricus* is restricted to the upper *gigas*-zone. The fauna has many species in common with that described by Seddon (1970*b*) from crack fillings in the Pillar Bluff area, notably that from locality TF–294, which is correlated with Ziegler's upper *gigas*-zone.

Acknowledgements

This work was carried out as a project of the Geological Survey of New South Wales. It is published with the permission of the Under Secretary, New South Wales Department of Mines.

Systematic Palaeontology

Genus Ancyrognathus Branson and Mehl 1934

Type species : *Ancyrognathus symmetricus* Branson and Mehl 1934.

Ancyrognathus asymmetricus (Ulrich and Bassler 1926).

Plate I, Figs. 3–6

1926. *Palmatolepis asymmetrica* Ulrich and Bassler, p. 50, Pl. 7, Fig. 18.

1966. *Ancyrognathus asymmetrica* Glenister and Klapper, p. 801, Pl. 87, Figs. 1–5. (*cum syn.*).

1967. *Ancyrognathus asymmetrica* Adrichem Boogaert, p. 178, Pl. 1, Fig. 2.

1968. *Ancyrognathus asymmetrica* Huddle, p. 7, Pl. 13, Figs. 11, 12.

1969. *Ancyrognathus asymmetrica* Pölsler, p. 405.

1970*b*. *Ancyrognathus asymmetrica* Seddon, Pl. 8, Figs. 12–14.

Material : Seven more or less complete specimens.

Remarks : The specimens referred by various authors to this species show a range of variation in the ornament of the oral surface and the position of the blade in relation to the margin of the anterior limb. In typical *A. asymmetricus* the blade lies at the interior edge of the oral surface of the unit, although the carina below is more or less median. This situation pertains in the holotype, the Iowa specimens of Müller and Müller (1957), the Kellerwald specimens of Müller (1956) (" *Ancyroides* cf. *uddeni* "), the Western Australian material (Glenister and Furnish, 1966) and the present specimens. In this respect the specimen from the Western Sahara figured by Ethington and Furnish (1962) differs from the type, as the blade is approximately median. Bischoff's (1956) material from the Kellerwald shows specimens of both types, and he considers the non-marginal condition to be characteristic of gerontic specimens. Glenister and Furnish remark (1966, p. 800) that the exact position of the blade on the anterior lobe is highly variable. Within the present population (seven specimens only) this feature is consistent, as is also the surface ornament with its median row of nodes on each lobe of the unit. The greatest variation is in the width of the external lobe at its base. The tip of this lobe is markedly deflected aborally, as in the Western Australian material (Glenister and Klapper, 1966, Pl. 87, Fig. 3), Bischoff's material (1956, Pl. 8, Figs. 7, 8), and that of Seddon (1970*b*) from Texas. The paratype of *Ancyroides uddeni* Miller and Youngquist (1947), figured on Pl. 74, Fig. 16, and subsequently referred to *Ancyrognathus asymmetrica* by Ethington and Furnish (1962), differs in the median position of the blade, as well as having a surface ornament of nodes which are less well differentiated into median rows of larger and lateral rows of smaller nodes.

The species is apparently confined to the upper part of the *Manticoceras* zone of the Late Devonian (toIδ), according to Ziegler (1962) to the upper part of the *P. gigas* zone. In Western Australia it occurs in the lower part of the Virgin Hills Formation.

Genus Apatognathus Branson and Mehl 1934

Type species : *Apatognathus varians* Branson and Mehl 1934.

Apatognathus sp. nov.

Plate I, Figs. 8–10

Remarks : The few specimens of this species are fragmentary, so no formal description is undertaken. The species differs from *A. varians* chiefly in the presence of denticles of two sizes, smaller ones occurring notably between the main cusp and the first lateral denticles, but also between the other larger denticles of the bars.

Genus Icriodus Branson and Mehl 1938

Type species : *Icriodus expansus* Branson and Mehl 1938.

Icriodus brevis angustulus Seddon 1970

Plate I, Figs. 16–17

1968. *Icriodus angustus* Stewart and Sweet, Mound, Pl. 6, Figs. 23, 33.

1970*a*. *Icriodus brevis angustulus* Seddon, Pl. 11, Figs. 16–24.

Remarks : The present specimens are more similar to the Canadian ones figured by Mound in the consistent arrangement of the denticles into strong transverse rows, whereas in the Western Australian specimens " the median denticles alternate with the lateral denticles in immature specimens but bear no regular mutual alignment in mature ones ". The Canning Basin material also tends to be higher posteriorly, while the Canadian and New South Wales material maintains much the same height over the full length of the unit. The outline of the basal cavity is nearly symmetrical, and rounded posteriorly, just as described by Seddon for the Canning Basin specimens. In the arrangement of denticles in transverse rows the specimens from Ettrema and those from Canada come closer to the types of *I. angustus* Stewart and Sweet. In the holotype of this species, however, the denticles of the posterior blade are directed obliquely backwards, while those of specimens from the other three occurrences are approximately vertical.

Icriodus expansus Branson and Mehl 1938

Plate I, Figs. 18, 19

1938. *Icriodus expansus* Branson and Mehl, Pl. 26, Figs. 18–31.

1968. *Icriodus expansus* Mound, p. 488, Pl. 66, Figs. 38–39 (*sum syn.*).

1970*a*. *Icriodus expansus* Seddon, p. 736, Pl. 11, Figs. 30–32, Pl. 12, Figs. 1–2.

Remarks : On Seddon's figured specimen of this species the denticles of the median row are not alternate with those of the lateral rows, as is the case with the present specimens and that figured by Mound (1968) ; the type specimens show both conditions. Branson and Mehl remark that younger representatives of the species tend to have the three rows of nodes reduced to transverse ridges, a condition Seddon's specimen approaches. The Ettrema specimens are markedly alternate. The basal cavity of the present specimens and of those from Western Australia is very much expanded, being much broader than in most specimens referred to the species by other authors.

Genus Palmatolepis Ulrich and Bassler 1926

Type species: *Palmatolepis perlobata* Ulrich and Bassler 1926.

Palmatolepis hassi Müller and Müller.
Plate II, Fig. 12

1957. *Palmatolepis hassi* Müller and Müller, p. 1102, Pl. 139, Fig. 2, Pl. 140, Figs. 2–4.

1970*a*. *Palmatolepis hassi* Seddon, p. 738, Pl. 12, Fig. 27 (*cum syn.*).

1970*b*. *Palmatolepis hassi* Seddon, Pl. 10, Figs. 5–6.

Remarks: This species is represented by a single, rather small specimen, which is virtually identical with the paratype figured by Müller and Müller on Pl. 139, Fig. 2. In Western Australia it occurs commonly, chiefly in samples of toIγ age. Müller and Müller report the species from the Amana beds, the Independence Shale and the Sweetland Creek Shale. Seddon's specimens from Texas range well into toIδ time.

Genus Pelekysgnathus Thomas 1949

Type species: *Pelekysgnathus inclinatus* Thomas 1949.

Pelekysgnathus cf. *planus* Sannemann 1955.
Plate II, Figs. 13–16

1955. *Pelekysgnathus planus* Sannemann, p. 149, Pl. 4, Figs. 22, 23.

1970*a*. *Pelekysgnathus planus* Seddon, p. 738, Pl. 11, Figs. 1–12 (*cum syn.*).

Remarks: Seddon describes a wide range of variations for Western Australian representatives of this species. Many of his remarks are applicable here. The species is morphologically very close to *Icriodus brevis angustulus*, but the variation is not continuous between the two. In general, the degree of posterior taper is less than in Seddon's specimens. The Ettrema specimens are also narrower.

Genus Polygnathus Hinde 1879

Type species: *Polygnathus dubius* Hinde 1879.

Polygnathus nodocostatus ettremae subsp. nov.
Plate II, Figs. 17–19; Plate III, Figs. 1–5

Holotype: MMMC 0309.

Other Material: Figured paratypes MMMC 0322, 0323, 0324; 25 other specimens.

Diagnosis: Polygnathus nodocostata with a carina of fused nodes, a deep furrow on either side, bounded internally and externally by a submarginal ridge which may be slightly nodose, and which begins at the anterior edge of the platform but fades out posteriorly. A much lower row of nodes may be developed marginally.

Description: Polygnathus nodocostatus with very short blade and a platform which is only weakly arched in juvenile forms, but strongly arched in gerontic individuals. The outline of the platform is ovate-lanceolate or a little truncate anteriorly. The posterior third of the platform is deflected inwards, scarcely in juvenile specimens, strongly in gerontic individuals. The free portion of the blade is from 0·24 to 0·31 of the total length of the unit. It bears usually three denticles, the second being the tallest. The blade is continued as a carina over the full length of the unit. Frequently, though not invariably, the first denticle on the carina is as strong or nearly as strong as the second one on the blade. The carina is formed of a row of 10–15 fused denticles, those at the posterior of the unit being more discrete and represented as rounded nodes, about four in number. On either side of the carina is a wide deep furrow, progressively less well defined posteriorly. The abcarinal side of the furrow is formed by a fairly straight ridge, made up of a row of nodes, sometimes so fused as to be almost indistinguishable. Marginal to this is a narrow aborally curved zone which usually bears another row of smaller nodes. In the inward deflected posterior portion of the platform the lateral ornament disappears, the carina being flanked by a narrow smooth area or a few small nodes. In profile the unit is deepest anteriorly, the aboral surface arching up strongly to its highest point at the pit, near the centre of the unit, turning again aborally at the posterior. The highest point of the platform profile is just posterior of the pit. The platform is moderately arched in both longitudinal and transverse directions, the degree of arching being greatest in gerontic specimens. The aboral surface bears a strong keel occupying a median position over the full length of the unit. The pit is small, situated slightly forward of centre. The pit is tapered at both front and back, but no extension of it along the keel can be made out. A pronounced crimp is present. Ornament of growth lines may occur.

Remarks: Of those specimens of *P. nodocostatus* of which figures have been published, the two which approximate most closely to the norm of the present population are that of

Glenister and Klapper (1966), Pl. 94, Figs. 8–9, and the juvenile specimen figured by Helms (1961), Pl. 1, Fig. 13. The figure of the earliest representative of the group in Helms' Text-fig. 17 (*P. nodocostatus nodocostatus*) is also fairly close.

The Western Australian occurrence is of a single specimen from borehole Wapet C, sample C 44′–66′; the stratigraphic level is high in the Virgin Hills Formation. Here it is associated with *Palmatolepis minuta minuta, Pa. glabra glabra, Pa. glabra pectinata, Scutula bipennata* and *Palmatodella delicatula*, an assemblage referred by Glenister and Klapper to the lower *Pa. quadrantinodosa* zone. Helms' figured specimen is from the upper part of the lower *Cheiloceras*-Stufe, high toIIα. Both of these occurrences are substantially younger than that at Ettrema, which is the earliest occurrence of *P. nodocostatus*.

The species shows the most resemblance to *P. nodocostatus nodocostatus* Branson and Mehl as described by Helms (1961). Glenister and Klapper (1966, p. 829) point out that the lectotype of *P. nodocostatus* showed an x-shaped convergence of the rows of nodes on the platform, so that Helms' subspecies *P. nodocostatus incurvatus* is a junior synonym of the type species. The present material exhibits no such incurving of the rows of nodes, and is in this respect most similar to those specimens assigned by Helms to the nominate subspecies. Points in which *P. n. ettremae* differs from *P. n. nodocostatus* are the greater arching of the unit, the strong furrows, the ridge-like rows of nodes and the three or four prominent posterior nodes on the carina.

Polygnathus normalis Miller and Youngquist 1947

Plate III, Figs. 6–9

1947. *Polygnathus normalis* Miller and Youngquist, p. 515, Pl. 74, Figs. 4–5.

1968. *Polygnathus normalis* Mound, p. 509, Pl. 69, Figs. 30–31, Pl. 70, Figs. 1, 2, 5 (*cum syn.*).

1969. *Polygnathus normalis* Druce, p. 102, Pl. 19, Figs. 7*a*–10*b*.

1970*a*. *Polygnathus normalis* Seddon, Pl. 16, Figs. 19–22.

1970*b*. *Polygnathus normalis* Seddon, Pl. 15, Figs. 8–10.

Remarks: Mound (1968) indicates that the two species *P. normalis* and *P. webbi* occur together. To judge by his figures, the major point of difference is the depth of the free part of the blade (Pl. 70, Fig. 7). The present specimens cover the range of variation shown in Mound's figures, but I am unable to separate them into two groups. The original figures of the types of *P. webbi* show no details of the profile of the blade. In material from Western Australia Seddon appears to have experienced difficulty in separating the species, and speaks of the "*P. webbi-P. normalis* complex". In the range of variation he describes for the Western Australian material, those from Ettrema conform most closely to his group 2, "typical specimens of *P. normalis*", even including the tendency for the ornament of transverse ridges to break up into nodes on the posterior third of the platform. Mound (1968, p. 510) also mentions nodose ornament, but does not indicate that this is confined to any part of the platform. His specimen figured on Pl. 69, Figs. 30 and 31 has a virtually entirely nodose surface, and is quite different from all specimens in the present population.

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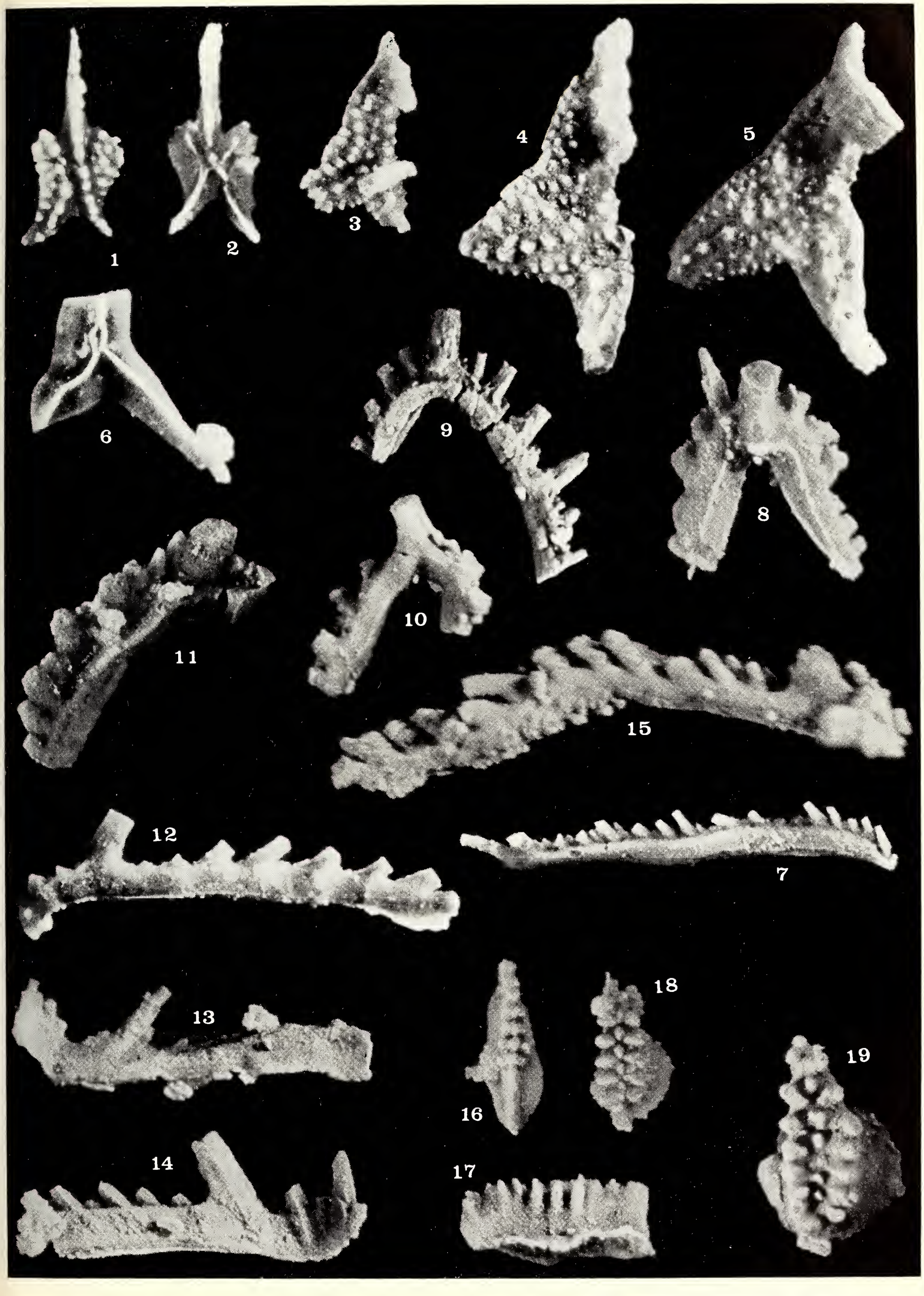
(Received 17 August 1972)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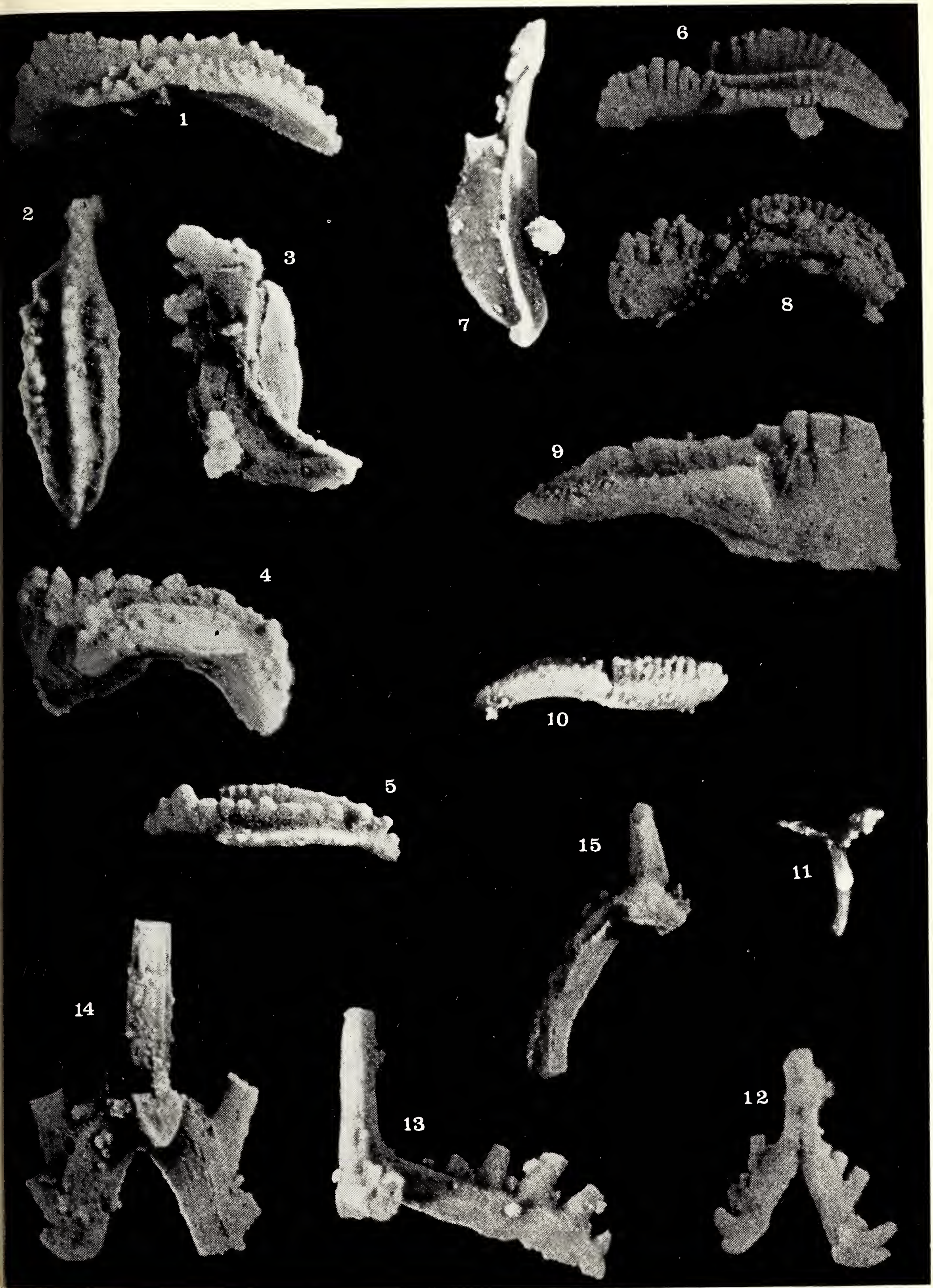
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EXPLANATION OF PLATES

All Figures are ×40. Specimen numbers refer to the micropalaeontological type collection of the Geological Survey of New South Wales, housed at the Geological and Mining Museum, Sydney. Unretouched photographs except Pl. I, Figs. 1, 2, Pl. II, Fig. 14, and Pl. III, Figs. 2, 4, 5, in which the background only has been blackened. Unless otherwise stated, the specimens are all from Jones Creek, upstream from Ettrema Mine.

Plate I

Figs. 1–2.—*Ancyrodella curvata* (Branson and Mehl). Oral and aboral views of specimen MMMC 0325.

Figs. 3–6.—*Ancyrognathus asymmetricus* (Ulrich and Bassler). Oral views of specimens MMMC 0296, 0297, 0293, respectively ; aboral view of MMMC 0295.

Fig. 7.—*Angulodus walrathi* (Hibbard). Inner lateral view of MMMC 0331.

Fig. 8.—*Apatognathus varians* Branson and Mehl. Inner lateral view of MMMC 0317.

Figs. 9–10.—*Apatognathus* sp. nov. Inner lateral views of specimens MMMC 0333, 0329.

Fig. 11.—*Bryantodus* sp. Inner lateral view of specimen MMMC 0326.

Fig. 12.—*Hindeodella germana* ? Holmes. Inner lateral view of MMMC 0302.

Figs. 13–14.—*Hindeodella subtilis* Bassler. Inner lateral views of MMMC 0303 and 0304.

Fig. 15.—*Hindeodella* sp. Inner lateral view of specimen MMMC 0310 from locality 2, Ettrema Creek.

Figs. 16–17.—*Icriodus brevis angustulus* Seddon. Oral view of MMMC 0313, inner lateral view of MMMC 0314.

Fig. 18.—*Icriodus expansus* Branson and Mehl. Oral view of MMMC 0319.

Fig. 19.—*Icriodus* cf. *expansus* Branson and Mehl. Oral view of MMMC 0311 from locality 2, Ettrema Creek.

Plate II

Figs. 1–3.—*Ligonodina magnidens* Ulrich and Bassler. Inner lateral views of MMMC 0289, 0292, 0307 respectively.

Fig. 4.—*Ligonodina* sp. Inner lateral view of MMMC 0328.

Fig. 5.—*Ligonodina* ? sp. Inner lateral view of MMMC 0308.

Figs. 6–7.—*Lonchodina robusta* ? Branson and Mehl. Inner lateral views of MMMC 0294 and 0298.

Fig. 8.—*Lonchodina typicalis* Bassler. Inner lateral view of specimen MMMC 0306.

Fig. 9.—*Lonchodina* sp. Inner lateral view of ? juvenile specimen MMMC 0301.

Fig. 10.—*Ozarkodina elegans* Stauffer. Outer lateral view of specimen MMMC 0299.

Fig. 11.—*Ozarkodina immersa* Hinde. Inner lateral view of MMMC 0290.

Fig. 12.—*Palmatolepis hassi* Müller and Müller. Oral view of specimen MMMC 0300.

Figs. 13–16.—*Pelekysgnathus* cf. *planus* Sannemann. Oral aboral, outer lateral and inner lateral views of the same specimen, MMMC 0318.

Figs. 17–19.—*Polygnathus nodocostatus ettremae* subsp. nov. Oral, aboral and somewhat oblique inner lateral views of paratype MMMC 0324.

Plate III

Figs. 1–5.—*Polygnathus nodocostatus ettremae* subsp. nov. 1, 2, Inner lateral and oral views of holotype MMMC 0309. 3, 4, Aboral and inner lateral views of gerontic individual, paratype MMMC 0322. 5, Oblique inner lateral view of juvenile, paratype MMMC 0323.

Figs. 6–9.—*Polygnathus normalis* Miller and Youngquist. 6, 7, Oblique and aboral views of specimen MMMC 0321. 8, Inner lateral view of specimen MMMC 0312 from locality 2, Ettrema Creek. 9, Outer lateral view of individual with deep blade, MMMC 0320.

Fig. 10.—*Polygnathus xylus* ? Stauffer. Inner lateral view of specimen MMMC 0332.

Figs. 11–13.—*Roundya aurita* Sannemann. 11, Oral view of MMMC 0305. 12, Oblique aboral view of MMMC 0315. 13, Lateral view of MMMC 0291.

Fig. 14.—*Roundya* sp. Posterior view of specimen MMMC 0316.

Fig. 15.—*Synprioniodina alternata* Ulrich and Bassler. Lateral view of MMMC 0327.

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 39–42, 1972

A Study of Root Concretions at Kurnell, N.S.W.

G. S. Gibbons and J. L. Gordon

Abstract—At Kurnell, 16 km. south of Sydney, N.S.W., there is a large wind-blown dune area consisting of sand blown from an adjacent beach. Within these dunes can be seen old soil profiles with which are associated tube-concretions of carbonate-cemented quartz grains, apparently following former root systems. Experiments indicate that the concretions develop over a long period by evaporation of carbonate-saturated ground water in the region of the decaying root.

Introduction: The Geological Setting

The Kurnell Peninsula (Figure 1) covers some 13 sq. km., 16 km. south of Sydney on the central coast of New South Wales, Australia. To the south and east is the Pacific Ocean, while to the north is Botany Bay, a shallow, land-locked area of some 36 sq. km.

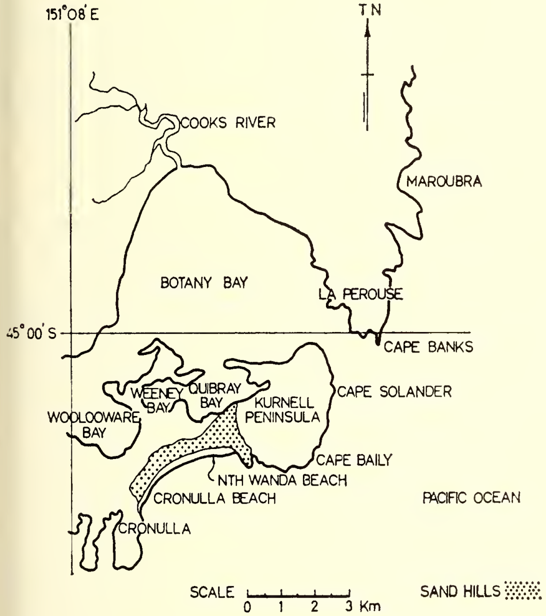

Figure 1.—Map of the district around Kurnell, N.S.W.

The Peninsula itself has a rocky cliffed headland in the east, consisting of white, quartzose Hawkesbury Sandstone; while the main part of the Peninsula is an area of 5 km^2. of rolling wind-blown dunes, part of which is stabilized by scrubby vegetation. Sand extends to as much as 60 m. below sea-level, and rests on a Hawkesbury Sandstone base in the east and on clay elsewhere (G. R. Wallis, pers. comm.).

At the time of the last glaciation the sea-level was some 100 m. below that at the present and the coast line was approximately 16 km. east of its present position (Griffin, 1963; Bird, 1964; C. V. G. Phipps, pers. comm.). A deep valley cut through Botany Bay and the present dune area. Following the post-glacial rise in sea-level 6,000 years ago (Fairbridge, 1961), this valley area filled with sediment; Botany Bay became shallow, and areas to the north and south became dry land. The Kurnell Peninsula area grew as winds added sand from North Wanda Beach immediately to the south; this process can be seen today near Quibray Bay (Figure 1).

Quarrying of sand has exposed sections of the dunes to nearly sea-level, and as many as three separate soil profiles (including that associated with the present surface) can be seen. These profiles are essentially humic layers of about 30 cm. depth, with 60–120 cm. of the underlying sand showing iron oxide staining. These layers need not correspond to climatic changes; at the present time, vegetated dunes are being overrun by active sand in parts of the Peninsula, while elsewhere dunes are becoming more stabilized.

Description of Concretions

The concretions studied occur beneath a buried soil profile about 2 m. below the present-day surface of a stabilized dune 10 m. above sea-level. They are nearly vertical, up to 1 m. long and 1–4 cm. in diameter (Figure 2).

In terms of cross-sectional area, the outermost three-tenths is cemented quartz sand; one-half is micro-crystalline calcite (by X-ray diffraction); and the central one-fifth is fibrous humic material. If the fine calcite is replacing original root material, the root would have initially taken up half of the present volume of the concretion.

A size analysis of quartz grains within the concretion was compared with analyses of

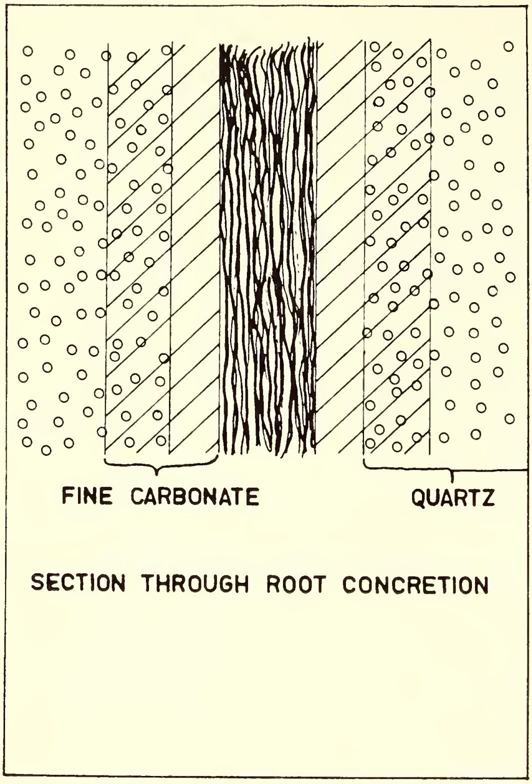

Figure 2.—Diagrammatic section of a large root concretion from Kurnell. (Carbonate is almost pure calcite.)

nearby dune-sand (Figure 3) ; cementing of quartz grains *in situ* has apparently produced the outer crust of the concretions.

Initial Observations

(1) The concretions follow root systems, possibly similar to the present Banksia flora (*Banksia collina*).

(2) They form after the plants die, and above the water table.

(3) Absence of concretions from live or recently-dead trees suggests slow formation (rather than changed conditions).

(4) Movement of ground-water (or soil-water) is the obvious mechanism for transport of carbonate : shell fragments in the sand would provide the source.

(5) Water movement could be gravitational (Figure 4 (2)) or capillary (Figure 4 (1), (3)).

Because the concretions are shallow and only a few thousand years (at most) are available for their formation, temperature and pressure gradients cannot be the cause of the carbonate transport, while chemical and biological effects around a rotting root would increase (not decrease) carbonate solubility. However, evaporation and CO_2-release could simultaneously precipitate carbonate and maintain water movement.

Experimental Evaluation

The evaporation theory outlined above has been tested in terms of its competence to produce the observed phenomena in available time.

The present sea-level dates from 6,000 years B.P. ; the landform from 3,000 years. Climate may be assumed to have been constant over this period.

There is about 9 g. of added carbonate per centimetre in depth in the larger concretions. Ground water contains 200 p.p.m. $CaCO_3$. Assuming total deposition and time 3,000 years, a total of 1·5 l. per year must be evaporated for a concretion 100 cm. long with root area 5 cm.^{2}, corresponding to 4 ml water per day. Such a concretion can hold 6 ml./cm. by capillarity ; saturating it and then drying it just five times every two years would provide adequate evaporation.

Experiments

The end of a coarse string was suspended in carbonated water saturated with respect to solid calcite. Solid $CaCO_3$ was deposited among the fibres through capillary rise and evaporation. A string was then suspended in a tube filled with dune sand. After one day equilibrium was reached, moisture having travelled much further up the string than up the sand column.

A dry section of concretion like that of Figure 2 was suspended vertically with one end just below a free water surface. It took up more than 200 ml. in 24 hours, corresponding to saturation (6 ml. per cm.) to 30 cm. above free water level. Ultimately moisture climbed the full height—48 cm.—of the concretion. The concretion was then buried in air-dried sand. It lost 2 ml. per cm. by capillary action into the surrounding sand, which became damp for 0·5 cm. from the concretion surface. The saturated concretion was then jacketed with plastic wrapping. Evaporation from one end was at a rate exceeding 2 ml./day, slowly dropping to 1·8 ml./day after a week, in a sheltered indoors location. Under similar conditions, a short (15 cm.) length of similar concretion lost an average 26 ml. per day from its exposed surface when tested over a five-week period.

Finally, a tube of air-dried dune sand packed to 35% porosity was erected vertically with the lower end in water. After 24 hours a steady state had been reached. Capillary water had reached a height of 24 cm., with moisture content decreasing from saturation near the base to 7% v/v (normal field capacity) at the top.

24 cm. into dry sand, perhaps with a free end exposed or very close to dune surface. Such an evaporation rate is close to the upper limit of reasonable assumption, even assuming that the local water table was generally close to the lower ends of the concretions. If the larger concretions formed in a shorter time interval—say, a couple of centuries—some other mechanism

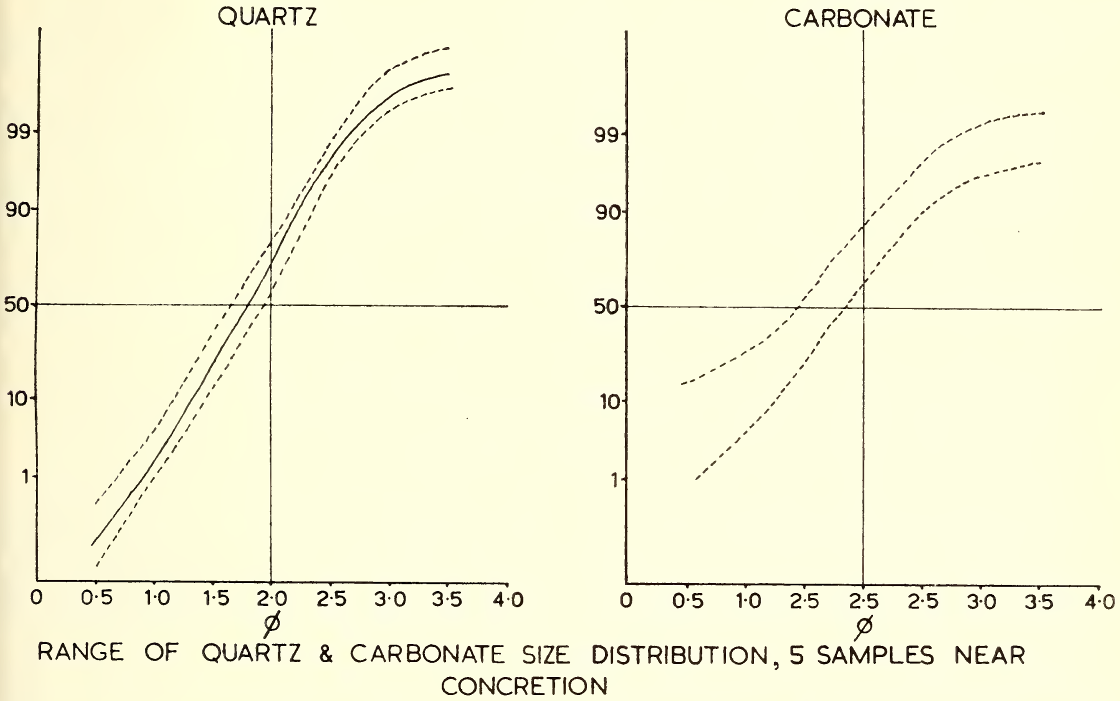

Figure 3.—Size analyses of Kurnell dune sand. Full line in quartz diagram represents carbonate-cemented quartz grains from the outer zone of a concretion. (Refer Figure 2.)

Inferences from Experiments

The type of large concretion tested can absorb over 150 ml. per week from a water-saturated region. This would vary as the concretion developed, but indicates the approximate rate of absorption. The water needed for a concretion of length 100 cm. could be absorbed in 30,000 weeks. The experiments show that capillarity draws water more than 24 cm. above the vadose zone. In a temperate area of widely divergent (60 cm. to nil) monthly rainfall, with bare or sparsely vegetated dunes, an inference of 30 weeks per year active water-rise seems reasonable. A total time of 1,000 years would thus be indicated.

The question of evaporation rate within a dry, porous sand is very complex, but the experiments suggest evaporation of some 20 ml. per day from a damp concretion extending some would be required. For any more definitive data on rates, however, field tests would be required ; uncontrolled variables would render these difficult.

Conclusions

The kind of carbonate concretion found around decayed root systems in coastal sand-dunes at Kurnell are formed by evaporation of soil-water or ground-water. This precipitates calcium carbonate (derived from shell fragments in the sand), which cements a zone of normal dune-sand enveloping the original root, and replaces the root as it withers and rots. The microcrystalline carbonate, like the original root material, has strong capillary effects ; these promote the movement of water, which is drawn considerably higher in the root system than it is in the surrounding sand.

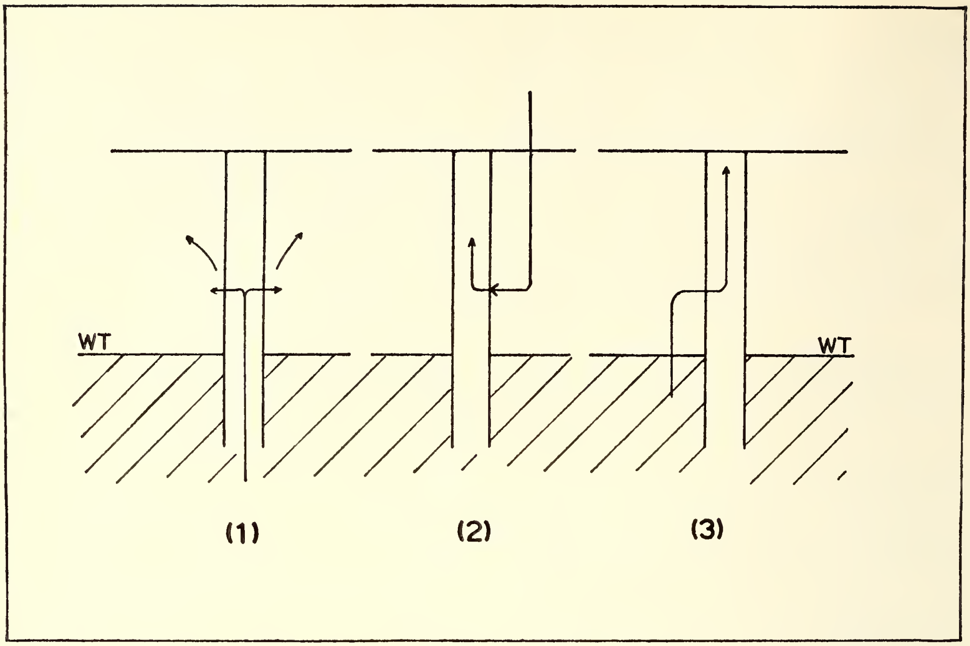

Figure 4.—Possible movement paths of carbonate-bearing solutions leading to development of concretions.

Carbonate solutions are drawn from below the water table ; lateral movement might occur from surrounding sand when it is wet beyond normal field capacity by percolating rain-water (diagrams 1 and 2 of Figure 4). Occasional flushing by heavy rain is indicated, since sulphates and chlorides are absent from concretions observed.

Experiments indicate a minimum age for the concretions of order 1,000 years ; the absolute upper limit is 6,000 years.

Acknowledgements

Dr. C. T. McElroy and Mr. R. Horne drew the Kurnell root concretions to our attention ; Mr. J. Herlihy assisted with experimentation and draughting ; and Mr. J. Bogi carried out X-ray studies on concretion material. Very useful discussions have been had with Mr. G. R. Wallis and Dr. C. V. G. Phipps. To all these we express thanks.

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(Received 23 March 1972)

Report of the Council for the Year Ended 31st March, 1972

Presented at the Annual General Meeting of the Society held on 5th April, 1972, in accordance with Rule 18 (*a*).

At the end of the period under review the composition of the membership was 345 members, 13 associate members and nine honorary members.

During the year 10 new members, one associate member and one honorary member were elected. Seven members and one associate member resigned, one member and one associate member were written off under Rule 5 (*b*).

Honorary member elected at Council meeting held on 23rd February, 1972 :

Sir J. Philip Baxter.

It is with regret that we announce the loss by death of :

Mr. E. J. W. Hampton (elected 1949).
Dr. Thomas Iredale (elected 1943).
Dr. F. Lions (elected 1929).
Professor Sir Ronald S. Nyholm (elected 1940).
Mr. R. Boswell Scammell (elected 1920).

Both Professor Sir Ronald Nyholm and Dr. Thomas Iredale were esteemed honorary members of the Society.

Nine monthly meetings were held. The abstracts of addresses have been printed on the notice papers. The proceedings of these will appear later in the issue of the *Journal and Proceedings*. The members of Council wish to express their sincere thanks and appreciation to the nine speakers who contributed to the success of these meetings, the average attendance being 39.

The sesqui-centenary of the Philosophical Society of Australasia, forerunner to The Royal Society of New South Wales, was celebrated at the general monthly meeting on 7th July, 1971, when Dr. D. F. Branagan gave an address entitled " Words, Actions, People : 150 Years of the Scientific Societies ". Members were invited to a display of letters, minutes and original drawings from the Archives of the Society held in the Society's rooms in Science House.

The Annual Social Function was held at the Pitt Club, Sydney, and was attended by 59 members and guests.

The Society's Medal for 1971 : Professor J. L. Griffith, B.A., M.Sc.

The Walter Burfitt Prize and Medal for 1971 : Dr. Max R. Lemberg, D.Phil., F.R.S., F.A.A.

The Edgeworth David Medal for 1971 : Dr. William F. Budd, Ph.D., Dip.Ed.

The Clarke Memorial Lecture for 1971, entitled " The Bearing of Palaeozoic Corals on the Continental Drift Hypothesis ", was delivered by Professor Dorothy Hill of the Department of Geology and Mineralogy, University of Queensland.

In conjunction with the Australian Institute of Physics a special lecture was held in Science House, 157 Gloucester Street, Sydney, entitled " Physics and Music ". The lecture was delivered by Dr. H. R. Allan, Reader in Physics at the University of London.

The Society has again received a grant from the Government of New South Wales of $1,500. The Government's continued interest in the work of the Society is much appreciated.

The Summer School was once again a significant success. This year the subject was Earth Sciences, with the title of " Down to Earth ". The Society expresses thanks and appreciation to Professor J. J. Frankel for permission to allow the School to be held in the School of Applied Geology, University of New South Wales, in January, 1972. The Council records its thanks to the organizers and lecturers for their effort in making the Summer School a worthwhile venture. A report of the Summer School will follow.

The Society's financial statement shows a surplus of $2,900.44.

The New England Branch of the Society held meetings and activities which will be included in the proceedings of the Branch, to follow.

A report of the proceedings of the South Coast Branch will also follow.

The Section of Geology continued to hold regular meetings, and the annual report is tabled.

The President represented the Society at the celebrations of the Captain Cook Landing at Kurnell and placed a wreath on the Banks Memorial ; the Annual Dinner of the Chamber of Manufactures of New South Wales ; the Annual Dinner of the Sydney Division of The Institution of Engineers, Australia ; Dinner and Pawsey Memorial Lecture arranged by the Australian Institute of Physics ; opening of forecourt to Law Courts in Liverpool Street, Sydney ; and the Annual Dinner of the New South Wales Division of the Institution of Surveyors, Australia.

Three parts of the *Journal and Proceedings* were published during the year : Volume 103, Parts 2 and 3–4. Volume 104, Part 1–2, is expected from the printer in April, 1972. Council decided to publish the *Journal and Proceedings* twice yearly, i.e. Parts 1–2 and 3–4, due to increase in postage costs and change in Post Office regulations regarding " Periodical Registration ".

Council held 11 ordinary meetings, and attendances were as follows : Mr. M. J. Puttock, 11 ; Mr. E. K. Chaffer, 10 ; Dr. J. Pickett, 7 ; Mrs. M. Krysko v. Tryst, 10 ; Mr. W. H. G. Poggendorff, 10 ; Professor W. E. Smith, 7 ; Professor R. J. W. Le Fevre, 10 ; Professor W. B. Smith-White, 9 ; Mr. W. H. Robertson, 8 ; Mr. J. C. Cameron, 8 ; Professor L. J. Lawrence, 6 ; Mr. D. S. Bridges, 9 ; Mr. J. W. Humphries, 9 ; Dr. P. D. Tilley, 8 ; Dr. B. E. Clancy, 3 ; Mr. J. P. Pollard, 5 ; Mr. S. S. Sampson, 2 ; Dr. A. Reichel, nil ; Professor R. L. Stanton, nil ; Professor A. Keane, nil.

The Library.—The number of items received and processed in the Library was 2,791. These were periodicals received by exchange from 394 societies and institutions, donations, and by the purchase of periodicals, on which $264.41 was expended.

Among the institutions who made use of the Library through the inter-library loan scheme were :

New South Wales State Government Departments : Geological Survey of N.S.W. ; Department of Agriculture ; Electricity Commission ; M.W.S. and D. Board ; Water Conservation and Irrigation Commission ; Department of Health ; Department of Conservation ; Department of the Attorney-General and Justice ; Division of Wood Technology ; Department of Mines ; Public Service Board ; State Planning Authority.

Other State Government Departments : Geological Survey of Queensland ; Department of Primary Industry, Queensland ; Department of Agriculture, Western Australia ; Department of Agriculture and Stock, Territory of Papua and New Guinea.

Commonwealth Government Departments : Atomic Energy Commission ; Department of Customs and Excise ; C.S.I.R.O. ; Mineral Chemistry ; Animal Physiology, Prospect ; Coal Research ; Textile Physics ; National Standards Laboratory ; Animal Genetics, North Ryde ; Food Research ; Canberra Laboratories ; Tasmanian Regional Laboratory ; Wild Life Research, Canberra.

Universities and Colleges : Sydney Technical College : University of : Sydney, New South Wales, Macquarie, Newcastle, New England, James Cook University of North Queensland, Melbourne, Queensland, La Trobe, Wollongong University College, Australian National University, Monash, Tasmania, Papua and New Guinea, Broken Hill University College, Wagga Wagga Teachers' College, Wollongong Teachers' College.

Companies : C.S.R. Research ; C.S.R. Technical Library ; B.H.P., Shortland ; B.H.P., Newcastle ; Australian Anglo-American Ltd. ; Peko-Wallsend ; Australian Consolidated Industries ; I.C.I. ; Amalgamated Wireless Australasia Ltd. ; British Tobacco Co. (Aust.) Ltd. ; Electrolytic Zinc Co. of Australasia Ltd., Hobart ; Eastern Copper Mines ; Roche Products Pty. Ltd. ; John Lysaght (Aust.) Ltd. ; W. D. Scott & Co. Pty. Ltd. ; Planet Management and Research Pty. Ltd.

Research Institutes : Reserve Bank Research Library, Sydney ; Waite Agricultural Research Institute, Glen Osmond ; Queensland Institute of Technology, Toowoomba ; Australasian Food Research Laboratories, Coorangong ; National Biological Standards Laboratory ; Australian Coal Industry Research Laboratories, Sydney ; Western Australian Institute of Technology, Kalgoorlie ; Sugar Research Institute, Mackay.

Museums : Australian Museum.

Miscellaneous : The Institution of Engineers ; St. Vincent's Hospital ; Prince of Wales' Hospital ; Royal Newcastle Hospital.

Borrowings for the year 1971–72 : members, 62 ; others, 445 ; requests for photocopies, 52 ; total, 559.

During the year a photocopier was purchased jointly by the Society and the Linnean Society of New South Wales. This has enabled the Library to fill requests for material before 1900, and in circumstances where it is impractical to despatch the periodical. The total number of pages copied was 660, from 52 requests.

Mrs. G. Proctor, the Assistant Librarian, with her wide knowledge and library experience, has continued to keep the Library in excellent order and regularized many library procedures.

Resumption of Science House.—The resumption of Science House by the Sydney Cove Redevelopment Authority was reported in the previous annual report. Your Council submitted a claim for compensation on the Authority, and to date this claim is still awaiting consideration by the Authority. Council has, however, applied for an advance on the compensation money, and has been advised that this will be forthcoming very shortly.

Science Centre Project.—In September, 1971, the President wrote to all members informing them of the steps being taken by Council to provide for the future of the Society, and particularly to provide a new home for the Society. The Council, in conjunction with the Council of the Linnean Society of New South Wales, has formed a Planning Committee for a Science Centre. This Centre will provide a suitable home for the two Societies and at the same time provide appropriate accommodation and facilities at low cost for other similar societies and groups. This Planning Committee has been very active, and with the aid of consultants appointed by the two Societies—Messrs. Jones, Lang, Wootton as property consultants and Messrs. Stephen, Jaques & Stephen as legal advisers—a considerable amount of investigation and preliminary planning has been accomplished.

Your President, in conjunction with the Vice-President of the Linnean Society, has had two interviews with the Minister for Cultural Activities in relation to the proposed Science Centre, and has received encouragement to go ahead with the project. The secretary of the Planning Committee, in conjunction with the consultants, has met with representatives of the Sydney Cove Redevelopment Authority, the Treasury, and the Public Service Board to discuss the possibility of Government involvement in the project.

It is hoped that during the coming year the financial aspects of the project will be satisfactorily resolved and that progress will be made in the detailed planning of the Centre.

Act of Incorporation.—One outcome of the investigations into the proposed Science Centre was that for the Royal and Linnean Societies to operate the Centre satisfactorily it will be necessary for the Societies jointly to form a company for this purpose. To enable the Society to do this, amendments to the Act of Incorporation are required. The matter is currently in the hands of the Parliamentary Draughtsman, and the Minister for Cultural Activities has offered his assistance in bringing forward an enabling Act.

Report of the South Coast Branch of the Royal Society of New South Wales

During 1971 the Illawarra Branch of the Royal Society held only one meeting—on 22nd October, 1971. At that meeting, which was jointly sponsored by the Branch and the Wollongong University College, the lecturer was Professor L. C. Woods, Professor of Mathematics (Plasma Physics) at Oxford University. Professor Woods spoke on " The Art of Physical and Mathematical Modelling " to an audience of approximately 100, which was followed by a luncheon at the Y.M.C.A. The Annual General Meeting followed the luncheon, and at the meeting Professor A. Keane was elected Chairman, Dr. D. Thompson was elected Secretary, and Dr. R. A. Facer as Representative on Council.

The financial report of the Branch for 1971 is that at the beginning of the year the Branch had $20.95 in its account. After a payment of $25 to Professor L. C. Woods and the receipt of $50 from the Society, the account now stands at $49.95.

A. Keane,
Chairman.

Honorary Treasurer's Report

There was a surplus for the period of $2,900 as against a surplus of $3,550, resulting in a total decrease of $650, made up as follows:

		$
Increase in General Interest		482
Increase in Commission received ..		20
Increase in Subscriptions to Journal		409
Increase in Surplus from Summer School		226
Reduction in Printing Costs		1,873
		$3,010
Less	$	
Increase in Salary Cost ..	897	
Reduction in Subscriptions received	42	
Reduction in Donations received	400	
Reduction in Sale of Reprints	473	
Reduction in Sale of Back Numbers	1,139	
Increase in General Expenses	709	
		$3,660
Total Decline		$650

As a result of the resumption of Science House by the Sydney Cove Redevelopment Authority, the share of the original cost ($30,470) has been excluded from the Balance Sheet. It is understood that the compensation likely to be obtained will be in excess of this figure.

In accordance with Council's direction that expenses towards establishment of the proposed New Science Centre be debited against the advance on Science House Compensation Funds, when received, and not from accumulated funds, an amount of $559 being expenditure to date is shown in the Balance Sheet.

J. W. Rickett,
Honorary Treasurer.

THE ROYAL SOCIETY OF NEW SOUTH WALES

BALANCE SHEET AS AT 29th FEBRUARY, 1972

LIABILITIES

1971 $		$	$
327	Sundry Creditors and Accruals		379.87
60	Subscriptions Paid in Advance		98.80
99	Life Members' Subscriptions—Amount carried forward		90.30
	Trust Funds (detailed below) :		
4,669	Clarke Memorial	4,165.33	
2,651	Walter Burfitt Prize	2,717.49	
1,524	Liversidge Bequest	1,606.63	
810	Ollé Bequest	852.26	
			9,341.71
63,362	Accumulated Funds		35,769.45
8,898	Library Reserve Account		8,898.49
$82,400			$54,578.62

ASSETS

1971 $		$	$
198	Cash at Bank and in Hand		1,226.52
	Investments—		
	Commonwealth Bonds and Inscribed Stock—At Face Value—held for :		
3,600	Clarke Memorial Fund	3,600.00	
2,000	Walter Burfitt Prize Fund	2,000.00	
1,400	Liversidge Bequest	1,400.00	
9,680	General Purposes	9,680.00	
9,600	Library Fund	9,600.00	
			26,280.00
	Deposits at Call—held for :		
2,654	Trust Funds Reserve	2,341.71	
631	Long Service Leave Fund	672.58	
4,082	General Purposes	5,256.51	
			8,270.80
30,470	Science House—One-third Capital Cost		—
13,600	Library—At 1936 Valuation		13,600.00
1,661	Furniture and Office Equipment —At Cost, *less* Depreciation		1,864.97
19	Pictures—At Cost, *less* Depreciation		17.65
2	Lantern—At Cost, *less* Depreciation		2.00
2,520	Centenary Volume :		
	Stock	2,380.75	
	Reprints	38.70	
			2,419.45
—	Debtors for Subscriptions	654.60	
	Less Reserve for Bad Debts	654.60	
			—
283	Sundry Debtors—Other		337.64
—	Science Centre Project		559.59
$82,400			$54,578.62

NOTES

Science House : Following the resumption of Science House by the Sydney Cove Redevelopment Authority a claim for compensation has been submitted.

Science Centre Project : The Society is currently planning a joint venture with the Linnean Society for the establishment, in the Sydney Cove Redevelopment Area, of a Science Centre for New South Wales.

TRUST FUNDS

	Clarke Memorial	Walter Burfitt Prize	Liversidge Bequest	Ollé Bequest
	$	$	$	$
Capital at 29th February, 1972	3,600.00	2,000.00	1,400.00	—
Revenue :				
Balance at 28th February, 1971 ..	1,069.12	650.98	123.33	810.26
Income for Period	214.20	119.00	83.30	102.00
	1,283.32	769.98	206.63	912.26
Less Expenditure	717.99	52.49	—	60.00
	$565.33	$717.49	$206.63	$852.26

ACCUMULATED FUNDS

	$	$
Balance at 28th February, 1971		63,361.59
Add :		
Surplus for Period		2,900.44
Reduction in Provision for Bad Debts ..		45.20
		66,307.23
Less :		
Subscriptions Written Off	67.35	
Science House—One-third Capital Cost ..	30,470.43	
		30,537.78
		$35,769.45

Auditors' Report

The above Balance Sheet has been prepared from the Books of Account, Accounts and Vouchers of the Royal Society of New South Wales and is a correct statement of the position of the Society's affairs on 29th February, 1972, as disclosed thereby. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

HORLEY & HORLEY,
Chartered Accountants,
Registered under the Public Accountants
Registration Act 1945, as amended.

65 York Street,
Sydney.
29th March, 1972.

J. W. PICKETT,
Hon. Treasurer.

M. J. PUTTOCK,
President.

INCOME AND EXPENDITURE ACCOUNT

1st March, 1971, to 29th FEBRUARY, 1972

1971 $		$
3,222	Membership Subscriptions	3,176.00
4	Proportion of Life Members' Subscriptions	8.40
1,500	Government Subsidy	1,500.00
7,216	Science House Management—Share of Surplus	7,215.14
1,069	Interest on General Investments	1,551.93
—	Commission	20.45
400	Donations	—
580	Sale of Reprints	107.18
1,122	Subscriptions to Journal	1,531.04
1,201	Sale of Back Numbers	62.25
	Refunds :	
137	Postages	191.12
29	Xerox Copying	11.26
17	Summer School Surplus	243.38
$16,497		$15,618.15

1971 $		$	$
285	Accountancy		300.00
111	Advertising		222.40
60	Annual Social		158.65
110	Audit		110.00
100	Branches of the Society		50.00
110	Cleaning		90.60
86	Depreciation		93.86
63	Electricity		74.84
15	Entertaining		19.63
116	Insurance		130.15
157	Library Purchases		264.41
232	Miscellaneous		242.13
417	Postages and Telegrams		525.63
	Printing :		
	Vol. 103, Parts 2, 3 and 4	$1,228.80	
	Guide to Authors	90.00	
	Binding	94.76	
	Postages	232.08	
3,519			1,645.64
204	Printing—General and Stationery		474.19
4,124	Rent—Science House Management		4,150.00
6	Repairs		28.39
3,105	Salaries		4,001.54
127	Telephone		135.65
12,947			12,717.71
3,550	Surplus for Period		2,900.44
$16,497			$15,618.15

Abstract of Proceedings

7th April, 1971

The one hundred and fourth Annual Meeting of the Society was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Professor W. E. Smith, was in the chair. There were present 36 members and visitors.

The awards of the Society were announced as follows :

- The Society's Medal for 1970 : Dr. J. A. Dulhunty.
- The Clarke Medal for 1971 : Dr. Nancy T. Burbidge.
- The Edgeworth David Medal for 1970 : Dr. D. A. Buckingham.
- Archibald D. Ollé Prize, 1970 : Dr. B. B. Guy.

The Annual Report of the Council and the Financial Statement for the year ended 28th February, 1971, were presented and adopted.

Messrs. Horley & Horley were re-elected Auditors of the Society for 1971–1972.

Office-bearers for 1971–1972 were elected as follows :

- President : M. J. Puttock, B.Sc.(Eng.), A.Inst.P.
- Vice-Presidents : W. E. Smith, Ph.D. ; J. L. Pollard, M.Sc., Dip.App.Chem. ; W. H. Robertson, B.Sc. ; R. J. W. Le Fevre, D.Sc., F.R.S., F.A.A. ; J. C. Cameron, M.A., B.Sc. (Edin.), D.I.C.
- Hon. Secretaries : E. K. Chaffer (General) ; M. Krysko v. Tryst (Mrs.), B.Sc.Grad.Dip. (Editorial).
- Hon. Treasurer : J. W. Pickett, M.Sc. (N.E.), Dr.phil.nat. (Frankfurt/M.).
- Hon. Librarian : W. H. G. Poggendorff, B.Sc.Agr.
- Members of Council : B. E. Clancy, M.Sc. ; A. Reichel, Ph.D., M.Sc. ; J. W. Humphries, B.Sc. ; W. B. Smith-White, M.A. ; S. S. Sampson ; P. D. Tilley, B.A., Ph.D. ; D. S. Bridges ; L. J. Lawrence, D.Sc., Ph.D. ; R. L. Stanton, Ph.D. ; A. Keane, Ph.D.

The retiring President then welcomed Mr. M. J. Puttock to the Presidential Chair.

The address of the retiring President, Professor W. E. Smith, entitled " Radiation Pressure and Related Forces ", was delivered.

5th May, 1971

The eight hundred and fifty-first General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock, was in the chair. There were present 22 members and visitors.

The following were elected members of the Society : Philip W. Thompson, Alfred J. van der Poorten, Geoffrey Isaacs, James P. Lucas, Frederick W. Brown, Joseph Moldovan (associate member).

An address entitled " The Forces Between Biological Cells " was delivered by Professor B. W. Ninham, Department of Mathematics, Research School of Physical Sciences at the Australian National University, Canberra.

During the course of the meeting Mr. T. E. Kitamura asked if the Council would keep all members informed of the position regarding the compensation for Science House and also the progress in negotiations for the re-housing of the Society.

The President, in reply, stated that an approach was being made to the Government for the provision of a site within the Rocks Area of Sydney upon which it was proposed that a new Science Centre be erected.

The present proposition was that such a centre would provide ample space for letting to other societies and organizations at preferential rates and also for additional space to be let at normal commercial rates. It was envisaged that such a centre would provide services such as accounting, secretarial, editorial and library facilities, etc. Further information would be conveyed to members as developments occurred.

The cost of the proposed new Centre was too great for any one society to finance independently, therefore the Royal Society of New South Wales and the Linnean Society of New South Wales were obtaining legal advice on a partnership. It was proposed that the compensation money from the resumption of the present Science House be re-invested in the construction of a new Science Centre, and that any additional finance required for the project be raised by borrowing.

Mr. Kitamura, expressing his own opinion, felt that the Royal Society of New South Wales and the Linnean Society of New South Wales should have exclusive ownership of the new centre, and that it would be preferable to operate it in this manner rather than to form a piecemeal ownership among many organizations.

2nd June, 1971

The eight hundred and fifty-second General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock, was in the chair. There were present 70 members and visitors.

The following application for membership was read for the first time : Russell John Korsch.

An address entitled " Extinction and Man " was delivered by Mr. Ronald Strahan, Director of the Taronga Park Zoological Trust.

7th July, 1971

The eight hundred and fifty-third General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock, was in the chair. There were present 43 members and visitors.

Russell John Korsch was elected a member of the Society.

The sesqui-centenary address to commemorate the forming of the Philosophical Society of Australasia in 1821, the forerunner of the Royal Society of New South Wales, was delivered by Dr. David Branagan of the Department of Geology and Geophysics at the University of Sydney, entitled " Words, Actions, People : 150 Years of the Scientific Societies ".

An exhibition of archival material was held in the Society's rooms.

In reply to a question asked by Mr. T. E. Kitamura on the progress of the proposed new Science Centre, the President stated that a letter had been forwarded to the Deputy Premier and Minister for Education and Science, Mr. C. B. Cutler, outlining the proposal for the Science Centre. This was to be a joint venture between the Royal Society of New South Wales and the Linnean Society of New South Wales. At the present time we were awaiting the pleasure of a reply from the Government, which was anticipated in the near future.

The two Societies had also set up a Planning Committee, which had sought expert advice in the establishment of the proposed scheme. Members would be informed as further developments occurred.

4th August, 1971

The eight hundred and fifty-fourth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock, was in the chair. There were present 33 members and visitors.

The death was announced with regret of Dr. Thomas Iredale, an honorary member of the Society and member since 1943.

The following papers were read by title only :

- " Relativistic Motion in Two Spacelike Dimensions ", by N. W. Taylor and L. McL. Marsh.
- " Potassium-Argon Ages for Leucite-bearing Rocks for N.S.W., Australia ", by P. Wellman, A. Cundari and I. McDougall.
- " Occultations Observed at Sydney Observatory during 1970 ", by K. P. Sims.
- " The Nature of Time and Its Measurement ", by S. J. Prokhovnik.
- " On the Metric of an Astronomical Object in the Lyttleton-Bondi Theory ", by R. R. Burman.
- " Light Tracks Near a Dense Charged Star ", by R. R. Burman.

An address entitled " Current Redevelopments Around the World " was delivered by Colonel D. O. Magee, Deputy Chairman, Sydney Cove Redevelopment Authority.

1st September, 1971

The eight hundred and fifty-fifth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock, was in the chair. There were present 43 members and visitors.

The following applicant was elected a member : William Francis Budd.

The following paper was read by title only :

- " Magnetic Properties of Rocks from the Giles Complex, Central Australia ", by R. A. Facer.

An address entitled " The Value of Communicating Science to the General Public " was delivered by Dr. P. Pockley, Head of Science Programmes for the Australian Broadcasting Commission.

6th October, 1971

The eight hundred and fifty-sixth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock, was in the chair. There were present 22 members and visitors.

The following paper was read by title only :

- " Precise Observations of Minor Planets at Sydney Observatory during 1969 and 1970 ", by W. H. Robertson.

An address entitled " Australian Cretaceous in a Broader Context " was delivered by Dr. Viera Scheibner of Mining Museum, Geological Survey of N.S.W.

3rd November, 1971

The eight hundred and fifty-seventh General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock, was in the chair. There were present 50 members and visitors.

The death was announced with regret of Rupert Boswood Scammell, life member and member since 1920.

The following were elected members of the Society : Cynthia G. Young, Patrick Arthur Price and Ronald Robert Staer.

Paper (read by title only) : " Potassium-Argon Dating of Basalts and Their Significance in the Mudgee-Gulgong-Ilford Region ", by J. A. Dulhunty.

An address entitled " Potential and Problems of Spacecraft Resource Evaluation : Remote Sensing in the Seventies " was delivered by Professor D. S. Simonett, Department of Geography at the University of Sydney.

1st December, 1971

The eight hundred and fifty-eighth General Monthly Meeting was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock, was in the chair. There were present 40 members and visitors.

The following new member was elected : Thomas Aquinas Lambert.

Papers (read by title only) :

- " Longitudinal Free Oscillations of Jervis Bay, New South Wales ", by D. J. Clarke.
- " The Phytochemical History of Torbanites ", by R. F. Cane and P. R. Albion.

An address entitled " Developments in Nuclear Power and Their Relation to Australia " was delivered by Sir J. Philip Baxter, Chairman, Australian Atomic Energy Commission.

Section of Geology

Abstract of Proceedings, 1971

Five meetings were held during this year, the average attendance being about 17 members and visitors.

MARCH 19th (Annual Meeting) :

(1) Election of office-bearers : Chairman, Dr. B. B. Guy ; Hon. Secretary, E. V. Lassak.

(2) Address by Dr. B. McMahon, "What is Engineering Geology ?".

Engineering geology is a border subject and requires competence in both geology and engineering, supplemented by bona fide construction experience. Examples of the application of engineering geology in both civil and mining engineering projects were given.

MAY 21st :

(1) Address by Mr. G. Z. Foldvary, "Geology of the Bogan Gate-Trundle District".

The sequence of Upper Silurian to Lower Mid-Devonian strata near the centre of New South Wales, previously known as the "Trundle Beds", is now called the Trundle Group. It has been subdivided into three main units : the Edols Sandstone (most probably of late Silurian age), the Yarrabandai Formation (almost entirely Lower Devonian), and the Botfield Formation.

The rocks of the Trundle Group are very rich in fossils. Amongst these three new species have been identified and described.

(2) Address by Dr. E. R. Phillips, "Myrmekite from Broken Hill".

Myrmekite is believed to be essentially an exsolution phenomena and it is formed by the release of oligoclase from alkali felspar to rim positions on adjacent plagioclase grains or to intergranular positions between two adjacent alkali felspar crystals. Concomitant with the exsolution of the plagioclase quartz is formed and its amount is usually governed by the initial calcium content of the alkali felspar, giving proportionality relationships between the basicity of the plagioclase and the volume of intergrown quartz vermicules. Work on retrograde gneisses from Broken Hill has suggested, however, that destruction of potash felspar may lead to the development of muscovite and quartz, which may supplement the amount derived by exsolution. Thus an association of myrmekite with muscovite may indicate the development of a myrmekite somewhat different from "primary" myrmekite seen in many igneous rocks.

JULY 16th :

(1) Address by Dr. J. G. Jones, "Australia's Cainozoic Drift".

Stratigraphic evidence indicates a late Eocene inception of Australia's southern and eastern continental margins in conformity with continental motion inferred from sea floor and continental magnetic data. The dilation of the southern ocean and Tasman Sea are viewed as a simple consequence of Australia's cainozoic drift.

(2) Address by Mr. A. Hossein, "Mineralized Bacteria in Beach Sand".

Grains of pyritized bacteria (size 105–74 microns) from East Pakistan provide an example of metal sulphide transformation in the beach or coastal environment. The marshy and waterlogged regions in the back-dune area, containing enough entrapped sea-water rich in sulphides, are ideal places for the precipitation or transformation of metal sulphides by sulphate reducing bacteria such as *Desulphurovibris desulphuricans*.

SEPTEMBER 17th :

Address by Dr. A. Ritchie, "Devonian Fossil Fishing in Australia and Antarctica".

Research into Devonian fish faunas was initially based on Northern Hemisphere discoveries. Rather belatedly, Australian and Antarctic Devonian sediments are yielding rich fish faunas with many new and interesting taxa. The speaker described his own research work into Devonian fish from western N.S.W. and gave some details of the beautifully preserved material now available from the Kimberley Devonian reef complexes. The latter part of the talk concerned an expedition to southern Victoria Land, Antarctica, between November, 1970, and January, 1971, to prospect known and suspected Upper Devonian fish sites—with considerable success.

NOVEMBER 19th :

Address by Professor L. V. Hawkins, "Plate Tectonics and Continental Drift".

The speaker reviewed present knowledge of plate tectonics.

The earth's crust is divided into a number of rigid plates, the boundaries of which can be inferred from seismic activity data. Continents are embedded in these plates and move on them.

The differences between plate tectonic theory and classical continental drift were outlined.

Citations

The Society's Medal for 1971

The Society's Medal is awarded to a member of the Society for " meritorious contributions to the advancement of science. This may include administration and organization of scientific endeavour ; and for services to the Society." Considered annually. First awarded 1884.

The award for 1971 is made to Associate Professor J. L. Griffith of the School of Mathematics, University of New South Wales.

James Langford Griffith became a member of the Royal Society of New South Wales in 1952. He joined the Council of the Society in 1954, and except for his year on sabbatical leave has remained on it continuously until 1968. During this time he was President in 1958 and has also served three terms as Honorary Secretary, covering a period of eight years. Throughout his membership, he has rendered most valuable and distinguished service to the Society in helping to direct and conduct its business and in helping to carry out its aims and exert its influence on the scientific community in this State.

Professor Griffith has contributed numerous papers on his subject to the Society's *Journal and Proceedings*. His mathematical interests have been in the direction of integral transforms and certain branches of functional analysis. His paper on the Gibbs phenomenon in n-dimensional Fourier transforms, published in Vol. 97 (1963/64) shared the Ollé Prize of the Society.

The Clarke Medal for 1971

The Clarke Medal is awarded for distinguished work in the Natural Sciences done in, or on, the Australian Commonwealth and its territories.

Nancy Tyson Burbidge has made distinguished contributions to the fields of Australian taxonomic botany and ecology. She graduated from the University of Western Australia, and her early researches were concerned with the ecology, taxonomy, morphology and anatomy of plants of that State. About 1947 she was appointed a Research Officer in C.S.I.R.O., working in the herbarium of the Division of Plant Industry at Canberra. She rose in the reconstituted C.S.I.R.O. to the position of Senior Principal Research Scientist in charge of the herbarium.

Her published taxonomic studies have made notable contributions to knowledge of a number of plant families. A very significant paper dealt with the phytogeography of the Australian region. To facilitate identification of grasses by field workers and landholders, she has published three volumes with copious illustrations on grasses respectively of the Southern Tablelands, Northern Tablelands and Coast districts of New South Wales. She is joint author of the excellent *Flora of the Australian Capital Territory*.

Apart from her own numerous research studies, Dr. Burbidge has performed outstanding and unselfish service to all Australian taxonomists in laboriously assembling and making readily available in printed or duplicated form information which would otherwise be difficult and time-consuming to obtain. While Australian Liaison Officer at the Royal Botanic Gardens, Kew, she secured photographs of the Lindley collection at Cambridge, listed type specimens of Australian plants in the Kew herbarium, and arranged for the microfilming of the unpublished manuscript descriptions of Australian plants by Robert Brown (who collected in Australia during 1802-1805 and made the first major contribution to the botany of the Australian mainland) as well as producing a monumental index to the 22 reels of film. She has published accounts of the plants of Cook's second voyage, the collecting localities of Robert Brown, and G. F. Hills' collecting localities on the Barclay Expedition to the Northern Territory. In 1963 she published a Dictionary of Australian Plant Genera.

To her taxonomic colleagues in Australia, Dr. Burbidge has always been helpful and generous in assistance with their problems, and she has proved a devoted worker in her chosen field.

Edgeworth David Medal for 1971

The Society awards the Edgeworth David Medal annually to scholars under the age of 35 years for distinguished work contributing to the advancement of Australian science done mainly in Australia or its territories.

The award for 1971 is made to Dr. William Francis Budd, of the Antarctic Division, Commonwealth Department of Supply, in Melbourne, in recognition of his outstanding contributions to the field of glaciology.

Dr. Budd was born on 16th October, 1938, at Mt. Hope, New South Wales. He graduated B.Sc. in mathematics at Sydney University in 1959, M.Sc. in 1966 and Ph.D. in 1968 in glaciology at the University of Melbourne. Since joining the Australian National

Antarctic Research Expeditions as glaciologist to Wilkes Station in 1961 and to Mawson Station in 1964, Dr. Budd has assumed increasing responsibility for the Australian glaciological research programme in Antarctica. He is now Senior Glaciologist of the Antarctic Division. Dr. Budd represents Australia on the Co-ordinating Council of the International Antarctic Glaciological Project (IAGP). In 1971 he was a Visiting Professor of the University of Washington at Seattle, and was elected a member of our Society.

Using his own field observations, together with those of his Antarctic colleagues, Dr. Budd has greatly improved our knowledge of the Wilkes Ice Cap and the Amery Ice Shelf regions of eastern Antarctica. He also shared in the pioneer survey of snow drifting at Byrd Station on the western side of the continent. Such work will be a notable part of the Atlas of the derived physical characteristics of Antarctica on which Dr. Budd is now actively engaged. At the same time his studies of snow and ice accumulation, movement and ablation in these areas has contributed to the knowledge of ice-mass dynamics in general, especially of the longitudinal velocity profiles formed when ice bodies move over irregular bedrock surfaces. His paper on the drifting of non-uniform snow particles remains as noteworthy today as it was when first published six years ago. In his singular ability to combine painstaking field work with fruitful theoretical, often mathematical, interpretation, Dr. Budd may justly be considered a worthy successor to Edgeworth David in Antarctic research.

Walter Burfitt Prize for 1971

The Walter Burfitt Prize is awarded at intervals of three years to the worker in pure or applied science, resident in Australia or New Zealand, whose papers and other novel and original contributions published during the previous six years are deemed to have been of the highest scientific merit.

The award for 1971 is made to Max Rudolph Lemberg, D.Phil., F.R.S., F.A.A.

Max Rudolph Lemberg, Head of Biochemical Research since 1935, and Assistant Director of Medical Research since 1953 at the Royal North Shore Hospital, more than fulfils the requirements for this prize.

He is internationally known for his researches and writings on bile pigments, porphyrin derivatives, respiratory enzymes, phycobilins of photo-synthetic algae, etc.

He joined this Society in 1936 and is now a life member. He has served on the Council, and was President in 1955. He delivered the Liversidge Research Lecture in 1954 and was awarded the Society's James Cook Medal for 1964.

Curriculum Vitae.—Dr. Lemberg was born in Breslau on 19th October, 1896, and became a Ph.D. of his home university in 1921, an occasion which marked the beginning of a most distinguished scientific career. He was: 1929–33, Privatdozent at Heidelberg University; 1930–32, Rockefeller Foundation Fellow at the Biochemistry Institute, Cambridge, U.K., and from 1935 has been at the Royal North Shore Hospital, Sydney. During 1966 he was a Visiting Professor at the University of Pennsylvania, Philadelphia. Recognition of his work has resulted in the following honours: the Coronation Medal and election to the Royal Society Fellowship in 1952; the H. G. Smith Medal of the Royal Australian Chemical Institute in 1949; Foundation Fellowship of the Australian Academy of Science in 1954; Professor Emeritus of the University of Heidelberg in 1956; the James Cook Medallist of the Royal Society of N.S.W. for 1964; and he was awarded the Australian Britannica Award for Science in 1965. He is an honorary member of many famous scientific societies througnout the world, has been an invited participant at Gordon Research Conferences in 1966 and in 1968, and has been President and Guest of Honour at many International Symposia.

Publications.—Dr. Lemberg is the author, or part-author, of three books: *Haematin Compounds and Bile Pigments*, Interscience, 1949; *Haematin Enzymes*, Editor (with J. Falk and R. K. Morton), I.U.B. Symposium, Pergamon Press, 1961; *Cytochromes* (with J. Barrett), Academic Press, London (with the printers). He has published many Reviews and over 120 original Research Papers.

General.—Following his earlier studies of the haematin compounds, during the last 15 years Dr. Lemberg's interests have widened from investigations on the prosthetic group to a study of the cytochrome as a whole. He prepared compounds resembling the natural haemoproteins α and demonstrated the importance of lipids in the natural cytochrome complex, and, more recently, through his work on native cytochrome oxidase, has greatly contributed to the clarification of the nature and mode of action of the cytochrome enzyme.

The contributions which he and his research team at the Royal North Shore Hospital have contributed to this branch of biochemistry have established him as one of the world's greatest biochemists, added considerably to the international status of Australian science, and attracted distinguished overseas workers to his research laboratories.

Any citation of Dr. Lemberg's work would be incomplete without reference to his deep interest in the relationship between religion and science and the influence his own religious beliefs have had on his scientific life.

Obituaries

Dr. Thomas Iredale

Dr. Thomas Iredale, honorary member of the Royal Society of New South Wales and member since 1943, died at his home in Sydney on 28th July, at the age of 75. After 35 years' distinguished service in the Department of Physical Chemistry, University of Sydney, he enjoyed a quiet retirement for some 10 years, punctuated by occasional forays into his old haunts to renew friendships with former research associates.

Born on 11th June, 1897, he was educated at Sydney Grammar School and the University of Sydney. He was awarded the Caird Scholarship in 1918 and a N.S.W. Government science research scholarship in 1920. In 1921 an 1851 scholarship took him to the University of London, from which he subsequently graduated D.Sc. After a brief period as a lecturer at the University of Durham (1925–1927) he returned to his alma mater, where he rose from Lecturer to Senior Lecturer (in 1944) and finally to Reader (in 1947).

Tom's contribution to the undergraduate teaching of the department depended not so much on his lecturing skills, which he made little attempt to develop, but on his continuing concern for and involvement in the personal problems of his students. His dignified, almost military, bearing would generate an awe-struck silence in all but the most ebullient undergraduates, but a disarming question from Tom (delivered as part of the continuous sociological survey he conducted throughout his career) would quickly establish rapport.

He retained a lively interest in new research developments right through his career, venturing into the burgeoning area of nuclear spectrometry only five years before his retirement. This continuing vitality was reflected in his decision to accept a visiting professorship in the West Indies in the early '60s and to announce on his return that the pace of life was too slow there for his liking.

Thomas Iredale served his university and the international scientific community in a variety of ways with considerable distinction, and his departure leaves his former colleagues with a deep sense of personal loss.

Sir Ronald Nyholm

The death of Sir Ronald Nyholm in a road accident near Cambridge on 4th December, 1971, cut short, at its height, a distinguished career.

Ronald Sidney Nyholm was born in Broken Hill on 29th January, 1917. At the age of 17 he left that city to take up an Exhibition at Sydney University, where, four years later, he graduated with First-class Honours in Chemistry.

It was in his honours year that, as a result of the influence of the late G. J. Burrows, he became interested in the co-ordination chemistry of arsenic, a subject that was to become a constantly-recurring theme in many of his later researches.

After graduation, he spent a brief period in industry, but it was not long before he decided that his future did not lie in that direction and joined the staff of the Sydney Technical College. Here, in collaboration with his close friend the late Frank Dwyer, he began a long series of researches on the arsine complexes of some of the platinum metals.

He became a member of the Society in 1940, and much of this work is described in the 24 papers he contributed to the *Journal and Proceedings*.

In 1947 he took up an Imperial Chemical Industry Fellowship at University College, London, where some of his most outstanding work, for which he was awarded the degree of Doctor of Philosophy and later the D.Sc., concerned among other subjects the metal complexes of di-tertiary arsines.

After a short period as lecturer in chemistry at University College, he accepted the position of Associate Professor at the University of Technology (now the University of New South Wales). There he laid the foundations of a vigorous and active Department of Inorganic Chemistry and left behind him a lasting reputation for being able to acquire, by means of his great drive, persistence and persuasive powers, unusually ample funds for the support of chemical endeavours.

He served on the Society's Council from 1944 to 1954, holding the office of President during the last year of this period.

In 1955 he returned to University College, London, as Professor of Chemistry. Eight years later he became Head of its Department of Chemistry, a position he held at the time of his death.

In the years immediately following the Second World War, inorganic chemistry underwent a period of unusually rapid development in which new physical techniques and theories were applied with increasing success to this branch of chemistry. It was to these developments that Nyholm made his most important contributions. His studies of the synthesis, properties and structure of tertiary arsine, phosphine, perfluoro and carbonyl complexes of the transition metals did much to increase our understanding of the oxidation states, co-ordination numbers, and stereochemistries of these elements. In the course of these investigations, he applied the techniques of magnetochemistry to great advantage, especially in unravelling the nature of the metal-ligand bond. It was to the subject of magnetochemistry that he devoted his Presidential Address. His interest in the Society did not lapse with his departure to the United Kingdom. He kept in constant touch with it on many matters, and was especially interested in the subject of the resumption of Science House and the future home of the Society.

He received many awards: the Corday Morgan Medal and Prize (1952), the H. G. Smith Memorial Medal of the Royal Australian Chemical Institute (1955). and the Medal of the Royal Society of New South Wales.

He became a Fellow of the Royal Society (1958), the Tilden Lecturer (1961), Vice-President of the Chemical Society (1966), the Dalton Lecturer (1966), President of the Chemical Section of the British Association for the Advancement of Science (1966), the Liversidge Lecturer (1967), Dwyer Lecturer (1968), President of the Chemical Society (1968), and President of the Twelfth International Conference on Co-ordination Chemistry, Sydney (1968).

In 1967 he was knighted for his distinguished services to science and was elected an honorary member of the Royal Society of New South Wales in August, 1969.

In recognition of his outstanding contributions to chemistry, the University of New South Wales conferred on him the honorary degree of Doctor of Science, the third such degree he had received, the two previous ones having been conferred by the City University (London) and the University of East Anglia.

An unusual distinction conferred on him, but one which pleased him greatly, was his election in 1959 as a corresponding member of the Finnish Chemical Society. His paternal grandfather, Erik Nyholm (1850–1887), a coppersmith, was born in Nykaleby, Finland. He had migrated to Adelaide in 1873.

Ron Nyholm was a man of boundless energy and great political skill, as those who served with him on the Council will recall. His interests ranged widely. He was, for instance, Chairman of the Chemistry Grants Committee of the Department of Scientific and Industrial Research, a member of the Science Research Council, and a Trustee of the British Museum.

Throughout his career, he took an active interest in chemical education not only in the university but also in the secondary school. He was a member of a small group in the University of New South Wales that began to co-operate with secondary school science teachers during the early fifties. He continued to develop these interests in the United Kingdom. He was President of the Science Education Association, Vice-Chairman of the Nuffield Foundation Committee on the 0-level chemistry programme, and one of the founders of the Royal Institute of Chemistry's journal *Education in Chemistry*.

Nyholm was a man of great personal warmth and friendliness, infectious enthusiasm, good humour and tolerance—qualities that endeared him to his many friends in many parts of the world. His untimely death is a source of great sadness to them. Their sympathy is extended to his wife Maureen and three children, Peter, Elizabeth and Rosemary.

Rupert Boswood Scammell

Rupert Boswood Scammell was born in Adelaide on 28th December, 1896. He came to Sydney at the age of 11 years and lived in Sydney for substantially the rest of his life. He completed his schooling at Sydney Church of England Grammar School (" Shore ") and later studied at Sydney University, from which he graduated as a Bachelor of Science. Upon leaving University he joined F. H. Faulding & Co. Limited, and his early experience with that company was in the laboratories in Sydney and Adelaide. He later became Managing Director of the company and held that position until he retired in 1952.

He became a member of the Royal Society in 1920 and was a life member of the Society at the time of his death. From 1937 to 1939 he was the New South Wales Branch President of the Royal Australian Chemical Institute, and during his presidency the Institute held its first exhibition. For many years, and up to his death, he was a Trustee of the New South Wales Division of the Liberal Party of Australia. He served as President of the New South Wales Club and as a member of the Council of the Royal Commonwealth Society at various times. He was also for some years a member of the New South Wales Government's Poisons Advisory Committee. In 1935 he joined the Council of the Standards Association of Australia. He was a member of the Association's Mark Committee for many years, and its Chairman from 1966 to 1968. When he died, he was a member of the Executive Committee of the Association and one of the Trustees of the Association's staff superannuation funds.

For many years Scammell was closely associated with Dr. Barnardo's Homes in Australia, first as Chairman of Attorneys in Australia and later as Honorary Treasurer of the Australian Committee, which he was instrumental in establishing at the request of Dr. Barnardo's Homes in London. It was very largely his work which put Dr. Barnardo's Homes in Australia on a firm financial footing. In recognition of his many services to the community he was awarded the O.B.E. in the 1971 Queen's Birthday Honours List.

As a man, he was modest, kind and generous and devoted to his family. He had many hobbies, particularly gardening, photography and painting. Shortly before his death he completed a manuscript for a comprehensive book on gardening, accompanied by his own illustrations. In everything he did he was thorough, and earned the respect of his colleagues in all spheres for his wisdom and commonsense. In 1930 he married Dagmar, and in 1936 had a son, Peter. Both survived him. He died suddenly on 24th October, 1971.

Dr. Francis Lions

Dr. Francis Lions, a life member of the Royal Society of New South Wales since 1929, passed away suddenly at his home in March, 1972, at the age of 70 years.

Dr. Lions, a former pupil of Sydney Boys' High School, graduated in 1923 as Bachelor of Science with First-class Honours and the University Medal from the University of Sydney. He obtained the Doctor of Philosophy at Manchester University and subsequently undertook post-doctoral research work at Brasenose College, Oxford. He was appointed lecturer and demonstrator in the Department of Chemistry, University of Sydney, in 1926. His distinguished academic career included a Senior Lectureship (1944) and a Readership (1946) at the same university. During the years 1930 and 1937 Dr. Lions served as Acting Professor of Organic Chemistry. In 1947 he became a Research Fellow at the University of Illinois, and in 1964 he obtained a similar position at Manchester University. From 1949 to 1959 Dr. Lions was a Fellow of the Senate, and he retired in 1966 from the University of Sydney after having served 40 years as a member of the teaching staff.

Dr. Lions actively supported the Royal Society of New South Wales, publishing 56 papers in the Journal, and was awarded the Society's Medal in 1965. He served the Council loyally for many years, presiding over the Society during 1946.

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Royal Society of New South Wales

OFFICERS FOR 1971-1972

NOTICE

The Royal Society of New South Wales originated in 1821 as the "Philosophical Society of Australasia"; after an interval of inactivity it was resuscitated in 1850 under the name of the "Australian Philosophical Society", by which title it was known until 1856, when the name was changed to "Philosophical Society of New South Wales". In 1866, by the sanction of Her Most Gracious Majesty Queen Victoria, the Society assumed its present title, and was incorporated by Act of Parliament of New South Wales in 1881.

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Journal and Proceedings of the

Royal Society of New South Wales

VOLUME 105 1972 PARTS 3 and 4

Published by the Society
Science House, Gloucester and Essex Streets, Sydney
Issued 5th September, 1973

NOTICE TO AUTHORS

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General. Manuscripts submitted by a non-member must be communicated by a member of the Society.

Manuscripts should be addressed to the Honorary Secretary, Royal Society of N.S.W., at the address given above. Two copies each of the following are required:

Manuscript—including title, author's name, address, and establishment where work carried out.

Abstract.

References—alphabetical list.

Captions for illustrations.

Shortened title, if necessary.

In addition one fair copy of all illustrations for final reproduction, together with one set of all illustrations, of same size or smaller than the fair copies, for the use of the referees.

Papers should be prepared according to the general style adopted in this journal. They should be as concise as possible consistent with adequate presentation and, other than those specially invited by Council, they will only be considered for publication if the content is substantially new material not previously published or submitted concurrently elsewhere.

Manuscripts should be typed in double spacing with generous margins. Headings should be typed without underlining and, if a paper is long, the headings should also be given in a Table of Contents typed on a separate sheet for the guidance of the Editor. Spelling shall be in accordance with the Concise Oxford Dictionary. The Title should be as concise as possible yet clearly stating the nature of the communication, and if the title is long a shortened title of not more than 50 letters should be given for reproduction at the head of each printed page.

Original papers or illustrations published in the Journal and Proceedings of the Society may be reproduced only with the permission of the author and of the Council of the Society.

Abstract. A brief but fully informative abstract which will be printed at the beginning of the paper must be provided.

Tables should be typed on separate sheets and column lines should *not* be ruled in. Units of measurement should always be indicated in the headings of the columns or rows to which they apply. Tables shall be numbered (serially) and should preferably be given a caption.

Illustrations. Diagrams and graphs shall be in *Indian ink* on tracing cloth, tracing paper or white card and lines shall be bold enough to permit appropriate reduction. All printing should preferably be inserted on an accompanying copy and if it must be inserted on the original then it shall be in soft lead.

Photographs should only be included where essential. They should be sharp with good contrast, on glossy paper, unmounted, and any lettering should be on a transparent overlay.

Maps should not be larger, when reduced, than two pages of the printed journal. All information, legends, symbols, etc., should be within the frame of the map.

Authors are requested to indicate clearly for all illustrations the scale of reduction they require.

Captions for all illustrations should be typed in numerical order on a separate sheet.

References are to be cited in the text by giving the author's name and year of publication, e.g. Bragg (1933). At the end of the paper all references shall be given in a list in alphabetical order and each shall comprise the author's name and initials, year of publication, abbreviated title of journal, volume number and first page.

Reprints may be purchased provided they are ordered by the author when returning the galley proofs. An author who is a member of the Society will receive 25 reprints of his paper free.

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 57–60, 1972

A Method for the Exact Orientation of the Plane Table

A. D. Albani

Introduction

The method for the exact orientation of the plane table may have numerous applications, although in modern practice the Plane Table is advantageously replaced by other instruments.

The graphic determination of the station point by means of three known points and, consequently, the correct orientation of the Plane Table, is known as the Snellius Problem or the Three-point Problem.

Many methods have been presented to solve this case, which is indeterminate only if the three known selected points and the station point lie on the same circumference (the great circle). Therefore, the known points are generally selected so that the station point, which is to be determined, lies either inside or outside the triangle formed by the three known points (the great triangle).

Among the many methods normally described in surveying textbooks, the " Tracing Paper Method " and the " Similar Triangle Method " lack accuracy and the " Intersecting Circle Method ", as well as the " Bessel's (Italian)

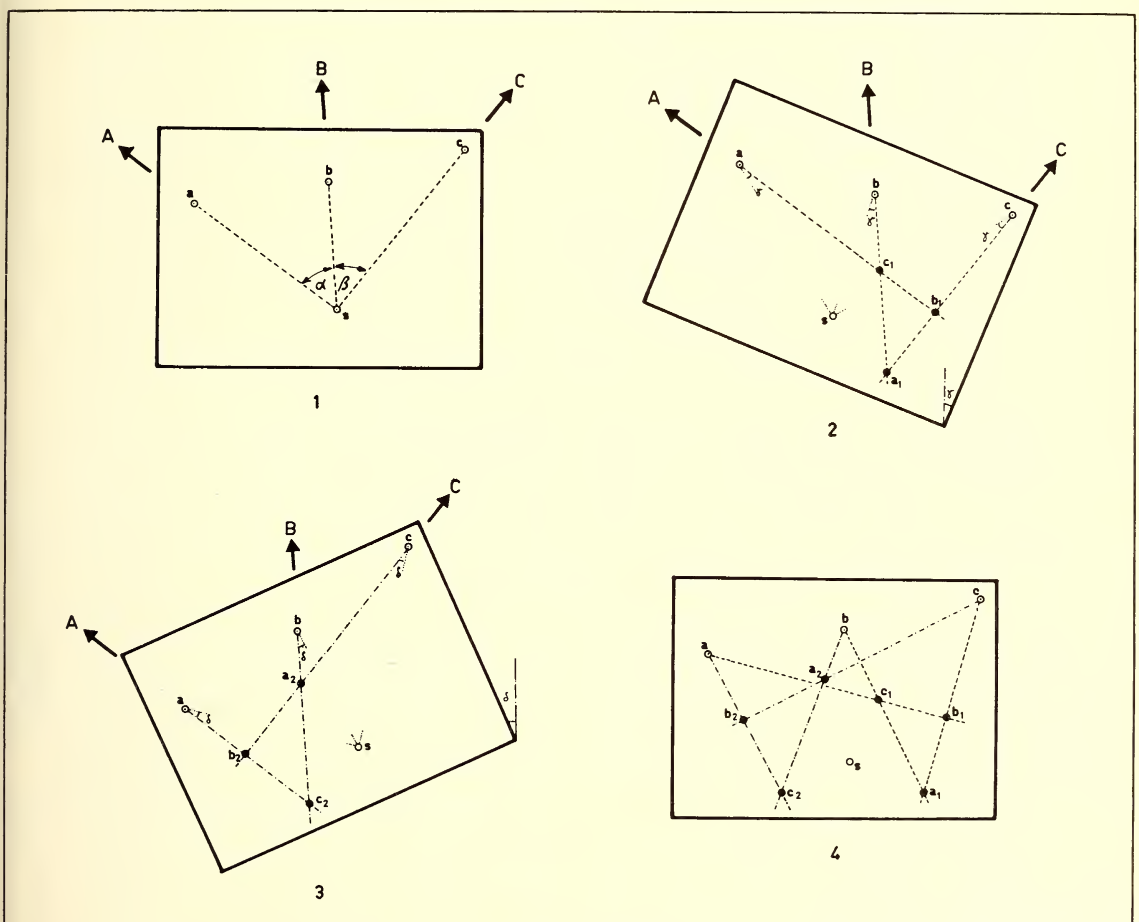

Fig. 1.

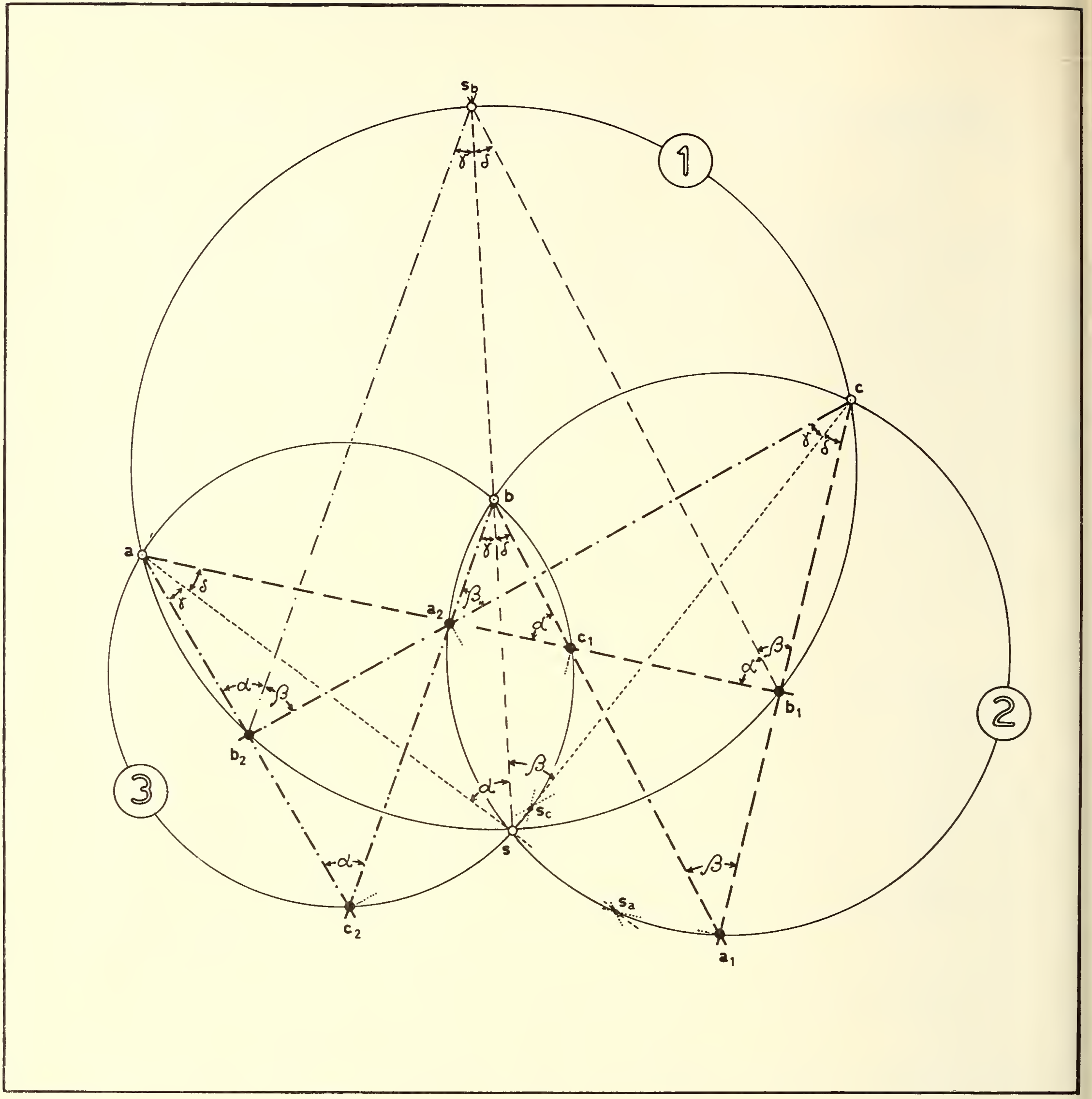

Fig. 2.

Method ", although accurate, require constructions which sometimes may fall off the sheet.

The method here described is accurate and, at the same time, its construction falls always within the sheet; it has been derived from the graphic solution of the intersecting circles here briefly reconsidered.

The Graphic Solution

The graphic solution of the intersecting circles has been shown and analytically studied by Albani (1942, 1948) and later simplified and applied in aerial phogrammetry (Albani, 1964).

The three known ground points A, B, C and the unknown station point S are represented on the plane table by the points a, b, c and s (Fig. 1 (1)). The station point s forms the angle α with the known points a and b, and the angle β with the known points b and c.

By disorienting the plane table of the amount γ with respect to the line of sight bB (Fig. 1 (2)) the triangle of error a_1, b_1, c_1 is obtained; the table is then disoriented of the amount δ in the opposite direction with respect to bB (Fig. 1 (3)) and a second triangle of error a_2, b_2, c_2 is similarly obtained.

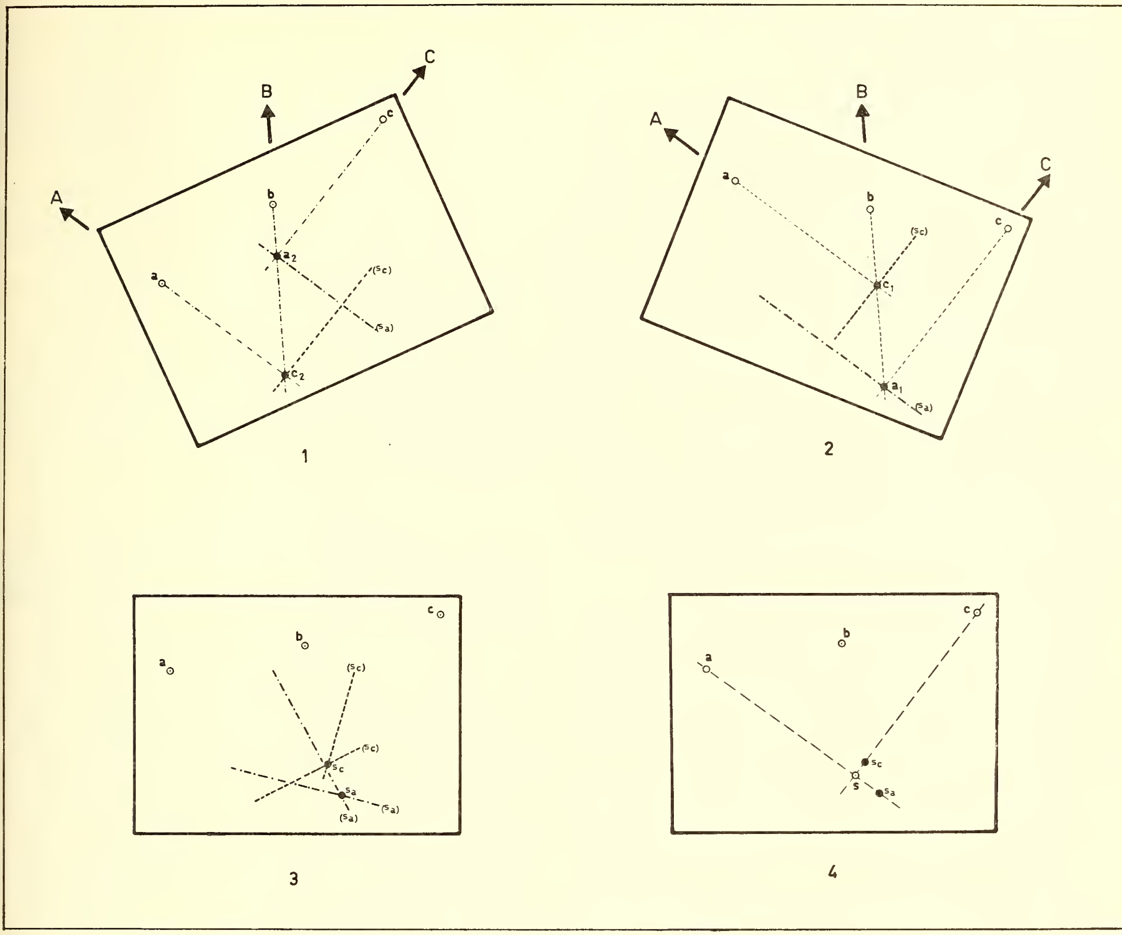

Fig. 3.

At this stage on the plane table both triangles of error are present (Fig. 1 (4)) and the angles in a_1, b_1 and c_1 as well as those in a_2, b_2 and c_2 could be considered to be equal to those in s because the small excentricity which exists between the vertices of the triangles of error and the station point s is neutralized by the graphic method itself.

It is possible, therefore, to draw three circles (Fig. 2) each subtending the angles :

$\alpha+\beta$ subtended between c and a, at b_1 and b_2 (circle 1),

β subtended between b and c, at a_1 and a_2 (circle 2), and

α subtended between a and b, at c_1 and c_2 (circle 3).

The station point s is determined by the intersection of the three circles.

The operational method, object of this study, is based on the following considerations.

(1) The line joining s and b meets the circle 1 in the auxiliary point s_b and, because angles at the circle subtended by the same chords, the following relationships exist :

(circle 1) $s\widehat{s_b}b_2=s\hat{a}b_2=\gamma$

and $s\widehat{s_b}b_1=s\hat{c}b_1=\delta$

(circle 2) $s\hat{c}a_2=s\hat{b}a_2=\gamma$

and $s\hat{c}a_1=s\hat{b}a_1=\delta$;

(circle 3) $s\hat{a}c_2=s\hat{b}c_2=\gamma$

$s\hat{a}c_1=s\hat{b}c_1=\delta$.

In particular $s\widehat{s_b}b_2=s\hat{b}c_2=\gamma$ and

$s\widehat{s_b}b_1=s\hat{b}a_1=\delta$;

consequently s_bb_2 is parallel to bc_2 and s_bb_1 is parallel to ba_1.

It is possible, therefore, to determine the auxiliary point s_b by the intersection of the lines parallel to c_2a_2b and a_1c_1b conducted from b_2 and b_1 respectively.

(2) Similar construction can be applied to the other auxiliary points s_a and s_c, obtained joining s with a and c.

The point s_a is determined, at the same time, by the intersection of the lines drawn from the point a_2 and parallel to ac_2 and from the point a_1 and parallel to ab_1; similarly, the auxiliary point s_c by the intersection of the lines drawn from c_1 and c_2 and parallel to bc_2 and cb_2 respectively.

It is important to note that such auxiliary points are obtained with an angle of intersection equal to that imposed by the operator in disorienting the plane table $\gamma+\delta$.

The Operational Method

A, B and C are three known ground points, their plotted position on the table being a, b and c. Object of the exercise is to determine graphically and accurately the position of the station point s.

The method can be described, simply, as a step-by-step operation (Fig. 3).

1. Having placed the instrument on station at S, the table is disoriented with respect to bB and the line of sight bB is drawn (Fig. 3 (1)).
2. The point A is sighted with the pin in a, obtaining c_2 at the intersection with bB.
3. a_2 is similarly obtained sighting at C with the pin in c.
4. Through the points a_2 and c_2 two lines are now drawn parallel to ac_2 and ca_2 respectively.
   It is along these lines that the auxiliary points s_a and s_c will be located.
5. The table is now disoriented in the opposite direction (Fig. 3 (2)) and another line of sight bB is drawn.

6, 7, 8. Steps similar to 2, 3 and 4 are now repeated.

9. The intersections of the (s_a) and (s_c) lines obtained from the two constructions (Fig. 3 (3)) will determine the position of the auxiliary points s_a and s_c.
10. The lines $s_a a$ and $s_c c$ (Fig. 3 (4)) will determine the lines of sight $s_a aA$ and $s_c cC$ and their intersection will position graphically the station point s.
11. An immediate control is given by the line of sight sbB.

The auxiliary points s_a and s_c can be obtained even if the disorientation of the table is carried out both times on the same side of bB and thus preventing the possibility of one of the vertices to fall outside the table itself.

Acknowledgements

The author wishes to thank his father, whose wide and profound experience in surveying has supported and guided the present study.

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(Received 22 March 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 61-70, 1972

The Geology of the Mt. View Range District, Pokolbin, N.S.W.

A. T. Brakel

Abstract—A re-examination of the geology of the Carboniferous Mt. Bright Inlier of the Mt. View Range, near Pokolbin, N.S.W., has led to modification of previous maps and the definition of formal stratigraphic nomenclature for the suite of volcanic and sedimentary rocks exposed therein. This succession consists of a "Kuttung" sequence of the Pokolbin Hills Volcanics and Seaham Formation overlying non-conformably the Lower Carboniferous Mt. View Range Granodiorite. Within the Pokolbin Hills Volcanics, the Mt. Bright Rhyolitic Ignimbrite Member, Flying Fox Gully Trachyandesite Member, Vineyard Lookout Volcanic Agglomerate Member, and Matthews Gap Dacitic Tuff Member have been named. The Carboniferous rocks are overlain by Permian sediments and basalt, and Triassic sandstones.

Introduction

The Carboniferous Mt. Bright Inlier of the Mt. View Range district occupies approximately 20 km^2 of country 6 km west of Cessnock, N.S.W. Details of the physiography have been described previously (Browne and Walkom, 1911). The dominant landform is a steep scarp which forms the eastern side of the Mt. View Range, facing the lowlands of the Hunter Valley. The scarp line turns westerly near Matthews Gap, and then northerly to form the slopes of the Brokenback Range. This study has indicated that the scarp near Mt. Bright is composed of rhyolitic ignimbrite, a hard siliceous rock, which overlies granodiorite at the foot of the range.

The purpose of this paper is to define new units and describe the geology in the area. The grid references given to localities in the text are taken from the 1954 Cessnock One-Mile Military Sheet.

Stratigraphy

To date the Carboniferous rocks of this district have not been defined as stratigraphic units although Browne and Walkom (1911) and others have regarded the volcanic sequence to be "Upper Kuttung" in age. Since the correlation of these rocks with defined units north of the Hunter Thrust is impractical, the writer proposes to set up stratigraphic nomenclature for the units concerned. Those named are shown in Table 1 and their distribution in Figure 1.

Mt. View Range Granodiorite

Synonomy: Granodiorite and "quartz diorite with zircons" (David, 1907); granodiorite (Browne and Walkom, 1911).

Derivation: Mt. View Range.

Lithology: Granodiorite, and minor aplite and schorl rock.

Type Outcrop: An exposure in a creek (292422) in the south-western corner of Mt. Pleasant Vineyard property, at the foot of the Mt. View Range.

Age and Relationships: The biotite in this rock has given a minimum K-Ar age of 336 million years (Harding, 1969, p. 15), indicating that it was emplaced in Lower Carboniferous times. The granodiorite is nonconformable with the overlying Mt. Bright Rhyolitic Ignimbrite Member of the Pokolbin Hills Volcanics and the writer has confirmed the presence of granodiorite pebbles in the basal breccia of the latter, first reported by Browne and Walkom (1911).

Petrology: The granodiorite is a holocrystalline, medium and relatively even-grained rock with a typical granitoid texture. The average grain size is 2 mm. The minerals present and their average proportions, in their apparent order of crystallization, are: apatite and zircon, magnetite and sphene, hornblende (5·5%), augite (2·5%), biotite (11%), plagioclase (An_{40}) (51%), orthoclase (13%), quartz (16%). The proportions of minerals in individual rock specimens vary. Examples of Bowen's reaction series can frequently be seen. Augite is almost invariably surrounded by a rim of hornblende, which may in turn be in contact with biotite. Much of the pyroxene and amphibole has been altered to greenish chlorite, while the biotite is altered to epidote, penninite, and magnetite.

In the type outcrop, the rock consists of leucocratic and melanocratic phases, between which is a sharp contact. A pinkish coloured albitized phase, usually developed along joints, is also common. Albite comprises about three-quarters of this rock and chlorite the remainder. Quartz is usually absent. There are minor occurrences of pink aplite and schorl rock, but pegmatite veins are rare. At the northern extent of the unit, some copper and iron mineralization is present in some old prospect shafts.

As the granodiorite does not crop out in the southern half of its extent, mapping of the rock here was based on the characteristic micaceous soil it produces on weathering.

in the Pokolbin region, and it is proposed that it should include the volcanics of the Drake's Hill district not dealt with in this paper. The unit overlies nonconformably the Mt. View Range Granodiorite and is in turn overlain in apparent unconformity by sediments equivalent to the Seaham Formation and the Permian Dalwood Group.

TABLE 1
Stratigraphic Nomenclature

Age	Group/Formation	Named Members
Lower Triassic	Gosford Formation (Rng)	
	(Unconformity)	
Upper Permian	Singleton Coal Measures (Ps)	
	Branxton Formation (Pmb)	Muree Sandstone Member (Pmm)
	(Matthews Gap Fault)	
Lower Permian	Dalwood Group (Pd)	
Upper Carboniferous	Seaham Formation (Cus)	
	(Unconformity)	
Upper or Middle Carboniferous	Pokolbin Hills Volcanics (Cp)	Matthews Gap Dacitic Tuff Member (Cpm) Vineyard Lookout Volcanic Agglomerate Member (Cpv) Flying Fox Gully Trachyandesite Member (Cpf) Mt. Bright Rhyolitic Ignimbrite Member (Cpb)
	(Nonconformity)	
Lower Carboniferous	Mt. View Range Granodiorite (Cgv)	

Pokolbin Hills Volcanics

Synonomy: The Carboniferous volcanic rocks and interbedded sediments of the Pokolbin region mentioned by David (1907), Browne and Walkom (1911) and Walkom (1913).

Derivation: The Pokolbin Hills, between the Brokenback and Mt. View Ranges.

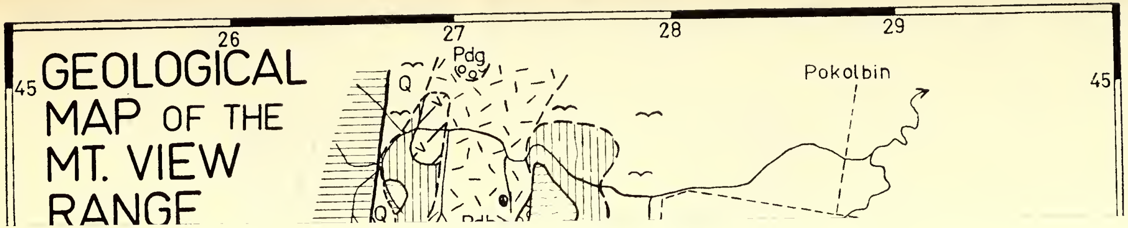
Lithology: Ignimbrites, tuffs, trachyandesites, trachytes, andesite, pitchstone, agglomerate, and some sediments.

Type Section: From the Mt. View Granodiorite contact (288420) in a gully above the type outcrop of the latter, along section line AA in Fig. 1 to the upper contact with Seaham Formation sediments (266427).

Thickness: 950 m measured in type section. This section is interrupted by the Moogering Fault, an easterly-dipping normal fault estimated to have a displacement of about 50 m at Grid Reference (275436). Assuming the displacement in the type section to be the same, the true thickness will be 900 m.

Age and Relationships: This formation embraces the entire Carboniferous volcanic sequence

The sequence was assigned an "Upper Kuttung" age by Browne and Walkom (1911), on the basis of scanty remains of *Rhacopteris* and *Cardiopteris* found in some of the tuffs. While it is certainly a terrestrial, and therefore "Kuttung" sequence (Engel, 1965), the only definite statement that can be made regarding its age is that it is post-Lower Carboniferous and pre-Permian. Its nonconformable relation with the Mt. View Granodiorite indicates that sufficient time must have elapsed for the pluton to be exposed at the surface by erosion before the volcanics were extruded. An Upper Carboniferous age therefore seems most likely. However, the Miocene batholiths of Alaska (Pitcher and Flinn, 1965, p. 34) and the Pleistocene plutons of the Himalayan region and New Guinea show that the time for erosion and exposure can be very short, so a Middle Carboniferous age cannot be excluded. Consequently, the correlation of this unit with the Carboniferous rocks on the northern side of the Hunter Valley is uncertain. It may be the time equivalent of the Paterson Volcanics, the volcanic members of the Seaham Formation, or the Gilmore Volcanics.



LEGEND

QUATERNARY

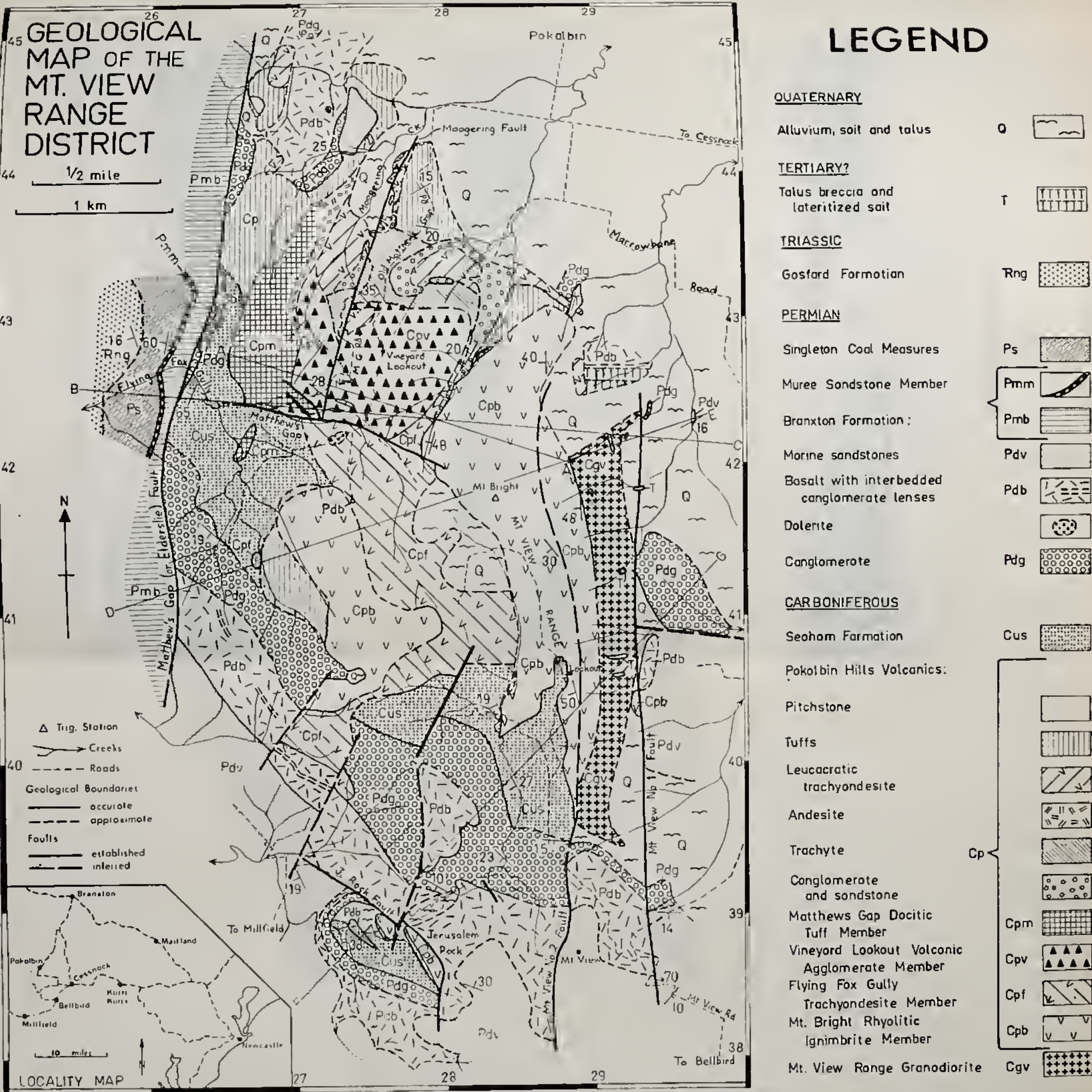


Fig. 1.—Geological map of the Mt. View Range district, N.S.W.

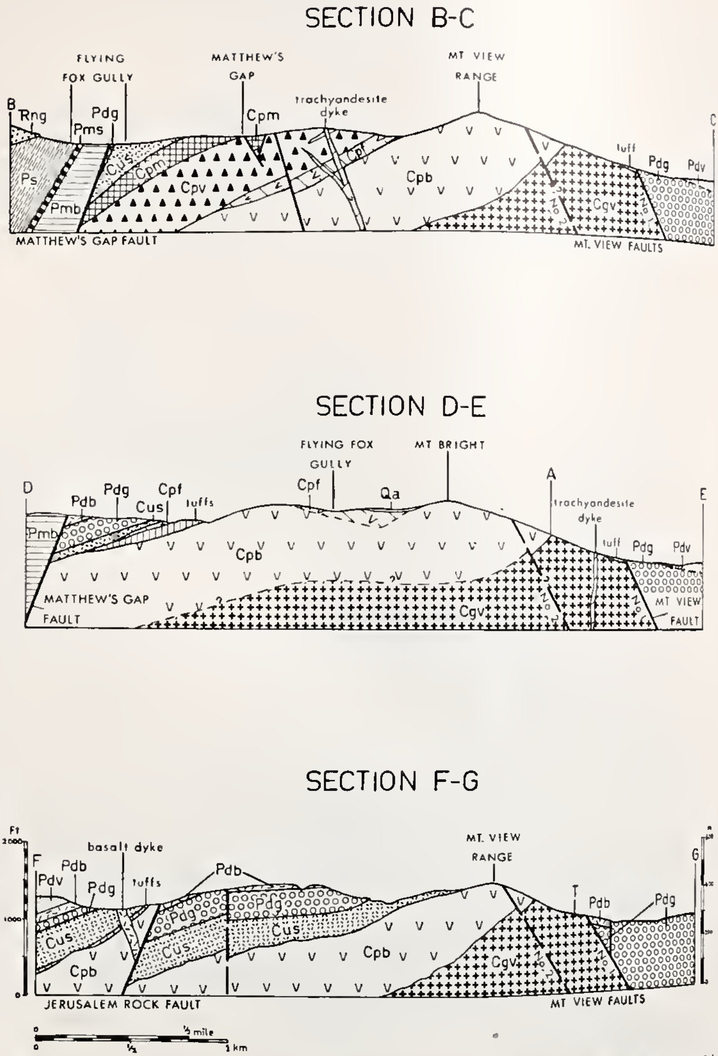


FIG. 2.—Cross-sections to accompany the geological map of the Mt. View Range district.

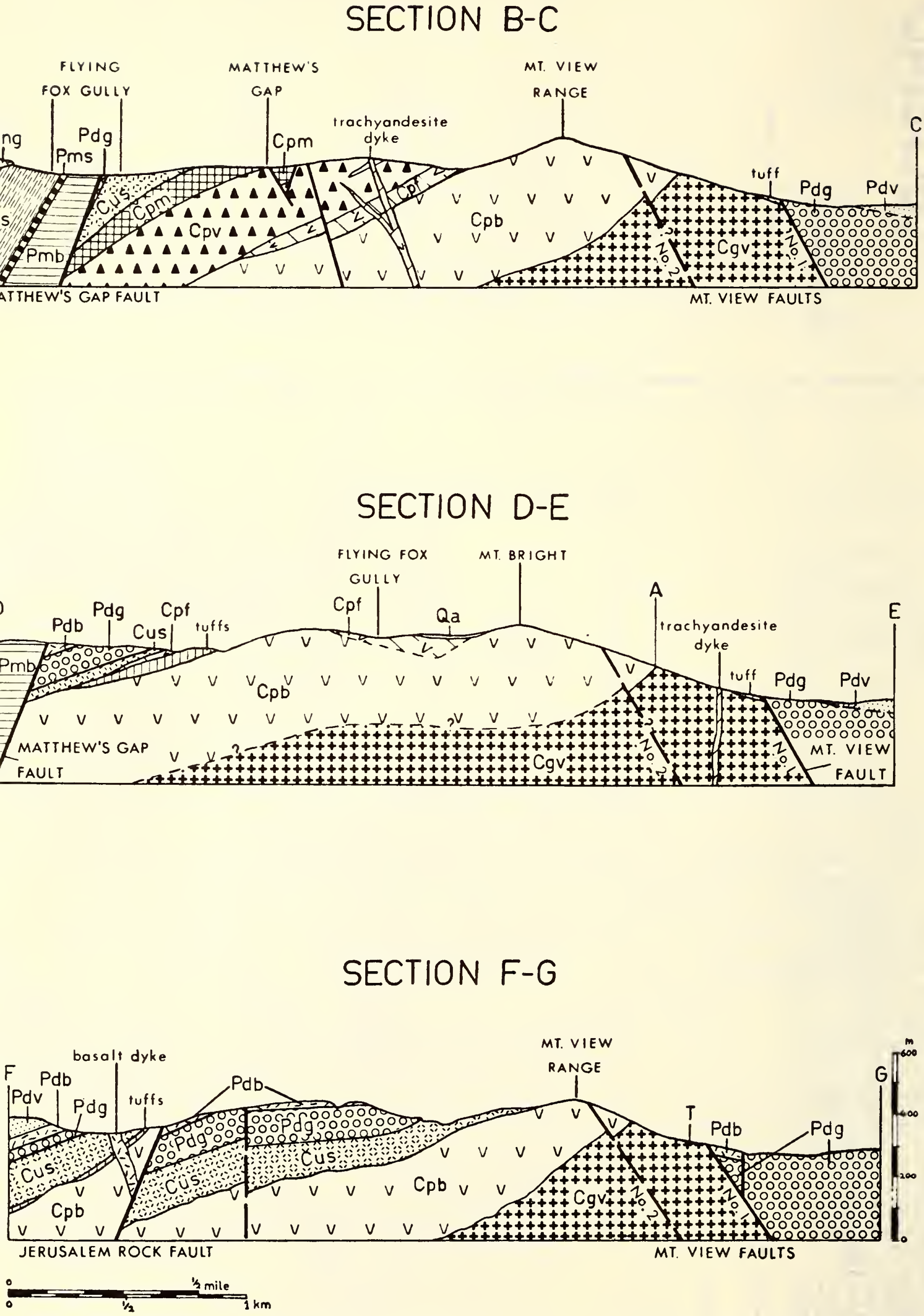


Fig. 2.—Cross-sections to accompany the geological map of the Mt. View Range district.

Description : The Mt. Bright Rhyolitic Ignimbrite Member forms the basal unit of the formation, and is succeeded by a sequence of tuffs, tuff breccias, sandstones and conglomerates, which in some places had apparently been removed by erosion before later units were deposited. In the type section only 20 m of the upper part of this sequence are present. In the deep gully east of Vineyard Lookout (282428), the basal beds consist chiefly of coarse lithic tuffs and tuff breccias. Occasionally they contain rounded pebbles and an abundance of fragments from the underlying rhyolitic ignimbrite, showing that a proportion of the tuffs is sedimentary in character. Next in the sequence is a distinctive fine pale green tuff which weathers to a light brown colour. It is overlain by coarse to medium grained, poorly sorted lithic sandstone, which is pebbly in places. West of the old Matthew's Gap Road the rock is a conglomerate composed of volcanic, subangular to rounded clasts up to 15 cm in diameter, set in a poorly sorted matrix of coarse to medium grained sandstone with a clay cement. The unit is overlain by the Flying Fox Gully Trachyandesite Member, except at its north-western extent, where acid tuffs and intermediate extrusives comprise the younger rocks.

Elsewhere in the Mt. View Range district the tuff sequence has developed differently. For example, near Grid Reference (270410) it comprises an estimated 30 m of rhyolitic conglomerate, consisting entirely of pebbles and fragments of rhyolitic ignimbrite, overlain by 35 m of mainly coarse tuffs and tuff breccias. The sequence here is overlapped by Permian conglomerate. Small occurrences of tuff breccia also exist on the western side of Jerusalem Rock, and in the creek at Grid Reference (284405).

Above the Flying Fox Gully Trachyandesite Member there is developed a further sequence of volcanics in the Moogering Creek district. The stratigraphy of the individual members, being restricted in lateral and vertical extent, is complex. Near Matthews Gap the sequence is simplest and consists of the Vineyard Lookout Volcanic Agglomerate Member overlying the Flying Fox Gully Trachyandesite Member, followed by the Matthews Gap Dacitic Tuff Member. To the north of Matthews Gap the sequence is more complicated and the aforementioned members are absent. Instead, the tuff sequence previously described is overlain by trachyte, acid tuffs, leucocratic trachyandesites, minor ignimbrites, conglomerates, andesite, tuff breccias and andesitic pitchstone. These members are usually developed as tongues and lenses. Large amounts of secondary calcite often occur in the lava flow rocks. In the extreme north of the district there are outcrops of volcanic rocks which may form a small inlier separated from the main one by Permian basalt and conglomerate, or alternatively may link up with the main inlier by a narrow isthmus-like connection. The true situation is obscured by soil.

The members of the Pokolbin Hills Volcanics named above are formally defined below.

Mt. Bright Rhyolitic Ignimbrite Member

Synonomy : The " rhyolite " of David (1907) and Browne and Walkom (1911).

Derivation : Mt. Bright (283418).

Lithology : Rhyolitic ignimbrite, tuffs, breccia.

Principal Section : From the granodiorite contact (289417), in an abandoned prospect shaft, to the top of the ridge (285416) and thence to the contact with the overlying Flying Fox Gully Trachyandesite (283415).

Thickness : Estimated at approximately 460 m in the principal section. The upper contact is concealed by thick soil and the section may have been affected by faulting. In the Pokolbin Hills Volcanics type section, the thickness measured is 440 m.

Relationships and Petrology : At the base of the member is a tuff breccia developed as lenses, resting on an irregular surface of the Mt. View Granodiorite. The rock contains clasts, up to 8 cm in diameter, of granodiorite, granite, aplite, and volcanics. The roundness of the clasts varies from place to place in the rock body as does the dominant clast size and abundance. The matrix is a green tuff consisting of unsorted angular fragments of quartz and feldspar ranging down to less than one micron in size.

The 34 m of the unit overlying the basal breccia is dominated by light green rhyolitic rocks, weathering pink or light brown, with a variety of ignimbritic textures. This rock contains lithic and pumice fragments up to 16 mm long, and white or pinkish-brown euhedral feldspar crystals up to 3 mm long, comprising mainly potash feldspar and some plagioclase. Under the microscope the matrix is revealed as slightly welded glass shards, which have devitrified to axiolitic, granular or spherulitic aggregates. The green colour of the rock is due to secondary celadonite, formed by alteration of rock glass. This mineral decomposes during weathering, resulting in a rock which is pink or light brown in colour. Thin lenses of tuffaceous material, similar to some parts of the basal breccia, are interbedded with these ignimbrites.

The remaining 420 m of the unit consists of rhyolitic ignimbrite which varies in colour, probably due to weathering, from white to cream and sometimes dark red. The texture in handspecimen varies from massive to a well-developed pseudo-flow fabric. Devitrified glass shards form "flow-lamellae", which bend around lithic and pumiceous fragments, and phenocrysts. The phenocrysts are usually no larger than 2 mm and consist of subhedral quartz, albite and potash feldspar, rounded and embayed by resorption. Microscopic examination discloses that the rock has undergone extreme welding, since most of the shards and pumice fragments have been compressed into thin lenses and streaks. In places small lenses of light grey to reddish opaque chalcedony occur.

Ross and Smith (1961) made the general observation that ignimbrite units usually have a densely welded central zone which grades to poorly welded zones above and below it. The absence of a slightly welded or non-welded top zone in this member is probably due to its removal by erosion. As mentioned previously, tuffaceous sediments and tuffs containing an abundance of rhyolitic ignimbrite fragments overlie the member in a number of places, thus providing evidence of such erosion. The ignimbrite at Jerusalem Rock is unusual in that it often contains a high proportion of plastically-flattened, lenticular pumice fragments, which are usually less than 2 cm in length but may exceed 4 cm. Some of these still have some of their original pore space remaining, demonstrating the start of a trend to less extreme welding.

Flying Fox Gully Trachyandesite Member

Synonomy: Browne and Walkom's (1911) leucocratic trachyte west of Mt. Bright.

Derivation: The headwaters of Flying Fox Gully.

Lithology: Leucocratic trachyandesite.

Thickness: About 45 m in the Pokolbin Hills Volcanics type section, thinning northwards. Elsewhere the thickness cannot be determined.

Relationships and Petrology: The unit overlies disconformably the Mt. Bright Rhyolitic Ignimbrite Member, except in the gully east of the old Matthews Gap Road, where it is conformable on tuffs and tuffaceous sediments and underlies the Vineyard Lookout Volcanic Agglomerate Member. West of the Mt. View Range the member probably fills a valley in the Mt. Bright Rhyolitic Ignimbrite Member and may be underlain by tuffaceous sediments. Elsewhere it underlies unconformably Seaham Formation sediments and Permian sediments of the Dalwood Group. The small area of trachyandesite at Grid Reference (267414) is probably the cross-section of a single, narrow lava flow.

Macroscopically, the fresh rock is a light grey trachyandesite, which may contain subhedral dark pink plagioclase phenocrysts up to 4 mm long. Usually the rock is weathered to a yellowish-brown or light brown colour. Thin sections reveal subhedral phenocrysts of andesine (An_{45}) and occasional potash feldspar set in a trachytic groundmass of laths of potash feldspar and some andesine (An_{40}). Apatite and magnetite are accessory minerals. Practically no ferromagnesian minerals remain in the rock, but rare biotite and a few instances of chlorite and magnetite replacing a euhedral rectangular crystal were observed. Chlorite also occurs interstitially, often as spherulites. Secondary silica is present in the groundmass as microcrystalline aggregates.

Vineyard Lookout Volcanic Agglomerate Member

Synonomy: Browne and Walkom's (1911) volcanic agglomerate, trachyandesite, and some nearby "andesite" and trachyte.

Derivation: Vineyard Lookout (276427).

Principal Section: An east-west section across Vineyard Lookout Hill from (279423) to (270426), which is part of the Pokolbin Hills Volcanics type section.

Thickness: About 190 m in the principal section, assuming a displacement of 50 m on the Moogering Fault.

Lithology: Conglomerates, agglomerates of trachytic and trachyandesitic composition, trachyte and trachyandesites.

Relationships and Petrology: This member of the Pokolbin Hills Volcanics overlies the Flying Fox Gully Trachyandesite Member near Matthews Gap. At the base of the member is a melanocratic trachytic unit, which is usually agglomeratic. This unit shows considerable variation, from a massive, dark grey trachyte to fragmentary rocks with irregular blocks of pumice, trachyte and rhyolitic ignimbrite set in a lava or tuff matrix. The blocks may be up to one metre in length. There is an irregular lithofacies variation from massive trachyte south of the principal section to agglomeratic trachyte northwards.

This basal unit is overlain by an agglomerate with rounded clasts, which vary greatly in size, and may exceed one metre in diameter. There is a lateral facies variation from south to north. In the south, rounded boulders of melanocratic trachyte, some trachyandesite, and occasional banded rhyolite are set in an epiclastic matrix. Northwards, this epiclastic subdomain grades irregularly into a rock consisting of blocks set in dark grey trachyte. Some lithic tuff and roundstone conglomerate occur in places in this northern extent (277428).

A younger unit, forming the top of Vineyard Lookout, is of melanocratic trachyandesite and lenses out to the north. The rock is altered and is dark purple in colour. It is massive but contains rare, small, lithic fragments. The texture varies from almost aphyric to porphyritic with andesine (An_{35}) laths up to 5 mm long. The laths are white in colour, but often have a light pinkish tint due to alteration of the rock.

Overlying the trachyandesite is another agglomerate unit with many lateral and vertical facies variations. The largest clast observed was a boulder 110 cm across at its greatest dimension. The base of this unit consists mainly of trachyandesite and trachyte enclosing fragments and rounded pebbles of similar compositions, while along the new Matthews Gap Road the rock is composed of boulders set in an epiclastic matrix. A trachyandesite flow in the sequence along the road has a similar appearance to the trachyandesite of Vineyard Lookout, but the feldspar laths are more abundant. Above this trachyandesite the rock is a coarse conglomerate similar to the rock below it. The top of the unit is composed of a melanocratic trachyte with occasional clasts. It is overlain by the Matthews Gap Dacitic Tuff Member.

Matthews Gap Dacitic Tuff Member

Synonomy: "Dacite" of Browne and Walkom (1911).

Derivation: Matthews Gap (270425).

Principal Section: An east-west section across the ridge west of Moogering Creek, from (270426) to (265427). This is part of the Pokolbin Hills Volcanics type section.

Lithology: Dacitic crystal vitric tuff.

Thickness: About 205 m in the principal section.

Relationships and Petrology: The unit is a member of the Pokolbin Hills Volcanics and directly overlies the Vineyard Lookout Volcanic Agglomerate Member and andesite to the east. To the north-west it underlies tuffs while to the south-west it is overlain by conglomerates and sandstones of the Seaham Formation.

The rock is composed of a high proportion of crystal fragments, mainly quartz and plagioclase, set in a fine ash matrix containing reddish-brown glass shards. The crystals are up to 4 mm long. The rock usually has a weathered reddish-brown colour, but fresher samples are olive-green. Inclusions of brown, devitrified ignimbrite, up to 25 mm in diameter, occasionally occur.

Seaham Formation

Synonomy: The conglomerate and chocolate shales below the base of the "Lower Marine Series" reported by David (1907), and the "Carboniferous conglomerates, shales, and sandstones" of Browne and Walkom (1911).

Lithology: Varvoid laminites, mudstones, diamictite, sandstones and conglomerates.

Thickness: 170 m south-west of Mt. Bright Lookout.

Age and Relationships: The formation was regarded as having a Carboniferous age by David (1907) and Browne and Walkom (1911). An analysis of the microflora in a specimen of fine standstone by R. Helby (B. Runnegar, pers. comm.) has revealed the presence of the *Potonieisporites* microflora known to occur in the Seaham Formation, usually regarded as Upper Carboniferous.

Although the succession here differs from that at Seaham, the setting up of a new formation to include the sequence in this district is hampered by the absence of available geographical names. However, since the Seaham Formation west of Seaham shows great variations in stratigraphy, its extension to this district may be justified.

The unit directly overlies different members of the Pokolbin Hills Volcanics, thereby indicating an unconformable relationship. This is confirmed by the measurement of a dip of 15°W near its base in the embayment at Mt. Bright Lookout (288406) whereas the eutaxitic lamination in the underlying Mt. Bright Rhyolitic Ignimbrite Member dips at 40° to 60°W near this spot. The formation is conformably overlain by Permian conglomerate, but there is no sharp boundary between the two, as the upper volcanic conglomerate member grades into the polymictic Permian conglomerate due to the introduction of clasts of exotic derivation. The Permo-Carboniferous boundary was arbitrarily set at the first appearance of pebbles of a distinctive quartz-feldspar porphyry which is not of local provenance.

Description: South-west of Mt. Bright Lookout, the basal members vary from pebbly sandstones to volcanic cobble conglomerates with coarse sandy lenses. These basal members are not everywhere present. The overlying sequence, of which there are some good outcrops in the unnamed south-flowing creek, consists of varvoid laminites and sandstones, minor diamictite, and mudstone with dropstones, chocolate brown or light grey in colour. Fine sandstone comprises the greatest proportion of the varvoid laminites. The laminations vary in thickness from less than 1 cm to 5 cm, and occasional dropstones of volcanic rock up to 13 cm. in diameter are found in it. The fine sandstone contains an abundance of indeterminate plant remains in places.

The top portion of the formation consists of cliff-forming coarse conglomerates and some interbedded coarse sandstone. The conglomerate phenoclasts are rounded, range from pebbles to boulders, and are composed entirely of local volcanic rock, except for rare jasper which is probably derived from secondary silica infillings in the underlying Mt. Bright Rhyolitic Ignimbrite Member. The conglomerate frequently contains a high proportion of rhyolitic ignimbrite fragments where it is adjacent to this Member, suggesting that it was deposited against cliffs of the ignimbrite from which the debris was derived. The transition to the overlying Permian conglomerate occurs in the second cliff west of the creek.

Dalwood Group

At the assumed base of the Permian succession is a polymictic conglomerate containing clasts of quartz-feldspar porphyry, quartzite, hornfels, schist, chert, jasper, quartz, granite, aplite, and Carboniferous volcanics. The unit contains lenses of medium-grained lithic sandstone. At (271405) and (274396) the rock is fine sandstone and contains large plant stems. Next in the succession is a basalt with an interbedded conglomerate member in its south-western outcrop and often containing amygdules of a wide variety of secondary minerals. Microscopically the rock consists of some phenocrysts of labradorite (An_{70}), augite and olivine set in a groundmass of labradorite (An_{65}) laths, augite, olivine and magnetite. The ferromaguesian minerals are almost invariably found to be altered to chlorite, calcite, and clay minerals.

The succeeding Dalwood Group sediments are chiefly fine sandstones with marine fossils, and minor siltstones, tuff, and conglomerate, described by previous workers.

Publications by David (1907), Browne and Walkom (1911), Walkom (1913), and Osborne (1950) differ in their conclusions as to the correlations of the Lower Permian rocks with formations defined in the Lower Hunter Valley. These correlations are still uncertain, but the polymictic conglomerate, basalt, and an overlying lens of tuff containing *Eurydesma cordatum* may be correlatable with the Lochinvar and Allandale Formations, while the succeeding sandstones are probably correlatable with the Rutherford and Farley Formations.

Upper Permian and Triassic

West of the Matthews Gap Fault, rocks of the Branxton Formation (including the Muree Sandstone Member), Singleton Coal Measures, and Gosford Formation crop out. The Muree Sandstone Member forms poor outcrops in most of the area mapped and is not exposed on the spur just north of Flying Fox Gully. This is in contrast to the good marker horizon it usually provides to the south in the Millfield area. Dips of 60°W in the Singleton Coal Measures and 16°W at the base of the Gosford Formation agree with the observations of David (1907) that there is an unconformity between the Permian and Triassic Systems at this locality, and this would seem to be further supported by the absence of the Munmorah Conglomerate, Tuggerah Formation, and Collaroy Claystone, which comprise the basal formations of the Narrabeen Group near the coast. It is also possible that the absence of these units is due to facies changes towards the coast, and that the difference in dip readings between the Triassic and the Singleton Coal Measures is the result of the latter having undergone greater disturbance through being closer to the Matthews Gap Fault. However, the observations of David (1907), Jones (1939) and McIntosh (1968) of a marked unconformity between the Muree Sandstone Member and Gosford Formation about 20 km to the south support the interpretation of an unconformity in this area.

Tertiary to Recent Deposits

Portions of the area are covered by unconsolidated alluvium, talus and soils. Talus fans have formed along the scarp of the Mt. View Range and are composed of angular blocks of ignimbrite derived from the cliffs of the Mt. Bright Rhyolitic Ignimbrite Member. The largest block encountered was 5 m across. The talus has been lithified in places along the foot of the Mt. View Range to form superficial deposits of talus breccia. The age of this rock is uncertain. Similar formations were thought to be Quaternary by Browne (1926, pp. 249–251), and some of the deposits do seem to be of this age, but others may date back to Tertiary times. Small areas of lateritized granodioritic soil, probably of Tertiary age, also occur.

Dykes and Plugs

Several isolated, elongated occurrences of leucocratic trachyandesite in the district are thought to be dykes related to the Flying Fox Gully Trachyandesite Member and the other leucocratic trachyandesites of the Pokolbin Hills Volcanics.

West of Jerusalem Rock there is a discordant body of basalt which is interpreted as a dyke, near Matthews Gap (273422) there is a dolerite body exposed in a road cutting which could be a volcanic plug, and south of it (274418) there is a small occurrence of basalt boulders which may indicate another dyke. These rocks are mineralogically similar to the Permian basalt, and probably represent feeders to the basalt flows.

Faulting

The area is situated on the central west portion of the Lochinvar Anticline which has a roughly meridional axis. Consequently, the dips of all the rock units are westerly or south-westerly. The Mt. Bright Inlier is part of a horst, bounded on the east by the Mt. View Faults and on the west by the Elderslie (David, 1907) or Matthews Gap (Raggatt, 1929) Fault. Both sides of the latter fault have been affected by drag along the fault plane, and dips of 65°W and 60°W were recorded near its eastern and western sides respectively. The Jerusalem Rock Fault may be a continuation or branch of the Matthews Gap Fault. Its existence was postulated by Browne and Walkom (1911) on the basis of physiographic evidence, and has been confirmed by the finding of a line of calcite boulders south of Jerusalem Rock, and a shear zone with some slickensiding. It is more likely, however, that the fault runs along the eastern side of Jerusalem Rock, as there is no evidence of it on the western side where the sequence is similar to that in other parts of the district.

If this interpretation is correct, it will require a younger fault to offset the main fault. Such a fault could also explain why the base of the basalt in the outlier to its east is topographically above the top of the basalt to its west, and this fault may continue along the outlier to join up with a fault to the north.

The position of the two Mt. View Faults has been modified from that given by Browne and Walkom (1911). The Mt. View No. 1 Fault can be seen in a cutting on the Mt. View Road (294385), and has been extended northwards on the evidence of discontinuities in formation outcrops. The Mt. View No. 2 Fault has been inferred from the displacement of basalt, but its extension northwards along the Mt. View Range is uncertain.

Browne and Walkom (1911) postulated an east-west fault along the headwater tributary of Flying Fox Gully south of the Matthews Gap Road on the grounds that a sharp boundary existed between the Flying Fox Gully Trachyandesite Member and the Vineyard Lookout Volcanic Agglomerate Member. This discontinuity has been confirmed, but no fault zone could be observed.

The Moogering Fault extends along the eastern side of the valley of Moogering Creek. The fault plane or breccia zones are exposed in cuttings at several places along the new Matthews Gap Road. At Grid Reference (275436) it dips 75° in the direction S60°E with an estimated throw of 50 m, assuming that the conglomerates on either side of the fault are the same unit. This assumption is a reasonable one, as the lithologies are the same and both are underlain by a thin ignimbrite unit, although on the eastern side the ignimbrite is very weathered and unrecognizable in hand specimen.

Near Matthews Gap two smaller faults of unknown displacements form a small graben structure.

The faulting in the district was almost certainly associated with movements which formed the Lochinvar Anticline at the end of the Permian.

Concluding Discussion

The high mica content of the Mt. View Range Granodiorite indicates that the rock is of the peraluminous type which Kleeman (1965) considered to be derived from sediments near the base of a geosyncline by partial melting. The rock fits Buddington's (1959) description of the characteristics of epizonal plutons, and a high level of crustal emplacement would explain its exposure at the surface during a period of erosion before being covered by the Pokolbin Hills Volcanics.

The volcanic sequence is a complex of intertonguing lenses and lithofacies variations diagnostic of an environment near a volcanic centre, which therefore must have been nearby. Measurement of dips in the volcanic rocks is often difficult and imprecise, and calculations of unit thicknesses based on these dips may consequently be only approximate.

The rock analyses given by Browne and Walkom (1911) show that the Pokolbin Hills Volcanics belong to a Carboniferous suite of the calc-alkaline association. Nashar (1969) has plotted the chemical analyses of Carboniferous volcanic rocks from the northern side of the Hunter Valley and from this district on the alkali–($Fe^{2+}+Fe^{3+}$)–Mg triangular diagram of

Nockolds and Allen (1953), and both groups of rocks lie within the belt of calc-alkaline variation. Wilkinson (1971) investigated selected volcanic rocks from the northern side of the Hunter Valley and concluded that the available data do not favour the derivation of the rocks from a basaltic parent magma, but suggest instead that the dacites were generated by the dry partial melting of high alumina quartz eclogite in the upper mantle, and that some of the more salic volcanics are low pressure differentiates of the dacitic melts. It is likely that the eruptives of the Pokolbin Hills Volcanics had similar origins.

After the cessation of Carboniferous volcanicity, an interval of erosion resulted in the volcanic rocks forming a hill which supplied debris for the overlying Seaham Formation. By Lower Permian times the hill appears to have formed an island or rise in a shallow sea.

The Mt. Bright Inlier is an important one in that it provides a specimen of the Carboniferous rocks underlying the Permian System in this region, and is one of the few localities in the Hunter Valley where the Permian-Carboniferous boundary is not a faulted contact or obscured by Quaternary deposits.

As a result of the re-examination of this district, the previous geological maps have been revised, and ignimbrites have been recognized in the inlier for the first time.

Acknowledgements

The writer wishes to express his thanks to the staff of the Geology Department of The University of Newcastle for their assistance and encouraging interest throughout the duration of the work. In particular he is indebted to Dr. J. H. Rattigan, a former member of staff, for his assistance in the field, and to Professor B. Nashar and Mr. B. A. Engel, for their encouragenent and constructive criticism of the manuscript. Helpful discussions were also had during the preparation of this paper with Dr. B. Runnegar of the University of New England, concerning the southern portion of the district. Finally, the writer gratefully acknowledges the co-operation of the local residents.

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(Received 9 February 1973)

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Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 71–76, 1972

Potassium-Argon Dating and Occurrence of Tertiary and Mesozoic Basalts in the Binnaway District

J. A. Dulhunty

Abstract—Two Miocene and three Mesozoic K-Ar dates are recorded for basalts occurring in the Castlereagh River Valley. Miocene flows co-extensive with Warrumbungle Mountain basalt flows, indicate a pre-Warrumbungle Castlereagh Valley, similar to, but deeper than, the present valley. Mesozoic Garrawilla lavas, inter-bedded between Purlawaugh and Napperby sediments extend 16 km south of Binnaway to the southern margin of their area of extrusion, beyond which the Garrawilla horizon has been followed into southern areas where no lavas occur. A tuffaceous mudstone bed associated with late Garrawilla volcanism is described partly as an inter-flow sediment and partly as an open-topped deposit, disconformably overlain by Purlawaugh sediments.

Introduction

The purpose of this paper is to record results of K-Ar dating of Tertiary and Mesozoic basalt flows in the Castlereagh River Valley between Ulamambri, Binnaway and Neilrex (see Fig. 1), and to consider results in relation to Tertiary geomorphology and Mesozoic stratigraphy.

Field studies were carried out in the Binnaway district with the object of obtaining data bearing on the correlation of Mesozoic stratigraphy in the Coonabarabran-Gunnedah-Narrabri region in northern New South Wales, with that of the Dubbo-Dunnedoo-Wollar region in the central west of the State. The Binnaway district was selected for this purpose as it provides an area of more or less continuous outcrop, along the Castlereagh Valley, linking the two regions.

Inter-bedded Mesozoic olivine basalts, well known as the Garrawilla lavas (Kenny, 1963, Dulhunty and McDougall, 1966, Dulhunty, 1967) occur extensively in the Coonabarabran-Gunnedah district north-east of the Binnaway area, but are unknown in the central-western region to the south. The probable extension of Garrawilla lavas south from Ulamambri into the Binnaway district was originally suggested by Kenny (1963), and certain areas of basalt were mapped as Garrawilla lavas occurring in association with Tertiary basalts, by Offenberg (1968). In the present investigation it was necessary to distinguish reliably between Tertiary and Mesozoic basalts in the Binnaway district, and to establish with certainty the occurrence of Garrawilla lavas south of Binnaway, and so confirm the southern limits of occurrence whence their horizon could be followed into the Mesozoic sequence of the central west. Potassium-Argon dating was used for this purpose, as the two basalts frequently occur together, with Tertiary basalt at times lying on eroded surfaces of Mesozoic lava. The two are so similar in constitution that they cannot be separated with certainty by petrography, and field studies are not reliable owing to poor outcrops and difficulties in distinguishing between inter-bedded Mesozoic flows and Tertiary basalts lying in valleys eroded into outcrops of Mesozoic sediments.

The general sequence of Mesozoic sediments in the Binnaway district is similar to that of the Coonabarabran-Gunnedah district (Kenny, 1963). Large areas of upper Jurassic, yellow-red, coarse quartz sandstone, generally referred to as Pilliga sandstone, overlie shales, lithic sandstones, coal seams and ferruginous mudstones with "red bed" outcrops, generally known as the Purlawaugh beds, almost certainly of mid or lower Jurassic age. Beneath the Purlawaugh beds there occur light grey, sandy, micaceous shales, fine white flaggy sandstone and massive, light grey quartz sandstone, probably of Triassic age and referred to by Kenny (1968) as the Napperby beds. In the Coonabarabran-Gunnedah district the Garrawilla lavas occur between the Purlawaugh and Napperby beds.

The foregoing stratigraphical terms have been used, more or less informally, by Kenny (1963), Offenberg (1968) and Dulhunty (1967) in the Coonabarabran-Gunnedah district and northern parts of the Binnaway district. They are names by which the main subdivisions of the Mesozoic are well known in the areas concerned. It is intended to use such names, informally, for the purpose of the present paper, and to postpone proposals for formal nomenclature until relations of units in different regions are better understood, and they can be properly defined.

For the general pattern of outcrop geology of the Binnaway district, reference should be made to the Gilgandra 1 : 250,000 geological sheet by Offenberg (1968), although some amendments to this map will be necessary in the light of results recorded here and as an outcome of field studies at present in progress.

Selection of Basalts for K-Ar Dating

The Mesozoic sediments of the Binnaway district outcrop along the broad valley of the Castlereagh River which runs generally from north to south, from Ulamambri to Neilrex. Near Ulamambri the valley has dissected the Piliga sandstone, exposed the full thickness of Purlawaugh beds and revealed underlying Garrawilla lavas. Some 5 km downstream the top of the Napperby beds outcrops on the floor of the valley. Dissection becomes progressively deeper as the valley runs south, and at Neilrex the full section is exposed from Piliga sandstone down through Purlawaugh and Napperby beds to Palaeozoic basement. Residuals of basalt flows occur on erosion surfaces on Piliga sandstone, on the low plateau either side of the Castlereagh Valley, and on the sides and floor of the valley where Purlawaugh and Napperby beds outcrop. The flows on Piliga sandstone are undoubtedly of Tertiary age, but those within the valley are of both Tertiary and Mesozoic age. At Ulamambri Kenny (1963) mapped Tertiary basalt lying on eroded surfaces of Garrawilla lava, and at Binnaway Offenberg (1968) mapped the two in close proximity. East of Neilrex, however, along the valley of Butheroo Creek there occur good exposures of full sections of Purlawaugh and Napperby beds, but no Garrawilla lavas are present.

The present investigation required accurate distinction between Tertiary and Mesozoic basalts at places along the Castlereagh Valley where stratigraphical relations of Garrawilla lavas could be studied in the Mesozoic sequence, and their southern limits of extrusion determined. With this purpose in view, basalts suitable for K-Ar dating were selected from five critical points along the valley, where results would be of greatest significance (Fig. 1). Potassium-Argon age investigations were carried out at Tohoku University, Japan. Specimen numbers (Syd. Uni. K-Ar dated specimens), localities as shown in Figs. 1 and 2, and results are as follows : (see also Appendix).

Specimen K23. Ulamambri. Age 171·5 m.y.

Collected from an outcrop on a low rise at a point 185 m south from the Coonabarabran-Ulamambri road, and 370 m west from the bridge where this road crosses the Castlereagh River at 12 km by road from Coonabarabran Post Office.

Specimen K5. Ulinda Creek. Age 197 m.y.

Collected from an outcrop on a steep slope 110 m west from Ulinda Creek, at a point 300 m upstream from the Binnaway-Coolah road bridge at 4·9 km by road from Binnaway Post Office.

Specimen K22. Dandaloo. Age 201·5 m.y.

Collected from an outcrop on a steep slope 100 m west from the Binnaway-Ringwood road at 5·8 km from Binnaway Post Office, on the western side of the Castlereagh River.

Specimen K7. Piambra. Age 14·5 m.y.

Collected from a roadside cutting on the eastern side of the Binnaway-Neilrex road at 1·3 km north from Piambra Rail Siding, and 104 m from the eastern bank of the Castlereagh River.

Specimen K6. Toogalan. Age 17 m.y.

Collected from the steep western bank of the Castlereagh River, 1·25 km upstream from Toogalan Homestead and 2·1 km by road from Neilrex Post Office.

The Ulamambri flow (K23) was selected for dating, to confirm Kenny's original mapping of Tertiary basalts lying on Mesozoic lavas, and to determine the age and relations of ferruginous sediments associated with upper Garrawilla lavas, (Sect. A–B, Fig. 2). The Ulinda flow (K5) was dated, to confirm the occurrence of Garrawilla lavas in the vicinity of Binnaway as mapped in part by Offenberg, and to assist in detail studies of relations between Purlawaugh beds and ferruginous sediments occurring in association with the flow, (Sect. C–D–E–F, Fig. 2). The Dandaloo, Piambra and Toogalan flows (K22, K7 and K6 respectively) were dated, to distinguish between Tertiary and Mesozoic basalts occurring on the floor of the Castlereagh Valley beneath the present river bed, and to determine the southern limits of extrusion of Garrawilla lavas in the Binnaway district.

The five specimens were all alkali olivine basalts very similar petrographically, consisting essentially of olivine, plagioclase clinopyroxene and iron oxide. They were virtually free from atmospheric weathering and very low in intersertal poorly-crystallized felsic material. Specimens K6 and K7 showed very little dueteric alteration, whilst K5, K22 and K23 were somewhat more altered but within acceptable limits.

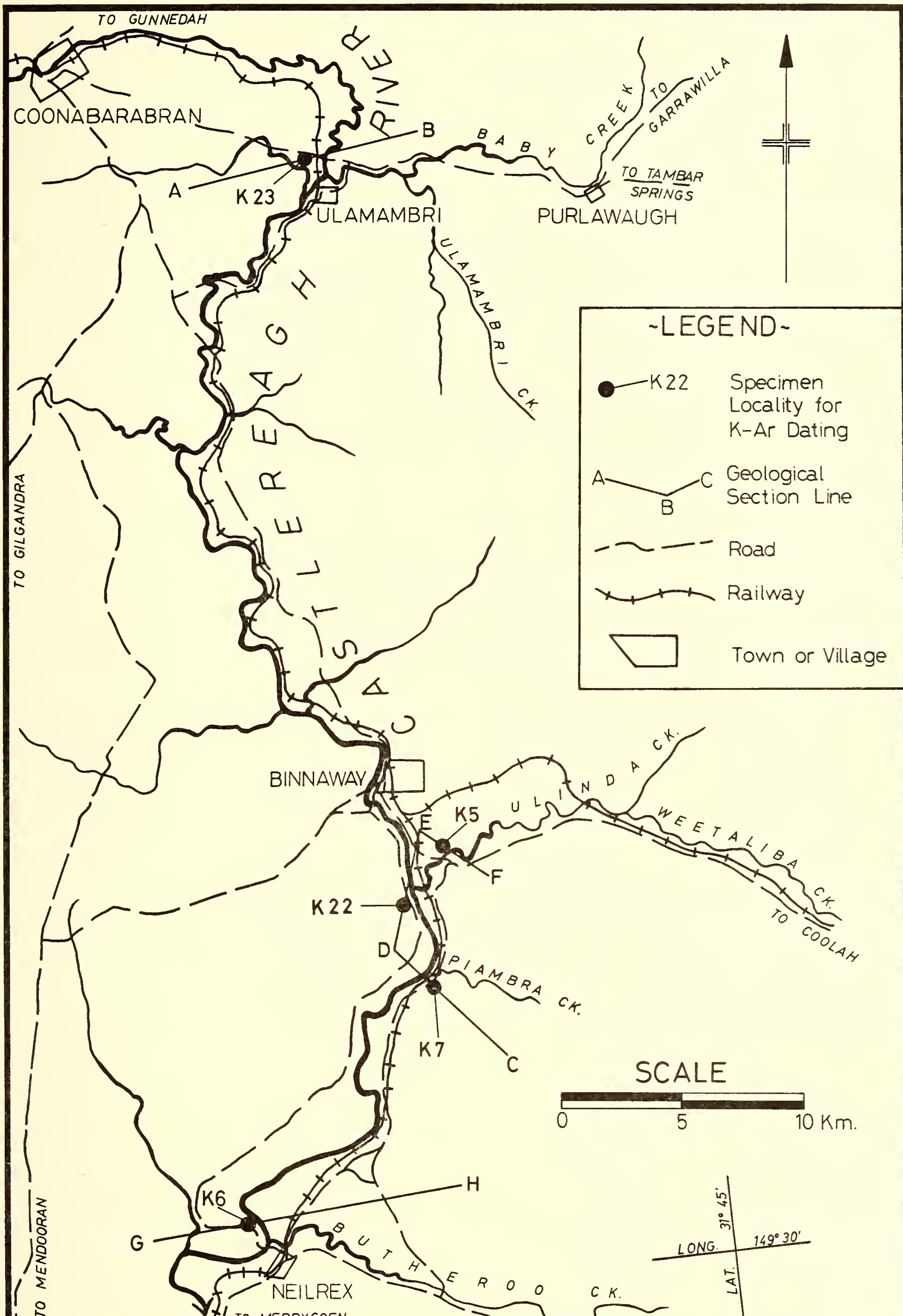

FIGURE 1.—Locality map of the Binnaway district.

Significance of Results

From the foregoing results it is evident that the Piambra and Toogalan flows (K7 and K6 respectively) are of Tertiary age, and that the Ulamambri, Ulinda and Dandaloo flows (K23, K5 and K22 respectively) are of Mesozoic age and belong to the Garrawilla Lavas.

Tertiary Geomorphology

The Tertiary flows occurring in the Castlereagh Valley, dated at 14·5 m.y. and 17 m.y. in this investigation, belong in general to a group of Miocene basalts extruded at many places over a wide area of central-western and eastern New South Wales. Their erosional residuals occur mainly in the lower areas of the eastern Highlands, and in old pre-basalt valleys now undergoing re-excavation as in the Cudgegong Valley near Gulgong (Dulhunty, 1971). The Miocene basalts of the Binnaway district, occur at all levels in the Castlereagh Valley from beneath the present river bed, up over the valley sides to positions on the low plateau surfaces on either side, as illustrated in the section of Fig. 2. West of the valley, between Ulamambri and Coonabarabran (Sect. A–B, Fig. 2) the Miocene basalt flows increase in thickness and become more continuous as they

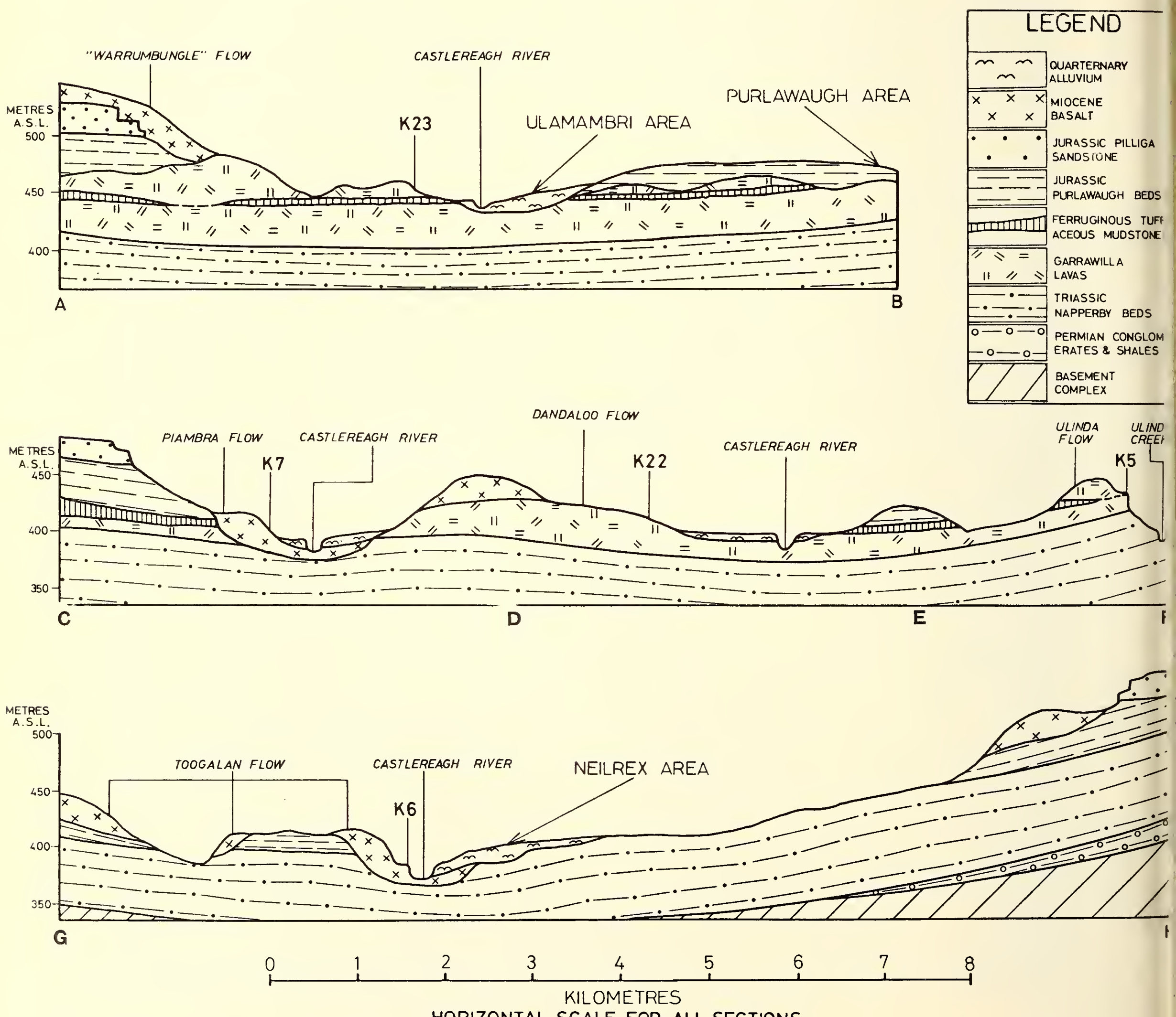

FIGURE 2.—Geological sections illustrating the occurrence of basalt flows in the Binnaway district.

pass towards the Warrumbungle Mountains, where they are associated with trachyte lavas, forming part of the Warrumbungle volcanics. At two localities along the Coonabarabran-Gilgandra road, similar Miocene basalt flows on the southern slopes of the mountains, were previously dated at 13·5 m.y. and 13·8 m.y. (Dulhunty and McDougall, 1966). The similarity in K-Ar ages of the Warrumbungle Mountain Miocene basalts and those of the Castlereagh Valley, and their close field relations, is sufficient to correlate the two as co-extrusive. This suggests a pre-Miocene basalt, and pre-Warrumbungle Mountain, drainage pattern in the Binnaway district similar to the present upper Castlereagh system, with a valley of similar profile and even a little deeper than the present river valley. All east-west sections across the valley, including those illustrated in Fig. 2, show broad synclinal warping with the river situated approximately in the centre of the structure. This suggests that the north-south trend of the Castlereagh River, from Coonabarabran to Mendoran was originally determined by pre-Miocene basalt warping which confined the Miocene ancestor of the present Castlereagh River to the syncline.

Mesozoic Stratigraphy

The results obtained for the Ulamambri, Ulinda and Dandaloo flows, 171 m.y., 197 m.y., and 201 m.y. respectively, confirm that they belong to the Garrawilla lavas. The dates agree very well with results of 181 m.y. and 193 m.y., previously obtained for Garrawilla lavas between Coonabarabran and Gunnedah (Dulhunty and McDougall 1966) the averages being 187 m.y. for the previous results and 190 for the present dates.

The result obtained from the Ulamambri flow confirms Kenny's mapping of Miocene basalt on Garrawilla lava between Coonabarabran and Ulamambri, as illustrated in Sec. A–B, Fig. 1. It also suggests that the highly ferruginous, and probably tuffaceous mudstone between the Ulamambri flow and the lower Garrawilla lavas is a contemporary inter-flow deposit. It occurs near the top of the Garrawilla lavas, and is distinct from the overlying Purlawaugh beds, which normally exhibit a disconformable relation to the lavas, onlapping eroded flanks of lava piles and flows.

The Mesozoic age obtained for the Ulinda flow confirms Offenberg's mapping of the basalt as a Garrawilla Lava, but a similar result for the Dandaloo flow, which he had mapped as Tertiary, means that the Ulinda flow dips west, passes beneath the Castlereagh River and outcrops low on the western side of the valley. Higher on the valley side the Garrawilla lava is concealed beneath Miocene basalt (Sec. C–D–E–F, Fig. 2) which passes up over outcrops of Pilliga sandstone to the west.

In the vicinity of Binnaway there is evidence of a very ferruginous, basic tuffaceous mudstone occurring in association with the top of the Garrawilla lavas and beneath the Purlawaugh beds. It is similar to the Ulamambri occurrence but more strongly developed. Outcrops occur along the northern side of Gamble Creek, between 1 and 3 km above its junction with the Castlereagh River. It also outcrops close to the northern side of the Binnaway-Coolah road, about half-way between Ulinda Creek bridge and Binnaway, where it reaches some 9·3 m in thickness, and lies between the Purlawaugh beds and the top of the Garrawilla lavas. From this point it passes west towards the main outcrop of the Ulinda flow on the western side of Ulinda Creek, but is largely obscured by alluvium, and then it appears to wedge out into the Ulinda flow, as illustrated in Sect. C–D–E–F, Fig. 2. It may be concluded that the basic tuffaceous mudstone was deposited contemporaneously with the closing stages of extrusion of the Garrawilla lavas, occurring partly as an inter-flow bed and partly as an open deposit, prior to disconformable deposition of the Purlawaugh beds. Whilst this bed is believed to be more closely related in time to Garrawilla lavas than Purlawaugh sediments, it is not intended to propose a formal name until more is known of its relations and extent.

The abundance of Garrawilla lavas immediately south of Binnaway, and their complete absence from sections exposed along Butheroo Creek, east of Neilrex on the southern side of the district, confirms Offenberg's mapping (1968) which places the southern margin of Garrawilla lavas between Piambra and Neilrex, some 15 km south of Binnaway.

Acknowledgements

In conclusion it is wished to acknowledge research facilities of the Department of Geology and Geophysics, University of Sydney, and the helpful co-operation of landholders in the Binnaway district, over whose properties the investigations were carried out, in particular Messrs. Jones and Watson of Hawthorne Station.

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(Received 1 December 1972)

Appendix

Syd. Uni. K-Ar Dated Specimen No.	Potassium Analysis K%	Ar^{40}/K^{40}	Atmos. Argon. Contam. %	Age m.y.
K7	1·67	0·000846	57·01	14
	1·67	0·000920	58·18	15
K6	1·48	0·001013	68·81	17
	1·48	0·001002	78·21	17
K23	0·92	0·010494	25·01	172
	0·92	0·010427	15·29	171
K22	1·47	0·012413	10·18	201
	1·47	0·012439	3·32	202
K5	1·09	0·012073	5·21	197

Constants used :

$\lambda_e = 0 \cdot 584 \times 10^{-10}\ yr^{-1}$

$\lambda_\beta = 4 \cdot 72 \times 10^{-10}\ yr^{-1}$

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 77–85, 1972

The Stratigraphy of the Bowan Park Group, New South Wales

V. Semeniuk

Communicated by Dr. B. D. Webby

Abstract—The Ordovician Bowan Park Group, 560 m. thick, disconformably overlies Cargo Andesite and contains three limestone formations. The lower unit, Daylesford Limestone, contains six members at its type section ; in ascending order, these are : Ranch Member, Bourimbla Limestone Member, Manooka Limestone Member, Gerybong Limestone Member, Glenrae Limestone Member and Davys Plains Limestone Member. In eastern parts of the Bowan Park area the Oakley Limestone Member is equivalent to Manooka and Gerybong Limestone Members. The Quondong Limestone, the most fossiliferous formation in the sequence, disconformably overlies the Daylesford Limestone. The Ballingoole Limestone, which conformably overlies Quondong Limestone, contains three members ; in ascending order, these are : Corner Limestone Member, Clearview Limestone Member and Downderry Limestone Member. The contact of Bowan Park Group with the overlying Malachi's Hill Beds is redefined and placed at a disconformity.

Introduction

This paper describes the stratigraphy of Ordovician limestones throughout the area of outcrop of the Bowan Park Group and formally names the member subdivisions in the group. It also redefines the contact between Bowan Park Group and overlying Malachi's Hill Beds. Preliminary work on limestones of the Bowan Park Group, and general stratigraphy of the Bowan Park area have been published by Semeniuk (1970). The present work is based on a study of 820 samples collected from the Bowan Park Group at 10 localities (Appendix I). Classification of Dunham (1962) is used for nomenclature of the limestones.

General Geology

The Bowan Park area, located in the Central Fold Belt (Packham, 1969) of New South Wales, contains Ordovician rocks (Cargo Andesite, Bowan Park Group, Malachi's Hill Beds), which are separated from Silurian rocks by a major strike fault (Figure 1). On the western margin of the area, a large north-trending thrust fault that is probably the northern extension of the Canangle Thrust south of Cargo (Ryall, 1965), separates Silurian sediments from Ordovician limestones of the Bowan Park Group (Semeniuk, 1970). In the vicinity of the " Marylebone " homestead (Figure 1), this thrust fault curves and splits into a complex of east-west trending strike faults (possibly wrench faults). The strike faults join a major north-trending fault system in the east portion of the area (Figure 1). These strike faults cause east-west wedging-out of some rock units. Faulting also may have flexed the Palaeozoic rocks from the regional north-south strike into an east-west strike position.

The Bowan Park Group disconformably overlies the Cargo Andesite and is disconformably overlain by the Malachi's Hill Beds. The Cargo Andesite (Stevens, 1950, 1956), the oldest formation in the Bowan Park area, is composed of andesites, basalts and volcanic breccias. The Malachi's Hill Beds (Stevens, 1956 ; Semeniuk, 1970) are composed mainly of laminated siliceous siltstones, volcanic and lithic sandstones, volcanic breccias and lavas ; volcanic rocks and breccias are most abundant in the upper half of the unit (Figure 1).

The contact between Bowan Park Group and Malachi's Hill Beds previously was considered to be gradational (Stevens, 1956, p. 47 ; Semeniuk, 1970, pp. 21–22) with the top of the Bowan Park Group defined by the uppermost carbonate horizons. However, a disconformity separates thinly-bedded skeletal grainstones (Bowan Park Group) from laminated lithic calcilutites and minor limestone breccia. The contact between Malachi's Hill Beds and Bowan Park Group is redefined and placed at this disconformity (Figure 2) as the laminated calcilutites grade vertically into siliceous siltstones of the Malachi's Hill Beds, and contain graptolites and sedimentary structures similar to those of the Malachi's Hill Beds.

Bowan Park Group

The Bowan Park Group (Semeniuk, 1970 ; redefined here) disconformably overlies the Cargo Andesite and is disconformably overlain by the Malachi's Hill Beds. The group consists

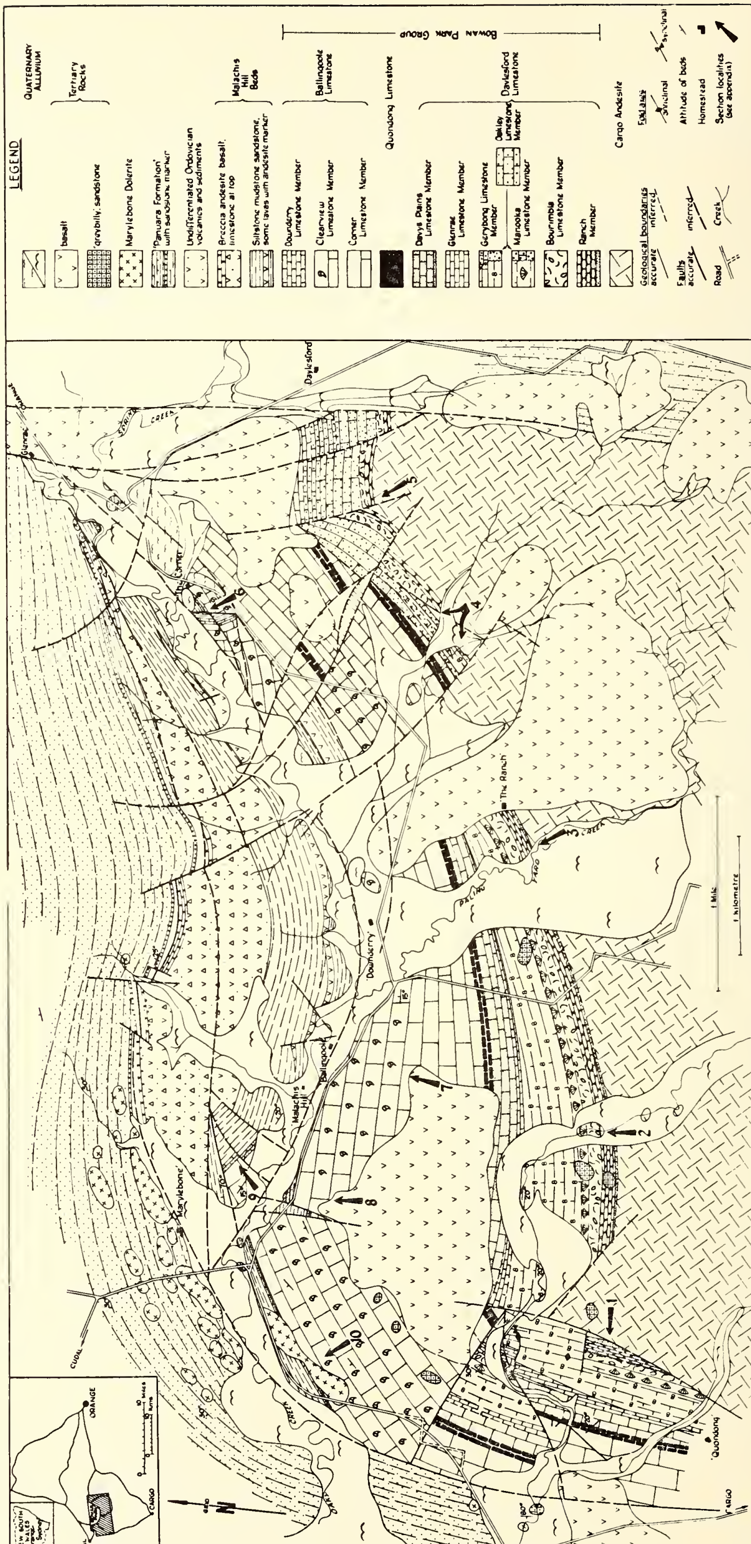

FIG. 1.—Geological map of the Bowan Park area.

predominantly of limestone and contains in descending order—

(3) Ballingoole Limestone, 280 m. thick; mainly massive, generally unfossiliferous limestone; disconformably overlain by Malachi's Hill Beds; conformably overlies

(2) Quondong Limestone, 34 m. thick; fossiliferous, thinly to thickly bedded limestone and marl; disconformably overlies

(1) Daylesford Limestone, 250 m. thick; terrigenous sediment and marl in basal part, thinly bedded to massive limestone in middle part, and mainly massive limestone in upper part; disconformably overlies Cargo Andesite.

The names Daylesford Limestone, Quondong Limestone and Ballingoole Limestone are proposed for the Daylesford Formation, Quondong Formation and Ballingoole Formation of Semeniuk (1970), as the formations are mainly limestones with minor terrigenous sediments. Informal subdivisions of these formations (Semeniuk, 1970) are formally named in this paper (Table 1).

TABLE 1
Stratigraphic Units, Bowan Park Group

Formation	Units of Semeniuk, 1970	This Paper
Ballingoole Limestone	" calcarenite unit " " *Streptelasma* unit " " massive unit "	Downderry Limestone Member Clearview Limestone Member Corner Limestone Member
Quondong Limestone	No formal subdivision	
Daylesford Limestone	" pisolite unit " " light grey unit " not in area " gastropod unit " " *Ischadites* unit " " brachiopod unit " " lithic unit "	Davys Plains Limestone Member Glenrae Limestone Member Oakley Limestone Member Gerybong Limestone Member Manooka Limestone Member Bourimbla Limestone Member Ranch Member

Erosional disconformities

Erosional disconformities are common in the Bowan Park Group. Major erosional breaks separate many of the limestone units, and numerous minor breaks occur within most members. The following criteria were used to recognize breaks—

(1) Irregular karst surfaces, characterized by depressions and cracks with relief in the order of a few centimetres to several metres and filled by soil or marine sediment.

(2) Pinching-out of units.

(3) Horizons of gravel- and sand-sized lithoclasts and reworked fossils above erosional surfaces.

(4) Solution cavities with or without fill of diagenetic sediment (mainly " crystal silt ") below the erosional surface.

(5) *In situ* soils, composed mainly of lithoclasts with limonite-stained cryptocrystalline calcite rinds, and calcrete-ooids (Read, 1971).

Daylesford Limestone

The Daylesford Limestone disconformably overlies Cargo Andesite and is disconformably overlain by the Quondong Limestone. At the type section the unit is 250 m. thick and contains six members; these are in descending order—

(6) *Davys Plains Limestone Member* (95 m. thick), composed mainly of massive skeletal lithoclast grainstone, skeletal packstone and wackestone and pellet packstone; disconformably overlain by Quondong Limestone and disconformably overlies

(5) *Glenrae Limestone Member* (25 m. thick), composed of intercalated grainstone, light grey skeletal wackestone and lime mudstone in the lower part and massive light grey, mottled limestone in the upper part; conformably overlies and grades into

(4) *Gerybong Limestone Member* (64 m. thick), composed of thinly bedded, dark grey lime mudstone and skeletal wackestone; equivalent in the east to upper part of Oakley Limestone Member; at type section conformably overlies

(3) *Manooka Limestone Member* (16 m. thick), composed of skeletal grainstone, skeletal lithoclast grainstone, skeletal packstone and wackestone, lime mudstone ; equivalent to lower part of Oakley Limestone Member in the east ; at type section disconformably overlies

(2) *Bourimbla Limestone Member* (16 m. thick), composed of thinly bedded to massive skeletal wackestone and packstone, and lime mudstone ; *faulted contact with

(1) *Ranch Member* (34 m. thick), composed of thinly bedded marl, terrigenous mudstone, and towards the base, lithic sandstone and mudstone ; disconformably overlies Cargo Andesite.

A unit of massive skeletal grainstone and skeletal lithoclast grainstone, totalling 90 m., is recognized in the eastern part of the area and is termed Oakley Limestone Member. This unit is facies equivalent to the Gerybong and Manooka Limestone Members.

Erosional disconformities are common in the Daylesford Limestone, separating some members and occurring within units.

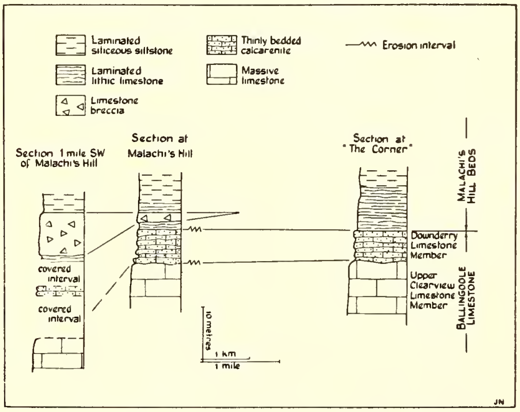

Fig. 2.—Detail of contact between Ballingoole Limestone and Malachi's Hill Beds. Covered interval immediately below breccia at section S.W. of Malachi's Hill is weathered Marylebone Dolerite.

Ranch Member

The unit consists of strongly outcropping, thickly bedded, lithic sandstone (3·6 m. thick) overlain by 7–8 m. of thinly bedded green and red mudstones, passing up into thinly bedded limestones, marls and some terrigenous mudstones. Carbonate lithologies include skeletal grainstone, skeletal pellet grainstone, marly skeletal packstone and wackestone and lime mudstone. Thin beds of lithoclastic grainstone also occur in some horizons, especially in localities to the west. The Ranch Member apparently thins from west to east.

Bourimbla Limestone Member

This unit consists of thinly bedded to massive, brown to grey skeletal wackestones, packstones and lime mudstones, and a horizon of marly limestone in the middle of the member. Skeletal limestones characteristically contain the brachiopod *Eodinobolus*, cylindrical stromatoporoid *Alleynodictyon* and coral *Tetradium*. The member attains a maximum thickness of 24 m. at Paling Yard Creek ; the type section is strike faulted at the base and is only 16 m. thick.

Manooka Limestone Member

The Manooka Limestone Member consists of intercalated, thick bedded to massive, light grey to brown grainstones and thinly to thickly bedded dark grey packstones, skeletal wackestones, and burrowed lime mudstones. Grainstones in the unit contain algal, echinoderm and molluscan fossils, whereas skeletal wackestones and packstones mainly contain algal debris. The large dasycladacean alga *Ischadites* is characteristic of skeletal wackestones in the unit. East of the type section, the member interfingers with massive grainstones of the Oakley Limestone Member.

Gerybong Limestone Member

The unit consists of thinly to thickly bedded, dark grey limestones, mainly burrowed lime mudstones and skeletal wackestones. Lime mudstones are dominant in lower sections, and skeletal wackestones are more common in the upper parts. Skeletal wackestones contain *Tetradium tenue*, *?Tetradium* (large species), and a variety of gastropods including *Lophospira*, *Maclurites*, *Ectomaria*, *Hormotoma* and others. The Gerybong Limestone Member interfingers with grainstones of the Oakley Limestone Member at " The Ranch " homestead and further east.

Oakley Limestone Member

This unit is composed dominantly of massive grainstones and is laterally equivalent to the Manooka and Gerybong Limestone Members. Lithologies include skeletal grainstones and skeletal lithoclast grainstones.

* At Paling Yard Creek, Bourimbla Limestone Member (24 m. thick) disconformably overlies Ranch Member.

A creek section illustrating facies relationship between muddy limestones (of western localities) and grainstones of this unit occurs 1 km. east of " The Ranch " homestead. The transitional sequence consists of rapidly alternating thickly bedded to massive, skeletal grainstone, wackestone and packstone, pellet packstone and lime mudstone. Contacts between different sediment types are commonly burrowed.

Glenrae Limestone Member

The Glenrae Limestone Member is massive light grey limestone that is best developed on the " Quondong " property where it varies in thickness from 25 m. (at the type section of the Daylesford Limestone) to 21 m. and 30 m. along strike from the type section. The lower part of the unit grades into underlying Gerybong Limestone Member and consists of light grey burrow-mottled skeletal grainstone, skeletal wackestone and lime mudstone. The upper part of the unit is altered (in patches) to microcrystalline and cryptocrystalline calcite, and contains abundant solution cavities and cracks filled with internal sediment ; the original lithology of the upper Glenrae Limestone Member appears to have been predominantly grainstone. In eastern localities the Glenrae Limestone Member overlies Oakley Limestone Member, but the alteration of the unit is not as well developed.

Davys Plains Limestone Member

The Davys Plains Limestone Member mainly contains massive pisolitic skeletal lithoclast grainstones, skeletal wackestones and packstones, and pellet packstones ; a 3 m. thick horizon of thinly bedded fossiliferous marl occurs in the middle of the unit. Erosional disconformities are common in the member. Between disconformities the following sediment associations occur—

(1) pisolitic lithoclast* grainstone and skeletal lithoclast* grainstone that grade vertically into and are interbedded with burrowed pellet packstone (or skeletal wackestone/packstone), and some lime mudstone,

(2) skeletal wackestone/packstone interbedded with lime mudstone,

(3) homogenous sections of burrow-mottled packstone and wackestone that grade down into partly burrowed sections of sediment associations 1 and 2.

* Lithoclasts in these sediments were misidentified as intraclasts in Semeniuk (1970).

The Davys Plains Limestone Member is important because it contains first appearances in the sequence of corals and stromatoporoids belonging to Fauna II of Webby (1969).

Palaeontology

Fossils of the Daylesford Limestone have been listed by Semeniuk (1970). More detailed studies of fauna and flora have been carried out by Webby (1969, 1971*a*, 1971*b*), Webby and Semeniuk (1971), and Semeniuk and Byrnes (1971). A more complete list of fossils is given in Table 2.

The coral-stromatoporoid fauna in the Ranch, Bourimbla, Manooka and Gerybong Limestone Members belongs to Fauna I of Webby (1969), and includes *Stratodictyon ozakii*, *S. columnare*, *Alleynodictyon nicholsoni*, *Tetradium compactum*, *T. apertum*, *T. bowanense*, *T. tenue* and *Labechia regularis*. Fauna II commences in the Davys Plains Limestone Member and continues into the overlying Quondong Limestone : Fauna II in the Davys Plains Limestone Member is characterized by *Ecclimadictyon nestori*, *E. amzassensis*, *Clathrodictyon*, *Labechia variablis* and *Tetradium cribriforme*.

Quondong Limestone

The Quondong Limestone (34 m. thick at the type section) disconformably overlies Daylesford Limestone with a pebbly lithoclast skeletal grainstone veneering the disconformity surface. The formation is conformably overlain by Ballingoole Limestone with a gradational contact : thinly bedded marly lime mudstones grade vertically within 2 m. into massive grainstone and packstone.

The Quondong Limestone consists of limestone, marl and minor terrigenous mudstone ; lithologies alternate rapidly and sediments occur in thin units. Numerous erosional breaks occur and cause pinch-out of beds towards the east.

The formation may be subdivided into a lower and upper unit. The lower 20 m. is composed dominantly of thinly bedded skeletal grainstone and lithoclast skeletal grainstone ; other lithologies include pellet packstone, skeletal wackestone and packstone, burrowed lime mudstone and intraclast grainstone. Sediments rapidly alternate and numerous breaks occur. The upper 10 m. of the Quondong Limestone is composed mainly of thinly bedded, marly lime mudstone and pellet packstone ; other lithologies include skeletal wackestone and packstone and thin terrigenous mudstone. Sediments are more uniform in the upper unit and do not alternate

Table 2
Fossil List, Daylesford Limestone

	Ranch	Bourimbla	Manooka	Gerybong	Oakley	Glenrae	Davys Plains
ALGAE							
Girvanella	×	×	×	×	×		×
Solenopora	×	×	×	×	×		×
Parachaetetes	×						
Dasyporella							×
Vermiporella	×	×	×	×	×		×
Ischadites			×				
indet. codiacean	×						
CORALS							
Tetradium apertum	×	×					
T. tenue			×	×			
T. bowanense		×					
T. compactum		×					
T. cribriforme							×
T. sp.						×	
Lichenaria	×						
Heliolites	×	×		×			×
Propora	×	×			×		×
Coccoseris	×	×	×		×		×
Plasmoporella					×	×	×
Nyctopora		×	×				
Eofletcheria							×
STROMATOPOROIDS							
Stratodictyon ozakii	×						
S. columnare	×						
Labechia regularis		×					
L. variablis							×
Alleynodictyon nicholsoni	×	×					
Cystostroma cliefdenense				×			
Clathrodictyon							×
Ecclimadictyon nestori							×
E. amzassensis							×
BRYOZOANS							
Prasopora	×	×					
Strictopora		×					
indet. bryozoans			×		×		×
BRACHIOPODS							
Eodinobolus		×					
Protozyga	×	×	×	×			×
Catazyga	×	×	×	×	×		
Leptellina			×		×		×
MOLLUSCS							
Lophospira	×	×	×	×			×
Ectomaria				×			
Hormotoma				×			
Maclurites		×		×			
indet. gastropods	×	×	×	×	×	×	×
Hardmanoceras				×			
indet. pelecypods	×	×					×
?*Ctenodonta*		×					
orthoconic nautiloids	×	×		×	×	×	×
ARTHROPODS							
cf. *Kloedinia*		×	×	×			
Pliomerina		×	×	×			
indet. trilobites	×	×	×	×	×	×	×

as rapidly as in lower sections of the formation. The formation thins to the east where lower and upper subdivisions are still recognized.

Palaeontology

The Quondong Limestone contains the most abundant and diverse fauna and flora of rocks in the area (Semeniuk, 1970). Fossils occur in the grainstones, skeletal packstones and wackestones. Skeletons composing the grainstones are mainly an algal-echinoderm-mollusc assemblage, but other skeletons are locally abundant in horizons and produce distinctive gravel layers ; e.g. *Girvanella* pisolites, strophomenid brachiopod gravel, heliolitid coral and stromatoporoid gravel, bryozoan and brachiopod gravel. Fossils in skeletal wackestones and packstones are mostly gravel-sized and whole and consist of one of the following assemblages : (1) gastropod-coral (*Lophospira*, *Maclurites*, and corals *Heliolites*, *Propora*, *Hillophyllum*), (2) brachiopod-gastropod (brachiopods *Leptellina*, *Strophomena* and other strophomenids, *Catazyga*), (3) bryozoan-brachiopod (*Strictopora* and *Catazyga*), and (4) coral-stromatoporoid-algal (with *Tetradium cribriforme*, heliolitids and clathrodictiids).

The coral-stromatoporoid assemblage in the formation belongs to Fauna II (Webby, 1969). Elements of Fauna II that are restricted to the Quondong Limestone (in this area) include *Hillophyllum* and *Palaeophyllum*.

Ballingoole Limestone

The Ballingoole Limestone, 280 m. thick, conformably overlies the Quondong Limestone, and is disconformably overlain by the Malachi's Hill Beds. The formation consists mainly of massive limestone with thinly bedded limestone at the top. Three members occur in the Ballingoole Limestone ; these are in descending order—

(3) *Downderry Limestone Member* (7·5 m. thick), composed of thinly bedded skeletal grainstone ; disconformably overlain by Malachi's Hill Beds, disconformably overlies

(2) *Clearview Limestone Member* (152 m. thick), composed of massive skeletal grainstone, skeletal wackestone, lime mudstone ; disconformably overlain by Downderry Limestone Member, disconformably overlies

(1) *Corner Limestone Member* (120 m. thick), composed of massive skeletal grainstone with minor skeletal and pellet packstone ; disconformably overlain by Clearview Limestone Member, conformably overlies Quondong Limestone.

Corner Limestone Member

The Corner Limestone Member is well developed at " Quondong " and Paling Yard Creek. Limestones are typically massive, and four sediment types occur in the unit. Well sorted grainstones are dominant ; they are skeletal or lithoclast skeletal grainstones, bedded in units up to 2 m. thick. Overlying and interbedded with grainstones are either algal (*Vermiporella*) wackestones or pellet packstones ; contacts between packstones/wackestones and grainstones are commonly burrowed. Lime mudstone forms a minor part of the unit. Erosional breaks are common and spaced (on average) every 10–15 m.

Clearview Limestone Member

The Clearview Limestone Member is well exposed along the road near the " Ballingoole " homestead (Figure 1), and in the eastern part of the area. The unit is composed mainly of skeletal grainstone, pellet packstone, skeletal wackestone, lime mudstone and minor skeletal pellet grainstone and intraclast grainstone. Two sediment associations occur in the member—

(1) skeletal grainstone/pellet packstone (or algal wackestone)

(2) skeletal wackestone/lime mudstone.

Skeletal grainstone and minor skeletal lithoclast grainstone grade into and alternate with pellet packstone or algal (*Vermiporella*) wackestone ; this is a similar succession of rock types to the Corner Limestone Member. Laminated skeletal pellet grainstone and intraclast grainstone are interbedded with skeletal grainstone in some horizons of this member. The skeletal pellet grainstones contain birdseyes or " laminoid fenestral fabrics " (Tebbutt, *et al.*, 1965) and flat intraclast pebbles. Skeletal pellet grainstone horizons are generally only thin, but a 1·5 m. thick section occurs near the top of the member near " The Corner " homestead.

The second sediment association consists of *Tetradium* wackestone intercalated with coral-stromatoporoid wackestone and light grey lime mudstone ; these occur at several levels in the unit ; some light grey lime mudstones exhibit desiccation features. Skeletal wackestone horizons are separated from the main grainstone/pellet packstone or algal (*Vermiporella*) wackestone sequence by erosional breaks.

The palaeontological characteric of the Clearview Limestone Member is the occurrence of *Streptelasma* in grainstones and skeletal wackestones. This rugose coral makes its first appearance in New South Wales above the disconformity at the unit's base and marks the commencement of Fauna III of Webby (1969).

Downderry Limestone Member

The topmost unit of the Ballingoole Limestone, the Downderry Limestone Member, consisting of thinly bedded skeletal grainstones, disconformably overlies the Clearview Limestone Member. Solution cavities are common beneath the contact, and lithoclast pebbles occur above it. The unit is 7·5 m. thick at Malachi's Hill and thins slightly eastwards (Figure 2). The Member is disconformably overlain by laminated lithic limestones (calcilutites) of the Malachi's Hill Beds (Figure 2).

Palaeontology

Fossils are rare in the Corner Limestone Member, though fragmentary heliolitids occur throughout, and molluscan debris, echinoderm ossicles and calcareous algae (mainly *Vermiporella*) occur in the grainstones. The Clearview Limestone Member is more fossiliferous and contains elements of Fauna III of Webby (1969), including corals *Streptelasma*, *Plasmoporella inflata*, *Plasmoporella* sp., *Tetradium* and *Nyctopora*, and stromatoporoids *Ecclimadictyon nestori*, *E. amzassensis*, *Clathrodictyon* cf. *microundulatum*, and *Pseudostylodictyon inequale*. Towards the top of the member corals *Halysites praecedens* and *Palaeofavosites* make their first appearance in the sequence. The Downderry Limestone Member to date has yielded few fossils other than trilobites and fragmentary echinoderm skeletons.

Acknowledgements

The author wishes to thank B. D. Webby and J. F. Read for critically reading the manuscript. This work, carried out at the University of Sydney, was supported by a Commonwealth Post-graduate Scholarship. Costs of manuscript preparation were partly met by a University of Western Australia Research Grant.

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(Received 6 December 1972)

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Appendix I

Section localities referred to in Figure 1. Thickness of units are given where practicable.

Locality 1; "Quondong"

Unit	*Thickness (metres)*
Corner Limestone Member	66
Quondong Limestone	34
Davys Plains Limestone Member	95
Glenrae Limestone Member	25
Gerybong Limestone Member	64
Manooka Limestone Member	16
Bourimbla Limestone Member	16
strike fault	
Ranch Member	34
Cargo Andesite	

Locality 2

Unit	*Thickness (metres)*
Lower Gerybong Limestone Member	?
covered interval	
Manooka Limestone Member	?
Bourimbla Limestone Member	29+
covered interval	
Cargo Andesite	

Locality 3; Paling Yard Creek

Unit	*Thickness (metres)*
Corner Limestone Member	74
Quondong Limestone	35
Davys Plains Limestone Member	78
Glenrae Limestone Member	6
Gerybong Limestone Member	*ca.* 60
Manooka Limestone Member	*ca.* 16
Bourimbla Limestone Member	24
Ranch Member	34
Cargo Andesite	

Locality 4

Unit	*Thickness (metres)*
Corner Limestone Member	
Quondong Limestone	
Davys Plains Limestone Member	?
strike fault	
Gerybong Limestone Member intercalated with Oakley Limestone Member	60+
Bourimbla Limestone Member	6+
strike fault	
Ranch Member	9
Cargo Andesite	

Locality 5; "Daylesford" property

Unit	*Thickness (metres)*
Tertiary basalt cover	
Glenrae Limestone Member	45
Oakley Limestone Member	90
Bourimbla Limestone Member	?
covered interval	
Cargo Andesite	

Locality 6; "The Corner" homestead

Unit	*Thickness (metres)*
Malachi's Hill Beds	
Downderry Limestone Member	6
Clearview Limestone Member	37+

Locality 7; south of "Ballingoole" homestead

Unit	*Thickness (metres)*
Clearview Limestone Member	120+

Locality 8; south of Malachi's Hill

Unit	*Thickness (metres)*
Downderry Limestone Member	11
Clearview Limestone Member	128

Locality 9; Malachi's Hill

Unit	*Thickness (metres)*
Malachi's Hill Beds	
Downderry Limestone Member	7·5
Clearview Limestone Member	*ca.* 60

Locality 10; 1 mile SW of Malachi's Hill

Unit	*Thickness (metres)*
Malachi's Hill Beds	
covered interval	
Downderry Limestone Member	?
covered interval	
Clearview Limestone Member	72+

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 86–93, 1972

The Palaeomagnetism of Some Palaeozoic Sediments from Central Australia

B. J. J. Embleton

Communicated by Dr. K. A. W. Crook

Abstract—Stable components of magnetic remanence have been isolated (using the partial thermal demagnetization technique) in rock samples collected from the Middle Ordovician Stairway Sandstone and the Siluro ?–Devonian Mereenie Sandstone. The stable magnetic remanence is interpreted to be of primary origin. The Stairway Sandstone, sampled over about 350 metres, yields a palaeomagnetic south pole situated at 2°S, 50·5°E ($\alpha_{95}=8\cdot5°$) and the Mereenie Sandstone sampled over the lower 100 metres of a 300 metre succession, yields the pole position 41·5°S, 40·5°E ($\alpha_{95}=10\cdot5°$). The Ordovician pole supports previous results but the Siluro ?–Devonian pole is situated on an older portion of the Australian polar wander curve than would be expected when compared with published Silurian data.

1. Introduction

This paper deals with the palaeomagnetism of the Stairway Sandstone (of Middle Ordovician age) and the Mereenie Sandstone (at least in part Devonian but possibly extending back into the Silurian) and complements previous work reported by Embleton (1972). Since the early investigations by Irving and Green (1958), few results have been obtained from Lower Palaeozoic rock formations within Australia. The polar wander curve for Australia, beyond the Carboniferous, is based on Cambrian data from the Northern Territory (McElhinny and Luck, 1970 and Embleton, 1972), a single Ordovician

Table 1a

Stairway Sandstone : summary of directions of remanent magnetization with respect to bedding, before cleaning (NRM) and after treatment (600–630°C).

	NRM					600–630°C			
Sample	N	R	D°	I°	Int. × 10⁻⁶ Gauss	N	R	D°	I°
A70	2	1·932	297·5	+15·5	10·7	2	1·941	259·0	+20·0
A71	3	2·962	327·0	+16·5	15·1	3	2·961	268·5	+14·0
A72	3	2·999	273·5	+22·5	7·3	3	2·998	277·0	+23·0
A73	4	3·966	299·0	+28·5	9·8	3	2·970	259·5	−0·5
A74	3	2·970	282·0	+8·0	12·2	2	1·998	276·5	+11·0
A75	3	2·999	297·0	+13·0	5·6	3	2·960	274·5	+16·0
A76	2	1·999	308·5	+20·5	15·6	2	1·990	281·0	+34·0
A77	4	3·989	316·0	+30·5	16·4	3	2·707	266·0	+14·5
A78	3	2·956	292·5	+25·0	10·7	3	2·904	251·0	+5·0
A79	3	2·990	324·5	+17·5	58·7	2	1·965	298·0	+6·0
A80*	3	2·999	353·0	−5·5	86·3 †		—	349·5	−1·5
A81*	2	1·999	360·0	+5·5	85·2 †		—	358·5	+7·5
A82*	3	2·999	358·0	−4·0	75·3 †		—	6·0	+9·0
A83*	3	2·990	350·0	+4·5	98·5 †		—	348·0	+12·5

* Samples "remagnetized", contain a thermally stable secondary component.
† Pilot specimens.

Table 1b

Formation mean direction and pole position after thermal treatment.

	n	R	D°	I°	$\alpha°_{95}$	Lat.	Long.	$\alpha°_{95}$
(i) 600–630°C	10	9·636	271·0	+14·5	10·0	2°S	50·5°E	8·5
(ii) 630–660°C	10	8·714	275·0	+22·5	19·5	0°	59·0°E	16·0

Symbol notation : N=number of specimens, n, number of samples, R=resultant of N or n unit vectors, D°=declination, I°=inclination, Int.=intensity of NRM, α_{95}=semi-angle of the cone of confidence at the 95% probability level.

result from the Northern Territory (Luck, 1970) and a result for the Silurian from eastern New South Wales (Briden, 1966). Several recent interpretations of the data can be seen in McElhinny and Luck (1970), Creer (1970) and Embleton (1972).

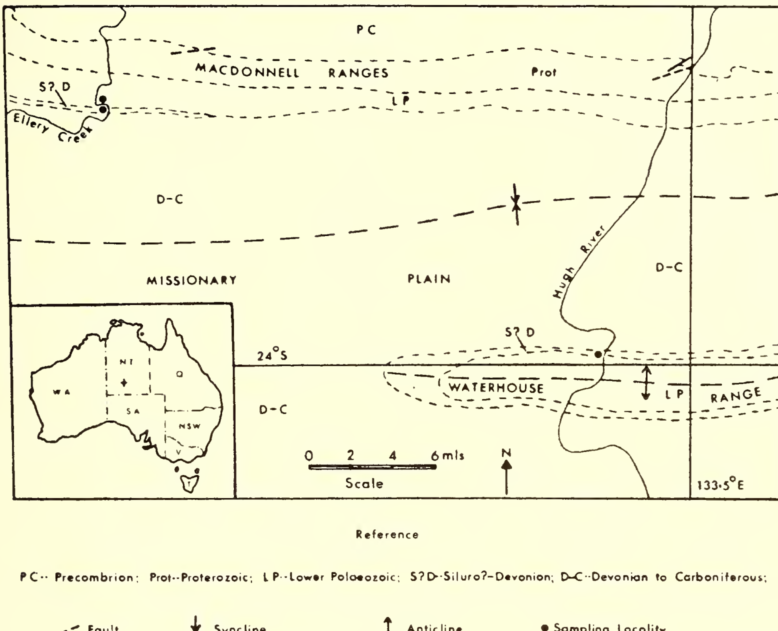

FIGURE 1.—Geological sketch map of the sampling locality. Dots indicate the localities from which samples were obtained.

Localities in which to sample material for palaeomagnetic investigation were chosen remote from south-east Australia in view of the complex geological history that region suffered (Brown *et al.*, 1968), and following some modern ideas which question the relative geological antiquity of south-east Australia and the physical integrity of the region during the Lower Palaeozoic (Oversby, 1971).

2. Brief Geology of the Area Sampled

The Stairway Sandstone and the Mereenie Sandstone occur as successive stratigraphic units in the Ellery Creek section of the Palaeozoic sedimentary sequence in the Amadeus Basin, central Australia (23·8°S, 133°E). Palaeomagnetic results have been described from the Arumbera Sandstone (Proterozoic-Cambrian) and the Hugh River Shale (Lower-Middle Cambrian) from the same locality by Embleton (1972). According to Prichard and Quinlan (1962) the Stairway Sandstone is about 350 metres thick at Ellery Creek and consists of about 60 percent of fine and medium grained quartz grey-wacke, sometimes quite silty and about 40 percent of cleaner quartz sandstone. Ten oriented samples (A70–A79) were collected from five deep red siltstone bands, ($\frac{1}{2}$ metre–$1\frac{1}{2}$ metres thick) which occur at intervals throughout the middle and upper beds of the sequence. Four samples (A80–A83) of fine-grained sandstone, rather pinkish and poorly cemented, were collected near the top of the formation. The beds dip uniformly southwards at about 60°. The age of the Stairway Sandstone is well established palaeontologically (Wells *et al.*, 1970), and ranges from Upper Llanvirnian to Llandeilian.

The Mereenie Sandstone unconformably overlies the Stairway Sandstone. The beds again dip uniformly southwards but with a somewhat shallower inclination—about 55°. Twenty-eight oriented samples (A84–A112, A93 was not collected) were collected from the lower beds where it forms a prominent " . . . red wall on the north side of the curve in the Creek (Ellery) just before the stream enters the congolmerate hills (Pertnjara Group) " (Madigan, 1932, p. 690). In the sampling locality, the formation is about 300 metres thick, and approximately the lower 100 metres were sampled for palaeomagnetic study. It is a fine to medium grained, red-brown sandstone with cross-bedding more conspicuously developed in the middle and upper beds of the sequence. Few fossils have been found in the Mereenie Sandstone, but Milton (1967) has reported the presence of some Devonian fish fragments, so that it is in part Devonian. The overlying Parke Siltstone (basal member of the Partnjara Group) is also Devonian in age (Wells *et al.*, 1970). In sections through the Palaeozoic sequence further west, the Mereenie Sandstone apparently rests conformably on the Carmichael Sandstone. The latter formation is considered Upper Ordovician in age. It therefore seems probable that the Mereenie Sandstone could extend back into the Silurian—hence the designated age of Siluro ?–Devonian—but as yet there is no fossil evidence to support this. A further five samples (A144–A148) were collected from north-dipping beds in the Waterhouse Range about twenty-five miles south-east of Ellery Creek. A geological sketch map of the sampling locality is shown in Figure 1.

3. Palaeomagnetic Results

Cylindrical specimens (2·8 cm. dia., 2·8 cm. high) were cut from the oriented samples and measured for directions and intensities of magnetization using a high sensitivity spinner magnetometer. The partial thermal demagnetization technique was employed to (i) test the stability of the magnetic remanence and (ii) remove secondary components of magnetization. Directions of magnetization were analysed following the method devised by Fisher (1953) and palaeomagnetic pole positions were calculated by assigning unit weight to each sample. In Figures 2, 4 and 5, the directions are plotted stereographically on a Wulff net.

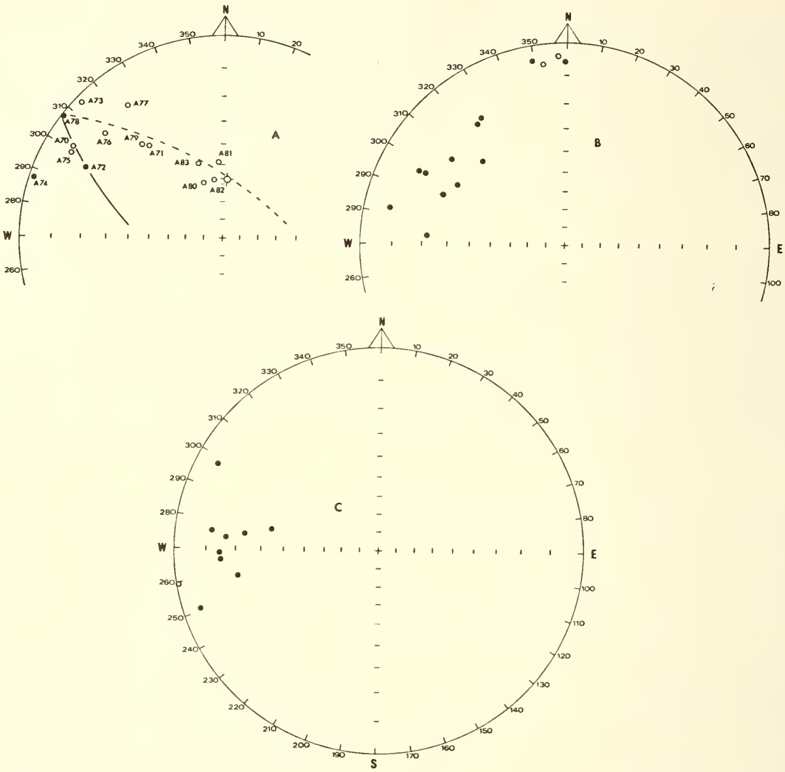

FIGURE 2.—Sample-mean directions of remanent magnetization measured in the Stairway Sandstone. Parts A and B show the NRM directions referred to the present horizontal and palaeohorizontal (bedding plane) respectively; the NRM distribution is streaked through the present field direction denoted by the open star in A. Part C shows the 600–630° C population; the streaking has been eliminated. Open symbols represent negative (upward pointing) directions and closed symbols positive (down pointing) directions.

3.1 The Stairway Sandstone

Sample-mean directions of natural remanent magnetization (NRM) exhibit a streaked distribution which, when plotted with respect to the present horizontal, are approximately directed along a great circle passing through the present field axis (see Figure 2A). The four samples that were collected near the top of the formation (numbers A80–A83) group close to the direction of the present field, and their NRM intensities (Table 1a) are also much higher than the NRM intensities of samples A70–A78. Although sample A79 also had a high NRM intensity, it did respond to thermal treatment—whereas samples A80–A83 maintained their initial directions of magnetization up to temperatures in the region of 650° (Table 1a lists their directions up to 630°C and since no apparent change has occurred, they are classed as " remagnetized "). Streaking was almost eliminated from the remainder of the samples after partial thermal demagnetization at about 500°C. They were treated at two further steps to effectively isolate the primary component of magnetic remanence. Sample-mean data after treatment at 600–630°C is listed in Table 1a and Table 1b compares the 600–630°C sample population with the 630–660°C population. The demagnetization-intensity curves shown in Figure 3 illustrate the relatively lower stability of magnetic remanence of samples A80–A83 compared with samples A70–A79, although some overlap in stability is apparent. The isolated component of remanence (reversed polarization, Figure 2C) is strongly oblique to the present geomagnetic field direction and is quite stable up to the blocking temperatures of magnetic mineral phases (probably in the region 600–650°C). The position of the south palaeomagnetic pole computed from sample virtual geomagnetic poles (VGPs), after treatment at 600–630°C, is 2°S, 50·5°E (α_{95}=8·5°).

3.2 The Mereenie Sandstone

Relatively strong secondary components of magnetic remanence have been acquired in the direction of the present geomagnetic field—Figure 4A shows the thirty-three sample-mean directions tightly grouped about the present field axis (situated at 005°, −58°). After correction for bedding tilt two populations emerge : (i) comprised of samples from south-dipping beds (A84–A112), and (ii) of samples from the north-dipping beds (A144–A148). None of the samples from the latter group responded successfully to thermal treatment, so precluding the possibility of applying the fold test (Graham, 1949) after treatment. Eleven of the twenty-eight samples from the south-dipping beds were successfully " cleaned ". Fourteen of the remainder (samples A84–A88 and A95–A103) maintained their NRM directions up to 650°C, and the three samples A91–A94 behaved erratically. Sample-mean intensities of remanent magnetization varied in such a way that those samples which ultimately responded

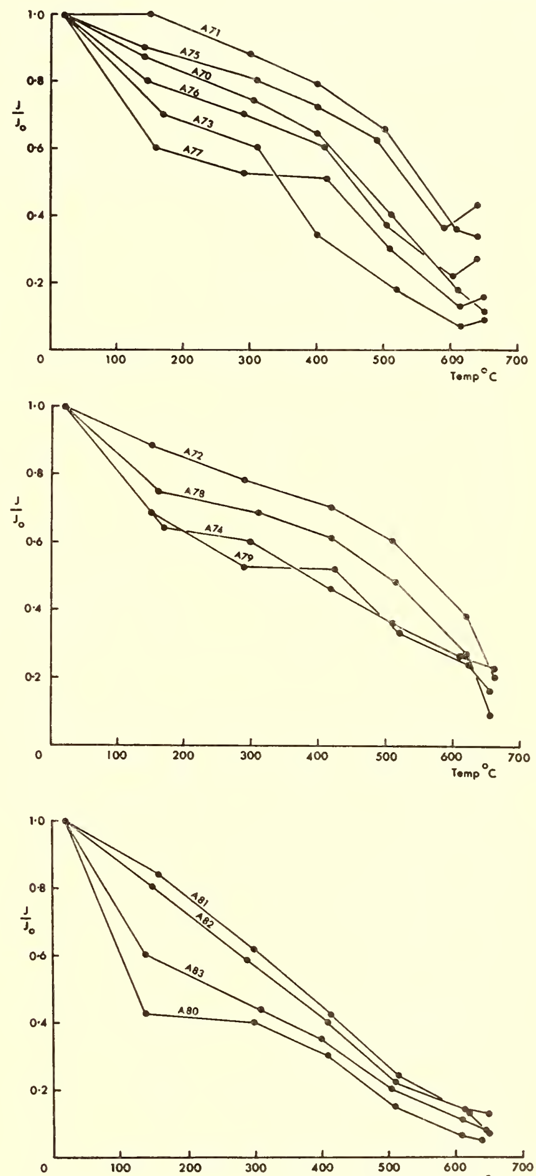

FIGURE 3.—Normalized demagnetization-intensity curves for pilot specimens of Stairway Sandstone. (J/J_0 is the ratio of the intensity of magnetization at a particular temperature to the NRM intensity value).

successfully to treatment had the lowest NRM values. The arithmetic-mean NRM values of intensity for each group were $2 \cdot 8 \times 10^{-5}$ gauss (accepted samples, $n=11$) and $1 \cdot 1 \times 10^{-4}$ gauss (rejected samples, $n=22$).

Pilot specimen data from the accepted samples is shown in Figure 5—only after high-temperature treatment did they reveal any tendency to group significantly away from the present field axis. Further specimens were then treated at 590–620°C and at 620–650°C. Figures 4c and D indicate the reduced scatter achieved at the higher of the two temperatures. Specimen directions from two samples (A89 and A109) rotated into a position reversed with respect to the main population—they were not collected from a common stratigraphic horizon so the implication of the reversal remains obscure. However, the presence of both polarities, approximately anti-parallel and oblique to the present field axis, lends weight to the significance of the result even though the origin of the phenomenon is uncertain. Table 2 lists the sample-mean data after "cleaning" and the corresponding palaeomagnetic south-pole calculated from sample VGPs is situated at 41·5°S, 40·5°E ($\alpha_{95}=10 \cdot 5°$).

4. Discussion

Interpretation of the results reported here will be restricted to the implications they have for the existing palaeomagnetic record of Australia. All samples of Stairway Sandstone which were judged to have retained a proportion

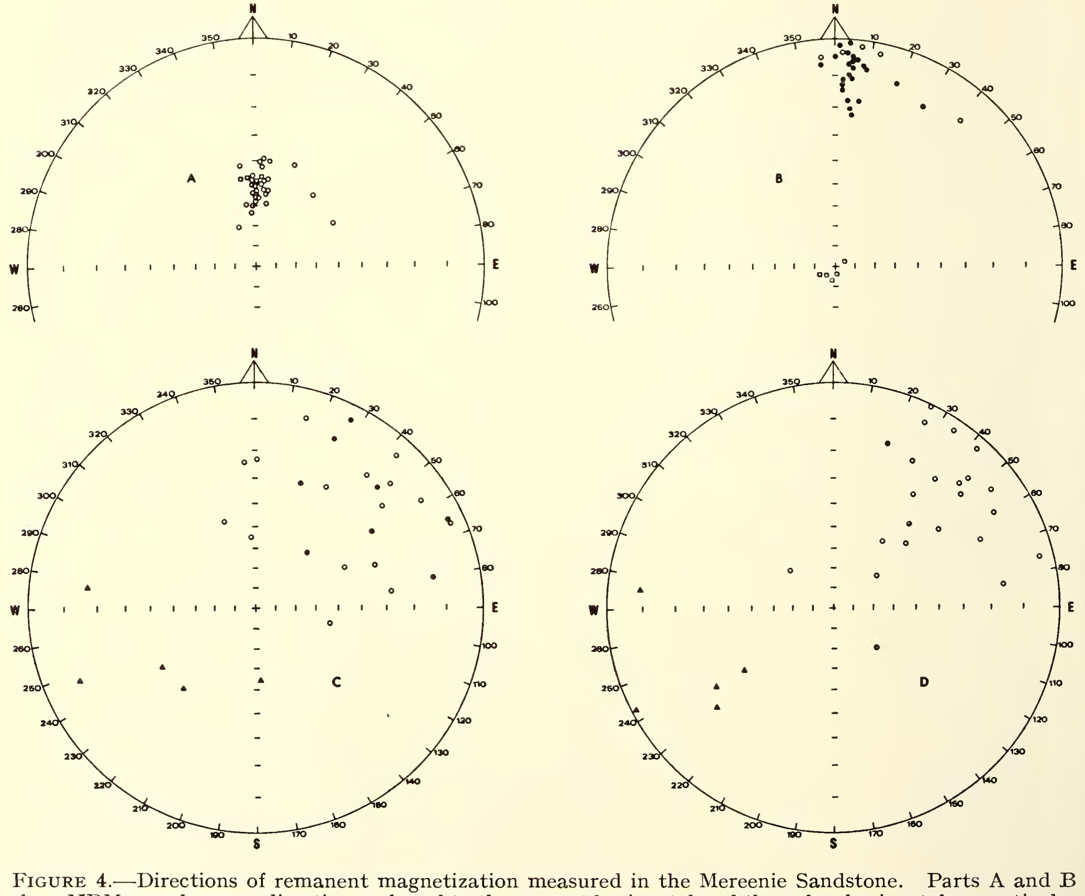

FIGURE 4.—Directions of remanent magnetization measured in the Mereenie Sandstone. Parts A and B show NRM sample-mean directions referred to the present horizontal and the palaeohorizontal respectively. The cluster around the present field axis at about 005°, −58° (part A) indicates that the bulk of the remanence is of recent origin—this is fully substantiated by the two groups of directions revealed after applying the bedding correction (part B); the folding is late Palaeozoic. Samples collected from the south-dipping limb are denoted by circles (A84–A112) and those from the north-dipping limb by squares (A144–A148). Parts C and D show the specimen populations after treatment at 590–620° C and 620–650° C respectively. Triangles denote specimens with reversed polarity.

of their primary remanence were reversely magnetized. The computed mean pole position agrees reasonably well with the Lower Ordovician pole position reported by Luck (1970). The Jinduckin Formation, sampled at locality 14°S, 132°E, yielded a palaeomagnetic south pole position at 16°S, 29°E (α_{95}=17°). Both poles are shown in Figure 6 and lie close to the apparent polar wander curve connecting the Lower-Middle Cambrian and the Siluro ?–Devonian polar regions. No other investigations have successfully produced palaeomagnetic poles from rocks of Ordovician age in Australia.

TABLE 2

The Mereenie Sandstone, summary of sample-mean data after partial thermal demagnetization. Directions are restored to the bedding planes.

	590–620°C				620–650°C			
Sample	N	R	D°	I°	N	R	D°	I°
A89 ..	2	1·513	243·5	+47·5	2	1·870	257·0	+18·5
A90 ..	2	1·949	81·5	−50·5	2	1·970	80·5	−60·0
A104 ..	2	1·984	61·0	−2·0	2	1·997	56·0	−9·5
A105 ..	2	1·805	33·0	−6·5	2	1·898	41·5	−32·0
A106 ..	3	2·737	31·0	−17·5	3	2·869	42·5	−14·5
A107 ..	3	2·338	28·0	−27·0	3	2·678	37·0	−18·5
A108 ..	3	2·727	44·5	−4·0	3	2·809	24·5	−35·0
A109 ..	3	2·728	237·5	+23·0	3	2·867	236·0	+20·0
A110 ..	3	2·621	54·0	+0·5	3	2·818	51·0	−13·0
A111 ..	2	1·891	41·0	−34·0	2	1·789	48·2	−37·5
A112 ..	3	2·472	35·0	−18·5	3	2·714	46·5	−7·0
Mean	n=11	10·226	47·0	−21·5	n=11	10·353	50·0	−24·5

Mean of sample VGPs after 620–650°C treatment: (samples A89 and A109 reversed)

n	R	Lat.	Long.	α_{95}
11	10·474	41·5°S	40·5°E	10·5°

Symbol notation as for Table 1.

Much palaeomagnetic work has been carried out on Devonian rock formations, but the absence of laboratory stability tests has led to the results being omitted from the polar-wander curve (for example see Creer (1970) and McElhinny and Luck (1970)). Results from two rock sequences which were " cleaned " (viz. the Housetop Granite plus aureole (Briden, 1967) and the Dotswood red beds (Chamalaun, 1968)) indicated that their magnetic remanence is younger than the rock ages, so they also have been omitted. There are therefore no results with which to compare directly the pole yielded by the Mereenie Sandstone. A Silurian pole position is available from the Mugga Mugga Porphyry, reported by Briden (1966), but the pole obtained from the Mereenie Sandstone, can be seen from Figure 6 to lie on an *older* portion of the apparent polar-wander curve. This discrepancy may be explained by one of the following possibilities: (i) one or the other, or even both rock units have not retained their primary remanence, (ii) the rock ages are incorrect, or (iii) relative displacements of the crustal regions containing each rock unit have occurred since their formation, either by local block rotation or by translation. With regard to possibility (i), the directions of magnetic remanence are believed to be primary in both cases, but a further point is whether the secular variation of the geomagnetic field has been accounted for by sampling over a sufficient time interval. Explanation (ii) certainly does not appear as a likely solution—the physical age of the Mugga Mugga Porphyry, determined using the Rb-Sr isochron method (Bofinger *et al.*, 1970) is 423±9 My (^{87}Rb decay constant $1{\cdot}39\times10^{-11}$ yr^{-1}) and the Devonian age for the Mereenie Sandstone is based on the presence of diagnostic fish fragments which occur in the sequence (see section 2). Furthermore, there is no suggestion that the Sandstone could be older than Silurian. The Mugga Mugga Porphyry is located in south-east Australia, a region whose suitability as a collecting ground for Lower Palaeozoic material has been questioned by the author on the basis of arguments which raise doubt about the physical integrity of south-east Australia at that time. It may be that possibility (iii) has contributed to the disparity between the results. It is unlikely that central Australia has suffered significant translational or rotational movements relative to the main shield areas, at least since the uppermost Pre-Cambrian (Embleton, 1972). Until further investigations are made, however, it remains premature to reach a definite conclusion

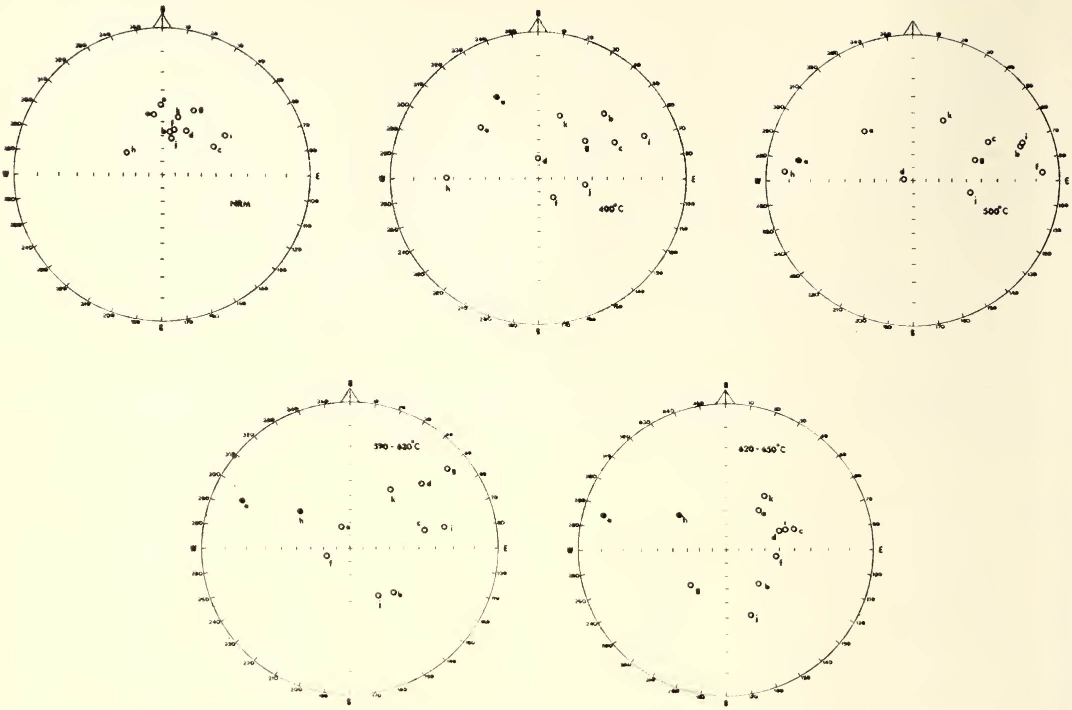

FIGURE 5.—Mereenie Sandstone pilot specimen populations; directions are referred to the present horizontal. A letter is allocated to each specimen for comparison of its direction after treatment at the various temperatures indicated in the Figure.

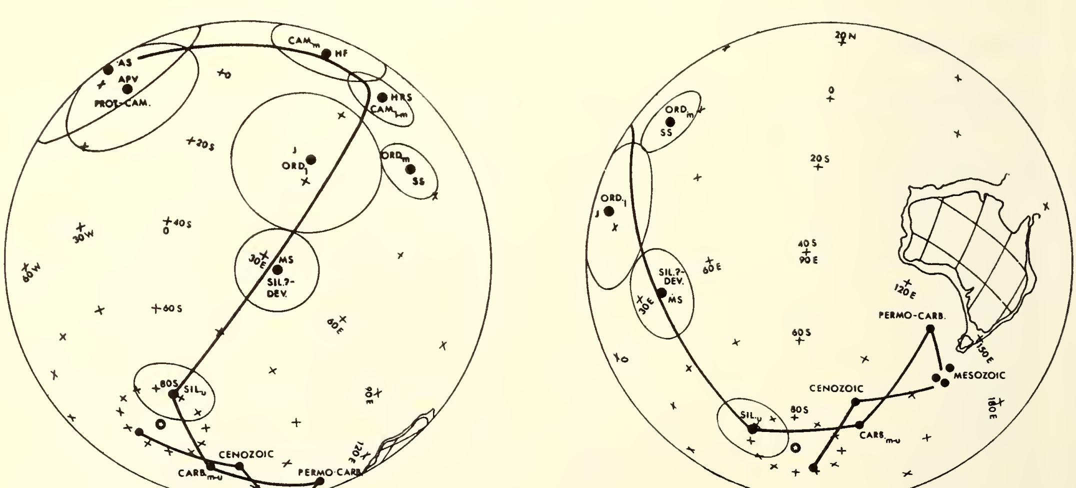

FIGURE 6.—The polar wander curve for Australia. All Lower Palaeozoic pole positions are plotted with their respective circles of confidence at the 95 per cent probability level (P=0·05), Fisher (1953). APV=Antrim Plateau Volcanics, McElhinny and Luck (1970); AS=Arumbera Sandstone and HRS=High River Shale, Embleton (1972); HF=Hudson Formation, Luck (1972); J=Jinduckin Formation, Luck (1970); SS=Stairway Sandstone and MS=Mereenie Sandstone, this paper. The Upper Silurian pole position was reported by Briden (1966) from a study of the Mugga Mugga Porphyry. The Upper Palaeozoic and younger portion of the curve has been described by Irving (1966) and McElhinny and Luck (1970).

about the Silurian and Devonian palaeomagnetic pole position which is valid for the main shield area of Australia.

Acknowledgement

The author expresses his thanks to Mr. D. J. Edwards for the competent assistance he offered in the field.

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(Received 26 June 1972)

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 94–96, 1972

Special Maps in Banach-spaces: p-summing, p-radonifying, p-integral, p-nuclear Maps*

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Many types of linear continuous maps between Banach spaces have been studied in the past years, all having the so-called "ideal property": (1) if u and v are such special maps from E into F, so are $u+v$ and ku, k scalar; (2) if u is such a special map, and if v and w are continuous linear maps, vuw is a special map of the same kind. Examples: the compact maps, the integral maps, the nuclear maps, the Hilbert-Schmidt maps in the case of Hilbert spaces. The aim of this lecture is to study some special maps having the ideal property, and depending on an index $p>0$.

§1. The p-summing Maps

Let E be a Banach space. A sequence $e=(e_n)_{n\in N}$ of elements of E is said to be l^p ($p>0$), if

$$\| e \|_p = \left(\sum_{n=0}^{+\infty} \| e_n \|_E^p \right)^{\frac{1}{p}} < +\infty,$$

$$(\operatorname*{Sup}_{n\in N} \| e_n \|_E < +\infty \text{ for } p=+\infty).$$

It is said to be scalarly l^p, if, for every $\xi \in E'$,

$$\left(\sum_{n=0}^{+\infty} | \langle e_n,\xi \rangle |^p \right)^{\frac{1}{p}} < +\infty;$$

in this case, one sees easily that

$$\| e \|_p^* = \operatorname*{Sup}_{\substack{\xi\in E' \\ \|\xi\|\leqslant 1}} \left(\sum_{n=0}^{+\infty} | \langle e_n,\xi \rangle |^p \right)^{\frac{1}{p}} < +\infty.$$

Of course a sequence which is l^p is scalarly l^p, and the converse is not true. A continuous linear map: $E \to G$ is said to be p-summing, $p>0$, if it transforms every scalarly l^p sequence into an l^p sequence. In that case there exists a constant $M\geqslant 0$ such that, for every sequence $e=(e_n)_{n\in N}$ of elements of E, $\| u(e) \|_p \leqslant M \| e \|_p^*$; the smallest possible M is denoted by $\pi_p(u)$.

Observations and Examples

(1) If $u(E)$ is finite dimensional (in particular if G is finite dimensional), u is always p-summing.

(2) If E and G are Hilbert spaces, and $p<+\infty$, u is p-summing if and only if u is Hilbert-Schmidt, and the Hilbert-Schmidt norm of u is $\pi_2(u)$. This is not at all a trivial result.

(3) Every continuous linear map is $+\infty$-summing, and $\pi_{+\infty}(u)=\| u \|$.

(4) One has the ideal property, and the inequalities:

$$\pi_p(u+v) \leqslant \pi_p(u)+\pi_p(v) \qquad \text{if } p\geqslant 1,$$
$$(\pi_p(u+v))^p \leqslant (\pi_p(u))^p+(\pi_p(v))^p \qquad \text{if } p\leqslant 1,$$
$$\pi_p(vuw) \leqslant \| v \| \pi_p(u) \| w \|.$$

(5) There exists a useful generalization, introduced by Maurey, for $-1<p\leqslant 0$.

Pietsch's theorem. *Let* u : E → G *be linear continuous.*

(1) *If* u *is* p*-summing, it is* q*-summing, and* $\pi_q(u) \leqslant \pi_p(u)$, *for* $q\geqslant p$.

(2) *For* $p<+\infty$, *for* u *to be* p*-summing, it is necessary and sufficient that there exists a Radon probability* ν *on a compact space* Z, *and a continuous linear map* v *from* E *into* $L^\infty(Z,\nu)$, *such that* $\| u(x) \|_G \leqslant \| v(x) \|_{L^p(Z,\nu)}$ *for every* $x \in E$.

In this case, $\pi_p(u) = Inf \| v \|$ *for all the possible* v.

Observations and Consequences

(1) From (1) it results that there exists a p_0, $-1\leqslant p\leqslant +\infty$, such that u is p-summing for $p>p_0$, and is not for $p<p_0$. A conjecture by Pietsch is that $p_0=-1$ or $p_0\geqslant 1$: if u is $(1-\varepsilon)$-summing, $\varepsilon>0$, then it is p-summing for every $p>-1$. This conjecture has been proved recently by Simone Chevet and Bernard Maurey.

(2) From (2) it results that, if ν is a Radon probability on a compact space Z, the canonical injection $j: L^\infty(Z,\nu) \xrightarrow{j} L^p(Z,\nu)$ is p-summing, and $\pi_p(j)\leqslant 1$.

§2. The p-integral Maps

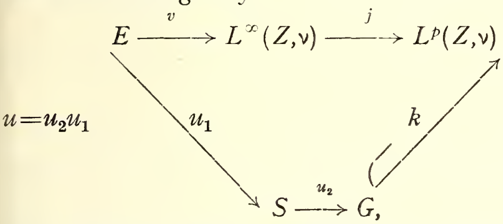
A map $u: E \to G$ is said to be p-integral, $p>0$, if it factorizes in the following way:

$$E \xrightarrow{v} L^\infty(Z,\nu) \xrightarrow{j} L^p(Z,\nu) \xrightarrow{u_2} G,$$

where ν is a Radon probability on a compact space Z, and j the canonical injection. The p-integral norm u is the infimum of $\| v \|$, for all these possible representations for which

* Pollock Memorial Lecture, delivered on 3rd August, 1972.

$\| u_2 \| \leqslant 1$. For $p=1$, it is very near to the notion of integral map introduced by Grothendieck. By the ideal property, a p-integral map is p-summing; the converse is true for $p=2$, not in the other cases. But let us say that u is p-subintegral if it factorizes in the following way:



the diagram being commutative, j being the canonical injection, S being a closed vector subspace of $L^p(Z,\nu)$ with the induced norm and k the canonical injection. The p-subintegral norm will be the infimum of $\| v \|$, for all these representations for which $\| u_2 \| \leqslant 1$.

Then Pietsch's theorem of §1 is equivalent to saying that, for $p<+\infty$, u is p-summing if and only if it is p-subintegral, and its p-subintegral norm is exactly $\pi_p(u)$.

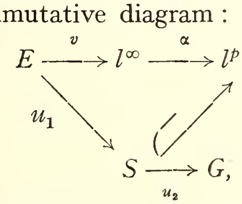
§3. The p-nuclear Norms

We call diagonal map from l^∞ into l^p a multiplication: $(t_n)_{n\varepsilon N} \to (\alpha_n t_n)_{n\varepsilon N}$ by a sequence $\alpha=(\alpha_n)_{n\varepsilon N} \;\varepsilon\; l^p$.

A map $u: E \to G$ is said to be p-nuclear, $p>0$, if it factorizes in the following way:

$$E \overset{v}{\to} l^\infty \overset{\alpha}{\to} l^p \overset{u_2}{\to} G, \text{ with } \alpha \;\varepsilon\; l^p.$$

The p-nuclear norm is the infimum of $\| \alpha \|_{l^p}$, for all the possible factorizations with $\| v \| \leqslant 1$, $\| u_2 \| \leqslant 1$. For $p=1$, one obtains exactly the nuclear maps introduced by Grothendieck. In the same direction, u will be called p-subnuclear if it factorizes as $u=u_2u_1$, with the commutative diagram:



with the same kind of conditions as in §2 for the p-subintegral maps; the p-subnuclear norm of u is the infimum of $\| \alpha \|_{l^p}$, when $\| v \| \leqslant 1$, $\| u_2 \| \leqslant 1$. One sees easily that a p-nuclear (resp. p-subnuclear) map is a fortiori p-integral (resp. sub-integral), therefore p-summing. The converse is not true, but

Persson's theorem. *If* E *is reflexive, every* p-*integral map* (*resp.* p-*subintegral map*) *from* E *into* G *is* p-*nuclear* (*resp.* p-*subnuclear*).

§4. The p-radonifying Maps

Let λ be a Radon probability on E. One puts

$$\| \lambda \|_p = \left(\int_E \| x \|_E^p d\lambda(x)\right)^{\frac{1}{p}}, \text{ and}$$

$$\| \lambda \|_p^* = \sup_{\substack{\xi \varepsilon E' \\ \| \xi \| \leqslant 1}} \left(\int_E | <\xi, x> |^p d\lambda(x)\right)^{\frac{1}{p}}.$$

The probability λ is said to be of order p if $\| \lambda \|_p < +\infty$, of type p if $\| \lambda \|_p^* < +\infty$. If it is of order p, it is of type p, and $\| \lambda \|_p^* \leqslant \| \lambda \|_p$. If λ is a countable discrete sum of point-masses, the previous notions are very similar to those of l^p sequences and scalarly l^p sequences of §1.

It is possible to generalize considerably the notion of Radon probability λ on E by that of cylindrical probability on E. We shall not give here the complete definition, which is rather abstract. Let us simply say that the order and $\| \lambda \|_p$ cannot be extended to cylindrical probabilities, but that the type and $\| \lambda \|_p^*$ can be. Let us mention also that if E is a Hilbert space, the Gauss probability, well known if E is finite dimensional, can always be defined in the infinite dimensional case as a cylindrical probability, related to the white noise and to Wiener measure.

A continuous linear map $u: E \to G$ is said to be p-radonifying, if it transforms every cylindrical probability on E, of type p, into a Radon probability on G, of order p. A p-radonifying map is trivially p-summing. The converse is not true, but

Theorem. *The two following properties are equivalent:*

(1) u *is* p-*summing from* E *into* G;

(2) u *is approximately* p-*radonifying from* E *into the bidual* σ(G″,G′).

We shall not define the precise meaning of the word "approximately". Let us simply point out the following improvements.

The word "approximately" can be dropped if E' has the Banach approximation property [i.e. there exists a net $(w_i)_{i\varepsilon I}$ of continuous linear maps from E' into itself, of norm $\leqslant 1$, of finite rank, such that $\lim_i w_i(\xi)=\xi$ for every $\xi \;\varepsilon\; E'$. It had been conjectured by Banach that every Banach space has this property. It has been proved just a few weeks ago that this conjecture is false], or if $p \geqslant 1$. The bidual $\sigma(G'',G')$ can be replaced by G itself, if G is reflexive, or if $1<p<+\infty$. In particular, for $1<p<+\infty$, u is p-radonifying if and only if it is p-summing.

The p-radonifying maps have a lot of applications in probabilities, so that functional analysis may apply to probabilities in a new way. Conversely, some results of probabilities can prove theorems of functional analysis, about p-summing or p-nuclear maps.

§5. Radonifying Maps between the Spaces l^q

Set a' the conjugate exponent of a, $1 \leqslant a \leqslant +\infty$. Let $\alpha = (\alpha_n)_{n \in N}$, and consider the diagonal map defined by α, $(t_n)_{n \in N} \to (\alpha_n t_n)_{n \in N}$. Then

Theorem. *The diagonal map* α *is* p-*radonifying,* $-1 < p < 1$, *from* $l^{a'}$ *into* l^b, *if and only if*

(1) $\alpha \in l^{b-}$, i.e. $\sum_{n=0}^{\infty} |\alpha_n|^b \left(1 + \left|\log \frac{1}{|\alpha_n|}\right|\right) < +\infty$, if $a = b < 2$;

(2) $\alpha \in l^a$, if $a \geqslant b \geqslant 2$;

(3) $\alpha \in l^r$, $\frac{1}{r} = \frac{1}{a} + \frac{1}{b} - \frac{1}{2}$, if $a > 2 \geqslant b$;

(4) $\alpha \in l^{\mathrm{Min}(a,b)}$ in the other cases.

§6. Radonifying Maps between Spaces of Distributions

Let us call $(L^a_{\mathrm{loc}})^\alpha$ the space of distributions on R^n, whose derivative of order α lies in L^a_{loc} ($1 \leqslant a \leqslant +\infty$, $\alpha \in R$; the derivatives of non-integer order are defined by suitable convolutions). By Sobolev's inequalities, $(L^a_{\mathrm{loc}})^\alpha \subset (L^b_{\mathrm{loc}})^\beta$ when

$$\frac{\alpha - \beta}{n} > \left(\frac{1}{a} - \frac{1}{b}\right)^+ = \mathrm{Max}\left(\frac{1}{a} - \frac{1}{b},\ 0\right).$$

Then

Theorem.

(1) *If* $\frac{\alpha - \beta}{n} \frac{1}{p} + \left(\frac{1}{a} - \frac{1}{b}\right)^+$, $1 \leqslant p \leqslant +\infty$, *the injection from* $(L^a_{\mathrm{loc}})^\alpha$ *into* $(L^b_{\mathrm{loc}})^\beta$ *is* p-*radonifying*;

(2) *If* $\frac{\alpha - \beta}{n} > \mathrm{Max}\left(1 - \frac{1}{b},\ \mathrm{Min}\left(\frac{1}{2}, \frac{1}{a}\right)\right)$, *the same injection is* p-*radonifying for every* $p > -1$.

Let us give an application to the brownian motion. The white noise corresponds to the Gauss cylindrical probability on L^2 (in the case $n = 1$); it is of type p for every finite p. The primitive of the white noise is exactly the brownian motion; it is defined by a cylindrical probability γ on $(L^2_{\mathrm{loc}})^1$, of type p for every finite p.

Is the brownian motion *almost surely* continuous, hölderian of order β? This would imply that γ is a Radon probability on $(L^\infty_{\mathrm{loc}})^{\beta - \varepsilon}$, and would be implied by γ being a Radon probability on $(L^\infty_{\mathrm{loc}})^{\beta + \varepsilon}$, whatever be $\varepsilon > 0$. Therefore, this will be assured if the injection of $(L^2_{\mathrm{loc}})^1$ into $(L^\infty_{\mathrm{loc}})^\beta$ is p-radonifying, for some p finite because γ is of type p. By the first part of the previous theorem, this will be true if $1 - \beta > \frac{1}{p} + \frac{1}{2}$ for some p finite; it is true for $1 - \beta > \frac{1}{2}$ or $\beta < \frac{1}{2}$: the brownian motion is almost surely continuous, hölderian of any order $\beta < \frac{1}{2}$. It is known that it is almost surely not hölderian of order $\frac{1}{2}$.

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The p-summing maps have been introduced by Kwapien. The first main properties have been proved by Pietsch in "Absolut p-summierende Abbildungen in Normierten Räumen", *Studia Mathematica*, **28** (1967), pp. 333–353. A lot of very refined results have been found by Pelczynski, Lindenstrauss, Persson, Kwapien, Saphar, Garling, Dudley, Simone Chevet, Maurey, Rosenthal, etc.

The integral and nuclear maps have been introduced by Grothendieck in his thesis "Produits tensoriels topologiques et espaces nucléaires", *Memoirs of the American Mathematical Society*, 1955; the p-integral and p-nuclear maps are a generalization. Persson's theorem of §3 is published in *Studia Mathematica*, **33** (1969).

The theorem of §4 is due to me, partly in collaboration with Kwapien, and has been published in the Séminaire de l'Ecole Polytechnique, 1969–70, and in "Probabilités cylindriques et applications radonifiantes", *Journal of the Faculty of Science, The University of Tokyo*, **18** (1971), pp. 139–286.

The theorem of §5 has been published in "Mesures cylindriques et applications radonifiantes dans les espaces de suites", Laurent Schwartz, *Proceedings of the International Conference in Analysis and Related Topics, Tokyo*, 1969, pp. 41–59. It concerns only the case $-1 < p < 1$. The case of arbitrary p has been partly solved by Pietsch, Séminaire de l'Ecole Polytechnique, 1970–71, exposés 29 and 31, and improved by Garling in a paper to appear shortly; however, it is not yet completely solved. The properties of the brownian motions are well known; I published the proof given here in the Séminaire de l'Ecole Polytechnique, 1969–70, exposé 15. The p-radonifying maps from $(L^a_{\mathrm{loc}})^\alpha$ into $(L^b_{\mathrm{loc}})^\beta$ on R^n, depending on the six quantities a, α, b, β, p, n, still pose a lot of open problems!

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(Received 11 January 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 105, pp. 97–102, 1972

The Measurement Revolution*

M. J. Puttock

1. Introduction

Two previous Presidents of this Society have given an address dealing with measurements and standards of measurement. I venture to speak also on the same topic since it is the one which has absorbed my interest and in which I have been engaged for the best part of a lifetime. I choose tonight to comment on some of the significant developments in the field of measurement science which have occurred in recent times.

I am indebted for the title of my address to Dr. A. V. Astin who was the Director of the National Bureau of Standards in the U.S.A. from 1952 to 1969. Dr. Astin used this term in an address to a Conference on Standards, and he was referring to the period roughly from the turn of the century to the present time. During this period quite astonishing progress has been made not only in the accuracy of physical measurements but also in the extent and range over which measurements can be made and in the very standards of measurement themselves. As an example—at the beginning of the century long distances were measured by survey tape and theodolite triangulation with an accuracy of about one part in 100,000—now we can measure the distance from a point on earth to a point on the moon to an accuracy of two parts in one million (about 800 metres) and we can measure changes in this distance to better than one part in 100 million (4 metres).

It was Lord Kelvin, one of the most illustrious scientists of the last century, who once remarked in a lecture : " I often say that when you can measure what you are speaking about and express it in numbers you know something about it ; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind." He could also have added that the more accurate your measurement the greater your knowledge and the greater your understanding. It cannot be denied that the outstanding technological progress made this century stems directly from our ability to measure more precisely.

There are two contributory factors to measurement. The standard, which is a physical representation of the unit, and the process by which we compare our unknown quantity with the standard. This comparison process may involve a number of " steps ", and it often happens that the difference between two quantities may be determined more accurately than their individual values in terms of the standard. In this address I will in general be more concerned with the realization of the unit of measurement, that is, the physical standard, though I do not propose to ignore the measurement process. It will also be necessary for me to be selective in the topics and to restrict the depth of discussion in most instances.

2. Time and Frequency

The measurement of time is one of the oldest branches of science and it is appropriate that it should be considered first.

There are two concepts of time to be considered. First there is the concept of duration from a particular epoch, the measurement of which locates an event on some arbitrary scale, such as the calendar, so that the position in time of that event is unambiguously identifiable. Secondly, there is the concept of time interval, the measurement of brief (relatively) intervals of time. From the dawn of civilization until quite recently the solar day, that is, the rotation of the earth about its axis, has provided (by subdivision) the unit of time interval. In conjunction with the solar year, the rotation of the earth around the sun, it has also provided the unit for the time scale of duration. Unfortunately, these bases for the measurement of time have many shortcomings, some of which, such as perturbations in the earth's movements, are beyond our control and variations of the order eight parts in 10^8 ($0 \cdot 007$ second in a day or $2 \cdot 5$ seconds in a year) have occurred during the last two centuries. This may seem very small, but not only does it present difficulties

*Presidential Address delivered to the Royal Society of New South Wales at Science House, Gloucester Street, Sydney, 5th April, 1972.

in the preparation of astronomical tables, it is also a very serious limitation in precise time and frequency measurements ; the unit of frequency is, of course, the reciprocal of the unit of time interval.

At the beginning of this century time interval was measured using pendulum clocks having an accuracy of the order of about two parts in 10^7. Then came the clock based on the vibration of a tuning fork, which achieved an accuracy of one in 10^7. In the 1930's the quartz-ring oscillator was developed, and subsequent improvements in design and control circuitry led to the achievement of an accuracy of about one part in 10^8 over periods up to two years with short-term accuracy of one in 10^{10}.

In their search for a more precise unit for time interval and for frequency, scientists turned to the atom. Electromagnetic radiation is emitted or absorbed whenever the energy level of the atom is changed.

The " atomic " clock (which first arrived on the scene in the 1950's) is based on the phenomenon that two atoms otherwise identical but at different energy levels behave as if they have different magnetic polarity and will be deflected along different paths when passed through a magnetic field. A stream of atoms, all of identical mass (that is from an isotope), are fired through a strong magnetic field which induces a magnetic moment in the atcms, and these are deflected from the axis. The atoms then pass through an oscillating electromagnetic field (controlled by an R.F. oscillator). If the frequency of this field is not in resonance with the transition frequency of the atoms they are unchanged, and on passing through a second magnetic field they are further deflected away from the axis. If, however, the oscillator frequency is in resonance with the transition frequency, the effective moment of the atoms is reversed and they are deflected on to the detector. A feed back loop to the oscillator controls the frequency at the precise value required for the energy level transition. Since this energy level transition is independent of conditions external to the atom, the associated frequency is unique. An accuracy of one part in 10^{10} ($0{\cdot}1\mu$s in one day) can now be achieved, and the unit of time interval, 1 second, is defined as " the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom ".

In just over half a century we have seen a 100,000-fold increase in the accuracy of our standard of time interval and frequency, and frequencies can now be compared with accuracies of a few parts in 10^{13}.

Examples of developments stemming from the ability to measure time interval, frequency and frequency changes so accurately are the equipment used to measure the speed of space rockets (by doppler frequency shift), " radar " speed traps, an aircraft navigation system (also doppler shift), microwave and electro-optical distance measuring equipment for the surveyor (I shall mention these again later) and many others.

3. Length

Now let us consider the measurement of length, a branch of science which has also been around for a long time. I believe that the oldest length standard still in existence is a length scale made of shell dating from approximately 3000 B.C. At the beginning of this century our standards of length were still scales, bars of metal with lines engraved upon them. As you might expect, after 5,000 years these line standards had been developed into very precise standards, and they could be considered to have an effective accuracy of about one part in one million. In actual fact the two fundamental standards, the Imperial Standard Yard and the International Prototype Metre, were, by definition, absolutely precise. However, since they were metal bars there was always an uncertainty in their length due to lack of knowledge of their *precise* temperature. Also, the special equipment (micrometer microscopes, etc.) used to transfer the length of the fundamental standard to a working standard introduced uncertainties. So you see that although by definition the fundamental standards had absolute precision, immediately they were used uncertainties were introduced. Additionally, there was the problem of the instability of the fundamental standards. Few if any materials can be considered to be 100% stable, almost all undergo dimensional changes with time. The International Prototype Metre, made of a 90% platinum-10% iridium alloy, proved to be very stable ; at least no significant changes in length had been detected up to a few years ago. The Imperial Standard Yard (made of Mr. Bailey's metal—16 parts copper, 2½ parts tin and 1 part zinc) was, however, unstable ; it was (still is) shrinking by approximately one millionth of an inch per annum—not very much, but decidedly important when measurements of the highest accuracy are required.

Another problem with these material standards, of course, is that they are liable to be damaged or lost—in fact one of the earlier yard standards was lost in the fire in the Houses of Parliament in 1834.

Once again scientists in their quest for a more satisfactory standard turned to the atom as in the case of frequency, and the emission of radiation due to a change in energy level induced in the atom supplied the answer. The electromagnetic radiation in this case, however, is in the visible region—light waves.

As early as 1827 a French scientist, Babinet, suggested that the wavelength of a monochromatic (i.e. single frequency) light source might be used as a standard of length. The techniques of using light waves as length scales is known as interferometry. At the end of the last century the first successful measurements of the length of the metre in terms of the red radiation from a cadmium lamp were made by a very involved technique. One of the main complicating factors was that natural cadmium was used, and this contains several isotopes of slightly different masses (i.e. several slightly different atoms), each emitting a red radiation slightly different from the others. The net result is that the direct interference effects can only be obtained over relatively short distances, in the case of cadmium about 100 mm. If a single isotope is used, however, the interference effects can be obtained over much greater lengths.

Production of single isotopes, suitable for and in sufficient quantities for use as light sources, was achieved some 30 years ago, and after much research and development led to the redefinition, in 1960, of the metre as being " equal to 1,650 763·73 wavelengths, in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom ". This radiation is in the orange-red part of the spectrum. The effective accuracy of this standard is one in 10^8, an improvement by a factor of 100 over the old metal bar standards.

One of the most dramatic advances in the field of length measurement occurred with the development (1960) of the laser (an acronym for light amplification by stimulated emission of radiation). This is a device by means of which a substance (gas, solid or liquid) is stimulated to emit light (usually by microwave radiation) in the form of a very narrow beam having a single frequency and an extremely narrow line width. For measurement of length by interferometry it is necessary to have a continuous emission of light, and the He-Ne gas laser is currently the most commonly used laser for this purpose, the atoms involved in the lasing action being those of the neon (about 10% of the mixture).

The lasing action which gives the light emitted its unique properties of coherence (i.e. all waves emitted are exactly in phase), intensity, directionality and narrow line width arise from the physical shape of the glass envelope containing the He-Ne mixture. It is essentially a glass tube at the ends of which are optically flat, semi-transparent mirrors which are mutually parallel (this is the form most readily understood, but curved mirrors may also be used). The gas mixture inside the glass envelope is excited, most commonly by means of a microwave field.

When an atom, in this case of neon, is excited to a higher energy level and then drops to a lower level, it emits a photon (or wavelength packet if you like). This photon travels down the tube and is reflected from the mirror. When it encounters another excited atom it triggers that atom to fall to its lower level and emit another photon. This happens repeatedly as the photons are reflected back and forth and on every occasion the new photon is precisely in phase with the triggering photon. In this way the intensity of the beam is built up until surplus photons are emitted through the semi-transparent mirror as an intense coherent beam. Because multiple reflections are needed to effect the lasing action, the mirrors have to be very closely parallel, and only those photons whose paths are normal to the mirror surface take part—hence the emergent beam is extremely parallel (divergence is of the order of only a few minutes of arc).

The precise value of the wavelength emitted by a laser is a function of the physical separation of the mirrors at each end of the laser cavity. Since this separation may vary due to a number of factors—temperature, instability of material, pressure changes—the laser at the moment cannot replace the radiation from the Kr-86 atom as the standard of length. However, there appears to be a reasonable certainty that before long we will have a laser the separation of the mirrors of which may be automatically controlled by a unique atomic feature (probably an absorption line of an isotope of iodine). This will make the laser a true " atomic " standard of length and the expected precision is 100 times that of the Kr_{86} standard.

The use of a laser for the measurement of length is not confined to the laboratory. Laser interferometers are commercially available, and these permit the measurement of the movement of the reflector (mounted, say, on a machine tool table) to an accuracy approaching one in 10^6 and with a range up to 60 m (200 ft). For measuring even longer distances (including the distance to the moon) a different technique is used. The laser light is emitted in pulses and the time of travel (there and back) measured. Half of this time multiplied by the velocity of light (299,792·5 km/sec *in vacuo*) gives the distance.

This introduces another concept into the measurement of length—the use of the velocity of light (or more correctly of electromagnetic radiation) as a standard in conjunction with the standard of time interval (frequency). The latter, as we have seen, is usable to an accuracy of one in 10^{11}. The velocity of light has been the subject of a large number of experimental determinations (there were 27 in the years 1947–1967) and it is considered that it is now known to an accuracy of about $1\frac{1}{2}$ parts in a million. The main problem has been that of measuring frequency in the visible or near visible range of the electromagnetic spectrum. There are signs, however, of an impending break-through in this area, and it could well be that in the not too distant future length will be defined in terms of an absolute value for the velocity of light and of frequency.

The activities of surveyors, particularly the geodetic and topographic surveyors, have been revolutionized by the development of instruments using time interval (frequency) and the velocity of light as the bases for length measurement. Only a relatively few years ago surveying was by triangulation out from a carefully measured (by tapes) base line a few miles long. By the time the triangulation had been extended a hundred miles the effect of small errors in the hundreds of theodolite measurements involved became quite significant. Also, the process was extremely time-consuming.

In 1949 Bergstrand (Sweden) produced the first survey distance measuring instrument using light waves—the Geodimeter. In 1957 Wadley (South Africa) produced the first instrument using microwaves—the Tellurometer. Both instruments operate on essentially the same principle. A transmitter sends out a beam of electromagnetic radiation (light or microwave) modulated by an imposed frequency (rather like the way radio is transmitted by a signal frequency imposed on the carrier frequency), which is crystal controlled. A reflecting unit at the far end of the distance to be measured sends the beam back to be received at the transmitter. The phase of the incoming signal is compared with that of the outgoing, and the fractional difference is a function of the distance travelled by the beam. There are, of course, techniques for determining the number of whole phases that have to be added to the fraction of a phase to give the true total time of travel. The accuracy achieved is of the order of three parts in 10^6. The significant point, however, is in the time saved. The distance between two points, say, 50 miles apart can be measured by Tellurometer in about one hour (including set-up time)—by triangulation it could take weeks.

4. Mass

The third most important quantity to be considered is that of mass. This is the one quantity which has not been the subject of spectacular advances either in the fundamental standard or in measuring equipment or technique. It is true that, by attention to detail, measuring equipment and techniques have shown an improvement of about one order during this century, and masses may now be compared to an accuracy of one in 10^8. The standard itself is (and has been for almost a century) a kilogram of platinum-iridium (90% Pt, 10% Ir) in the form of a polished cylinder of diameter and height equal to 39 mm.

A significant improvement in the lower grade working standards was made in 1947 with the introduction of masses made of stainless steel (25% Cr, 20% Ni) which have much improved stability over those of brass or nichrome. As a previous President, Mr. J. W. Humphries, pointed out in his address, the possibility of an " atomic " standard of mass is decidedly remote ; Mr. Humphries estimated that if one counted the atoms in a kilogram of a gas (about 10^{26}) at a rate of 10 million per second the task would take 10^{19} seconds, which is longer than the estimated life of our universe. So it seems that for some time to come we must accept our material standard.

5. Electric Potential

A unit which has quite recently had a " shot in the arm ", so to speak, is the unit of electrical potential, the volt. The universally used reference standard of voltage is the Weston cadmium cell, the original patent for which dates from 1891. The Commonwealth standard of voltage is in effect the mean value of a bank of Weston standard cells held at the National Standards Laboratory. Every three years these cells are intercompared, at the B.I.P.M., Sèvres, with similar cells from other countries, The International standard of voltage determined, and values are assigned to each national standard. The precision of these intercomparisons and of the values assigned to the National standards is limited by factors inherent in the cells themselves. These factors are :

- Sensitivity to temperature changes (40 p.p.m./° C).
- Sensitivity to temperature gradient (300 p.p.m./° C).
- Sensitivity to mechanical disturbance.
- Sensitivity to electrical loading.
- Long-term instability (the main reason for frequent intercomparisons).

Standard cells may be compared with a precision of one in 10^8, but the accuracy of a national standard volt is estimated to be seven in 10^6.

Once again the step forward is " down " to the atom. In 1962 B. D. Josephson *predicted* two basic phenomena related to the electrical properties of a weak link (or barrier) between two superconducting materials maintained at a low temperature (about 4 K). One, the d.c. Josephson effect, is that a current will pass through such a junction with zero potential difference. The other, the a.c. Josephson effect, in which a potential V established across the junction results in the generation within the junction of an alternating current having a frequency f given by

$$f=\frac{2e}{h}\cdot V\approx 483\ \mathrm{MHz}/\mu\mathrm{V}$$

where e is the electron charge and h is Planck's constant. Both effects have been confirmed experimentally, and it is the a.c. Josephson effect which is of interest to us here.

Since both e and h are atomic constants which are completely independent of conditions external to the atom, $2e/h$ is likewise constant and independent. Now since we can measure frequency to one in 10^{11}, then in theory we should know the volt to much the same accuracy. Unfortunately, we need to know the volt before we know the precise value of $2e/h$, an apparent impasse. What we can do, however, and this is the important point, is to monitor the standard volt and maintain it at an agreed (international) value to a much greater precision than before—the N.S.L. standard is regularly monitored to a precision of one in 10^7. The next move is for international agreement on the value to be assigned to $2e/h$ and for all national volts to be based on this and the standard of frequency.

In a practical realization a Josephson junction, a point contact formed by pressing a sharpened niobium wire against a flat niobium anvil or a sandwich of two lead films separated by a thin insulating layer of lead oxide is immersed in liquid helium (4·2 K) and irradiated with a precisely known microwave frequency. This causes steps of constant voltage to appear in the current/voltage characteristic of the junction — these steps occur whenever the junction frequency is a multiple of the frequency of the microwave source. By appropriate techniques the junction voltage is related to the voltage of a standard cell and the value of the standard cell voltage can be monitored as frequently as desired.

6. Conclusion

It has not been possible in this address to cover all the fields of measurement science, and there are many developments which I have not had time to discuss, some of which are :

(1) The development (at N.S.L.) of the calculable capacitor which has revolutionized the measurement of capacitance by providing a standard accurate to two in 10^6 and reproducible to three in 10^8 ;

(2) the developments in the field of thermometry, particularly the continual improvements being made in the International Practical Temperature scale ;

(3) the developments (at N.S.L. in particular) of a new method for realizing the candela (unit of luminous intensity). In 1969 an international comparison showed discrepancies between national laboratories of 16 in 10^3. The new method should reduce these discrepancies by at least one order ;

(4) the new fundamental determinations of the acceleration due to gravity (one has just been completed at N.S.L.) which will improve the accuracy of this " constant " to about two in 10^7 and enable the realization of the unit of force to five in 10^7 ;

(5) the development of sophisticated measuring devices capable of accurately indicating minute changes in a given quantity—for example, a probe-type surface measuring instrument with a magnification of 1,000,000× and capable of discriminating surface irregularities of 5Å (a few molecules) in height ;

(6) the new technique of holography whereby by rather special photography, using a

> laser as light source, it is possible to compare an object with an image of itself. If the comparison is made between an object first undistorted then distorted the resultant image exhibits interference fringes which are contours of the distortion.

It is unfortunately true that most people take this business of measurement very much for granted. In actual fact it is a field in which quite spectacular advances are currently being made and which will inevitably lead to a better understanding of the multitude of natural and man-made processes that make up the world around and within us.

The address was illustrated by a selection of slides.

National Standards Laboratory,
CSIRO,
University Grounds,
City Road,
Chippendale, 2008, N.S.W.

(Received 31 March 1973)

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AUSTRALASIAN MEDICAL PUBLISHING CO. LTD.
71-79 ARUNDEL ST., GLEBE, N.S.W., 2037
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THE ROYAL SOCIETY OF NEW SOUTH WALES

The Society originated in the year 1821 as the Philosophical Society of Australasia. Its main function is the promotion of Science through the following activities: Publication of results of scientific investigation through its Journal and Proceedings; the Library; award of Prizes and Medals; liaison with other Scientific Societies; Monthly Meetings; and Summer Schools. Special meetings are held for the Pollock Memorial Lecture in Physics and Mathematics, the Liversidge Research Lecture in Chemistry, and the Clarke Memorial Lecture in Geology.

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OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 106

PARTS 1 - 4

1973

PUBLISHED BY THE SOCIETY,
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

Royal Society of New South Wales

OFFICERS FOR 1973-1974

NOTICE

The Royal Society of New South Wales originated in 1821 as the "Philosophical Society of Australasia"; after an interval of inactivity it was resuscitated in 1850 under the name of the "Australian Philosophical Society", by which title it was known until 1856, when the name was changed to "Philosophical Society of New South Wales". In 1866, by the sanction of Her Most Gracious Majesty Queen Victoria, the Society assumed its present title, and was incorporated by Act of Parliament of New South Wales in 1881.

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Published by the Society
Science House, Gloucester and Essex Streets, Sydney
Issued 21st November, 1973

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PREFACE

Nearly twenty years ago, during the Premiership of the late Mr. J. J. Cahill, the Government of New South Wales decided that Sydney, in keeping with other major cities of the world, ought to have a music centre. The location chosen was Bennelong Point—an area in itself of historical significance and within sight of Sydney's famous Harbour Bridge. The resulting activities that led to the design and construction of this centre, the Sydney Opera House, are now part of Sydney's history. Most of us will forget the frustrations and difficulties associated with the project as we stand in admiration of the completed work, a monument to the achievements of modern technology. Along with the Harbour Bridge, it will remain a continuing source of pride for Australia, and especially the people of Sydney.

On the occasion of the opening of the Opera House by Her Majesty Queen Elizabeth II, the Royal Society of New South Wales is proud to publish this special issue of the *Journal and Proceedings* to commemorate the event. The issue is devoted to the contributions by those people responsible for the various aspects of the Sydney Opera House design and development.

Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 3–17, 1973

The Sydney Opera House
The Contractor and Some Aspects of Stage III

Abstract—The article briefly recounts the history of the area known as Bennelong Point, and then describes in some detail the Sydney Opera House project from the time of the architectural competition when the design of the now famous shells was chosen, to its completion as a complex catering for many forms of arts and sciences. The paper deals with the various activities of the main contractor's site organization, the difficulties of design and construction posed by this unique building, and the resultant solutions gained by the teamwork of the architect, consultant and builder.

The Site

When the First Fleet arrived in 1788, it landed its small herd of cattle on an isthmus they named Cattle Point. Later the name was changed to Bennelong Point after the aboriginal who lived there with his wife and achieved some fame by his services to Governor Phillip.

The site had its first association with the performing arts when it was the locale for the first corroboree performed by aboriginals for the entertainment of white men on 3rd August, 1811.

The first structure on the point was a fortification consisting of a small redoubt with two guns completed on New Year's Day, 1789. This was later superseded by Fort Macquarie, built by convict labour with stone from the Domain during the period December, 1817, to November, 1819. The structure was in the form of a square and became a Sydney landmark until it was demolished to clear the site for the construction of the Opera House. Its guns were never fired in defence. In 1903 the interior of the fort was converted into a tramway depot, which it remained until demolished.

The point has been described as an isthmus with a narrow approach at high tide. Although the earlier pictorial records do not clearly illustrate this, it is a fact that all manner of filling material was dumped on the approaches to the point. Apart from what is reputed to be ship's ballast, namely river gravel and some highly corrosive slag, the debris from construction works in the new Colony was deposited here, no doubt to form a serviceable wharf from the original jetty—Man-of-War Steps—which is still used and recently repaired. Rubble from the rock excavation to the Quay, and especially from the large excavation of the Argyle Cut in the Rocks, was deposited here. It has been encountered in all the excavation for the substructure work of the Opera House, as well as at least three stone sea walls that formed the early limits of Circular Quay.

This, then, was the site chosen for the Sydney Opera House by a committee appointed by the New South Wales Government in 1954.

The Architects and Engineers

On the basis of a design submitted as a result of a world-wide competition, Mr. Jørn Utzon of Denmark was appointed architect for the Opera House in 1957.

The consulting structural engineers appointed on his recommendation were Ove Arup and Partners.

Jørn Utzon resigned in 1966 following disagreements with the New South Wales Government at a time when the erection of the concrete shells was substantially complete.

A consortium of Australian architects, Messrs. Hall, Todd and Littlemore, was commissioned to complete the building, and commenced a review of the project in the latter part of 1966.

The Construction Contracts

The work has been carried out by private contractors under the supervision of the New South Wales Government and appointed architects and engineers.

There have been three main contracts, three separate contracts, and with fees and charges the project has cost approximately $100M, as follows:

		$
Stage I, 1959—Podium, Civil & Civic Pty. Ltd.	approx.	5·5M
Stage II, 1962—Roof Shells, M. R. Hornibrook (N.S.W.) Pty. Ltd. ..	approx.	12·5M
Stage III, 1966—Completion, The Hornibrook Group		56·5M
Separate contracts — Stage Equipment, Stage Lighting, Organ		9 M
Fees and other costs		16·5M
		$100 M

Stage I was let by competitive tender, and work commenced before the superstructure and the roof design had been finalized. Modifications to the plan and uncertainty regarding the roof structure extended contract time and cost.

Stage II. Whilst Stage I was under construction the engineers and architects investigated many different ways in which the roofs could be constructed.

Originally intended by Utzon to be a system of parabolas built in off-form concrete, it finally appeared that the only viable solution would be precast and stressed concrete, using pairs of balanced shells, necessitating modification of the geometry to spheroid in curvature. Utzon redrew his design, making use of a constant radius of 246 ft (75 m) for all shells, and gained the volume or shape that he desired by a variation in the pitch of the arches.

More than two years of work, involving the use of digital computers and extensive model tests, was necessary to evolve a practical design. Even during construction computer programmes designed to check the erection procedure required access to the computer used by the Weapons Research Establishment in South Australia. It is estimated that computer work undertaken would have required 100,000 man-years of mathematicians' time.

Construction of the roof shells involved techniques never before attempted in building construction, and in the words of Ove Arup, " on the boundaries of what is technically possible ". For this reason it was not considered that the contract could be the normal firm price system, and M. R. Hornibrook (N.S.W.) Pty. Ltd. entered into a cost plus fixed fee arrangement to undertake the work.

Stage III. In 1966, with the end of the Stage II contract in sight, and coincident with a change in the architects, the New South Wales Government entered into a further contract with Hornibrook, by then a division of Wood Hall Ltd., to complete the remainder of the building. This was by far the greatest value of the main contracts placed, and whilst it consisted of more traditional building works and services, did include work unique to the Opera House.

The infill walls between the concrete shells such as the bronze walls and glass walls had not been designed, and the whole concept of the Opera House as a Performing Arts Centre was under review by the new architects.

Separate contracts let by Utzon for stage machinery to Waagner-Biro of Vienna, and stage lighting to Siemens Industries Ltd. had also to be revised.

Revision of Use

Utzon's scheme envisaged two main halls, namely:

(1) A dual-purpose Concert Hall and Opera or Ballet Theatre;

(2) a Drama Theatre.

A small chamber music room and rehearsal and experimental halls were also provided.

Peter Hall, the design architect in the new consortium, was not satisfied that the dual purpose hall could be achieved in view of the conflicting demands of concert and theatre in both seating arrangements and acoustic qualities. Thus he and his partners eventually proposed to the Government that the project be revised to provide

(1) a Concert Hall,

(2) an Opera and Ballet Theatre,

(3) a Drama Theatre,

(4) Music Room and Cinema.

In addition, a Recording and Rehearsal Studio, a large Rehearsal Theatre, an intimate Recital Room, as well as an Exhibition area, were to be incorporated.

Utzon's scheme had depended upon the isolation of the two main halls to overcome sound attenuation, but in Hall's scheme the auditoria were much closer to each other (in fact they are not only cheek by jowl but overhead as well), so that reliance had to be placed upon engineering structural design to achieve the sound isolation that was necessary for the extremely high acoustic criteria.

Furthermore, the original concept had only intended to air condition the main hall or the smaller hall, but not both together. There was no air conditioning to the dressing rooms. The proposal to air condition all the areas within the complex not only meant designing a much larger plant but called for its installation within a concrete structure of such complexity that to cut any hole more than 9 in square (5,800·0 sq mm) called for a structural engineering decision.

However, the New South Wales Government was convinced of the advantages of the proposal, and in 1967 authorised the revision to proceed.

Revision Work

As a result of the revised plan, some structures already partly complete had to be demolished or modified. Principally these were:

(*a*) The stage tower steelwork to the main hall already complete was dismantled and removed;

(*b*) the minor hall pit structure was progressively demolished and reconstructed further south to provide a larger orchestra pit;

(*c*) the experimental theatre stage area was remodelled to provide a revolving stage structure as well as a thrust forestage for drama.

(*d*) the mechanical stage and lighting equipment was redesigned to accommodate the revised areas in the minor hall and the Drama Theatre.

At this time, however, the problems of the infilling external bronze and glass walls were still unresolved as well as the major decision regarding the ceiling structures within the two main auditoria.

Target Programme

When the review of programme was undertaken in mid-1967, it was decided that the target completion date was to be December, 1972.

To realize this, it was apparent that progress must be such as to expend in excess of $1M per month at peak production, and this to be maintained for some months. Doubts were expressed that this could be achieved on such a complex project, for such an output had only been possible on one previous project in Australia: a large airport terminal which was more suited to concentrations of labour and repetitive construction.

Not only was the project used for a full-scale concert in December, 1972, but as is reported later, the rate of output was more than double the anticipated $1M per month due to greatly increased budgets and requirements.

Site Management

From the contractor's point of view, the biggest difficulty in the early months of Stage III was to weld together a construction team that had to work hand in glove with architects and consultants as the design progressed on the board and who had to start work as soon as the drawings came out of the printing machine.

The production task was subdivided into five main responsibilities:

(1) Co-ordination. This was the team who from initial co-ordination with the designers checked out and overcame the inevitable physical conflicts in design, the routes of pipes, the preference of one service over another, etc.

(2) Planning. This team worked alongside the co-ordinators and from network diagrams of each area built up the overall programme.

(3) Field Supervision. This was the labour control under a Project Superintendent, who on average had five area superintendents answering to him.

(4) Subcontractors' Control. This team administered the whole of the subcontractors other than the field control. As the subcontracts were valued at more than the direct labour component, this administration accounted for the greater part of the project.

(5) Administration. This control dealt with all clerical work, stores, wages, bookkeeping and accounts, as well as the formal industrial matters not handled by the field office.

All these site executives reported to the Project Manager, who was resident on site (Figure 1). Their duties are recorded in more detail later in this paper.

Apart from numerous day-to-day meetings at all levels, the continuity of communications and control was maintained by the following regular assemblies:

(*a*) weekly management meeting of Project Manager and his staff,

(*b*) weekly meeting of Project Manager with Architects and Client Authority on policy and technical matters,

(*c*) fortnightly meeting with Architect and Client on administrative matters,

(*d*) weekly meeting (later fortnightly) with Architect, Client and Quantity Surveyor on Cost Control,

(*e*) monthly meeting of Architect and all contracting firms on progress.

Co-ordination of Services

The Co-ordination Group was initially set up during September, 1970, between the

Architects (Hall, Todd and Littlemore), Mechanical Consultants (Steensen and Varming), Electrical Consultants (Julius Poole and Gibson) and the Head Contractor (the Hornibrook Group) to handle all aspects of the co-ordination of services throughout the complex. All parties worked together as a complete team.

The Hornibrook Group section of the team participated in the design co-ordination of all areas in checking combined service layouts as regards their feasibility for installation. All the relevant subcontractors were consulted in detail at this stage prior to the preparation of their shop drawings. This enabled direct information to be given to them so that they were aware of all other services that could conflict with their own.

There were two main criteria in these solutions: economics and job progress. Site sketches were prepared as a result and approved by all parties. These sketches were issued under site instructions from either the consultants and/or the architects.

Each member of the Hornibrook section worked in with the relevant area site supervisor on site matters and also the area programmer on the programming of the services. They also helped in site clearances such as areas above ceilings, together with the Clerk of Works prior to the erection of any ceilings and partition walling surrounding service ducts.

One of the main areas of activity was the co-ordination of services and equipment in the kitchen and bar areas. Hornibrook worked in direct conjunction with the architectural design office, and drew up set-out points for kitchen ceilings, electrical points and equipment together with all the cool rooms.

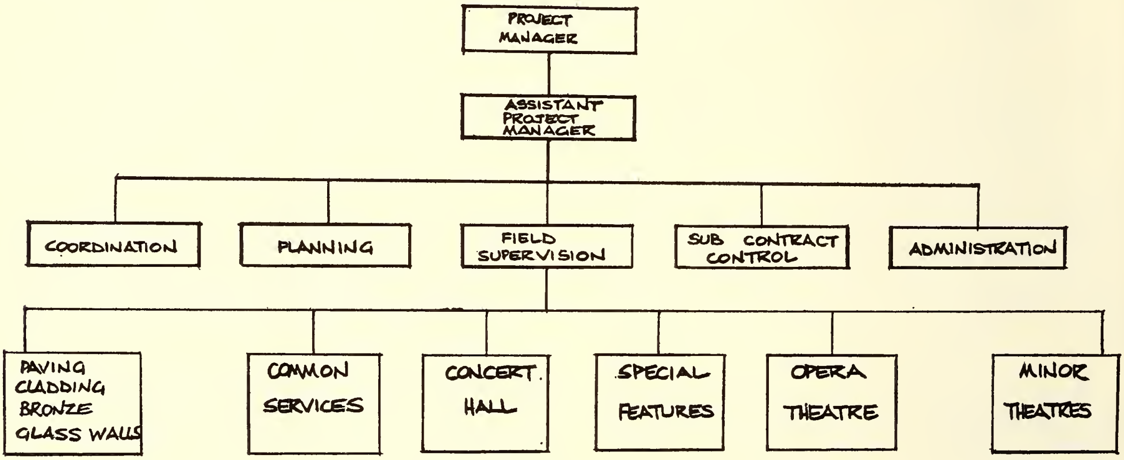

FIGURE 1.—Site staff organization.

There were many very complex areas and it was necessary in direct consultation with the subcontractors to prepare detailed combined service drawings with enlarged cross-sections at strategic points to sort out the " jungle " of services.

The main area of activity was in direct site control and liaison with subcontractors. Each member of the Hornibrook section was directly responsible for a set area. They would make regular site inspections and check the levels and positions of all services against both the shop drawings and the combined services drawings. They were also responsible for the initial approval of shop drawings before they were approved by the architects and consultants. If a " foul " were encountered, then the group gathered all the interested parties together and resolved the problem in the best way possible.

The team functioned very well and the results bear witness to the effectiveness of the participation of all the consultants, architects and subcontractors in this aspect of the project.

Planning Phase III

Planning for Stage III was unlike most contracts because there were no definite start dates, no detailed design for majority of the works, few output activity rates, as most design entailed new, or relatively new concepts. The only programme criteria in most cases were design start dates and target completion.

The three major programming steps were as follows:

Major Overall Job Network

This was a very broad network, splitting the job into five sections (Concert Hall, Opera Theatre, "A" Areas, "B" Areas, "C", "D", "E" Areas) and showing overall priorities.

Major Section Networks

These were still very broad networks, but projected the design, construction and finished durations of major trades.

Detailed Programmes

This stage of the planning saw the setting up of a large programming/co-ordination team to compile and progress these programmes. Sections of the job were split into smaller areas (total 64) and a detailed programme compiled for each area, group of areas, or in some cases part of an area. These programmes covered all phases, i.e. architectural and consulting engineers' preliminary and final design, shop drawings and all relevant approvals, and checking off site fabrication. Planners and co-ordinators liaised with all parties, endeavouring to meet this design and construction programme.

The use of a computer programme was considered and was initially commenced but soon abandoned as so much flexibility was required due to the continued changing and updating resulting from the design, that the staff necessary to handle this operation successfully could produce progress and action sheets with more accuracy and regularity than would have been probable with a computer.

Furthermore, the use of the computer to produce a print-out programme appeared to make the logic too remote when considering the innumerable variations that were necessary, nor was the available experience and assistance from the trade supervision readily forthcoming when a computer programme was produced.

Field Supervision

As can be seen from the organization chart, the supervision of works was a key post and thus was filled by the Project Superintendent. His control in the field was through five superintendents, consisting of four area supervisors and one general services supervisor. The former was responsible for an area of the project, e.g. the Concert Hall, and the latter for support services such as concrete batching, rigging crew and survey, etc. Each area supervisor controlled work similar in value to a large size city building of some $5–10M.

In addition, and from time to time, a supervisor would be appointed to oversee special features; e.g. the suspended ceilings in the main halls, which were the responsibility of one supervisor to maintain continuity with the subcontractor and to take advantage of the experience gained.

Liaison and co-ordination with the mechanical and electrical consultants and subcontractors were maintained by the main contractor's Mechanical and Electrical Engineer. This was a particularly demanding task in view of the magnitude of the installations, especially since commencement of one trade depended upon the progress of another. For instance, the central heat pump was needed for hot or chilled supplies to the air conditioning, which had to function before the vast timber linings could be installed in the auditoria, and all of which needed transformers and electrical power to supply energy.

Subcontract Control

This division dealt with the documentation, calling of tenders, entering into contracts and the general administration of contractual matters including payments.

Documentation was subdivided into four headings, viz.:

(*a*) Tender Conditions.

(*b*) General Conditions of Subcontract.

(*c*) Specification.

(*d*) Appendix to the General Conditions.

A Bill of Quantities was usually part of the above documents, either as information to tenderers or as a measured basis if conditions of tender called for remeasure on completion.

(*a*) *Tender Conditions*

These generally set out the requirements of the tender, such as lodgment of documents, tender closing date, what hours and/or days are worked, etc.

(*b*) *General Conditions of Subcontract*

These were the rules and regulations under which the subcontract would be administered, and were of a general nature as it was impracticable to write special conditions for every subcontract. The conditions dealt with insurance, drawings, method of payment, submission of claims, arbitration procedure, subletting, time for completion, etc. However, because these conditions were of a general nature there was a specific appendix.

(*d*) *Appendix to the General Conditions*

In the appendix reference was made to the particular clauses under the General Conditions, and then pertinent facts were given, such as:

Time for completion: The exact date was given.

Payment: The exact date of submission of claims and payments was given.

Liquidated damages: The exact formula was stated.

Drawings: To be supplied or not.

Defects Liability Period: The exact period was given.

Etc.

(*c*) *Specification*

This part of the documentation dealt exclusively with the technical aspect of the job and, in combination with the tender drawings, enabled the tenderers to arrive at a proper tender price. It was usually imperative to inspect the site during the tender period.

(*e*) *Tender Form*

The documents contained a special tender form on which the contractor stated his price and any schedules of rates if applicable. The form was signed, witnessed and submitted on or before the due date.

(*f*) *Selection of Subcontractors*

Invariably the tenderers for sections of the work were selected and invited. Having invited tenders, it became almost obligatory to accept the lowest bid unless there was some grave error in pricing, in interpretation of the requirements, or if there was some qualification to the offer.

It was therefore necessary to carefully investigate the potential stability of the subcontractor before inviting tenders. This scrutiny was not only concerned with financial stability but also with the availability to the subcontractor of proper and adequate supervision and whether their work load was such that they could cope with the Opera House demands within the given time.

Not the least consideration was the labour force engaged by the subcontractor, whether he could sufficiently augment it, and whether the terms of engagement and rates of pay by the subcontractor were such as to cause dissatisfaction with other terms existing on site.

(*g*) *Variations*

It was imperative that the financial position between main contractor and subcontractors was up-to-date, and the regular placing of variation orders ensured this. Issuing first as a request for pricing, a standard form of variation was utilized that enabled the contract value to be recorded in a monthly statement to the client.

(*h*) *Payments*

Payments on account and in finalization of subcontracts were made through the normal accounts section of the project, but only after checking and authorization by the Subcontract Controller. This necessitated a form of book-keeping and ledgers in the Subcontract Controller's division dealing solely with those contractual accounts and their adjustments, containing more detail of variations, etc., than that usually contained in a set of company accounts.

Administration

Administration of the project covered the fields of accounting incorporating actual cost control, personnel and industrial relations, insurance, security and sundry items of a general administrative nature.

To maintain and report progressive costs, a computer programme was designed to produce a purchase journal, general journal, list and value of goods received and not yet invoiced, list of outstanding commitments, list of current outstanding orders, labour and material used in both hours and value, and finally a cost summary produced on a monthly basis. To enable the examination of costs against estimates, these accounting returns were broken up into areas and subdivisions to cover all breakdowns of work performed. A series of progressive code numbers was used to denote the various functions. The cost summary then gave a period (monthly) and an accumulative total for the overall job to date.

By feeding in orders as placed with estimated values, it was always possible to obtain fairly accurate costing of goods delivered by using a percentage of the total order represented by the delivery, thus ensuring the inclusion of costs on items for which no creditor's charge had been received.

The programme was based on the minimum number of account dissections commensurate with the detailed costing required, bearing in mind that much of the work on this project was of a "one off" nature and historical costing would be of little value.

The use of the computer enabled monthly costs to be available for examination within 7–10 days of the conclusion of the period. Whilst a staff saving results from the use of the computer, it does not obviate the detailed preparation of weekly input, which still requires personnel, though not necessarily all qualified.

The computer has also been used for the calculation of wages for several hundred employees. This was a great time saving.

Industrial relations on a project such as this have called for constant attention. Following as we did from Stage I of the project, during which a site allowance was agreed with the unions, considerable industrial unrest was experienced when it was made known that Stages II and III would be completed under award conditions and that no allowance would be paid unless appropriate rates or conditions were recognized by the Industrial Commission and inserted in the various awards. Despite constant pressure this condition has been achieved.

Insurance cover on such a complex project required special attention, calling for a very comprehensive Contractor's All Risks cover, including Latent Defects and Legal Liability. Because of the amount of cover required and the unusual features of the construction, the underwriting had to be spread over world markets, and some proportion of this insurance is underwritten in every continent of the globe.

The safety record is one of which we are very proud, considering the difficulties encountered in construction. Special attention to safety has been the constant concern of both the company's Safety Officer and employee safety representatives. This has paid handsome dividends in the prevention of lost time and insurance claims. The site boasts a full-time Industrial Nursing Sister and a well equipped First Aid post.

Security on such a large site, with both land and water frontages, has been a constant source of concern, but the use of private security guards and special site procedures covering entree and inspection of vehicles, has enabled us to protect the structure and keep losses within reason for the industry. Losses cannot be stopped, but they have been reasonably contained.

Area Definition

The whole project was subdivided into areas for the purpose of identification and control. In broad principle, the Concert Hall and ancillary areas became " A ", the Opera Theatre and support areas became " B ", and common areas were " C ", " D " and " E ".

These broad divisions were further divided into operational areas indicated by a number ; for instance the Concert auditorium was known as A.25, whilst the foyers around it became A.23 and A.26.

This system of area coding proved so successful that the system has been adopted as the permanent code and is incorporated in all signals manuals and operational signs.

In addition, each room had a construction number and each door opening was scheduled. This facilitated the door scheduling and the group master keying system which has been adopted.

Industrial Condition

When the contractor for Stage I commenced work he faced a demand for special site allowance. In those days a site allowance was a new form of reimbursement and generally confined to isolated projects or hazardous or unpleasant work. To expect a site allowance on a job in the heart of the city of Sydney was unexpected, but eventually the contractor established such an arrangement.

With the commencement of Stage II on a cost basis, the New South Wales Government was emphatic that only proper award rates should be paid, and there began a protracted and sometimes bitter industrial fight to obtain at least the over-award payments enjoyed on the previous contract. No agreement was reached to pay a site allowance but an award by Mr. Commissioner Menser made payable certain rates for disabilities and hazard when working above ground, on, and in the concrete shells.

During the period of Stage III this agreement was observed by all parties and was instrumental in bringing about a state of comparative harmony in industrial relations.

The site suffered from being involved in most of the disputes in the city, as well as a few peculiar to itself.

It also received much more than its share of publicity in this regard, especially from the TV news teams—due no doubt to the photogenic qualities of the building.

However, bearing in mind the scope of the work and the enormous number of man-hours involved, lost time was reasonable, as the following figures indicate. (Period 1st April, 1970, to 31st July 1973.)

Hornibrook Labour :		
Total effective hours ..	2,147,482	(92·10%)
Total spread hours ..	49,071	(2·12%)
Total lost hours	134,886	(5·78%)
Total available hours	2,331,439	

Note : Spread time is that time spent in general services, e.g. gate control, stores, off loading. etc.

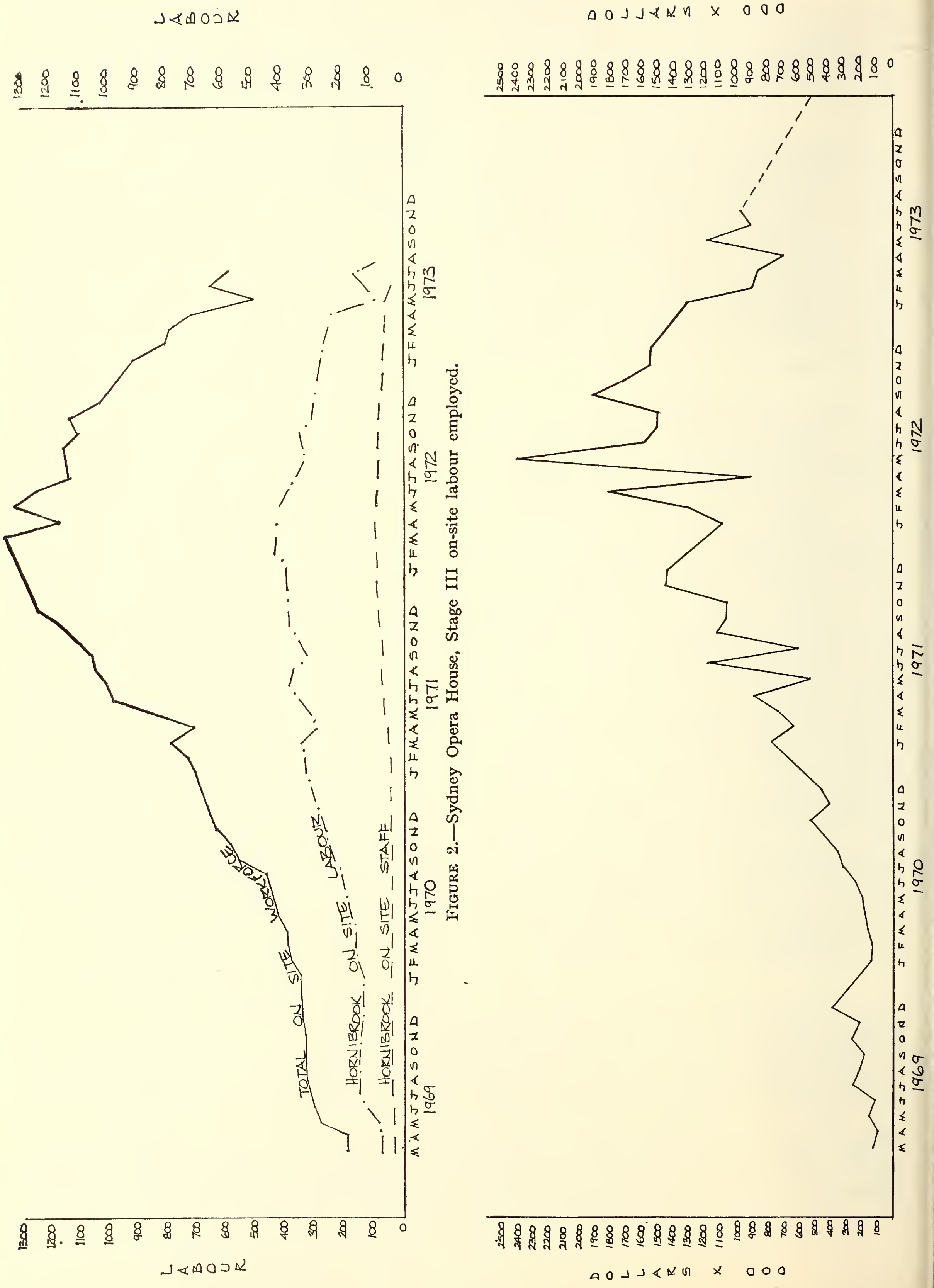

FIGURE 2.—Sydney Opera House, Stage III on-site labour employed.

Labour Force and Rate of Progress

The target programme had envisaged a work force of approximately 1,000 men, and it was considered that this would only be recruited with difficulty. For a number of reasons the anticipated rate of progress was not achieved in the years 1968 and 1969 and it became obvious that the work force needed to be well in excess of 1,000 in the years 1970–1972 to achieve the completion date.

Furthermore, costs and estimates were constantly increasing, not only because of the escalation in cost of labour and materials but also in the anticipated prices of some services. For this reason the budgets and designs were carefully controlled and it is a satisfaction to record that the work was completed within the framework of the 1967 estimate, but escalation in wages and material had inevitably and contractually to be met, which increased that estimate of $85M to $100M in the space of five years.

There were many nationalities employed on the works. All important signs on the site were in four languages. When a count was made on one occasion for a news article a total of 14 languages was recorded without distinguishing between the Australian tongue and the English.

The following graphs indicate the labour force engaged (Figure 2) and the progress that was recorded from the actual wages and accounts paid (Figures 3 and 4). It should be remembered that these amounts paid do not include work executed but not paid, retentions, and the like.

The labour force peaked at approximately 1,350 site operatives. An exact tally was not possible as some subcontractors and their supervision did not accurately record their attendance.

The maximum expenditure in one month was $2,450,000 approximately.

Both these figures are well in excess of any other similar construction performances in Australia.

Safety

As is generally found, those tasks that appear dangerous are treated carefully and usually are completed without mishap.

The whole of Stage II, the roof construction, was completed without one fatality and with very few serious accidents. This excellent record persisted into the latter period of Stage III when, unfortunately, a fatal accident occurred to a crane operator while rigging his machine.

Safety precautions were an important consideration in planning and supervising the work.

A resident Industrial Nursing Sister was located in the central First Aid station, and other First Aid posts were established throughout the building.

Personnel holding First Aid certificates were responsible for each post, and their names and locations were prominently displayed at the post.

A supervisor was appointed Safety Officer and two safety representatives were detailed from the work force. Their job was to correct minor breaches of safety, receive safety complaints from the men, and bring these to the attention of the Safety Officer.

Statistical records were kept by the Nursing Sister and detailed analyses of the types of injuries and circumstances under which they occurred were made. During the currency of Stage III full accident compensation became operable in the trade, but it is pleasing to report that the accident rate causing lost time was remarkably low and despite fears that full compensation may be abused there was little evidence of this.

Subcontracting

When awarding the contract to Hornibrook as main contractor for Stage III, the Minister for Public Works had assured the building trade that as much of the specialist work as was practical would be offered to subcontractors so that opportunities for participating in the project would be available.

It was therefore the intent from commencement of Stage III to subcontract as much work as was practical and economical, and the project was divided into sections and trades that enabled tenders to be called and subcontracts to be let.

The decision whether to sublet a particular section or to execute with directly employed labour generally revolved around the likelihood of obtaining satisfactory offers. It was soon found that the Opera House complex had engendered a hesitancy in the various trades, due, no doubt, to the involved geometry, the large scope of the work, and in some cases the unenviable reputation for industrial disputes that had surrounded the work in the early stages.

Some work could not be pre-priced. It was either too complicated and novel or the extent of the work was unpredictable. In such cases directly employed labour was invariably used, as it was if quotations received appeared to be excessive and unacceptable.

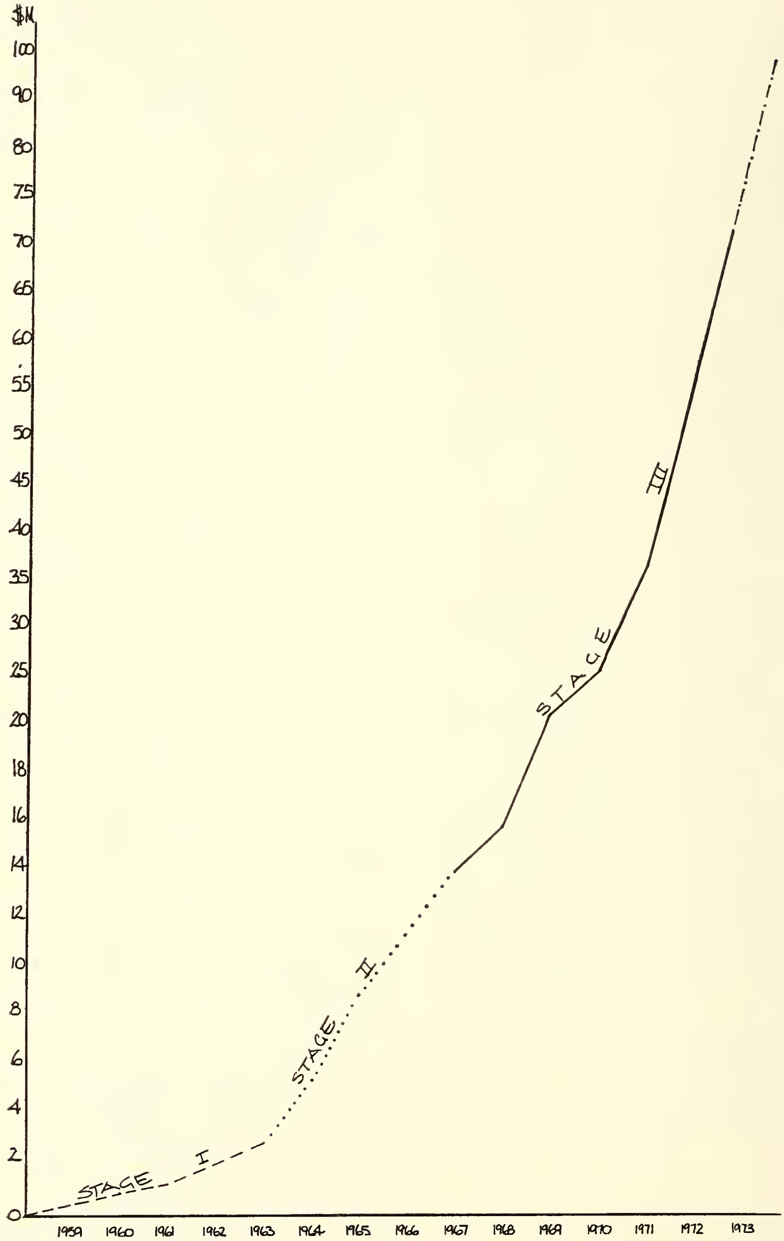

FIGURE 4.—Sydney Opera House accumulative expenditure.

All other work was sublet, but even then the terms of subcontract were drawn with a view to removing from the contract unusual risks or liabilities, thus attracting a more acceptable offer.

For instance, the original intent with the timber ceilings to the main halls was to leave to the subcontractor the responsibility for all survey, setting out, checking of panel sizes, etc. From preliminary discussions with the short-listed tenderers, it was evident that these responsibilities were causing considerable concern and being over-valued accordingly.

For the survey and setting out, one company intended using a firm of surveyors at a cost of $30,000, and other firms had not even reached that solution. There was not a shop large enough for a full-scale shop layout of the ceiling.

The conditions of subcontract eventually issued omitted all these requirements of the subcontractors—the main contractor's surveyors carried out the instrument work, the engineers computer defined the panel sizes—so that the subcontractor was left with work he well understood and could bid competitively.

Some subcontracts were let on a cost and material basis and one, the cutting and framing of the glass, was on a fee basis to a consortium of major glazing companies. These were negotiated with a view to obtaining the services of selected tradesmen and supervision.

The following is a list of the major subcontractors, with approximate values of the work executed in Stage III:

	$
Angus & Coote Acoustics Pty. Ltd.—Acoustic Doors	250,000
Arcos Industries Pty. Ltd.—Stage Tower Steelwork	300,000
A.W.A. Ltd.—Closed Circuit TV and Sound Systems	1,250,000
Aygee (Merchants) Pty. Ltd.—Dressing Room Furniture	135,000
J. W. Broomhead Pty. Ltd.—Steel Mullions	450,000
S. A. Butler Pty. Ltd.—Internal Painting	75,000
Carpet Manufacturers Ltd.—Carpets to non-Public Areas	130,000
Cemac Brooks Pty. Ltd.—Plywood Ceilings and Panels	1,250,000
Co-ordinated Design & Supply Pty. Ltd.—Auditoria Seating	1,250,000
E.I.L. Special Projects—Signals and Intercommunications	275,000
E.P.M. Concrete Pty. Ltd. — Precast Cladding	2,750,000
Fire Control Pty. Ltd.—Fire and Timber Doors	250,000
Frigrite Limited—Heat Pump	700,000
F. & T. Carpets—Carpets to Public Spaces	200,000
G.E.C.-Philips Pty. Ltd.—Lighting	2,500,000
George Hudson Pty. Ltd.—Timber Flooring	650,000
J. Goldstein Pty. Ltd.—Kitchen and Bar Equipment	380,000
Haden Engineering Pty. Ltd.—Air Conditioning and Hydraulic Fire Protection	4,750,000
J. M. Hargreaves & Son Pty. Ltd.—Plumbing Services	800,000
Hawker de Havilland Aust. Pty. Ltd.—Glass Wall Brackets	100,000
Indent Wall & Floor Tiles Pty. Ltd.—Ceramic Tiling	150,000
Instalrite Plastics Pty. Ltd.—PVC Piping	40,000
John M. Thomson & Co. Pty. Ltd.—Plastering	45,000
John Deck & Sons—Bronze Doors	40,000
Melocco Bros. Pty. Ltd. — Granolithic Paving	250,000
Nonoys Pty. Ltd.—Sliding Acoustic Doors	140,000
Nonporite (N.S.W.) Pty. Ltd.—Waterproof Rendering	45,000
Nucrete Pty. Ltd.—Pneumatic Concrete	200,000
O'Donnell Griffin Pty. Ltd.—Electrical Design and Installation	2,275,000

	$
Permasteel Windows Pty. Ltd.—Bronze Architectural Metalwork	1,600,000
G. Polhill & Sons Pty. Ltd.—Internal Painting	50,000
Premier Joinery Pty. Ltd.—Timber Flooring and Wall Panelling	900,000
Quick-steel Engineering Pty. Ltd.—Glass Wall Maintenance Equipment	60,000
Roof & Building Service Pty. Ltd.—Waterproof Membrane	180,000
S.T.C. Pty. Ltd.—P.A.B.X. System	95,000
Vasob Glass Pty. Ltd.—Glazing	450,000

Bronze and Glass Walls

Both of these sections of the work posed problems concerned with infilling the spaces between the overlapping concrete shells, and the solutions by both the architect and engineer were ingenious and intricate. Having devised the schemes, the designers looked to the contractor to implement them, which was done, but not without some misgivings and anxious moments until the unusual became commonplace.

Fortunately, there were still at hand the supervision and skills that had erected the concrete arched shells and had later threaded huge steel members through inadequate holes in the structure to form the internal steel skeleton from which the massive ceilings were suspended.

In the case of the bronze walls, the first problem consisted of providing access by way of working scaffold. The walls consist of an inner steel structure with vertically ribbed bronzed cladding externally, and sprayed concrete forming an inner face. The whole is warped and wreathed as the walls curve over the roof shells and twist forward as they rise.

To construct a scaffold on each side of the future wall necessitated surveyors constantly controlling the scaffolders so that an adequate and accurate working space was formed.

This and the subsequent construction of the steel and bronze work had to be executed high over and under the roof shells which form natural tunnels for wind currents and turbulent conditions.

The same crews of men were responsible for the erection of the steel mullions to the glass walls. These members were fabricated in lengths as long as practicable, pre-finished off site, so that handling and site working had to be with care.

The working tolerances allowed the manufacturer were more than could be permitted in the true line of the assembled structure as the depth of the rebate holding the glass was limited.

These unwieldy components had to be transported in special cradles, hoisted up and hung from the concrete shells, and then cross-braced and trued up by adjustable bracings until the line and position were within the acceptable tolerance of $\frac{1}{4}$ in. This tolerance was reduced to $\pm\frac{1}{16}$ in for bronze and glass.

All the glass sizes and shapes were computed, and although frequent checks from site measurements were made these were generally confined to abutments against the concrete structure or at intersections. The accuracy of the steel structure was of paramount importance.

Mechanical Services

The whole project is air conditioned or mechanically ventilated at a cost of $4M. The basic design principle was as far as practicable to provide localized plant rooms with heating and cooling coils throughout the building, thus reducing the amount of duct work and causing heat gains and losses to be kept to a minimum. Use is also made of vertical concrete shafts and double floor arrangements for air distribution. The air conditioning comprised installation of over 70 separate air handling systems, located in 24 plant rooms around the building and fed with heated and chilled water from a central refrigeration system. The air handling side consists of 120 fans (many of them two-speed fans), which move more than 1,000,000 c ft of air per minute when all the systems are running.

The conditioned air is distributed through approximately 12 miles of duct work to some 3,000 grilles and diffusers. The majority of rooms, and there are over 800 in this complex, are provided with individual temperature selection.

Ventilation, air conditioning and refrigeration machinery are all controlled by an electronic monitoring system located in the control room of the main plant room. This is the system's nerve centre. It automatically records an alarm when critical points of the system go outside predetermined limits. It raises an audio/visual alarm signal and automatically prints out, on a line printing machine, the source of the fault and the limit which has been exceeded.

Particular attention has been given to the problem of sound attenuation. All of the plant, equipment, duct work and piping is fixed with resilient mountings to prevent the transmission of vibrations, while ducts are internally lined and provided with silencers at strategic points. In addition, much of the duct work is fabricated in sandwich construction form (consisting of a number of layers of metal with rubber sheets in between) as an added sound-deadening barrier to prevent the entry of noise from outside into the system and hence to the auditorium. This causes the duct work to be very heavy—large pieces weigh anything up to half a ton each. To obtain an indication of the size of some of the ducting, it is no exaggeration to say that a car could be driven through it.

The installation in the Drama Theatre is unusual in that here is installed the first cooled ceiling in Australia. The intention is to give to a large group of people in a small space the feeling of comfort without moving large quantities of air with the attendant noise and draught problems.

The refrigeration plant which supplies heated and chilled water to the various air conditioning systems cost approximately $800,000. This plant incorporates a heat pump system, which through heat exchanger vessels uses the harbour as a heat source whenever the heating load exceeds the cooling load, and as a heat sink whenever the cooling load exceeds the heating load. The plant has a capacity of 1,500 tons of refrigeration, generated from three centrifugal hermatic machines, and with its associated sea water and fresh water circulating pumps has an electrical load of over 2,000 hp. The same control system previously mentioned automatically adjusts the output of the plant to maintain the desired water temperatures.

Lifts for the Opera House worth about $250,000 comprise seven electric lifts and three oil hydraulic lifts. Because of the Opera House design, these lifts are all driven from the bottom of the lift shafts.

Electrical Services

The main power for the site comes via high-voltage 11 kV mains to feed two substations at ground floor level. The installation comprises six 1,000 kVA dry type Tyree transformers, each of which weighs nearly four tons and is again mounted on resilient pads to reduce sound transmission.

Directly beneath the substation is the Main Switch Room where, at a cost of $100,000, has been installed a 60 ft long switchboard which houses all the tariff meters, switch gear and distribution equipment for machinery, light and power.

Emergency lighting and panic light systems are installed for use if the mains supply from both substations is interrupted. The huge battery comprises two banks of 190 cells each, operating in parallel with a capacity of 1,000 ampere hours. The nickel cadmium batteries weigh 12 tons. They are designed for a two-hour sustained load of 95 kW.

The principal electrical subcontractor has installed 250 miles of wiring.

The lighting installation, worth over $2M, has been handled by a consortium company especially formed for this project. The lighting is designed to highlight the internal and external features of the Opera House. There are nearly 14,000 lighting fittings installed. Incandescent fittings are used generally throughout the public areas, with some small halogen lights for accent purposes. Most of the working areas employ fluorescent lighting. Workshops are illuminated by colour-corrected mercury lamps. There are about 1,200 incandescent fittings for the dressing rooms.

Stage Equipment

Stage lighting and control equipment was the subject of a separate contract, for a little over $1M. Much of the basic equipment is of German origin. A contract was let some years ago for the supply and installation of stage machinery and, of course, it was essential for the stage erection and the stage lighting organizations to work in close collaboration with each other. Both the Drama and Opera Theatres have 50 ft diameter revolving platforms. The Opera Theatre Stage is some 35 ft above the set changing and preparation area. A vertical transport platform can travel up from the set change area to the performers' level, change over a set, and disappear again whilst a performance is still continuing on the front of the stage.

Fire Precautions

All the usual safety and fire precautionary measures are built into the project, and particularly the stage areas. It would be true to say that more precautions have been taken here than with any other theatrical building in use anywhere. Drencher curtain systems are installed to protect the fire safety curtains for the stage openings of Opera and Drama Theatres.

The more conventional fire protection facilities are worth nearly $1M and cover hydraulic sprinkler installations in most areas of the building, totalling nearly 7,000 sprinkler heads and 140 hydrant stations. Areas housing expensive electrical equipment, where damage from water could be as disastrous as that caused by fire, are protected with total flood B.C.F. gas-extinguishing systems. Kitchen areas have extract systems associated with cooking equipment, protected by CO_2 gas systems.

Communication Systems

Worthy of particular mention are some of the complex and advanced electronic systems associated with this project. There are electro-acoustic and simultaneous interpretation systems worth over $1M.

The electro-acoustic system provides comprehensive sound amplification and distribution in the various theatres and public areas. The equipment incorporates features which allow producers to control sound reproduction to suit their individual requirements.

Of particular interest is the electrically tapered speaker column used in the Concert Hall, which is the first of its kind in the world.

As performing arts do not normally occupy a total yearly season within the building, provisions have been made for extensive conference facilities. The simultaneous interpretation system allows multi-lingual conferences to be held. Speeches from either the dais or the body of the hall will be translated simultaneously to conference members and relayed over a radio induction loop under the floor of the auditorium. Delegates are provided with pocket radio receivers and may listen to any language they wish by selecting the appropriate channel on their receiver. In the Concert Hall and the Opera Theatre there is provision for five languages, and in the Drama Theatre, Cinema and Recital Hall for three languages. These head-sets have a jack incorporated which allows a patron to tape record a conference in any language being used. The system can also be used for patrons with hearing problems.

Part of the conference facilities is an Optronic Paging Device : a sign which allows a message to be illuminated on stage. This sign has a built-in memory so that the message can be repeated at given intervals until the call is answered.

The importance of communication between stars, stage administration technicians and patrons has led to the installation of many sophisticated electronic communications systems within the Sydney Opera House complex.

Apart from the systems which are available to normal occupants of the building, there are special systems which centralize around the Stage Doorkeeper's Office. All security services, alarm bells, fire warning lights, etc., terminate in the Doorkeeper's Office on a large mimic display panel. This panel is manned 24 hours a day and all building alarms are recorded on the panel. The lights throughout the project are indicated on mimic panel plans of the Opera House so that a constant monitor of lighting can be kept. Lights can also be switched from this panel when control is released from the local switch panels.

There is a Radio Paging Service throughout the building which can be initiated from the Stage Door or the telephone switchboard. If the Doorkeeper or the telephonist wishes to reach persons who are not at their telephone points, they can initiate a radio paging message which will be picked up by portable receivers issued to key personnel upon their arrival in the building.

In the case of key technical personnel, these radio signals are coupled with critical alarms. For example, a critical fault occurs in the mechanical ventilation system and records an alarm at the Doorkeeper's Office ; it automatically sends a warning signal to the Chief Engineer, who carries one of the receivers.

Security was a major consideration in the planning of this project. All external doors to the building are monitored for forced entry and automatically show whether the door is in an open or closed position or has been tampered with. This is recorded on the panel in the Doorkeeper's Security Office.

Facilities are located in the offices of key personnel and in stars' dressing rooms. All other dressing rooms and many other staff offices within the building have similar systems, but on a less comprehensive scale. The facilities are centralized in a wall unit called a " Room Service Module ".

Perhaps the best way to explain the capabilities of some of these systems is to take the example available in a conductor's room.

A conductor may wish to tune up an instrument in his room without having to resort to a tuning fork or calling in a passing oboist. He simply walks to his Room Service Module and presses a button. Through a speaker in this module a four forty cycle " A " tone is produced with all the overtones of a normal oboe. He is also linked through this module to the Stage Manager's call system. In each of the theatres the Stage Manager can call dressing rooms which are preselected to occur on an indicator on his desk. As there can be many performances at any one time, the dressing rooms for each of the theatres are allocated beforehand, so that each Stage Manager knows where the personnel for his performance are located. The allocated dressing rooms show up on his desk in the form of illuminated buttons. During a concert the Stage Manager might wish to call his conductor, and he does this by pressing a button and speaking into his microphone, which automatically reproduces his voice in the conductor's suite. The conductor, from anywhere in his suite, can speak at a normal voice level, his voice being picked up by a sensitive microphone and relayed to the Stage Manager's desk. A red light flashes over the Room Service Module when the area is being listened in to by the Stage Manager.

A conductor may wish to see how many people are attending his particular concert that evening, or watch a performance in another hall. He can do this by selecting the channel on his module, which will display on a 21 in television monitor screen in his room a closed circuit television picture of the selected auditorium. After the performance, or whilst relaxing, he may wish to watch normal television channels. These can also be picked up on his monitor by a selection made at the Room Service Module.

The conductor also has facilities to tune in and listen to the music or activities in any of the major rehearsal rooms or auditoria. This allows the conductor to get a high quality reproduction of sound of the activities in those rooms. He can listen to his orchestra warming up or rehearsing in his absence.

Attached to the module is a house telephone system which enables him to dial, without going through the operator, any other room in the building. There are facilities in each of these suites to have separately metered telephone calls, so that he may call any part of the world and have the charge debited against his personal account. He has the facility of using the main telephone operator for local calls or, for example, ordering a meal from the catering service.

The closed circuit television system previously briefly described, in the conductor's suite, has many other uses. Late-comers unable to enter the auditorium after the start of a performance can watch the performance in a Bar Area on the closed circuit television system. In the halls where a conductor will be operating there is a separate camera covering the conductor's movements. These are relayed to various rehearsal rooms and to the back stage area, so that artists who are awaiting their cue can come in on the correct beat. The major rehearsal room is coupled with the Opera Theatre through the sound system. An off stage choir can perform in this theatre and its sound be transmitted to the auditorium whilst having a visual display of the conductor.

Integrated with this system is a tele-cine machine. This allows any messages which need to be passed to the patrons, such as calling for a specific person or notification of changes of cast, to be put on to the television sets in exactly the same way as credits are given on commercial television at the end of programmes. It can also be used to transmit foreign language messages, 35 mm slides and 16 mm projection film.

Within the closed circuit television network provision is made for a videotape recording unit. This unit comprises a mobile trolley equipped with closed circuit television camera, a videotape recorder and monitors. The unit can be used for staff training, for example in the replacement of complicated pieces of machinery or in the setting up of scene sets for opera, for training performers during rehearsals by recording their sections on stage and replaying them after the production. It has potential also for use by visiting producers. In the past we have had producers from Covent Garden jetting to and from Australia whenever their time permits them, to produce an opera in Sydney. The frequency of these visits could be diminished and the production could be improved by sending videotapes to the producer overseas at significant stages during the rehearsals.

For overflow crowds at performances or big conventions, the closed circuit television network can be linked to other auditoria, indicating to them the activities in the hall of their choice.

Facts and Figures

Height of tallest shell	221 ft above sea-level
Weight of roof	26,800 tons
Weight of building (Excluding granite paving and cladding)	125,000 tons of concrete 6,000 tons of steel
Width of external approach stairway	282 ft
Ground area of building	$4\frac{1}{2}$ acres
External dimensions up to	611 ft × 379 ft
Number of precast tile panels	4,253 (containing over 1,056,000 tiles)
Number of precast segments in roof	2,194 (weighing up to 15 tons each)
Surface area of roofs	About 200,000 sq ft
Total length of stressing cables in roofs	217 miles
Unsupported span of concourse beams	From 136 ft to 164 ft
Area of granite paving and cladding	10 surface acres
Supporting piers and columns	The building is supported on about 550 3-ft diameter concrete piers, many sunk to more than 70 ft below sea level. End to end, they would extend for more than $2\frac{1}{2}$ miles. The roofs are supported on 32 columns, ranging in size from 4 ft to 8 ft square
Electrical installations	400 miles of cable in 60 miles of conduit with supply governed by 120 distribution switchboards. A bank of 12 tons of batteries is installed for emergency lighting
Air conditioning	The plant rooms will supply 20 tons of air per minute throughout the building

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(Received 27 August 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 18–32, 1973

Roof Cladding of the Sydney Opera House

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Abstract—The tiled roof cladding of the Sydney Opera House is probably the most important visual element of the building. It has been designed and constructed within the constraints of a strong geometric discipline which dominates the form of the Opera House structure. The paper outlines the design development and details, methods of construction used, and the techniques which were evolved to construct these elements by employing factory production methods to take advantage of the repetitive geometric forms which make up the roof structure.

Introduction

Much has been written about the Sydney Opera House, and numerous books and papers have been published (see References). Some describe the more controversial aspects of this unusual building, whilst others deal with technical considerations. The building is extremely complex, and in a paper such as this it is possible to highlight only a particular aspect of the structure. The roof cladding or " tile lids ", as they came to be described during the construction, constitute the most important visual element of the building. The selection of the tiles, the way in which they were fabricated into large pre-cast components, the accuracy of manufacture and placing, as well as the intricate pattern formed by the arrangement of tiles on the lids introduces a strong sense of geometric unity which is the central theme of the whole of the roof structure and its cladding.

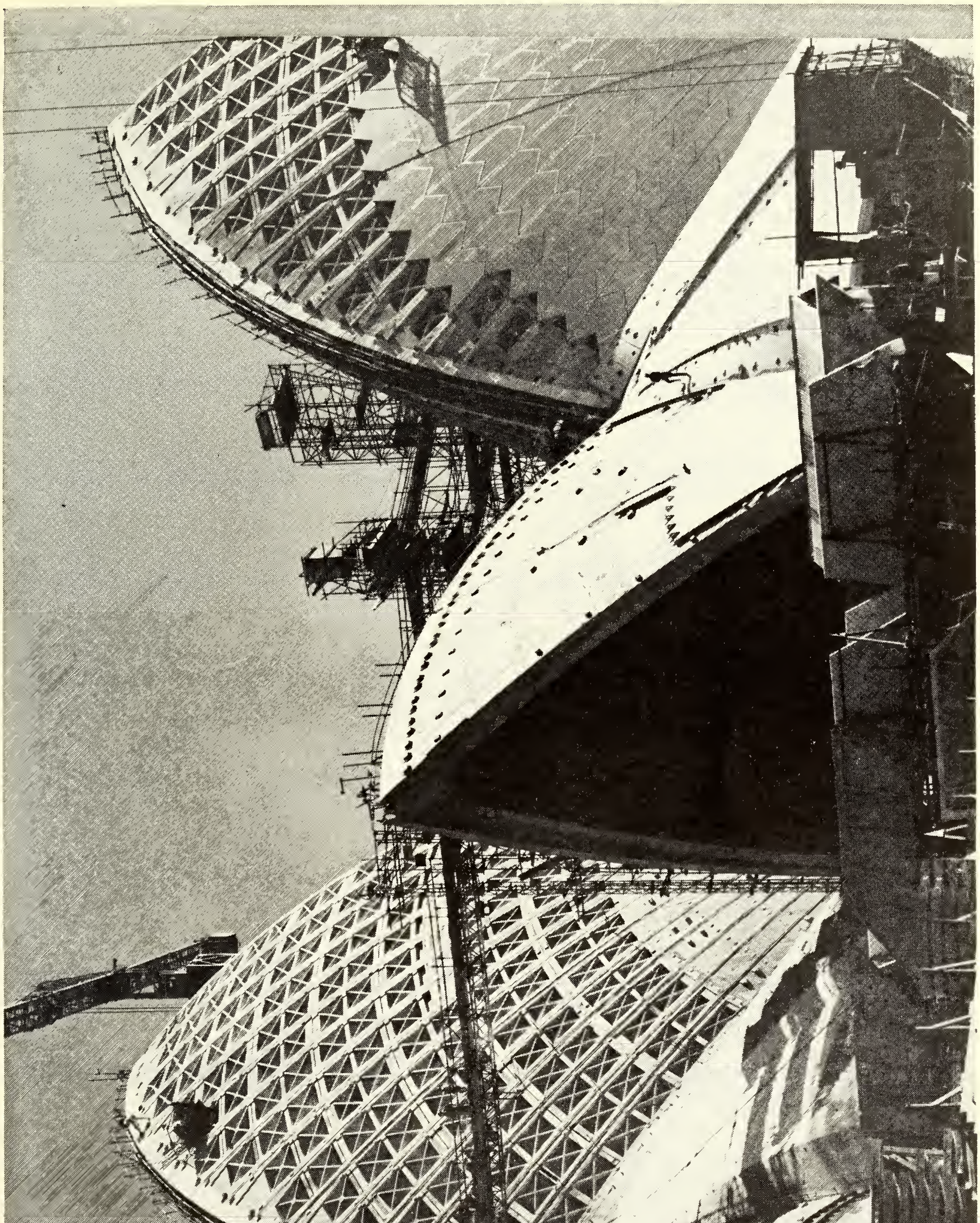
The Opera House is located on a peninsula jutting into Sydney Harbour on the northern end of the high-rise buildings in the central business area; it is adjacent to the harbour bridge and botanical gardens. It is a building which is seen in the round and from above—the sculptural form has been designed with this in mind and the selection of a material to cover that form was made by the Architect with great imagination and perceptiveness, producing a surface which expresses liveliness and interest under differing conditions of light—it is a form which is disciplined but never monotonous.

The Tiles

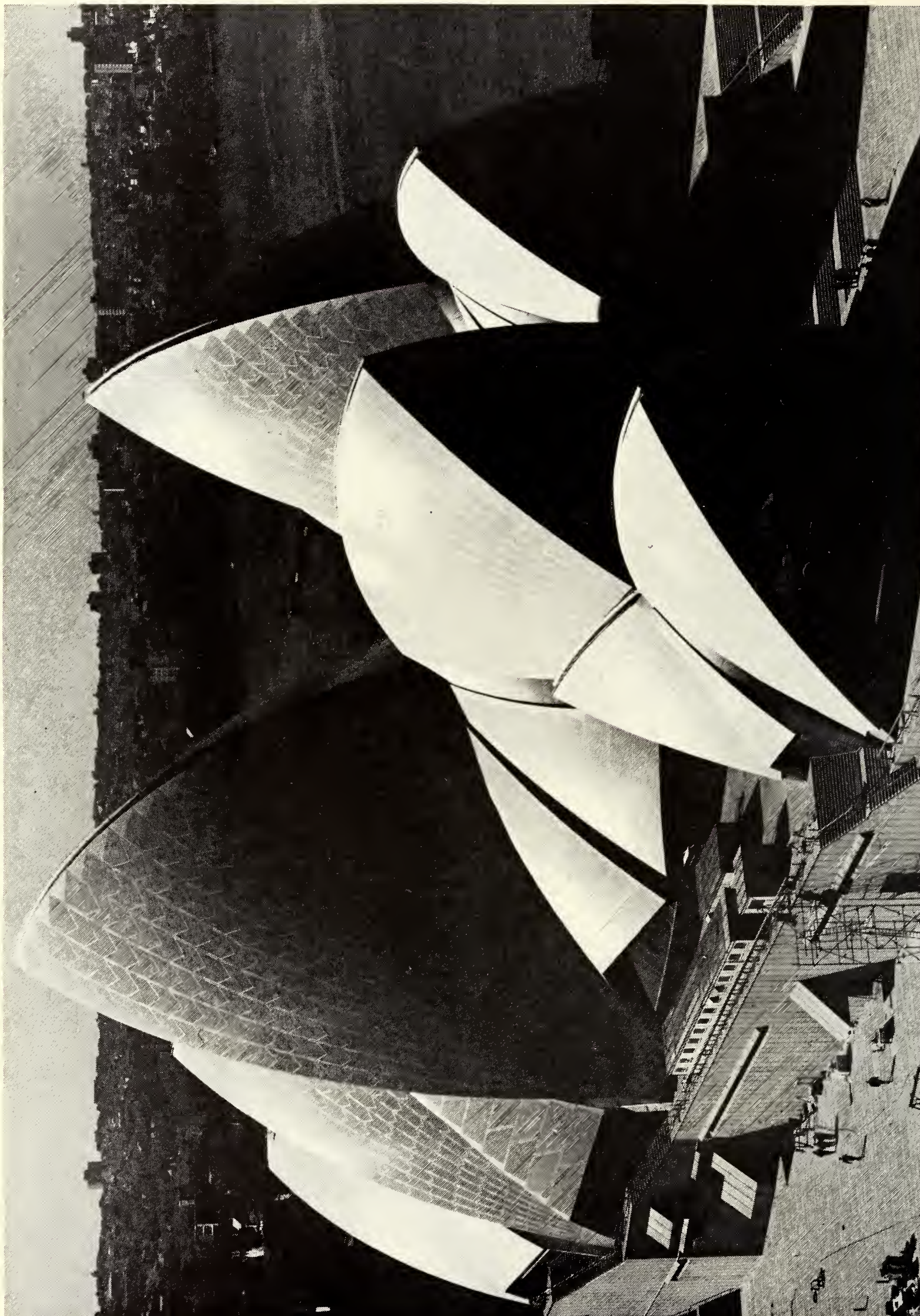
The tiles were manufactured in Hoganas, Sweden, after extensive research by the Architect to achieve a white ceramic tile with glazed finish and an underlying rough texture. There are two types of finish, " matt " and " glazed " which have been arranged in a specific pattern on the lids—although a close scrutiny of the tiles shows a marked difference between the two materials, the difference in reflectiveness creates a subtle pattern on the surface which defines the edges of the tile lids and introduces the underlying anatomy or structural form of the load-bearing elements beneath. Standard tiles are $4\frac{3}{4} \times 4\frac{3}{4}$ in (120×120 mm) and $\frac{5}{8}$ in (10 mm) thick—there are approximately 1,000,000 tiles cast on to 4,253 tile lids and eight different tile types. All tiles were cut to size in the factory before firing, packing and shipping from Sweden to Australia.

Tile Lids

In the original design submission, the Architect had expressed his intention to tile the roof, but the structure at that time was conceived as a cast *in situ* reinforced concrete shell comprising two thin concrete membranes separated by a cellular void. The geometry of the outer surface was defined by an elliptical paraboloid which was unsuitable for repetitive precasting. On such a surface, the tiles would have to be laid by traditional methods involving serious risk of tiles falling off due to thermal strain and inadequate bedding of individual tiles. It was inconceivable that this vast number of small tiles could be laid in a satisfactory manner by tilers working on the surface of the roof. This was an important consideration in the decision to change the geometric definition of the roof surface.[(1)]



Erection of tile lid.



View of completed roof

Geometry of the Roof Structure and Tile Lids

The roof structure covers the two main halls and the restaurant. There are three main elements forming each roof structure (Figure 1)—main shells (A1, A2, A3, A4), side shells (D5, D6, D7, D8) and louvre shells (C9, C10). Each shell is made up of two half-shells symmetrical about the central axis of the hall. Each half is a mirror reflection of the others about a vertical plane along the central axis of the hall. Some leading dimensions give an indication of the scale of the roof structure. The height to the top of the largest shell from its springing point is 179 feet (54·6 m). The longest rib is made from 13 segments covered with 26 tile lids; the arc length measured along its centre line is 210 ft (64 m). Each half main shell (A1, A2, A3, A4) appears in elevation as a curvilinear triangle standing on a vertex. Each triangle which forms the outer surface of the shell is a portion of a sphere whose radius is 246 ft (75 m). Each half main shell consists of a series of concrete ribs (B). The centre line of each rib is a great circle of the sphere. Centre lines are spaced 3·65° apart throughout each main shell. Each centre line passes through the pole of the sphere. In this way ribs and tile lids radiate from the podium and become wider up the shell, successive ribs becoming longer or shorter as the case may be. The cross-section of each rib varies by smooth surfaces from a solid T to an open Y at the upper end (Figure 2). The ribs coalesce into a reinforced concrete pedestal (J) which provides a common spring point for all the main shell precast concrete segments. This arrangement of ribs and tile lids comprising similar elements forming part of a spherical geometry made it possible to develop a sensible construction process embodying the maximum use of repetitive elements.

The louvre shells (C) are identical in principle to the main shells (A).

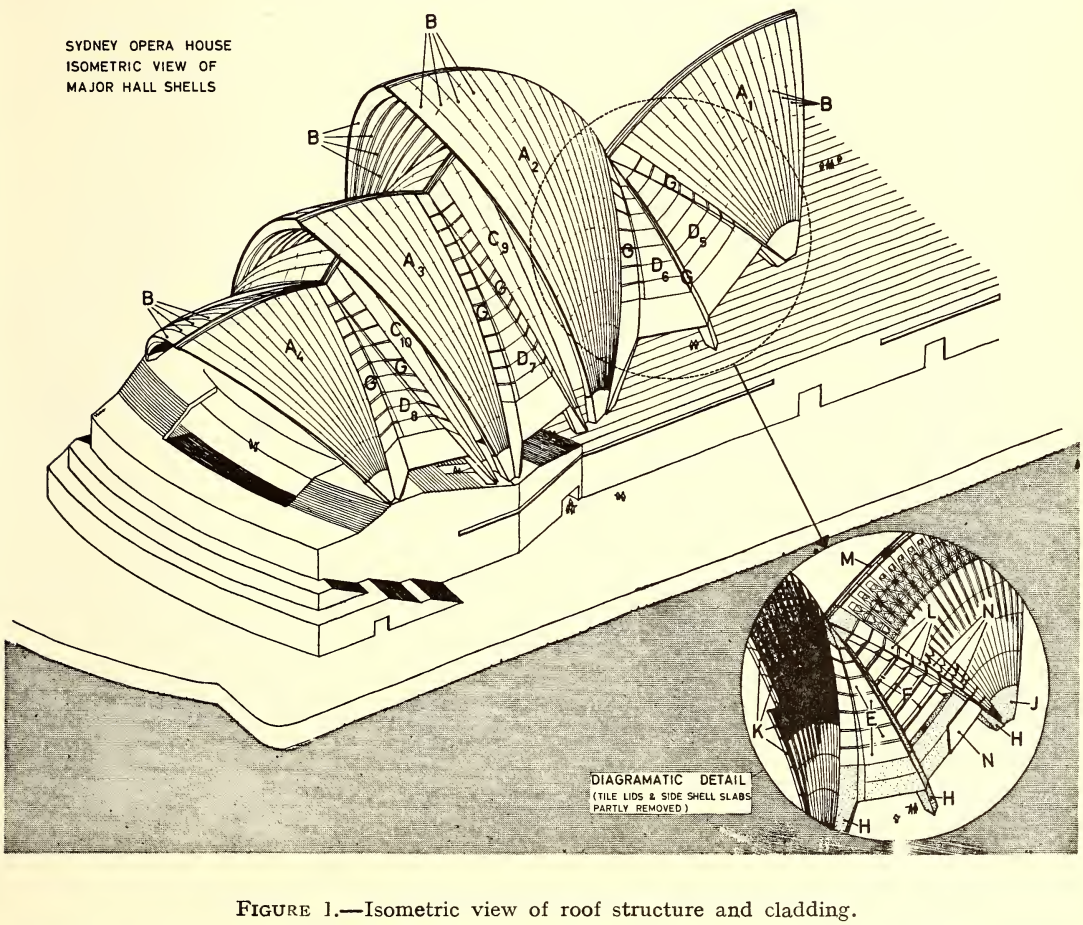


FIGURE 1.—Isometric view of roof structure and cladding.

Side shells (D) are spherical triangles which link main and louvre shells—geometric derivation is shown in Figure 4. Here again each shell forms part of the surface of the same sphere. The " meridian " passes through the vertex of each shell; the boundaries of the side shells are small circles. Great circles intersect this meridian at right angles at 7 ft 6 in (2·28 m) intervals. Although each spherical triangle forming a side shell is different, the geometric principles are the same and hence fabricating elements of the side shell structure and tile lids could be planned on a repetitive basis.

The space between the side shells and main shells is formed by a warped surface (G) described by two points which move up each shell boundary circle at the same rate and are joined by straight lines.

Main Shell Tile Lids

The arrangement of main shell tile lids (Figures 1, 2 and 3) follows the geometry of the main shell ribs. There are altogether 3,646 main shell lids and 26 types numbered from the lowest lid upwards varrying in overall dimension from 7 ft 6 in×1 ft 6 in to 11 ft 6 in×12 ft 6 in. The theoretical diameter of the spherical surface is 246 ft 8½ in. The tiles are arranged in a manner sympathetic with the chevron shape of the lids with matt tiles on the outer edges and standard glazed tiles covering the inside surface. The tiles are backed by a layer of " ferro cement " approximately 1⅛ in thick, which is cast monolithically with the tiles to make a slab of 1¾ in total thickness stiffened by 6 in deep ribs (see Figure 5). The backing slab of " ferro cement " is reinforced with three layers of galvanized steel mesh, comprising two layers of ½ in×½ in×16 gauge mesh with a separating layer of 3 in×3 in×16 gauge mesh. This represents a very heavily reinforced section, the cross-sectional area of the steel being 1·2% of the 1⅛ in thick concrete slab.

Laboratory tests on panels revealed a flexural deformation pattern which would be expected in a homogeneous, uncracked, flexible material rather than the characteristic behaviour of reinforced concrete where the deformation varies significantly between the uncracked and cracked conditions.

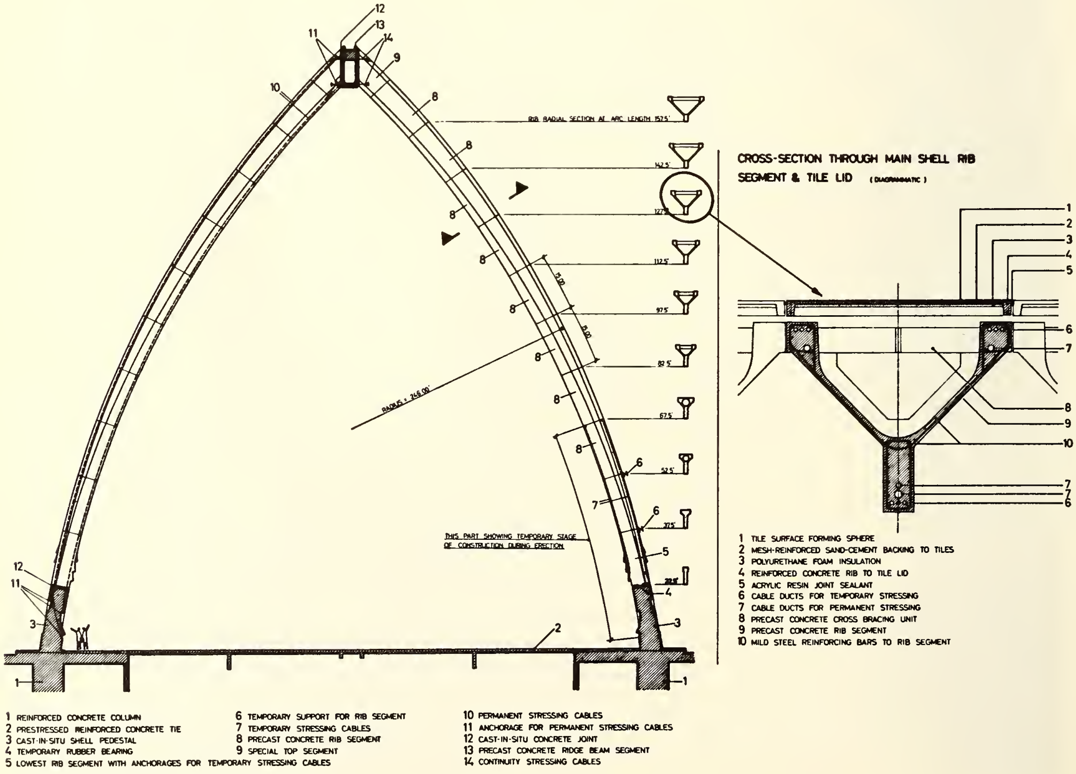


FIGURE 2.—Diagrammatic section through shell showing detail ot rib cross-section.

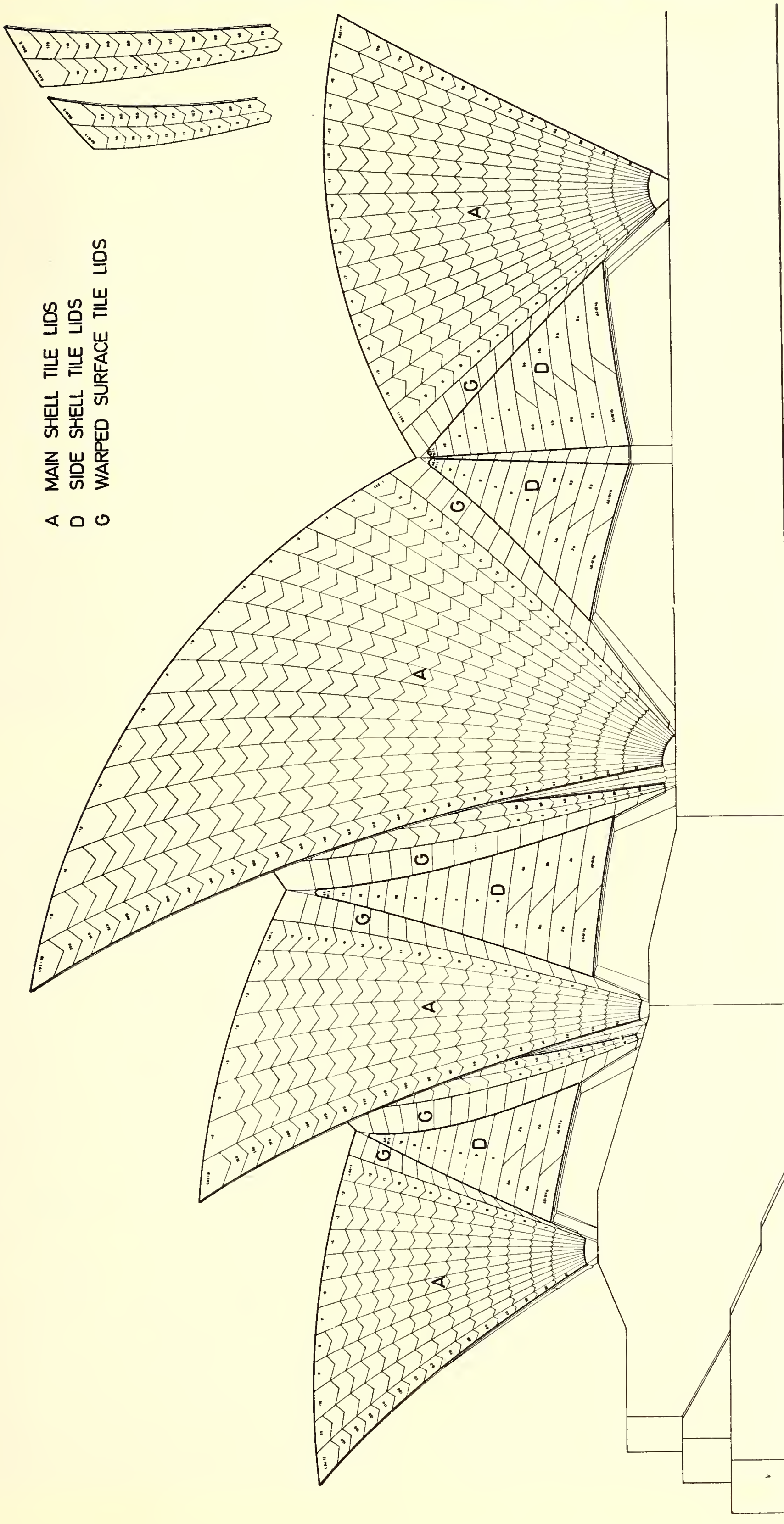


FIGURE 3.—Western elevation of Concert Hall showing arrangement of tile lids.

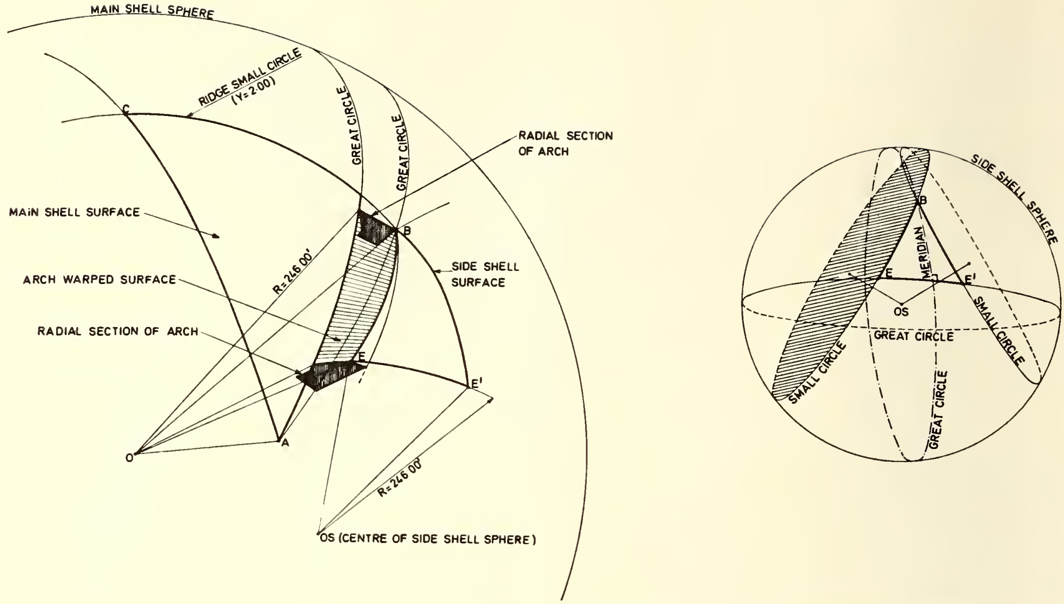


FIGURE 4.—Geometric relationship between main shell, side shell and warped surface.

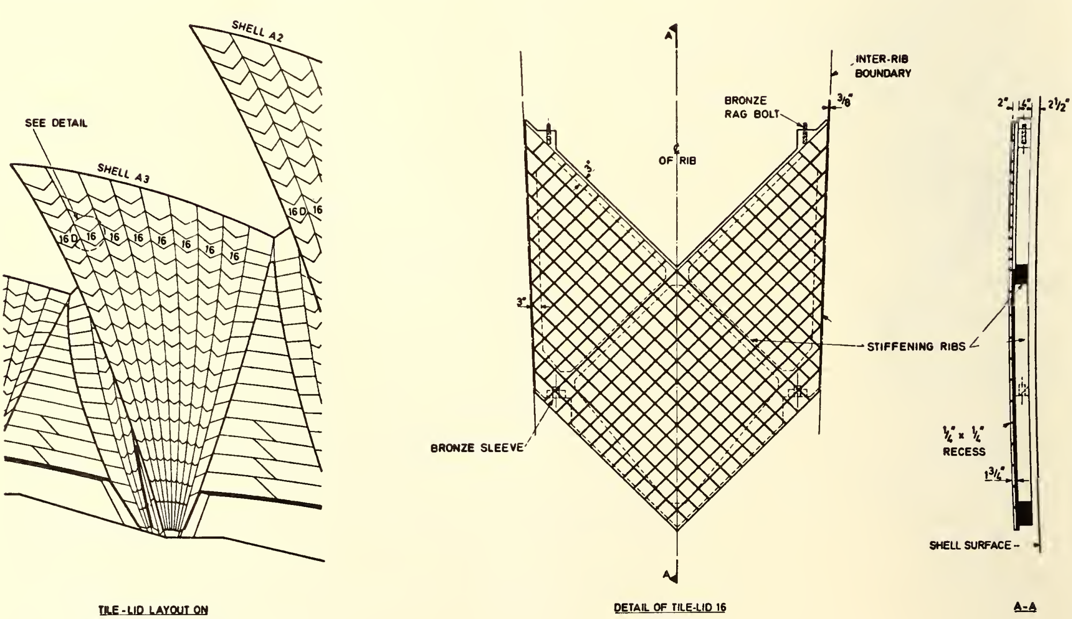
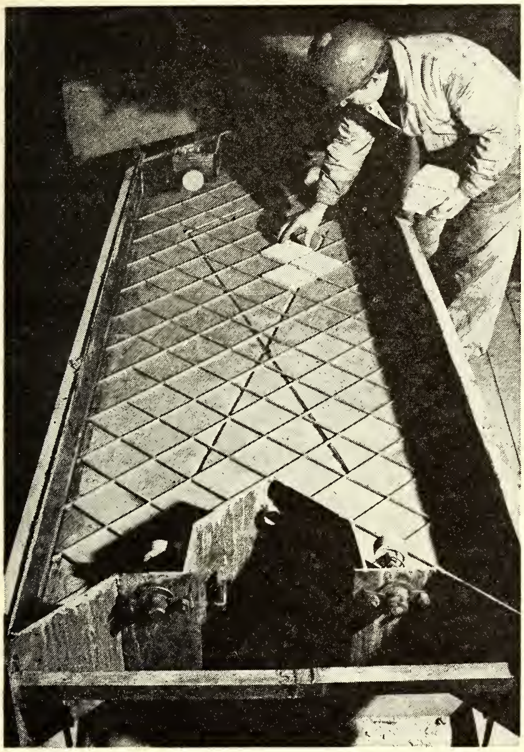


FIGURE 5.—Main shell tile lids.



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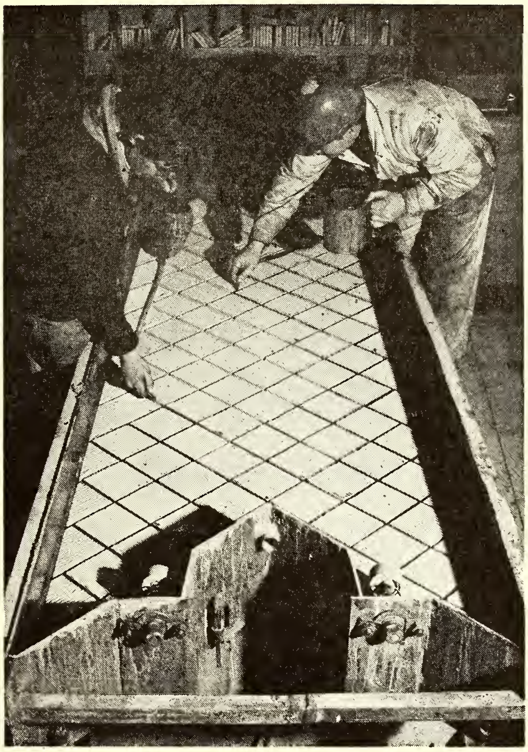

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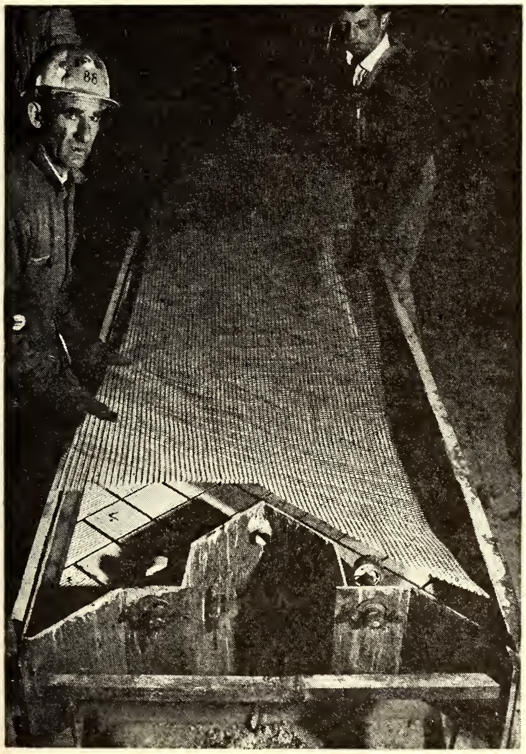

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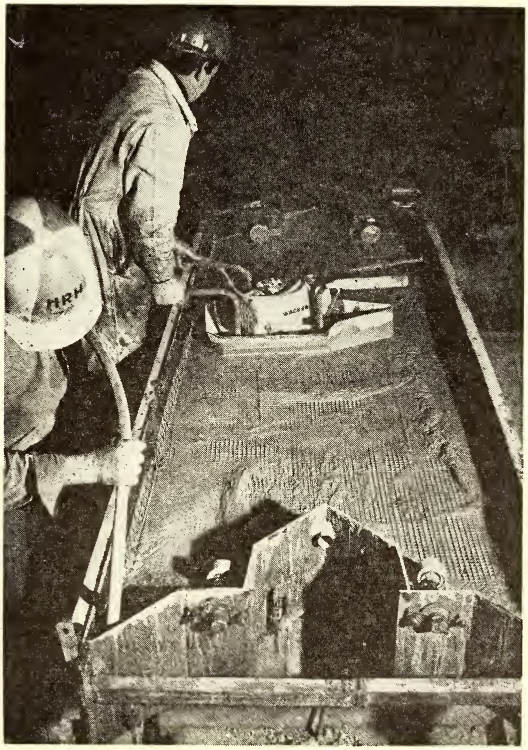

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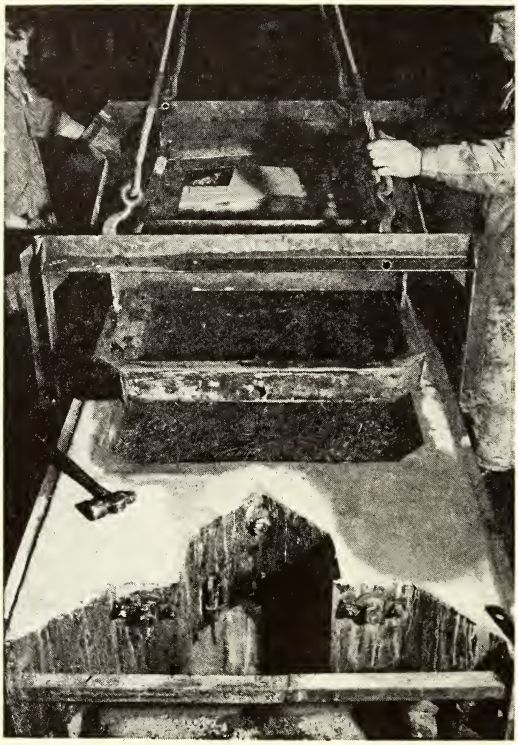
FIGURE 6(a).—Production techniques for main shell tile lids.



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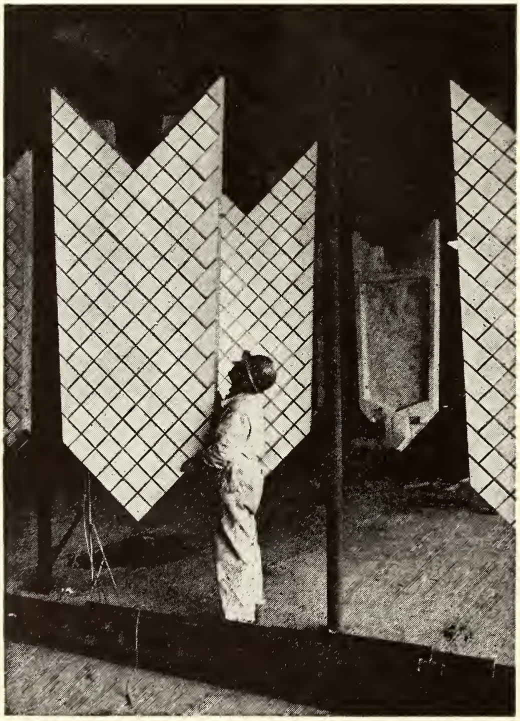

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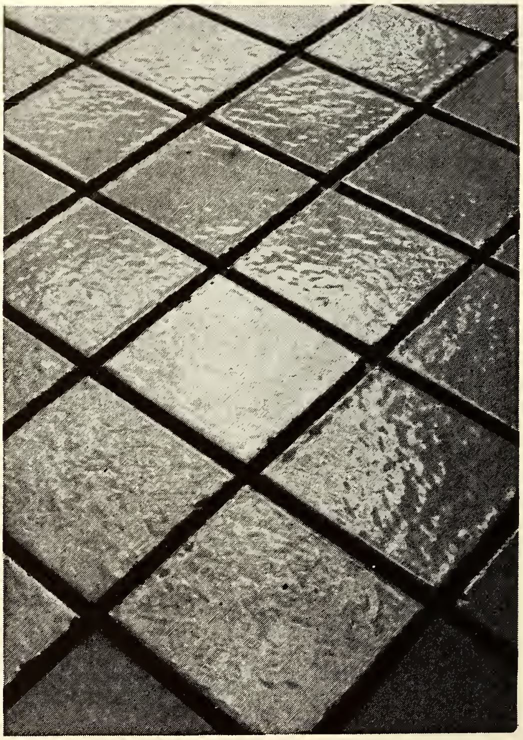

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FIGURE 6(b).—Production techniques for main shell tile lids.

The lids were manufactured in a factory which was established on site—refer to Figure 6.

(1) A concrete form for each of the standard main shell tile lids was built with the concrete surface made concave to a spherical form of radius 246 ft 8½ in. A grid of ¼ in square aluminium strip was fixed to the concrete mould to locate tiles; grooves were formed in the concrete surface to drain condensate resulting from the steam curing operation. Side forms were made of ¼ in steel plate with edge shaping to form a groove for the waterproofing backing strip between adjacent tile lids.

Tiles were placed face down in the mould between the aluminium ribs—this operation did not require traditional tiling skills and was done by builders' labourers.

Some of the tile lids types are repeated as much as 276 times—providing an excellent opportunity for re-use of the special forms.

(2) When all the tiles had been placed in position, the joints between tiles were partially filled with heated animal glue, which set on cooling (melting point 90–95° F) to prevent grout penetration on to the surface of the tile lids.

(3) Three pre-cut layers of galvanized steel mesh were placed on top of the tiles, using small pieces of asbestos cement as spacers to give $\frac{3}{16}$ in nominal cover of concrete between the mesh and the underside of tiles. Reinforcement in the ribs had been cut, bent and galvanized before fixing into position.

(4) Sand cement mortar was compacted by a heavy float vibrator and pencil vibrators. The surface was wood trowelled. The concrete mix was designed to a minimum cube crushing strength of 6,000 lb/in^2. The mortar had to be capable of penetrating through the fine mesh created by the reinforcement mats; the mix used consisted of one part cement, two parts Nepean sand of maximum size BS7. "Pozzolith" additive was used to maintain workability, with a water/cement ratio of 0·38. Average strength of 8,500 psi, with a standard deviation of 1,100 psi, was achieved. Internal rib forms were placed in position after the "ferro cement" slab had been cast. Quarter-inch diameter dowels were used for screeding in order to control the thickness of concrete cover on the trowelled underside of the tile lid.

(5) Steam curing was introduced by covering each tile lid with a tent-like PVC hessian hood to a maximum temperature of 170° F with a rate of temperature rise not greater than 40° F/hr. Steam curing did not start until three hours after pouring concrete, which meant that this was done at night to facilitate production on a daily repeating cycle. In the morning internal steel forms for the ribs were removed, which was followed by stripping of side forms.

(6) Heat from the steam curing had melted the animal glue, and tile lids were cleaned with steam prior to storage. The concrete cube strength at the time of stripping was a minimum of 5,000 psi.

(7) Storage on a "butcher's rack" basis prevented distortion due to stack loading.

(8) The finished tile surface has recessed grooves formed by the casting technique. Because the animal glue formed and hardened as a concave meniscus, the mortar in the joints was formed to a convex shape in cross-section. A sharp re-entrant angle between the mortar and the tile edge resulted, which gave concern that water penetration to the mesh reinforcement could take place; this could lead to eventual corrosion of the galvanized mesh reinforcement and rust staining on the tile lids. To prevent this, all recessed joints were sealed with an epoxy compound comprising "Epikote 815" Epoxy and Titanium Oxide filler in the ratio 20 : 3. The material was applied by squeezing through a nozzle in a plastic container directly into the recessed tile joint—the result was a concave meniscus leaving the recessed appearance, but ensuring maximum surface area for adhesion between tile edge and epoxy to seal the surface of the concrete.

Cut Off Tile Lids

At the top of each shell the pattern of standard tile lids is terminated when the curved surface of the shell intersects a vertical plane parallel to the centre plane of each building. This introduced a special "cut-off" lid at the top of each rib. There are altogether 276 "cut off" lids on the main shells—the largest covers an area of 11 ft 6 in × 21 ft—although they follow the chevron form of the standard lids, each lid is different and it was necessary to set up two special forms for manufacturing these units. This involved work by skilled tradesmen, who set up the forms for casting each lid—a process generally not required in the tile yard.

Side Shell Tile Lids

The side shell tile lids were limited to a size which could be handled and erected without suffering excessive stress or deformation due to self weight. To accommodate this requirement, the side shell lids at the lower levels are split at an angle 45° to the meridian, sympathetic with the tile pattern. The maximum size of the side shell lids is 7 ft 6 in $\times$30 ft approximately—as in the main shell lids, it is made up of $1\frac{1}{4}$ in composite slab of tiles and " ferro cement " stiffened by 6 in deep ribs.

Casting for all side shell lids was done on one mould with the need for individual setting up for each edge condition ; the great circles forming the top and bottom boundaries of the lids were identical for all lids.

Warped Surface Lids

Each warped surface lid is a composite concrete and tile slab $2\frac{1}{4}$ in thick ; although the lateral dimensions vary and are different for each lid, the distance along the great circle boundary of the main shell is constant at 7 ft $5\frac{1}{2}$ in. The " rate of twist " varies as the distance from the lower end of the tile lids increases, so that an adjustable form was devised which made it possible to cast the 358 warped surface tile lids on four identical casting beds—see Figure 7. The warp could be formed by casting the lid with three corners on a horizontal plane, the fourth corner set at a height to this plane. Close-spaced battens deflected relative to one another to form the surface ; these were lined with heavy-duty fibre reinforced aluminium foil and then small moulded crosses were fixed on the form to locate the tiles. All dimensional data for this work were produced by three-dimensional geometric analysis and programmed so that the print-outs from the computer were issued to the site as working drawings. Dimensions were checked by the provision of dimensions across the diagonal of each tile lid. The composite slab is reinforced with two layers of galvanized 3 $\times$3 in welded mesh of 3 gauge—1·8% of the concrete cross-sectional area. The tiles on the warped surface lids are all matt. After steam curing the tile lids, the lids were removed from the form and stacked vertically for curing.

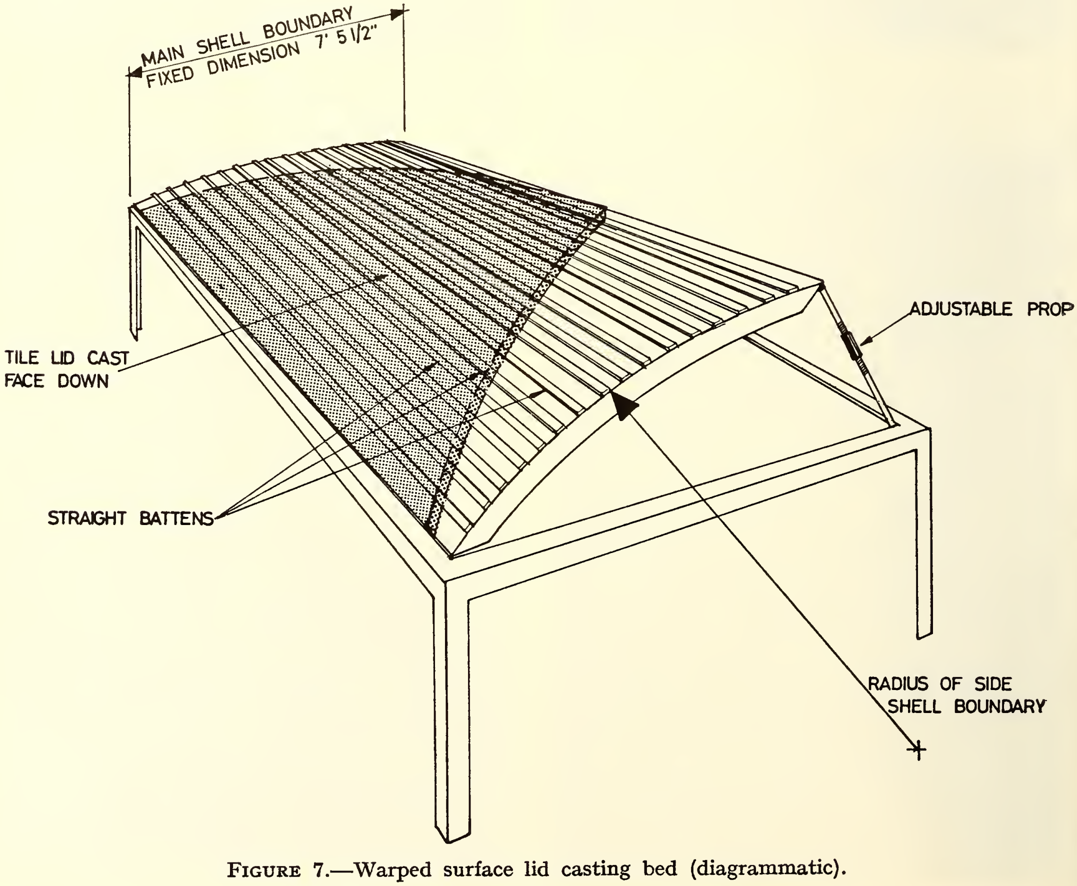

FIGURE 7.—Warped surface lid casting bed (diagrammatic).

An early trial erection of four lids revealed that differential shrinkage strain, a result of the restraint caused by the tiles on the one surface of the slab and an exposed face on the other, had resulted in bowing of the slabs by $\frac{1}{4}$ in to $\frac{3}{8}$ in on all edges. This was visually unacceptable, particularly along the side shell and main shell boundaries where a scalloped effect was evident. This had not occurred in main shell or side shell lids because of the stiffening effect of the ribs. The lids which had already been cast were corrected by pre-cutting cracks in the lid, bending and repairing with epoxy. All remaining tile lids were cast with an initial deflection of $\frac{1}{4}$ in, which was then compensated by the shrinkage strain which took place during curing. Some lids were damaged due to incorrect storage techniques—the damage generally resulted in " flattening " of the warp. This was corrected by using the same process which had been adopted for eliminating the effect of differential shrinkage strain.

Insulation and Waterproofing

In order to reduce stresses in the superstructure caused by the differential of conditioned air at constant temperature on the inside surface and variable temperature conditions on the outside, a layer of insulation was applied to the underside of all main shell and side shell tile lids. This was first done by spraying self-foaming polyurethane on the underside of the tile lids. However, after a few months' exposure in the storage racks there were signs that the foam appeared to be expanding laterally and adhesion to the concrete surface had failed. To prevent this happening in service, the polyurethane was cut into 2×2 ft sections and a " safety net " of fibre glass mesh fixed to the concrete using brass screws and PVC or Neoprene strip washers. After this experience the self-foaming polyurethane was replaced by pre-cut " self-extinguishing " foamed polyurethane of density $0 \cdot 2$ lb/ft^3 in sheets of $\frac{3}{4}$ in thickness with a maximum enduring K factor of 0·11.

The side shell structure was waterproofed by applying a sprayed PVC waterproofing membrane on the surface of the concrete. Joints between main shell ribs were rendered waterproof by caulking a lead sheet across adjacent flanges. In addition to making the structure waterproof, the tile lids were made waterproof by sealing the joints between tile lids with a two-part acrylic compound—" Monolastomeric ". This material was chosen after an extensive survey and test programme involving numerous available sealants and methods of application. The acrylic sealant was gunned into the joints after a PVC backing strip had been installed. The gunning of mastic into joints less than $\frac{1}{4}$ in wide was found to be unsatisfactory, and this was established as a minimum joint width between tile lids. The cavity between the main and side shells is open at the top and bottom of the shells, but flashed to prevent the entry of rain.

Production and Cost

All tile lids were produced on site. The number of beds used for casting was related to the demands of the programme for completing the roof structure. The following rates of production were achieved:

Table 1.

Type of Tile Lid	Number of Casting Beds	Weekly Production Rates		Man-Hours per square foot	
		Maximum	Average	Minimum	Average
Main shell	19	65	50	0·33	0·40
Cut-off	2	9	6	0·38	0·40
Side shell	1*	6	4	0·40	0·50
Warped surface	4	10	6	0·55	0·75

*The casting bed was large enough to cast two small lids at a time.

Because the production man-hours spent was concentrated on the edges of the lids, the larger side shell and cut-off lids tend to reflect a lower cost rate of man-hours per square foot.

The direct cost of producing the pre-cast tile lids, excluding epoxy sealing of joints, was \$3.95 per square foot. The cost is made up of

Permanent materials ..		50·2%
Tiles	45·8%	
Concrete	8·1%	
Reinforcing steel ..	21·5%	
Bronze fixings ..	17·3%	
Miscellaneous	7·3%	

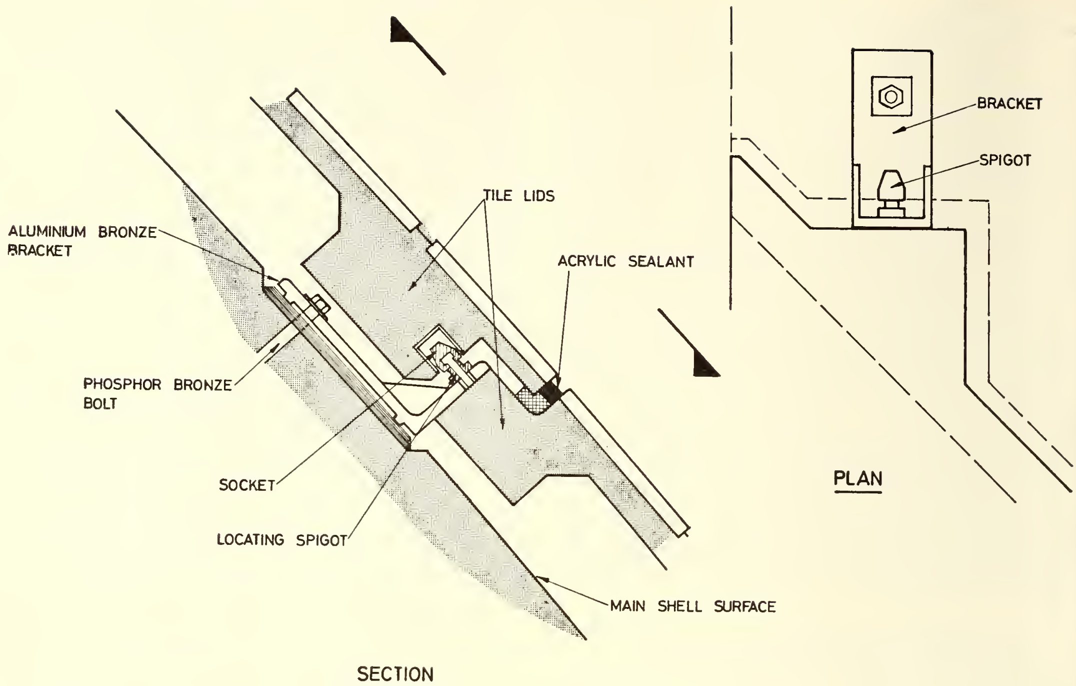

FIGURE 8.—Diagrammatic arrangement of main shell tile lid fixings.

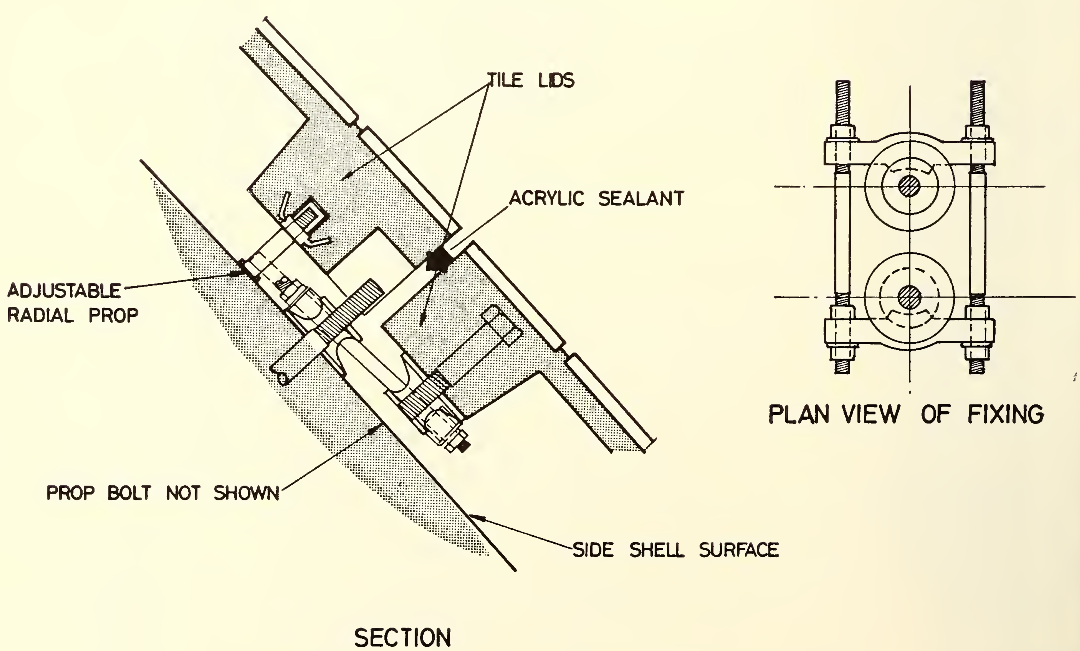

FIGURE 9.—Side shell lid fixing detail—diagrammatic.

Temporary materials used in manufacture	6·2%
Forms, hardware, lifting gear, etc.. .	4·3%
Sub - contractors (polyurethane supply and spray)	2·7%
Labour used in manufacture ..	29·0%
Labour used in setting up yard and casting beds	7·6%

Work was completed in March, 1967.

Fixing and Erecting Tile Lids

Each tile lid is designed to be fixed independently of adjacent lids in a manner which permits thermal expansion and contraction to take place without impinging on adjacent lids. Interaction between lids could result in overstressing of fixing brackets and bolts as well as possible damage to lids and tiles.

terms, see Figure 11.) The rib-to-rib width was not expected to vary a great deal, although it was expected that relative radial displacements between main ribs could create " steps " in the radial direction.

These requirements resulted in the design of a fixing which provided a reasonable degree of radial adjustment of tile lids to reduce the radial stepping effect at the boundary plane, but provided in the normal and tangential direction for only small casting errors in the bolt position. The rib-to-rib joint was fixed nominally as 1 in; the lid-to-lid boundary plane joint was fixed nominally at $\frac{3}{4}$ in; the chevron joint was fixed nominally at $\frac{5}{16}$ in. This appeared to satisfy the requirements of a continuous surface with minimal radial steps between adjacent lids.

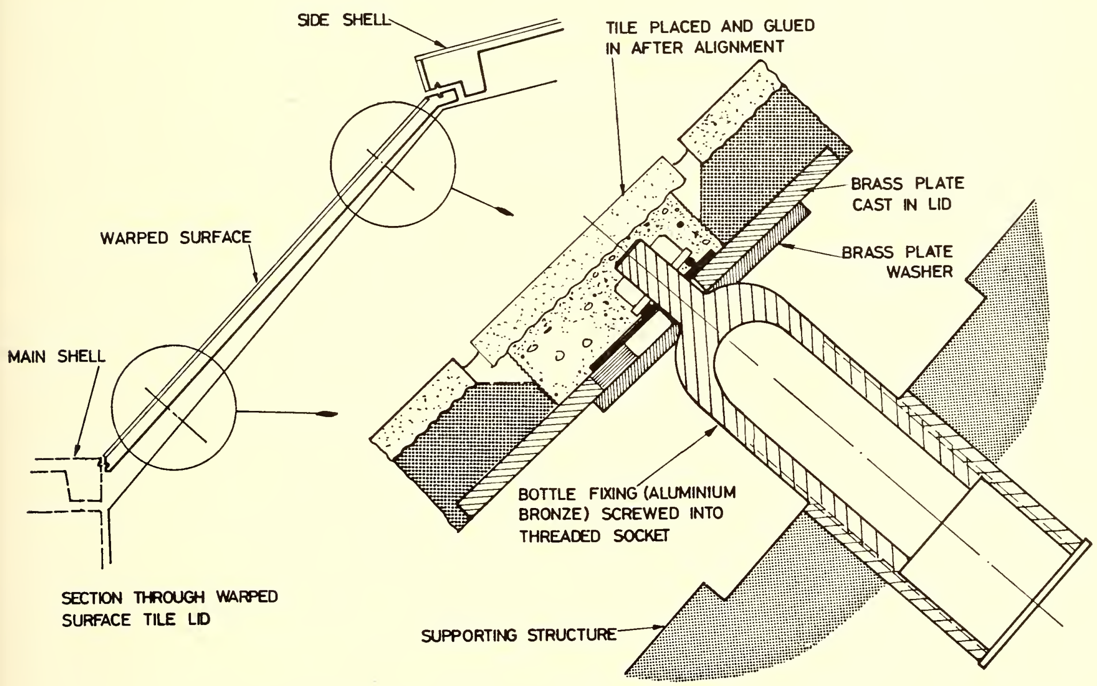

FIGURE 10.—Warped surface tile lid fixing—diagrammatic.

The design was initially prepared with the intention that the main shell tile lids should be fixed to the supporting ribs along a common great circle plane. It was considered generally undesirable to fix tiles after erection of lids and by introducing the concealed spigot and socket system of interconnection (see Figure 8) a continuous surface in the tangential direction was made possible. (For definition of geometric

Side shell fixing bolts were cast into side shell beams. The normal plane joints of the side shells were made $\frac{3}{4}$ in wide and " split " side shell lids were separated by joints of $\frac{3}{8}$ in width (this was later increased to $\frac{3}{4}$ in). A typical fixing detail is shown in Figure 9.

Warped surface tile lids were originally designed to follow the surface of the supporting structure. However, in mid-1963 it was decided to introduce a step at the junction between each warped surface and adjacent side shell. This introduced a restraint on the location and erection of tile lids, namely that warped surface lids had to be erected before side shell lids. Warped surface lid fixings were developed with a view to providing maximum fixing tolerance, and this method required that the tiles above the fixings were laid after the lids had been erected.

warped surface lids as they were formed in the casting yard. Adequate tolerances were built into the design of each fixing. Final adjustment was made on site because the warped surface fixings, unlike the other tile lids, were exposed during erection. After all the lids had been satisfactorily aligned the fixings were concealed by gluing in place with epoxy, the tiles which had been left out to accommodate the fixing plates.

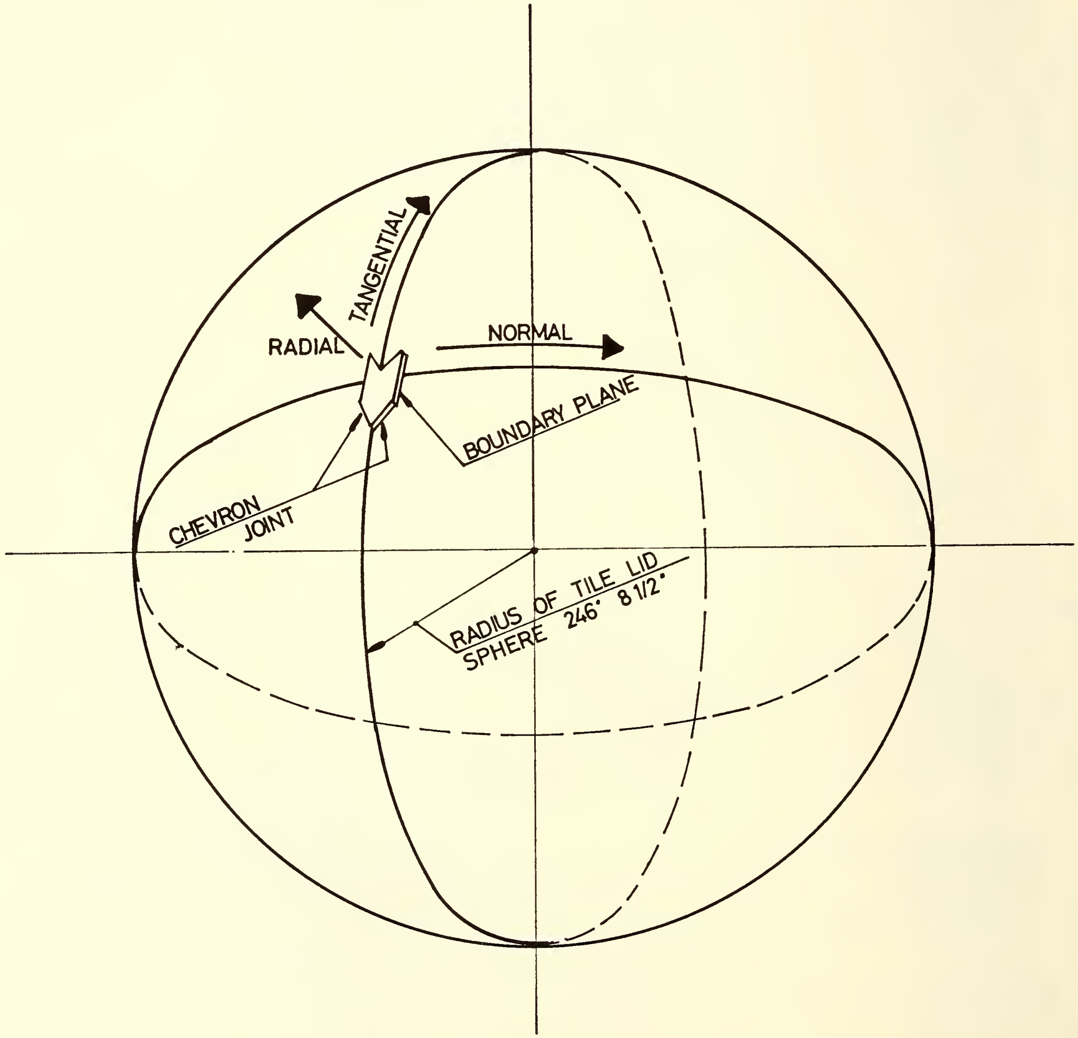

Figure 11.—Diagram showing spherical ordinates and terminology.

The location of " bottle " fixings (see Figure 10) on the superstructure warped surfaces was established by survey and the amount of projection of the fixing established. This information was translated back to give a location for the fixing plates in the pre-cast

In order to test and prove the principles and details of connection which had been developed for the main and side shells, it was decided to carry out a series of prototype erections. These trial erections, culminating with the erection of tile lids on part of the completed structure, revealed that the fit between adjacent lids along the " chevron joint " had a serious impact on both normal and tangential accuracy (see Figure 11). Furthermore, manufacturing errors, although very small, tended to result in lids which were generally slightly larger than the form size. This made the original design requirement of a nominal $\frac{5}{16}$ in chevron joint impracticable; forms for the remaining tile lids had to be adjusted to compensate for this " growth " in dimension. All the tile lids which had already been cast could be utilized in the structure, together with smaller tile lids which were made so as to increase the nominal chevron joint size to $\frac{5}{8}$ in. The compounding of a multiplicity of minor errors in casting of tile lids, location of fixing bolts in ribs, and distortion of the ribs during construction was such as to make it impossible to erect the tile lids to follow the surface of the structure and at the same time maintain the basic demands for a continuous surface free of steps between lids. The requirements of a minimum joint width for waterproofing, together with the desire for visual continuity of joints, had to be accommodated. This resulted in a complete loss of tolerance for adjustment after a number of consecutive lids had been erected on this basis.

Consequently, fixing systems were adapted and erection techniques developed in order to place each tile lid in its theoretical position in space without regard to the location of adjacent lids. Each tile lid was checked for accuracy of casting by means of measuring templates; the surface being spherical or twisted meant that there was no easy reference plane for measurement—all templates were three-dimensional. Tile lid fixings were designed to allow for adjustment in any direction, and since each tile lid was located inside the envelope of acceptable tolerances the fit between adjacent lids was assured. This system of fixing necessitated a detailed and accurate survey of the actual location of all the tile lid fixing bolts on the structure—a total of approximately 10,000. A computer programme had already been written and was operative as a method of controlling the position of ribs as they were constructed. This survey programme related the spherical geometry of the theoretical shell surface and the location of stations around the site in such a way as to eliminate all the tedious calculations which would normally follow survey measurements. The programme was further advanced so that adjustments to brackets were fed out from the computer and used by the field construction teams to set and adjust brackets on tile lids prior to erection. In this way it became unnecessary to make adjustment to the position of lids after release from the crane and a very high level of sophisticated preplanning resulted in speedy and efficient site erection work.

With the exception of warped surface lids, the brackets and bolts are totally inaccessible after erection—they are located in a void between the outer surface of the structure and the undersurface of the tile lids. In such a location they are exposed to the atmosphere but not visible, so that it was necessary to use a metal which would be free from risk of corrosion. Many alternatives were investigated and it became apparent that the selection of materials and suitable stress levels would be determined by conditions of stress corrosion. Copper, brass and manganese bronze are all susceptible to stress corrosion and were eliminated. The materials chosen for use were phosphor bronze (BS. 369—hard) for rods and bolts, and aluminium bronze (BS. 1400 AB2–C) for castings. Working tensile stresses were limited to 9 tons/in^2 and 6 tons/in^2 respectively in order to keep within the range of $0{\cdot}25$–$0{\cdot}50$ of the $0{\cdot}1\%$ proof stress. Account had to be taken of possible stress concentrations and residual stresses in castings.

The fixing of the tile lids on the spherical or twisted surfaces of the Opera House roof was virtually unprecedented—in most buildings there are plane surfaces which form a simple base for measurement; in some structures at least the generator of a curve is a straight line. The solution of the problem lay in the use of accurate and sophisticated surveying techniques coupled with design of versatile adjustable fixing brackets so that the tile lids could be located accurately in their theoretical position in space with the fixings taking up inaccuracies in casting and construction of the main structure. This was accompanied by extensive detailed pre-planning so as to eliminate almost entirely the need for adjustment of the position of each lid after it had been released from the crane.

Acknowledgements

The work was carried out under the general direction of the Minister for Public Works for the Government of New South Wales.

Jørn Utzon was the architect appointed for the project until his resignation in February, 1966.

Hall, Todd and Littlemore were the architects in charge of Stage III, responsible for the completion of the project.

D. C. Gore, B.E., M.I.E.(Aust.) was the director and project manager for M. R. Hornibrook (N.S.W.) Pty. Ltd., who, together with his colleagues, built the roof structure.

H. R. Hoare, F.I.O.B., F.A.I.B., was the director and project manager for the Hornibrook Group for the third and final stage of construction.

The structural and civil engineering work described in this paper was carried out in the London and Sydney offices of Ove Arup and Partners, Consulting Engineers, and is the product of years of effort by many members of the firm.

The photographs were taken by Max Dupain.

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(Received 29 August 1973)

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Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 33-53, 1973

Acoustical Design Considerations of the Sydney Opera House

V. L. Jordan

Abstract—The Opera House, which is now completed (inauguration October, 1973) has a unique history of construction. While actual construction started in 1959, a subsequent change in administration led to a complete reprogramming and redesign of the interior spaces including the acoustical designs.

The large halls were tested with the aid of models during both periods. The results of the model tests are compared with the results obtained from tests of the completed halls.

Other features of the designs such as the smaller halls and sound isolation are reported too.

1. Introduction

A time period of more than sixteen years lies between the very first design of the complex and the actual completion of the Sydney Opera House. Construction of interior shapes and spaces began four years ago.

No wonder that this unique situation has involved several major changes of the general design, and also corresponding changes of the acoustical design of the interiors.

Design changes occurred frequently in the early period (the Utzon period) as consequences of the changing concepts of the architect. Changes in design in the later period (the Peter Hall period) were motivated mainly by the complete change of the whole programme for the uses of the building, although some changes also occurred as a result of the acoustical model testing of the large halls.

It may therefore be well worth the effort to give an account of this " acoustical design development ", thus exposing some of the problems encountered during the whole period. Most of these problems refer to the two larger halls, but the design of the smaller halls and the aspects of sound isolation are included.

2. The First Programme and the First Design

The main emphasis of the first programme was assigned to the two large halls, " Major Hall " and " Minor Hall ", although requirements for an experimental theatre, an orchestra rehearsal room and a chamber music room were also included.

Several uses of the Major Hall were listed, but most important was " symphony concerts " (approx. 2,800 seats), closely followed by " grand opera " (approx. 1,800 seats). It has never been queried that this dual purpose could be achieved with reasonably good acoustical quality for both uses of the hall, provided that the general design was adapted in accordance with acoustical requirements. It is obvious, however, that a dual purpose hall may never reach that level of perfection which a single purpose hall can aim at and probably achieve. This is particularly true of the Opera House design by Utzon, where the boundaries of the shells and the areas encompassed by the shells define, to a large extent, a specific category of interior shape which is only remotely associated with acoustical requirements of large halls. It must be admitted, however, that these requirements, generally speaking, are much better known today than they were sixteen years ago.

The first design of the Major Hall is shown in Figure 1 (two alternatives, with and without balcony) in long section as well as in plan (Utzon, 1958). The ceiling shape was influenced by the idea of an even distribution of ceiling reflection from the stage, whereas the shape in the plan expressed the thinking that parallel side walls (in sections) were advantageous in

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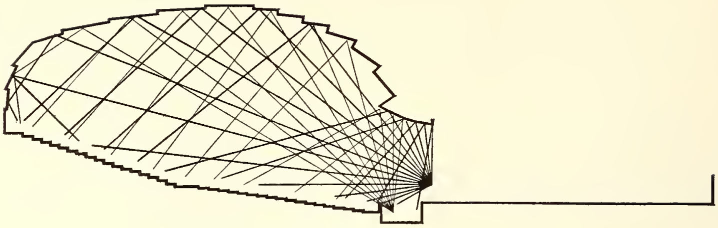

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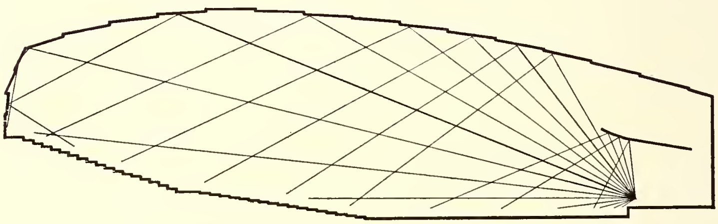

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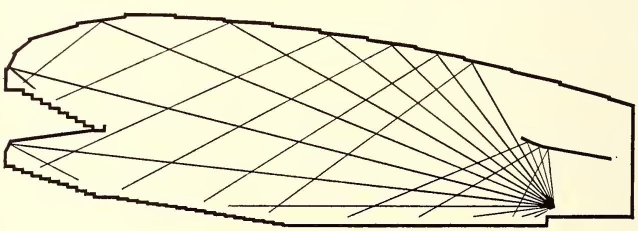

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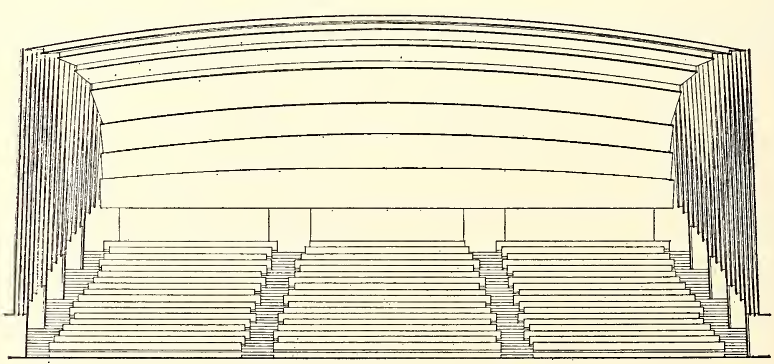

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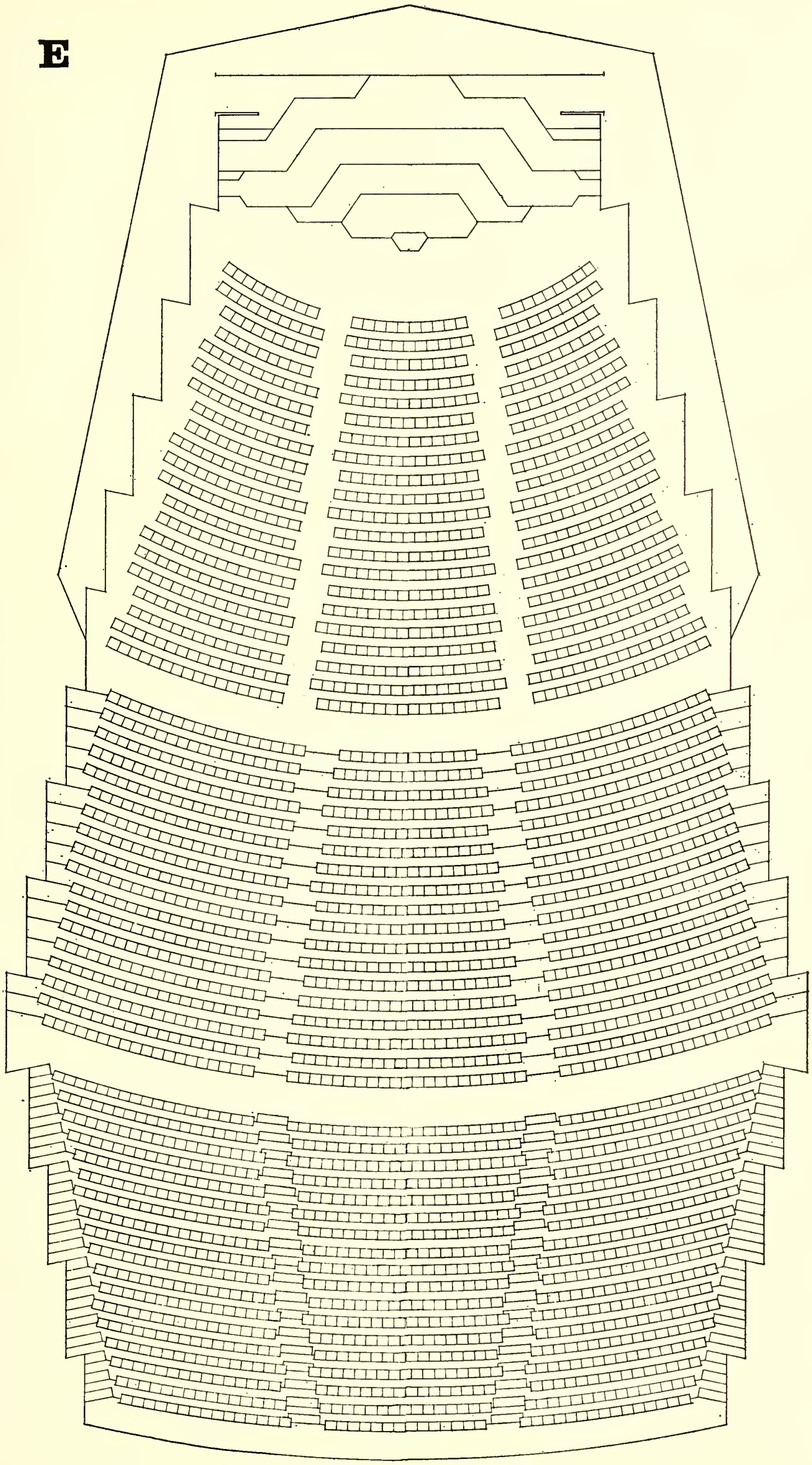


Figure 1.—First design of Major Hall.

(A) Longitudinal section (case of " Grand Opera ").
(B) Longitudinal section (case of Concert Hall, alt. 1).
(C) Longitudinal section (case of Concert Hall, alt. 2).
(D) Cross-section at the rear.
(E) Plan, seating.

order to obtain multiple reflections crosswise. The same thinking influenced the nearly vertical side walls.

It should be noted, however, that at this early stage of the design it was not fully realized that the near vertical side walls would actually pierce through the limiting boundaries of the shell system. The design was unrealistic.

With regard to the uses of the Minor Hall, the first programme indicated two main purposes: (1) drama, and (2) intimate opera, with a seating capacity of about 1,000–1,100.

Hall at a scale of 1 : 10. The design in plan was as shown, whereas the ceiling design had been changed to a stepping ceiling with horizontally oriented sections.

The choice of the scale factor (1 : 10) was guided by the fact that the influence of sound absorption in the air increases rapidly with frequency, so that model frequencies in excess of 30–40 kHz would not permit a reasonably good simulation of the acoustical properties without including a complicated dehumidifying procedure of the air inside the model. The

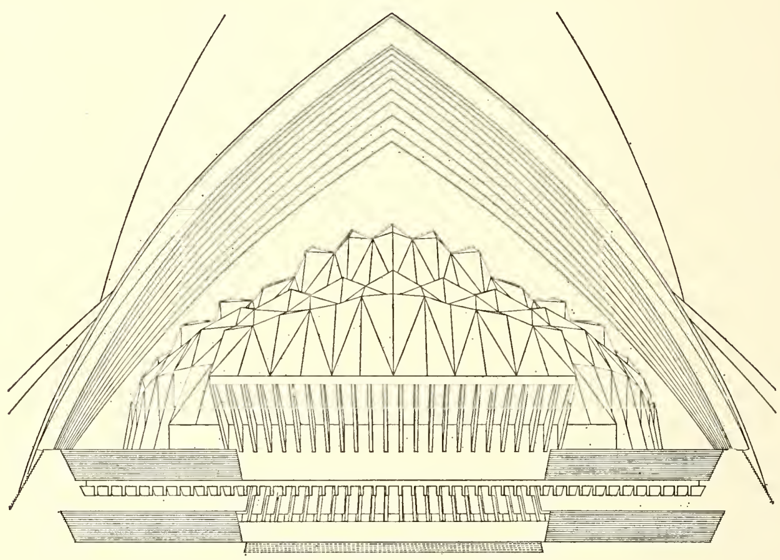


FIGURE 2.—Second design of Major Hall. North elevation.

The first design proposals of the Minor Hall were very sketchy and did not really attack the problems of acoustics. At this stage, in 1958, it was agreed that a prejudgment of the acoustics of both halls should be aimed at, not only by calculations of reverberation time (RT) and geometric constructions of reflections, but by acoustical model testing. It may very well be argued that at the time scientific evidence of the validity of acoustical testing on scaled models was only about to be established and also that there hardly existed quantitatively defined criteria (other than RT) which could be measured, either in halls or in models.

However, the importance of the acoustical design for the Opera House overshadowed these hesitations and it was recommended and decided to start off with a model of the Major

instrumentation for model testing included a high quality tape recorder with a speed relationship of 1 : 10, thus making it possible to obtain direct listening tests as well as objective testing. A reasonably good agreement between absorption of the model boundaries and the expected wall and ceiling panelling of the hall (wooden panels) at corresponding frequencies was achieved by shaping the model of hard fibre boards (varnished on the inside). To simulate an audience absorption at model frequencies blankets of fibre glass material of 4 in. thickness were applied. This crude approximation was later to be refined in several steps. The similarity of the model to the projected hall was checked by measurements of RT in the model and by comparing the measured values with the calculated values of RT in the hall.

The problem of establishing quantitative criteria had previously been approached by the author in another context. The Concert Studio in the Radiohus and the Tivoli Concert Hall in Copenhagen had been used as objects for a study of the so-called "Rise Time" (Jordan, 1959). A similar method was adopted for the model testing of the Major Hall model, but the loudspeaker instrumentation was a limiting factor at the time. Electrostatic speakers with twelve membranes mounted on a sphere were not sufficiently uniform in radiation pattern at model frequencies to give reliable readings for the building-up process of pulses of random noise.

The third and final phase of the Utzon design period showed still another approach to the interior design of the two large halls. Here the Major Hall design became radically changed compared with previous attempts. The original idea used the stage area proper for the seating of no less than 1,000 persons during concert performances, the remaining 1,800 seats being located in the auditorium proper, while when used for opera the 1,000 seats on the stage should disappear.

This concept made it necessary, in case of concerts, to establish a very large reflecting ceiling to shield off the stage loft. The mechanics of introducing an immense movable ceiling were never really attacked. The new design tried to avoid this problem altogether by moving all seats (even in the case of concerts) out in front of the proscenium frame, thus changing the stage into a normal theatre stage with an orchestra shell for housing the orchestra.

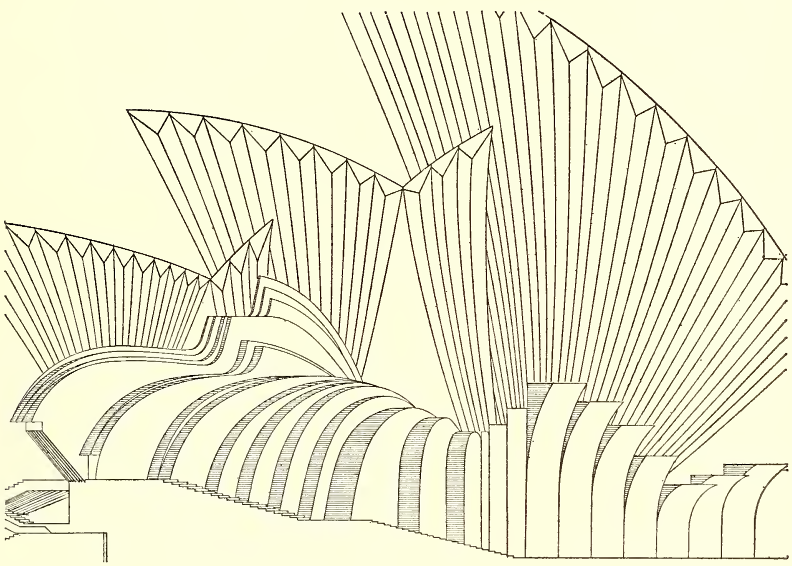


FIGURE 3.—Second design of Minor Hall. Longitudinal section (showing interior elevation).

For this purpose the auditorium had to be widened with side terraces and the seats had to be closed up. Nevertheless the seating would still fall short of the design goal of 2,800 seats by several hundred.

The shape of the ceiling of the Major Hall was changed once more, this time into strips of saw-toothed profiles in the long section (Figure 4 (A)). The side walls became elements of

3. Major Hall and Minor Hall, Several Alternatives

The model of the Major Hall became outdated when the architect introduced quite different concepts for both halls. The Major Hall in the second design had a "diamond" ceiling, no doubt with a high degree of sound-diffusing capacity, but it also had extremely low side walls which certainly had the advantage that they would not pierce through the shells (Figure 2) (Utzon *et al.*, 1962). The Minor Hall in this design had a vault-like ceiling shape which had little relation to the acoustical design (Figure 3). Neither of these designs was tested acoustically by model testing.

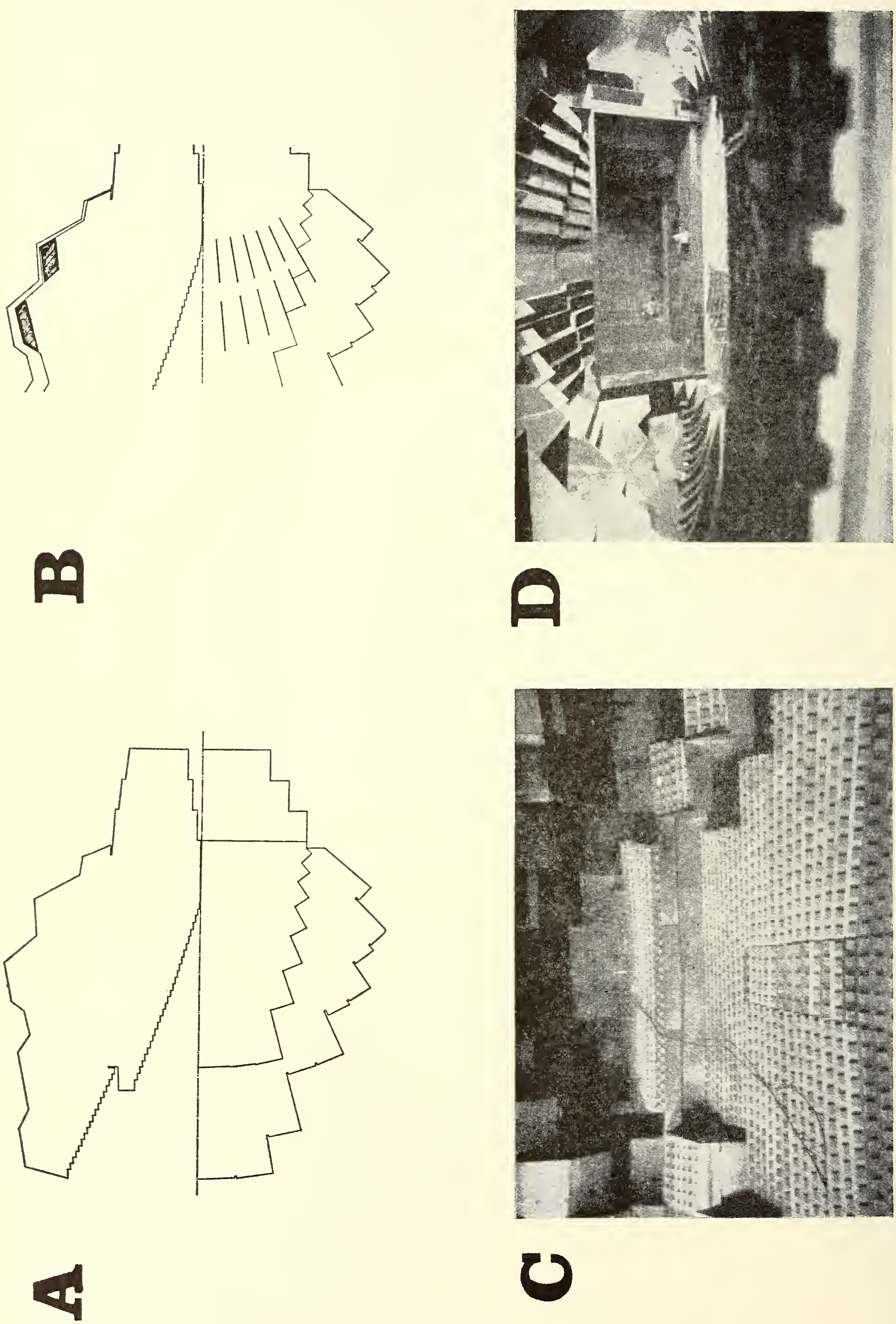


FIGURE 4.—Third design of Major Hall.
(A) Longitudinal section and plan.
(B) Longitudinal section with additional suspended baffles.
(C) View of the model towards the rear.
(D) View of the model towards the stage (podium).

focal oriented planes interrupted by radial concave segments.

This design was subsequently tested in two different models, one located at Professor Cremer's institute in West Berlin and one located in Gevninge, Denmark. Testing methods were not similar, so that results were difficult to compare. The method used at the author's laboratory in Denmark was a development of the previously applied method using the " Rise Time " criterion. A new concept called " the Steepness " was introduced. This was defined as the steepness at a certain level of a recorded random noise pulse radiated into the model, or auditorium, and picked up by a microphone at different locations.

The method had been tried out in another case, the New York State Theater (completed in 1964), of which a 1 : 10 scale model had been tested in Gevninge, Denmark (Jordan, 1964). Results obtained on this model had been compared with results later obtained in the completed theatre auditorium, and the agreement was found to be reasonably good.

Whether the suspension of vertically oriented baffles along the ceiling profiles could be used to improve measured values of steepness at certain locations in the auditorium, especially in the centre locations of the orchestra level, represented a special problem of model testing in this third design of the Major Hall. The model tests indicated that this might be feasible (Jordan, 1965).

Figure 4 (B) shows long section and plan of this model with the suspended baffles indicated.

It is worth noting that in this model the audience plus seats simulation had been improved compared with previous models. The individual persons were simulated by small blocks of neoprene and the seat-backs by continuous strips of fibre board. Two views of the model are shown in Figure 4 (C) and (D).

The Minor Hall design, too, was a radical departure from previous attempts. It was characterized by ceiling profiles of large, convex elements oriented along radii from a focal point on the stage. This design was tested in a 1 : 10 model at Professor Cremer's institute in West Berlin. Oscilloscopic pictures of short pulses in different locations were applied to evaluate the influence of the various reflections from the ceiling and the walls. Subsequently, minor corrective measures were suggested (Cremer, 1965).

Although acoustical model research was applied to evaluate this final Utzon design of the Major and Minor Halls, the results of these tests did not adequately support the design which at least partly had been adopted for aesthetical reasons. Moreover, other aspects (e.g. such as the available volume of the Major Hall auditorium per seat) indicated that the value of RT with capacity audience would be rather low for a concert hall of this size.

However, at this stage events quite irrelevant to any of the acoustical problems led to a complete change of the administration of the project. During the year 1966 a new team of architects had taken over the responsibility of completing the design and construction of the Opera House. Since most of the exterior design had been completed and constructed, this responsibility concerned mainly the interior design. In fact, there appears to be a rather clear cut between the two design periods: while the exterior design was almost exclusively founded on Utzon's concepts, the interior design subsequently developed into something absolutely different.

4. Reprogramming and Redesign

The new Design Architect, Peter Hall, assisted by the late Theatre Architect, Ben Schlanger, and the author formed a small study group in order to take a new look at the problems, starting with the following question: Given the empty spaces below the shells, what does the City of Sydney most urgently need to accommodate in its arts centre?

What should the programme of the building be like? About ten years had elapsed since the original programme was edited, did it need a thorough revision? The answer was yes, and out of the discussions and considerations the following main items evolved:

(1) The Major Hall to be *the* Concert Hall (approx. 2,800 seats).

(2) The Minor Hall to be *the* Opera Theatre (approx. 1,600 seats).

(3) The empty " under stage " below the previous Major Hall to be the Orchestra Rehearsal and Recording Studio.

(4) The Experimental Theatre to be the Drama Theatre (approx. 550 seats).

(5) Empty workshop space to be the Chamber Music/Cinema and the Exhibition Area.

(6) The space previously intended to house the Chamber Music Room to be the Recital Hall.

Out of a session in London during mid-1967, the first redesign of the Major Hall developed (Called now the Concert Hall). To integrate

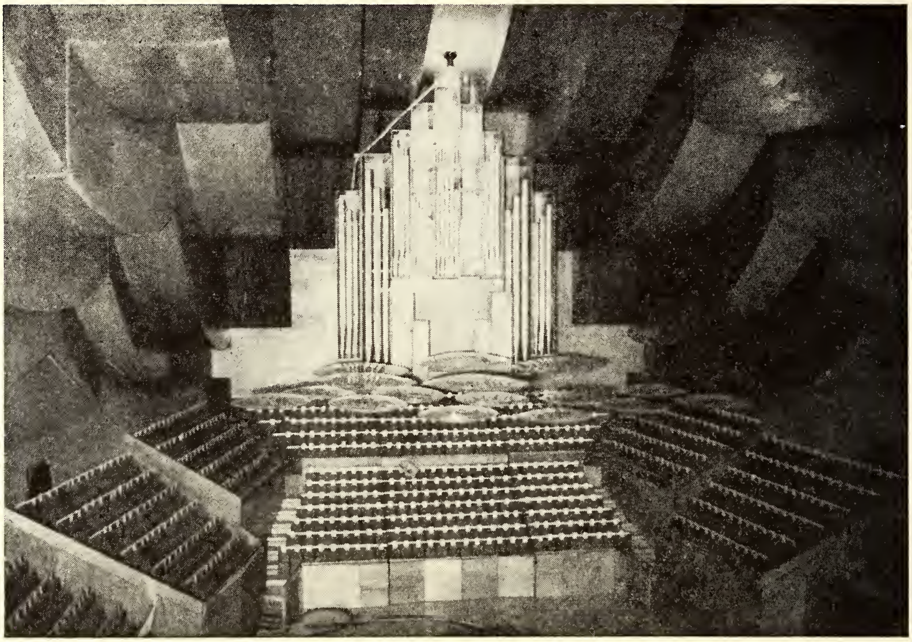


Figure 5a.

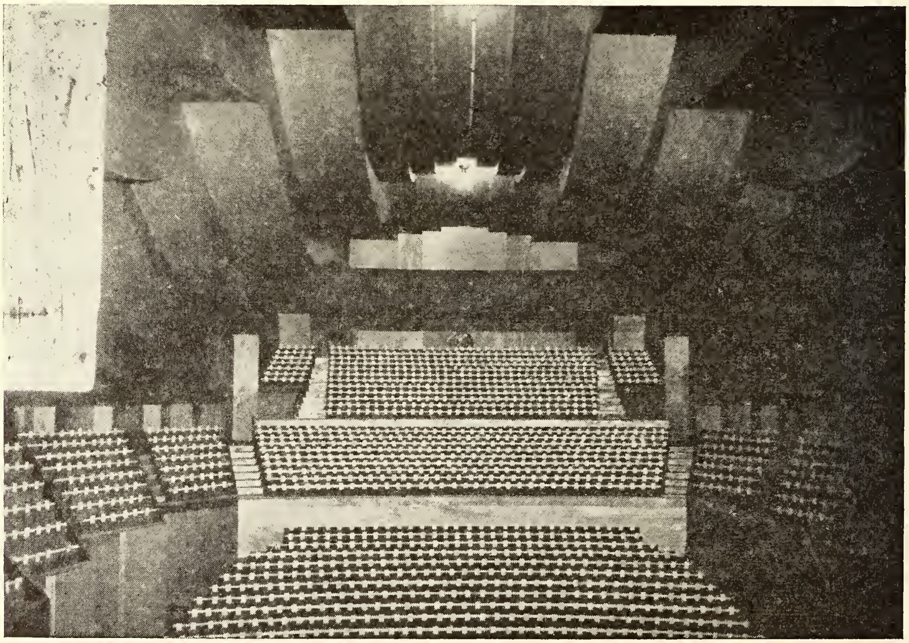


Figure 5b.

C

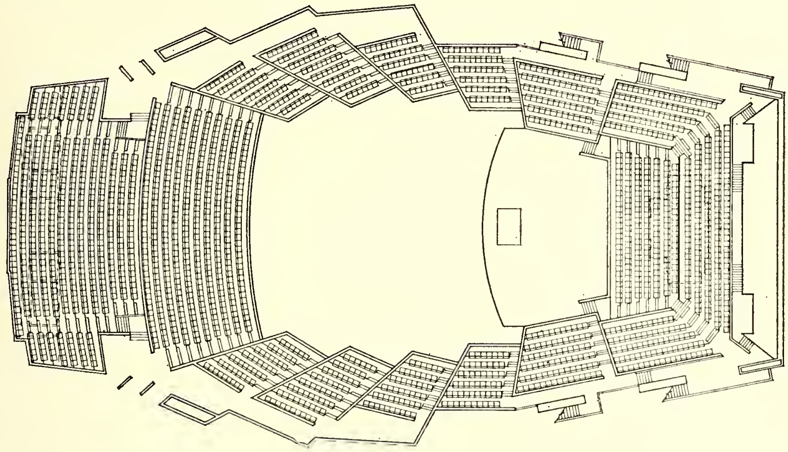


FIGURE 5C.

FIGURE 5.—First design of the Concert Hall.

(A) View of the model towards the organ.
(B) View of the model towards the rear.
(C) Plan of the outlay and seating (terrace level).

completely the volume under the main A-shells, the stage and the auditorium were merged and the ceiling was pushed upwards to increase the total volume. The gross shape in plan became essentially a double spade, which has certain inherent acoustical merits. The orchestra stage, originally intended to be at the extreme end of the hall, was moved towards the centre, thereby creating seating behind the orchestra not only for a choir but for an audience as well. The complete wall behind this seating was to be the organ façade. Never before in the design development had there been a solution to the problem where to locate an organ when a theatre stage had to be included. The seating in front of the orchestra stage consisted now of the orchestra level, the first and second terraces, and side-boxes along the periphery to the left and right.

The shape of the ceiling in Peter Hall's first design showed faint reminiscences of Utzon's latest design of the Minor Hall : large convex surfaces in a kind of catenary succession. The side walls represented a problem : how to obtain the benefit of vertical elements to give side reflections and at the same time adapt them to the shape of the shells. The result became a staircase arrangement where the horizontal steps defined the catenaries of the ceiling (in the direction of the long axis) (Figure 5 (A), (B) and (C)).

5. Model Research of the Concert Hall and the Opera Theatre

The idea of evaluating the acoustics of large halls by pretesting models was still maintained, and it was decided to build 1 : 10 scale models of the Concert Hall and the Opera Theatre. This time the models would be located at the Opera House site in an empty rehearsal space in the basement.

The models were built of thick plywood and varnished on the interior surfaces. Further progress in audience simulation had been developed for use in other models. The seats were made of continuous strips of neoprene, while persons were represented by individual neoprene blocks topped with small squares of cardboard simulating the heads.

The instrumentation, too, had advanced. Pulses were now generated by a high-tension spark source which radiated sound pulses of very short duration. The signal was picked up by small condenser microphones with $\frac{1}{4}$ in. diameter and recorded on high-speed tape recorders. The tapes were later analysed in the author's laboratories in Gevninge, Denmark.

The method of applying short pulses to test the acoustics of a room had been developed by applying M. R. Schroeder's theory (Schroeder, 1965) and had been used in a 1 : 10 model of the New Metropolitan Opera House, Lincoln Center, New York) (Jordan, 1969, 1970).

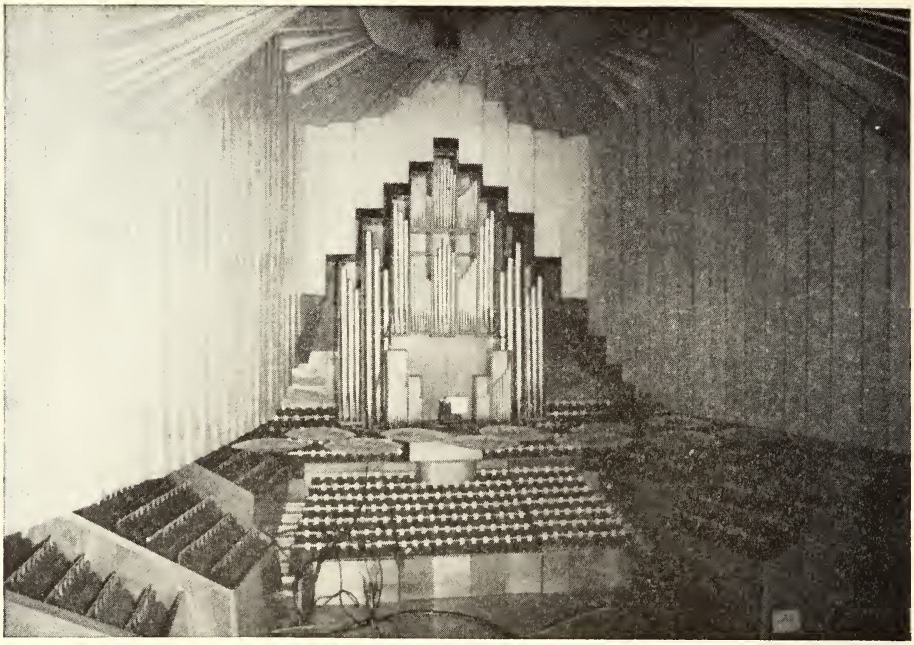


Figure 6a.

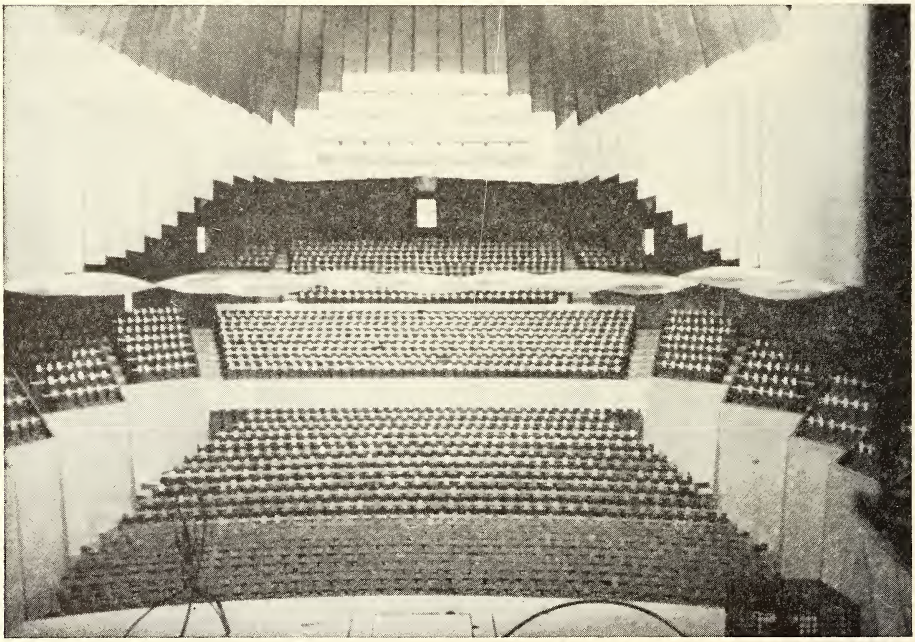


Figure 6b.

Figure 6.—Second (and final) design of the Concert Hall.
(A) View of the model towards the organ.
(B) View of the model towards the rear.

The early criteria of " rise time " and " steepness " were gradually being replaced by a new criterion, " Early Decay Time " (EDT). This criterion was known to be correlated with subjective impressions of reverberation as found in the investigation undertaken by M. R. Schroeder and his co-workers (Atal *et al.*, 1965). Furthermore, a working hypothesis was developed on the assumption that values of EDT should not be much lower than values of statistical RT (no more than 10–20% lower). This would be applied to individual locations throughout a model or a hall.

Averaging values of EDT, measured in the audience area and comparing it with the average value of EDT measured on the orchestra stage, produces a coefficient termed " Inversion Index ". This index should never be less than 1·0, i.e., the EDT should be at a higher level in the audience area than the average level in the stage area. This hypothesis has developed with the different criteria starting with rise time, which preferably should be shorter on the stage than in the auditorium, followed by steepness, which preferably should have higher values on the stage than in the auditorium. Incidentally, a certain relationship of reciprocity exists between steepness and EDT, as became evident from the considerations of M. R. Schroeder (Schroeder, 1966).

A complete survey and evaluation of modern acoustical criteria has been given by W. Reichardt (Reichardt, 1970).

The results of the model testing for the first design of the Concert Hall were reported upon early in 1968 and were followed by subsequent reports, including the testing of the Opera Theatre model, 1968–69 (Jordan, 1968–69).

In accordance with the working hypothesis mentioned above, the measured values of EDT were compared with the average value of RT for different locations in the model. The inversion index was calculated for two different cases : (*a*) with the circular, convex reflectors of plexiglass suspended above the orchestra stage ; (*b*) with the reflectors removed. A definite indication of higher values of inversion index was observed with the reflectors above the orchestra platform.

Generally speaking, deficiencies in EDT values were observed in the orchestra level seating. Certain improvements, e.g. increasing the ceiling height to some extent above the terrace area, did not result in any considerable overall improvement of these deficiencies.

Obviously, only a quite radical departure from this first design could improve conditions at the orchestra level. An improvement could only be obtained if side reflections were increased in strength compared to reflections from the ceiling. One way of decreasing the dominance of ceiling reflections would be to move the ceiling further up and to straighten it out. Furthermore, if at the same time the side walls lost their step-like arrangement and were brought closer together the side reflections would take more dominance. An arrangement with side boxes meant that the side walls above the boxes could come closer together and the boxes would become as recessed into these walls. The ceiling design resulted in a crown piece above the stage and a beam-like structure, above the main body of the hall, radiating from the crown (Figure 6 (A) and (B)).

These changes were subsequently carried out on the model and a new test series was undertaken. The values of EDT in the orchestra level seating increased quite considerably due to the changes, while the inversion index still showed adequate values.

This design became adopted as the final design for the Concert Hall. Certain modifications of the crown above the stage and of diffusing boxes along the ceiling beams were included without too noticeable effects on the main results. The fact that the reflectors improved the general conditions was repeatedly experienced.

In most of the test series only one octave band (16 kHz octave) had been tested, but in the final test series the octave bands 2 and 8 kHz were included. It was noted that at 2 kHz the values of EDT in the orchestra level seating were lower, which was interpreted as due to a not quite sufficient ceiling diffusion. It was recommended to include more of the diffusing boxes in the final design of the hall itself.

The first design of the Opera Theatre was ready for testing early in 1969. This design (shown in Figure 7) had a relatively low flat ceiling (Hall, Todd and Littlemore, 1968).

In the model of the Opera Theatre the sound source (spark gap) had to be located alternatively in the orchestra pit and upon the stage or forestage, so that EDT values at different microphone locations could be measured in both cases. In addition to the evaluation already explained, the closeness of the values of the inversion index in these two cases was now included as a specific characteristic of the Opera Theatre design.

All the test series undertaken in the Opera Theatre model have shown values of EDT in excess of the values of the statistical RT. The

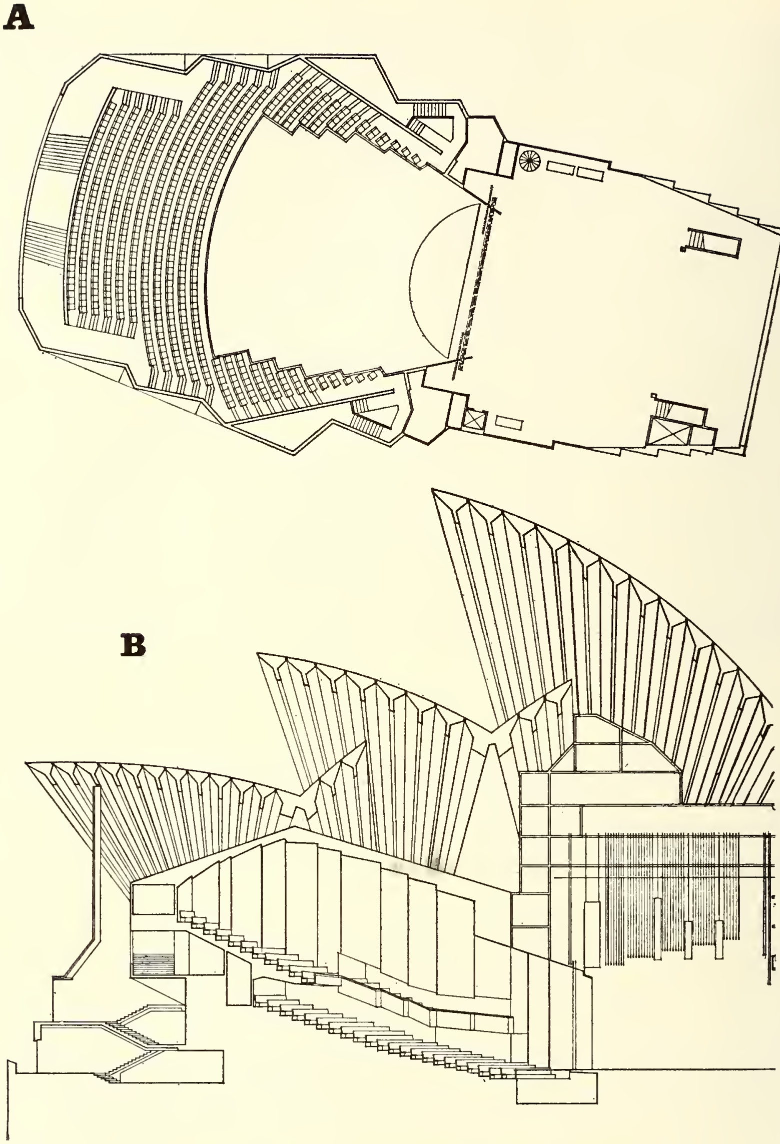


FIGURE 7.—First design of the Opera Theatre.
(A) Plan.
(B) Longitudinal section.

calculated values of the inversion index, however, showed considerable spacing between the pit case and the stage case, the pit values being highest, the stage values actually being below 1·0. In subsequent designs of this model the ceiling of the auditorium was gradually moved upwards, the tests indicating each time an improvement in values of the inversion index. In the final design the ceiling was moved upwards as far as the shell structure permitted. Figure 8 shows a picture of the model of this design. Testing of the final design showed better agreement between the values of the inversion index for the two cases, both having values exceeding 1·0.

This design was finally adopted for the Opera Theatre with minor alterations such as the placing of suspended reflectors above the orchestra seating area.

6. Various other Design Features of the Opera House

6.1. The Chamber Music/Cinema

The Reception Hall was in the first design period known as the Chamber Music Room. The seating capacity of 250 seats, however, was found insufficient and at the time of reprogramming a separate area, adjacent to the Central Passage, was preferred for housing a Chamber Music Hall of 400 seats. However, it was also felt that the Arts Centre of Sydney would need an arts cinema, and therefore the difficult combination of Chamber Music and Cinema was proposed. After struggling for a number of years with the problems inherent in such a dual purpose hall (variable acoustics, movable stage, etc.), the following recommendation was made—this hall should be exclusively an arts cinema and chamber music should be played in the other halls (Concert Hall, Opera Theatre and Drama Theatre). This recommendation was accepted, but unfortunately a certain ambiguity in terms lingered on and the term " Chamber Music/Cinema " was even used in pre-publications, although the design and construction of a hall exclusively for cinema use proceeded.

At a far too late stage the authority which eventually had to run the complex (the Opera House Trust) requested a compromise to be made. The feasible, but not very significant, increase of reverberation was implemented and a musician's platform was designed and constructed.

The hall has now received its name : " The Music Room ", a somewhat dubious choice of name for what will remain in the future a last-minute compromise solution.

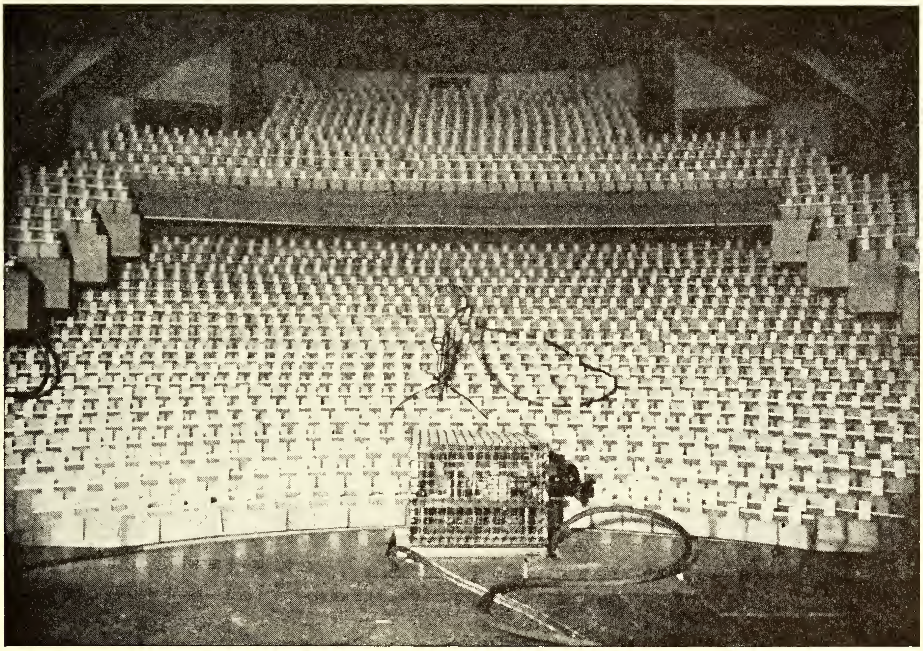


FIGURE 8.—Final design of the Opera Theatre. View of the model towards the rear.

6.2. The Drama Theatre

This area, originally the space for the Experimental Theatre of the Utzon period, has a seating capacity of 550 seats and a reverberation time close to $0 \cdot 9$ sec which must be considered ideal for a drama theatre of this size. No problems of dual purpose have troubled the design of this addition to the original programme.

6.3. The Rehearsal/Recording Studio (R/R)

Due to the reprogramming, the immense understage of the previous Major Hall was changed into a sizeable Orchestra Rehearsal Hall (Figure 9) which has a volume of approx. 5,200 m^3 and a reverberation time of $2 \cdot 0$ sec.

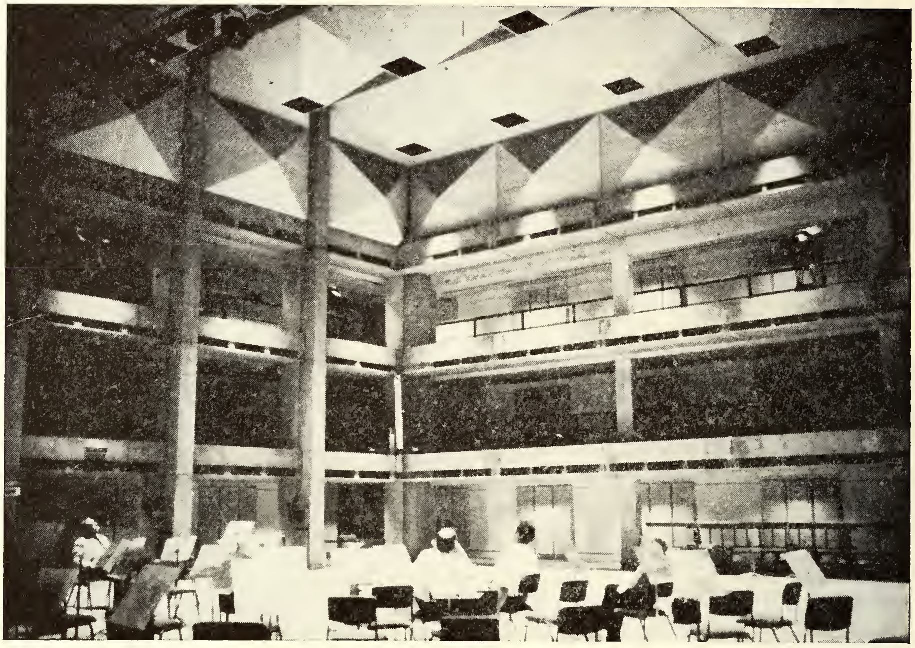


FIGURE 9.—View of the completed Rehearsal/Recording Studio.

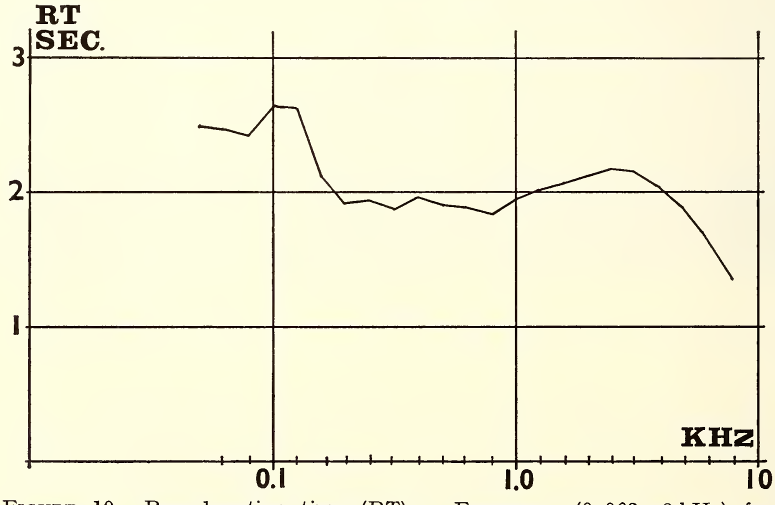


FIGURE 10.—Reverberation time (RT) *v*. Frequency (0·063—8 kHz) for Rehearsal/Recording Studio. $\frac{1}{3}$ octave values.

Incidentally, this value of RT brings R/R on to the same level as the Concert Hall, which has RT close to 2·1 sec.

The much discussed variation of RT with frequency has not been of too great concern. A slight increase of RT towards low frequencies is strongly advocated by some authorities, and has in fact been aimed at, although the author does not share this opinion.

Far more important, in the opinion of the author, is the frequency dependence of the medium frequencies to the higher frequencies. It has often been experienced that a certain suppression of the range between 400 and 1,000 hz (and a corresponding emphasis of the range above 1,000 hz) has decidedly a merit for studios and concert halls (Jordan, 1947).

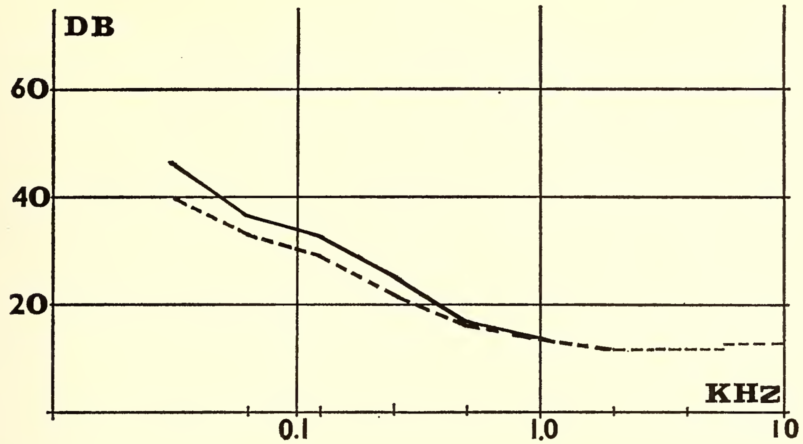


Figure 11.—Noise levels in the Concert Hall due to helicopter outside the building (200 ft above sea-level).

——— Noise level with helicopter present.
– – – – – Ambient noise level.

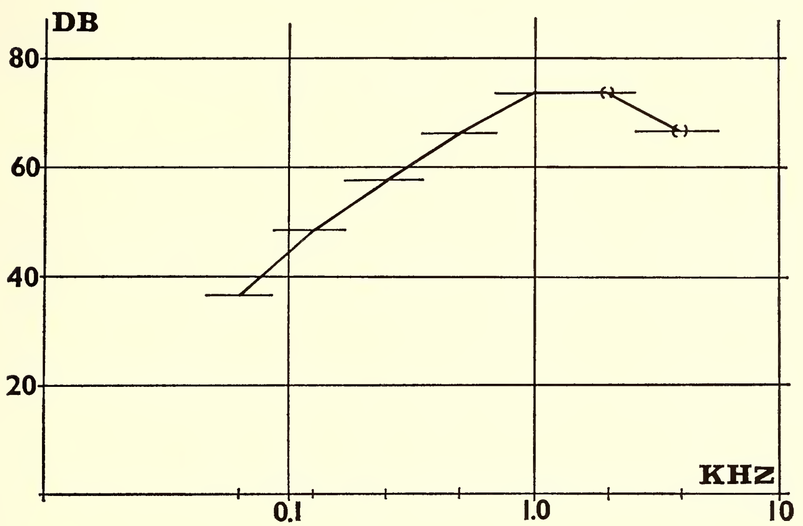


Figure 12.—Transmission loss between Rehearsal/Recording Studio and Concert Hall. (Values in brackets influenced by ambient noise level. True values greater than or equal.)

In the case of the R/R, a special type of panelling (thick, slot-perforated plywood with backing of mineral wood) has been used to obtain this particular RT dependence of frequency. Figure 10 shows the RT *v.* frequency characteristic measured in one-third octave steps.

For the benefit of using this area for television production, curtain tracks along the periphery of the balcony fronts have been installed in order to achieve a lower value of RT.

6.4. Examples of Sound Isolation Design

The problem of excluding exterior noise, especially from the large halls, has been a constant worry throughout the design period. The large halls have large areas exposed to the exterior, directly at the shells, indirectly at the glass façades and at the louvre walls.

In the first design period it was attempted to arrive at an acceptable if not ideal solution to this problem. Inner ceiling constructions were thought of as sandwich combinations of two

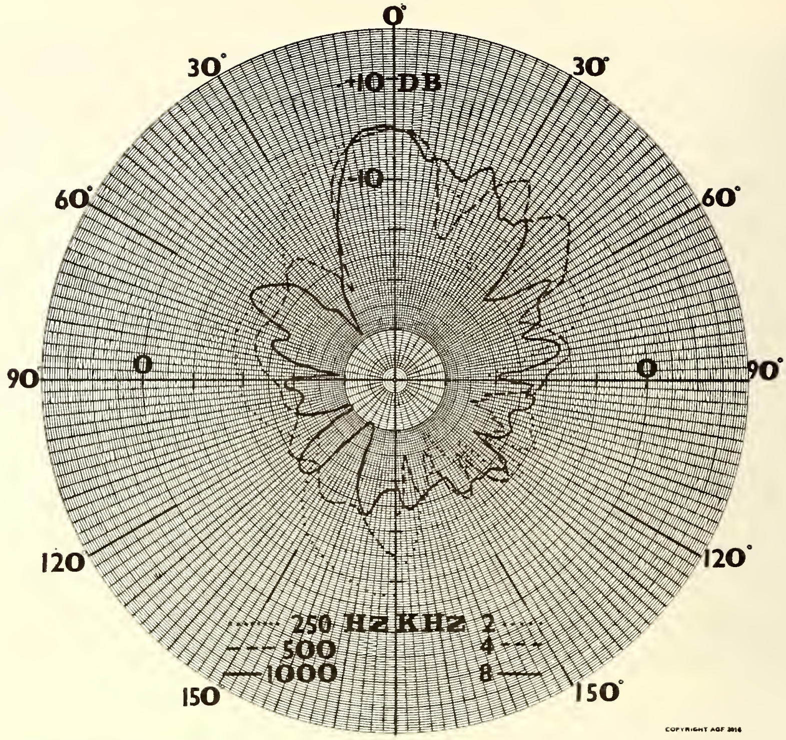


FIGURE 13.—Diagram of vertical polar pattern of the electrically tapered 13′ column. (Applied in the Concert Hall.)

layers of plywood with an intervening layer of mineral wool. On account of the revision of programme and design it became possible to redesign the ceiling also with regard to sound isolation. An interior "cocoon" of sprayed concrete on a supported steel mesh (under the shells) forms a separate sound isolating barrier on the inside of which the actual panelling (a plaster/ply combination) is mounted. Several glass constructions were tested for the large glass walls and finally a laminated construction with two layers, totalling $\frac{3}{4}$ in. thickness, was selected.

Actual testing of noise isolation from exterior noise by means of a helicopter hovering at a constant level of 200 ft above sea-level has shown that the interiors of the halls are very well protected against noise. Figure 11 shows a diagram to support this statement.

Sound isolation between various areas inside the complex have received much attention. Especially worth mentioning is the difficult case of separating the Concert Hall from the Rehearsal Hall underneath. Double slabs of heavy concrete isolated mutually by neoprene pads were used in conjunction with separate isolated walls of the Rehearsal Hall. Figure 12 shows a diagram of the results obtained.

6.5. Electro-acoustical System (*ELA*)

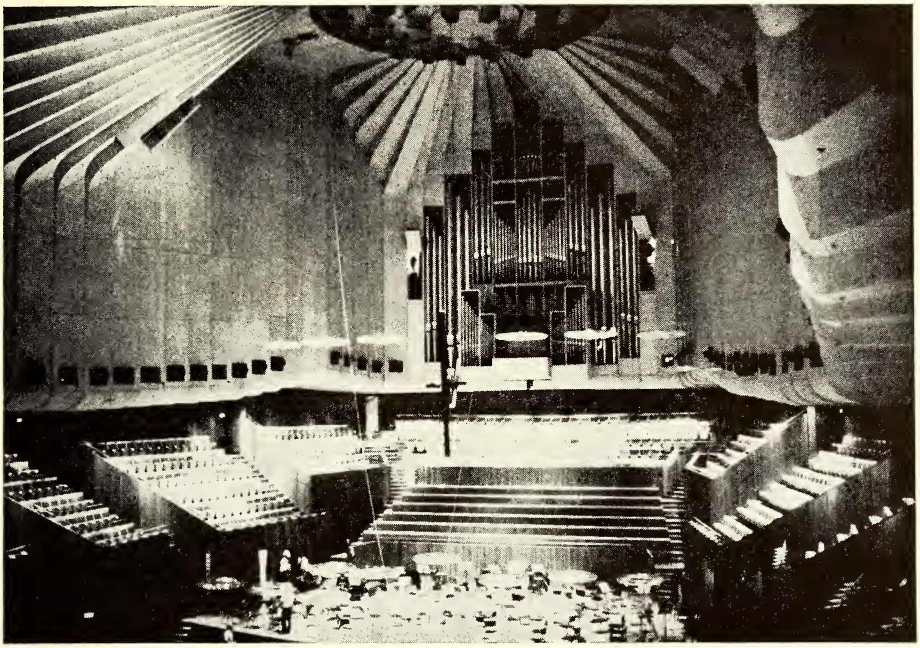
The design of the electro-acoustical system has developed considerably since the first design period, especially when it was decided to include Simultaneous Interpretation (SI) and to integrate this system with the ELA system.

Only a few features need to be mentioned here: those which are directly related to the acoustical design problems of the large halls (the Concert Hall and the Opera Theatre).

To incorporate a loudspeaker system in a concert hall with a reverberation time of 2·1 sec entails certain well-known difficulties, e.g., a narrow margin between feedback level and maximum permissible speech level.

The ways to overcome these difficulties are different, and in the case of the Concert Hall it was decided to use a centrally located speaker system with very highly directional sound columns. A thorough investigation of large sound columns led to the following two different solutions. Suspended above the stage in the Concert Hall, both were tried out with prototypes, one with acoustically tapered speakers and another with electrically tapered speakers.

Although the preliminary investigations had supported the first alternative, the final practical test showed clearly the superiority of the second.



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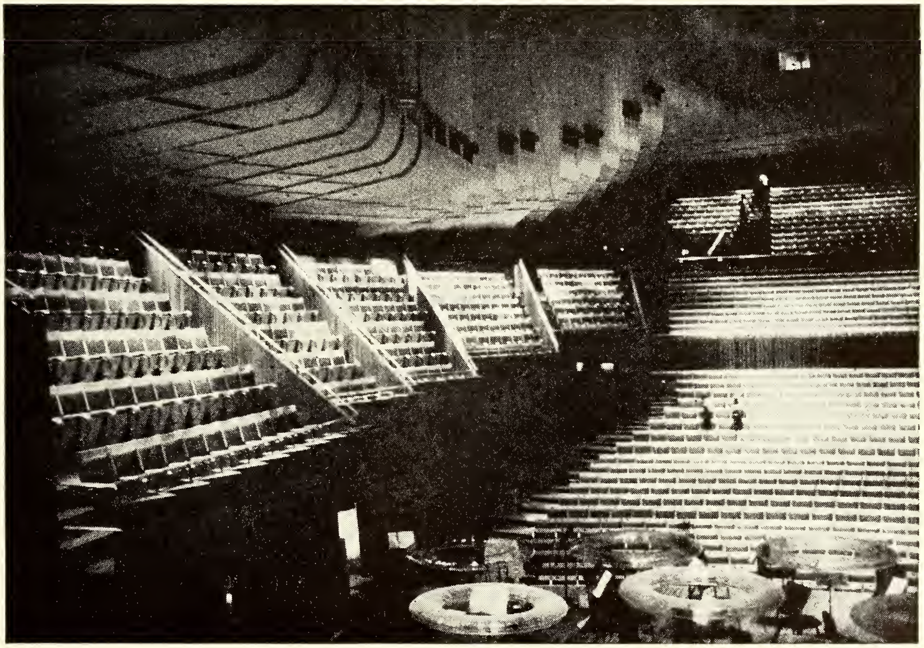


B

FIGURE 14.—Views of the completed Concert Hall.
(A) View towards the organ.
(B) View towards the rear.

A diagram of polar patterns is shown in Figure 13. The second system was finally adopted after testing it for announcements at the second test concert.

The Opera Theatre system of speakers is inserted into the proscenium frame as shorter sound columns, right, centre and left, following the profile of the proscenium. Additional speakers in the ceiling may be used for special effects, e.g. delays or reverberation. Under the balcony soffit delayed speakers assist in increasing the sound level of the spoken word.

These speaker systems are of course *not* used for voice or music amplification, but only for auxiliary purposes.

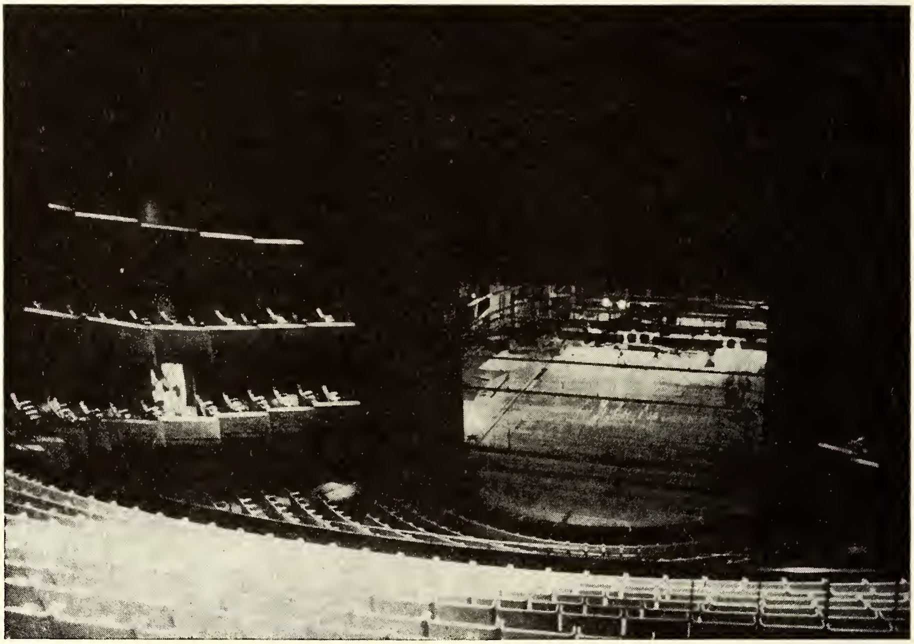


FIGURE 15.—View of the completed Opera Theatre. View towards the stage.

7. Testing of the Completed Large Halls

During a special testing session (at New Year, 1972–73) including actual musical performances in the presence of an audience, the acoustical results were measured and later evaluated.

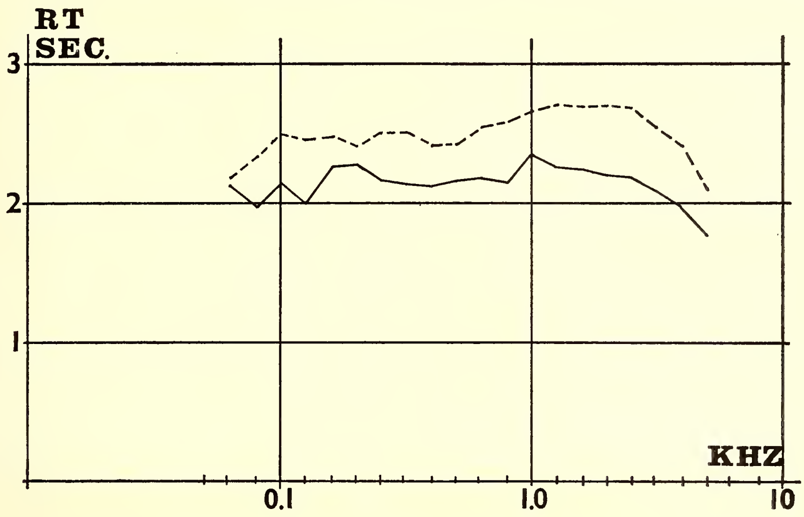
Pictures of the completed Concert Hall and Opera Theatre are shown in Figures 14 (A) and (B) and 15.

Two different testing methods were applied:

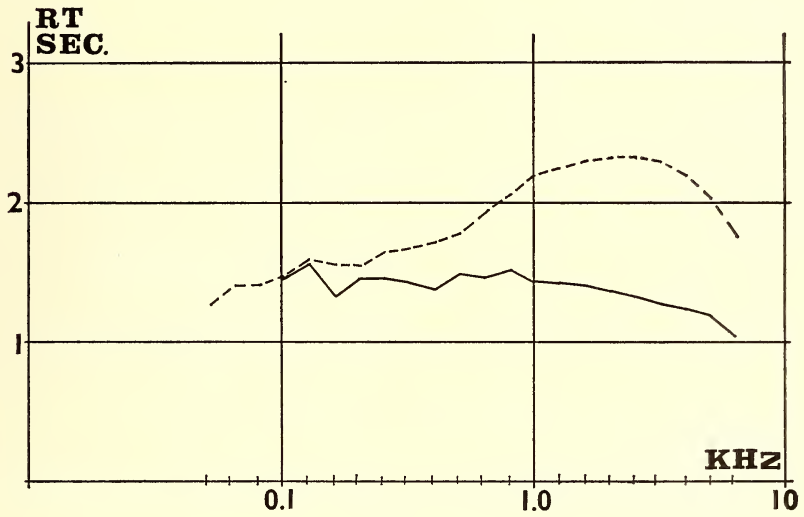
(1) To measure statistical RT: The music from the very first bars of the Beethoven *Coriolanus* overture, played by the Sydney Symphony Orchestra, were recorded on tape at a number of locations in the Concert Hall. The locations corresponded to those used in the model of the Concert Hall during the model testing. Later the tapes were analysed by filtering through 1/3 octave or 1/1 octave filters and recording on a level recorder. This method is only reliable in the case of very precise playing, which was obtained due to the skill of the conductor (Sir Bernard Heinze) and the Sydney Symphony Orchestra.

Incidentally, this method has some historical background. It was used for the first time in 1934–35 to test the RT of the old Philharmonic Hall of Berlin (now destroyed) (Meyer and Jordan, 1935).

(2) The method, previously used to measure statistical RT as well as EDT, was also used for the testing of the halls. Instead of the high-voltage spark (used in the models as a sound source) a pistol or a shotgun was fired (using blanks) from the stage of the Concert Hall as well as from the stage and the pit of the Opera Theatre. The shots were recorded at the same locations as used in the models.



A



B

Figure 16.—Reverberation time (RT) *v.* Frequency (0·063—5 kHz) in $\frac{1}{3}$ octave values.

(A) ———— Concert Hall, capacity audience.
– – – – – Concert Hall empty.
(B) ———— Opera Theatre, capacity audience.
– – – – – Opera Theatre empty.

The tapes were later analysed by filtering, reverse recording of the tape, and by integrating the signal. The integrated signal was fed to a level recorder and the values of EDT measured from the curves recorded. The same method, minus the integration, was used to obtain the values of RT.

Both methods were used in the empty halls as well as in the halls with near capacity audiences present ; in the Concert Hall test concerts were held on 17th December, 1972, and 21st January, 1973 ; in the Opera Theatre one test concert was held on 21st January, 1973. The results cannot be recorded in detail here, but examples of RT characteristics are shown in Figure 16 (A) and (B). Further, it should be mentioned that the detailed analysis of EDT values has shown a general consistency with values measured in the model, although some individual locations may show discrepancies.

A few locations in the Concert Hall have values of EDT which at low frequencies fall a little short of the RT value. This, however, varies with the elevation of the reflectors above the stage. The shape of the reflectors in the final design has been changed from circular (spherical) to toroïdal for two reasons : to reduce the area and to achieve more diffusion in the horizontal direction.

None of the locations in the Opera Theatre have values of EDT short of the average RT value.

Most interesting results have been obtained by calculating the inversion index for the different cases and a quite convincing agreement between model values and hall values can be seen in Tables 1 and 2.

TABLE 1
Inversion Index for the Concert Hall

	16 kHz Octave	Average Value 2–8–16 kHz	
Model, first design :			
Reflectors at sidebox soffit level	1, 10	—	
Without reflectors . .	1, 01	—	
Model, second design :			
Reflectors at sidebox soffit level	1, 19	1, 11	
Reflectors just below the crown	1, 13	1, 05	
	2 kHz Octave	**Average Values 125–4000**	**Average Values 500–4000**
Hall empty :			
Reflectors at sidebox soffit level	1, 14	1, 14	1, 18
Reflectors just below the crown	1, 10	1, 09	1, 11
Hall capacity audience :			
Reflectors at sidebox soffit level	1, 00	0, 97	0, 99
Reflectors just below the crown . .	1, 04	1, 05	1, 05
Reflectors at 34 ft above stage . .	1, 10	—	1, 11

From the values for the Concert Hall it seems legitimate to conclude that the intermediate position of the reflectors has the greatest merit. Why the sense of variation of inversion index with the elevation of the reflectors is reversed in the hall with capacity audience is not readily explainable. Maybe the lack of orchestra musicians simulation in the model can explain this result.

TABLE 2
Inversion Index for the Opera Theatre

Model	16 kHz Octave		Average Value 8–16 kHz	
With sound source at . .	Pit	Stage	Pit	Stage
Flat ceiling design. . . .	1, 15	0, 90	—	—
Stepped ceiling	1, 13	0, 97	—	—
High ceiling, balconies . .	1, 26	1, 15	1.17	1.11
			Average value 2–4–8–16 kHz	
Final design . .	1, 27	1, 10	1.22	1.13
Opera Theatre	**2 kHz, Octave**		**Average value 125–4000 Hz**	
With sound source at . .	Pit	Stage	Pit	Stage
Capacity audience. . . .	1, 28	1, 15	1.22	1.10

For the various model designs of the Opera Theatre it is seen that the values of inversion index for the pit and the stage series approach each other as the design advanced.

The values of inversion index of the Opera Theatre with capacity audience are very close to values of the final design model. Average values and values at one of the highest octaves used do not seem to disagree very much.

As for the musical judgments of all auditoria, the author wishes to refrain from citing any comments. Let the results speak for themselves.

8. Acknowledgements

The documentation exposed in Jørn Utzon's two reports (" the red book " of 1958 and " the white book " of 1962) has been used repeatedly to reproduce the designs of " Major Hall " and " Minor Hall " of the Utzon period (1957–66).

For the account of the early model testing during the same period the author has used his own files, in a single instance supplemented with information from an unpublished report by Lothar Cremer.

The later adopted method of pulse testing, which became vital in testing of models as well as of completed halls, is based on the general theory of M. R. Schroeder.

The development of acoustical criteria over the whole period is only partly exposed in this article, but interested readers can gain much supplementary information from the references given. Especially, the survey of W. Reichardt is most valuable in this respect.

The documentation relating to the second design period (the Peter Hall period, 1966–73) is based on pictures and drawings of models and designs available to the author due to his close co-operation with the architects, Peter Hall, Lionel Todd and David Littlemoıe.

A considerable part of the instrumentation for the model testing was put at the author's disposal through the co-operation of the Project Officer, Philip Taylor (of the Public Works Department).

The actual construction of the very exact plywood models was undertaken by Hornibrooks Ltd. (in charge of model teams : Frank Daniels).

During the model testing Peter Knowland assisted the author in extended investigations.

Never shall the author forget the co-operation with Peter Hall and the late Ben Schlanger during the period of reprogramming, the outcome of which became the basis for all subsequent interior designs of the Opera House. A majority of the joint recommendations were accepted and were closely followed up by the redesign of the interior.

The former Minister for Public Works, Davis Hughes, took a vivid interest in the acoustical design problems of the Opera House during these seven years.

As professional architect, Lionel Todd supported the author strongly in aiming at the very best solution to the problems of sound isolation, especially of the large halls.

The excellent preparation of the test concerts was due to the co-operation of several organizations in a special committee.

It is appropriate to emphasize the contribution of Sam Hoare and his co-workers of Hornibrooks who were responsible for all practical arrangements. The acoustical testing team was organized by Niels Jordan, who manned the taping locations with volunteers.

The Sydney Symphony Orchestra, conducted by Sir Bernard Heinze, performed at the very first concert given in the Concert Hall. For the benefit of the acoustical tests they patiently repeated the first bars of the *Coriolanus* several times.

The ABC National Training Orchestra, conducted by Robert Miller, together with the soloists Elizabeth Fretwell and Donald Smith, all performed at the subsequent test concert in the Concert Hall and in the Opera Theatre.

Illustrations, diagrams and tables for this article have been prepared by Niels V. Jordan at short notice.

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The Design of the Concert Hall of the Sydney Opera House

Peter Hall

Abstract—This paper deals with the Concert Hall only. It sets out initially the most important design criteria influencing the architecture of rooms for music, then deals with the Client Brief and its resolution in terms of volume, audience arrangement, ceiling design and choice of materials. The room is designed to seat 2,690 people with good seating and viewing conditions, to accommodate a large orchestra and choir and to have a reverberation time in the middle frequencies of the order of two seconds. In addition it is designed to satisfy the subjective criteria of musical quality. It describes the solutions chosen to achieve these ends. The hall embodies the attributes currently recognized as desirable in large concert halls.

Design Criteria Generally

I believe architectural design, or any other design for that matter, is impossible without constraints and without a set of requirements, the needs for which have to be resolved. Architects are trained essentially as problem solvers, consequently one must not complain at the complexity of the problem set. A building for music in itself is about the most complex modern architectural problem.

It was not always so. The designers of Concertgebouw, Amsterdam, or Musikvereinssaal in Vienna faced only some of the problems of the Sydney Opera House. Noise levels in the cities in general would have been much lower: no buses, no jet aircraft, much less efficient ships' sirens, no air conditioning, smaller audiences, fewer alternative entertainments. The large audience is a modern economic necessity, not always conducive to the best quality in a room. Neither, apparently, were people so critical about their bodily comfort. It was quite possible to sit them close together (e.g. in Concertgebouw, with 28·5 in row spacing and 20·5 in chair width) in hard, uncomfortable chairs, which probably rattled even when they were new when people moved in them. Sight lines and vision also would not have been nearly so critically looked at as they are now. Furthermore, the buildings were given time to achieve a reputation through the performances and the bad halls were torn down. Some of the world's great halls are great because great companies have performed in them and they have acquired reputation and glamour as they have aged and as the number of great performances has increased. Covent Garden, for example, would not be regarded as an ideal theatre. There are seats there, conspicuously the gallery slips, from which it is possible to see very little.

Table 1

Typical Overall Noise Levels, Expressed in Decibels, Measured at a Given Distance from the Noise Source (Levels below 85 dB are weighted)

(L. Doelle, 1965)

Noise Source	Noise Level, dB, *re* 0·0002 Microbar
Ticking of watch	20
Quiet garden	30
Average residential environment ..	43
Light traffic (100′)	45
Average private business office ..	50
Accounting office	65
Average traffic (100′)	67
Boeing 707–120 jet at touch-down (3,300′)	70
Automobile (20′)	74
Heavy traffic (25′ to 50′)	75
Average light truck in city (20′) ..	77
Lathes (3′)	80
Cotton spinning machines (3′) ..	85
Inside sedan in city traffic	86
10 hp outboard (50′)	88
Boeing 707–120 jet at take-off (3,300′)	90
Inside motor bus	91
Train whistles (500′)	92
Average heavy truck (20′)	93
Subway train (20′)	95
Sewing machines (3′)	96
Looms (3′)	97
Riveting gun (3′)	100
Wood saw (3′)	100
Inside DC–6 airliner	105
Chipping hammer (3′)	108
Automatic punch press (3′) ..	112
Car horn (3′)	114
Pneumatic chipper (5′)	123
Large pneumatic riveter (4′) ..	128
Hydraulic press (3′)	129
F84 jet at take-off (80′ from tail)	132
50 hp siren (100′)	138

But if there is a notable performance (and most of the opera performances at Covent Garden have fallen into this category since the days of

Sir Thomas Beecham) people are glad to be there, to see part of the stage, if any, but to hear, to stand when they really feel they must see, and, most important of all, to have been there while the event happened. Professor Cremer, the celebrated German acoustician, who worked for a time on Stage II of the Sydney Opera House, made exactly such a comment. He said he believed the reputation of the old Berlin Philharmonic had been made for it by the performances there, that Furtwangler made the reputation of the old Philharmonic Hall, and he hoped that von Karajan was about to do the same for his new Philharmonic.

any serious acoustical defect, however good the excuses offered by the designers.

Let us look at some of the problems confronting the designer of any building for music and then let us multiply their complexity by some special Opera House factor arising from the peculiar internal geometry of the volumes under the shells, by the weight restrictions arising partly from the extraordinarily difficult engineering task of building those shells at all, and the statically indeterminate podium, designed on inadequate information about sound transmission and sound isolation, with the result that its load carrying capacity was less than desirable. Add to this the consideration that practically every surface or projection which is designed into a room has some effect on its acoustics. The audience must be arranged in such a way that it is comfortable, and that its relationship to other parts of the audience is satisfactory. The audience must see and hear the performers and the performers must be able to hear themselves. Both audience and performers must be brought in and taken out of the auditorium safely. The noise level inside the room must be low and the sound inside the

TABLE 2
Vocabulary of Subjective Attributes of Musical-Acoustic Quality
(Beranek, 1965)

Quality		Antithesis	
Noun Form	Adjectival Form	Noun Form	Adjectival Form
intimacy, presence	intimate	lack of intimacy, lack of presence	non-intimate
liveness, fullness of tone	live	dryness deadness	dry dead
reverberation	reverberant	lack of reverberation	unreverberant
resonance	resonant	dryness	dry
warmth	warm	lack of bass	brittle
loudness of the direct sound	loud direct sound	faintness . . . weakness . . .	faint . . . weak . . .
loudness of the reverberant sound	loud . . .	faintness . . . weakness . . .	faint . . . weak . . .
definition, clarity	clear	poor definition	muddy
brilliance	brilliant	dullness	dull
diffusion	diffuse	poor diffusion	non-diffuse
balance	balanced	imbalance	unbalanced
blend	blended	poor blend	unblended
ensemble	——	poor ensemble	——
response, attack	responsive	poor attack	unresponsive
texture	——	poor texture	——
no echo	echo-free anechoic	echo	with echo echoic
quiet	quiet	noise	noisy
dynamic range	——	narrow dynamic range	——
no distortion	undistorted	distortion	distorted
uniformity	uniform	non-uniformity	non-uniform

But in a new hall one cannot expect to be allowed this ingredient of time to evaluate it. In the case of the Sydney Opera House (which had a formidable reputation when my partners and I took over from Jørn Utzon in 1966) there was every reason to expect that there would be a great focus of critical attention on the building, consequently every possible scientific means of prediction should be used to ensure that the building would meet high standards of quality. Neither the audience nor a professional critic could be expected to excuse room controlled and distributed so that there are no places where people do not hear well. Finally, both performers and audience should enjoy the whole experience. The solution of this design problem placed extraordinary demands on the consultants and client and all submitted patiently to the long period of investigation, testing and design development involved.

seating and good sight lines. The staging requirements for concerts should be sufficient to accommodate a large choir, preferably an organ of adequate proportions for concert work and capable of the performance of the large-scale works in the standard repertoire. The performers and the audience should be in the same acoustical space. Presumably this point was made to express the ABC's reluctance to have

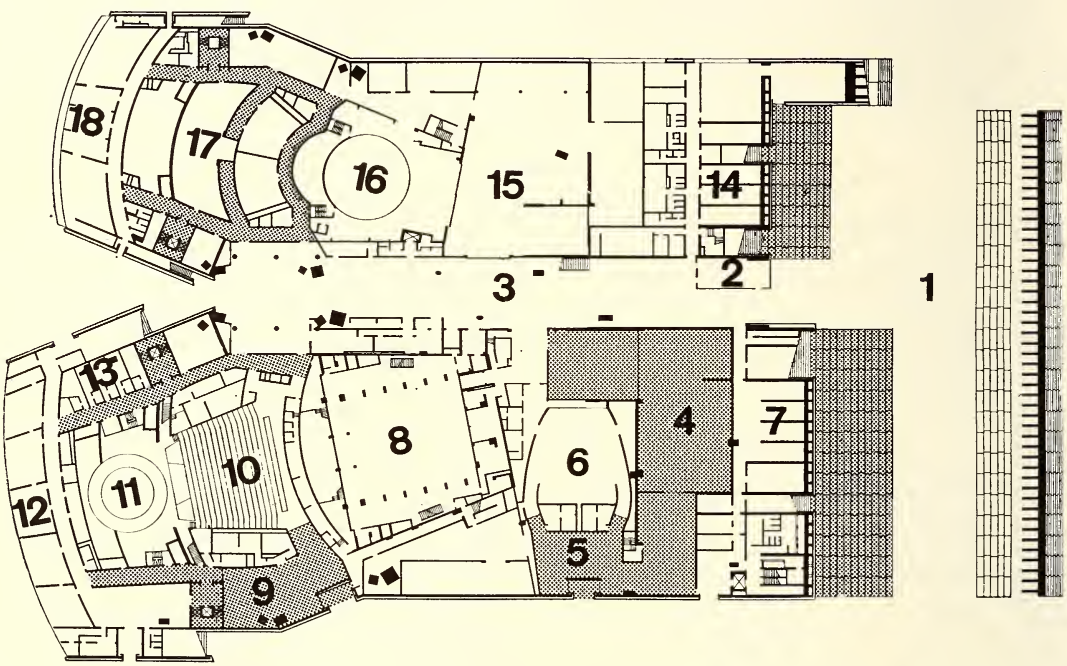


FIGURE 1.—Ground floor.

1. Car concourse.
2. Stage door.
3. Central services passage.
4. Exhibition hall.
5. Cinema/Chamber music hall foyer.
6. Cinema/Chamber music hall.
7. Catering stores.
8. Rehearsal/Recording hall.
9. Drama theatre foyer.
10. Drama theatre.
11. Drama theatre stage.
12. Administrative offices.
13. Dressing rooms for drama theatre.
14. Staff areas.
15. Set storage and scene changing area.
16. Opera theatre below stage.
17. Rehearsal rooms.
18. Broadwalk restaurant.

The Brief for the Concert Hall

The Concert Hall design was done first and was fundamental to the whole project, because from a decision on the use of this room all other decisions flowed in 1966. The basis for the brief was contained in a letter written by the General Manager of the Australian Broadcasting Commission on 7th June, 1966, to the N.S.W. Government Architect, Mr. Farmer. The stated requirements of the ABC were a seating capacity of 2,800, with comfortable the orchestra perform on a stage with a proscenium opening between it and the audience. This produces the effect of the orchestra playing in a coupled room and does not give the audience the effect of actually sitting in the music which is desirable if the quality of intimacy is to be experienced. Aesthetically the acoustics required were stated as having a reverberation time in the middle frequencies in the region of two seconds when fully occupied and electronic assistance was specifically not required. The character of the sound considered desirable was such as is found in the Boston Symphony Hall, Concertgebouw, Amsterdam, Old St. Andrew's Hall, Glasgow, and the Grande Salle of Place des Arts in Montreal. Two other desirable attributes were stated to be the exclusion of all extraneous sounds from the Hall, and a quiet, well-designed system of air conditioning. In terms of Beranek's noise criteria this should be no greater than N.C. 25.

The two most readily identifiable objective criteria are clearly seating and reverberation time, since seats can be counted and reverberation time can be measured. Clarity, diffusion, brilliance, etc., form part of the subjective experience of the listener and the performer, and are not so readily identifiable. In fact, I believe there is as yet no satisfactory way of measuring these and it will be some time before they can be stated as design criteria, although it can be

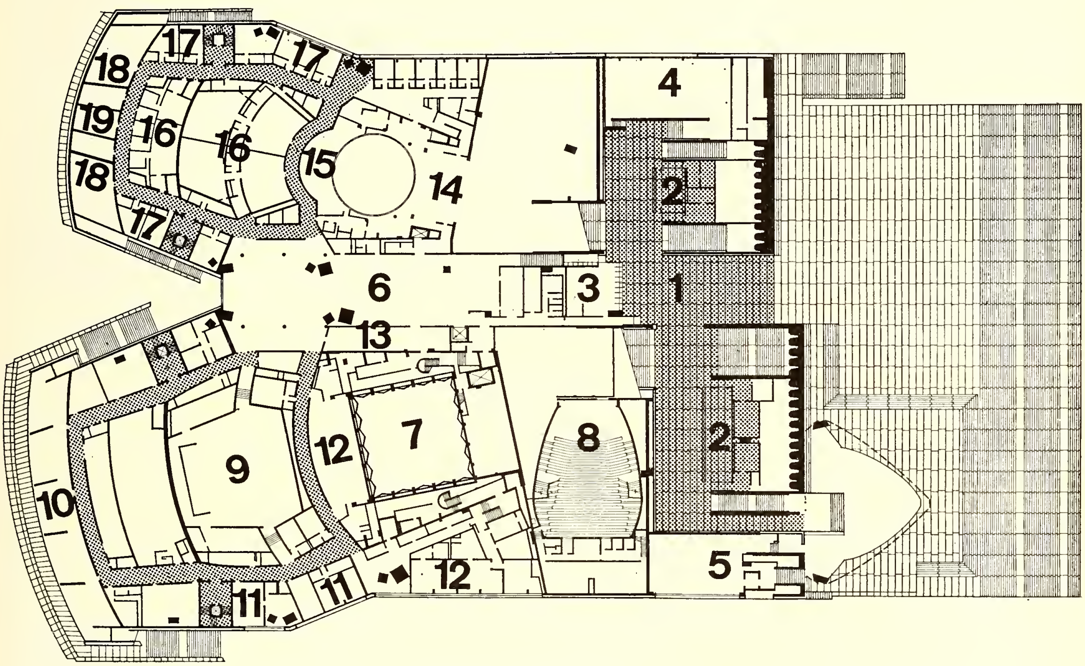


FIGURE 2.—First floor.

1. Foyer.
2. Cloak rooms and toilets.
3. Box office.
4. Recital/Reception room.
5. Main kitchen.
6. Artists' lounge and buffet.
7. Upper part rehearsal hall.
8. Cinema/Chamber music hall.
9. Rehearsal room.
10. Administrative offices.
11. Conductors' suites.
12. Orchestra dressing rooms and instrument store.
13. Music library.
14. Opera theatre below stage.
15. Orchestra pit.
16. Chorus and orchestra dressing rooms.
17. Principals' dressing rooms.
18. Costume stores.
19. Rehearsal rooms.

These requirements were formulated by the ABC's competent acoustic staff and present a good summary of currently accepted acoustic standards for large concert halls generally. A great deal of subsequent research, the findings of Beranek (1962) and Doelle (1965), the experience of Kosten and deLange in the new de Doelen Hall at Rotterdam, of Professor Cremer in the new Berlin Philharmonic, and the writings and views of many other authorities confirm this.

said that many of the attributes of a room capable of producing this good subjective response have been identified. In Christopher Gilford's article, he writes :

" Thus it appears that the sound quality of a hall may be determined not only by the reverberation time, the diffuseness of the sound field, and the distribution of early reflections, but also on the height-to-breadth ratio and the shape of the ceiling zone. Clearly,

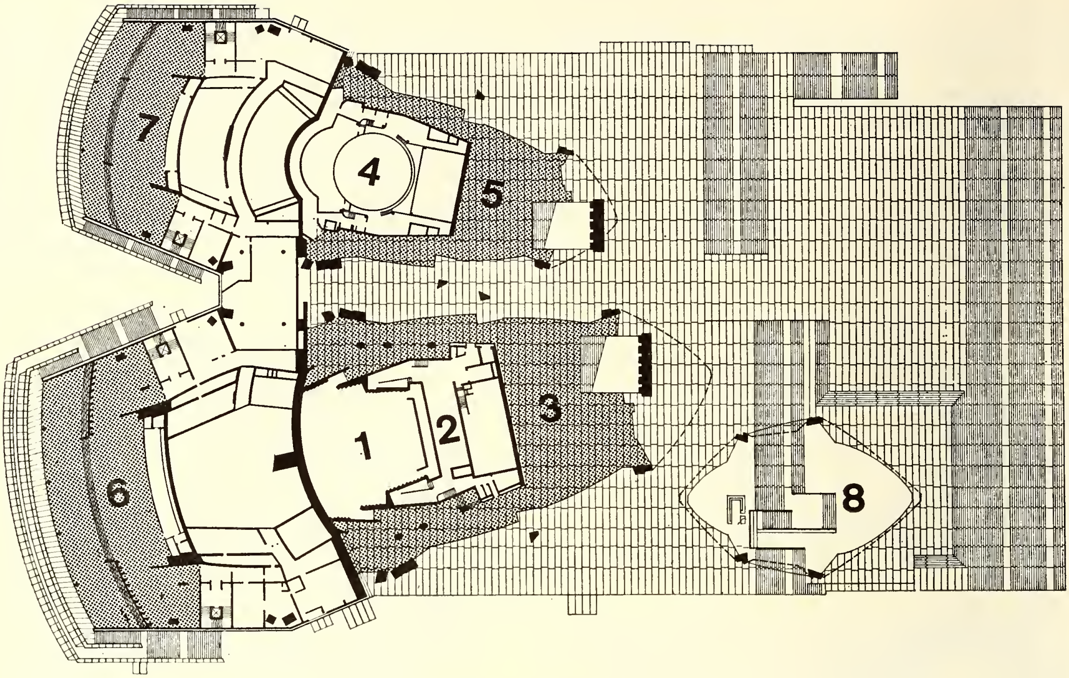


FIGURE 3.—Second floor.

1. Concert hall.
2. Orchestra assembly.
3. Concert hall foyer.
4. Opera theatre stage, lower level.
5. Opera theatre foyer.
6. Concert hall promenade lounge.
7. Opera theatre promenade lounge.
8. Main restaurant.

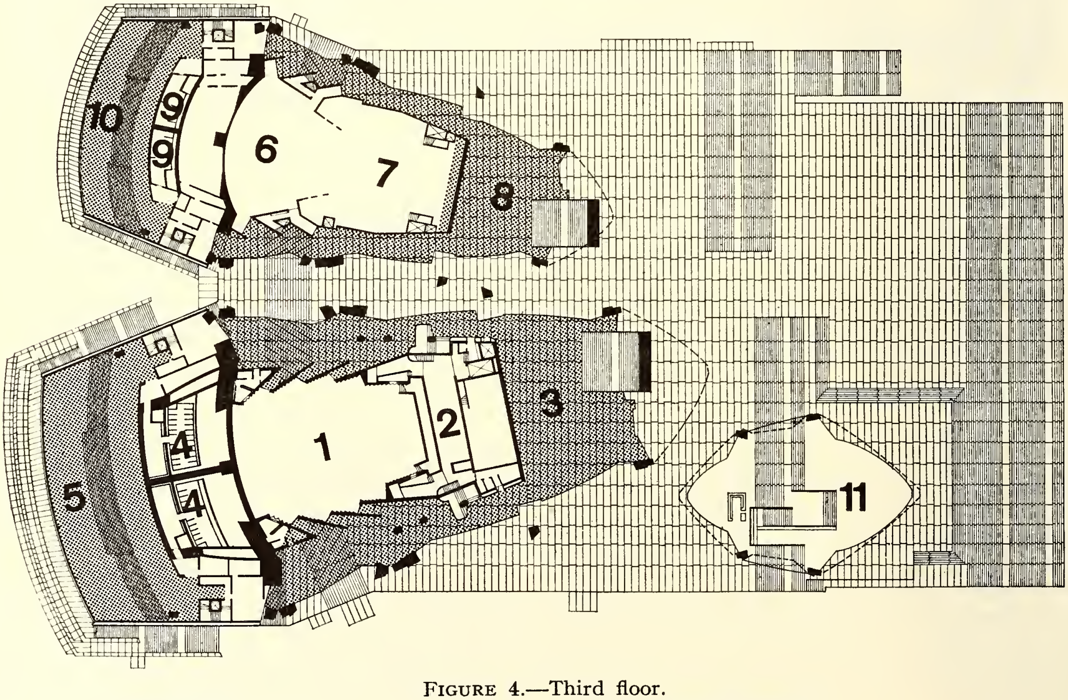


FIGURE 4.—Third floor.

1. Concert hall.
2. Orchestra assembly.
3. Concert hall foyer.
4. Toilets.
5. Concert hall promenade lounge.
6. Opera theatre.
7. Opera theatre stage.
8. Opera theatre foyer.
9. Toilets.
10. Opera theatre promenade lounge.
11. Main restaurant.

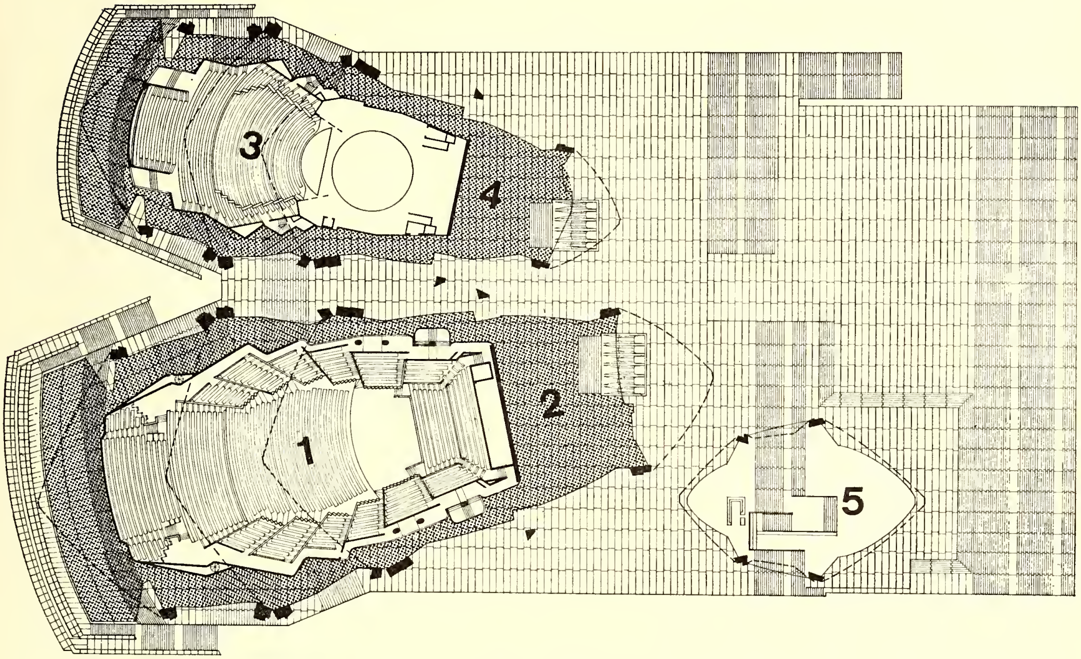


FIGURE 5.—Main auditorium plans.

1. Concert hall.
2. Concert hall foyer.
3. Opera theatre.
4. Opera theatre foyer.
5. Main restaurant.

this requires further investigation, but the general excellence of the Elizabeth Hall lends support to the idea.

Conclusions

The lessons to be learnt from the Elizabeth Hall are :

1. Reverberation time still remains the best indicator of the general acoustic quality and the fullness of tone : it is largely determined by the volume of hall per square foot of seating area, and accurate calculation on this basis is now possible.

2. Satisfactory tonal quality and definition is obtained without deliberate production of early reflections, provided that the diffusion is good.

3. The reason for the characteristic ' singing tone ' of the best traditional halls is still not fully understood ; it may require the existence of an appreciable height above the highest seating bounded by substantially vertical surfaces, as in this hall."

The 2,800 seat requirement of the ABC is, of course, a commercial one. Many of the great halls are smaller and the Berlin Philharmonic seats only 2,200. The classic way to achieve greater numbers of seats is to use balconies which give in effect a multi-floor situation. The inward taper of the shells at the Sydney Opera House severely limited this possibility. In the case of the Concert Hall, where the number of seats clearly meant an enlarging of the seating area already available, this was done by building out with cantilevered galleries over the side foyers and with a very large cantilever at the north end of the building which contains the terrace seating.

The Effect of Volume on Reverberation Time

In the case of reverberation time, it is well established that volume is the single most critical factor in achieving long reverberation time. Many of the concert halls built in the 1950's fell short of their target reverberation time because the effect of audience seating area in relation to volume was not realized. It is not only the number of people in the room, but

TABLE 3 Concert halls: dimensional and acoustical characteristics and year of dedication

Name	V Volume Ft^3 (m^3)	SA Audience Area Ft^2 (m^2)	So Orchestra Area Ft^2 (m^2)	ST Total Area Ft^2 (m^2)	V/ST Ft (m)	NA Seats	V/NA Ft^3 (m^3)	SA/NA Ft^2 (m^2)	T500-1000 (Occup.) Reverberation Time T mid sec	t_I Initial-Time-Delay Gap msec	Average Bass Ratio	Year Dedicated	SEAT SPACING Main Floor Row-to-Row in. (cm)	Main Floor Seat-to-Seat in. (cm)	Balcony Row-to-Row in. (cm)	Balcony Seat-to-Seat in. (cm)	Stage Height in. (cm)
AMERICA																	
Baltimore Lyric Theatre	744,000 (21,000)	16,700 (1,550)	1690 (157)	18,400 (1,710)	40.4 (12.2)	2616	284 (8.0)	6.4 (0.59)	1.5	21;11	1.05	1894	31 (79)	19.5 (51)	31-33 (79-84)	20 (51)	51.5 (131)
Boston, Symphony Hall	662,000 (18,740)	15,000 (1,390)	1600 (149)	16,600 (1,550)	39.9 (12.1)	2631	252 (7.1)	5.7 (0.53)	1.8	15;7	1.17	1900	30-33 (76-84)	21 (53)	29-33 (74-84)	21 (53)	54 (137)
Chicago, Orchestra Hall	536,000 (15,170)	18,000 (1,670)	2000 (186)	20,000 (1,855)	26.8 (8.12)	2582	208 (5.9)	7.0 (0.65)	1.3*	40;24	ca.1.18	1905	34 (86.4)	19 (48)	34 (86.4)	21 (53)	43 (109)
Cleveland, Severance Hall	554,000 (15,700)	13,000 (1,210)	2000 (186)	15,000 (1,395)	36.9 (11.2)	1890	289 (8.2)	6.9 (0.64)	1.7	20;13	ca.1.18	1930	38 (97)	22 (56)	30 (76)	20 (51)	32 (81)
Lenox, Massachusetts, Tanglewood Music Shed	1,500,000 (42,450)	30,800 (2,860)	2200 (204)	33,000 (3,065)	45.5 (13.8)	6000	250 (7.1)	5.1 (0.47)	2.05	19;12	1.24	1938	33 (84)	17-20 (43-51)	-	-	30 (76)
New York, Carnegie Hall	857,000 (24,250)	19,160 (1,780)	2200 (204)	21,360 (1,985)	40.1 (12.2)	2760	311 (8.8)	6.9 (0.64)	1.7	23;16	1.06	1891	33-35 (84-89)	22-23 (56-58)	32-35 (81-89)	20-22 (51-56)	48 (122)
Philadelphia, Academy of Music	555,000 (15,700)	16,700 (1,550)	2000 (186)	18,700 (1,735)	29.7 (9.0)	2984	186 (5.3)	5.6 (0.52)	1.4	19;10	1.11	1857	30-33 (76-84	20-21.5 (51-55)	30-32 (76-81)	18-21 (46-53)	52 (132)
AUSTRIA																	
Salzburg, Neues Festspielhaus	547,500 (15,500)	14,800 (1,375)	2100 (195)	16,900 (1,570)	32.4 (9.82)	2158	254 (7.2)	6.9 (0.64)	1.5	23;14	1.08	1960	29.5-31.5 (75-80)	17-20 (43-51)	29.5 (75)	17-20 (43-51)	35.5 (90)
Vienna, Grosser	530,000 (15,000)	10,600 (985)	1,400 (130)	12,000 (1,115)	44.2 (13.4)	1680	315 (8.9)	6.3 (0.59)	2.05	12;9	1.12	1870	31 (79)	21 (53)	36 (91)	21 (53)	39 (99)
BELGIUM																	
Brussels, Palais des Beaux-Arts	442,000 (12,500)	14,000 (1,300)	2,000 (186)	16,000 (1,485)	27.6 (8.36)	2150	206 (5.8)	6.5 (0.60)	1.42	23;4	1.34	1929	33 (84)	22 (56)	35-36 (89-91)	22 (56)	46.5 (118)
CANADA																	
Edmonton and Calgary Alberta Jubilee Auditoriums	759,000 (21,480)	21,000 (1,950)	2,000 (186)	23,000 (2,135)	33.0 (10.0)	2731	278 (7.9)	7.7 (0.72)	1.42	31;8	0.95	1957	33 (84)	20-22 (51-56)	36-37 (91-94)	24-27.5 (61-70)	42 (107)
DENMARK																	
Copenhagen Radiohuset, Studio 1	420,000 (11,890)	8,700 (810)	2,300 (214)	11,000 (1,015)	38.2 (11.6)	1093	384 (10.9)	8.0 (0.74)	1.5	29;27	1.07	1945	32-34 (81-86)	21-22 (53-56)	32-34 (81-86)	21-22 (53-56)	27.5 (70)
Copenhagen, Tivoli Koncertsal	450,000 (12,740)	12,240 (1,136)	2,100 (195)	14,340 (1,330)	31.0 (9.39)	1789	252 (7.1)	6.8 (0.63)	1.3	16;14	1.10	1956	31-32 (79-81)	23-25 (58-64)	31-32 (79-81)	23-25 (58-64)	32 (81)
GERMANY																	
Berlin, Benjamin Franklin Kongresshalle	457,500 (12,950)	10,300 (960)	1,000 (93)	11,300 (1,055)	40.5 (12.3)	1220	375 (10.6)	8.4 (0.78)	1.2	25;19	ca.1.30	1957	39 (99)	25.5 (65)	-	-	26.7 (68)
Leipzig Neues Gewandhaus	375,000 (10,600)	9,750 (950)	1,250 (116)	11,000 (1,020)	34.0 (10.3)	1560	240 (6.8)	6.3 (0.59)	1.55	8;6	1.00	1886	29-30 (73-76)	21.5-22.5 (55-57)	31.5 (80)	20 (51)	36 (91)
Munich Herkulessaal	480,000 (13,600)	7,250 (675)	1,810 (168)	9,060 (845)	53.0 (16.1)	1287	373 (10.6)	5.6 (0.52)	1.85	24;10	1.10	1953	31 (78)	20 (51)	33 (84)	19-20 (48-51)	37 (94)
Stuttgart Liederhalle, Grosser Saal	(16,000) 565,000	14,000 (1,300)	1,900* (177)*	16,500 (1,535)	34.2 (10.4)	2000	283 (8.1)	7.0 (0.65)	1.62	29;12	1.06	1956	39-40 (99-102)	23.5 (60)	39 (99)	20 (51)	49 (125)

*Estimate

*Plus 600 ft^2 (55.7m^2) of chorus area.

TABLE 3 Concert halls: dimensional and acoustical characteristics and year of dedication (continued)

Name	V Volume Area Ft^3 (m^3)	SA Audience Area Ft^2 (m^2)	SO Orchestra Area Ft^2 (m^2)	ST Total Area Ft^2 (m^2)	V/ST Ft (m)	NA Seats	V/NA Ft^3 (m^3)	SA/NA Ft^2 (m^2)	T500-1000 (Occup.) Reverberation Time T mid sec	t_I Initial-Time-Delay Gap msec	Average Bass Ratio	Year Dedicated	SEAT SPACING: Main Floor Row-to-Row in. (cm)	SEAT SPACING: Main Floor Seat-to-Seat in. (cm)	SEAT SPACING: Balcony Row-to-Row in. (cm)	SEAT SPACING: Balcony Seat-to-Seat in. (cm)	Stage Height in. (cm)
GREAT BRITAIN																	
Bristol, Colston Hall	475,000 (13,450)	12,310 (1,145)	1,150 (107)	13,460 (1,250)	35.3 (10.7)	2180	218 (6.2)	5.6 (0.52)	1.7	14;6	1.04	1951	29.5-30.5 (75-78)	20 (51)	32 (81)	20 (51)	43 (109)
Edinburgh, Usher Hall	565,000 (16,000)	15,300 (1,420)	1,200 (111)	16,500 (1,530)	34.2 (10.4)	2760	205 (5.8)	5.5 (0.51)	1.65	33;11	1.15	1914	28-33.5 (71-85)	19.5-21.5 (50-55)	28 (71)	19-20 (48-51)	53 (135)
Glasgow, St.Andrew's Hall	569,000 (16,100)	13,500 (1,255)	1,400 (130)	14,900 (1,385)	38.2 (11.6)	2133	267 (7.6)	6.3 (0.59)	1.9	20;8	0.95	1877	31.5 (80)	20 (51)	29 (74)	20 (51)	56.5 (144)
London, Royal Albert Hall	3,060,000 (86,600)	37,800 (3,510)	2,200 (204)	40,000 (3,715)	76.5 (23.2)	6080	503 (14.2)	6.2 (0.58)	2.5	65(35);70	1.29	1871	33-37 (84-94)	23.5 (60)	32 (81)	18.5 (47)	40 (102)
London, Royal Festival Hall	775,000 (22,000)	21,230 (1,970)	1,860 (173)	23,090 (2.145)	33.6 (10.2)	3000	258 (7.3)	7.1 (0.66)	1.47	34;14	0.88	1951	31 (79)	21.5 (55)	34 (86)	20 (51)	30 (76)
ISRAEL																	
Jerusalem, Binyanei Ha'Oomah	873,C00 (24,700)	23,000 (2,140)	2,800 (260)	25,800 (2,400)	33.8 (10.2)	3142	278 (7.9)	7.3 (0.68)	1.75	26;13	1.20	1960	35.5 (90)	19.5-27 (50-69)	35.5 (90)	20 (51)	44.5 (113)
Tel Aviv, Fredric R.Mann Auditorium	750,000 (21,200)	18,300 (1,700)	2,100+ (195)+	20,800 (1,930)	36.0 (10.9)	2715	276 (7.8)	6.7 (0.62)	1.55	30;7	0.98	1957	30-33 (76-84)	20 (51)	35 (89)	19 (48)	30 (76)
NETHERLANDS																	
Amsterdam, Concertgebouw	663,000 (18,700)	12,200 (1,135)	1,600 (149)	13,800 (1,285)	48.0 (14.5)	2206	301 (8.5)	5.5 (0.51)	2.0	21;9	1.10	1887	28.5 (72)	20.5 (52)	30-33 (76-84)	20-22 (51-56)	58.5 (149)
SWEDEN																	
Gothenburg, Konserthus	420,000 (11,900)	8,900 (830)	1,450 (135)	10,350 (965)	40.6 (12.3)	1371	306 (8.7)	6.5 (0.60)	1.7	33;22	1.06	1935	35.5 (90)	21.5 (55)	35.5 (90)	21.5 (55)	47 (119)

+ Plus 400 ft^2 (37.2 m^2) of chorus area.

TABLE 3 Opera houses: dimensional and acoustical characteristics and year of dedication

Name	V Volume Ft^3 (m^3)	SA Audience Area with Standees Ft^2 (m^2)	SO Pit Area (Open) Ft^2 (m^2)	SOF Pit Area (Floor) Ft^2 (m^2)	SP Proscenium Area Ft^2 (m^2)	ST Total Area Ft^2 (m^2)	V/ST Ft (m)	NA Seats	NST Standees	NT Effective	V/NT Ft^3 (m^3)	SA/NT Ft^2 (m^2)	T500-1000 (Occup.) Reverber-ation Time T mid sec	t_I Initial-Time-Delay Gap sec	Year Dedi-cated	SEAT SPACING: Main Floor Row-to-Row In. (cm)	SEAT SPACING: Main Floor Seat-to-Seat In. (cm)	SEAT SPACING: Balcony Row-to-Row in. (cm)	SEAT SPACING: Balcony Seat-to-Seat in. (cm)
AMERICA																			
Lafayette, Indiana, Purdue University Hall of Music	1,270,000 (35,900)	37,210 (3,460)	840 (78)	840 (78)	3,626 (337)	41,680 (3,875)	30.5 (9.24)	6107		6107	208 (5.9)	6.1 (0.57)	1.45	45;6	1940	33 (84)	25 (64)	32 (81)	21.5 (55)

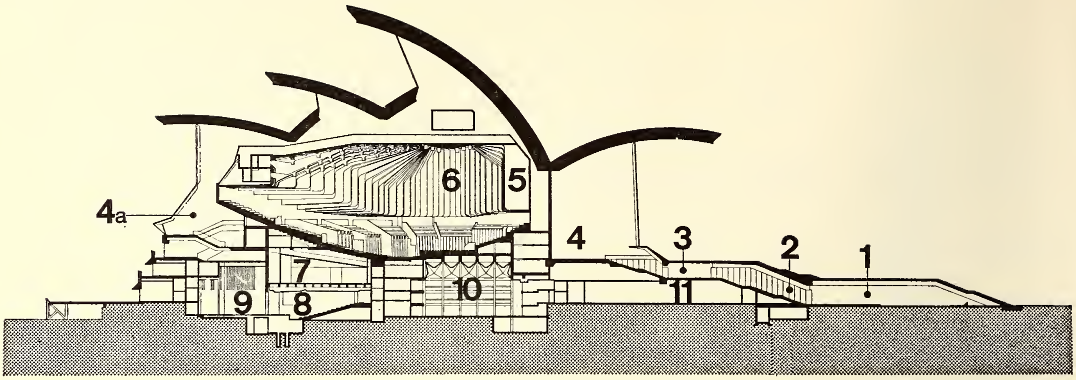


FIGURE 6.—Concert hall axial section.

1. Car concourse.
2. Staircase to foyer.
3. Foyer, box office, cloak rooms.
4. Concert hall foyer.
4A. Promenade lounge.
5. Organ loft.
6. Concert hall.
7. Rehearsal room.
8. Drama theatre.
9. Drama theatre stage.
10. Rehearsal/Recording hall.
11. Cinema/Chamber music hall and exhibition hall foyer.

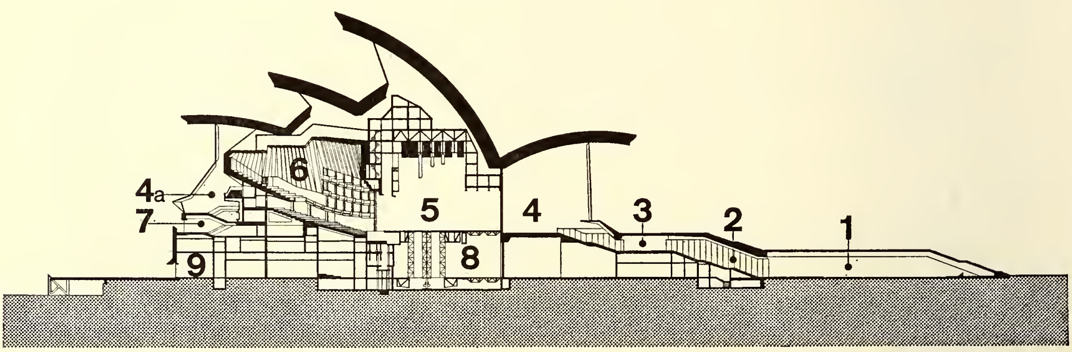


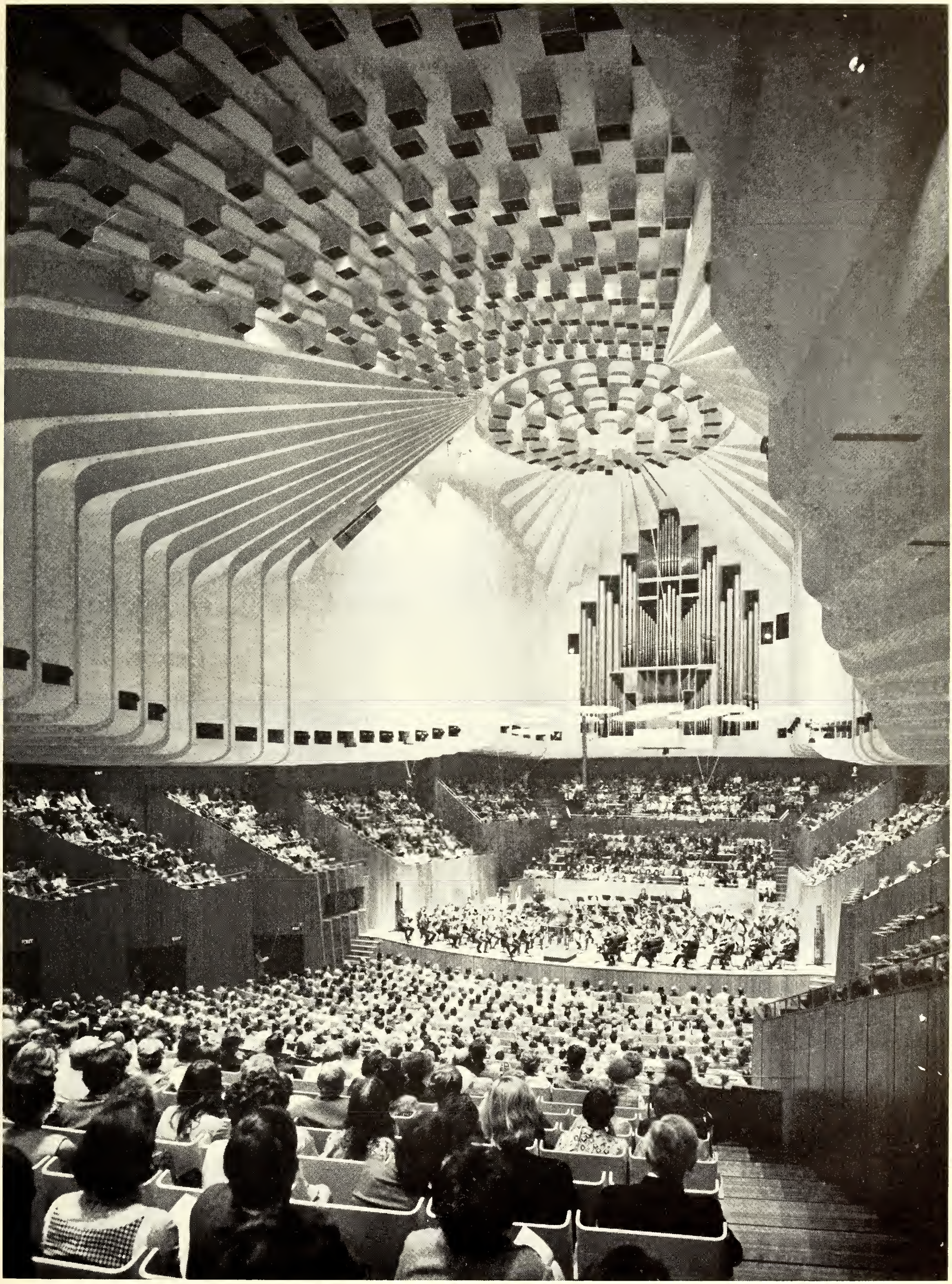
FIGURE 7.—Opera theatre axial section.

1. Car concourse.
2. Staircase to foyer.
3. Foyer, box office, cloak rooms.
4. Opera theatre foyer.
4A. Promenade lounge.
5. Opera theatre stage.
6. Opera theatre.
7. Opera theatre lounge.
8. Below stage area.
9. Broadwalk restaurant.

it is the area they occupy which has to be taken into account in considering the volume-per-person ratio. Depending on the surfaces used and the shape of the room, the necessary volume per person would lie in the range of 320 ft³ to approximately 400 ft³ per person. In de Doelen the figure is as high as 400, but in Dr. Jordan's opinion this is a little too much volume. Beranek's table (Table 3) provides useful comparative data to which we can now add these figures for the Concert Hall in the Sydney Opera House:

V Volume	Sa Audience Area	So Orchestra Area	NA Seats	V/NA
870,000 ft³	13,590	2,000 ft²	2,690	325 ft³

T500–1000 (occup.) Reverberation Time T mid	Seat Spacing: Row to Row	Seat Spacing: Seat to Seat	Stage Height (In)
2.1	36″–38″	20″–22″	50



1.—Concert Hall with the Sydney Symphony Orchestra.

2.—Long-shot of eastern profile of the Opera House from Lady Macquarie's Chair.

3.—Northern foyer to the Concert Hall.

Seating

A fundamental early decision taken was to use continental seating. When the seats are arranged in this way, there are no longitudinal aisles. Obviously, when aisles run the length of the hall, in the centre they occupy some of the best area available for viewing. It is common sense to put seats in these positions. The second great advantage of continental seating is that better advantage can be taken of irregular shapes since the circulation space is located at the edge of the hall. The third great advantage is that there has to be room for people to get past those already seated, albeit at the expense of the possible movement of their knees as somebody passes. But the rest of the time that a person is sitting in the chair, which is after all a much longer time than that taken by people to get past, there is more leg room available than is normally provided in multi-aisle arrangements. Further, continental seating offers a safety advantage. Ben Schlanger, our consulting theatre architect, had, shortly before we engaged him to work on the Sydney Opera House, recently completed a draft for a new code for places of public assembly for New York City. In the course of his research for this he had observed that the history of theatre disasters showed that loss of life was caused not by people being overcome by smoke or flames, but by being trampled because of poor exit and safety arrangements. He concluded that it was not desirable that a row of seats should quickly discharge into an intersection at aisles, neither was it necessary that a room be cleared instantly. What was important was that people should get, in reasonably fast time, from their seats to a safe area and that some control of the rate at which they reached the doors and entered that safe area was desirable. Continental seating introduces virtually a queueing condition, and unless rows are spaced extraordinarily far apart people will not try to overtake other people, with the consequent risk that somebody will be knocked down, but they will proceed in an orderly manner to doors the width of which is calculated to be adequate for the number of people using them and to empty the hall quickly. The test concerts so far held in the Opera House have confirmed that the auditoria in fact emptied much faster than others in the city and that the audience dispersed through the foyers at a very quick and comfortable rate.

The dimensions of the seats themselves range from 20 in to 22 in and the row spacing varies from 36 in to 38 in (Table 4 shows surveyed comparative dimensions for existing theatres in Sydney). Special attention has been paid to the design of the individual chairs. A hydraulic tilting mechanism has been chosen because of greater quietness and reliability than springs and slower action than weights. One of the least satisfactory qualities of most theatre seating is that it is visually disorderly. Tip-up chairs do not all return to the same angle, and the individual chairs with gaps between look like a collection of postage stamps. An acoustic requirement of Dr. Jordan that there should be some exposed hard surface above the shoulders of the audience helped in the solution of this visual problem, which resulted in placing the upholstered back of the chair in a curved plywood shell. The same plywood as for the ceiling of the hall is used. This material is used extensively throughout the building, helping to achieve a unity of material difficult to attain in such a large and complex building as the Sydney Opera House. From both front and back the rows of seating take on the character of continuous arcs, not a collection of individual postage stamps.

The upholstery material is a polyurethane foam chosen because of its firmness and because it could be well contoured to support the important areas of the small of the back and the popliteal muscles under the thighs. The upholstery does not readily yield when people sit on it, but most experience shows that this produces longer lasting comfort than soft upholstery, which compresses to the shape of the user's body and as a result does not give support. This thinking is now evident in the design of seating for motor and racing cars in which driver fatigue and comfort are critical. There are also modern classics of furniture design, for example by Breuer and Tobia Scarpa, which are very firm indeed. Although the fire risks associated with it are slight, the polyurethane is encased in a flameproof wrapper and then covered, in the Concert Hall (and all auditoria other than the Opera Theatre), in pure wool. In the Opera Theatre the covering is leather. The reason for the difference is that the absorption of the chairs in the Concert Hall is designed to be close to that of a person, whereas in the Opera Theatre, where there is a very much lower volume ratio per person, Dr. Jordan wanted empty seats to add to the reverberation through the use of a reflective upholstery fabric, hence the leather.

The seats, arranged in this system, are subdivided into relatively small areas. This is made necessary partly by sight line considera-

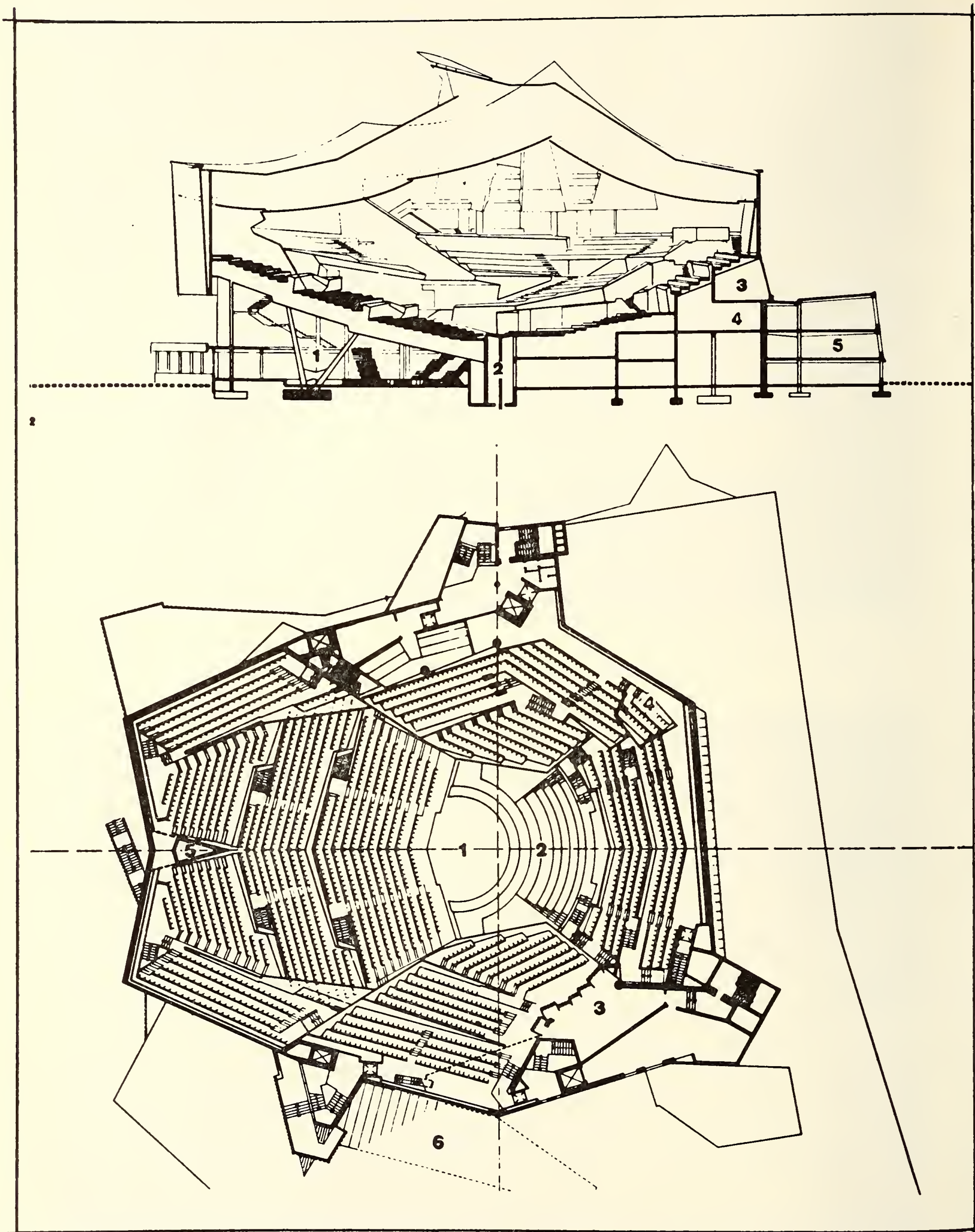


FIGURE 8.—Berlin—Philharmonie.

tions, because in the side terraces the closer one is to the platform the steeper the rake of the seats has to be, partly because subdivision of any audience of 2,700 into smaller groups is psychologically desirable and partly by the requirement that the furthest seat should not be too far from the source of sound, which is why there are some audience seats behind the platform. Provided the sound is good in such a location, these are not objectionable seats, giving an excellent view of the conductor.

The seating arrangement has some of the qualities of de Doelen and the Berlin Philharmonic, which has an even less regular arrangement of seats than we have and is a room which it is good to experience. The plan form at Sydney was of course largely dictated by what was already built during Stages I and II.

The Ceiling

While seating is determined by capacity, comfort and sight lines, the design of the ceiling is the area in which collaboration of architect, acoustician and engineer becomes of the greatest importance, since it is here that the acoustics of the room will really be determined. Within the limits set by the shells (some 1,000,000 cu ft in all) its overall volume is determined by the volume/audience area relationship and by the need to arrange surfaces in such a way as to allow a build-up of reverberation and a distribution of sound evenly over the seating area. The ceiling is supported from the shells by trusses hanging between the arches. On the outside is the layer of thin concrete referred to by Dr. Jordan. In the void between the outer and inner layers run the services. The inner layer is made up of ½ in plywood with a backing

Table 4

Sydney Theatre Seat Spacing (1966)

Theatre	Row to Row	Centres of Arm Rests	Comments
St. James:			
Stalls	2′ 11″	1′ 7″	
Lounge	3′ 0″	1′ 8″	Fairly comfortable
Dress Circle	3′ 0″	1′ 8″	,, ,,
Royal:			
Lounge	3′ 0″	1′ 8″	,, ,,
Phillip:			
Main Floor	2′ 11″	1′ 7″	
Rear	2′ 10″	1′ 6″	Tight, especially in width
Tivoli:			
Lounge	3′ 0″	1′ 7½″	Fairly comfortable
Gallery	2′ 8″	1′ 5″	Excessively tight, both ways
Town Hall:			
Main Floor	2′ 11″ (approx.)	1′ 9″	
Side Gallery	2′ 11″	1′ 9″	Reasonable, not much leg room
Back Gallery	2′ 9″–2′ 10″	1′ 9″	Tight for leg room
Barclay:			
Stalls	3′ 1½″	1′ 7″	New seating (four years old). Comfortable, especially as regards leg room
Gallery	3′ 2″	1′ 8″	
Her Majesty's:			
Lounge	3′ 5″	1′ 9″	Very comfortable — Manager thinks these are the largest seats in Sydney
Stalls	3′ 2″	1′ 7″	Comfortable
Gallery	2′ 8″–2′ 9″	1′ 8″–1′ 9″	Too tight as regards leg room

Aisles vary between 3′ 6″ and 3′ 8″

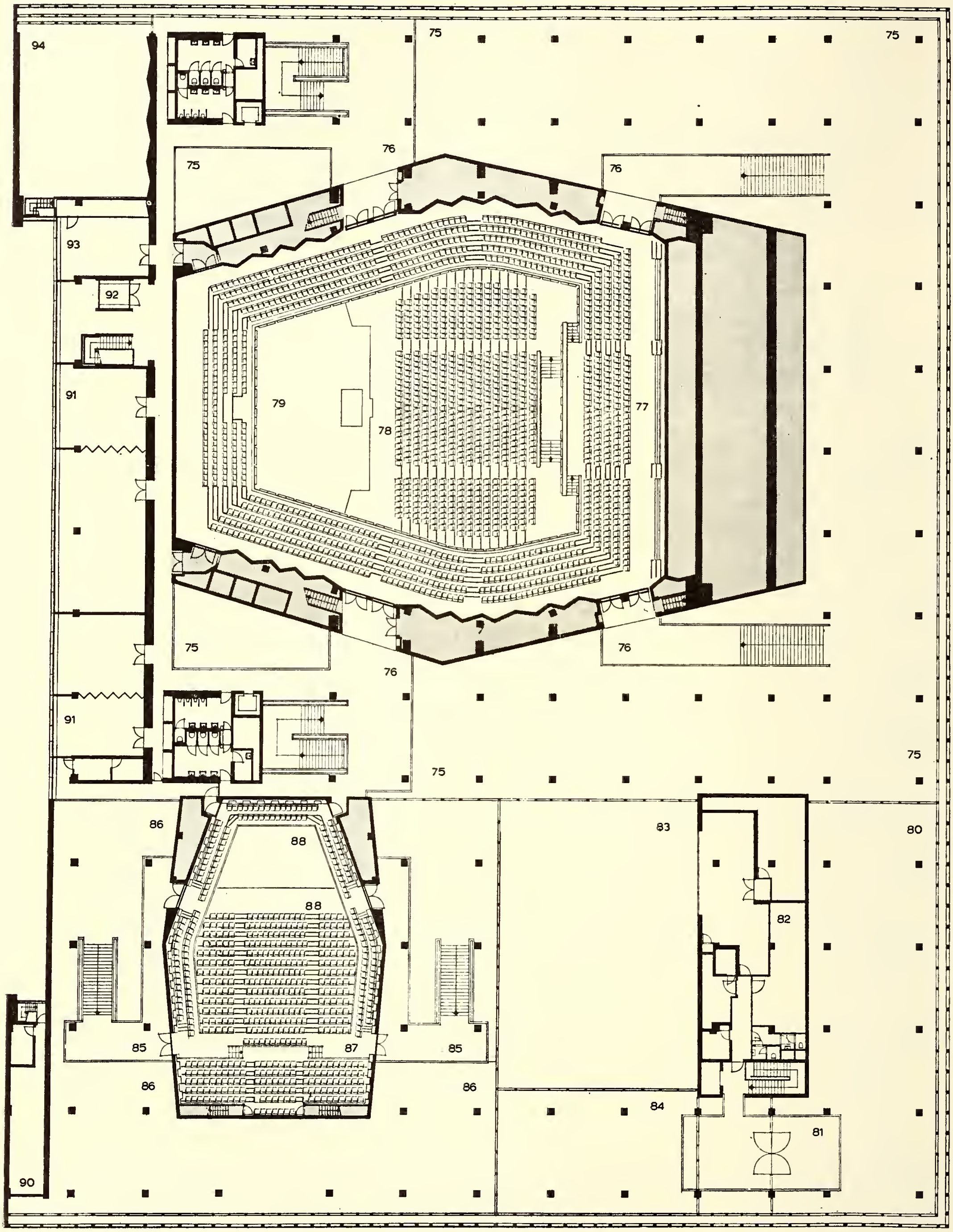


FIGURE 9.—Rotterdam—de Doelen.

of 1 in plasterboard. Plywood was chosen because the steel trusses will inevitably flex a little and a continuous envelope such as plaster would not have been practicable, even had it been thought aesthetically desirable. Thin plywood by itself, however, would not retain the bass sufficiently well for the music to have enough warmth, hence the plasterboard backing, a system developed with Dr. Jordan to retain the bass without exceeding the very stringent weight restrictions. This material was capable of complete prefabrication off the site, and of the use of dry jointing techniques using plastic gaskets.

It is not easy to achieve a relationship between the ceiling of a hall and the audience because when the audience is broken up into its individual seats it is rather small in scale, whereas the ceiling of a hall with a volume of the order of 850,000 cu ft is of necessity very large. The plywood ribs have accordingly been arranged in a way related to Japanese paper folding, with two major bends in them as they radiate from the platform zone. They follow the audience's sight lines to the chosen arrival points of sight. On the way they have a number of protrusions, some of which accommodate lighting and which act like the coffering of a Victorian hall. The planes step in relationship to each other, and this stepping gives much the character of pilasters in the old halls, with resulting improvement in diffusion and sound quality.

Materials

Since heavy materials like off-form concrete or marble, as used at de Doelen, were out of the question the important lower surfaces surrounding the orchestra and separating the various seating groups had to be both reasonably light but retentive of the bass. For these surfaces and the floor solid thick timber, laminated brush box, was chosen. Like the ceiling, this could be prefabricated off-site, with the advantages of time-saving and improved quality control implicit in prefabrication in a factory. The result is an all-wooden room which is designed, because of the small number of materials used, to offer little to distract the observer from appreciating the volume, the forms enclosing it, and the bright façade of the impressive Sharp organ over the choir.

Conclusion

So far, objective and subjective assessment of the room has been good. Oddly enough, I believe the shells themselves, although a sort of restrictive straitjacket and the source of much design difficulty for architects and consultants alike, have contributed to this result. While their shapes, volume limitation and load capacity posed difficulties, they forced on us a long, narrow room with greater than normal height which is certainly contributing to people's visual experience and may well assist in producing Gilford's " singing tone ". Certainly the room embodies much current philosophy on concert hall acoustics and shows promise of achieving in use many of the characteristics thought desirable. It is now for the performers, over an extended period, to find out whether it fulfils this promise.

Acknowledgements

Important contributions were made by all those acknowledged by Dr. Jordan. In addition much useful information and advice was given in the early stages by Warwick Mehaffey, acoustic engineer with the ABC, and Dean Dixon, then Musical Director of the ABC.

The realization of the design made necessary, because of the interaction of every component, an extraordinarily close collaboration between architects and consultants. Special mention should be made of Michael Lewis, Ian Mackenzie and Frank Manly (Ove Arup and Partners), Arne Larsen and Edvard Mortensen (Steensen and Varming), Frank Matthews (Julius, Poole and Gibson), Dick Chappell and David McKellar (lighting).

In the execution of the work the sub-contractors made every effort to achieve standards of workmanship and quality rare in building anywhere in the world. In particular, the work of Cemac Brooks, who tackled the job of building the ceiling on a firm price basis and performed splendidly, deserves special commendation. This sub-contract did much to dispel the then prevalent belief that prediction and planning were so difficult as to make firm prices and programmes impossible on the Opera House.

Phil Peach, of Co-ordinated Design and Supply, the seating suppliers, collaborated with us in developing the design of the chairs through successive prototype stages. Continental seating had not previously been used in N.S.W. and at the time of its design was not legal. Aden MacFarlane, of the Chief Secretary's Department, made a careful study of its advantages and formulated dimensional criteria resulting in its acceptance by his Department. Not only was this vital to us, but it will prove an important milestone in theatre design here.

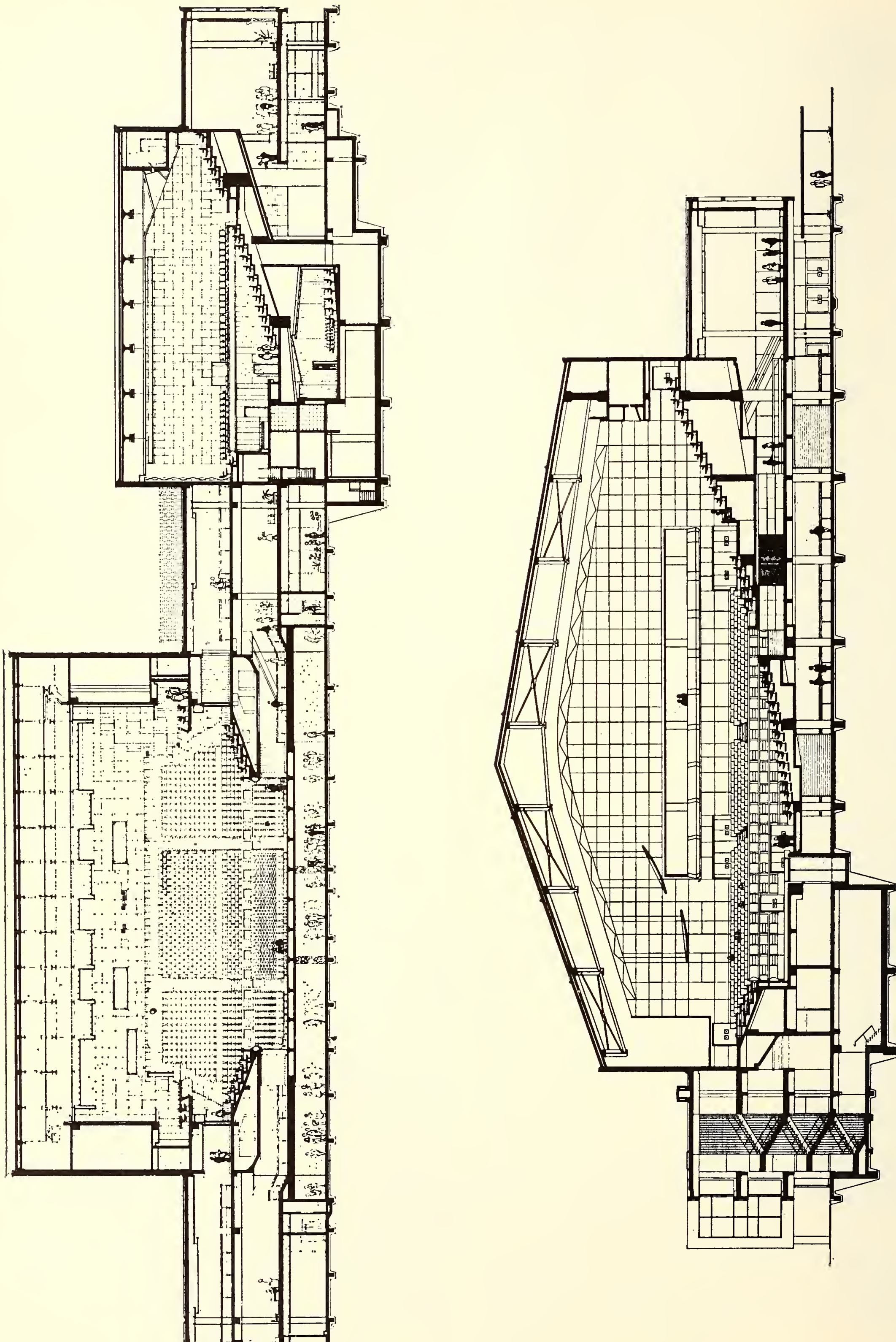


FIGURE 10.—Cross section and long section, Rotterdam—de Doelen

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(Received 13 September 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 70–80, 1973

The Grand Organ in the Sydney Opera House

Ronald Sharp

Abstract—The building of the Opera House Organ is a milestone in the world of music. The Concert Hall has provided a unique opportunity for the installation of what will be the world's largest mechanical action pipe organ in the best position possible, acoustically and visually.

The organ specification includes all schools of organ building that are considered to have aesthetic and historical validity so as to be able to demonstrate these characteristics to the people of Sydney. Every family of stops is represented, but no stop is redundant. The organ will not only be able to interpret these various schools but will have an overall character and musical unity of its own.

1. Introduction

From an early stage it was decided to have a large fixed organ in the Concert Hall, which could be used for solo work or with orchestra, choir or chamber music groups. It would also be used at ceremonies and conventions and must be able to play popular music.

The organ would therefore have to be a large comprehensive instrument. It must be suitable both for solo use and as an accompanimental instrument. To be successful it must be able to demonstrate to people in Sydney the best characteristics of the different national schools, past and present, that are considered to have aesthetic or historical value.

Despite its versatility in being able to play music in the correct tone for these different national schools the organ must have a musical unity and be able to succeed for itself as a solo instrument. It cannot be purely imitative but must have an overall character and musical unity of its own.

It is hoped that an organ with the above characteristics will excite the attention of Australian composers. The Concert Hall in the Opera House provided a unique opportunity to install such an organ in the best musical, acoustical and visual location high up on the front wall. As in many of the famous cathedrals in Europe, this has always been considered the optimum position.

To achieve these musical aims, it is necessary to use relatively low wind pressure and mechanical playing action throughout. The nature of the project is such that only the finest of pipe metals and materials have been used.

In an organ of this size, operating convenience becomes an important element. An unusually versatile system of stop control and registration aid has been devised using the latest developments in electronic technology.

The organ is scheduled to be completed in 1976.

2. Overall Design of the Organ

The organ is contained in a specially built shell-shaped concrete chamber 15 m (46 ft) high and stands on a cantilevered steel platform which overhangs the audience seating. The front pipes of the façade are in line with the walls of the Concert Hall and the depth of the organ is approximately 6 m (18 ft). The console is located on an extension of the organ platform and is approximately 2 m (6 ft) in front of the organ. On either side of the console is the Ruckpositiv division, so divided to allow the audience to see the organist.

The Brustwerk division, with its 4 ft show pipes, is situated in the main case immediately above the console.

The Hauptwerk division, with its 16 ft show pipes, is situated above the Brustwerk.

The Oberwerk is above the Hauptwerk and behind the top group of show pipes, and the Kronwerk at the very top of the organ.

The large pedal pipes are contained in the front on each side and at the rear of the organ chamber, the smaller pedal pipes are on each side of the organ chamber.

The frame of the organ is of special steel sections and welded on the site. It contains stairways and a spiral staircase for easy access to the different divisions.

Access to the organ is from outside the Hall via a spiral staircase to the rear of the organ chamber. The organist then walks through the organ to the console, some 10 m (30 ft) above the main floor of the Hall.

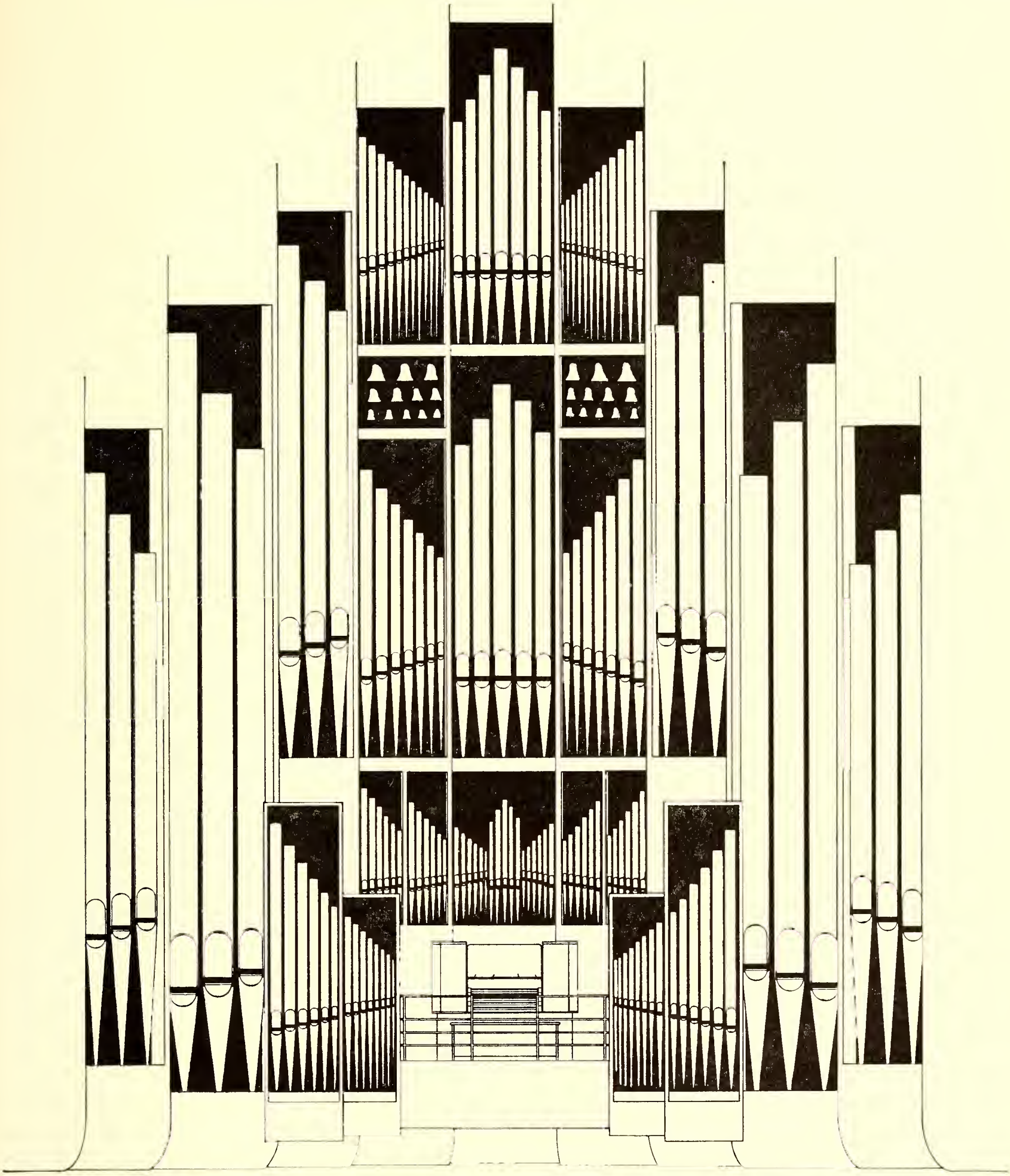

FIGURE 1.—The façade of the organ showing the position of console and disposition of the various departments.

The largest pipes of the organ belong to the Prinzipal 32 ft, the biggest four are constructed of 50 mm (2 in) thick marine plywood and are hung on the rear wall.

Because of the distance of the console from the conductor, a number of communication aids are built into the console. These include two closed circuit television screens giving the organist views of the conductor and of the stage, a speaker from the stage to the organist, a telephone from the organist to the conductor and stage manager and a microphone to enable the organist to speak over the public address system.

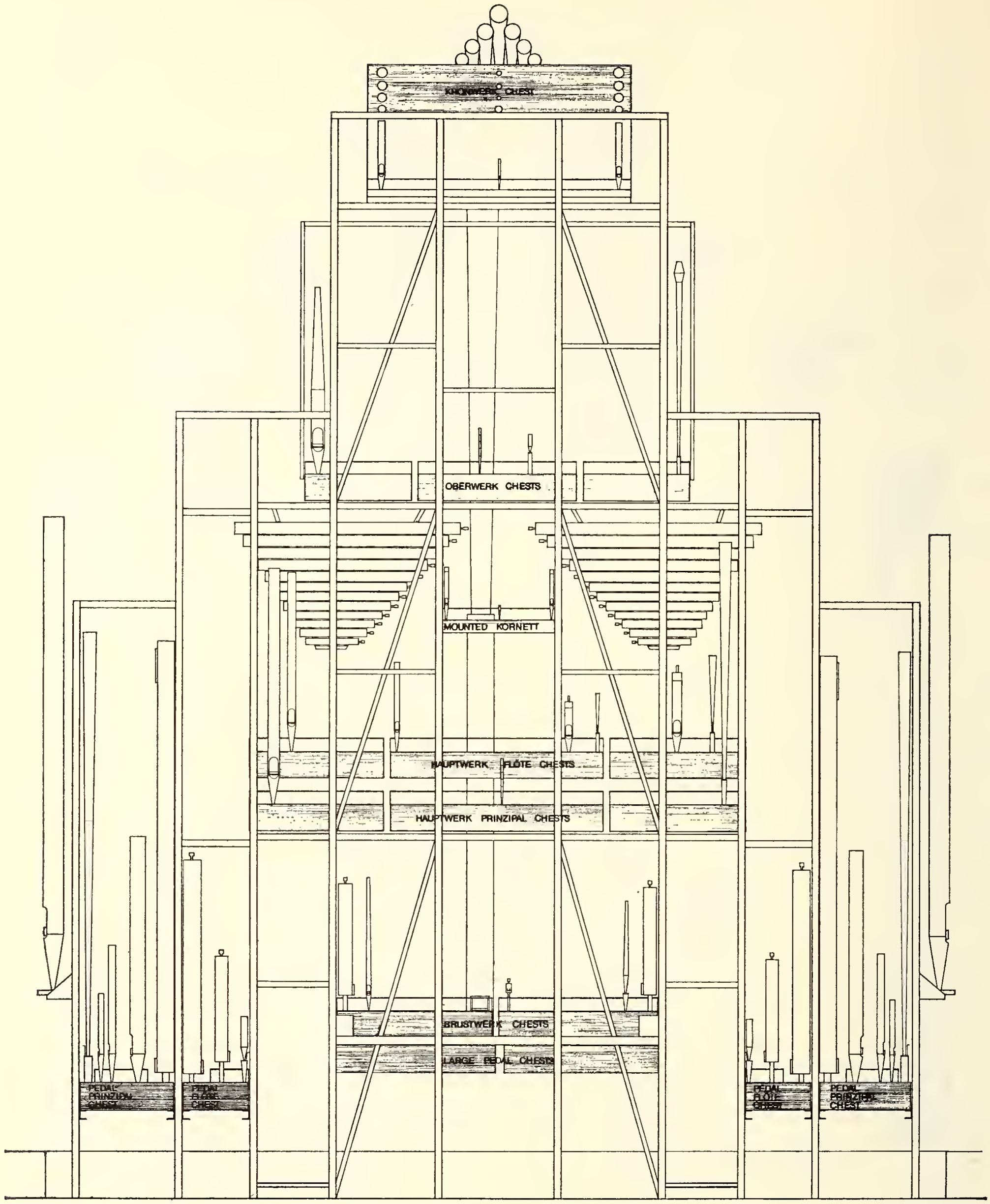

FIGURE 2.—Front view of steel frame showing position of pipe windchests of the various departments. Some of the larger pipes are shown in position.

3. National Tone Characteristics

Examples of some of the national schools of organ building as represented in the Opera House organ are shown by the following specifications. By comparison, it is possible to see how these have influenced the total design of the organ.

Examples represented are :

English : Trinity College, Cambridge, 1860—Hill.

Classical French : Ste. Gervais, Paris, 1768—Cliquot.

Romantic French : Ste. Clothilde, Paris, 1858—Cavaillé-Coll.

Italian : St. Guiseppe Brescia, 1581—Antegnati.

North German : St. Jacobi, Hamburg, 1688—Schnitger.

ENGLAND
Typical Specification of Organ by William Hill, 1860

Great Organ	Choir Organ	Solo Organ	Swell Organ	Pedal Organ
Double Open Diapason 16′	Double Dulciana 16′	Harmonic Flute 8′	Double Diapason 16′	Sub-bourdon 32′
Open Diapason 8′	Dulciana 8′	Harmonic Flute 4′	Open Diapason 8′	Open Diapason 16′
Open Diapason 8′	Open Diapason 8′	Vox angelica 8′	Salicional 8′	Open Diapason 16′
Salicional 8′	Claribel 8′	Lieblich Flute 4′	Cone Gamba 8′	Violon 16′
Gamba 8′	Viola da Gamba 8′	Piccolo 2′	Stopped Diapason 8′	Bourdon 16′
Stopped Diapason 8′	Stopped Diapason 8′	Tuba mirabilis 8′	Suabe Flute 4′	Principal 8′
Quint $5\frac{1}{3}$′	Stopped Flute 4′	Vox humana 8′	Principal 4′	Bass Flute 8′
Principal 4′	Principal 4′	Orchestral Oboe 8′	Fifteenth 2′	Fifteenth 4′
Wald Flute 4′	Flautino 2′		Mixture III	Mixture III
Nason 4′	Cremona 8′		Double Trumpet 16′	Trombone 16′
Twelfth $2\frac{2}{3}$′			Trumpet 8′	Clarion 8′
Fifteenth 2′			Cornopean 8′	
Full Mixture III			Oboe 8′	
Sharp Mixture II			Clarion 4′	
Trumpet 8′				
Clairon 4′				

The Sydney Town Hall organ, built in 1886, represents the culmination of English romantic organ building by William Hill and is an entirely different concept to the Opera House organ.

FRANCE
Typical Specification of Organ by Cliquot, 1768

Grand Orgue	Positif	Bombarde	Récit	Echo	Pedale
Montre 16′	Flûte 8′	Bombarde 16′	Cornet III	Flûte d'echo 8′	Flûte 16′
Bourdon 16′	Bourdon 8′		Hautbois 8′	Trompette 8′	Flûte 8′
Montre 8′	Prestant 4′				Flûte 4′
Bourdon 8′	Nazard $2\frac{2}{3}$′				Bombarde 16′
Flûte 8′	Doublette 2′				Trompette 8′
Prestant 4′	Tierce $1^3/_5$′				Clairon 4′
Nazard $2\frac{2}{3}$′	Plein jeu IV				
Doublette 2′	Trompette 8′				
Quarte de Nazard 2′	Cromorne 8′				
Tierce $1^3/_5$′	Basson-Clarinette 8′				
Grand Cornet V	Clairon 4′				
Plein jeu VI					
I. Trompette 8′					
II. Trompette 8′					
Voix humaine 8′					
Clairon 4′					

FRANCE
Typical Specification of Organ by Aristide Cavaillé-Coll, 1858

Grande Orgue	Positiv	Récit	Pedale
Montre 16′	Bourdon 16′	Bourdon 8′	Quintaton 32′
Bourdon 16′	Montre 8′	Flûte Harmonique 8′	Contrebasse 16′
Montre 8′	Gambe 8′	Voile de Gambe 8′	Flûte 8′
Gambe 8′	Flûte Harmonique 8′	Voix Céleste 8′	Octave 4′
Flûte Harmonique 8′	Bourdon 8′	Flûte Octaviante 4′	Bombarde 16′
Bourdon 8′	Salicional 8′	Octavin 2′	Basson 16′
Prestant 4′	Prestant 4′	Basson-Hautbois 8′	Trompette 8′
Octave 4′	Flûte Octaviante 4′	Voix Humaine 8′	Clairon 4′
Quinte $2\frac{2}{3}$′	Quinte $2\frac{2}{3}$′	Trompette 8′	
Doublette 2′	Doublette 2′	Clairon 4′	
Plein Jeu V	Clarinette 8′		
Bombarde 16′	Trompette 8′		
Trompette 8′	Clairon 4′		
Clairon 4′			

ITALY
Typical Specification of Organ by Antegnati, 1581

1. Principale 16′
2. Principale 16′
3. Ottaua 8′
4. Decima quinta 4′
5. Decima nona 2⅔′
6. Vigesima seconda 2′
7. Vigesima sesta 1⅓′
8. Vigesima nona 1′
9. Trigesima terza ⅔′
10. Flauto in quintadecima 4′
11. Flauto in duodecima 5⅓′
12. Flauto in ottaua 8′
13. Fiffaro (voce umana) 8′

As the keyboard extended into the bass one octave lower than present-day organs (it was coupled to the pedals), the above specification should be read as one octave higher, i.e. Principale 8′, etc.

musical point of view; from the position of a listener accustomed to orchestral and recital concerts rather than from the position of an organ enthusiast or that of a trained organist who expects certain traditional concepts; a view of balance, blend, freedom from harshness and extraneous noise, a singing quality.

The voicing of the Hauptwerk and Positiv will be similar except that the Hauptwerk is larger scaled and on a higher wind pressure, therefore being slightly louder; so that by selection of the appropriate Hauptwerk mixtures, e.g. Scharff and Zimbel with the foundation stops, an Italian-like plenum is possible, though without the possibility of adding individual ranks of upper pitches.

The speech and tone of the whole organ is unforced, so tending to be inoffensive and not tiring to the ear. Adequate loudness and the

NORTH GERMANY
Typical Specification of Organ by Arp Schnitger, 1688

Hauptwerk	Ruckpositiv	Brustwerk	Oberwerk	Pedal
Prinzipal 16′	Prinzipal 8′	Holzprincipal 8′	Prinzipal 8′	Prinzipal 32′
Quintatön 16′	Gedeckt 8′	Oktave 4′	Holzflöte 8′	Oktave 16′
Oktave 8′	Quintatön 8′	Hohlflöte 4′	Rohrflöte 8′	Sub-bass 16′
Spitzflöte 8′	Oktave 4′	Waldflöte 2′	Oktave 4′	Oktave 8′
Gedeckt 8′	Blockflöte 4′	Sesquialter 2 ranks	Spitzflöte 4′	Oktave 4′
Oktave 4′	Nasat 2⅔′	Scharff 4–6 ranks	Nasat 2⅔′	Nachthorn 2′
Rohrflöte 4′	Oktave 2′	Dulzian 8′	Oktave 2′	Mixtur 6–8 ranks
Superoktave 2′	Sifflöte 1⅓′	Trechterregal 8′	Gemshorn 2′	Rauschpfeife 3 ranks
Flachflöte 2′	Sesquialter 2 ranks		Scharff 4–6 ranks	Posaune 32′
Rauschpfeife 3 ranks	Scharff 4–6 ranks		Zimbel 3 ranks	Posaune 16′
Mixtur 6–8 ranks	Dulzian 16′		Trompete 8′	Dulzian 16′
Trompete 16′	Bärpfeife 8′		Vox humana 8′	Trompete 8′
	Schalmei 4′		Trompete 4′	Trompete 4′
				Kornett 2′

4. Tonal Design

4.1. Frequency Range of the Organ

A stop is labelled in terms of the type of tone it produces, e.g. Prinzipal, Flute, Trompet, and the pitch of the sound in relation to piano pitch. The pitch is specified in terms of the longest pipe in the rank. Thus a stop labelled 8′ pitch represents a rank of open pipes ranging from 8 ft in length two octaves below middle C through five octaves to a ¼ ft pipe.

A stop labelled 4′ would sound an octave higher and 16′ an octave lower.

The frequency range of the organ is from 16·35 Hz (32 ft) to 16,744 Hz at $\frac{1}{32}$ ft 10 mm (⅜ in).

4.2. The Overall Concept

The overall concept was to approach the design and voicing of the organ from a detached

effect of fulness is obtained by the fact that most upper ranks break back at the ⅛ ft pipe to the ¼ ft pipe. This concentrates the highest proportion of energy of sound in the fundamental pitch range 2,000–5,000 Hz which, on the Fletcher-Munson curves is the area of greatest sensitivity of the ear. This breaking sequence spreads the pitch range 2,000–5,000 Hz over the entire compass of the keyboard.

4.3. The Purpose of the Upperwork

(*a*) To duplicate the harmonics of the foundation ranks and so increase their power and loudness.
(*b*) By giving emphasis to different harmonics, formats are produced which alter the character of tone, as well as the loudness.
(*c*) The pitches and breaks of the Upperwork mixtures may be arranged to vary these

SOUTH GERMANY Weingarten Abbey
Organ by Josef Gabler 1737

(Plan und Anordnung der Register nach dem Spieltisch)

I. Manual (Haupwerk)		*II. Manual* (Oberwerk)	
Praestant	16′	Borduen 2 – 3 f.	16′
Principal	8′	Principal Tutti	8′
Rohrflaut	8′	Violoncell 1 – 3 f.	8′
Oktav 1 – 2 f.	4′	Coppel	8′
Superoktav 2 f.	2′	Hohlflaut	8′
Hohlflaut	2′	Unda maris	8′
Mixtur 9 – 10 f.	2′	Solicinale	8′
Cimbalum 12 f.	1′	Mixtur 9 – 12 f.	4′
Sesquialter 8 – 9 f.	1½′	*Oktav douce	4′
Piffaro 5 – 7 f.	8′	*Viola 2 f.	4′
Trombetten	8′	*Cimbalum 2 f. (+ 3 f.)	2′
		*Nasat	2′
(′ = Fußlänge der Pfeifenreihe)		(*stehen im Kronpositiv)	

III. Manual (Echowerk)		*IV. Manual* (Brustpositiv)	
Borduen	16′	Principal doux	8′
Principal	8′	Flaut douce	8′
Flauten	8′	Quintatön	8′
Quintatön	8′	Violoncell	8′
Violon douce	8′	Rohrflaut	4′
Octav	4′	Querflaut	4′
Hohlflaut 2 f.	4′	Flaut travers 2 f.	4′
Piffaro douce 2 f.	4′	Flageolet	2′
Superoctav	2′	Piffaro 5 – 6 f.	4′
Mixtur 5 – 6 f.	2′	Cornet 8 – 11 f	2′
Cornet 5 – 6 f.	1′	Vox humana	8′
Hautbois	8′	Hautbois	4′
		Tremulant	

Pedal (Haupt-)		(Brustpositiv-)	
Contrabaß 2 f.	32′	Quintatönbaß	16′
Subbaß	32′	Superoctavbaß	8′
Octavbaß	16′	Flaut douce	8′
Violonbaß 2 f.	16′	Violoncellbaß	8′
Mixturbaß 5 – 6 f.	8′	Hohlflautbaß	4′
Posaunenbaß	16′	Cornetbaß 10 – 11 f.	4′
Bombardbaß	32′	Sesquialter 6 – 7 f.	3′
La force (C)	49 f.	Trombetbaß	8′
Carillon ped.	2′	Fagotbaß	8′

Nebenregister: Cuculus, Rossignol, Cymbala, Tympanum, Carillon Man. (IV).

Copplungen: I. zu II. Man., II. zu III. Man., III. zu IV. Man., P. zu I. Man., P. zu II. Man., Cronpositivcopplung.

formats according to the different positions in the compass, so producing a human singing quality which may have a different character on different manual departments.

4.4. Hauptwerk Division

In the Hauptwerk (main organ chorus) the provision of many mixtures of different composition will allow formats resembling those of the Italian, French and German schools to be produced. Basically, this division is the author's own concept of organ chorus and tone, containing elements of French, Italian and German character.

4.7. Brustwerk

This division with swell shutters is enclosed within the lower case of the organ and is basically a Cornet depicting the classical French echo Cornet. It also contains examples of early German short length reeds, the Brustwerk of the Gothic organ in St. Jacobi, Lübeck and modern mutations.

4.8. Kronwerk

This division is situated above the Oberwerk right at the top of the organ and is basically a solo department. It contains three ranks of brilliant sounding trumpets and a Vox Humana all " en chamade ", that is, lying horizontal and pointing directly into the Concert Hall. There is also a powerful twelve-rank Cornet and an Ophicleide of sonorous quality.

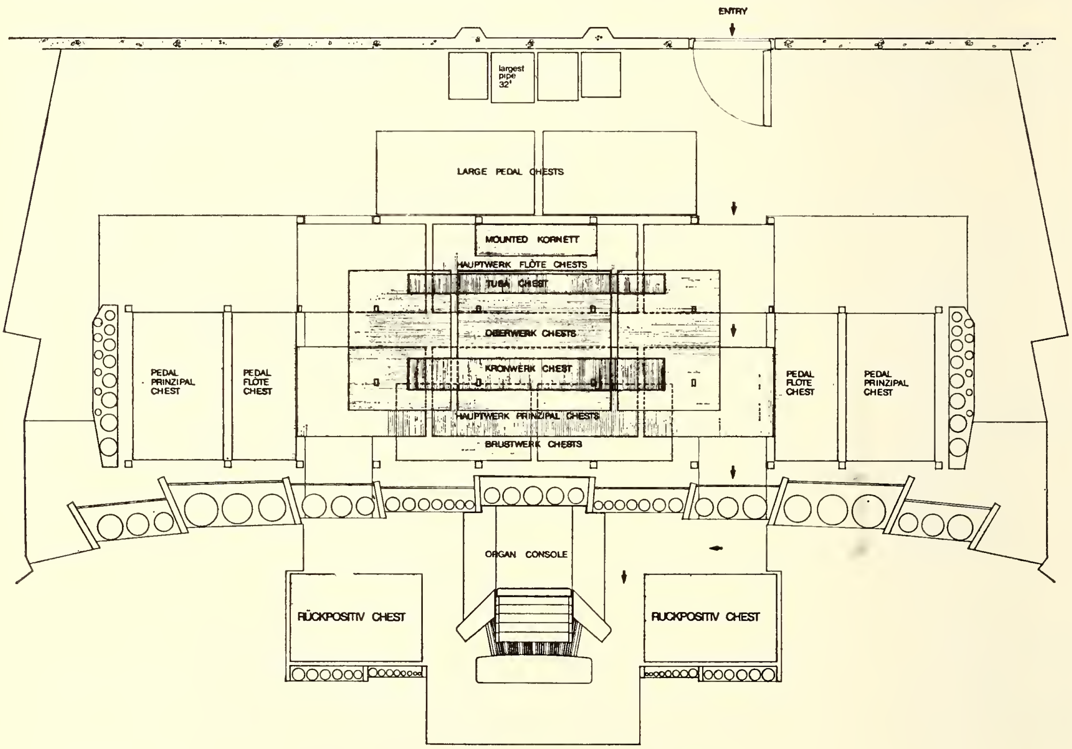

FIGURE 3.—Plan view of organ layout.

4.5. Oberwerk

This large division is contained in a swell box which has, as well as the main front shutters, a separate set of shutters opening at the rear of the box for echo effect. Essentially it is North German Schnitger in tone, with elements of French romantic school.

4.6. Ruckpositiv

This division is basically Italian in concept but contains elements of French and German characters.

4.9. Pedal

This division contains a cross-section of the elements of typical French, English and German classifications, plus additional and separated synthesizing upper partials of the fundamental pitch in order to produce, in the ear of a listener, a resultant fundamental of high power.

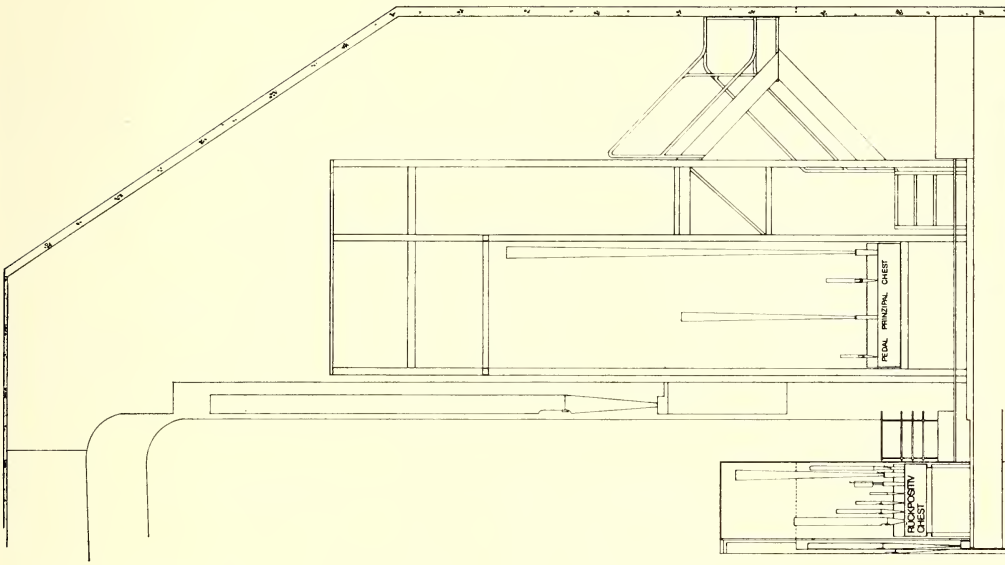

FIGURE 5.—Side view showing one of the stairways.

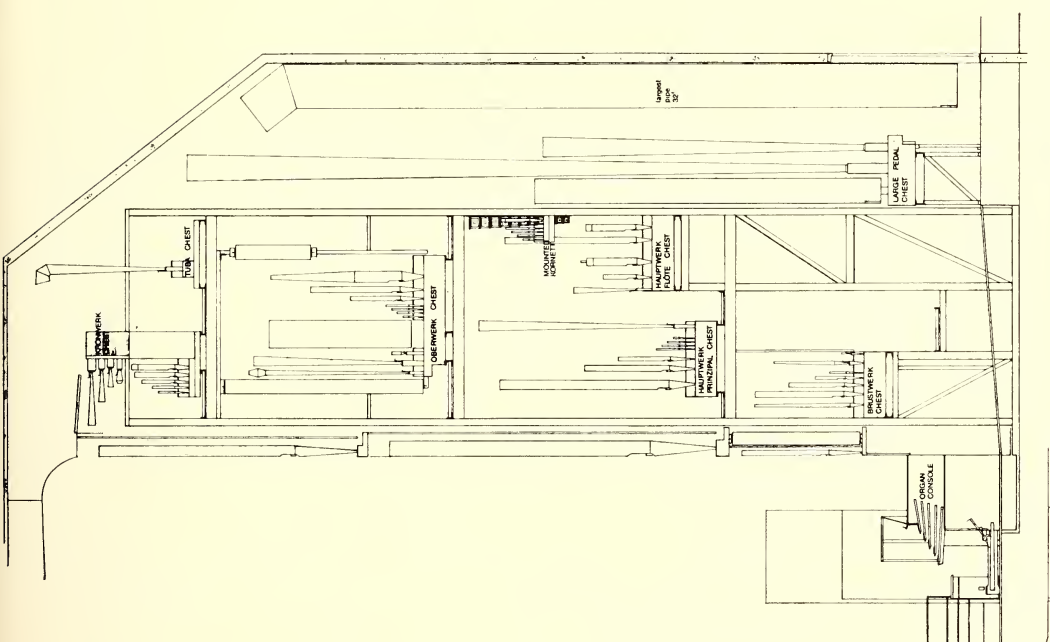

FIGURE 4.—Side view of steel frame showing position of console, windchests and the largest pipes.

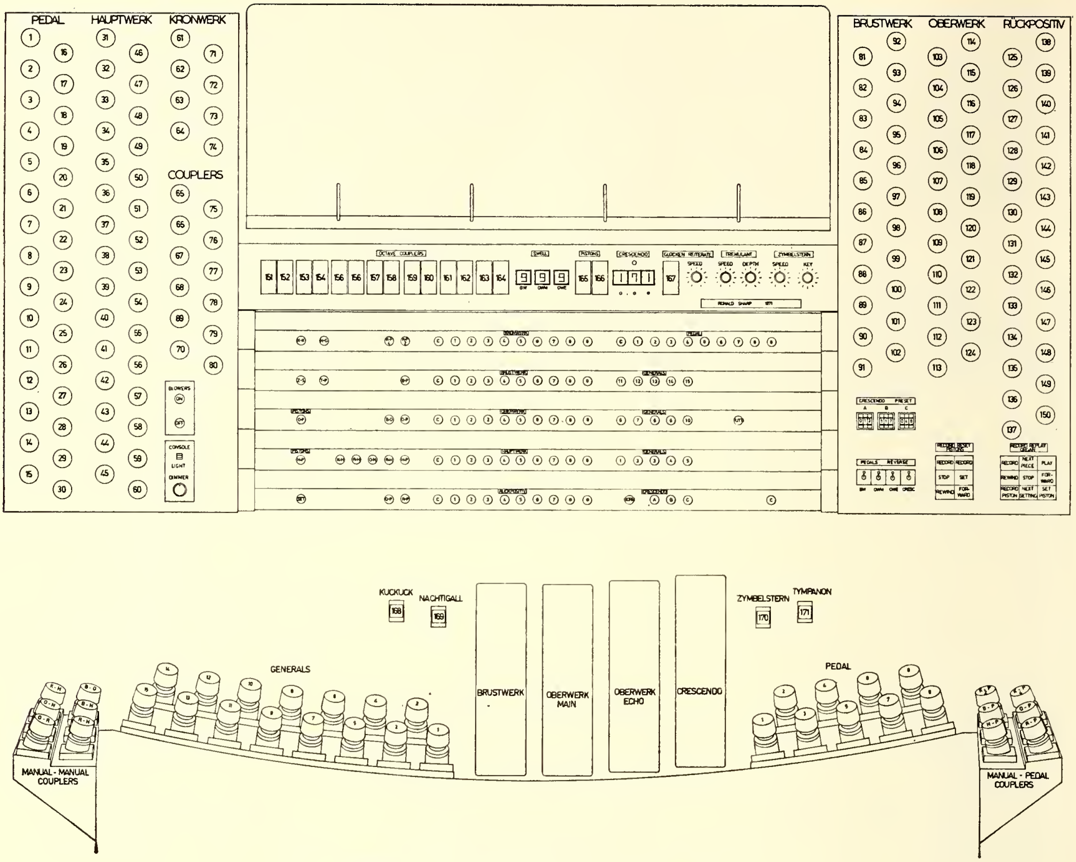

FIGURE 6.—Layout of the console.

The author feels that this is musically preferable to gaining fundamental strength in the bass by the use of excessively energized large pipes. In the latter case, the absorption of the room acoustics in the very low organ bass range would require such a large energy input to the large pipes that the upper harmonics would become harsh and unblending. The pedal does in fact have large scaled heavyweight 32 ft and 16 ft ranks, but the energy input to these is sufficient only to provide a pure foundation of moderately low power which may be used with the softest stops of the organ. Increase in power is then obtained by reinforcement of the harmonics by the upper ranks.

5. Accessories and Controls

5.1. Accessories

A tremulant is provided for each department, including the pedal organ, and there are controls to adjust the tremulant speed and depth. A Glockenspiel of 73 bronze hand bells, 24 of which are visible, and a Carillon of 24 bronze hand bells are operated electrically and playable from the keyboard and pedal board. The Carillon or Zymbelstern is comprised of six bells selected from the 24 and struck one after the other in a preselected order. They may be selected for the appropriate key signature. The speed at which these bells are struck is also adjustable. The Glockenspiel is fitted with a reiterating control, which may be adjusted to give from one stroke to many strokes per key operation.

Balanced swell pedals control the Oberwerk main and echo shutters and the Brustwerk shutters. Direction reverse switches are fitted. Digital displays give an indication of the position of each of the swell shutters.

A crescendo pedal operates on all the registers of the organ. It controls the stops directly with no movement of the draw stops or rocking tablets on the console. It operates in addition to the stops already in use and provides a gradual build up from the softest stop on the organ to full organ when the normal crescendo piston is pressed. Three pre-set pistons are available to allow the organist to move to a crescendo

PEDAL
C1 - g32

29	PRINZIPAL	32
28	HOLZPRINZIPAL	16
27	OKTAV	16
26	VIOLONBASS	16
15	SUBBASS	16
14	ROHRQUINT	10 2/3
25	OKTAV	8
24	VIOLON	8
13	GEDACKT	8
12	GROSSTERZ	6 2/5
23	QUINT	5 1/3
22	OKTAV	4
11	BLOCKFLÖTE	4
21	TERZ	3 1/5
20	QUINT	2 2/3
19	SEPTIME	2 2/7
10	NACHTHORN	2
9	BAUERNFLÖTE	1
18	RAUSCHPFEIFE	III
17	MIXTUR	V
16	SCHARFF	VII
8	POSAUNE	32
7	POSAUNE	16
6	FAGOTT	16
5	TROMPETE	8
4	DULZIAN	8
3	TROMPETE	4
2	SINGEND KORNETT	2
1	GLOCKEN	4+2
30	TREMULANT	

RUCKPOSITIV
C1 - c61

135	PRINZIPAL	8
136	FIFFARO	8
149	GEDACKT	8
150	QUINTADENA	8
134	OKTAV	4
148	NACHTHORN	4
147	ROHRFLÖTE	4
146	NASAT	2 2/3
133	OKTAV	2
145	SPITZFLÖTE	2
144	TERZ	1 3/5
132	QUINT	1 1/3
143	SIFFLÖTE	1 1/3
131	OKTAV	1
130	QUINT	2/3
129	OKTAV	1/2
128	QUINT	1/3
127	OKTAV	1/4
126	QUINT	1/6
125	OKTAV	1/8
142	SESQUIALTERA	II
141	RANKETT	16
140	TROMPETE	8
139	DULZIAN	8
138	GLOCKEN	1
137	TREMULANT	

HAUPTWERK
C1 - c61

59	PRINZIPAL	16
45	GEDACKT	16
58	OKTAV	8
57	GAMBA	8
44	QUERFLÖTE	8
43	HOLZFLÖTE	8
42	ROHRFLÖTE	8
56	QUINT	5 1/3
41	GROSSNASAT	5 1/3
55	OKTAV	4
54	GAMBA	4
40	SPITZFLÖTE	4
39	GROSSTERZ	3 1/5
53	QUINT	2 2/3
38	NASAT	2 2/3
52	OKTAV	2
37	HOHLFLÖTE	2
36	TERZ	1 3/5
51	PIFFARO	IV-VI
50	TERZIAN	II
49	KORNETT MIXTUR	III-VI
48	MIXTUR	VI
47	SCHARFF	V
46	ZIMBEL	IV
35	KORNETT	VI
34	TROMPETE	16
33	TROMPETE	8
32	TROMPETE	4
31	GLOCKEN	2
60	TREMULANT	

OBERWERK
C1 - c61

112	HOLZPRINZIPAL	16
111	QUINTATON	16
110	PRINZIPAL	8
123	SALIZIONAL	8
124	SCHWEBUNG	8
122	SPILLFLÖTE	8
109	OKTAV	4
121	SALIZIONAL	4
120	WALDFLÖTE	4
119	QUERFLÖTE	2
108	RAUSCHPFEIFE	II
107	TERZIAN	II
106	MIXTUR	V-VII
105	SCHARFF	IV
104	TERZ ZIMBEL	III
118	SEPTIMEN KORNETT	V
117	KOPFTROMPETE	16
116	TROMPETE	8
115	OBOE	8
103	VOX HUMANA	8
114	SCHALMEI	4
113	TREMULANT	

BRUSTWERK
C1 - c61

89	GEMSHORN	8
90	UNDA MARIS	8
102	OFFENFLÖTE	8
101	GEDACKT	8
88	PRINZIPAL	4
100	QUINTADENA	4
99	NASAT	2 2/3
87	FLACHFLÖTE	2
98	TERZ	1 3/5
86	QUINT	1 1/3
97	SEPTIME	1 1/7
85	SCHWIEGEL	1
96	NONE	8/9
84	GLOCKLEINTON	II
83	SCHARFF	II
82	ZIMBEL	I
95	MUSETTE	16
94	KRUMMHORN	8
81	REGAL	8
93	TROMPETENREGAL	4
92	GLOCKEN	1/2
91	TREMULANT	

*81 REGAL 8
INTERCHANGEABLE RESONATORS

KRONWERK
C1 - c61

72	KORNETT	VIII-XII
64	TROMPETE	16
63	FELDTROMPETE	8
73	VOX HUMANA	8
62	HELLTROMPETE	4
71	OPHECLEIDE	8
61	GLOCKEN	2
74	TREMULANT	

ANCILLARIES

167	GLOCKEN REITERATE
168	KUCKUCK
169	NACHTIGALL
170	ZYMBELSTERN
171	TYMPANON

GLOCKEN-ZYMBELSTERN
97 BRONZE HAND BELLS

TYMPANON
SOFT BASS DRUM ROLL

COUPLERS
drawstops

70	OBERWERK	TO	RUCKPOSITIV	
69	RUCKPOSITIV	TO	HAUPTWERK	
68	OBERWERK	TO	HAUPTWERK	
67	BRUSTWERK	TO	HAUPTWERK	
66	KRONWERK	TO	HAUPTWERK	
65	BRUSTWERK	TO	OBERWERK	
80	RUCKPOSITIV	TO	PEDAL	
79	HAUPTWERK	TO	PEDAL	
78	OBERWERK	TO	PEDAL	
77	BRUSTWERK	TO	PEDAL	
76	KRONWERK	TO	PEDAL	4'
75	KRONWERK	TO	PEDAL	2'

COUPLERS
rocking tablets

151	RUCKPOSITIV	TO	RUCKPOSITIV	16'
152	RUCKPOSITIV	TO	RUCKPOSITIV	4'
153	OBERWERK	TO	OBERWERK	16'
154	OBERWERK	TO	OBERWERK	4'
155	BRUSTWERK	TO	BRUSTWERK	16'
156	BRUSTWERK	TO	BRUSTWERK	4'
157	KRONWERK	TO	KRONWERK	16'
158	KRONWERK	TO	KRONWERK	4'
159	RUCKPOSITIV	TO	HAUPTWERK	16'
160	RUCKPOSITIV	TO	HAUPTWERK	4'
161	OBERWERK	TO	HAUPTWERK	16'
162	OBERWERK	TO	HAUPTWERK	4'
163	KRONWERK	TO	HAUPTWERK	16'
164	KRONWERK	TO	HAUPTWERK	4'
165	HAUPTWERK AND PEDAL PISTONS			
166	OBERWERK AND PEDAL PISTONS			

ADJUSTABLE PISTONS

GENERAL PISTONS

15 GENERALS DUPLICATED BY TOE STUDS.

DEPARTMENTAL PISTONS

9 POSITIV
9 HAUPTWERK
9 OBERWERK
9 BRUSTWERK
9 KRONWERK
9 PEDAL DUPLICATED BY TOE STUDS

REVERSIBLE PISTONS

DUPLICATED BY TOE STUDS

1	OBERWERK	TO	RUCKPOSITIV	
1	RUCKPOSITIV	TO	HAUPTWERK	
1	OBERWERK	TO	HAUPTWERK	
1	BRUSTWERK	TO	HAUPTWERK	
1	KRONWERK	TO	HAUPTWERK	
1	BRUSTWERK	TO	OBERWERK	
1	RUCKPOSITIV	TO	PEDAL	
1	HAUPTWERK	TO	PEDAL	
1	OBERWERK	TO	PEDAL	
1	BRUSTWERK	TO	PEDAL	
1	KRONWERK	TO	PEDAL	4'
1	KRONWERK	TO	PEDAL	2'

ACCESSORIES

TREMULANT SPEED AND DEPTH CONTROLS
GLOCKEN REITERATE SPEED CONTROL
ZYMBELSTERN SPEED AND KEY CONTROLS
PLUS SEQUENCE ADJUSTING
CRESCENDO PEDAL WITH 4 PISTONS TO
OPERATE
NORMAL AND 3 PRESET LEVELS
OBERWERK MAIN AND ECHO SWELL PEDALS
BRUSTWERK SWELL PEDAL

CONSOLE AIDS
electrically adjustable

DIRECTION REVERSE SWITCHES FOR
SWELL AND CRESCENDO PEDALS

ACTION

KEY ACTION	MECHANICAL
STOP ACTION	ELECTRO-PNEUMATIC
COUPLERS 77-80,65	MECHANICAL
COUPLERS 66-70,75-76 151-164	ELECTRIC
PERCUSSIONS	ELECTRIC
PISTONS	ELECTRONIC CAPTURE
AUTOMATIC PLAYBACK	ELECTRIC
WIND SUPPLY	9 BLOWERS

RECORDING FACILITIES

PISTON RECORDING TAPE DECK ON CONSOLE

COMPLETE PISTON SETTINGS RECORDED OR RESET IN 12 SECONDS.
100 COMPLETE SETTINGS MAY BE STORED ON ONE TAPE.
DUPLICATE TAPES MAY BE RECORDED.

ORGAN RECORDING TAPE DECK ON CONSOLE

THE ORGAN MAY BE RECORDED ON COMPUTER TAPE AND REPLAYED AS PERFORMED (BUT WITH ELECTRIC KEY ACTION).
REPLAY CONTROLS WOULD BE LOCATED IN THE CONCERT HALL SEATING AREA AND AT THE STAGE MANAGERS DESK.

USES IN ORDER OF IMPORTANCE:-

1. ORGANIST RECORDS REHEARSAL AND CHECKS REGISTRATION AND BALANCE FROM AUDIENCE POSITION AND MAY USE RECORDED ACCOMPANIMENT DURING CONCERTO REHEARSALS.
2. STAGE MANAGER PLAYS THE ORGAN FROM TAPES, FOR USE AT CONVENTIONS, RELIGIOUS CONFERENCES, ETC., IF ORGANIST UNAVAILABLE.
3. ORGAN MAY BE PLAYED FROM TAPES FOR TOURISTS AND VISITORS.
4. EXPERIMENTAL MUSIC.

SUMMARY OF PIPES
front pipes 95% tin

TOTAL NUMBER OF STOPS	127
TOTAL NUMBER OF RANKS	205
APPROXIMATE NUMBER OF PIPES	10,500

COMMUNICATION AIDS

C.C.T.V. - 2 SCREENS ON CONSOLE
CONDUCTOR
GENERAL STAGE

SPEAKER - ORGANIST FROM STAGE

TELEPHONE - ORGANIST TO
CONDUCTOR/
STAGE MANAGER

MICROPHONE - ORGANIST TO P.A. SYSTEM

FIGURE 7.—The specification.

setting independently from the stops selected by the draw stops and rocking tablets. The crescendo pedal, then, will control the stops from this pre-set position and the organ will return to normal stop operation when the crescendo off piston is pressed. A digital display indicates the state of the crescendo at all times and allows accurate control to any of the 171 positions. The crescendo pedal itself gives a rate control rather than the positional control of the swell pedals. This allows easier control of slow build ups.

5.2. Controls

Because of the large number of stops, a very versatile system of stop control and registration aids has been included. These allow easy and instant operation of the stops and couplers. The drawstop action is electric and the combination piston action is electronic.

Four manual to pedal couplers operate by mechanical key action, as does the Brustwerk to Oberwerk coupler. The other manual and pedal couplers are operated by electric action. Rocking tablets above the top keyboard operate octave couplers and two couplers connecting manual and pedal pistons.

The piston mechanism is a full capture unit which allows the organist to select any required number of stops on any piston. Fifteen pistons control the whole organ and each division has nine independent pistons. The piston unit has a tape recorder fitted which allows all the piston settings to be recorded on cassette tapes. One cassette will record approximately 100 complete settings, and to record, or re-set, the organ takes approximately 12 seconds.

The player unit is a new development which enables the organist to record his performance on cassette tape, which can then be played back on the organ itself. This is possible through the additional fitting of electric action, as well as the mechanical key action. On replay the organ operates by electric action but simulates the timing of the original performance as accurately as is possible, considering the limitations of the recording medium. The organ faithfully follows all stop changes, piston operations, swell and crescendo pedal movements.

The organist can control the replay of the organ from a position in the audience seating. He can, from this position, alter the stop settings, swell positions and piston settings, if he feels it necessary. These new settings remain programmed in the organ.

By recording one part of the score, e.g. orchestral accompaniment, the organist may play the organ through its normal mechanical action against this recording, to practise, e.g., organ concertos. It will also be possible for the stage manager to play the organ from tapes during conventions and conferences and for the benefit of visitors, if an organist is not available.

6. Technical Details—Summary

The organ has five manuals and pedal and contains approximately 10,500 pipes, of which 109 are visible. There are 205 ranks of pipes grouped into 127 speaking stops, with 28 couplers. The front show pipes are of 95% tin, 5% lead and are burnished to a mirror-like finish. The largest front pipe is E in the 32 ft octave with a diameter of 430 mm and a length of 9·26 m. It weighs 340 kg.

There is a Glockenspiel of 73 bronze hand bells, 24 of which are visible, and a Carillon of 24 small bronze hand bells. The Tympanon operates a soft bass drum roll and there is an imitation cuckoo and nightingale.

Power for the organ is via two DC (direct current) rectifiers supplying 400 amps at 17 volts. The wind supply is by nine electric centrifugal blowers, each one contained in a silencing box equipped with BCF (bromochlorodifluoromethane) gas fire extinguishers and temperature sensing alarm. A sprinkler system is also built into the organ chamber.

The total weight of the organ is 37 tonnes.

Acknowledgement

The diagrams in this article were reproduced by kind permission of Hall, Todd and Littlemore, Architects.

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(Received 5 September 1973)

AUSTRALASIAN MEDICAL PUBLISHING CO. LTD.
71-79 ARUNDEL ST., GLEBE, N.S.W., 2037
1973

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1973

Journal and Proceedings of the Royal Society of New South Wales

VOLUME 106 1973 PARTS 3 and 4

Published by the Society
Science House, Gloucester and Essex Streets, Sydney
Issued 6th February, 1974

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Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 81–83, 1973

Occultations Observed at Sydney Observatory during 1972

K. P. Sims

The following observations of occultations were made at Sydney Observatory with the 11½-inch telescope. A tapping key was used to record the times on a chronograph. The reduction elements were computed by the method given in the occultation Supplement to the *Nautical Almanac* for 1938 and the reduction completed by the method given there. Since the observed times were in terms of coordinated time (UTC), a correction for occultations prior to the 30th of June, 1972 of +0·01134 hour (=40·84 seconds) was applied to these observed times to convert them to ephemeris time with which *The Astronomical Ephemeris for 1972* was entered to obtain the position and parallax of the Moon in terms of the FK_4 coordinate system. For occultations observed between the 1st of July, 1972 and the 31st of December, 1972, the corresponding correction was +0·01162 hour (=41·84 seconds). The apparent places of the stars of the 1972 occultations were provided by H.M. Nautical Almanac Office.

Table I gives the observational material. The serial numbers follow on from those of the previous report (Sims, 1971). The observers were W. H. Robertson (R), K. P. Sims (S), and H. W. Wood (W). Except for occultations 667, 668, 684, 685, 686, 687, which were reappearances at the dark limb, the phase observed was disappearance of the dark limb. Table II gives the results of the reductions which were carried out in duplicate. The Z.C. or S.A.O. numbers given in Table I are from the *Catalog of 3539 Zodiacal Stars for Equinox* 1950·0 (Robertson, 1940) and the *Smithsonian Astrophysical Observatory Star Catalog.*

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Table I

Serial No.	S.A.O. or Z.C. No.	Mag.	Date	U.T.C.	Observer
656	077960	7·6	1972 Apr. 18	9 07 21·1	W
657	077974	7·5	1972 Apr. 18	9 23 02·0	W
658	926	7·0	1972 Apr. 18	9 32 43·6	W
659	1335	6·3	1972 Apr. 21	09 08 36·1	R
660	0844	5·7	1972 May 15	07 57 30·0	S
661	078629	8·0	1972 May 16	7 41 15·0	R
662	1030	3·2	1972 May 16	9 05 48·6	R
663	079628	7·1	1972 May 17	8 28 21·4	S
664	1167	6·3	1972 May 17	8 39 01·2	S
665	097996	8·5	1972 May 18	9 02 43·7	R
666	138395	7·7	1972 May 22	8 46 27·0	S
667	092278	8·5	1972 Jul. 4	16 42 32·0	R
668	092320	8·4	1972 Jul. 4	19 06 23·6	R
669	118318	8·6	1972 Jul. 14	8 21 28·3	R
670	118331	7·8	1972 Jul. 14	9 16 13·1	R
671	118751	8·4	1972 Jul. 15	9 09 09·0	W
672	138935	7·6	1972 Jul. 17	7 32 03·4	S
673	138945	8·6	1972 Jul. 17	8 01 39·7	S
674	157965	8·9	1972 Jul. 18	8 25 35·5	R
675	157983	8·8	1972 Jul. 18	9 42 54·5	R
676	1944	5·6	1972 Jul. 18	10 29 10·0	R
677	158047	8·5	1972 Jul. 18	13 12 58·7	W
678	158542	7·9	1972 Jul. 19	13 14 35·4	W
679	183168	6·9	1972 Jul. 20	7 44 47·9	R
680	2157	6·1	1972 Jul. 20	7 55 31·8	R
681	2286	5·4	1972 Jul. 21	8 23 05·1	S

TABLE I—*continued*

Serial No.	S.A.O. or Z.C. No.	Mag.	Date	U.T.C.	Observer
682	2295	7·0	1972 Jul. 21	11 25 59·7	S
683	2299	6·4	1972 Jul. 21	12 10 56·4	S
684	076267	9·1	1972 Aug. 3	17 48 14·8	R
685	0574	6·8	1972 Aug. 3	18 18 54·8	R
686	076281	8·4	1972 Aug. 3	18 22 28·0	R
687	076296	8·6	1972 Aug. 3	18 56 16·5	R
688	138356	9·0	1972 Aug. 12	8 21 41·9	W
689	183671	8·3	1972 Aug. 17	8 06 41·0	R
690	183673	8·7	1972 Aug. 17	8 27 56·6	R
691	2237	5·1	1972 Aug. 17	8 41 01·5	R
692	183725	8·4	1972 Aug. 17	10 54 26·5	R
693	2822	5·6	1972 Aug. 21	11 38 11·3	S
694	1967	5·7	1972 Sep. 11	8 41 55·1	S
695	158142	8·8	1972 Sep. 11	9 06 30·2	S
696	2194	8·7	1972 Sep. 13	8 39 16·7	S
697	183419	8·3	1972 Sep. 13	8 52 00·0	S
698	183446	8·5	1972 Sep. 13	10 14 39·3	S
699	185134	8·3	1972 Sep. 15	11 39 59·7	S
700	185140	8·7	1972 Sep. 15	11 50 07·7	S
701	184027	7·8	1972 Oct. 11	10 35 31·3	S
702	184678	8·0	1972 Oct. 12	8 58 27·1	S
703	184700	8·2	1972 Oct. 12	9 15 07·6	S
704	184743	8·8	1972 Oct. 12	10 24 17·9	S
705	184750	8·6	1972 Oct. 12	10 28 18·9	S
706	185698	8·7	1972 Oct. 13	10 12 16·4	R
707	185743	8·7	1972 Oct. 13	11 12 48·2	R
708	185830	8·0	1972 Oct. 13	12 41 21·0	W
709	2714	6·1	1972 Oct. 14	12 11 14·8	W
710	163217	8·9	1972 Nov. 12	9 18 46·8	W
711	163240	9·0	1972 Nov. 12	9 45 12·3	W
712	163244	9·0	1972 Nov. 12	9 56 37·9	W
713	163260	8·3	1972 Nov. 12	10 18 12·2	W
714	146513	9·0	1972 Dec. 13	10 29 52·0	

TABLE II

Serial No.	Lunation No.	p	q	p^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of	
										$\Delta\alpha$	$\Delta\delta$
656	610	+91	−41	83	−37	17	−1·0	−0·9	+0·4	+11·7	−0·49
657	610	+97	+26	93	+25	7	0·0	0·0	0·0	+13·2	+0·17
658	610	+93	+37	86	+34	14	−0·5	−0·5	−0·2	+12·8	+0·28
659	610	+71	+70	51	+50	49	−0·8	−0·6	−0·6	+13·1	+0·40
660	611	+90	+43	81	+39	19	−1·1	−1·0	−0·5	+12·2	+0·40
661	611	+88	−47	78	−41	22	+1·0	+0·9	−0·5	+10·9	−0·60
662	611	+95	−31	90	−29	10	−0·6	−0·6	+0·2	+12·1	−0·45
663	611	+86	−52	73	−44	27	+3·4	+2·9	−1·8	+ 9·7	−0·72
664	611	+95	+32	90	+30	10	+0·1	+0·1	0·0	+13·8	+0·07
665	611	+76	−65	58	−49	42	+1·4	+1·1	−0·9	+ 7·1	−0·87
666	611	+55	−83	31	−46	69	+1·7	+0·9	−1·4	+ 2·0	−0·99
667	612	−99	−16	97	+16	3	+0·8	−0·8	−0·1	−12·4	−0·53
668	612	−64	−77	41	+49	59	−0·4	+0·3	+0·3	− 4·2	−0·96
669	613	+98	+18	97	+18	3	−0·9	−0·9	−0·2	+14·4	−0·26
670	613	+48	+88	23	+42	77	−0·8	−0·4	−0·7	+12·0	+0·59
671	613	+73	+68	53	+50	47	−1·6	−1·2	−1·1	+14·3	+0·29
672	613	+54	+84	29	+45	71	−0·6	−0·3	−0·5	+12·4	+0·54
673	613	+99	+11	99	+11	1	+0·4	+0·4	0·0	+14·1	−0·30
674	613	+49	−87	24	−43	76	+1·0	+0·5	−0·9	+ 1·9	−0·99
675	613	+74	−67	55	−50	45	+0·4	+0·3	−0·3	+ 6·4	−0·90

TABLE II—*continued*

Serial No.	Lunation No.	p	q	p^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of	
										$\Delta\alpha$	$\Delta\delta$
676	613	+88	−48	77	−42	23	−0·1	−0·1	0·0	+ 9·3	−0·76
677	613	+99	+16	97	+16	3	−0·2	−0·2	0·0	+14·2	−0·20
678	613	+93	−38	86	−35	14	−1·3	−1·2	+0·5	+10·9	−0·64
679	613	+71	−71	50	−50	50	+1·9	+1·3	−1·3	+ 7·2	−0·86
680	613	+48	+88	23	+42	77	−0·9	−0·4	−0·8	+ 9·4	+0·74
681	613	+72	−69	52	−50	48	+2·0	+1·4	−1·4	+ 8·3	−0·79
682	613	+87	−50	75	−43	25	−0·2	−0·2	+0·1	+10·7	−0·61
683	613	+68	+73	47	+50	53	−0·3	−0·2	−0–2	+10·6	+0·63
684	613	−74	+68	54	−50	46	+1·0	−0·7	+0·7	−11·4	+0·54
685	613	−85	−52	73	+44	27	+0·4	−0·3	−0·2	−10·3	−0·65
686	613	−99	+13	98	−13	2	−0·8	+0·8	−0·1	−13·5	−0·04
687	613	−85	+52	73	−44	27	−0·1	+0·1	−0·1	−12·6	+0·37
688	614	+79	−61	63	−48	37	+1·8	+1·4	−1·1	+ 6·6	−0·90
689	614	+85	+52	73	+44	27	−1·2	−1·0	−0·6	+12·8	+0·35
690	614	+47	+88	22	+41	78	−0·7	−0·3	−0·6	+ 8·6	+0·78
691	614	+78	+62	61	+49	39	−1·0	−0·8	−0·6	+12·1	+0·47
692	614	+65	−76	42	−49	58	+1·2	+0·8	−0·9	+ 6·9	−0·86
693	614	+38	+93	14	+35	86	−0·3	−0·1	−0·3	+ 2·2	+0·99
694	615	+95	−31	90	−29	10	−1·0	−1·0	+0·3	+11·2	−0·63
695	615	+52	+85	28	+45	72	−0·5	−0·3	−0·4	+11·5	+0·61
696	615	+100	− 2	100	− 2	0	0·0	0·0	0·0	+13·4	−0·23
697	615	+94	+33	89	+31	11	−0·5	−0·5	−0·2	+13·7	+0·12
698	615	+85	+52	73	+44	27	−3·1	−2·6	−1·6	+13·0	+0·34
699	615	+99	−13	98	−13	2	+1·3	+1·3	−0·2	+13·4	−0·14
700	615	+100	− 7	100	− 7	0	+0·3	+0·3	0·0	+13·5	−0·08
701	616	+85	−52	73	−44	27	+1·1	+0·9	−0·6	+10·6	−0·64
702	616	+21	+98	4	+21	96	−0·9	−0·2	−0·9	+ 3·5	+0·97
703	616	+88	−48	77	−42	23	−0·8	−0·7	+0·4	+11·6	−0·52
704	616	+92	−39	85	−36	15	−3·3	−3·0	+1·3	+12·2	−0·43
705	616	+100	−10	99	−10	1	+1·4	+1·4	−0·1	+13·5	−0·14
706	616	+77	−64	59	−49	41	0·0	0·0	0·0	+10·9	−0·59
707	616	+68	+74	46	+50	54	−0·2	−0·1	−0·1	+ 8·6	+0·78
708	616	+96	+29	92	+28	8	+1·3	+1·2	+0·4	+12·8	+0·35
709	616	+67	−74	45	−50	55	+0·6	+0·4	−0·4	+10·7	−0·63
710	617	+51	+86	26	+44	74	+0·4	+0·2	+0·3	+ 3·4	+0·97
711	617	+89	+46	79	+41	21	−0·5	−0·4	−0·2	+10·2	+0·70
712	617	+81	+58	66	+47	34	−1·3	−1·1	−0·8	+ 8·6	+0·79
713	617	+97	+25	94	+24	6	−0·1	−0·1	0·0	+12·1	+0·52
714	618	+72	−70	51	−50	49	+2·5	+1·8	−1·8	+14·3	−0·32

(Received 2nd August, 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 84–88, 1973

Precise Observations of Minor Planets at Sydney Observatory during 1971 and 1972

W. H. Robertson

Abstract—Positions of 2 Pallas, 3 Juno, 4 Vesta, 6 Hebe and 7 Iris obtained with the 23 cm. camera are given.

The programme of precise observations of selected minor planets which was begun in 1955 is being continued and the results for 1971 and 1972 are given here. The methods of observation and reduction were described in the first paper (Robertson 1958). All the plates were taken with the 23 cm. camera (scale 116″ to the millimetre). Four exposures were made on each plate. The plates for 4 Vesta were taken with a coarse wire grating in front of the lens. The side images were measured for the planet.

In Table I are given the means for all four images for the separate groups of stars at the mean of the times. The differences between the results average $0^{s}\cdot030 \sec \delta$ in right ascension and $0''\cdot43$ in declination. This corresponds to probable errors for the mean of the two results from one plate of $0^{s}\cdot012 \sec \delta$ and $0''\cdot19$. The result from the first two exposures was compared with that from the last two by adding the movement computed from the ephemeris. The means of the differences were $0^{s}\cdot010 \sec \delta$ in right ascension and $0''\cdot09$ in declination. It is expected that the two results from each plate will be combined into one when they are used. However, they are published in the present form so that any alteration of the positions of the reference stars can be conveniently applied by using the dependences from Table II. No correction has been applied for aberration, light time or parallax, but the factors give the parallax correction when divided by the distance. The observers at the telescope were W. H. Robertson (R), K. P. Sims (S) and Harley Wood (W).

In accordance with the recommendation of Commission 20 of the International Astronomical Union, Table II gives for each observation the positions of the reference stars and the dependences. The columns headed " R.A. " and " Dec. " give the seconds of time and arc with proper motion correction applied to bring the catalogue position to the epoch of the plate. The column headed " Star " gives the number from the Yale Catalogue (Vols. 11, 12, 13, 14, 16, 17, 20, 21, 22, 28). The plates were measured by Miss K. Luxton, Miss R. Stanfield, Miss M. Telfer and Miss E. Wiegold who have also assisted with the reductions.

Reference

Robertson, W. H., 1958. *J. Roy. Soc. N.S.W.*, 92, 18. Sydney Observatory Papers No. 33

Table I

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		7 Iris									
		1971 U.T.									
1099	Mar.	18·61671	12	23	45·825	−11	29	51·92	+0·022	−3·30	R
1100	Mar.	18·61671	12	23	45·854	−11	29	51·68			
1101	Mar.	30·57047	12	12	36·297	−10	15	11·82	+0·004	−3·48	W
1102	Mar.	30·57047	12	12	36·382	−10	15	10·88			
1103	Apr.	14·51698	11	59	57·441	−08	31	27·92	−0·008	−3·72	S
1104	Apr.	14·51698	11	59	57·426	−08	31	27·99			
1105	Apr.	27·48163	11	52	05·136	−07	09	09·75	+0·009	−3·91	R
1106	Apr.	27·48163	11	52	05·112	−07	09	10·40			
1107	May	24·42309	11	48	14·882	−05	26	07·82	+0 064	−4·15	S
1108	May	24·42309	11	48	14·904	−05	26	08·58			

TABLE I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		2 Pallas									
		1971 U.T.									
1109	Sep.	13·77978	04	24	13·322	−11	05	50·50	−0·020	−3·38	R
1110	Sep.	13·77978	04	24	13·386	−11	05	49·92			
1111	Sep.	21·76378	04	30	15·240	−13	21	05·94	−0·015	−3·06	S
1112	Sep.	21·76378	04	30	15·321	−13	21	05·85			
1113	Oct.	11·73049	04	38	51·679	−19	35	13·50	−0·035	−2·15	R
1114	Oct.	11·73049	04	38	51·729	−19	35	13·23			
1115	Oct.	25·67807	04	38	24·500	−24	01	06·38	−0·011	−1·48	W
1116	Oct.	25·67807	04	38	24·502	−24	01	06·57			
1117	Nov.	08·63960	04	32	25·720	−27	55	14·64	+0·003	−0·89	R
1118	Nov.	08·63960	04	32	25·606	−27	55	14·64			
1119	Nov.	22·58709	04	22	02·559	−30	42	58·40	−0·023	−0·47	W
1120	Nov.	22·58709	04	22	02·588	−30	42	58·40			
1121	Dec.	29·48107	03	54	40·798	−30	37	42·39	+0·027	−0·47	S
1122	Dec.	29·48107	03	54	40·794	−30	37	42·23			
		1972 U.T.									
1123	Jan.	21·43227	03	53	42·967	−26	04	51·54	+0·076	−1·20	S
1124	Jan.	21·43227	03	53	42·930	−26	04	50·48			
		4 Vesta									
		1971 U.T.									
1125	Jun.	21·70090	20	31	55·518	−20	10	02·26	+0·040	−2·07	S
1126	Jun.	21·70090	20	31	55·491	−20	10	01·36			
1127	Jun.	29·67633	20	28	06·460	−21	00	13·03	+0·043	−1·95	W
1128	Jun.	29·67633	20	28	06·446	−21	00	13·56			
1129	Jul.	12·61746	20	18	18·570	−22	33	25·92	−0·014	−1·71	R
1130	Jul.	12·61746	20	18	18·594	−22	33	25·11			
1131	Jul.	20·59245	20	10	48·239	−23	32	17·92	−0·008	−1·56	S
1132	Jul.	20·59245	20	10	48·250	−23	32	18·38			
1133	Jul.	28·57620	20	02	59·290	−24	27	25·14	+0·029	−1·42	W
1134	Jul.	28·57620	20	02	59·269	−24	27	25·42			
1135	Aug.	09·52351	19	52	24·598	−25	35	42·80	−0·013	−1·25	S
1136	Aug.	09·52351	19	52	24·588	−25	35	42·64			
1137	Aug.	18·49791	19	46	28·220	−26	12	53·06	−0·003	−1·15	R
1138	Aug.	18·49791	19	46	28·268	−26	12	52·50			
1139	Aug.	23·48667	19	44	11·378	−26	28	02·20	−0·011	−1·11	S
1140	Aug.	23·48667	19	44	11·414	−26	28	03·60			
1141	Aug.	31·47995	19	42	15·144	−26	44	29·03	+0·067	−1·10	R
1142	Aug.	31·47995	19	42	15·178	−26	44	28·34			
1143	Sep.	13·43560	19	43	40·493	−26	52	35·10	+0·034	−1·06	S
1144	Sep.	13·43560	19	43	40·560	−26	52	36·25			
1145	Sep.	22·41540	19	47	47·532	−26	46	24·12	+0·039	−1·07	R
1146	Sep.	22·41540	19	47	47·490	−26	46	24·18			
1147	Sep.	28·40106	19	51	49·592	−26	37	23·10	+0·036	−1·10	R
1148	Sep.	28·40106	19	51	49·650	−26	37	23·60			
		3 Juno									
		1972 U.T.									
1149	Mar.	13·65586	13	06	39·848	−00	35	34·44	+0·015	−4·78	S
1150	Mar.	13·65586	13	06	39·831	−00	35	34·17			
1151	Apr.	12·55987	12	44	01·616	+03	33	26·28	+0·020	−5·30	R
1152	Apr.	12·55987	12	44	01·658	+03	33	27·09			
1153	Apr.	20·52758	12	38	24·648	+04	25	58·76	−0·001	−5·41	S
1154	Apr.	20·52758	12	38	24·646	+04	25	59·22			
1155	May	18·43751	12	26	50·142	+06	03	08·16	−0·018	−5·60	R
1156	May	18·43751	12	26	50·118	+06	03	08·72			
		6 Hebe									
		1972 U.T.									
1157	Jun.	13·73776	21	09	25·493	−07	18	31·26	+0·011	−3·92	S
1158	Jun.	13·73776	21	09	25·479	−07	18	30·80			
1159	Jul.	04·67200	21	09	28·890	−08	41	12·64	−0·105	−3·73	R
1160	Jul.	04·67200	21	09	28·896	−08	41	12·68			
1161	Jul.	12·65722	21	06	19·287	−09	43	07·52	+0·013	−3·58	S

TABLE I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		6 Hebe—*continued*									
		1972 U.T.									
1162	Jul.	12·65722	21	06	19·256	−09	43	07·46			
1163	Jul.	18·62798	21	02	54·112	−10	40	23·72	−0·019	−3·45	W
1164	Jul.	18·62798	21	02	54·070	−10	40	23·72			
1165	Jul.	31·60194	20	53	07·200	−13	11	27·27	+0·032	−3·09	R
1166	Jul.	31·60194	20	53	07·135	−13	11	26·78			
1167	Aug.	08·50825	20	46	16·348	−14	55	49·72	+0·049	−2·85	S
1168	Aug.	08·58025	20	46	16·411	−14	55	49·76			
1169	Aug.	17·54928	20	38	50·534	−16	54	43·96	+0·044	−2·56	W
1170	Aug.	17·54928	20	38	50·538	−16	54	44·22			
1171	Sep.	04·48103	20	28	33·746	−20	26	38·30	+0·005	−2·02	R
1172	Sep.	04·48103	20	28	33·768	−20	26	38·40			
1173	Sep.	14·44996	20	27	05·202	−21	57	18·24	−0·004	−1·80	W
1174	Sep.	14·44996	20	27	05·154	−21	57	17·95			
1175	Oct.	03·40852	20	34	01·835	−23	46	07·56	+0·015	−1·53	W
1176	Oct.	03·40852	20	34	01·808	−23	46	07·72			
1177	Oct.	12·40494	20	41	30·926	−24	09	23·49	+0·068	−1·49	W
1178	Oct.	12·40494	20	41	30·958	−24	09	24·64			
1179	Oct.	23·39477	20	53	47·328	−24	14	47·16	+0·016	−1·51	R
1180	Oct.	23·39477	20	53	47·322	−24	14	46·90			
1181	Oct.	30·39428	21	03	07·462	−24	05	49·76	+0·146	−1·59	R
1182	Oct.	30·39428	21	03	07·490	−24	05	50·32			
		7 Iris									
		1972 U.T.									
1183	Jun.	08·62079	18	03	33·757	−22	28	21·98	+0·005	−1·71	R
1184	Jun.	08·62079	18	03	33·784	−22	28	21·40			
1185	Jun.	13·60673	17	58	27·613	−22	18	52·89	+0·015	−1·73	S
1186	Jun.	13·60673	17	58	27·596	−22	18	53·04			
1187	Jul.	05·52457	17	35	21·898	−21	31	59·99	−0·005	−1·85	R
1188	Jul.	05·52457	17	35	21·816	−21	32	00·24			
1189	Jul.	12·50721	17	29	03·055	−21	17	02·60	+0·015	−1·89	S
1190	Jul.	12·50721	17	29	03·022	−21	17	02·32			
1191	Jul.	18·47323	17	24	29·808	−21	05	10·18	−0·032	−1·92	R
1192	Jul.	18·47323	17	24	29·820	−21	05	10·00			

TABLE II

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
1099	4517	0·306125	01·582	13·74	1105	4404	0·336670	30·351	42·13
	4524	0·464163	47·152	06·91		4416	0·358264	09·073	29·45
	4534	0·229712	01·983	19·60		4418	0·305066	41·150	38·26
1100	4503	0·364994	57·278	13·80	1106	4405	0·320770	03·092	21·43
	4523	0·272860	31·492	34·59		4412	0·475484	50·306	10·30
	4540	0·362146	48·312	19·91		4433	0·203746	51·554	05·66
1101	4491	0·408386	57·969	16·39	1107	4418	0·344300	19·911	00·84
	4525	0·313921	05·397	32·66		4423	0·300714	55·685	42·71
	4481	9·277692	08·474	54·56		4443	0·354987	11·718	13·61
1102	4462	0·309722	17·144	14·82	1108	4411	0·353499	36·474	09·42
	4490	0·315147	14·281	06·27		4433	0·335304	30·333	42·90
	4503	0·375131	27·515	24·54		4437	0·311197	01·970	26·44
1103	4441	0·453194	05·706	51·03	1109	1056	0·338694	32·236	00·71
	4459	0·087964	39·763	24·95		1062	0·322470	38·080	47·70
	4463	0·458842	27·343	56·11		1099	0·338836	24·770	49·39
1104	4439	0·247286	35·469	01·77	1110	1064	0·318591	16·789	58·33
	4443	0·348908	40·583	20·51		1067	0·329296	38·284	55·24
	4467	0·393806	09·526	54·15		1080	0·352114	37·523	01·86

Table II—*continued*

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
1111	1098	0·270178	15·697	53·15	1133	13967	0·425776	02·582	40·94
	1113	0·364378	30·240	17·10		13994	0·257718	06·661	07·90
	1121	0·365444	28·725	55·36		14000	0·316506	41·242	41·89
1112	1090	0·381175	39·998	10·96	1134	13972	0·385802	27·842	29·31
	1120	0·434614	27·318	54·94		13980	0·286408	13·378	04·72
	1267	0·184211	50·712	02·30		14005	0·327790	26·713	45·24
1113	1435	0·382480	16·754	58·73	1135	13839	0·371585	43·350	27·45
	1488	0·366080	07·590	13·94		13858	0·350977	09·996	24·59
	1467	0·251440	31·289	06·07		13928	0·277438	35·016	28·05
1114	1448	0·341192	42·318	05·81	1136	13841	0·293048	49·241	06·82
	1490	0·285248	20·220	15·78		13878	0·335922	48·752	49·65
	1461	0·373560	10·309	31·56		13893	0·371031	05·479	24·88
1115	2208	0·217754	55·179	37·61	1137	13783	0·277790	56·710	50·78
	2216	0·369729	29·784	14·13		13789	0·322540	37·009	03·31
	2222	0·412517	06·879	52·71		13839	0·399670	43·350	27·45
1116	2182	0·231568	48·813	20·49	1138	13781	0·257520	38·844	11·81
	2219	0·406715	38·209	53·87		13809	0·410164	18·261	34·07
	2241	0·361717	05·365	43·54		13815	0·332316	37·717	59·73
1117	1856	0·205462	12·067	26·28	1139	13748	0·413478	21·880	37·51
	1871	0·481999	19·777	54·82		13789	0·244629	37·099	03·31
	1884	0·312538	02·892	17·89		13809	0·341893	18·261	34·07
1118	1865	0·421436	35·362	54·81	1140	12953	0·320176	48·250	34·54
	1874	0·406220	36·262	47·53		13763	0·237128	22·725	14·57
	1883	0·172344	03·569	03·50		13807	0·442695	53·129	18·94
1119	1606	0·541968	11·316	36·89	1141	12896	0·322206	43·251	45·40
	1634	0·234100	13·871	35·23		13763	0·401379	22·725	14·58
	1635	0·223932	14·551	42·65		13809	0·276415	18·263	34·05
1120	1609	0·261979	39·511	06·70	1142	13728	0·288824	19·647	46·03
	1611	0·408496	00·883	38·36		13781	0·350438	38·845	11·83
	1638	0·329525	25·448	21·92		12965	0·360738	14·632	17·84
1121	1416	0·229392	13·396	47·49	1143	13748	0·317586	21·880	37·51
	1426	0·445407	31·774	19·31		13804	0·400819	48·560	07·25
	1443	0·325201	36·392	30·40		12965	0·281595	14·630	17·89
1122	1404	0·302650	05·351	58·15	1144	12942	0·335109	16·761	43·43
	1432	0·234469	37·383	38·83		13781	0·441846	38·844	11·81
	1442	0·462881	33·947	51·23		13809	0·223045	18·262	34·07
1123	1817	0·328332	35·237	22·12	1145	12994	0·274317	22·114	12·67
	1831	0·208292	16·387	23·36		13054	0·285276	21·049	26·05
	1850	0·463376	25·264	57·39		13814	0·440407	38·613	55·08
1124	1811	0·368375	54·040	42·80	1146	13783	0·215264	56·710	50·79
	1826	0·274254	42·349	31·87		13839	0·444140	43·350	27·45
	1861	0·357371	23·870	05·15		13021	0·340596	41·827	41·78
1125	8796	0·331949	54·749	02·84	1147	13839	0·376442	43·350	27·45
	8830	0·390896	26·963	16·79		13894	0·301121	12·680	09·19
	8838	0·277155	36·005	40·92		13070	0·322437	03·510	30·24
1126	8806	0·499763	41·230	22·32	1148	13814	0·342498	38·613	55·09
	8821	0·216731	30·893	21·96		13921	0·308899	52·550	59·26
	8844	0·283506	24·667	09·73		13065	0·348603	36·920	09·39
1127	8764	0·341118	57·342	33·80	1149	3527	0·258506	36·984	17·22
	8807	0·282534	53·838	26·03		3538	0·389248	20·376	16·24
	8809	0·376348	31·871	49·48		3540	0·352246	09·273	11·51
1128	8779	0·449730	37·751	42·60	1150	3525	0·310582	36·994	52·57
	8792	0·305588	28·593	53·41		3537	0·388940	52·929	07·25
	8830	0·244682	26·964	16·80		3546	0·300478	33·906	46·36
1129	14103	0·351124	15·489	06·90	1151	4554	0·281612	26·272	21·12
	14130	0·438178	27·287	22·36		4561	0·346757	56·792	16·47
	14156	0·210698	25·537	43·36		4575	0·371631	59·833	05·34
1130	14107	0·385772	38·472	21·55	1152	4550	0·397127	13·074	18·68
	14134	0·458598	47·416	48·13		4565	0·335704	50·971	03·46
	14153	0·155630	01·393	24·37		4581	0·267169	25·602	11·88
1131	14025	0·425324	54·357	06·68	1153	4519	0·356029	05·775	25·09
	14049	0·307026	20·698	40·48		4559	0·257945	48·212	50·40
	14097	0·267651	56·313	04·45		6209	0·386026	22·977	27·68
1132	14010	0·240776	52·197	26·33	1554	6181	0·366511	15·392	38·10
	14035	0·426996	01·489	42·31		4534	0·340238	59·191	59·46
	14107	0·332228	38·473	21·55		4560	0·293251	50·552	05·88

TABLE II—*continued*

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
1155	6116	0·280147	44·297	06·44	1174	8779	0·343916	37·749	42·62
	6129	0·291885	03·489	48·63		8809	0·204524	31·872	49·50
	6161	0·427968	43·948	26·70		14216	0·451560	38·039	05·66
1156	6117	0·345070	49·651	04·97	1175	14268	0·332126	40·293	22·53
	6148	0·300326	09·871	02·31		14314	0·255186	07·693	31·31
	6156	0·354604	36·591	04·29		14326	0·412688	03·437	15·18
1157	7583	0·275592	05·191	23·57	1176	14280	0·136186	01·489	32·65
	7604	0·217822	11·471	04·63		14290	0·534406	37·748	10·23
	7619	0·506587	20·433	37·23		14336	0·329407	07·614	42·29
1158	7590	0·379906	03·257	26·15	1177	14366	0·416324	40·089	03·91
	7591	0·226574	23·412	21·04		14384	0·333667	43·390	08·75
	7629	0·393520	52·916	16·81		14420	0·250009	18·945	31·19
1159	7584	0·248988	52·883	47·86	1178	14374	0·325938	36·851	23·22
	7609	0·448670	59·418	59·01		14376	0·350518	43·483	03·52
	7610	0·302342	02·614	55·78		14405	0·323543	16·653	56·48
1160	7593	0·276158	45·727	47·81	1179	14484	0·320142	05·210	15·45
	7601	0·344141	32·153	00·17		14519	0·418215	58·506	32·15
	7620	0·379701	35·309	10·69		14520	0·261643	11·319	59·75
1161	7477	0·371820	40·164	46·90	1180	14500	0·288194	22·732	33·95
	7522	0·347355	58·171	07·63		14510	0·439623	07·558	28·84
	7581	0·280825	24·247	37·52		14515	0·272183	44·177	57·54
1162	7470	0·264012	02·342	16·70	1181	14573	0·207715	01·554	54·01
	7508	0·335536	02·266	50·45		14583	0·499732	05·888	38·45
	7592	0·400451	42·294	21·81		14590	0·292553	56·925	24·26
1163	7458	0·440857	05·029	20·59	1182	14559	0·355660	27·625	53·44
	7487	0·318447	50·555	39·43		14589	0·310890	57·545	14·18
	7494	0·240696	30·089	16·52		14600	0·333450	11·166	42·13
1164	7459	0·356908	09·877	59·45	1183	12449	0·392650	12·348	52·24
	7470	0·302346	02·342	16·70		12479	0·269026	10·454	43·10
	7499	0·340745	32·021	55·55		12491	0·338324	39·037	03·94
1165	7390	0·397354	45·626	31·30	1184	7412	0·317344	21·292	50·16
	7421	0·370214	21·358	31·60		12492	0·303304	42·130	59·08
	7890	0·232433	17·647	24·64		12516	0·379351	11·180	32·96
1166	7398	0·404898	12·981	55·27	1185	12324	0·315050	38·669	43·94
	7430	0·334024	20·246	37·13		12449	0·292362	12·348	52·24
	7869	0·261078	57·603	23·94		7390	0·392588	07·729	52·51
1167	7816	0·268704	35·574	02·53	1186	12298	0·463623	42·792	45·37
	7843	0·298737	43·253	26·53		12405	0·214812	40·936	32·09
	7851	0·432559	14·856	41·43		7448	0·321565	22·486	38·24
1168	7823	0·461488	21·671	03·96	1187	12071	0·213332	33·863	15·96
	7846	0·285860	48·239	53·13		12115	0·329318	49·350	39·04
	7848	0·252625	02·378	16·78		7235	0·457350	49·922	45·48
1169	7775	0·390286	17·695	50·61	1188	7214	0·374749	22·531	52·73
	7790	0·273054	29·370	40·19		7223	0·353922	32·035	37·44
	7812	0·336660	04·676	01·37		7255	0·271329	12·364	07·03
1170	7768	0·457118	52·732	29·16	1189	7162	0·262700	16·644	22·42
	7799	0·327742	57·357	19·90		7179	0·381516	39·320	18·82
	7818	0·215140	26·229	39·34		7184	0·355784	26·949	43·59
1171	8779	0·258368	37·749	42·62	1190	7158	0·377693	34·897	43·32
	8780	0·259323	45·896	26·99		7178	0·322759	06·579	49·16
	8817	0·482308	37·925	00·18		7214	0·299458	22·531	52·73
1172	8776	0·334886	27·187	41·22	1191	7148	0·358698	44·035	18·52
	8796	0·188988	54·753	02·86		7149	0·354050	49·589	55·26
	8814	0·476127	00·757	38·17		7162	0·287252	16·644	22·42
1173	14184	0·215647	04·757	19·58	1192	7139	0·257302	34·455	02·50
	14254	0·275036	20·062	54·96		7153	0·263446	24·347	32·47
	8790	0·509317	08·551	31·93		7158	0·479252	34·897	43·32

(Received 24·5·1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 89–97, 1973

The Clarke Memorial Lecture for 1973

The Late Precambrian Glaciation, with Particular Reference to the Southern Hemisphere

Kalervo Rankama

Mr. Chairman, Ladies and Gentlemen,

We are assembled here tonight in commemoration of the Reverend William Branwhite Clarke, the "Founding Father" of the Royal Society of New South Wales, a great citizen and scientist justly called the "Father of Australian Geology". I feel greatly honoured to have been asked by the Council to deliver the Thirty-seventh Clarke Memorial Lecture. In fact, this is a double honour because, insofar as I know, I am the second non-Australian—the second alien that is, ever invited to deliver this lecture.

When I was checking some information for my lecture, I was astonished to find that, 25 years ago almost to the day, on 15th July, 1948, Sir Douglas Mawson delivered the Clarke Memorial Lecture. His topic was the Late Precambrian Ice Age and the glacial record of a part of the Flinders Ranges in South Australia. This is a most remarkable coincidence.

I shall today deal with more or less the same topic, a topic not appreciated and explored by geologists in Clarke's day. I shall talk about some current research that has been sponsored by the Subcommission on Precambrian Stratigraphy of the International Union of Geological Sciences and by the International Geological Correlation Programme. This research deals with the Late Precambrian glaciation.

Introduction

The last glaciation is not a thing of a remote past. Right now, we are living in an interglacial period, at a time between two glaciations. It has been customary to assume, for the Northern Hemisphere, the existence of four Pleistocene glaciations, each as long as 100,000 years, or kiloyears (ka), separated by warm interglacial periods with a length of 100–300 ka.

At the time when the Pleistocene ice sheets grew and diminished in the Northern Hemisphere, highlands in eastern Australia were also glaciated. At the same time, the sea level in the Southern Hemisphere changed many times.

However, in the Northern Hemisphere, results obtained only a year ago have considerably changed the picture. Emiliani (1972) reported in his studies, by oxygen-isotope thermometry, on foraminifers in sediment cores from the Caribbean. His results, and those of David Ericson and Goesta Wollin, show that the glaciations lasted for only 10–20 ka. Emiliani concluded that, geologically speaking, the warm intervals between the glaciations were also brief. His results indicated at least eight glaciations and seven warm intervals in the Northern Hemisphere during the past 400 ka.

The present warm period has lasted already 12 ka and might end soon, perhaps within the next 2 or 3 ka, which means that there is a new glaciation knocking at the door.

The global cooling that reversed the warm trend of the 1940's still continues. Perhaps, as during the Pleistocene glaciation, Australia is going to have a much wetter climate than now, along with a drop in the sea level.

I shall next give some background information.

In 1966, the International Union of Geological Sciences decided to establish the Subcommission on Precambrian Stratigraphy, and I was asked to act as the President of the new Subcommission which operates as a part of the Commission on Stratigraphy. The Subcommission has nine titular members from various countries with Precambrian bedrock in the Northern and Southern Hemispheres. It also has 19 correspondents from many countries.

In 1970, the Subcommission decided to start a research project called Project Hemispheres, for comparison and correlation of sequences of Late Precambrian unmetamorphosed sedimentary rocks from the Northern and Southern Hemispheres. This project was sponsored by the International Geological Correlation Programme, and its ultimate purpose is the establishment of world-wide Precambrian chronostratigraphic units. The first stage of the project was completed during my third stay in Australia in 1970–1971. A small *ad hoc* working group was established, consisting of Mr. P. R. Dunn, at that time with the Bureau of Mineral Resources in Canberra, Mr. B. P. Thomson of the Geological Survey of South Australia, and myself.

To briefly summarize our results, we think that the widespread occurrence of Late Precambrian glaciogenic rocks provides an ideal situation for the establishment of a world-wide Precambrian chronostratigraphic unit (Dunn, Thomson and Rankama, 1971). We propose, for use in Australia, a chronostratigraphic unit based on the well-exposed and well-documented Late Precambrian glaciogenic rocks of the Continent. We also hope that the unit will eventually be accepted for use throughout the world.

Glaciations in General

A glaciation is a major geological event. The distinguishing geological features produced by a glaciation are glacial abrasion, transportation of abraded rock material, and its deposition as glaciogenic sediments that form in a cool or cold climate. They incorporate also glacial-marine sediments in addition to sediments deposited on land areas.

A moving ice sheet polishes and grooves rock surfaces to form glaciated pavements. Material transported by ice will be deposited on such pavements and elsewhere in the glaciated environment. Such deposits are non-layered, unsorted, and pressed tightly together. They are moraines, and their material is called till.

Tillite, again, is indurated till that was produced by an ancient glaciation. Till contains much rock flour and silt, and in tillite these materials are indurated. Till and tillite also contain, in a haphazard arrangement, small and large, angular, subangular, and rounded clasts, that is, pebbles, cobbles, boulders, and blocks. The clasts consist of both local rock material and rocks transported by the ice from remote localities. This material is crushed, or polished and grooved, by the ice sheet.

A glaciation also produces large exotic boulders transported by the ice sheet for long distances, and finely bedded and fine-grained sediments containing dropstones transported by ice floes and icebergs and dropped during the melting of the ice. Some of the clasts and dropstones are striated. Incidentally, the dropstones deposited in an aqueous environment furnish one of the best kinds of evidence of ancient glaciations, because they survive for very long periods of time.

There exists still other evidence of glaciations, such as the glacial-marine sediments deposited on the bottom of the sea. They are typical argillaceous sediments that contain gravel transported to salt-water bodies by ice, and some sand and silt.

As to terminology, the term tillite is a comprehensive genetic term incorporating both continentally deposited and ice-rafted indurated tills. The glaciogenic origin of any rock called tillite must, of course, have been proved beyond doubt. The term mixtite refers to sedimentary rocks that resemble tillites but are of uncertain or unknown origin. Other terms, including tilloid, have been used for such rocks but are unsatisfactory and unacceptable (Kröner and Rankama, 1972).

Stratigraphic Boundaries in the Precambrian

One of the basic problems in the study of the Precambrian is its chronostratigraphic and geochronologic subdivision. The Precambrian covers 85% of the total length of geological time and thus is the longest division of geological time extant. Numerous regional and continent-wide schemes of subdivision exist, but there is still no generally accepted global subdivision of the Precambrian into sections of System (Period) or higher rank. It goes without saying that a standard subdivision serving the purposes of both pure and applied geology needs to be established.

The establishment of global chronostratigraphic and geochronologic subdivisions for the Upper (Late) Precambrian, or the so-called Proterozoic, is a particularly important task. I think that much progress can be made by comparing well-preserved sequences of Late Precambrian sedimentary rocks between the Northern and Southern Hemispheres for the establishment of stratotypes. Late Precambrian sedimentary rocks that underlie Cambrian sequences without a significant stratigraphic break form a natural starting point for stratigraphic studies in the Precambrian.

My two Australian colleagues and I propose to use the beginning of the Late Precambrian glaciation in Australia as a stratigraphic boundary to define a continent-wide stratigraphic unit. Late Precambrian strata in many parts of Australia contain plenty of well-established and reliable evidence of a long and uncommonly severe ice age towards the end of Precambrian (Adelaidean) time. A large part of Australia is known to have been glaciated about 700 million years (Ma) ago or, to be more exact, about 750–650 Ma ago. The ice age consisted of at least two major glaciations and left immense deposits of glaciogenic sediments and other evidence, including glaciated and striated pavements, as a striking record of a great glaciation. The sedimentary sequence connected with the ice age extends from preglacial sediments through glacial and interglacial sediments to postglacial ones, all now present as relatively unmetamorphosed sedimentary rocks. In fact, the Late Adelaidean sedimentary sequences in the East Kimberley region in Western Australia and in South Australia contain some of the best exposed, most extensive, and least disturbed Precambrian glaciogenic rocks in the world.

The Late Precambrian Glaciation Outside Australia

Several glaciations have been reported in the Precambrian. The oldest known, the Gowganda Glaciation, recorded in southern Canada, took place about 2,300 Ma ago (Young, 1970). The most widespread Precambrian glaciation is represented by Late Precambrian glaciogenic sedimentary rocks, including tillites, with an assumed age of about 750–600 Ma. Such rocks occur in Scotland, Ireland, Scandinavia, Spitsbergen, and East Greenland in the North Atlantic area, in France and Czechoslovakia in western and central Europe, in various parts of the U.S.S.R., and in eastern Canada, the Appalachians, the Rocky Mountains and, perhaps, in western Canada in North America. Similar rocks of assumedly the same age occur in many parts of Africa, in north-eastern Asia, and probably in South America.

The world-wide Late Precambrian ice age appears to have been longer and of a more severe climate than any of the Phanerozoic glaciations. Mawson (1948) was the first scientist to reach this conclusion. The most widespread among the Late Precambrian glaciations is probably the oldest, which is characterized by a double tillite horizon in several parts of the world.

The Late Precambrian glaciation ranks as one of the outstanding and exceptional physical events in the history of the Earth. In Australia, the ice age was definitely very long, covering a time span of about 100 Ma. Therefore, it is to be expected that different ages will be obtained for Late Precambrian glaciogenic rocks in different parts of the world. It is also to be expected that the glacial periods, or the maxima of glaciation, in the Northern and Southern Hemispheres were not necessarily synchronous.

In the Northern Hemisphere, the Late Precambrian glaciation has been variously called the Infracambrian or Eocambrian Glaciation or the Varanger (Varangian) Ice Age. The last name is derived from the Varanger Peninsula in northern Norway, where the Norwegian geologist H. Reusch in 1891 discovered a tillite, called " Reusch's moraine ". However, the name, the Varanger Ice Age, is not suitable, because this glaciation has not yet been definitely dated, and the proper name to be used is the Late Precambrian glaciation.

Pringle (1973) published an age of about 670 Ma for this glaciation. He dated interglacial shales lying between the two tillite horizons. This age allows a tentative correlation with the younger glaciation of the two discovered in Australia, or the so-called Egan (Marinoan) Glaciation. Eric Welin (personal communication, 1973), who is currently carrying out an extensive radiometric dating programme to obtain ages for glaciogenic rocks in northern and central Scandinavia, reported 630 Ma as the minimum age of deposition of the Ekre Shale overlying the Moelv Tillite in southern Norway.

Glaciogenic rocks of Late Precambrian age have been described, in great detail, from the Inner Hebrides in Scotland (Spencer, 1971), but the exact age of these rocks is still unknown.

No radiometric ages are available for the Late Precambrian tillites in East Greenland. In fact, radiometric ages of Late Precambrian glaciogenic rocks are too few, and many of them are unreliable.

In the U.S.S.R., the Late Precambrian (Vendian) glaciation is placed halfway between 680 and 570 Ma ago. In China, four Late Precambrian glaciations plus an Early Cambrian glaciation are claimed to have ages in the range 950–570 Ma. Norin (1937) described from north-western China a sequence of Late Precambrian sedimentary rocks that appears to be very much similar to the glaciogenic rocks in Australia and in southern Africa.

The two Late Precambrian glaciations recognized in Australia have also been registered in southern and central Africa, but no definite radiometric ages have yet been reported. Kröner and Rankama (1972) published an account on Late Precambrian glaciogenic rocks in southern Africa, noting that the stratigraphic sequence in South West Africa, as far as the glaciogenic sedimentary rocks are considered, is astonishingly similar to the sequence in Australia. According to Alfred Köner (personal communication, 1971), the Numees Glaciation, which is the first Late Precambrian glaciation recorded in southern Africa, appears to correspond closely in age to the older Late Precambrian glaciation in Australia. The age of the Numees Glaciation is estimated as 720–700 Ma. The second glaciation, called the Nama-Damara Glaciation, is probably not very much younger than the Numees Glaciation and may have an age of about 650 Ma. Comprehensive radiometric dating of Late Precambrian glaciogenic rocks in southern Africa is now in progress (John de Villiers, personal communication, 1973). The results available at this time indicate that both glaciations in southern Africa fall within the age span of 750–650 Ma, which is the age span for the glaciations in Australia.

TABLE 1
Some Precambrian Glaciations
(Ages in Ma)

North America	Brazil	Australia	South Africa and South-West Africa	Norway
		(Overall 750–650)		
	$>$600			
				S. Norway $>$630
		Marinoan and Egan $\sim$650	Nama-Damara $\sim$650	
				N. Norway ("Varanger") $\sim$670
			Numees 720–700	
		Sturtian and Moonlight Valley 750–740		
Gowganda $\sim$2,300 ↓				

Actually, Late Precambrian glaciogenic sedimentary rocks indicating the existence of two or more glaciations occur in many parts of Africa. Most of them have not been adequately dated, and only a few tentative ages are available. However, it appears possible that the Late Precambrian glaciations in both Australia and Africa were coeval. At least, it is possible that two continent-wide glaciations took place in Africa during Late Precambrian time.

There are also indications of a Late Precambrian glaciation in Brazil. Ellert (1973) suggested that there exist three Precambrian rock sequences in various parts of Brazil that may be glaciogenic. Isotta, Rocha-Campos and Yoshida (1969) described, from the Jequitaí Formation in northern Minas Gerais, an extensive glaciated pavement in a Precambrian quartzite, directly overlain by a mixtite of probable Late Precambrian age. The basal shales of the Bambuí Group overlying the mixtite have an age of about 600 Ma (A. C. Rocha-Campos, personal communication, 1972). Other radiometric ages are not available, but an age dating programme is currently being carried out (Reinholt Ellert, personal communication, 1973).

The more satisfactorily dated Precambrian glaciations and their ages are listed in Table 1.

The Late Precambrian Glaciation in Australia

General Comments

Evidence of Late Precambrian (Adelaidean) ice ages is widespread through the central part of Australia from the Kimberley region in the north-west to the Adelaide Geosyncline in South Australia. The so-called King Island Tillite in the Bass Strait appears not to be glaciogenic, according to observations made by Jago (1973) and myself.

At several places a sedimentary sequence, with probably only minor interruptions, passes up from the uppermost glaciogenic strata into fossil-bearing Cambrian strata. The thickness of this sequence ranges from about 300 m in the Amadeus Basin to about 6,000 m in the once rapidly subsiding trough of the Adelaide Geosyncline.

The principal evidence of the glaciations is the presence of glaciogenic sedimentary rocks—mostly containing faceted, striated and polished pebbles, cobbles and boulders—and glaciated pavements, particularly in the Kimberley region.

Two separate periods of glaciation are represented. The older glaciation is called the Sturtian Glaciation in South and Central

Australia and the Moonlight Valley Glaciation in the Kimberley region. It is the more widespread of the two glaciations and is commonly represented by two tillite units. The younger glaciation is called the Marinoan Glaciation in the south and the Egan Glaciation in the Kimberley region. It has generally produced thinner and more localized tillites than has the older glaciation.

A feature that many tillite exposures have in common is the presence of a remarkably persistent pink laminated dolostone unit that crops out immediately above the tillite. The significance of the dolostone is not known, but similar rocks have been noted in the Congo-Zambia region and in southern Africa. In addition, calcitic limestone or dolostone is a common associate of Late Precambrian tillites in the Northern Hemisphere.

Radiometric age determinations have been carried out on shales within, above, and beneath the tillites in the Kimberley region, the Amadeus Basin, and the Adelaide Geosyncline. The most definitive ages were obtained from the Kimberley region. The radiometric datings indicate for the lower tillites an age of about 750 Ma and for the upper tillites an age of about 670 Ma.

The Kimberley Region

In the Kimberley region, the Late Precambrian glaciogenic rocks have been studied in detail by geologists of the Bureau of Mineral Resources. A summary of the Late Adelaidean glaciogenic successions was given by Plumb (1973).

Two distinct sequences of glaciogenic rocks that grade into marine shales and siltstones occur in the Kimberley region. They are separated by an unconformity. The tillites have a maximum thickness of about 200 m. They are noteworthy for the prevalence of striated, faceted, and polished cobbles and boulders, the remarkably fresh and unmetamorphosed state of the matrix, and the presence of underlying glaciated pavements. According to Plumb (1973), already 20 separate glaciated pavements have been discovered in the Kimberley region. Pavements are most common beneath the lower tillite but have also been noted beneath the upper tillite. Most of the pavements show that the ice sheet moved from north to south, but pavements beneath the lowermost older tillite show local variations in the direction of the movement.

The state of preservation of glaciogenic features in the Kimberley region is almost unbelievable.

Glaciogenic sedimentary rocks with faceted and striated cobbles and boulders occur also in the Ngalia Basin, the Georgina Basin, and the Amadeus Basin in Northern Territory.

The Adelaide Geosyncline

In the Adelaide Geosyncline in South Australia the Late Precambrian glaciogenic sedimentary rock-units are thicker than elsewhere in Australia.

The study of Late Precambrian glaciogenic rocks in South Australia started already in 1884, when H. P. Woodward recognized the glaciogenic origin of sedimentary rocks in the northern Flinders Ranges. In 1901 Walter Howchin obtained first evidence of the glaciogenic origin of rocks, previously considered conglomerates, in the Sturt Gorge near Adelaide. In 1912 Sir Douglas Mawson correlated the Sturtian glaciogenic rocks in South Australia with those in the Broken Hill area in New South Wales. Finally, in 1922, E. C. Andrews, the distinguished Government Geologist of New South Wales, first suggested a Precambrian age for the Sturtian Glaciation.

According to Coats (1973), the Sturtian Glaciation consisted of two phases, separated by a period of tectonic activity and erosion.

The type area of the Sturt Tillite is near Adelaide, and there the tillite is about 300 m thick. There is an excellent exposure of the tillite in the Lockler quarry near Kulpara, about 130 km north-east of Adelaide. In the Mount Painter area, in the northern Flinders Ranges, the tillite and the glaciogenic sedimentary rocks of the Sturtian Glaciation have a thickness of more than 6,000 m, according to Coats (1973). He thinks that the Sturt Tillite is probably of glacial-marine origin.

A glaciated pavement has been discovered at Merinjina Creek in the northern Flinders Ranges (Mirams, 1964), but its glaciogenic origin is doubted by some geologists.

In New South Wales a Sturtian sequence containing mixtites occurs in the Broken Hill area. It has a thickness exceeding 2,000 m (Tuckwell, 1973). The only unquestionable glaciogenic sedimentary rock occurs in the Mount Woowoolahra area, about 100 km north of Broken Hill. At this locality a tillite contains hundreds, perhaps thousands, of striated clasts of various sizes (Cooper, 1973). This is a unique locality and, in my opinion, should be preserved as a geological site.

The Sturtian Glaciation abraded a large belt of crystalline basement, called the Willyama Land, along the eastern flank of the Adelaide

Geosyncline. The area was probably ice-capped and assumedly extended northwards about 1,400 km, from Adelaide to the Georgina Basin.

In the Adelaide Geosyncline, the Sturtian Glaciation was followed by the deposition of a dolostone-siltstone sequence about 3,000–5,000 m thick. This interglacial sequence is very widespread and persistent in Australia and apparently marks an abrupt change in climate at the close of the Sturtian Glaciation. According to the results of Glaessner, Preiss and Walter (1969), stromatolites in the interglacial sequence may be correlated with Russian genera and species that occur in the 950–570 Ma age range.

The effects of the Marinoan Glaciation in southern Australia, and in central and northern Australia, are less intense and widespread than those of the Sturtian Glaciation. The Marinoan glaciogenic sedimentary sequence in South Australia is confined to the eastern part of the Adelaide Geosyncline and has a maximum thickness of 1,500 m. The maximum observed thickness of the Marinoan Tillite is about 200 m. The tillite contains faceted and striated clasts.

The Marinoan postglacial sequence is remarkably consistent in facies in its lower part throughout Australia. In the Adelaide Geosyncline, the sequence consists of dolostone, shale, siltstone and sandstone. The maximum thickness of the sequence in the northern Flinders Ranges is about 6,500 m, and a comparable thickness of the possible equivalent is known in New South Wales. In the northern Flinders Ranges the Pound Quartzite, the uppermost unit of the sequence, is the host of the remarkable Ediacara fauna that comprises megafossils of a variety of soft-bodied Precambrian marine animals. They are of considerable biostratigraphic value.

It is possible that sedimentation was continuous from the Adelaidean into the Cambrian in the central part of the Adelaide Geosyncline.

The Sturtian and Marinoan glaciogenic and interglacial sedimentary rocks extend over the Adelaide Geosyncline and north-westwards into Western Australia. In the Officer Basin in Western Australia and in South Australia, two tillite localities have been discovered.

The Sturtian (Moonlight Valley) Glaciation as a Stratigraphic Boundary

Harland (1964, 1965) proposed the creation of a new " System " in the Precambrian, starting with the onset of the great " Infracambrian " Glaciation and concluding before the introduction of recognized Cambrian faunas. He proposed the name Infracambrian System or Varangian System for this unit. He also thought that glaciogenic sedimentary rocks might be the best basis for the establishment of Precambrian " Systems " that would be internationally recognized.

My two Australian colleagues and I have elaborated on Harland's suggestion and propose to use the body of rocks accumulated between the deposition of the oldest Sturtian (Moonlight Valley) glaciogenic sediments and the deposition of the basal unit of the Cambrian to define a chronostratigraphic unit in Australia. It is well to remember, however, that the basal unit of the Cambrian still remains to be established. In other words, the boundary between the Precambrian and the Cambrian still remains to be defined. My colleagues and I propose to mark the base of the suggested unit by a reference point that we call the Sturt Marker (Marker Horizon) and have provisionally placed in the type section in the Mount Painter region in the northern Flinders Ranges, on the eastern flank of the Adelaide Geosyncline. The sequence in the Mount Painter region is the thickest known glaciogenic sequence in Australia and is believed to incorporate the earliest sedimentary record of the Sturtian Glaciation.

As to giving a formal name to the proposed chronostratigraphic unit, at this stage we prefer only to define its lower boundary by the Sturt Marker reference point. In other words, we define a boundary stratotype.

The corresponding continent-wide geochronologic unit represents the time between the onset of the Sturtian (Moonlight Valley) Glaciation and the beginning of the Cambrian Period (end of the Precambrian). We propose to refer to it provisionally in Australia as the Late Adelaidean.

The geochronologic unit proposed by us has a time span of about 180 Ma, or somewhat longer than the duration of the Mesozoic Era.

Tentatively, we place the beginning of the Sturtian (Moonlight Valley) Glaciation at about 750 Ma ago, based on the probable age of the early phase of the Moonlight Valley Glaciation. Tentatively, we also place the beginning of the Cambrian Period, and the end of Precambrian time, at 570 Ma ago, pending a more accurate age for the Precambrian-Cambrian boundary. According to Martin Glaessner (personal communication, 1973), 570 Ma is still the most acceptable age of the boundary.

The age relationships of the Late Precambrian glaciations in Australia are presented in Table 2.

TABLE 2

Age Relationships of the Late Precambrian Glaciations in Australia

				Age (Ma)
CAMBRIAN				
				570
Adelaidean	Proposed unit ("Late Adelaidean")	Subunit 1	Egan Glaciation and Marinoan Glaciation	650
				700
		Subunit 2	Moonlight Valley Glaciation and Sturtian Glaciation	740 (Late phase)
				750 (Early phase)
				750 (Sturt Marker Horizon)

My Australian colleagues and I propose to place the Sturt Marker in South Australia largely because of the completeness of the sedimentary record there and because there may be no significant stratigraphic break between the start of the Sturtian Glaciation and the Cambrian in some parts of that State. Even though more accurate age data are available from the Kimberley region, several unconformities exist there between the glaciogenic sedimentary rocks and the Cambrian strata. When more radiometric ages for the sedimentary rocks underlying and overlying the tillite units become available, the beginning of the glaciation can be dated more accurately.

Incidentally, some geologists may wonder why we have placed a stratigraphic boundary at the beginning of a glaciation. In fact, there is nothing remarkable in doing so. It has been done previously, when the boundary between the Pliocene and the Pleistocene—or between the Tertiary and the Quaternary—was once placed at the abrupt and severe onset of the first Pleistocene glaciation. Global glaciations no doubt are major geological events and mark the beginning of episodes of cold-facies sedimentation. Therefore, they are " natural boundaries " or " natural breaks " indicating important geological events and are inextricably tied to the rock record.

My Australian colleagues and I think that dating a glaciation produces more definite and accurate information about the age of a geological event than can be obtained by dating an orogeny that has a hazy beginning and a vague end. We hope that, when the age of the lower boundary of the unit has been established more accurately by radiometric dating and when the problem of the age of the Precambrian-Cambrian boundary has been solved, the corresponding geochronologic unit will be found favourable for world-wide correlation and will be accepted as a global unit. Then it can be used as a global standard of reference, whether or not exactly similar rock sequences exist elsewhere.

The coevality of the Late Precambrian glaciation in the Northern and the Southern Hemispheres has been doubted by some geologists (Crawford and Daily, 1971 ; Cloud, 1972). Cloud, as a matter of fact, thought that global freezing is impossible. He suggested that the Late Precambrian glaciation reflects an episode of relatively rapid drift of the continents over the polar regions, or a clustering of continental crust around a pole, or around both poles. However, because of the long duration of the glaciation, it is not necessary that the glacial ages, or the maxima of glaciation, were synchronous in the Northern and Southern Hemispheres. Other students of this glaciation, including Harland (1964) and Crowell and Frakes (1970), have previously reached the same conclusion.

Future Research

From all available evidence one may conclude that the Southern Hemisphere was extensively glaciated during Late Precambrian time. The next stage in the study of this glaciation will be the extension of correlations to cover Australia, much of Africa, and parts of South America, when the necessary age data have been obtained. Attempts are now being made to correlate the Late Precambrian glaciogenic rocks in the Northern Hemisphere with those in the Southern Hemisphere on the basis of detailed geochronologic, sedimentologic and tectonic data. So far this work has been carried out under the auspices of the International Geological Correlation Programme, as a part of the activities of the Subcommission on Precambrian Stratigraphy.

The Subcommission met in Adelaide in May, 1973, and a part of its programme consisted of field trips to study the Adelaidean glaciogenic sequences. After the meeting, a symposium dealing with the Late Precambrian glaciation, with particular reference to the Southern Hemisphere, was held in Adelaide. The Subcommission discussed the use of the Late Precambrian glaciation as a stratigraphic boundary and recommended the determination of the location of palaeopoles at the time of deposition of the glaciogenic sediments. While the Subcommission felt that many more radiometric ages pertaining to the glaciation are necessary, it was hopeful that the Late Precambrian glaciogenic sequences can be used to establish chronostratigraphic units.

There are several other possibilities of correlation, among which I shall mention only the correlation based on stromatolites, calcareous algal sediment growths attributed to blue-green and green algae. I feel that, in general, not only correlations between the Northern and the Southern Hemispheres are important, but also correlations within the Southern Hemisphere and within the Northern Hemisphere. There is currently much interest in carrying out correlations in several parts of the world.

* * * *

It has been a great privilege and pleasure for me to deliver tonight the Clarke Memorial Lecture for 1973. The Reverend Clarke concluded his Inaugural Address to the first meeting of the Society under its Royal title on 9th July, 1867, by saying, among other things : " We have in this Colony a vast region, much of which is still untrodden ground. We have, as it were, . . . a new earth for geology."

His statement has not lost any of its validity. Australia, even today, is a new Earth for geology. Clarke's accomplishments will certainly inspire future generations of Australian geologists. I, for one, am fascinated by the possibilities offered by Australia for Precambrian research. I have tried to call the attention of overseas Precambrian geologists and stratigraphers to the unique Late Precambrian sedimentary rocks in Australia, hoping to promote their comparison and correlation with corresponding sequences in other parts of the world. An increasing number of geologists all over the globe realize the great importance of the Precambrian in all fields of geological research.

I should like to conclude my lecture by quoting the slogan of the Subcommission on Precambrian Stratigraphy, an age-old Finnish proverb : " Nothing is so plentiful as Time ".

Postscript

My research dealing with Precambrian stratigraphy in Australia, started in 1965 and now completed, would not have been possible without the goodwill, help and hospitality of many Australian individuals, universities, Government organizations and mining companies, too numerous to be listed here. With particular reference to my studies of the Late Precambrian glaciation, I wish to extend my thanks to the Australian Academy of Science, the Bureau of Mineral Resources in Canberra, and the Geological Surveys of New South Wales and of South Australia. No other names are mentioned, but nobody is forgotten.

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General Note.—Some of the principal results reviewed in this lecture have been published and discussed in detail in the papers by Dunn, Thomson and Rankama (1971) and by Kröner and Rankama (1972) listed below. These papers, and the paper by Crawford and Daily (1971) also contain comprehensive bibliographies to which the reader is referred. Abstracts of papers presented at a meeting and Symposium of the Subcommission on Precambrian Stratigraphy in Adelaide in 1973 are marked thus : (Adelaide abstract).

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Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 98–103, 1973

Structural Analysis of the Palaeozoic Sediments in the Woolgoolga District, North Coast, New South Wales

R. J. Korsch

Abstract—Mesoscopic folds in the Coffs Harbour Beds are upright equant planar cylindrical folds with straight hinges. Folds are open in the north and adpressed to isoclinal in the south. Plunges change from subhorizontal in the north to steep in the south. These progressive changes can be explained by the simple theory of a southward increase in the dip of bedding relative to a stress field (and cleavage) of constant orientation. The theory is applicable if the strikes of bedding and cleavage are slightly different.

A reticulate cleavage, parallel to the axial planes of the folds, is present and one intersection with the bedding is homogeneous with the fold axis.

The beds have been affected by three phases of deformation. The first was a soft-sediment slumping and the other two were tectonic in origin, both being related in time to the Hunter-Bowen Orogeny. The second deformation produced mesoscopic folds and the axial-plane reticulate cleavage whereas the third deformation formed small scale monoclines in the bedding and cleavage.

The Redbank River Beds have suffered two tectonic deformations but these cannot be related to the deformations in the Coffs Harbour Beds. The first deformation produced tight folds, often isoclinal in style, and the second formed gentle warps on the limbs of the tight folds.

Introduction

The aim of this paper is to present a description of the mesoscopic structures of the Woolgoolga district and a macroscopic structural analysis. Sedimentological aspects of this area have been described previously (Korsch, 1971). Data for five mesoscopic structural elements are presented, these being bedding (*So*), fracture cleavage (S_1), axes of minor folds ($B^{S_1}_{S_0}$), bedding-cleavage lineation ($L_{(S_0 \times S_1)}$) and jointing (including quartz veins). The descriptive symbols follow Turner and Weiss (1963). The attitudes of the structures are shown on π-diagrams on an equatorial net of the Lambert projection density-contoured by the squared-grid method (Stauffer, 1966).

Coffs Harbour Beds

Mesoscopic Structures

Bedding and Lithological Layering (*So*). Bedding varies from a strike of 090° with a moderate dip in the north, to a strike of about 135° with a steep dip, to the north, in the southern part of the area. In almost every case the facing direction is upwards.

Fracture Cleavage ; *Variety* : *Reticulate Cleavage* (S_1). Cleavage occurs mainly in mudstones and siltstones and is commonly spaced at intervals of 3 mm. to 12 mm. ; it is quasi-planar and anastomoses and bifurcates. It is parallel to the axial-planes of the mesoscopic folds. There is no visible neocrystallization or orientation of mineral fabric parallel to the cleavage surface, and none has been recognized in microscopic studies.

Crook (1964) describes reticulate cleavage in mudstones near Tamworth. However, in the Woolgoolga district the cleavage is non-penetrative on the scale of the outcrop.

The fracture cleavage with an average orientation of 089°/N/82° (Figure 1*a*), the fold axes with a girdle of average attitude 096°/N/87° (Figure 1*b*) and the bedding-cleavage lineation with a girdle of average orientation of 100°/vertical (Figure 1*c*) are almost identical, which indicates that the fold axes always lie within the plane of the cleavage which therefore must be an axial-plane cleavage.

Mesoscopic Folds. The sandstone beds have a relatively constant orthogonal thickness and hence have an approximate concentric geometry (Ramsay, 1962). The intervening shales form less regular structures and these incompetent beds appear to have flowed between the more competent sandstone layers.

In describing the component parts of the folds, the terminology of Fleuty (1964) has been followed. The hinge is straight in most cases. The axial plane is parallel to the fracture cleavage and is quasi-planar in form. Most of the folds are equant with amplitudes of 15 cm. to 90 cm. and wavelengths of 30 cm. to 5 metres. A distinct and progressive tightening of the folds occurs with the inter-limb angles varying from those of open folds in the north to those of tight folds in the south (Figure 2*a*). This suggests that there was an increase, towards the south, in the intensity of the deformation which produced the folds. The anticlines and synclines are also cylindrical because *So*, when plotted as π-poles defines a great-circle girdle. There is a gradual increase in the plunge of the fold axes (Figure 2*b*), from sub-horizontal in the north at Arrawarra to steep in the south at Korora Basin. This change may be correlated with a decrease in the inter-limb angle. A small inter-limb angle occurs with a steeply plunging fold axis (Figure 2*c*).

Bedding-cleavage Lineation $L_{(So \times S_1)}$. This lineation is found only in the mudstones and siltstones, and its attitude was determined by plotting accurate measurements of bedding and fracture cleavage from the same small area on a stereographic projection and finding their intersection point.

Joints. There has been no differentiation between various types of joints in Figure 1*d*. The maximum defines a plane of attitude 005°/E/78°, which is perpendicular to the axis of the mesoscopic folds in the northern portion of the area where the fold axes are subhorizontal and hence in that area they are ac-joints. These joints are best developed in the coarser-grained sediments and frequently do not penetrate the finer-grained beds. It is concluded that the mesoscopic tectonic folds and the ac-joints have a consistent geometrical pattern and are possibly related to a common stress system.

A synoptic diagram of π-plots of quartz veins (Figure 1*e*) and rose diagram (Figure 1*h*) exhibits a point maximum thus defining a plane of attitude 002°/vertical. The veins have the same orientation as the ac-joints which provided spaces for easy access and deposition of quartz.

Macroscopic Analysis

Composite diagrams for the whole area have been compiled. The synoptic πSo diagram (Figure 1*f*) has a point maximum which defines an average attitude for the bedding in the whole area of 093°/N/79°.

There is a swing in the strike of the cleavage from 085° in the north to nearly 140° in the south of the area. The trend of the fold axes varies from about 080° in the north to about 135° in the south.

Structural Evolution of the Woolgoolga District

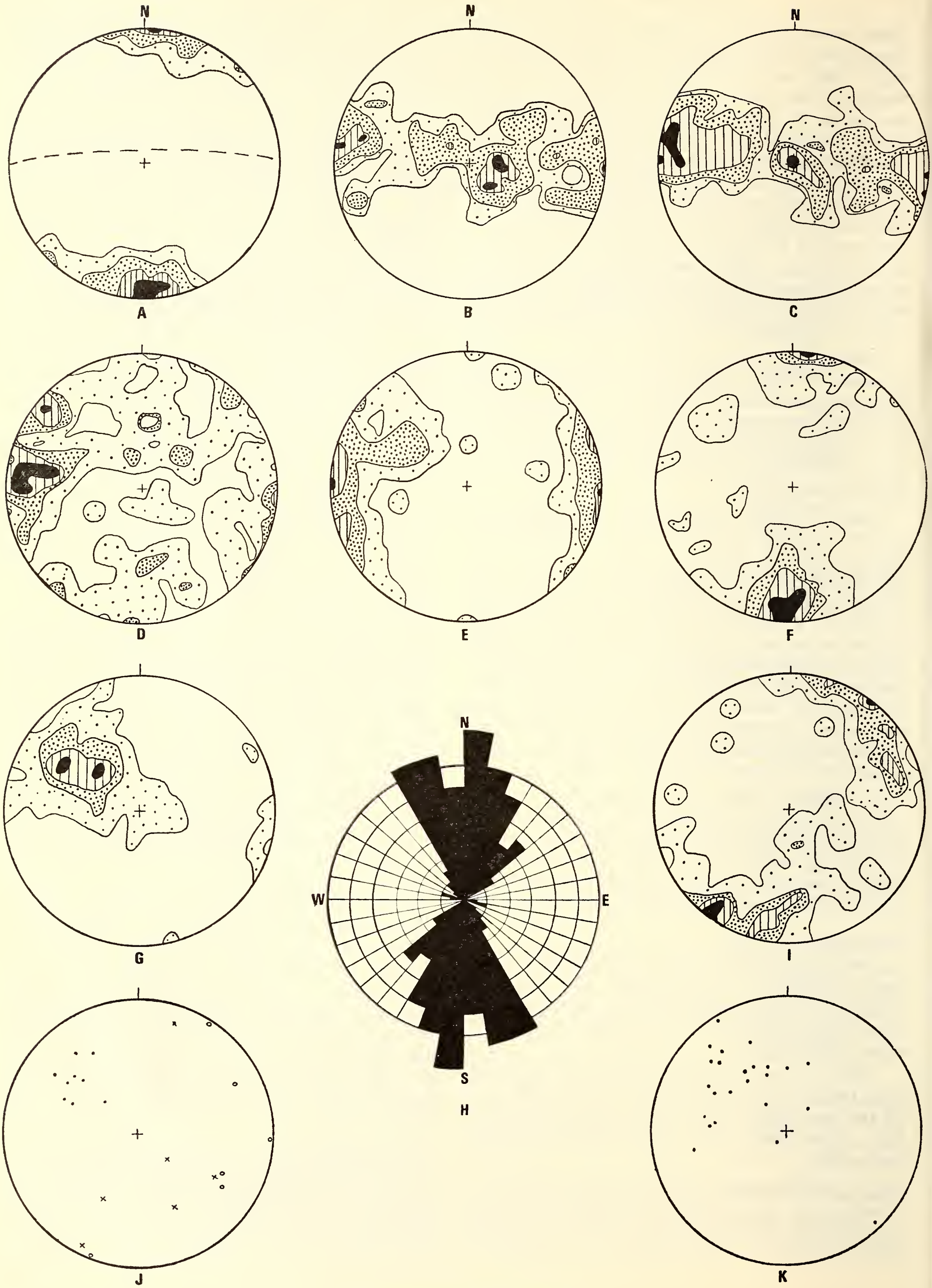
The major problem of the Woolgoolga district is to account for the variation in the plunge of the fold axes from north to south. Why does this change in plunge occur? The fold axes plot on a girdle (Figure 1*b*) and this could be explained by the following hypothesis:

If one assumes that bedding was once horizontal, then, as the intensity of folding increases the dip of the bedding must become steeper until the bedding is vertical and isoclinal folds occur. This can be represented by the theoretical graph (Figure 2*d*), where a constant vertical axial-plane cleavage is intersected by a bed of constant strike at an angle of 5° to the cleavage. If the dip of this bed progressively alters from 0° to 90° then the plunge of the fold axis also varies from 0° to 90°. This is part of a general theory which has been developed and will be published elsewhere. The real situation in the Woolgoolga district (Figure 2*b*) traces a similar curve to the theoretical curve and hence the variation in the plunge of the fold axes can be accounted for by this hypothesis. Hence there has been a change in the attitude of the marker horizon (bedding) relative to a stress field of constant orientation. This hypothesis is supported by the joint pattern which probably resulted from uniform stress system operating during and after folding.

A second period of tectonic deformation has also occurred. This is seen in gentle flexuring of the fracture cleavage and in the formation of small monoclines which show a consistent vergence (Wood, 1963) indicating a dextral sense of rotation throughout the area. Another feature of this deformation is the rotation in the vertical plane, of an originally parallel cleavage from a strike of 085° in the north to about 140° in the south. If the monoclines are mesoscopic folds on the limbs of a macroscopic fold then only one limb of the large fold occurs in the Woolgoolga district.

In the Woolgoolga district the first tectonic deformation was produced by a north-south compression and there was no substantial regional metamorphism associated with it at visible tectonic levels in the area. There could be a major fault near Red Rock headland if the jaspers there are an autochthonous part of the basement beneath the Coffs Harbour Beds, but the fault need not be postulated if the Red Rock sequence is a huge exotic block emplaced by gravity sliding.

The evidence seems to indicate that the Woolgoolga district is part of one limb of a synclinorium which has its hinge or trough line striking east-west somewhere to the north of the area.



See next page for Legend.

Regional Implications. The Coffs Harbour Beds occur in one of the upthrust blocks mapped by Voisey (1959) and are bounded to the north by the Mesozoic Clarence Basin, and in the south by the Cross Maglen Fault (Leitch *et al.*, 1969). Voisey (1959) inferred that a fault bounds the west of the beds, but in fact they may be part of the Upper Palaeozoic sequence that has been studied at Wongwibinda by Binns (1966) and elsewhere in New England by Binns and others (1967).

Age of the Tectonism. The preferred hypothesis is that the Coffs Harbour Beds are late Palaeozoic in age, rather than older Palaeozoic (Korsch, 1971). The Clarence Basin contains fresh-water sediments deposited during and after the Triassic Period, and they are only gently deformed and rest unconformably on the underlying Coffs Harbour Beds. Hence the tectonism probably occurred during the Permian or Early Triassic periods.

During late Palaeozoic time the following events occurred in the Woolgoolga district :

(1) Deposition of a thick sequence of sediments under unstable geosynclinal conditions by turbidity current media. Soft sediment deformation such as slumping occurred frequently.

(2) A period of tectonism that :

- (*a*) tilted the sequence northwards ; produced open to tight mesoscopic folds, possibly of slump or sliding origin, with an axial-plane fracture cleavage ; and increased in intensity towards the south ;
- (*b*) produced monoclinal flexuring of both the bedding and cleavage, and rotated the cleavage ;
- (*c*) produced both oblique and ac-joints and deposited quartz preferentially along some ac-joints ; and
- (*d*) aided the emplacement of the leuco-adamellite stock at " Granite Head ".

Conclusion. The Coffs Harbour Beds of the Woolgoolga district have been deformed by three periods or phases of deformation, at least two being tectonic in origin. The two tectonic phases occurred during one major period of tectonism in late Palaeozoic time and can be regarded as part of the Hunter-Bowen orogeny.

Redbank River Beds

The headland of Red Rock is considered to be a rock unit distinct from the Coffs Harbour Beds (Korsch, 1971), and hence a separate structural analysis of it was attempted. It appeared at first that the jaspers and associated rocks are chaotically deformed. Consequently the area was divided into five domains separated by supposed shear zones, and the attitudes of bedding, fold axes and axial planes were measured in each domain. It was surprising to find that the domains are not chaotic but homogeneous with respect to bedding and fold axes, so that the whole headland could be studied as one field.

Two distinct styles of folding are seen, one being very tight and often isoclinal, the other being a gentle warping of the limbs of the isoclinal folds.

Tight Folds

These folds very from folds with parallel limbs (true isoclinal folds), through folds with angular hinges to folds with rounded hinges. The rounded hinges occur in the thicker beds which were less able to bend on angular hinges. The π-plot of bedding (Figure 1*g*) consists mainly of beds forming the limbs of the tight folds. Two distinct maxima occur at 34° to 290° and 55° to 302°, these possibly being the orientations of each limb. The axial planes of several tight folds have an orignetation of

FIGURE 1.

(*a*) Composite cleavage for the Coffs Harbour Beds. $175\pi S1$. Contours 0, 1, 6, 17% per 1% area.
(*b*) 83 fold axes from the Coffs Harbour Beds. Contours 0, 1, 2, 6% per 1% area.
(*c*) 140 bedding-cleavage intersections from the Coffs Harbour Beds. Contours 0, 1, 2, 6% per 1% area.
(*d*) 129 poles to joints from the Coffs Harbour Beds. Contours 0, 1, 3, 5% per 1% area.
(*e*) 104 poles to quartz veins from the Coffs Harbour Beds. Contours 0, 1, 4, 9% per 1% area.
(*f*) $556\pi So$ from the Coffs Harbour Beds. Contours 1, 2, 4, 6% per 1% area.
(*g*) 297 poles to bedding from the Redbank River Beds. Contours 0, 1, 3, 6% per 1% area.
(*h*) Rose diagram for strikes of 105 quartz veins from the Coffs Harbour Beds. Interval for bearings 10°, two veins per circle.
(*i*) 92 fold axes for the tight folds in the Redbank River Beds. Contours 0, 1, 4, 6% per 1% area.
(*j*) Axial planes and fold axes for the gentle warps and axial planes for the tight folds from the Redbank River Beds.
● Nine axial planes for the tight folds.
○ Six axial planes for the gentle warps.
+ Six fold axes for the gentle warps.
(*k*) 24 poles to bedding from the limbs of gentle warps in the Redbank River Beds.

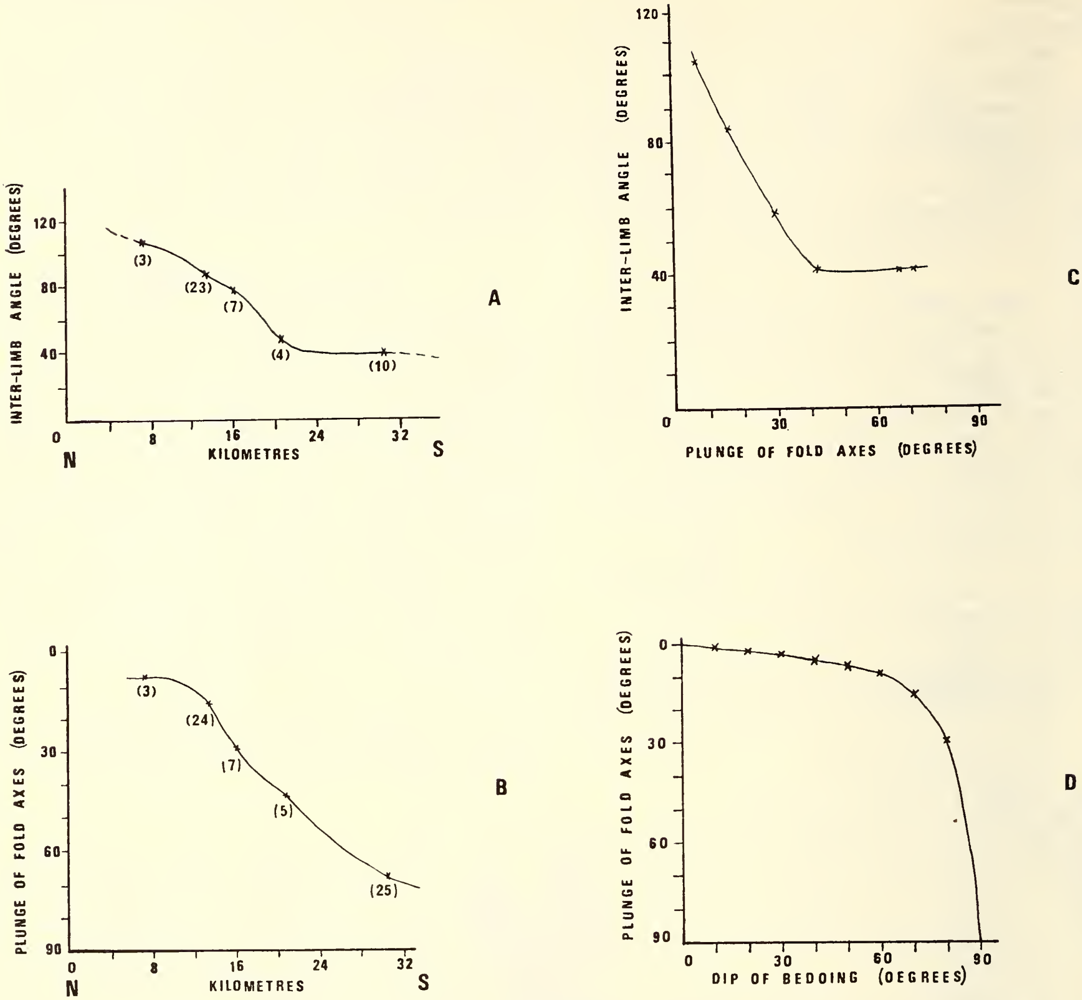


FIGURE 2.

(*a*) Variation from north to south in inter-limb angles of folds from the Coffs Harbour Beds. Values in parentheses indicate the number of measurements averaged to produce the mean value.

(*b*) Variation from north to south in the plunge of fold axes of mesoscopic folds in the Coffs Harbour Beds. Values in parentheses are number of individual measurements.

(*c*) Graph of inter-limb angles versus plunge of fold axes for the mesoscopic folds in the Coffs Harbour Beds.

(*d*) Graph showing the variation in plunge of a fold axis from 0° to 90° in a theoretical situation where (i) the axial plane cleavage maintains a constant strike and constant vertical dip, and (ii) the bedding maintains a constant strike at an angle of 5° to the cleavage and the dip varies from 0° to 90°.

024°/E/45°. Fold axes define a girdle (Figure 1*i*) which is very similar to the orientation of the bedding. Fold axes for both types of folds (Figure 1*j*) define a similar girdle with an orientation of about 032°/SE/50°.

Gentle Warps

The gentle warps occur on the limbs of the tight folds. The π-plot for bedding for areas influenced by the gentle flexuring (Figure 1*k*) exhibits a pattern similar to that of the bedding for the tight folds, which proves that the warps are very gentle and cause no marked change in the orientations of bedding. The axial planes however appear to be scattered about a girdle with an approximate orientation of 026°/E/33° (Figure 1*j*). The fold areas for the warps appear to be scattered over a similar girdle to that for the fold axes of the tight folds.

Discussion

Because the axial planes of the tight folds are non-planar and have been bent by the gentle flexuring, it is clear that the tight folds were the first to form. Moreover, the axial planes of the gentle folds appear to be straight and hence have not been deformed by later tectonic activity.

The axial planes of the tight folds have, by comparison with the axial planes of the gentle warps, a fairly uniform orientation and this suggests, falsely, that the tight folding was later than the gentle folding. Because of the very gentle nature of the second deformation only slight changes in the orientation of the axial planes of the tight folds resulted and hence the axial planes are uniform (Figure 1*j*). The variable orientations of the axial planes for the gentle flexures remains unexplained. The variation could be a result of the highly incompetent nature of cherts and their ability to become highly contorted (Bryan and Jones, 1962).

The axial planes of the tight folds with an average orientation of 025°/E/45° can in no way be related to the axial planes of the folds in the Coffs Harbour Beds which have an orientation parallel to the fracture cleavage of 089°/N/82°. The axial planes of the gentle warps also cannot be related to the folding in the Coffs Harbour Beds. Hence it is thought that the cherts and jaspers of the Red Rock Beds were subjected to a period of tectonism that occurred some time before the deposition of the Coffs Harbour Beds.

Conclusion

The cherts and jaspers have been subjected to two phases or periods of folding:

(1) An intense period of deformation of tectonic origin that produced tight folds often verging on isoclinal in places, with an average orientation of their axial planes as 025°/E/45°.

(2) The second less intense period of tectonic deformation produced gentle flexures on the limbs of the tight folds.

It is highly probable that both sets of folds were related as phases of one major period of deformation but because of the highly folded nature of the rocks and lack of correlation with the Coffs Harbour Beds it is thought that this tectonism occurred before the Coffs Harbour Beds were formed.

Acknowledgements

The author is indebted to Dr. H. J. Harrington for his supervision of the project and to Dr. E. C. Leitch for many helpful discussions. The work for this paper was undertaken for an Honours thesis during the tenure of a N.S.W. Department of Education Teachers College Scholarship at the University of New England.

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(Received 30.3.72)

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Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 104–110, 1973

Potassium-Argon Basalt Ages and their Significance in the Macquarie Valley, New South Wales

J. A. Dulhunty

Abstract—Potassium-Argon ages and modes of occurrence are recorded for Tertiary basalt flows in and near the Macquarie Valley region, and considered in relation to Tertiary volcanism geomorphology. Two age groups of Tertiary basalts occur. An older, mainly Eocene group, of the order of 40 to 55 m.y. was extruded in eastern areas of the region and now rests on remnants of an early or pre-Eocene surface along and near the Main Divide. A younger, or middle Meocene group, of the order of 11 to 15 m.y., was extruded across the region before tilting of the Western Slopes and subsequent removal of basalt from eastern areas, entrenchment of the Macquarie River to 60 m below the base of the basalt at Bathurst, and burying of basalt beneath river alluvium in western areas near Dubbo. Results for the Macquarie region correspond with similar results previously recorded for regions to the north along the Western Slopes.

Introduction

The purpose of this paper is to record K-Ar ages obtained for basalts in and near the region of the Macquarie Valley (see Figure 1), upstream from the vicinity of Dubbo to Bathurst and across the headwaters of the Abercrombie, Macquarie and Turon Rivers (excluding the Orange-Canowindra and Lachlan River districts), and to consider the significance of results in relation to Tertiary volcanism and geomorphology. The paper is not a complete study of either Tertiary volcanism or geomorphology of the region, but rather a record of some results and deductions, as a contribution to these subjects.

Recent studies of the age (see Table 2) and mode of occurrence of Tertiary basalt in the upper Castlereagh Valley near Coonabarabran (Dulhunty, 1973 ; Dulhunty and McDougall, 1966) have shown that middle Miocene flows of the order of 13 to 14 m.y. old and coextensive with Warrumbungle Mt. flows, occur on valley sides and extend down to within 40 m of the level of the Castlereagh River bed. Further down the valley, between Binnaway and Mendooran, it was shown that similar flows, of the order of 14 to 17 m.y. old, extend down the valley sides to levels of about 6 m below the river bed. These results were interpreted as indicative of a pre-middle Miocene " Castlereagh Valley ", once filled with middle Miocene basalt, but now almost completely re-excavated by the Castlereagh River, as a consequence of late Tertiary elevation to form the present Castlereagh Valley representing a restoration of its Miocene ancestor. No Tertiary basalts older than Miocene were recorded in the Coonabarabran-Binnaway-Mendooran region.

Studies of K-Ar ages (see Table 2) and distribution of basalts in the Gulgong-Mudgee-Ilford region (Dulhunty, 1971), have shown two age groups of flows representing separate epochs of extrusion. The older flows of lower Oligocene-upper Eocene age, of the order of 31–45 m.y., occur on the eastern side of the region as small residuals on high isolated remnants of an early or pre-Eocene surface, along the strongly elevated country of the Main Dividing Range between Rylstone and Ilford. The younger flows of middle Miocene age, of the order of 12–16 m.y., occur along the western side of the region, on the Western Slopes of the Eastern Highlands, near Gulgong in the valleys of the Cudgegong River and its tributaries, extending in places to 15 m below the present river bed. They partly filled the pre-Miocene valleys, but have now been largely removed by erosion to form the present valleys.

The present study of ages and modes of occurrence of basalt flows in the Macquarie Valley region, was undertaken to extend further south along the Western Slopes, the kind of results referred to above in the Castlereagh and Cudgegong Valleys.

For the purpose of this paper, the regions of the Macquarie, Cudgegong and Castlereagh Valleys, within the geographic limits indicated above for each, will be referred to as the Macquarie region, Cudgegong region and Castlereagh region. The term Western Slopes is used, with traditional meaning, in referring to the country sloping to the west from the Main Dividing Range down to the Western Plains.

All geological periods and epochs referred to in this paper, as equivalent to K-Ar dates in millions of years, are in accordance with the time scale by Funnell (1964), which was also used in the papers dealing with the Castlereagh and Cudgegong regions.

For detail outcrop geology of the Macquarie region and adjoining areas, reference should be made to 1:250,000 Geological Series Sheets (Geol. Surv., Dept. Mines, N.S.W., Sydney)—Bathurst SI 55–8, Dubbo SI 55–4 and Goulburn SI 55–12.

For previously recorded information bearing on the general setting of the Macquarie Valley region in relation to Tertiary volcanism and geomorphology of the Eastern Highlands of New South Wales, reference should be made, in the first place, to Vallance (1969), Wilkinson (1969) and Browne (1969).

These flows together with the plateau on which they rest, are being actively dissected on either side of the Main Divide by the headwaters of both eastern and western flowing streams.

No. 2: Some 25–50 km west of the Main Divide, small outliers of basalt capped erosional residuals of country rock on elevated country between the headwaters of western flowing streams, as at Big Brother Hill (Figure 2, Sec. 2, K–M) and Monkey Hill (Figure 1).

No. 3: In central areas of the region, basalt flows occur on broad valley floors and across lower country within the Macquarie watershed. Such flows, as at Mt. Panorama and Dunkheld near Bathurst (Figure 2, Sec. 2, K–O) and along the Macquarie Valley between the junction of the Turon River and Burrondong Dam, occur at levels down to 60 m above present river levels.

No. 4: In western areas, basalt flows extend across undulating country, down over gently sloping valley sides to levels below the present river bed. Such flows occur between Tongi, Wongarbon, Dubbo and Mogriguy, across the valleys of the Macquarie and Talbragar Rivers (Figure 2, Sec. 1, A–E).

TABLE 1

K-Ar Ages of Macquarie and Cudgegong Region Basalts

	Syd. Uni. Spec. No.	Geochron. Anal. No.	Locality	Average % K±2SD	Rad. 40-Ar (10^{-6} Std. cc/gm)	% Rad. 40-Ar	Calc. Age m.y.±1SD
MACQUARIE REGION	K–17	R–1929	Taralga-Richlands	1·097±0·001	1·934	34·66	43·5±2·1
	K–25	R–2227	Big Brother Hill	0·960±0·009	1·962	19·40	51·0±2·5
	K–16	R–1868	Bathurst-Dunkheld	1·886±0·019	0·936	42·65	12·4±0·9
	K–15	R–1795	Dubbo-Talbragar	2·564±0·011	1·412	29·90	13·9±0·9
CUDGEGONG REGION	K–8	R–1216	Fords Creek Gulgong	1·211±0·011	0·717	55·60	14·8±1·2
	K–9	R–1341	Two Mile Crk. Gulgong	1·530±0·040	0·852	45·40	13·8±1·1
	K–10	R–1267	Mt. Bocoble Cudgegong	1·361±0·020	1·949	69·90	35·6±2·1
	K–12	R–1676	Mt. Vernon Ilford	1·329±0·017	1·810	60·46	33·7±2·1
	K–13	R–1745	Mt. Carcalgong Pyramul	1·040±0·002	1·750	61·60	41·6±2·6

Constants used: $\lambda_\beta = 4{\cdot}72 \times 10^{-10}$/year; $\lambda_e = 0{\cdot}585 \times 10^{-10}$/year; $K^{40}/K = 1{\cdot}22 \times 10^{-4}$ g./g.

Occurrence of Tertiary Basalt Flows

In the Macquarie region (Figure 1) basalt occurs in four different topographical settings.

No. 1: In eastern areas, residual sheets of basalt rest on remnants of the high undissected plateau surface along the Main Dividing Range, across the headwaters of the Abercrombie, Macquarie and Turon Rivers, from Taralga to Oberon and Capertee (Figure 2, Sec. 2, F–K).

Selection of Basalts for K-Ar Dating, and Results

Basalt specimens suitable for K-Ar dating were collected from flows typical in mode of occurrence for each of the four topographical settings described above. Localities at which specimens were collected are shown by specimen numbers on the map in Figure 1, and in sections of Figure 2. Localities are also given by grid references on the 1 : 250,000 topographical sheets, series R502 for New South Wales, in the following specimen descriptions, together with the results of K-Ar age determinations on " whole rock " samples, carried out by Geochron Laboratories, Cambridge, U.S.A., as also set out in Table 1. All material selected for K-Ar dating was fresh in regard to atmospheric weathering and free from macroscopic evidence of deuteric alteration or amygdaloidal texture. Microscopic evidence of feldspar alteration and degree of crystallinity is noted in the following specimen descriptions.

Specimen K–17. Taralga-Richlands (*SI 55–12, 280759*). *Age 43·5±2·1 m.y.*

Collected from outcrop on eastern side of Taralga-Oberon road, 9·7 km from Taralga. Flow typical of topographical setting No. 1, forming a residual sheet on remnant of undissected plateau near the Main Dividing Range. Fine-grained holocrystalline olivine basalt with numerous small phenocrysts of olivine, minor alteration of feldspars and less than 10% of well crystallized interstitial material.

Specimen K–25. Big Brother Hill (*SI 55–8, 237842*). *Age 51±2·5 m.y.*

Collected from old quarry floor, 9 m above base of flow, on the northern side of the hill, 1·3 km west of the Georges Plains-Trunky Creek road, at 21 km by road from Georges Plains. Flow typical of topographical setting No. 2, forming a high outlier of basalt resting on an erosional remnant of country rock rising some 120 m above surrounding country. Medium-grained holocrystalline olivine basalt with numerous small phenocrysts of olivine showing marginal alteration, and minor feldspar alteration.

Specimen K–16. Bathurst-Dunkheld (*SI 55–8, 248872*). *Age 12·4±0·9 m.y.*

Collected from floor level of " blue metal " quarry 2·4 km north-east from Dunkheld at 8·9 km by road from Bathurst. The flow, typical of topographical setting No. 3, rests on an erosion surface 60 m above the bed of the nearby Macquarie River. Medium-fine grained olivine basalt with small olivine and feldspar phenocrysts. Minor feldspar alteration and less than 5% of poorly crystallized interstitial material.

TABLE 2

Region	Basalt Age Group	K-Ar Age Range—of the order of—m.y.	Geological Age (Funnell, 1964)
Macquarie	younger older	11–15 41–54	middle Miocene lower Oligocene ?–Eocene
Cudgegong	younger older	12–16 31–45	middle Miocene lower Oligocene–upper Eocene
Castlereagh	younger older	13–17 not recorded	middle Miocene
Overall-Coonabarabran, Dubbo, Bathurst ..	younger older	11–17 31–54	middle Miocene lower Oligocene–Eocene

Specimen K–15. Dubbo-Talbragar (*SI 55–4, 155017*). *Age 13·9±0·9 m.y.*

Collected from road cutting on Newell Highway, at the northern side of the Talbragar River Bridge, 2·1 km upstream from the Macquarie River junction, and 8 km by road from Dubbo Post Office. The flow, typical of topographical setting Nol 4, extends to about 9 m beneath the beds of the Talbragar and Macquarie Rivers. Fine-grained olivine basalt, slight feldspar alteration and less than 5% of poorly crystallized interstitial material.

Analytical data for the K-Ar age determinations of the four selected basalts in the Macquarie region, described above, are shown in Table 1 under their specimen numbers and locality names. Data for five additional specimens, K–8, 9, 10, 12 and 13, from the adjoining Cudgegong region are also shown in Table 1, as their K-Ar ages were recorded in a recent publication (Dulhunty, 1971) but analytical data was omitted. Also their ages and modes of occurrence are cited in the present paper in

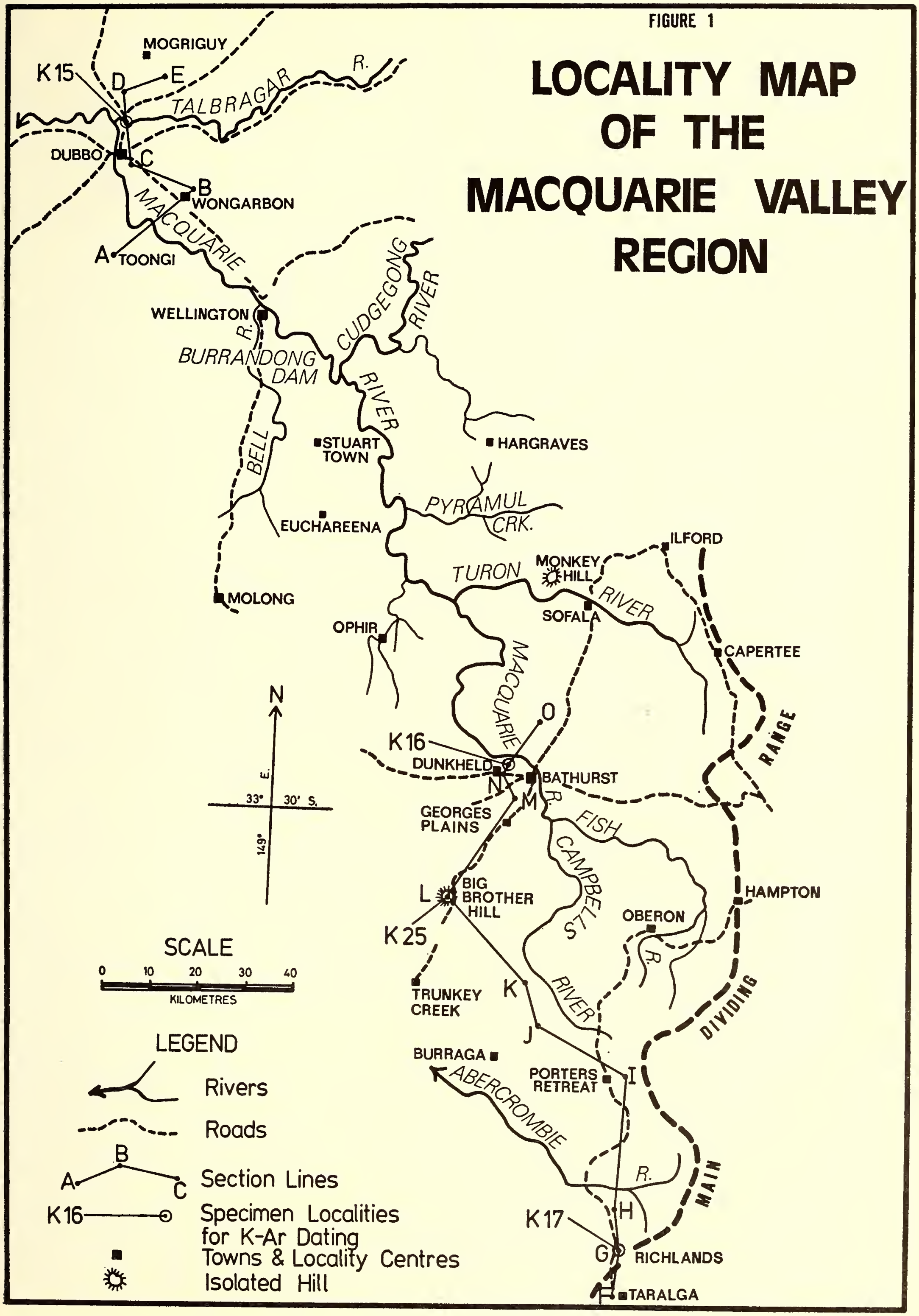
FIGURE 1
LOCALITY MAP
OF THE
MACQUARIE VALLEY
REGION
MOGRIGUY
K15
D
E
TALBRAGAR
R.
DUBBO
C
B
WONGARBON
MACQUARIE
A
TOONGI
WELLINGTON
R.
BURRANDONG
DAM
CUDGEGONG
RIVER
RIVER
BELL
STUART
TOWN
HARGRAVES
PYRAMUL
CRK.
EUCHAREENA
ILFORD
MONKEY
HILL
TURON
RIVER
MOLONG
SOFALA
OPHIR
CAPERTEE
MACQUARIE
N
O
RANGE
K16
DUNKHELD
BATHURST
33° 30′ S.
149° E.
N
M
R.
GEORGES
PLAINS
FISH
CAMPBELLS
L
BIG
BROTHER
HILL
HAMPTON
OBERON
K25
R.
SCALE
0 10 20 30 40
KILOMETRES
TRUNKEY
CREEK
K
RIVER
DIVIDING
J
LEGEND
BURRAGA
PORTERS
RETREAT
I
Rivers
ABERCROMBIE
Roads
B
A
C
Section Lines
R.
K16
Specimen Localities
for K-Ar Dating
Towns & Locality Centres
Isolated Hill
K17
H
MAIN
G
RICHLANDS
F
TARALGA

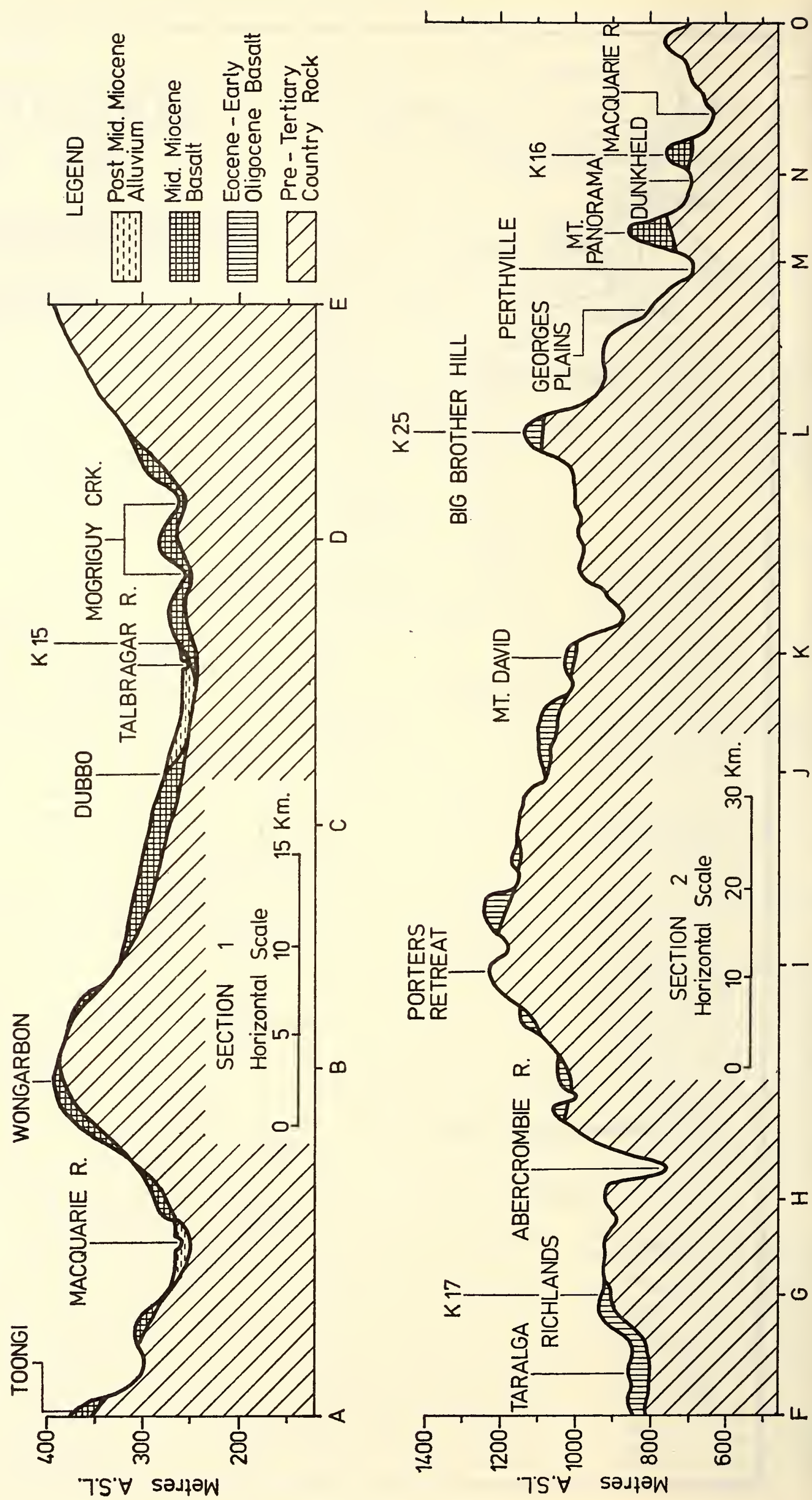

FIGURE 2

GEOLOGICAL SECTIONS across the MACQUARIE VALLEY REGION

SHOWING BASALT OCCURRENCES ALONG SECTION LINES IN FIGURE 1 connection with the interpretation of results for the four flows in the Macquarie region. Macroscopically the five Cudgegong basalts were free from atmospheric weathering, deuteric alteration and amygdaloidal texture. Their micropetrographic features are as follows: K–8: Fine grained olivine basalt with large laths of plagioclase, slight feldspar alteration and less than 5% of isotropic interstitial glass. K–9: Fine-grained olivine basalt, very little pyroxene, very slight alteration of feldspars and about 8% of isotropic glass. K–10: Coarse-grained holocrystalline olivine basalt, minor feldspar alteration, and about 10% of well crystallized interstitial material. K–12: Medium-coarse grained holocrystalline olivine basalt, minor feldspar alteration and about 10% of well-crystallized interstitial material. K–13: Medium-grained holocrystalline olivine basalt, slight feldspar alteration and less than 5% of poorly crystallized interstitial material.

It is understood that P. Wellman, in collaboration with I. McDougall of the Australian National University, Canberra, carried out K-Ar age determinations on basalts from flows in the Macquarie region during the period of the present investigation. Wellman's results, embodied in a Ph.D. thesis, at the Australian National University, have not yet been published, but it is anticipated that some of his results will carry interpretations similar to those based on K-Ar age determinations recorded here. It is wished to acknowledge Wellman's contemporary investigations.

Conclusions

After consideration of the K-Ar ages of the four selected basalt flows from the Macquarie region, in relation to their topographical settings and geographical positions, and in conjunction with previously recorded results for the Castlereagh and Cudgegong regions to the north (Dulhunty, 1971 and 1973) reviewed earlier in this paper, the following conclusions are drawn.

The Macquarie Region

1. Two age groups of Tertiary basalt flows occur in the region. A younger, middle Miocene group, with a range of the order of 11 to 15 m.y., and an older, lower Oligocene ?-Eocene group with a range of the order of 40 to 54 m.y. (See Table 2.)

2. The older age group was extruded over a late Cretaceous or early Tertiary erosion surface. Differences in elevation of the base of the basalt on the erosion surface (Figure 2, Sec. 2, F–L) are due largely to subsequent regional warping, and smaller movements, associated with the late Tertiary uplift of the Eastern Highlands. There appears, however, to have been some degree of mature pre-basalt topography on the Eocene or early Tertiary erosion surface. Careful field studies of the levels and general nature of the surfaces on which the basalts rest, between Taralga and Big Brother Hill, and also between Oberon, Hampton and Capertee, leave little doubt that the now discontinuous erosional residuals of basalt, along the Main Dividing Range, were once more or less continuous flows of the older age group.

3. The basalt flows of the older age group occur in eastern areas of the Macquarie region, whilst those of the younger age group occur in central and western areas.

4. Flows of the younger age group were extruded over an early Miocene erosion surface with undulating topography (Figure 2, Sec. 1) very similar to the present country in the Dubbo district. These flows extended down to levels beneath the present rivers in western areas near Dubbo, and down to within some 60 m above the river in central areas at Bathurst, but do not occur in eastern areas along the Main Dividing Range. This suggests (a) that the younger basalts may have been extruded, at places, across the whole of the Macquarie region which was later tilted to form the Western Slopes, and (b) that subsequent erosion removed all the younger basalts from the strongly elevated eastern areas of the region; entrenched the Macquarie River in central areas, near Bathurst, to a depth of some 60 m below its pre-basalt level; but did not deepen the valley at all in western areas near Dubbo where elevation was minimal. In fact, the occurrence of basalt below the present river bed near Dubbo, suggests a slight rise in river level as a result of over-alluviation, or dumping of products of erosion at the change of river gradient on the western side of the region, where the Western Slopes merge into the Western Plains.

5. Extrusion of the older basalt flows would appear to have been restricted to eastern areas of the Macquarie region, where elevation and erosion were maximal, and the flows now occur only as erosional residuals. Had they been extruded over the western areas, where elevation and erosion were minimal, ample evidence of their occurrence would be expected to have remained to the present day. The western limits of their extrusion may have been somewhere between the eastern and central areas of the region, where high outliers of basalt, on

remnants of country rock at Big Brother and Monkey Hills represent the most westerly evidence of the occurrence of older, or mainly Eocene basalts.

Correlation with Adjoining Regions

The younger basalt age group, of the order of 11 to 15 m.y., in the Macquarie region is equivalent in mode of occurrence to the basalt age groups of the order of 12 to 16 m.y. in the Cudgegong region, and 13 to 17 m.y. in the Castlereagh region (see Table 2). This suggests a general range of the order of 11 to 17 m.y., or middle Miocene age, for all the younger basalts with similar modes of occurrence and similarly situated in the Castlereagh, Cudgegong and Macquarie regions, along the lower, western side of the Western Slopes between Coonabarabran, Dubbo and Bathurst.

The older basalt age group, of the order of 41 to 54 m.y., in the Macquarie region is equivalent in mode of occurrence and geographical position, to the group of the order of 31 to 45 m.y. in the Cudgegong region (see Table 2). Also, the high outliers of older basalt resting on remnants of country rock, at Big Brother and Monkey Hills, are equivalent in mode of occurrence and geographical position to similar occurrences of older basalt at Mt. Boiga and Mt. Carcalgong in the Cudgegong region. These features suggest a general range of the order of 31 to 54 m.y., of lower Oligocene to lower Eocene age, for the older basalts of the Cudgegong and Macquarie regions, situated along the upper, eastern side of the Western Slopes between Rylstone, Oberon and Taralga.

Acknowledgements

In conclusion the author wishes to acknowledge research facilities, and assistance from the University Research Grant, Department of Geology and Geophysics, University of Sydney; valuable discussion with Dr. J. R. Richards, Australian National University, in presentation of analytical data; and the assistance of Associate Professor T. G. Vallance, University of Sydney, in selection of basalt specimens for K-Ar dating.

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(Received 17. 5. 73)

Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 111–114, 1973

Slow Transport as a Criterion for Synchronizing Clocks

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Abstract—If a clock is transported slowly from one point to another of an inertial system, the time-dilatation effect is small and varies with the velocity of transport. This variation permits detection of and compensation for the effect, thus providing a procedure for synchronizing separated clocks, which is equivalent to Einstein's light-signal convention. However, clocks so synchronized, with respect to a given inertial system, will not appear synchronous with respect to any inertial system. It is shown that the substratum formulation of Special Relativity provides a satisfactory interpretation of this phenomenon. Consideration is also given to the relation between the criteria for clock-synchronization and the status of light-velocity measurements.

1. Introduction

Einstein's convention for synchronizing two clocks stationary at locations A and A' in a given inertial system, I_A, depends on the following light-signal procedure. Imagine observers A and A' associated with the two clocks and their respective locations. At time $t_A{}^1$, according to his clock, observer A transmits a light-ray which reflects a reading $t_{A'}$ on the clock at A' and returns to A when his clock reads $t_A{}^3$. Then the clocks are taken to be synchronous according to the observer A if

$$t_{A'}=\tfrac{1}{2}(t_A{}^1+t_A{}^3).$$

This convention (like his other measurement conventions) is consistent with Einstein's basic assumption (the Light Principle) that the measured velocity of light is constant and isotropic with respect to any given inertial system. It follows that if the clocks are synchronous according to A, then they will also be synchronous according to A', that is, they are synchronous with respect to the system I_A.

There has been considerable argument, on a number of planes, about the significance of this convention and its relation to other possible criteria of synchronization. Reichenbach, Grunbaum and others consider that Einstein's criterion is quite arbitrary, that it merely lends descriptive simplicity to the relationships of Special Relativity. They also reject "slow transport" as an alternative method for synchronizing separated clocks. Following an article by Ellis and Bowman (1967), the problem has attracted considerable attention. However, it has been analysed mainly in terms of theoretical-philosophical arguments. We wish here to consider the slow transport criterion in the context of a substratum formulation of Special Relativity.

2. The Slow Transport Criterion

The slow transport criterion is based on transporting a clock M (similar to clock A) from A to A'. Let the clock M be transported by an associated observer M. At zero time (according to both clocks A and M), M departs from A with velocity v towards A' which is distant d_A from A, v and d_A being the I_A Einstein measures, that is according to observer A.

Let ΔT_A be the time taken, according to A, for M to reach A'; then

$$\Delta T_A=d_A/v.$$

However, on account of the time-dilatation result of Special Relativity, the transported clock M will read ΔT_M on reaching A', where

$$\left.\begin{aligned}\Delta T_M&=\Delta T_A(1-v^2/c^2)^{\frac{1}{2}}\\&=(d_A/v)(1-v^2/c^2)^{\frac{1}{2}}\end{aligned}\right\}\qquad(1)$$

The difference between the two readings is given by

$$\left.\begin{aligned}\Delta T_A-\Delta T_M&=(d_A/v)[1-(1-v^2/c^2)^{\frac{1}{2}}]\\&\simeq\tfrac{1}{2}vd_A/c^2\end{aligned}\right\}\qquad(2)$$

if v is small compared to c.

It is seen that since d_A and c are constants, we can make vd_A/c^2 as small as we like by making v sufficiently small. In practice, v cannot be made too small since the time of transport would then become inordinately long. However, if a number of similar clocks, M, M', etc., are synchronized with clock A and then transported over the same straight-line path from A to A' but with different velocities, then on account of (2) they will be non-synchronous when compared at their destination A'. In this way the variation of $(\Delta T_A-\Delta T_M)$ with v is revealed and so provides a basis for estimating and compensating for the time-dilatation factor responsible for the variation.

Ellis and Bowman (1967) propose a practical extrapolation procedure for determining the required compensation and hence achieving " slow transport synchrony " of two separated clocks stationary in a given inertial system. Bridgman (1962) proposes an alternative procedure based on taking the limit of the transport times as the " self-measured velocities " (of M, M', etc.) approach zero.

3. The Measurement of the Velocity of Light

The problem of criteria for synchronism is closely related to the status of measurements of the velocity of light. Einstein defines a two-way light-path procedure for this measure involving only a single clock. Clearly this provides a measure of the average velocity of a light-ray travelling over an out-and-return path. Measurements of one-way velocities require two separated synchronous clocks. However, as shown by Builder (1958*a*), if these clocks are synchronized in accordance with Einstein's convention, then the one-way measure remains equivalent to Einstein's out-and-return path procedure since the synchronization of the clocks is carried out on the assumption of light-velocity isotropy ; the method of synchronization ensures the same measure for the velocity of light for both directions, so under these conditions one-way measurements will not disclose any anisotropy of light propagation, even if such exists.

It might be imagined that the method of slow transport provides an alternative and independent criterion for synchronism, and so might be the basis of disclosing the " true " one-way velocity of light. However, further consideration shows that the independence of the two criteria is illusory, that the slow transport procedure achieves a synchronization which is identical with that achieved by Einstein's convention. After all slow transport synchronism is also defined and determined within the framework of the assumptions and results of Special Relativity. The time-dilatation effect eliminated by the extrapolation procedure is an effect considered relative to a set of clocks synchronous in I_A—a set of clocks synchronous precisely according to Einstein !

It follows, as originally claimed by Builder (1958*a*), that clocks in slow transport synchrony can yield no more information about one-way light-velocities than clocks synchronized according to Einstein. Now this has an interesting and apparently paradoxical implication. Clocks which are Einstein synchronous in respect to a given inertial system are not synchronous (in the same sense) in respect to any other inertial system, and this result must also apparently be true for clocks in slow-transport synchrony.

The substratum approach to Special Relativity provides a satisfactory interpretation (Prokhovnik, 1967) of this phenomenon for Einstein-synchronous clocks. It results from an anisotropy effect which applies, in different measure, to every inertial system except the basic one. This effect is manifested, through Einstein's synchronism criterion, in the different inertial systems. However it is by no means so obvious why this should apply when slow-transport synchrony is made the criterion of simultaneity, since such synchrony is ostensibly based on eliminating any effect of motion or change of motion associated with the transport, in respect to any inertial system. One might imagine that slow transport would provide a universal criterion of synchronism—equally valid for all inertial systems. Yet, as we have seen, this is not the case ; clocks in slow transport also appear to manifest the anisotropy effect. This is indeed puzzling from the substratum (or any other) viewpoint, and it will be instructive to further examine the problem from this viewpoint.

4. The Substratum Approach to the Problem

We will employ the approach and results of previous publications (e.g., Prokhovnik, 1967), assuming a basic reference frame, I_S, in respect to which light propagation is isotropic. Consider an observer A, associated with the reference frame I_A, moving with velocity u relative to I_S—that is, according to the Einstein measurements of an observer S stationary in I_S. Consider also an observer M who departs from A, at zero time according to the (then) synchronized similar clocks of A and M, and with relative velocity v according to the Einstein measurements of either of these observers. It will be sufficient for our purposes to consider the case when u and v are in the same direction according to S so that the velocity, w, of M relative to the reference frame I_S is given by

$$w = \frac{u+v}{1+uv/c^2}. \tag{3}$$

The relative velocity of A and M, according to S, will then be*

* Measurements considered in respect to a single reference frame (I_S in this case) are related according to ordinary vector algebra.

$$w-u=\frac{v(1-u^2/c^2)}{1+uv/c^2} \quad (4)$$

We note in accordance with our assumptions and their consequences, that when A synchronizes (according to Einstein) a set of similar clocks, stationary in I_A, along M's path, the synchronization procedure incorporates an anisotropy effect of magnitude $\beta ud/c^2$, where $\beta = (1-u^2/c^2)^{-\frac{1}{2}}$ and d is the I_S distance between A and a particular clock. Thus according to S, clocks synchronous in I_A, are retarded (relative to A's clock) by an interval of $\beta ud/c^2$ proportional to the distance d.†

Now imagine that a time ΔT (according to a similar clock used by S) has elapsed since M departed from A. According to A's clock the corresponding duration of time may be denoted by ΔT_A where

$$\Delta T_A = \Delta T(1-u^2/c^2)^{\frac{1}{2}} \quad (5)$$

on account of the absolute time-dilatation effect. M is now at a point A' whose I_S distance from A is given by

$$d=(w-u)\Delta T, \quad (6)$$

so that (according to S) the corresponding reading $\Delta T_{A'}$ of a clock at A' synchronous with A's clock in I_A, is given by

$$\left.\begin{aligned}\Delta T_{A'} &= \Delta T_A - \beta u(w-u)\Delta T/c^2 \\ &= \Delta T_A/(1+uv/c^2)\end{aligned}\right\} \quad (7)$$

on account of the anisotropy effect and invoking (5) and (4).

Also the reading of M's clock when he passes A' (as observed by S or A or any other observer) is given by

$$\begin{aligned}\Delta T_M &= \Delta T(1-w^2/c^2)^{\frac{1}{2}} \\ &= \frac{\Delta T(1-u^2/c^2)^{\frac{1}{2}}(1-v^2/c^2)^{\frac{1}{2}}}{1+uv/c^2}, \text{ using (3).}\end{aligned}$$

Hence, using (5)

$$\begin{aligned}\Delta T_M &= \frac{\Delta T_A(1-v^2/c^2)^{\frac{1}{2}}}{1+uv/c^2} \quad (8) \\ &= \Delta T_{A'}(1-v^2/c^2)^{\frac{1}{2}}, \text{ on account of (7).}\end{aligned}$$

The result is in full conformity with A's expectation that his inertial system can be considered as one in which light propagation is isotropic and for which the Lorentz transformation applies exactly in terms of Einstein's measurement definitions.

Note that according to S, M's clock has become retarded by the amount

$$\begin{aligned}\Delta T_A - \Delta T_M &= \Delta T_A\left[1-\frac{(1-v^2/c^2)^{\frac{1}{2}}}{1+uv/c^2}\right], \quad \text{from (8)} \\ &= \Delta T_A - (\Delta T_A - \beta du/c^2)(1-v^2/c^2)^{\frac{1}{2}}, \quad \text{using (7) and (6)}\end{aligned}$$

Hence $\Delta T_A - \Delta T_M \to \beta du/c^2$ as $v \to 0$.

Thus in terms of the I_S time-scale, no matter how slow the transport, M's clock will lose time relative to A's clock by a factor proportional to the separation distance. It is seen that this transport effect is identically equal to the anisotropy effect associated with clocks synchronized according to Einstein. It follows that A can never detect the transport factor since it is exactly compensated by the anisotropy effect incorporated in the I_A set of Einstein-synchronous clocks. By the same token, clocks in slow-transport synchrony will not enable A to detect any anisotropy of light propagation in respect to his inertial system. The two criteria of synchronization are theoretically mutually dependent and indeed identical when viewed from the substratum approach.

The emergence of this characteristic transport effect for a moving reference frame is not as contrary as may appear at first sight. According to S we may take A's and M's velocities in I_S as close enough to u and $u+v$ respectively. Hence approximately—

$$\begin{aligned}\Delta T_A - \Delta T_M &= \Delta T[(1-u^2/c^2)^{\frac{1}{2}} - (1-(u+v)^2/c^2)^{\frac{1}{2}}] \\ &\simeq \Delta T[\tfrac{1}{2}(u+v)^2/c^2 - \tfrac{1}{2}u^2/c^2] \\ &= \Delta T(uv/c^2 + \tfrac{1}{2}v^2/c^2),\end{aligned}$$

if u and v are small compared to c.

Hence $\Delta T_A - \Delta T_M \to ud/c^2$ as $v \to 0$.

Thus the result depends essentially on the arithmetical cliché that

$$(u+v)^2 - u^2 \neq v^2$$

but

$$= v^2 + 2uv,$$

involving a first order term in v.

5. Comparisons and Conclusions

It is seen that the substratum approach provides an interpretation of the nature and relationship of the two methods of synchronization. The approach is formally similar to that of Winnie (1970), who shows that if we assume the isotropy of light-propagation with respect to any given inertial reference frame, then the anisotropy with respect to all other inertial systems leads to a complex of associated effects which conceal the anisotropy and render all inertial systems Lorentz-equivalent. Thus he is able to show also that the slow transport and light-signal criteria for synchronism of clocks are not independent. Indeed in section 2 and section 3 of Einstein's original paper (1905) the anisotropy of light-propagation in all inertial systems, other than the "stationary" one, is also invoked to display the relativity of length and time measurements and to deduce the Lorentz transformation which relates such

† Reciprocally, clocks synchronous in I_S appear non-synchronous to A in the same manner.

measurements for different inertial systems. However, this treatment is hypothetical and ambiguous without the existence of one particular reference frame relative to which light propagation can be assumed to take place. In terms of such a reference frame the anisotropy effect, and the resultant absolute effects (e.g., time-dilatation) assume an unambiguous meaning. As Builder (1958*b*) insisted, the assumption of a fundamental reference frame for light-propagation is logically necessary as a basis for the existence of absolute relativistic effects, and as has been shown elsewhere (Prokhovnik, 1967) the assumption provides a sufficient basis for Special Relativity and its intelligible physical interpretation. Moreover, recent astronomical observations have now made it possible to distinguish in two separate ways (Prokhovnik, 1973) a fundamental cosmological reference frame : the consequences of motion relative to this frame remain concealed with respect to local observations and experiments (on account of the interaction of mutually-compensatory anisotropy effects) but not with respect to cosmological observations and laws such as the Hubble Law.

It follows that no local experiments can enable us to discern the anisotropy of light-propagation with respect to our reference frame. Neither Einstein's light-signal procedure, nor the slow-transport method for synchronizing clocks can provide any different measure of the velocity of light than that obtained by timing a light-ray over an out-and-return path. Only astronomical observation of the universe at large can disclose the anisotropy and make us aware of a fundamental reference frame which gives meaning to absolute effects associated with uniform motion.

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(Received 24.7.73)

Journal and Proceedings, Royal Society of New South Wales, Vol. 106, pp. 115–117, 1973

A Note on Recurrence Sequences

A. J. van der Poorten

Abstract—Sequences satisfying linear homogeneous difference equations (recurrence sequences) over a commutative ring R are investigated with a view to demonstrating without appeal to analytic techniques that the set of all such sequences is an R-algebra with respect to termwise operations. Explicit formulae are provided.

1. In this note we generalize well known results on sequences satisfying linear homogeneous recurrence relations of arbitrary order. Hereafter we refer to such sequences as *recurrence sequences*. Without the usual appeal to analytic techniques we show that the set of recurrence sequences over an arbitrary commutative ring R with unity forms an R-algebra with respect to the termwise operations on sequences. In particular, the termwise product of recurrence sequences is again a recurrence sequence. We provide an explicit expression for the auxiliary equation belonging to $\{k_n^r\}$, a power of a recurrence sequence $\{k_n\}$, thus generalizing such results for recurrence sequences of small order (cf.[4]). We should remark that the principal motive of this note is to show that the analytic techniques invariably applied to recurrence sequences over C are unnecessary and tend to disguise the formal structure of the situation. At the same time we collect, in a generalized form, results, which, though well known, are by no means readily accessible elsewhere in the literature.

2. Let $\{k_n\}$ be a sequence of elements, of an arbitrary commutative ring R with unity, satisfying a linear homogeneous recurrence relation of order t over R (so that $a_t \neq 0$)

$$k_n = a_1k_{n-1}+a_2k_{n-2}+\ldots+a_tk_{n-t}$$
$$= \sum_{j=1}^{t} a_jk_{n-j}\,; \quad n \geq t$$

where we are given initial values $k_0, k_1, \ldots, k_{t-1}$. By multiplying by X^n and summing over n we obtain

$$\sum_{n=t}^{\infty} k_nX^n = \sum_{j=1}^{t} a_jX^j \sum_{n=t-j}^{\infty} k_nX^n,$$

whence writing $k(X) = \sum_{n=0}^{\infty} k_nX^n$ for the generating function of the sequence, we obtain

$$\left(k(X)-k_{t-1}X^{t-1}-\ldots-k_1X-k_0\right)$$
$$= \sum_{j=1}^{t} a_jX^j\left(k(X)-k_{t-j-1}X^{t-j-1}-\ldots-k_1X-k_0\right)$$

and thus

$$k(X) = \frac{f(X)}{g(X)},$$

where

$$g(X) = 1-\sum_{j=1}^{t} a_jX^j \text{ and}$$
$$f(X) = \sum_{j=1}^{t}\left(k_{j-1}-\sum_{l=1}^{j-1} a_lk_{j-l-1}\right)X^{j-1}$$

Thus $k(X)$ is a rational function over R, whose denominator is a polynomial of degree t with constant coefficient 1, and whose numerator is a polynomial of degree at most $t-1$. Conversely we see by multiplying by $g(X)$ that any such rational function is the generating function of a sequence $\{k_n\}$ satisfying a linear homogeneous recurrence relation over R.

3. We turn now to consider the collection $D(R)$ of all recurrence sequences over R. We see immediately that the generating function of the termwise sum of two recurrence sequences is a rational function over R of the shape described in section 2 above. Accordingly the sum of two recurrence sequences is again a recurrence sequence, and thus we may view $D(R)$ as a R-submodule of the R-module R^N of all sequences over R.

Indeed if

$$k(X) = \sum k_nX^n = \frac{f(X)}{g(X)},$$

denote by $q(X)$ the polynomial

$$q(X) = X^tg(X^{-1}) = X^t-\sum_{j=1}^{t} a_jX^{t-j},$$

the so-called *auxiliary equation* to the recurrence relation satisfied by $\{k_n\}$. Denote by E the endomorphism of R^N which sends a sequence $\{u_n\}$ to the sequence $\{u_{n+1}\}$, the n-th term of which is u_{n+1}. Since the recurrence relation for $\{k_n\}$ is simply

$$q(E)\{k_n\} = \{0\}$$

we see that the recurrence sequences with auxiliary equation $q(X)$ constitute exactly the kernel of the endomorphism $q(E)$ on R^N. It follows that *the collection $D(R)$ of all recurrence sequences over R is exactly the R-submodule of R^N consisting of those sequences for which there exists a monic polynomial $h(X)$ over R with non-zero constant* *coefficient, so that the sequence lies in the kernel of the endomorphism* $h(E)$.

4. Rephrasing this result we see that it is appropriate to view R^N as an $R[E]$-module. Then the recurrence sequences $D(R)$ lie in exactly those $R[E]$-submodules of R^N which are finitely generated as R-modules and no element of which is annihilated by E (thus avoiding those sequences which satisfy a recurrence relation if some initial terns are excluded). To see this we require only elementary linear algebra (in effect the Cayley-Hamilton theorem) for then for each such submodule we can find a monic polynomial $q(X)$ with non-zero constant term, such that $q(E)$ annihilates the submodule.

We can identify the term by term sum of sequences with their direct sum, and the term by term product of sequences with the symmetric part of their tensor product. Then it is immediate that both the direct sum and tensor product of submodules as described are again invariant under E and finitely generated as R-modules and contain no element annihilated by E. Thus both the term by term sum and term by term product of recurrence sequences are again recurrence sequences and therefore $D(R)$ is an R-algebra. Hence was have shown that *the collection $D(R)$ of all recurrence sequences over a commutative ring R with unity is an R-algebra with respect to the termwise operations on sequences.*

5. In order to show that $D(C)$, the collection of recurrence sequences of complex numbers, forms a commutative ring Klarner[2] appealed to a result of Hadamard[5] (at page 157), to the effect that if $u(z)=\Sigma u_n z^n$, $v(z)=\Sigma v_n z^n$ are analytic in suitable regions about the origin, then

$$\Sigma u_n v_n z^n=\frac{1}{2\pi i}\int_\eta u(z/\gamma)v(\gamma)\frac{d\gamma}{\gamma}$$

where η is a closed contour in the γ-plane which includes the singularities of $u(z/\gamma)/\gamma$ and excludes those of $v(\gamma)$. It follows that if $u(z)$ and $v(z)$ are rational functions then $\Sigma u_n v_n z^n$ is rational and its poles are at (some of) the points of shape $\alpha\beta$ where $u(z)$ has a pole at α and $v(z)$ a pole at β. Hence the termwise product of recurrence sequences has a generating function of appropriate shape and is again a recurrence sequence. For further details of the complex analysis involved the reader is refered to[1] (at pp. 346–350).

We would however appear to obtain more insight from purely algebraic considerations. Given a monic polynomial $p(X) \varepsilon R[X]$ irreducible in $R[X]$ we can construct the quotient ring $R[X]/(p(X))$, where $(p(X))$ denotes the principal ideal generated by $p(X)$ in $R[X]$. The condition that $p(X)$ be monic suffices to guarantee that $(p(X))$ and R have trivial intersection, hence the quotient ring is an extension of R, and it obviously contains a zero of $p(X)$. Proceeding in this manner, simply echoing the well-known theory of finite algebraic extensions of fields, we can produce, for any given collection of monic polynomials in $R[X]$, an extension $\bar{R}$ of R in which each polynomial of that collection splits into monic linear factors. In this construction we are neither discomfited by the possible presence of zero divisors nor by factorization in $\bar{R}[X]$ not necessarily being unique.

Having constructed a suitable extension $\bar{R}$ for those polynomials we propose to factorize, we go over to the $\bar{R}$-module, $R^N\otimes_R\bar{R}\cong\bar{R}^N$ (which one might call the $\bar{R}$-ification of R^N in analogy with the familiar complexification of a real space). We wish to prove the following:

Suppose that over an extension $\bar{R}$ of R, the polynomial $q(X)$ factorizes into linear factors $q(X)=(X-\alpha_1)^{p_1+1}(X-\alpha_2)^{p_2+1}\ldots(X-\alpha_s)^{p_s+1}$ where $\alpha_1, \alpha_2, \ldots, \alpha_s$ are distinct elements of $\bar{R}$. Then the kernel of the endomorphism $q(E)$ on R^N consists exactly of those sequences $\{k_n\}$ where $k_n \varepsilon R$ is of the shape

$$k_n=b_1(n)\alpha_1^n+b_2(n)\alpha_2^n+\ldots+b_s(n)\alpha_s^n, \quad n\geq 0$$

and the $b_j(n)$ are polynomials in n over $\bar{R}$ of degree at most p_j respectively. Conversely if the sequence $\{k_n\}$ has its terms given by the above expression then the sequence is a recurrence sequence with auxiliary equation $q(X)$. To see this notice that if $\alpha\neq o\varepsilon\bar{R}$ then the kernel of the endomorphism $(E-\alpha)^{p+1}$ on $\bar{R}^N$ consists of sequences of $\bar{R}^N$ of the shape $\{b(n)\alpha^n\}$ where $b(n)$ is of degree at most p in n. It is now elementary linear algebra to see that the kernel of $q(E)$ is a sum of the shape indicated in the assertion. Conversely of course, the assertion is obvious; one sees, for example, that if $\{k_n\}$ is as in the assertion then the n-th term of the sequence $(E-\alpha_j)\{k_n\}$ has the shape given for k_n except that the coefficient of α_j^n has its degree reduced by 1.

6. There is an alternative explicit expression for the terms of recurrence sequences entirely in terms of the coefficients of the auxiliary equation and avoiding any question of determining the zeros of the auxiliary equation.

For let $\{u_n\}$ be a recurrence sequence satisfying the recurrence satisfied by $\{k_n\}$, and let the initial values $u_0, u_1, \ldots, u_{t-1}$ be given by

$$u_0=1 \text{ and } u_{j-1}=\sum_{l=1}^{j-1} a_l u_{j-l-1}\; j=2,\ldots,t.$$

Then the generating function $u(X)=\sum_{n=0}^{\infty} u_n X^n$ satisfies

$$u(X)=(g(X))^{-1}$$

and the sequences $\{k_n\}$ and $\{u_n\}$ are related by

$$f(X)u(X)=k(X),$$

so that on equating coefficients we obtain

$$k_n=\sum_{j=1}^{t} u_{n-j+1}\left(k_{j-1}-\sum_{l=1}^{j-1} a_l k_{j-l-1}\right) \quad n\geq 0,$$

(where, formally, one puts $u_m=k_m=0$ for $m<0$). Thus we have

$$u(X)=(g(X))^{-1}=\left(1-\sum_{j=1}^{t} a_j X^j\right)^{-1}$$

and expanding formally

$$u(X)=\sum_{m=0}^{\infty}\left(\sum_{j=1}^{t} a_j X^j\right)^m$$

$$=\sum_{m=0}^{\infty}\sum_{\lambda_1+\ldots+\lambda_t=m}\frac{m!}{\lambda_1!\lambda_2!\ldots\lambda_t!}a_1^{\lambda_1}a_2^{\lambda_2}\ldots$$

$$\ldots a_t^{\lambda_t}X^{\lambda_1+2\lambda_2+\ldots+t\lambda_t}$$

where the inner sum is over all non-negative integers $\lambda_1,\ldots,\lambda_t$ with sum m. Hence equating coefficients of X^n we see that for $n\geq 0$,

$$u_n=\sum_{\lambda_1+2\lambda_2+\ldots+t\lambda_t=n}\frac{(\lambda_1+\lambda_2+\ldots+\lambda_t)!}{\lambda_1!\lambda_2!\ldots\lambda_t!}a_1^{\lambda_1}a_2^{\lambda_2}\ldots a_t^{\lambda_t}$$

where the sum is over all non-negative integers $\lambda_1,\ldots,\lambda_t$ such that $\lambda_1+2\lambda_2+\ldots+t\lambda_t=n$.

Writing $\lambda_1=n-2\lambda_2-\ldots-t\lambda_t$ one reorganizes this result to obtain

$$u_n=\sum_{\lambda_2=0}^{[n/2]}\sum_{\lambda_3=0}^{[n/3]}\ldots$$

$$\ldots\sum_{\lambda_t=0}^{[n/t]}\binom{n-\lambda_2-2\lambda_3-\ldots-(t-1)\lambda_t}{\lambda_2+\lambda_3+\ldots+\lambda_t}\binom{\lambda_2+\ldots+\lambda_t}{\lambda_2}$$

$$\ldots\binom{\lambda_{t-1}+\lambda_t}{\lambda_{t-1}}a_1^{n-2\lambda_2-\ldots-t\lambda_t}a_2^{\lambda_2}\ldots a_t^{\lambda_t}$$

generalizing a formula proved in[3] for the case $t=3$. As usual $[n/j]$ means the greatest integer not larger than n/j. Combining the result for u_n with that expressing k_n in terms of u_n, one obtains an explicit expression for the k_n. The result is clearly of limited practical application but is a fount for interesting combinatorial identities.

As an example we see that the well-known Fibonacci sequence $\{u_n\}$ defined by the recurrence $u_n=u_{n-1}+u_{n-2}$ and the initial conditions $u_0=u_1=1$, has generating function

$$\Sigma u_n X^n=(1-X-X^2)^{-1}$$

whence

$$u_n=\sum_{\lambda=0}^{[n/2]}\binom{n-\lambda}{\lambda}$$

7. From the explicit expression for the terms of recurrence sequences given in section 5 one immediately reads off that for positive integers r the r-th power of a recurrence sequence has its term of shape

$$k_n^r=\sum_{\lambda_1+\lambda_2+\ldots+\lambda_s=r} b_{r,\underline{\lambda}}(n)(\alpha_1^{\lambda_1}\alpha_2^{\lambda_2}\ldots\alpha_s^{\lambda_s})^n \quad n\geq 0$$

where $b_{r,\underline{\lambda}}(n)$ are polynomials in n of degree at most $\lambda_1 p_1+\lambda_2 p_2+\ldots+\lambda_s p_s$. It follows that *if $\{k_n\}$ is a recurrence sequence over R with auxiliary equation $q(X)$, such that $q(X)$ factorizes over an extension $\overline{R}$ of R as*

$$q(X)=(X-\alpha_1)^{p_1+1}(X-\alpha_2)^{p_2+1}\ldots(X-\alpha_s)^{p_s+1}$$

then $\{k_n^r\}$ is a recurrence sequence with auxiliary equation $q_r(X)$ given by the monic lowest common multiple of the polynomials

$$(X-\alpha_1^{\lambda_1}\alpha_2^{\lambda_2}\ldots\alpha_s^{\lambda_s})^{\lambda_1 p_1+\ldots+\lambda_s p_s+1}.$$

$\lambda_1,\lambda_2,\ldots,\lambda_s$ running over all non-negative integers with sum r. Thus the generating function $k_r(X)=\Sigma k_n^r X^n$ is a rational function $f_r(X)/q_r(X)$, where we may write $f_r(X)$ explicitly in terms of the initial values of the sequence using the results of section 1 above. This result generalizes particular cases for $r=2$ and 3 mentioned in [4]. The reader should note that degeneracy is possible, and that whilst $\{k_n^r\}$ certainly satisfies the recurrence relation given by $q_r(X)$, it may satisfy a relation of smaller order.

Similarly the above described approach allows one to explicitly provide the auxiliary equation belonging to the term wise product of any infinite collection of recurrence sequences.

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(Received 27·6·73)

Report of the Council for the Year Ended 31st March, 1973

Presented at the Annual General Meeting of the Society held on 4th April, 1973 in accordance with Rule 18 (*a*).

At the end of the period under review the composition of the membership was 343 members, 15 associate members and seven honorary members.

During the year 13 new members and two associate members were elected and three members were written off under Rule 5 (*b*).

It is with regret that we announce the loss by death of the following members:

Sir Charles Bickerton Blackburn (1961).
Sir Lawrence Bragg (1960).
Professor Oscar Ulric Vonwiller (1929).
Mr. Lionel Lawry Waterhouse (1919).
Associate Professor Clive Melville Harris (1948).

Both Sir Charles Bickerton Blackburn and Sir Lawrence Bragg were esteemed honorary members of the Society.

Nine monthly meetings were held. The abstracts of addresses have been printed on the notice paper. The proceedings of these will appear later in the issue of the *Journal and Proceedings*. The members of Council wish to express their sincere thanks and appreciation to the nine speakers who contributed to the success of these meetings, the average attendance being 60.

The Lecture, under the joint auspices of the Society and the University of Sydney, was given by Professor Laurent Schwartz, Ecole Polytechnique, Paris, the title being "Cylindrical Probabilities and P-Radonifying Maps". The text of this lecture will appear later in the *Journal and Proceedings*.

The Annual Social Function was held at the Pitt Club on 21st March and was attended by 54 members and guests. The speaker was Dr. F. H. Talbot, Director of the Australian Museum, his subject being "Museums and Research".

The Society's Medal for 1972: Mr. W. H. G. Poggendorff, B.Sc.Agr.

The Clarke Medal for 1972: Mr. Haddon F. King, B.A.Sc.

The Edgeworth David Medal for 1972: Awarded jointly to Donald Harold Napper, M.Sc., Ph.D.; Jonathan Stone, B.Sc.(Med.), Ph.D.

The Society received a grant of $1,500 from the Government of New South Wales and it very much appreciates the Government's continued interest in the work of the Society.

After a considerable amount of preparatory work was carried out by the sub-committee, the Summer School was cancelled because of lack of support. Despite this disappointment, Council recommends that plans should be made for another School in January, 1974.

The Society's financial statement shows a surplus of $1,848.50.

The New England Branch had a successful year with six well attended meetings.

The South Coast Branch held several meetings, ncluding an Annual Dinner, during the year.

The Section of Geology continued to meet regularly throughout the year.

Proceedings of the Branches and Section of Geology will appear in the *Journal and Proceedings.*

The Council held 11 ordinary meetings and two special meetings. Attendances at ordinary meetings were as follows: Mr. J. C. Cameron, 10; Mr. M. J. Puttock, 8; Mr. E. K. Chaffer, 10; Mr. J. W. Pickett, 8; Mrs. M. Krysko v. Tryst, 10; Mr. W. H. G. Poggendorff, 11; Professor W. E. Smith, 8; Professor R. J. W. LeFevre, 6; Professor W. B. Smith-White, 7; Mr. W. H. Robertson, 6; Professor L. J. Lawrence, 6; Mr. D. S. Bridges, 7; Mr. J. W. Humphries, 11; Dr. P. D. Tilley, 7; Dr. B. E. Clancy, 3; Mr. J. P. Pollard, 7; Professor R. L. Stanton, nil; Dr. J. A. Facer, 1; Dr. A. J. van der Poorten, 4; Professor E. C. Watton, 3.

The President represented the Society at: The Celebrations of the Captain Cook Landing at Kurnell and placed a wreath on the Banks Memorial; The Annual Dinner of the Chamber of Manufactures of New South Wales; The Annual Dinner of the Sydney Division of the Institution of Engineers, Australia; The Annual Dinner of the N.S.W. Division of the Institution of Surveyors, Australia.

Four parts of the *Journal and Proceedings* were published during the year: Volume 104, parts 1 and 2 and Volume 104, parts 3 and 4. Volume 105, parts 1 and 2 is expected from the printer in a few weeks. Volume 105, parts 3 and 4 should be issued in July and Volume 106, parts 1 and 2 in November, 1973. A new cover has been designed for the *Journal* by Mr. Barry White and will appear on Volume 105, parts 1 and 2.

The Library.—The number of items received and processed was 3,755. These were periodicals received by exchange from 396 Societies and Institutions, donations and by the purchase of periodicals on which $428.86 was expended.

Among the Institutions who made use of the Library through the Inter-Library Loan Scheme were:

N.S.W. and Other State Governments: Geological Survey of New South Wales; N.S.W. Departments of Motor Transport, Health, Soil Conservation Service, Water Sewerage and Drainage Board; Conservation; Water Conservation and Irrigation Commission; Royal Botanic Gardens, Sydney, N.S.W.; Electricity Commission. Queensland: Irrigation and Water Supply Commission and Department of Primary Industries.

Commonwealth Government Departments: Department of Works, Royal Australian Navy.

C.S.I.R.O.: National Standards Laboratory, Textile Physics Division of Applied Chemistry, Animal Physiology, Mineral Chemistry, Radiophysics (all in Sydney); Long Pocket Laboratories, Meat Research Laboratory (in Queensland); Division of Wildlife Research and Canberra Laboratories (in Canberra).

Universities and Colleges: University of New South Wales; University of Sydney; Macquarie University; Institute of Technology, Gore Hill; Mitchell College of Advanced Education ; Darling Downs Institute of Advanced Education ; University of New England ; University of Queensland ; James Cook University of North Queensland ; Wollongong University College ; Newcastle Teachers' College ; University of Papua and New Guinea ; Granville Technical College ; University of Newcastle ; Hawkesbury Agricultural College ; Sydney Technical College ; School of General Studies, Australian National University ; Barr Smith Library, University of Adelaide ; University of Tasmania ; Queensland Institute of Technology.

Companies : Dulux Australia Ltd. ; James Hardie & Co. Pty. Ltd. ; Esso Exploration ; Peko Wallsend ; I.C.I. ; C.S.R. Research ; Roche Products Pty. Ltd. ; Sulphide Corporation Pty. Ltd. ; A.G.L. Co. ; M.I.M. Holdings Ltd. ; John Lysaght (Aust.) Ltd. ; B.H.P. Newcastle ; Shell Co. of Australia Ltd. ; Union Carbide Aust. Ltd. ; A.C.I. Technical Library ; Dames and Moore.

Research Institutes : Medical Library, University of Western Australia ; Australian Food Research Laboratories ; Waite Agricultural Research Institute.

Miscellaneous : Australian Broadcasting Commission, Gore Hill ; Institution of Engineers ; Snowy Mountains Hydro Electric Authority ; Commonwealth Serum Laboratories, Parkville ; Royal Newcastle Hospital.

A total of 334 loans were made to the above and 34 to members of the Society. There were 43 requests for photocopying of articles with a total of 967 pages copied.

Within the past two weeks the Society has been paid the final compensation monies relating to the resumption of Science House. Except for a relatively small sum, the compensation money has been invested in short-term securities awaiting the final decision on the Science Centre Project.

This project has been under earnest consideration during the year. The Planning Committee (formed jointly with the Linnean Society of New South Wales) has been in close consultation with its consultants, Messrs. Jones, Land and Wootton, who presently are negotiating for a site. A joint company has been formed by the Linnean Society and the Royal Society for the purposes of administering their share of the compensation funds received from the resumption of Science House, and ultimately to establish a Science Centre.

This Company, Science Centre Pty. Ltd. was formed during the past two weeks and replaces the Planning Committee referred to above. Each of the Societies has four Directors on the Board of the Company, those from the Royal Society being Mr. E. K. Chaffer, Mr. J. W. Humphries, Mr. M. J. Puttock and Prof. W. E. Smith.

Following the resignation of the Assistant Secretary, Mrs. Margaret Collier, the Council appointed Mrs. Valda Lyle to this position, on a full-time basis, from the 12th February, 1973.

J. W. Humphries,
Hon. Secretary (General)

Honorary Treasurer's Report

There was a surplus for the period of $1,849 as against a surplus for the previous year of $2,900 resulting in a total decrease of $1,051 made up as follows :

	$	$
Income in general interest		535
Increase in sale of back numbers		2,351
Increase in sale of reprints		206
Increase in commission received		2
Increase in donations received		17
		3,111
Less :		
Reduction in members' subscriptions	139	
Reduction in subscriptions to journal	163	
Reduction in Science House surplus	498	
Reduction in summer school surplus	243	
Increase in salary costs	813	
Increase in printing costs	1,910	
Increase in general expenses	396	
		4,162
Total decline		$1,051

The payment of compensation monies for the resumption of Science House has resulted in the loss of the income previously derived from that source. Anticipating that —it will be at least three years until the Society once again derives an income from rent of office space, budgets for the next three financial years have been drawn up allowing for a total deficit of $28,420 over the three year period. This deficit will be covered by a sum retained from the compensation money not reinvested in the Science Centre Project.

On the last financial statement the Society's share of the original cost of Science House was written off due to the resumption. This year it is replaced by a figure for the resumption reserve.

J. W. Pickett,
Hon. Treasurer.

Report of the South Coast Branch of the Royal Society of New South Wales

Annual General Meeting: 26th February, 1973, 8.30 p.m. to 9.00 p.m.

The meeting was preceded by a dinner and followed by two films on Wild Life Conservation.

Eleven (11) members were present.

Minutes of the previous meeting were read and adopted.

Election of Office-bearers took place:

President: B. Clancy; proposed W. Upfold, seconded A. Keane.

Secretary: G. Doherty; proposed A. Keane, seconded D. Thompson.

Council Rep.: G. Doherty; proposed B. Clancy, seconded W. Upfold.

(All elected unopposed.)

Moved: B. Clancy, seconded: W. Upfold—" that the next meeting of the Branch to be held in conjunction with a barbeque on Saturday, 28th April, 1973, at Jervis Bay ".

The hole dug by the A.A.E.C. for its proposed reactor was thought to be of some interest.

The availability of Professor Keane for membership of the Science Centre Trustee Committee was established.

FINANCIAL STATEMENT, 1972——

	$
Previous Balance	45.95
1972 Funds from Sydney	50.00
	$95.95
Subsidy towards Annual Dinner ..	39.85
	$56.10
1973 Funds from Sydney	50.00
Present Balance	$106.10

Report of the New England Branch of the Royal Society of New South Wales

Officers:

Chairman: H. G. Royle.

Secretary-Treasurer: T. O'Shea.

Committee: R. L. Stanton, D. H. Fayle, N. H. Fletcher, I. Douglas.

Branch Representative on Council: R. L. Stanton.

Since the last report of October, 1971, the following meetings were held:

6th October, 1971: Professor N. C. W. Beadle, University of New England. " Vegetation and Conservation in the Australian Arid Zone ".

25th November, 1971: Dr. D. J. Swain, Division of Mineral Chemistry, C.S.I.R.O. "The Relevance of Geo-chemistry to Problems of the Natural Environment."

7th March, 1972: Professor H. M. Whyte, The Australian National University, Canberra. " The Role of Nutrition in Heart Disease."

30th March, 1972: Dr. J. Beardsley, University of Hawaii. " The Biological Control of Insects."

28th June, 1972: Professor W. Stephenson, Professor of Zoology, University of Queensland. " My Life and Hard Times with Computers."

3rd August, 1972: Professor Court, California State University at Northridge. " Recent Advances in Weather Prediction."

30th November, 1972: Dr. J. Sands, Senior Physician at Royal Prince Alfred Hospital, Sydney. " The Renal Dialysis and Transplant Patient/Medical, Social, and Psychological Problems."

Financial Statement:

	$	$
Balance at University of New England Branch, C.B.C. Sydney at 6th October, 1971..	375.66	
Credit		
Remittance from Royal Society of N.S.W., 1971	50.00	
Interest to 31st December, 1971 ..	6.71	
Interest to 29th June, 1972	7.19	
Interest to 29th December, 1 ..972	6.45	
Remittance from Royal Society of N.S.W., 1973	50.00	
		496.01
Debit		
Expenses visit Prof. H. M. Whyte ..	62.80	
Expenses visit Dr. J. Sands ..	42.00	
Expenses visit Dr. D. J. Swain ..	53.20	
		158.00
Balance at 8th May, 1973		$338.01

T. O'Shea,

1/5/73 *Secretary-Treasurer.*

THE ROYAL SOCIETY OF NEW SOUTH WALES
BALANCE SHEET AS AT 28th FEBRUARY, 1973

1972 $		$	$
	RESERVES		
8,898	Library Reserve ..		8,898.49
—	Resumption reserve—note 1		435,897.79
35,770	ACCUMULATED FUNDS ..		37,367.29
$44,668	NET FUNDS ..		$482,163.57
	Represented by:		
	CURRENT ASSETS		
1,227	Cash at bank and in hand	601.69	
—	Debtors for subscriptions—note 2	—	
—	Debtor for compensation—note 1	428,500.00	
338	Other current debtors ..	828.14	
5,929	Deposits at call—note 3	15,847.47	
7,494			445,777.30
	Less:		
	CURRENT LIABILITIES		
380	Sundry creditors and accruals ..	340.77	
99	Subscriptions paid in advance ..	80.35	
9	Life members' subscriptions—current portion..	8.40	
—	Provision for specific commitments—note 4 ..	420,000.00	
488			420,429.52
7,006	NET CURRENT ASSETS ..		25,347.78
	Add:		
	FIXED ASSETS—note 5		
1,865	Furniture and office equipment	1,771.72	
2	Lantern ..	2.00	
13,600	Library ..	13,600.00	
18	Pictures ..	16.77	
15,485			15,390.49
	INVESTMENTS—note 6		
19,280	Commonwealth bonds and inscribed stock ..	9,680.00	
—	Deposits at call ..	9,600.00	
19,280			19,280.00
	TRUST FUNDS—note 7		
7,000	Commonwealth bonds and inscribed stock ..	7,000.00	
2,342	Deposits at call ..	2,703.61	
9,342			9,703.61
	NON-CURRENT ASSETS		
2,419	Centenary volume	2,218.80	
559	Science centre project—note 4 ..	420,000.00	
2,978			422,218.80
54,091			491,940.68
	Less:		
	NON-CURRENT LIABILITIES		
9,342	Trust funds—note 7 ..	9,703.61	
81	Life members' subscriptions—non-current portion ..	73.50	
9,423			9,777.11
$44,668	NET ASSETS ..		$482,163.57

(The above balance sheet is to be read in conjunction with the notes attached.)

(Signed) J. W. PICKETT, Hon. Treasurer. J. C. CAMERON, President.

THE ROYAL SOCIETY OF NEW SOUTH WALES
INCOME AND EXPENDITURE ACCOUNT
FOR THE YEAR ENDED 28TH FEBRUARY, 1973

1972 $		$	$
2,900	NET SURPLUS for period before bad debts		1,848.50
	Less :		
(45)	INCREASE in provision for bad debts	.56	
67	SUBSCRIPTIONS written off	250.10	
22			250.66
2,878	NET SURPLUS for period		1,597.84
	Add :		
—	COMPENSATION re resumption Science House		438,000.00
63,362	ACCUMULATED FUNDS brought forward from 1972		35,769.45
66,240	FUNDS AVAILABLE		475,367.29
	Less :		
30,470	SCIENCE HOUSE—one-third capital cost	—	
—	TRANSFER to resumption reserve—note 1	438,000.00	
30,740			438,000.00
$35,770	ACCUMULATED FUNDS—28th February, 1973		$37,367.29

(The above account is to be read in conjunction with the notes attached.)

AUDITORS' REPORT TO THE MEMBERS

1. In our opinion : (*a*) The attached Balance Sheet and Income and Expenditure Account, together with the notes thereon, have been properly drawn up so as to correctly show the state of the Society's affairs at 28th February, 1973 and the surplus for the year ended on that date.

   (*b*) The accounting and other records have been properly kept in accordance with the Rules of the Society.

2. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

HORLEY & HORLEY,
Chartered Accountants.
Registered under the Public Accountants
Registration Act 1945, as amended.

65 York Street,
Sydney.
26th March, 1973.

THE ROYAL SOCIETY OF NEW SOUTH WALES
NOTES ON ACCOUNTS—28th FEBRUARY, 1973

1. RESUMPTION RESERVE.

Compensation offered by the Sydney Cove Redevelopment Authority re the resumption of Science House (see below)	$438,000.00
Less :	
Expenditure incurred to date re Science Centre Project	2,101.21
	$435,897.79
Compensation received to date	9,500.00
Owing by the Sydney Cove Redevelopment Authority	428,500.00
	$438,000.00

2. DEBTORS FOR SUBSCRIPTIONS.

1972 $		$
655	Owing by members	655.16
	Less :	
655	Reserve for bad debts	655.16
$ —		$ —

3. DEPOSITS AT CALL.

1972 $		$
5,256	General funds	15,130.50
673	Long service leave fund	716.97
$5,929		$15,847.47

4. SCIENCE CENTRE PROJECT.

The Society is currently planning a joint venture with the Linnean Society for the establishment of a Science Centre for New South Wales and $420,000 is the anticipated amount to be contributed by each Society.

5. FIXED ASSETS.

The basis adopted for the valuation of fixed assets is:

Furniture and office equipment	—cost less depreciation
Lantern	—cost less depreciation
Library	—1936 valuation
Pictures	—cost less depreciation

6. INVESTMENTS.

1972 $		$
9,680	General funds	9,680.00
9,600	Library fund	9,600.00
$19,280		$19,280.00

7. TRUST FUNDS.

	Clarke Memorial $	Walter Burfitt Prize $	Liversidge Bequest $	Ollé Bequest $
Capital	3,600.00	2,000.00	1,400.00	—
Revenue:				
Income for period	211.32	117.40	82.18	101.00
Less :				
Expenditure	—	150.00	—	—
	211.32	(32.60)	82.18	101.00
Balance from 1972	565.33	717.49	206.63	852.26
	$776.65	$684.89	$288.81	$953.26

THE ROYAL SOCIETY OF NEW SOUTH WALES
DETAILED INCOME AND EXPENDITURE ACCOUNT
FOR YEAR ENDED 28th FEBRUARY, 1973

1972 $				$
	INCOME			
3,143	Membership subscriptions—ordinary			3,015.00
9	—life members			8.40
33	Application fees			23.00
3,185				3,046.40
1,531	Subscriptions to journal			1,368.46
1,500	Government subsidy			1,500.00
$6,216	Total memberhips and journal income			$5,914.86
7,215	Science House management—share of surplus			6,717.40
1,552	Interest on general investments			2,087.62
107	Sale of reprints			312.81
62	Sale of back numbers			2,413.41
21	Commission			23.05
—	Donations			16.90
243	Summer school surplus			—
$15,416	TOTAL INCOME			$17,486.05
	Less :		$	
	EXPENDITURE			
300	Accountancy		300.00	
222	Advertising		271.10	
158	Annual social		131.50	
110	Audit		110.00	
50	Branches of the society		100.00	
90	Cleaning		101.20	
94	Depreciation		94.13	
75	Electricity		69.16	
19	Entertaining		38.00	
130	Insurance		135.13	
265	Library purchases		428.86	
231	Miscellaneous		258.19	
335	Postages and telegrams		439.19	
	Printing—Vol. 104, Parts 1-4	3,153.30		
	Binding	95.00		
	Postages	307.61		
1,646			3,555.91	
474	Printing, general and stationery		365.42	
4,150	Rent		4,215.00	
29	Repairs		29.33	
4,002	Salaries		4,815.12	
136	Telephone		180.31	
12,516	TOTAL EXPENDITURE			15,637.55
$2,900	NET SURPLUS for period			$1,848.50

Abstract of Proceedings

5th April, 1972

The one hundred and fifth Annual Meeting of the Society was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. M. J. Puttock was in the chair. There were present 59 members and visitors.

The President announced with regret the death of:

Sir Ronald S. Nyholm, honorary member (elected in 1940).

Dr. Francis Lions, life member (elected in 1929).

It was announced that Sir J. Philip Baxter had been elected honorary member of the Society at a Council Meeting on 23rd February, 1972.

Mina J. Rhodes (Mrs.) was elected a member of the Society.

The awards of the Society were announced as follows:

The Society's Medal for 1971 to Professor J. L. Griffith.

3rd May, 1972

The eight hundred and fifty-ninth (859) General Monthly Meeting of the Royal Society of New South Wales was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron was in the chair. There were present 80 members and visitors.

An announcement was made that due to the sudden illness of Mr. E. K. Chaffer (Hon. Secretary) it was agreed at a Council Meeting held on 26th April, 1972, that Mr. J. W. Humphries be appointed Hon. Secretary and that Mr. Chaffer be elected a member of Council.

The following were elected members of the Society. Norman Arthur Clayton, Ian Douglas, George Seddon, David Hayes Small.

The following papers were read by title only:

" The Geology of the Coolac Serpentinite and Adjacent Rocks East of Tumut, N.S.W. ", by P. M. Ashley, B. E. Chenhall, P. L. Cremer, A. J. Irving.

" Mineralogical Changes as Marker Horizons for Stratigraphic Correlation in the Narrabeen Group of the Sydney Basin, N.S.W. ", by C. R. Ward.

" On Hoyle's Electrodynamic Version of the Steady-State Cosmology ", by R. R. Burman.

" Palaeozoic Sedimentology and Igneous Geology of the Woolgoolga District, North Coast, New South Wales ", by R. J. Korsch.

" Note on Sandstone Dykes at Minchinbury, N.S.W. ", by G. S. Gibbons.

" Words, Actions, People: 150 years of Scientific Societies in Australia ", by D. F. Branagan (Sesqui-centenary address).

" Radiation Pressure and Related Forces ", by W. E. Smith (Presidential Address, 1971).

Address.—An address entitled " Researches in Archaeo-Gemmology " was delivered by Dr. Leo Koch.

7th June, 1972

The eight hundred and sixtieth (860) General Monthly Meeting of the Royal Society of New South Wales was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron was in the chair. There were present 32 members and visitors.

Mr. Ian George Percival was elected an associate member of the Society.

The following paper was read by title only:

" On the Motion of Particles in Conformally Flat Space Times ", by R. R. Burman.

Address.—An address entitled " Galileo and the Shapes of Venus " was delivered by Professor J. B. Thornton.

5th July, 1972

The eight hundred and sixty-first (861) General Monthly Meeting of the Royal Society of New South Wales was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron was in the Chair. There were present 18 members and visitors.

The President announced with regret the death of Dr. R. K. Murphy, member since 1915.

Address.—In the absence of Mr. R. A. Hall the address was delivered by Mr. D. G. Christy, Principal Veterinary Officer.

2nd August, 1972

The eight hundred and sixty-second (862) General Monthly Meeting of the Royal Society of New South Wales was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron, was in the chair. There were present 60 members and visitors.

The following papers were read by title only:

" Occultations observed at Sydney Observatory during 1971 ", by K. P. Sims.

" A gabbo-troctolite-anorthosite intrusion at Dirnaseer, near Temore, New South Wales ", by P. M. Ashley and A. J. Irving.

Address.—An address entitled " Congenital Anomalies " was delivered by Dr. W. G. McBride.

6th September, 1972

The eight hundred and sixty-third (863) General Monthly Meeting of the Royal Society of New South Wales was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron was in the chair. There were present 36 members and visitors.

The death was announced with regret of Emeritus Professor Oscar U. Vonwiller, member since 1903, Past President and Honorary Secretary.

Elizabeth A. Walsh was elected member of the Society.

Ross E. Pogson was elected associate member of the Society.

Address.—An addresss titled " Antarctic Glaciology Provides a Unique Insight into the Problem of Long Term Changes of Climate ", was delivered by Dr. W. F. Budd, Antarctic Division, Dept. of Supply, Commonwealth of Australia.

4th October, 1972

The eight hundred and sixty-fourth (864) General Monthly Meeting of the Royal Society of New South Wales was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron, was in the chair. There were present 120 members and visitors.

Mr. T. S. M. Ranneft was elected as a member.

Dr. A. Kalokerinos of Collarenebri delivered an audio-visual lecture entitled " Australian Precious Opal ".

1st November, 1972

The eight hundred and sixty-fifth (865) General Monthly Meeting of the Royal Society of New South Wales was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron, was in the chair. There were 35 members and visitors present.

The death was announced with regret of : Sir Charles Bickerton Blackburn and Sir Lawrence Bragg, both honorary members of the Society.

Address.—An address entitled " Environmental Effects of Supersonic Transports " was delivered by Dr. R. G. Hewitt, Department of Theoretical Physics, University of Sydney.

6th December, 1972

The eight hundred and sixty-sixth (866) General Monthly Meeting of the Royal Society of New South Wales was held in the Large Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron, was in the chair. There were present 39 members and visitors.

The death was announced with regret of Lionel Lawry Waterhouse.

The following members were elected, John Pallister Barkas and Allan Ross Chivas.

The following papers were read by title only :

" Astronomical Objects Embedded in Matter I—External Metrics ", " Astronomical Objects Embedded in Matter II—Light Tracks ", by R. R. Burman.

" Late Devonian (Frasnian) conodonts from Ettrema, New South Wales ", by J. W. Pickett.

" A Study of Root Concretions at Kurnell, N.S.W. ", by G. S. Gibbons and J. L. Gordon.

Address.—An address entitled " Dietary and Nutrition Problems in the 70's " was delivered by Dr. W. F. Clements, School of Public Health and Tropical Medicine at the University of Sydney.

Section of Geology

Abstract of Meetings, 1972

Five meetings were held during 1972, the average attendance being about 12 members and visitors.

MARCH 17th (Annual Meeting) :

(1) Election of office-bearers : Chairman, Dr. B. B. Guy ; Hon. Secretary, Mr. E. V. Lassak.

(2) Address by Dr. R. Wass : " Recent Bryozoans and their Environmental Significance ".

Bryozoa, especially the Cheilostomata were discussed. They are found between widely ranging parameters but their best development is within a restricted range of temperature, salinity and depth. The growth type may be dependant on substrate and sedimentation rate.

(3) Presentation of Notes and Exhibits.

Dr. Pickett exhibited several specimens illustrating the interaction of species by examples from the fossil record.

Mr. Lassak exhibited a specimen of crystallized mordenite from the Omo valley in Ethiopia.

MAY 19th :

Address by Mr. K. Maiden : " The Metamorphism of the Broken Hill Sulphide Ore Body ".

In the Broken Hill orebody, mesoscopic structures such as layering, brecciation and ore veins, can be interpreted in terms of processes occurring during high grade metamorphism. These processes include plastic flow of sulphides, fluid phase transport, partial melting and recrystallization. From the relationship between the various structures, a history of events during deformation and metamorphism can be erected.

JULY 21st :

Address by Mr. R. Fountain : " Rock Alteration at Panguna ".

The porphyry copper deposit at Pangunaon Bougainville Island occurs in an andesitic host rock. The three stages of porphyry recognized are associated with four stages of quartz veins. The copper mineralization is related to stage two prophyry.

SEPTEMBER 15th :

Address by Dr. P. C. Rickwood : " New Zealand's Subantarctic Auckland Islands ".

Dr. Rickwood described the history, geography and geology of the Auckland Island group. The islands appear to be the remnants of two (or possibly three) volcanoes. Adams Island in the south is the remaining rim of the southern volcano. The island is composed of alkaline basalts including numerous lava flows. Extremely inclement weather during the speaker's visit made detailed geological examination almost impossible.

NOVEMBER 17th :

Address by Dr. M. B. Katz : " Paired Metamorphic Belts of the Gondwanaland Precambrian and Plate Tectonics ".

Precambrian, granulite facies, paired metamorphic belts can be traced throughout the basement rocks of Gondwanaland. These belts can be divided into a Barrovian-Abukuma couple, which run side by side with lithological-structural-chronological continuity. Their pattern suggests plate tectonic interactions between Indian, Antarctic-Australian and African proto plates in the early Precambrian.

Citations

The Society's Medal for 1972

The Royal Society of New South Wales' own Medal for service to Science and to the Society is awarded to Walter Poggendorff, B.Sc.Agr.

Walter Poggendorff, formerly Chief of the Division of Plant Industry, N.S.W. Department of Agriculture, has made notable contributions to Australian plant breeding. He is well known particularly for his work in the development of new rice strains, also for the development of three new varieties of canning peaches, a new variety of apricot and the only new commercial grape ever developed in Australasia to this date.

Walter Poggendorff became interested in agriculture from a very early age. He attended Hurlstone Agricultural High School and attended the Hawkesbury Agricultural College where he graduated with diplomas in both Agriculture and Dairying.

In January, 1924, he was granted a cadetship with the New South Wales Department of Agriculture. He attended the University of Sydney where he studied under Professor R. D. Watt and Dr. Walter Waterhouse, both late members of the Society. He graduated in 1928. It was Walter Waterhouse who influenced young Walter Poggendorff towards the field of plant breeding, a field in which he was later to enjoy such great success.

Upon graduation Mr. Poggendorff was posted to the Yanco Experiment Farm with the specific task of developing rice for the then fledgling N.S.W. rice industry. His responsibilities were not confined to this pursuit alone, for he was entrusted with research into any other crops which could offer commercial potentialities in the district.

The next 13 years of plant beeding at Yanco were very dedicated, productive and happy ones. For it was during this period that his main object of developing new rice strains was realized, together with his research on new canning peaches and the new commercial grape, the latter being achieved after 10,000 seedlings yielded three possibilities from which one finally proved to be of commercial value.

Mr. Poggendorff, in his capacity as an advisor on rice production to the New South Wales Rice Marketing Board visited the United States of America and Mexico in 1935.

In 1941 due to the outbreak of World War II he was recalled to the Head Office of the New South Wales Department of Agriculture (Sydney) to take up the post of Special Agronomist—miscellaneous crops.

In this capacity he was responsible for the crop development and production control of drugs, fibres, essential oils and others. At the same time he still continued with plant breeding especially rice at Yanco.

Mr. Poggendorff was seconded to the Commonwealth and also to a private development company for work in Northern Australia, Papua-New Guinea and the Solomon Islands in 1952, 1955, and 1965.

For a short time he held an appointment as Special Agronomist (Irrigation) and in 1953 he represented Australia at the International Rice Conference organized by the Food and Agriculture Organization of the United Nations (FAO). In 1966 he was a representative on the International Rice Commission of FAO in New Delhi.

In 1947 Mr. Poggendorff became Chief of the Division of Plant Industry for the New South Wales Department of Agriculture.

Walter Poggendorff has also been active in the New South Wales Branch of the Australian Institute of Agricultural Science and was president of the New South Wales Branch in 1947.

For the Royal Society of New South Wales Walter Poggendorff has given freely of his time and services over a lengthy period, being a member of Council and Executive Council since 1957.

His most notable contribution has been in his role as Honorary Librarian—a position he has fulfilled since 1968—for it was during this period that the then librarian of the Society, Mr. A. F. Day, revised the Society's Library so thoroughly and efficiently, a process demanding many extra chores of the Honorary Librarian, Walter Poggendorff.

It gives me and the Council great pleasure in conferring on Walter Poggendorff the Society's Medal for 1972.

The Clarke Medal for 1972

The Clarke Medal is awarded for distinguished work in the Natural Sciences done in or on the Australian Commonwealth and its territories. It is considered annually and is awarded in the fields of Geology, Botany and Zoology in rotation.

The award for 1972 goes to Mr. Haddon F. King, Consultant Geologist to Riotinto Zinc Corporation and Conzinc Riotinto Australia.

Mr. Haddon F. King was born in British Guiana and obtained the Bachelor of Science degree in Mining Geology at the University of Toronto, Canada. He came to Australia in 1934 and worked for several years as a geologist with Western Mining Corporation in Western Australia. In 1946, after war service in the South West Pacific, he joined the staff of The Zinc Corporation at Broken Hill and in 1953 was appointed Chief Geologist to Consolidated Zinc Pty. Ltd. in Melbourne. In 1964, after the formation of Conzinc Riotinto (Australia) Mr. King was appointed Director of Exploration and a Director of C.R.A. Exploration Pty. Ltd.

In addition to his outstanding work as a mine geologist at Broken Hill, Mr. King has been associated with some of the major mineral discoveries of recent years, in Australia and its Territories. These include the iron ore deposits of the Hammersley Ranges and Mount Tom Price in Western Australia and the copper deposits of Bougainville in the Territory of Papua and New Guinea.

Notwithstanding his heavy commitments as an executive member of a large mining company Haddon King has found time to contribute very substantially, and very significantly, to fundamental and applied research on the problems of ore genesis—particularly the origin of stratiform sulphide ores. His interest in this problem arose at Broken Hill where he formulated his (now widely accepted) concepts on the origin of syngenetic-stratiform base-metal deposits. This led to several original (and at that time controversial) papers on the origin of the Broken Hill orebody. During his numerous overseas visits he has been able to demonstrate that orebodies in other parts of the world had an origin similar to that at Broken Hill. In this way he has laid the foundations of a theory of ore genesis that is now universally accepted. His research in this field has revolutionized concepts on the origin of layered sulphide ores and has opened up new approaches to the exploration for these deposits. In recognition of his contributions to ore genesis research Mr. King was awarded the Penrose Medal of the Society of Economic Geologists in the United States of America.

The Edgeworth David Medal, 1972

The Edgeworth David Medal is awarded for distinguished contributions by young scientists, under the age of 35 for work done mainly in Australia or its territories or contributing to the advancement of Australian science.

The award for 1972 is made jointly to Dr. Donald Harold Napper, Senior Lecturer in Physical Chemistry, University of Sydney, for his work in four fields of physical chemistry and Dr. Jonathan Stone, for his work on certain aspects of the visual system.

Dr. Donald Harold Napper

Dr. Napper graduated as a Bachelor of Science with First Class Honours in Physical Chemistry from the University of Sydney in 1959, sharing the University Medal. He became a Master of Science at the same University in 1960 and obtained his Doctorate of Philosophy at Cambridge University in 1963.

From 1963–1966 he was a research officer at the Colonial Sugar Refining Company Research Laboratories, East Roseville, N.S.W., and from 1966 to 1968 he held a joint appointment as Lecturer in Physical Chemistry at the University of Bristol and as Research Officer in the Paints Division of Imperial Chemical Industries at Slough in the United Kingdom. He returned to the University of Sydney in 1968 as Queen Elizabeth II Research Fellow in the Department of Physical Chemistry, in which Department he is now a senior lecturer.

The research studies for which he received the Edgeworth David Award for 1972 fall into four main subject categories: polymerization kinetics, steric stabilization, dissolution kinetics and light scattering. Except for the light scattering studies which he carried out in England, most of this research was carried out in Sydney.

Dr. Napper's studies on steric stabilization which have been carried out in the last five years, are the most extensive and, in a sense, the most pioneering of those listed in the award. Steric stabilization refers to the stabilization against flocculation imparted to colloidal particles by non-ionic macromolecules. Although this phenomenon was well-known in early Egyptian technology, a proper understanding of its origins was lacking until recently.

The preparation of model sterically stabilized dispersions permitted a thorough investigation of the phenomenology of flocculation to be made. The application of modern theories of the thermodynamics of polymer solutions resulted in a quantitative theory of steric stabilization. Its predictions appear to be in accord with experiment.

The studies of the kinetics of polymerization were designed to clarify the role of surfactants in emulsion polymerizations. It was shown that, in addition to controlling colloid stability, surfactants may exert additional effects due to their charge (if ionic) or their polymeric nature (if non-ionic).

His studies in the field of Dissolution Kinetics of hydro-oxyapatite (which is the major inorganic component of teeth or bones) were undertaken in the research laboratories of the Colonial Sugar Refining Company. These fundamental studies were designed to establish possible mechanisms by which calcium sucrose phosphates (known commercially as "Anticay") can reduce the incidence of dental caries in children, as shown by clinical trials. A plant to manufacture "Anticay" on a commercial scale is currently being erected in Sydney.

The light scattering studies examined both experimentally and theoretically the scattering behaviour of particles containing edges and corners. It was shown how to handle such particles theoretically, at least in certain limiting cases.

Dr. Jonathan Stone

The greater part of Dr. Stone's work has been concerned with the structure and function of the retina and the visual pathways in the brain. The general aim of the work is to understand the functioning of the nervous system at the level of the single cell. In particular he has been concerned with the complex neuronal connections and circuits at the various levels in the visual pathway by which the cells code, transmit and analyse visual information.

Dr. Stone began his work on the visual system in 1962 when, as an undergraduate in the Faculty of Medicine at Sydney University, he spent an additional year in the Department of Physiology in order to take the degree of Bachelor of Science (Medical). He already had a distinguished record as a medical undergraduate. Nevertheless, his first experience in research made such a deep impression on him that he decided to embark immediately on a research career in neurophysiology without waiting till he had completed the clinical years of the medical course. He enrolled immediately as a candidate for the Ph.D. degree and he was still only 23 when he submitted his thesis for the degree.

His Ph.D. thesis was a remarkable achievement, leading to the publication of his first six papers. The quality of this work can be judged from the fact that Dr. Stone shared the award of the University of Sydney's P. J. Bancroft Prize for Medical Research in 1966.

Dr. Stone was responsible for the entirely new and important discovery of the presence of a naso-temporal overlap in the retina. This organization of the retina enables a vertical strip of ganglion cells centred on the vertical midline of the retina to send their axons to both cerebral hemispheres. This finding has since been confirmed by others using physiological methods and working at the levels of the lateral geniculate nucleus and the visual cortex. More recently Dr. Stone has again returned to this problem and, with his collaborators, he has now shown that this naso-temporal overlap is also present in the monkey, making the finding particularly relevant to human vision. The importance of Dr. Stone's discovery is that this overlap is a basic element in the binocular mechanisms which are now believed to be responsible for stereoscopic vision.

In his immediate post-doctoral year Dr. Stone made a detailed study of the dendritic morphology of ganglion cells in the retina and began the further study of the geniculate nucleus and cortex. These concepts of cortical function have challenged previous concepts which have envisaged only a hierarchical serial type of processing of information in the primary visual pathway.

Dr. Stone's work is very well known abroad and he has already earned for himself a high international reputation. Even as a graduate student working for the Ph.D. degree he showed himself to be a gifted and independent research worker. Since he has been in Canberra he has had a number of post-doctoral fellows from overseas working in collaboration with him, though there is no doubt that he has been the principal investigator and driving force in their various studies.

The Archibald D. Olle Prize

The Archibald D. Olle Prize may be awarded annually by the Council to a member of the Society who has submitted the best paper for publication in the Journal of the Society.

No award was made for the current year.

The James Cook Medal

The James Cook Medal may be awarded for outstanding contributions to Science and Human Welfare in and for the Southern Hemisphere.

No award was made for the current year.

Obituaries

Professor Oscar Ulrich Vonwiller

Professor Vonwiller joined the Royal Society of New South Wales in 1903, after obtaining his Bachelor of Science degree with First Class Honours in both physics and mathematics from the University of Sydney. Shortly afterwards, he started his career at the University of Sydney as a Demonstrator in Physics, was appointed to Assistant Lecturer in 1903 and became temporary Head of the Physics Department from 1914 to 1918 during Professor Pollock's absence on active service overseas. After Professor Pollock's death in 1922 O. U. Vonwiller was appointed to the Chair of Physics at the University of Sydney in 1923, a position he held until his retirement at the end of the Second World War.

During his retirement Professor Vonwiller chose a quiet life in the country. He mostly enjoyed good health until his death on 17th July, 1972.

Since 1903 Professor Vonwiller entertained a long and close relationship with the Royal Society of New South Wales. For a number of years (1923, 1924, 1927, 1928 and 1948) he loyally served the Society as an Honorary Secretary. During 1930 he held the office of President and delivered the first presidential address in the then new home of the Society : Science House, Sydney.

His presidential address was primarily concerned with the future of the Society, its aim and its purpose : a theme still very appropriate and alive in our present days of change. Professor Vonwiller stressed the important role the Society should and could play, a role that to-day is still as promising as it was then, i.e. " showing the people and their representatives the possibilities, and the limitations, of scientific endeavour ".

The year Professor Vonwiller held the presidential chair of the Society saw also the first Liversidge Memorial Lecture being delivered, a lecture which since has become famous and of a high integrity.

Clive Melville Harris

Clive Melville Harris, a member of the Society since 1948, died suddenly on 16th February at the comparatively early age of forty-six.

Soon after leaving Sydney High School in 1943, he joined the staff of the Museum of Applied Arts and Science and began studying in the evening for the Chemistry Diploma of Sydney Technical College. While still an undergraduate, he carried out investigations, the results of which were subsequently published in the Proceedings under the title " The Coordination Compounds of Copper " (1949, **52**, 281). This was the first of a series of papers that appeared in the Proceedings over the next few years. He was awarded a credit diploma in 1948.

In the following year he joined the staff of Sydney Technical College as a teacher of chemistry. In 1952, after graduating with an honours B.Sc., he was appointed lecturer in chemistry at the newly established University of Technology (later the University of New South Wales). He was awarded the degree of Doctor of Philosophy in 1955 and subsequently became a senior lecturer. He was appointed an Associate Professor in 1963, a position he held at the time of his death.

Altogether, he published somewhere between 60 and 70 original scientific papers on coordination compounds. He was especially interested in their magnetic properties and the relation of these to their atomic and molecular structure. For a thesis entitled " Studies in Unusual Coordination Numbers, Stereochemistries and Magnetic Properties of Metal Complexes ", the University of New South Wales in 1969 conferred on him the degree of Doctor of Science.

Harris was able to attract as research collaborators some of the most able men and women who were then passing through that university's School of Chemistry. He was, of course, not entirely preoccupied by science ; he was very fond of classical music and poetry and wrote, though he did not publish, a considerable amount of verse. He was a friendly man with a keen sense of humour. His sudden death shocked and greatly saddened his many friends. D.P.M.

Sir Charles Bickerton Blackburn

Sir Charles Blackburn, Chancellor Emeritus of the University of Sydney, N.S.W., and Honorary Member of the Royal Society of New South Wales since 1960, died on 20th July, 1972, at the age of ninety-eight.

Sir Charles was born at Greenhithe, Kent, in 1874. He attended the University of Adelaide, where he was awarded the Bachelor of Arts degree in 1893, and studied medicine at the University of Sydney, graduating M.B., Ch.M. in 1899 and M.D. in 1903. He was appointed to Royal Prince Alfred Hospital in 1899 as a Resident Medical Officer, and was Medical Superintendent from 1901 to 1904. From then until 1911 he was an Honorary Assistant Physician there, and Honorary Physician from 1911 to 1934, after which he was Honorary Consultant. He was also an Honorary Consultant to Prince Henry Hospital for almost thirty years. From 1912 to 1934 he was Lecturer in Clinical Medicine in the Faculty of Medicine in the University of Sydney, and from 1932 to 1935 was Dean of the Faculty.

Sir Charles was a Fellow of the Royal Australian College of Physicians and was President of that body in 1938. He was a Fellow also of the Royal College of Physicians and the Royal College of Physicians, Edinburgh. He was elected to the Branch Council of the B.M.A. in 1910 and was its President in the year 1920–21. He was awarded Honorary degrees by the Universities of New South Wales, New England, Melbourne, Tasmania, Queensland, Western Australia and Sydney.

He saw active service in the First World War as Lieutenant-Colonel in the Australian Medical Corps, was twice mentioned in despatches, and was awarded the O.B.E. In the Second World War Sir Charles again held active rank as Lieutenant-Colonel at 113th Australian General Hospital, Concord.

He was created a Knight Bachelor in 1936 and a Knight Commander of the Order of St. Michael and St. George in 1960.

In March, 1965, the Senate, by resolution, conferred on Sir Charles the title of Chancellor Emeritus, and in November of the same year he was awarded the degree of Doctor of Letters (*honoris causa*) in recognition of his services to the University.

(With acknowledgement to *The Gazette, University of Sydney*, September, 1972.)

Sir Lawrence Bragg

In the summer of 1912, W. L. Bragg, then a student at Cambridge, re-interpreted the X-ray (Laue) photographs which had been published by the Munich group earlier that year. With this achievement, he established a subject of wide-ranging significance with which he continued to be identified actively up to his death on 1st July, 1971.

For this work, he shared with his father, W. H. Bragg, then professor of physics at Leeds, the Nobel Prize for Physics in 1915, given " for their services in the analysis of crystal structure by means of X-rays ". His subsequent career established very clearly his right to this honour.

His was, in fact, an astonishing career in its length, its diversity, and its influence. It is difficult to appreciate the full impact on the science and technology of our present society of the work of Bragg and of the many research workers who derived from Sir Lawrence or his father, Sir William. One obvious reason is that it is almost impossible for us to return to the state of knowledge concerning the structure of matter which pertained in 1912 and thus to realize again the changes wrought and contributed to by X-ray diffraction during the intervening 60 years. Physics, chemistry, mineralogy, metallurgy and biology were all transformed, while new subjects such as chemical physics and molecular biology have been created whose existence can be related in large measure to the brilliant and seminal contributions of Sir Lawrence Bragg.

His investigations in the short period between 1912 and 1914 established the structures of zincblende, fluorspar, iron pyrites, calcite, dolomite and metallic copper. This activity was interrupted by the First World War. Bragg joined the cavalry and was engaged, *inter alia*, in the use of sound-ranging for the location of gun batteries.

After the war, he succeeded Rutherford at Manchester. Here, two main lines of work developed, one on the structure of silicates and the other on the relationship of the intensities of X-ray reflections and the state of periodic perfection of crystals. The former, probably better known, demonstrated the varied mode of linkage of SiO_4 tetrahedra by sharing corners, edges and faces to produce the diverse range of silicate structures based on linear, sheet or three-dimensional arrangements. The basic structural theme thus established has been elaborated since then in other inorganic oxide structures and, from this work, generalizations of wide-ranging implication followed.

The second interest belonging to this period involved a valuable association with C. G. Darwin and R. W. James. Darwin had, in 1914, written definitive theoretical papers on the relationship between structure (factor), F, and intensity, I. The experimental results were found in many cases to deviate from the predictions of the early theory and part of the theory was modified to take account of the inner morphology of the crystal. For the " perfect " crystal, $I \propto F$ and for the " ideally mosaic " crystal, $I \propto F^2$. Real crystals mostly lay somewhere between these two extremes. The resolution of this situation in a practical manner was of vital concern in order to yield direct information concerning the distribution of electrons around atoms, particularly with the provision by D. R. Hartree, at this time, of improved theoretical scattering factors. Bragg, with James and Bosanquet, therefore carried through very careful experiments to determine accurate structure factors for NaCl, devising methods of estimating the effect of " extinction " on the observed intensities. As a result of this work, a small meeting was held at Holzhausen in Bavaria in 1925, organized by P. P. Ewald, to discuss which was the proper relationship under specific circumstances, $I \propto F$ or F^2. The situation at that time was summarized by Bragg, Darwin and James in the *Philosophical Magazine* in 1926. For the majority of structure analyses in the next 15–20 years, using small crystals, it was assumed that, essentially $I \propto F^2$. On this basis an immense amount of structural information was derived. With the increasing use of quantum counters for single crystal intensity measurement in the late 50's and early 60's the question of accuracy and its allied problem, the relationship of intensity, I, and structure factor, F, was once more of importance. This led to the holding of an International Meeting on Accurate Determination of X-ray Intensities and Structure Factors in Cambridge in 1968 and it was entirely appropriate that Sir Lawrence opened this with recollections of the earlier work.

After his work on the silicates, summarized in *Atomic Structure of Minerals* (1937), his interest turned to the structure of metals, mainly in relation to order-disorder phenomena, much of this work being carried out with E. J. Williams. During this period he moved from Manchester to the National Physical Laboratory, and shortly after to the Cavendish. While still continuing his work on metals, it was during 1939 that he became more closely interested in the X-ray photographs of haemoglobin which M. F. Perutz had been engaged in taking. At this time the task of solving the structure of proteins seemed to many a completely hopeless endeavour. There were even those who felt that proteins were not homogeneous enough to yield identifiable atomic positions. There was, however, no doubt in Bragg's mind and he gave Perutz his full support and encouragement. With this sustained backing, Perutz and his associates gradually began to find out how to cope with the special problem posed by this new scale in structure analysis. Looking back, a critical first stage is indicated by the important letter to *Nature* in 1942 by Perutz and Boyes-Watson. Then in 1954 came the breakthrough when Perutz showed that the " heavy atom " method which had proved so valuable for smaller molecules could work also for proteins. From then on, the task of analysing the mass of diffraction data became feasible and the structures of myoglobin (Kendrew) and of haemoglobin (Perutz) were solved in the Medical Research Council unit, located then in the Cavendish. With this step (to which Bragg himself made contributions relating to the phase problem) the remarkable development of X-ray structure studies—from ZnS to proteins—reached a new height, again presided over by Sir Lawrence.

It was of course only a little later that Crick and Watson in the Cavendish demonstrated the power of X-ray techniques by re-interpreting the data of Wilkins and determining the structure of DNA.

Circa 1954 Bragg moved from the Cavendish to the Royal Institution and set up there a small group on protein structures under D. C. Phillips. It was this group that achieved for Bragg's 75th birthday the completed analysis of the third protein to be solved—the enzyme, lysozyme.

It was at the Royal Institution that his 80th birthday was celebrated with the Bragg Symposium 1970 in March of that year. The subjects dealt with were those to which he had contributed during his long life—minerals, metals, methods of analysis, and big molecules. As well as the presentation of scientific papers with Bragg himself as one of the most alert listeners and questioners, there was a fascinating display of his correspondence and papers particularly relating to the early era.

Sir Lawrence had always been an excellent and popular speaker, but during his period at the R.I. he further developed his interest in the popularization of science. He instituted a series of lectures which were attended by 22,000 school children each year.

The clear grasp of basic physical principles which characterized his approach to research also are illustrated by the models which he devised—the bubble raft model of metals, the X-ray microscope, and the fly's eye.

In a real sense, Sir Lawrence and his subject of X-ray diffraction were perfectly matched. His astute powers of piercing through the apparent complexities to their underlying simplicity were ideally adapted to this technique—a technique which is experimentally simple, and yet, in interpretation, both robust and subtle so that it has been capable of transforming whole subjects. He was indeed the *persona* of his subject.

With the death of Sir Lawrence Bragg, we seem to see the passing of a golden scientific era of expanding opportunities, of the discovery of new and exciting techniques, and of their application to matter in all its forms, elemental, inorganic, organic, biological. Some of us have been fortunate to have lived through at least part of this era and to have seen some of the developments take place in X-ray diffraction in these 60 years. All scientists owe him an immense debt.

A.McL.M.

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THE ROYAL SOCIETY OF NEW SOUTH WALES

The Society originated in the year 1821 as the Philosophical Society of Australasia. Its main function is the promotion of Science through the following activities: Publication of results of scientific investigation through its Journal and Proceedings; the Library; award of Prizes and Medals; liaison with other Scientific Societies; Monthly Meetings; and Summer Schools. Special meetings are held for the Pollock Memorial Lecture in Physics and Mathematics, the Liversidge Research Lecture in Chemistry, and the Clarke Memorial Lecture in Geology.

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ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 107

PARTS 1-4

1974

PUBLISHED BY THE SOCIETY,
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

Royal Society of New South Wales

OFFICERS FOR 1974-1975

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The Royal Society of New South Wales originated in 1821 as the "Philosophical Society of Australasia"; after an interval of inactivity it was resuscitated in 1850 under the name of the "Australian Philosophical Society", by which title it was known until 1856, when the name was changed to "Philosophical Society of New South Wales". In 1866, by the sanction of Her Most Gracious Majesty Queen Victoria, the Society assumed its present title, and was incorporated by Act of Parliament of New South Wales in 1881.

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Science House, Gloucester and Essex Streets, Sydney
Issued 5th June, 1974

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Abstract.

References—alphabetical list.

Captions for illustrations.

Shortened title, if necessary.

In addition one fair copy of all illustrations for final reproduction, together with one set of all illustrations, of same size or smaller than the fair copies, for the use of the referees.

Papers should be prepared according to the general style adopted in this journal. They should be as concise as possible consistent with adequate presentation and, other than those specially invited by Council, they will only be considered for publication if the content is substantially new material not previously published or submitted concurrently elsewhere.

Manuscripts should be typed in double spacing with generous margins. Headings should be typed without underlining and, if a paper is long, the headings should also be given in a Table of Contents typed on a separate sheet for the guidance of the Editor. Spelling shall be in accordance with the Concise Oxford Dictionary. The Title should be as concise as possible yet clearly stating the nature of the communication, and if the title is long a shortened title of not more than 50 letters should be given for reproduction at the head of each printed page.

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Tables should be typed on separate sheets and column lines should *not* be ruled in. Units of measurement should always be indicated in the headings of the columns or rows to which they apply. Tables shall be numbered (serially) and should preferably be given a caption.

Illustrations. Diagrams and graphs shall be in *Indian ink* on tracing cloth, tracing paper or white card and lines shall be bold enough to permit appropriate reduction.

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All letters shall be inserted on illustrations using plain upright capitals (lower case for units where appropriate). Lettering shall be clear and open and preferably be drawn with the aid of a stencil. After reduction capital letters and numbers shall be between 1·2 mm and 2·0 mm high. Preferred reductions are $\frac{1}{2}$ and $\frac{1}{4}$.

Maps should not be larger, when reduced, than two pages of the printed journal. All information, legends, symbols, etc., should be within the frame of the map.

Authors are requested to indicate clearly for all illustrations the scale of reduction they require.

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References are to be cited in the text by giving the author's name and year of publication, e.g. Bragg (1933). At the end of the paper all references shall be given in a list in alphabetical order and each shall comprise the author's name and initials, year of publication, abbreviated title of journal, volume number and first page.

Reprints may be purchased provided they are ordered by the author when returning the galley proofs. An author who is a member of the Society will receive 25 reprints of his paper free.

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 1–5, 1974

Sympathomimetic Tertiary Amines

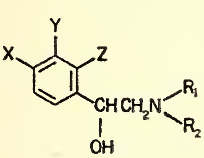
Robert A. Buist and Lyall R. Williams

Abstract—A series of arylamino ketones and phenylethanolamines containing different combinations of aryl substituents and a variety of cyclic tertiary amino groups have been synthesized. The results of preliminary biological testing reveal that many of the series exhibit β-adrenoreceptor agonist activity while several also exhibit concomitant α-adrenoreceptor antagonist activity.

Introduction

Once it was established that dilation of the bronchial smooth muscle was mediated by the activation of the β-adrenergic receptors, most chemical and pharmacological research associated with the therapeutic use of bronchodilator agents has centred on the development of drugs with a β-adrenoreceptor agonist activity.

As a result of this effort sympathomimetic amines that relax bronchial smooth muscle by stimulation of β-adrenoreceptors such as isoprenaline (I, X, Y=OH, Z=H and R_1=H, R_2=$-CH(CH_3)_2$) and more recently salbutamol (Cullum, Farmer, Jack and Levy, 1969) (I, X=OH, Y=CH_2OH, Z=H and R_1=H, R_2=$C(CH_3)_3$) which can exert some degree of selectivity for bronchial over cardiac muscle, have been developed and successfully used as bronchodilators.



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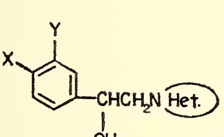

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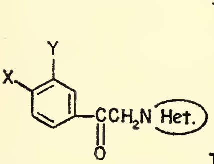


III

The experimental findings of several investigators have led to the suggestion that there might be a fine balance in bronchial smooth muscle between β-receptor stimulation causing bronchodilation and α-receptor stimulation causing bronchoconstriction (Szentivanyi, 1968; Cho, Aviado and Lish, 1968). Since then the existence of α-receptors in the bronchial smooth muscle of the human respiratory tract has been demonstrated (Mathé, Aström and Persson, 1971) thus lending strong support to the hypothesis. It was decided to attempt to design a series of compounds which would have not only β-agonist activity but also a mild α-antagonist activity. Compounds with these properties could have potential as new bronchodilator agents and in addition may have useful applications in the study of the role of α-receptors in bronchial smooth muscle.

Structure-Activity Studies

The structural requirements for maximal β-adrenoreceptor agonist activity are well documented: A phenylethylamine backbone requires 3′, 4′-dihydroxy substituents in the aryl ring, a secondary amino substituent and a 2-hydroxyl group on the ethyl side chain (Barlow, 1964). A study of the structure-activity relationship of the known β-adrenoreceptor agonists and α-adrenoreceptor antagonists was then undertaken to search for areas of comparability so that we could attempt to modify the optimum structural requirements for β-agonist activity to accommodate the additional α-antagonist activity.

α-Adrenergic blocking agents with a skeletal structure similar to isoprenaline have been studied by Chapman, Clarke and Harvey (1971). The most powerful of these contained a 2-halogen atom and a tertiary amine substituent, neither of which favours β-agonist activity, but other of their tertiary amine derivatives containing a 2-hydroxyl exhibited mild α-antagonist effects (I, X, Y=H, Z=CH_3, R_1=R_2=CH_3). Further examples of 2-hydroxyphenethyl amine derivatives with mild α-antagonist activity were found in a series of compounds reported by Carron, Jullien and Bucher (1971) and in this case the aryl substituent was more compatible with β-agonist activity requirements.

As other cyclic tertiary amine derivatives prepared by Heinzelman and Aspergren (1953) (II, X, Y=OH; pyrrolidine) and Larson and co-workers (1967) (II, X=OH, Y=$NHSO_2CH_3$; piperidine) possessed mild β-agonist activity it was decided to synthesize and evaluate the biological properties of a series of phenethanolamine derivatives with a variety of ring substituents and containing cyclic tertiary amines on the side chain.

Chemistry

The required phenylethanolamines (see Table 2) were prepared by reduction of the corresponding arylamino ketones III (see Table 1).

The synthesis of the hydrohalide salts of the mono-hydroxy and the 3′, 4-dihydroxyphenyl amino ketones (III, X=OH, Y=H; X=H, Y=OH and X=OH, Y=OH) proceeded via the reaction of halogenated acetophenones (commercially available or prepared by the bromination of the corresponding acetophenones with cupric bromide) with the various secondary amines using 2-propanol as solvent. Catalytic reduction (Pd–C/H_2) of the arylamino ketone salts in ethanol gave the phenethanolamines which crystallized as their hydrohalide salts.

The 4-hydroxyphenyl and the 3, 4-dihydroxyphenyl morpholino compounds (1, 4, 13 and 16) (Rubin and Day, 1940) and the 3, 4-dihydroxy pyrrolidino compounds (3, 15) (Heinzelman and Aspergren, 1953) have been described previously. The evaluation of their biological properties was not reported in sufficient detail to be of use to us and so they have been included in the present study.

Our melting point of 176–177° for 1-(3, 4-dihydroxyphenyl) 2-morpholino ethanol hydrochloride (13) is considerably lower than the value of 250° reported by Rubin and Day.

Compositional analysis figures for nitrogen and chlorine only were given for the compound with m.p. 250°, and as these are not sufficient to differentiate between the ketone and the alcohol, we suggest that the high melting point may indicate incomplete reduction. Consideration of our Tables 1 and 2 reveals that the alcohols have lower melting points than the parent ketone derivatives. Detailed spectral analysis has confirmed the purity and structure of our compound. In the n.m.r. spectrum reduction of compound (1) caused a shift of the methylene protons adjacent to the carbonyl from 4·95 ppm to 3·5 ppm with the six methylene protons adjacent to the nitrogen atom then having the same chemical shift. A triplet appeared at 5·2 ppm (1 proton CH(OH)) and in addition the deshielding effect of the carbonyl group on the adjacent aromatic protons was removed. The three aromatic protons of (1) at 7·6 ppm (doublet J 9·0 c/s), 7·4 ppm (singlet) and 7·0 ppm (doublet J 9·0 c/s) were all found at 7 ppm in the reduced

Table 1
Arylamino Ketones III

No.	X	Y	N Het	Yield %	Crystn Solvent[a]	Mp, °C	Formula	Analysis[b]
1	OH	OH	morpholino	69	A–D	227–228dec[c]	$C_{12}H_{15}NO_4$.HCl	C, H, N, Cl
2	OH	OH	piperidino	60	A–D	237–238dec	$C_{13}H_{17}NO_3$.HCl	C, H, N, Cl
3	OH	OH	pyrrolidino	60	A–B	244–245dec[d]	$C_{12}H_{15}NO_3$.HCl	C, H, N, Cl
4	OH	H	morpholino	75	A–B	230–235[e]	$C_{12}H_{15}NO_3$.HCl	C, H, N, Cl
5	OH	H	piperidino	72	A–B	254–255dec	$C_{13}H_{17}NO_2$.HCl	C, H, N, Cl
6	OH	H	pyrrolidino	59	A–B	233–234dec	$C_{12}H_{15}NO_2$.HCl	C, H, N, Cl
7	H	OH	morpholino	56	C	242–244dec	$C_{12}H_{17}NO_3$.HBr	C, H, N, Br
8	H	OH	piperidino	52	A–D	235–237dec	$C_{12}H_{17}NO_2$.HBr	C, H, N, Br
9	OH	OH	[f]	65	B	198–199dec	$C_{12}H_{20}N_2O_4$.HCl	C, H, N, Cl
10	OH	H	[f]	66	A	165–166dec	$C_{14}H_{20}N_2O_3$.HCl	C, H, N, Cl
11	OH	CO_2Me	morpholino	64	B–E	178–179dec	$C_{14}H_{17}NO_5$.HCl	C, H, N, Cl
12	OH	CO_2Me	piperidino	51	B–E	162–165dec	$C_{15}H_{19}NO_4$.HCl	C, H, N, Cl

[a] A, ethanol; B, methanol; C, 2-propanol; D, H_2O; E, Petroleum Ether 40–60°.
[b] Analyses are indicated only by the symbols of the elements, analytical values obtained were within ±0·4% of the calculated values.
[c] Rubin and Day reported m.p. 224–225° dec. (corr.).
[d] Heinzelman and Aspergren reported m.p. 244° dec.
[e] Rubin and Day reported m.p. 242–243° (corr.).
[f] N-β-hydroxyethyl piperazino.

TABLE 2
Phenylethanolamines II

No.	X	Y	N Het	Yield %	Crystn Solvent[a]	Mp, °C	Formula	Analysis[b]
13	OH	OH	morpholino	78	A–B	176–177dec[c]	$C_{12}H_{17}NO_4.HCl$	C, H, N, Cl
14	OH	OH	piperidino	74	C	157–158dec	$C_{13}H_{19}NO_3.HCl$	C, H, N, Cl
15	OH	OH	pyrrolidino	65	A	166–167dec[d]	$C_{12}H_{17}NO_3.HCl$	C, H, N, Cl
16	OH	H	morpholino	75	A–B	172–173dec[e]	$C_{12}H_{17}NO_3.HCl$	C, H, N, Cl
17	OH	H	piperidino	76	A	171–172dec	$C_{13}H_{19}NO_2.HCl$	C, H, N, Cl
18	OH	H	pyrrolidino	55	A–B	175–176dec	$C_{12}H_{17}NO_2.HCl$	C, H, N, Cl
19	H	OH	morpholino	58	C	128–129dec	$C_{12}H_{17}NO_3.HBr$	C, H, N, Br
20	H	OH	piperidino	61	A	121–122	$C_{13}H_{19}NO_2.HBr$	C, H, N, Br
21	OH	H	[f]	82	C	140–142dec	$C_{14}H_{22}N_2O_3HCl$	C, H, N, Cl
22[g]	OH	CH_2OH	morpholino	78	C	130–131	$C_{13}H_{19}NO_4$	C, H, N
23[g]	OH	CH_2OH	piperidino	50	C	112–113	$C_{14}H_{21}NO_3$	C, H, N

[a] A, ethanol; B, methanol; C, 2-propanol.
[b] Analyses are indicated only by the symbols of the elements, analytical values obtained were within ±0·4% of the calculated values.
[c] Rubin and Day reported m.p. 250° dec. (corr.).
[d] Heinzelman and Aspergren reported m.p. 168–169°.
[e] Rubin and Day reported m.p. 178° (corr.).
[f] N-β-hydroxyethyl piperazino.
[g] Prepared as the free base.

compound. The mass spectrum of the alcohol gave a peak at m/e 239 corresponding to the free base and the infra-red indicated that the carbonyl stretching band at 1,685 cms^{-1} had been removed.

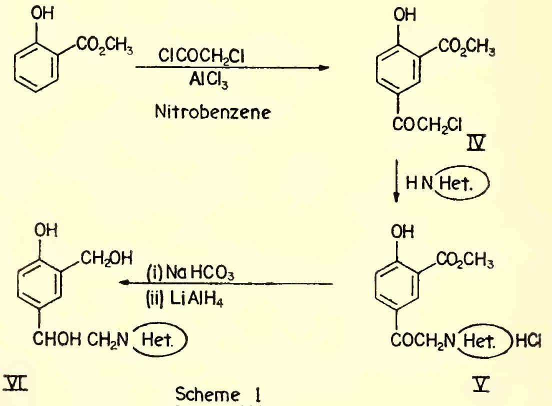
The tertiary amino analogues of salbutamol were prepared via the methyl salicylate IV (see scheme 1). The reaction sequence outlined in the scheme represents a shorter and more convenient pathway to salbutamol analogues than that reported by Collin and co-workers (1970), who synthesized methyl 5-bromoacetyl salicylate by the Fries rearrangement of the corresponding phenolic esters of salicylic acid followed by esterification and bromination steps.

We have been able to prepare methyl-5-chloroacetyl salicylate IV in one step in good yield by the Friedel-Crafts reaction of methyl salicylate with chloroacetyl chloride using nitrobenzene as solvent.

The chloro compound condensed readily with the secondary amines to give yields of the amino ketone salts V comparable to those obtained from methyl 5-bromoacetyl salicylate. Reduction of the ketone and ester groups of V was best performed on the free base with lithium aluminium hydride in ether. The saligenin derivatives VI were isolated by continuous extraction with chloroform.

Pharmacological Screening

The compounds were screened for β-adrenergic activity using isolated organs of the guinea pig (tracheal chains and atria) and α-adrenergic blocking activity using isolated guinea pig vas deferens. Several of the phenylethanolamines showed variable β-agonist and α-antagonist activity which was dependent upon the type of ring substituent and amine group, whereas the arylamino ketones in general showed no activity in the test systems used. A more detailed account of the results of the pharmacological tests will be reported elsewhere.



Scheme 1

Experimental

Microanalyses were carried out by the Australian Microanalytical Service, Melbourne. Infrared spectra were measured on a Perkin-Elmer 621 spectrometer, and n.m.r. spectra at 60 Mc/s in $CDCl_3$ or D_2O on a Varian A–60D spectrometer. Mass spectra were measured on an A.E.I. MS–12 spectrometer. Melting points were determined in open capillary tubes on a Gallenkamp Melting apparatus and were uncorrected. The secondary amines were obtained from Aldrich Chemical Company, Inc.

The numbers referred to in this section correspond to those shown in Tables 1 and 2.

N-(3′, 4′-dihydroxyphenacyl) piperidine hydrochloride (2)

Piperidine (42·5g, 0·5 mole) and α-chloro 3′, 4′-dihydroxyacetophenone (46·6g, 0·25 mole) were dissolved in 2-propanol (250 ml.) and heated under reflux for 3 hours. Hydrogen chloride gas was passed into the cooled reaction mixture and the brown solid that formed was isolated by filtration. Recrystallization from ethanol (95%) using charcoal gave (2) as colourless needles (37·5g, 55·2%) with m.p. 237–238° dec. (Found: C, 57·73; H, 6·85; Cl, 12·7; N, 5·22. $C_{13}H_{18}ClNO_3$ requires C, 57·46; H, 6·68; Cl, 13·0; N, 5·15%).

1-(3′,4′-dihydroxyphenyl)-2-piperidinoethanol hydrochloride (14)

The above amino ketone (2) (10·0 g, 0·037 mole) was dissolved in 100% ethanol (300 ml.). Pd–C catalyst 10% (1·4 g) was added and the mixture subjected to 3 atm hydrogen pressure in the Parr hydrogenator. Consumption of the required amount of hydrogen was completed after 6 hours. Removal of the catalyst and evaporation of the solvent gave an oily residue which was dissolved in hot 2-propanol (5 ml.). The resultant solid that formed as the solution cooled was collected by filtration. Recrystallization from 2-propanol gave (14) as white crystals (7·4g, 74%) with m.p. 157–158° dec. (Found: C, 57·33; H, 7·54; Cl, 12·8, N, 5·10. $C_{13}H_{20}ClNO_3$ requires C, 57·03; H, 7·36; Cl, 13·0; N, 5·12%).

1-(3′, 4′-dihydroxyphenyl)-2-morpholinoethanol hydrochloride (13)

This compound was prepared in a manner similar to that described above, as colourless needles with m.p. 176–177° dec. (Found: C, 52·08; H, 6·74; Cl, 12·4; N, 5·14. Calcd. for $C_{12}H_{18}ClNO_4$: C, 52·27; H, 6·58; Cl, 12·9; N, 5·08%). N.m.r. spectrum (D_2O) δ p.p.m.: 7·00 (singlet, three protons); 5·15 (triplet, one proton); 4·71 (singlet, exchangeable protons); 4·20–3·80 (multiplet, four protons); 3·80–3·30 (multiplet, six protons). Mass spectrum, m/e (%): 239 M^+ (0·7); 101 (6·1); 100 (100·0); 56 (11·5).

Methyl 5-chloroacetyl salicylate

A solution of methyl salicylate (30·5g, 0·2 mole), chloroacetyl chloride (34·0g, 0·3 mole) and nitrobenzene (75 ml.) was slowly added to a vigorously stirred solution of $AlCl_3$ (anhydrous) (74·0g, 0·55 mole) dissolved in nitrobenzene (100 ml.). The temperature was maintained below 25° during the addition to control the violent evolution of hydrogen chloride gas. The reaction mixture was then stirred for 3 hrs. at 60°, and poured into cold dilute HCl solution (500 ml.). The aqueous layer was separated from the organic layer, washed with ethyl acetate (2×250 ml.) and discarded. The combined ethyl acetate extracts and the organic layer was washed with water (5×150 ml.) and dried over anhydrous $MgSO_4$. The solvents were removed under vacuum (100°/0·1 mm.) and the resultant oily residue crystallized at room temperature. The crystals were washed with petroleum ether 40–60° and recrystallized from 2-propanol to give colourless needles (33·0g, 72·0%) with m.p. 106–107° (Granger, Corbier and Vinas (1952) report m.p. 110°). (Found: C, 52·69; H, 4·03; Cl, 15·5. Calcd. for $C_{10}H_9ClO_4$: C, 52·52; H, 3·94; Cl, 15·5%).

Methyl 5-morpholinoacetyl salicylate hydrochloride (11)

Morpholine (24·7g, 0·284 mole) was added to a solution of methyl 5-chloroacetyl salicylate (32·5g, 0·142 mole) dissolved in ethyl methyl ketone (800 ml.). The solution was refluxed for 3 hrs., cooled to 0°, and the morpholine hydrochloride salt removed by filtration. Hydrogen chloride gas was then bubbled through the filtrate to precipitate the morpholino compound (11). Nitrogen gas was used to remove excess hydrogen chloride and then the solvent was decanted and the precipitate washed several times with anhydrous ether and recrystallized from a methanol-diethyl ether mixture to give colourless needles (28·8g, 64%) with m.p. 178–179° dec. (Found: C, 52·96; H, 5·63; Cl, 11·0; N, 4·36. $C_{14}H_{18}ClNO_5$ requires C, 52·25; H, 5·75; Cl, 11·2; N, 4·44%).

1-(4-hydroxy-3-hydroxymethylphenyl)-2-morpholinoethanol (22)

Compound (11) (1·88g, 0·006 mole) and $NaHCO_3$ (2·2g) were warmed together in ethyl methyl ketone (40 ml.) for 5 min. The mixture was filtered and the solvent evaporated to give the free base as a yellow oil which was dissolved in anhydrous ether (30 ml.) and added to a solution of $LiAlH_4$ (0·76g) in diethyl ether (60 ml.). The mixture was refluxed for 14 hrs., cooled, and ethanol (Ca 10 ml.) added in small portions to destroy excess $LiAlH_4$. The mixture was adjusted to pH 3·0 with dil. HCl solution and stirred at 15°C. for 1 hr. $NaHCO_3$ solution (0·5 molar) was added dropwise until basic (pH 8·0) and the solution extracted continuously with $CHCl_3$ for 12 hrs. The $CHCl_3$ solvent was removed and the resultant oil recrystallized as colourless crystals from 2-propanol (0·935g, 62·3%) with m.p. 130–1°. (Found: C, 61·45; H, 7·54; N, 5·32. $C_{13}H_{19}NO_4$ requires C, 61·64; H, 7·56; N, 5·53%).

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(Received 5 September 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 6–10, 1974

The Re-deposition of Midden Material by Storm Waves

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Abstract—The results of a study of sixteen coastal midden-like deposits in southern New South Wales indicate that many such deposits are not undisturbed Aboriginal middens, but have been re-worked by storm waves. These re-worked middens are characterized by the presence of one or more of the following: shells of species and sizes not thought to be eaten by Aborigines, marine shell grit, water-worn shells, rounded pebbles and pumice.

Introduction

Coastal shell deposits in Australia are usually classed by researchers as either Aboriginal midden, or natural shell beds (e.g., Gill, 1951; Coutts, 1966) and criteria for distinguishing between them are given in Table 1. However, observations by the authors in southern coastal New South Wales (Figure 1) show the existence of a third type of deposit: midden material which has been transported and re-deposited by storm waves.

These re-worked deposits indicate heights reached by storm waves, evidence of wave activity that may have been ignored by geomorphologists who have assumed them to be undisturbed middens. Unless recognized as being disturbed they are also likely to provide misleading archaeological information because of mixing or removal of cultural material.

Characteristics of Wave Re-worked Middens

The deposits vary greatly in appearance and composition, some being barely distinguishable from undisturbed midden while others closely resemble natural shell beds. They consist mainly of midden shell with charcoal and stone artifacts, probably transported from a more shoreward location by storm waves. Included with this midden component are varying amounts of materials of marine origin: shells of species and sizes not usually eaten by Aborigines, shell grit, water-worn shell, rounded gravel, and pumice. As storm waves represent short-term very high energy events, they tend not to sort the materials they transport (Folk, 1968, p. 4) with the result that these wave re-worked middens comprise a very wide range of materials, in terms of both size and density.

A number of midden-like deposits were investigated to see whether wave re-worked middens could be distinguished from undisturbed middens or natural shell beds. (Figure 1, Table 2.) A small volume (approximately $0 \cdot 01$ m.^{3}) of each deposit was sieved through a 5 mm. sieve and each fraction examined, to see if it contained matter not usually present in undisturbed middens.

Table 1

Characteristics of Undisturbed Middens and Marine Shell Beds
Modified after Gill (1951)

Middens	Marine Shell Beds
Charcoal, burnt wood, blackened shells, artifacts, hearth stones	Absent
Unstratified or roughly stratified	Generally well stratified and show sedimentary features of water laid deposits
Edible shell species and sizes	Varied shell species and sizes both edible and non-edible
Absent	Shell often worn due to transport in the off-shore or beach zone
Bones of mammals used for food	Absent
Absent	Forms of marine life not used by Aborigines, e.g., corals, worm tubes

Shellfish too small to be eaten, but of species commonly used as food by Aborigines (Bowdler, 1970, p. 99; Lampert, 1971, pp. 12, 59), occur in undisturbed middens but make up less than 1% of the shell volume. Especially common are the gastropods *Melanerita* spp. and *Austrocochlea* spp. and it is probable that these were scooped up with the larger snails of these species. Consequently, small shells have been marked as " present " in the column in Table 2 for species and sizes not thought to be eaten, only where they make up more than 5% of the shell volume. Although *Galeolaria* worm tubes are occasionally found in middens, having been carried on to the sites attached to shells, where large fragments consisting of aggregates of these tubes were found, they were also included.

Marine-derived shell grit less than 5 mm. across is usually sub-rounded to well-rounded, due to abrasion of the shell in the surf zone. While finely divided shell less than 5 mm across commonly occurs in undisturbed middens, it is usually sub-angular to very angular, still showing clearly signs of fracturing. Where the shell is fresh in appearance the two types are easily recognized, but where it is poorly preserved finely divided midden shell tends to become indistinguishable from shell grit. Shell grit was noted as being present where it could be identified as forming 10% or more of the deposit.

Smooth, water-worn shells and fragments larger than 5 mm. are distinguishable from midden shells, especially when both are well-preserved. Water-worn shells were noted when recognized in the deposits.

Rounded beach pebbles were commonly used by Aborigines for making implements (Branagan

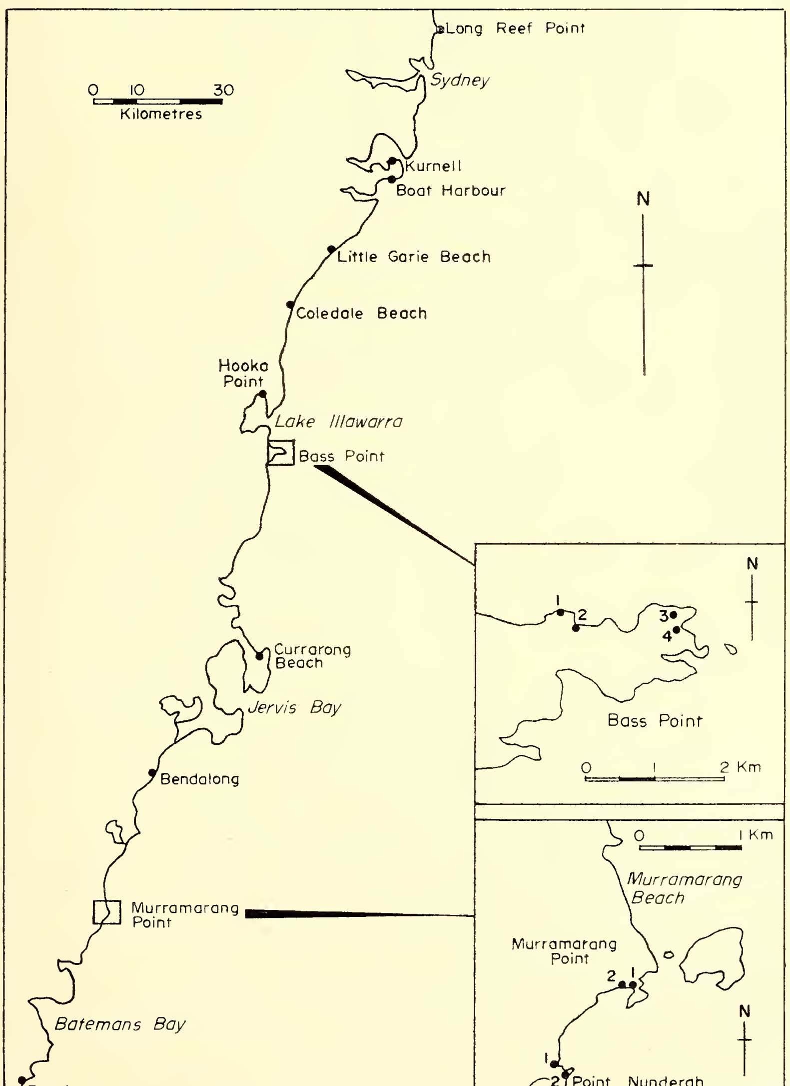

FIGURE 1.—Locality map showing location of sites studied.

TABLE 2

Location and Composition of the Midden-like Deposits Studied

Site	Site Location	Aspect and Exposure to Storm Waves	Approx. Height of Top of Deposit above Limit of Swash (m)	Approx. Distance from High Tide Limit (m)	Thickness of Deposit (cm)	Number of Layers	Shell Species and Sizes not Eaten	Shell Grit	Water-worn Shell	Rounded Gravel	Pumice	Charcoal	Stone Artifacts	Type of Deposit
Long Reef Point . .	backshore	20° exposed	2–5	5–10	50–150	several	+	+	+	+	+	+	+	re-worked
Boat Harbour . .	cliff top	180° exposed	15–20	10	100–150	several	—	—	—	—	—	+	+	undisturbed
Little Garie Beach . .	backshore	70° very exposed	3	10	40	1	—	+	+	++	—	+	—	re-worked
Coledale Beach . .	backshore	90° exposed	3	3	100	1	+	+	+	++	+	+	+	re-worked
Hooka Point . .	lake shore	—	—	—	100–200	3–20	+	+	+	++	+	+	+	re-worked
Bass Point 1 . .	high headland	0° exposed	10+	30+	60	2	—	—	—	—	—	+	+	undisturbed
2 . .	backshore	0° sheltered	1	2	15	1	+	+	+	+	+	+	+	re-worked
3 . .	backshore	0° exposed	1–2	5	40–100	1	+	+	+	+	+	+	—	re-worked
4 . .	backshore	90° very exposed	3–6	20	150–300	3–20	+	++	+	+	+	+	+	re-worked
Currarong Beach . .	dune	10° exposed	8	40	20–40	1	—	—	—	—	—	+	+	undisturbed
Bendalong	backshore	40° sheltered	2	5	10–50	1–3	+	++	+	+	—	+	+	re-worked
Murramarang Point 1	dune	225° exposed	6–8	20	40	1	—	—	—	—	—	+	+	undisturbed
2	dune	225° exposed	3	25	20	1	+	—	—	+	+	+	+	re-worked
Point Nunderah 1 . .	dune	45° exposed	3–4	20	30	1	+	—	+	—	+	+	+	re-worked
2 . .	backshore	90° very exposed	3	4	50–100	1–3	+	+	+	++	+	+	+	re-worked
Broulee	dune	135° exposed	1–2	5	20–40	1–2	+	+	+	+	+	+	+	re-worked

+ present ++ common — absent

and Megaw, 1969, p. 11 ; Lampert, 1971, p. 27) and whole pebbles, usually larger than 10 cm. across, are found in undisturbed middens. Rounded pebbles less than 5 cm. are rarely found in undisturbed middens, especially if the stone types are unsuitable for implements, and the presence of such pebbles was noted if they occurred in the deposits studied. Often small rounded pebbles were found in large numbers, for example, parts of the deposit at Hooka Point consists of 20–40% gravel finer than 5 cm., much of it being the local tuffaceous sandstone.

Pumice is commonly found in wave re-worked middens. At the northern end of Murramarang Beach, rounded fragments of pumice up to 0·5 cm. across were observed being blown over a level sand surface. Larger pieces were not moved, even by strong gusts of wind. As it is possible that small fragments of pumice could be blown into a midden this material was only recorded where pieces were larger than 1 cm. across. However, pumice smaller than this was only found at one site (Hooka Point), whereas pieces 5–10 cm. across were common. No pumice was found in any site subsequently classed as undisturbed.

Although no natural shell beds were found within the area studied, such beds could be distinguished from re-worked middens using criteria given in Table 1. They could also contain marine shell grit but would not contain significant amounts of charcoal, and could not contain other cultural materials such as stone artifacts. Some deposits consisted almost entirely of material of marine origin with a relatively small amount of culturally-derived material. Numerous fragments of charcoal, up to 2 cm. across, were found in all of the deposits studied, including those made up predominantly of materials of marine origin. In most cases stone artifacts were also present. The origin of water-worn shell and shell grit in these deposits is uncertain but it seems likely that much of it is midden shell modified by wave action.

Discussion

Descriptions of the deposits studied, including their composition, location, exposure to storm waves, and height above and distance from the highest limit of swash are given in Table 2. From these it has been concluded that many of the deposits consist primarily of midden material re-worked by storm waves. The results of this survey, while not conclusive, would indicate that many coastal midden-like deposits less than 6–7 m. above the upper limit of swash, especially in exposed locations, are re-worked in this way.

The presence of any of the five constituents described above, i.e., shell species and sizes not eaten by Aborigines, shell grit, water-worn shell, rounded gravel or pumice is sufficient to indicate that a midden-like deposit is re-worked. The composition of a re-worked midden will depend on the material available on the beach at the time of re-deposition by storm waves. Successive layers may vary considerably in composition, as at Bass Point 4, where many individual layers consist almost entirely of shell grit, midden shell or beach sand and gravel. The boundaries between such layers are generally more sharply defined than those which may occur in undisturbed middens.

It should be noted that the data in Table 2 refer to the seaward margin of each deposit, and it is possible that wave re-worked layers may give way to undisturbed midden further from the shoreline. Similarly, undisturbed midden may overlie wave re-deposited material. This has been noted at the Captain Cook landing site at Kurnell (M. A. J. Williams, pers. comm.) where the basal layer of wave re-worked midden, containing a high proportion of pumice, extends beneath the undisturbed midden layers.

The deposit at Hooka Point on the northern shore of Lake Illawarra has probably been disturbed more by lower energy wave action associated with fluctuating lake levels than by storm wave activity. Several phases of disdisturbance of the deposit are indicated by successive layers of comparatively well-sorted sediments and shells, up to 3 m. above the present lake level. The nature of this lake shore deposit with its distinctly sorted layers, contrasts markedly with the re-worked coastal deposits studied, where no sorting of material occurs within layers.

It seems likely from the state of preservation of the shell that the deposits are highly variable in age, and do not represent one phase of storminess. The deposit at Bendalong, for example, included rusted nails and worn glass. They are not to be regarded as evidence for a recent higher sea-level stand. Storm wave activity is part of the normal process of coastline development, and these deposits thus offer no indication of a different shoreline ecology in the past.

The deposit at Hooka Point however, does imply changes in lakeshore morphology and ecology. Lake levels 1–3 m. higher than at present would have caused the inundation of up to approximately 13 sq. km. of the surrounding land. Unless such levels were maintained for sufficiently long time periods for lacustrine shellfish (especially *Anadara trapezia*) to colonize the new near-shore zone, the shellfish food supply of Aborigines exploiting the lake resources would have been greatly restricted.

Although charcoal occurs within the re-worked deposits, ^{14}C dates of this material would in general refer to the age of the original midden, not to the time of deposition, and could only indicate a maximum age. Charcoal from bush-fires or middens could have been transported along shore and incorporated in any order in these deposits. Thus, ^{14}C dates need not show consistency with depth.

While beyond the scope of this study, it should be noted that midden deposits can be re-worked by other than marine or lacustrine processes. These include fluvial re-deposition, mass movement and very commonly, wind deflation (Coutts, 1972). While these processes concentrate or re-sort cultural deposits, they do not supply additional materials which may be confused with the cultural deposit—as do marine or lacustrine processes.

Conclusion

From this study of a small number of sites we conclude that deposits near the shoreline which appear to be undisturbed midden should be carefully investigated, as they may represent midden materials re-worked and re-deposited by storm waves or fluctuating lake levels.

Acknowledgements

We wish to thank Mr. R. J. Lampert, Australian National University, and Dr. M. A. J. Williams, Macquarie University for helpful comments on and criticisms of this paper, and also Mr. K. Maynard for drawing the location map.

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(Received 30 May 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 11-16, 1974

1973 Presidential Address
Sedimentary Basin Tectonics and a Geological Energy Reserve Appraisal

John Craig Cameron

Introduction

It is sobering to recall that a mere decade ago it was fashionable in geological circles to play down Australian prospects in the field of oil and natural gas exploration. Some of the popular arguments that were seriously advanced included lack of Phanerozoic section, the predominant area of Precambrian shield and even the fact that Australia is situated in the Southern Hemisphere.

The situation has changed dramatically due to commercial oil and gas discoveries in Bass Strait and the promise of even greater energy reserves, mainly in the form of natural gas, on the North West Shelf. As exploration and production technology have gathered momentum, it has become increasingly apparent that Australia possesses some extremely interesting basins with considerable promise of becoming petroleum producers in due course.

In my Presidential address I propose to discuss some of the geological, mainly structural, conditions that have contributed to this volte-face in Australia's hydrocarbon potential and to make from a geological standpoint a balanced comparison of the energy reserves available to the nation.

Impact of the new Global Tectonics

Australia's disengagement from Antarctica and its subsequent northward drift are relatively recent geological events (late Cretaceous to early Tertiary). This is reflected in the tectonic style and nature of the sediments in the Bass Strait Basins (offshore Gippsland, the Bass and Otway Basins) and the structural style of the North West Shelf.

In the Gippsland Basin, approximately, 5,500 m. (18,000 feet) of post Jurassic sedimentary section is preserved in what is basically a half graben type depositional environment. The style of tectonic deformation reflects basement activity and the role of major crustal dislocations rather than a compressional stress regime. This has given rise to important structures that predate or are synchronous with the epeirogenic manifestation of the Kosciusko Uplift of late Tertiary age.

On the North West Shelf the tensional regime is even more manifest in the "pull apart" tectonics on a regional scale. It is especially in evidence by the fault bounded horst structures on the Rankin Trend.

Despite the obvious limitation of analogies the author wishes to draw attention to the remarkably similar tectonic picture as seen in the section from Saudi Arabia, across the Persian Gulf to the Zagros ranges of Iran and the section from the North West Shelf to the Indonesian Island Arc (see Figure 1).

The analogy whilst good is not perfect. The major dissimilarity lies in the absence of a zone of subduction fronting the Zagros Range corresponding to the Benioff Zone forming the plate margin between South East Asia and the Indo-Australian plate.

Infra Basins

A dramatic consequence of the search for hydrocarbons has been the delineation of previously unsuspected relatively deep infra-basins beneath blanket cover of Mesozoic and Tertiary sediments.

In Western Australia, the Kidson and Joanna Springs infra-basins underlie the superficial cover of Canning Basin. A deep test by WAPET, Sahara 1, was abandoned at over 4,500 m. (15,000 feet) the sedimentary sequence proving considerably greater than the initial geological prognosis.

Possibly the best-known of these infra-basins occur in Eastern Australia underlying the Mesozoic of the Great Artesian Basin. The Adavale and Coopers Creek basins have considerable hydrocarbon potential. Gas from the Permian of the Coopers Creek Basin is already supplying Adelaide and will provide the main source of supply by 1975 to the Port Kembla-

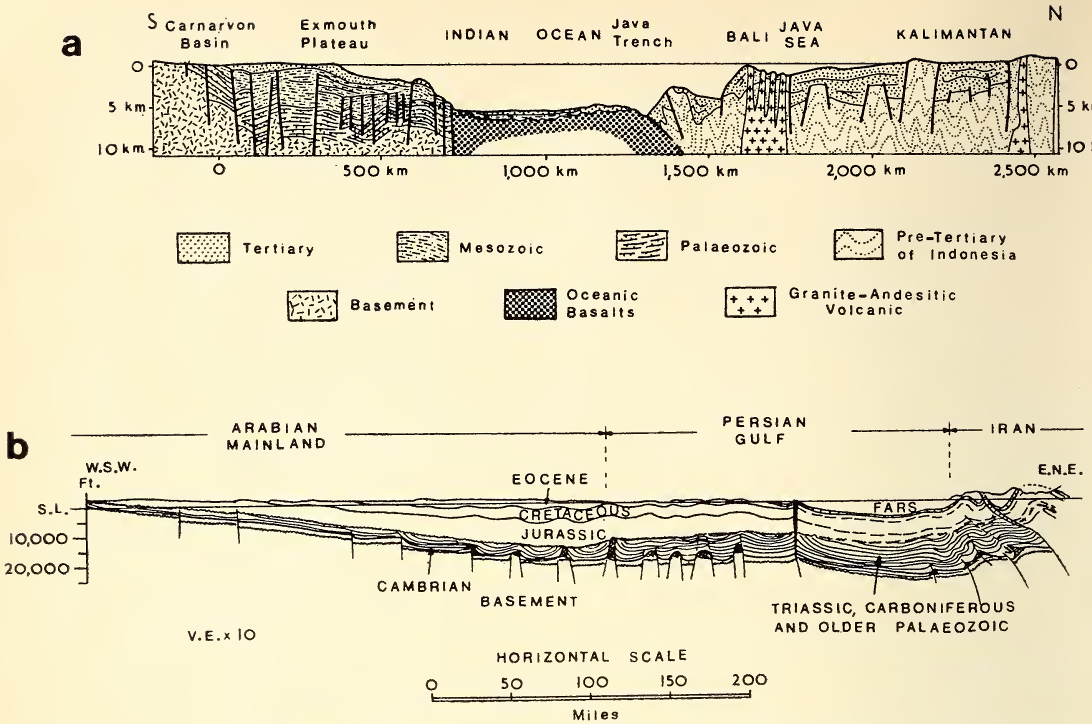

FIGURE 1.—Sections illustrating similarity of tectonic style.
(a) N.W. Australia to Indonesian Island Arc
(b) Saudi Arabia to Zagros Ranges, Iran.

Sydney-Newcastle conurbation. The gas potential of the Adavale basin awaits further evaluation before exploitation is possible. It should be recalled that Phillips Petroleum found substantial gas in Devonian sandstones on the Gilmore structure.

In the interests of logical scientific nomenclature a plea is made from the use of the term infra-basin for these deeper (often fault bounded) sedimentary sequences entirely masked by younger rocks and separated from them by numerous unconformities. The connotation " sub-basin " seems more appropriate as a designation for a lateral development of a major basin as in the Coonamble sub-basin which is a lateral appendage of the Great Artesian Basin.

The importance of these infra-basins is due to the very considerable geological section which may be present. The adjoining subsurface map of the Adavale Basin shows depth to basement exceeding 6,100 m. (20,000 feet) in several places. This is in marked contrast to the figure of 2,000 m. (7,000 feet) or so of sedimentary section considered likely only two decades ago.

Salt Tectonics (Halokinesis)

Geologists studying Australian stratigraphic successions have been somewhat baffled by the comparative lack of evaporites in Australian sequences. Evaporites and diapiric structures are known from the Amadeus Trough and halite has been encountered by WAPET in the Fitzroy Trough in earlier drilling, but there has been nothing to indicate the development of evaporites and especially halite on a scale similar to the Gulf Coast of North America or the Zechstein Sea area of North Europe.

Now, due entirely to exploration for oil and gas in the offshore Bonaparte Gulf Basin, it appears that a major halokinetic province has been found. Geophysical surveys (magnetic, gravity and seismic), followed by exploratory drilling have demonstrated the widespread distribution of salt of probable Devonian age and its important role in the structural evolution of the basin. All the classical structures of salt tectonics are present, salt domes, salt pillows, salt flowage. For further details on this exciting new development, the reader is referred to a recent paper by Crist and Hobday.

The discovery of this new salt province brings Australia into line with Africa where important salt basins have been found on the continental margin with obvious genetic implications with the separation process of Africa from its adjacent plates. It is interesting to note in the Bonaparte Gulf Basin that the salt predates considerably the rupture of Australia from Antarctica, confirming once again that an important tensional stress regime occurs well before the active drift episode—this is further corroboration for the observation by Dr. P. Kent in his 1973 address to the Australian Petroleum Exploration Association, that important tectonic events vital for economic hydrocarbon accumulation take place well before the actual physical separation of adjacent continental plates.

Continental Margins

Although exploration for oil and gas has by no means been exhaustive in the onshore basins of Australia, it is nevertheless true to say that possibly with one or two exceptions the tectonic style and the sedimentary facies have proven none too encouraging for major hydrocarbon accumulations.

However, when we turn our attention to the oil and gas potential of Australia's offshore margin the situation is much more optimistic. Not only are the sedimentary sections substantially greater but the geological environment or as geologists like to say the facies, tectonic and sedimentary are favourable.

It is worth studying the geometry and lithology of the sedimentary basins fringing the

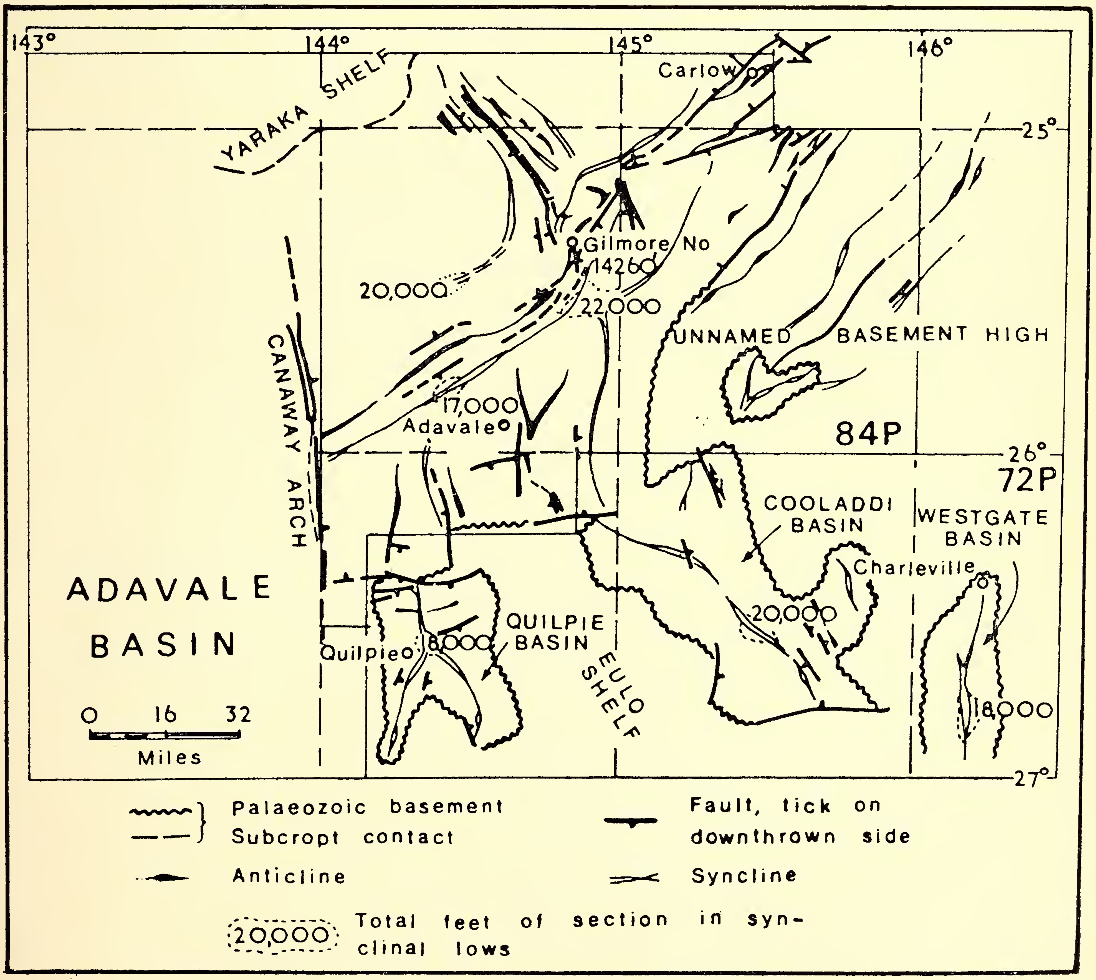

FIGURE 2.—Subsurface map of Adavale Basin showing depth to basement.

Australian coast line. Dr. R. Beck, Exploration Manager of the Shell Group of Companies, in a recent address to APEA provided the following illustrations of continental margins (see Figure 3).

With the possible exception of the third category (and this is probably due to delays in release of information) all the remaining variations are found in the marginal basins of Australia.

Energy Comparisons

In a recent paper on " Uranium Reserves and Prospects for a nuclear fuel industry " by Miles, South and Warner of the Australian Atomic Energy Commission, an extremely useful and valuable account was given of Australia's possible future role in the nuclear energy field. A tabulation comparing the reserve of the various forms of energy was also given. See Table I.

AUSTRALIAN ENERGY RESOURCES IN TERMS OF BLACK COAL EQUIVALENT

TABLE I

Type	Economically Recoverable Reserves	Black Coal Equivalent (12,000 Btu per lb.)
		(million tons)
Black Coal (non-coking)	5,000 million tons	5,000
Brown Coal	10,000 million tons	3,900
Natural Gas	14×10^{12} S. C. F.	520*
Natural Gas Liquids	300×10^{6} barrels	50
Oil	$1{,}824 \times 10^{9}$ barrels	360
Uranium	92,000 short tons U_3O_8	142,000
		151,830

* THE ORIGINAL FIGURE 5200 HAS BEEN ADJUSTED AS THIS IS AN OBVIOUS COMPUTATIONAL ERROR

TABLE II

Type	Reserves	Black Coal Equivalent
		(million tons)
Black Coal (non-coking)	8,000 million tons	8,000
Brown Coal	15,000 million tons	5,800
Natural Gas	140 trillion S. C. F. (140×10^{12} standard cubic ft.)	5,200
Natural Gas Liquids	3.5 billion barrels (3.5×10^{9} barrels)	700
Crude Oil	2 billion barrels (2×10^{9} barrels)	500
Uranium	200,000 short tons U_3O_8	4,500
		24,700

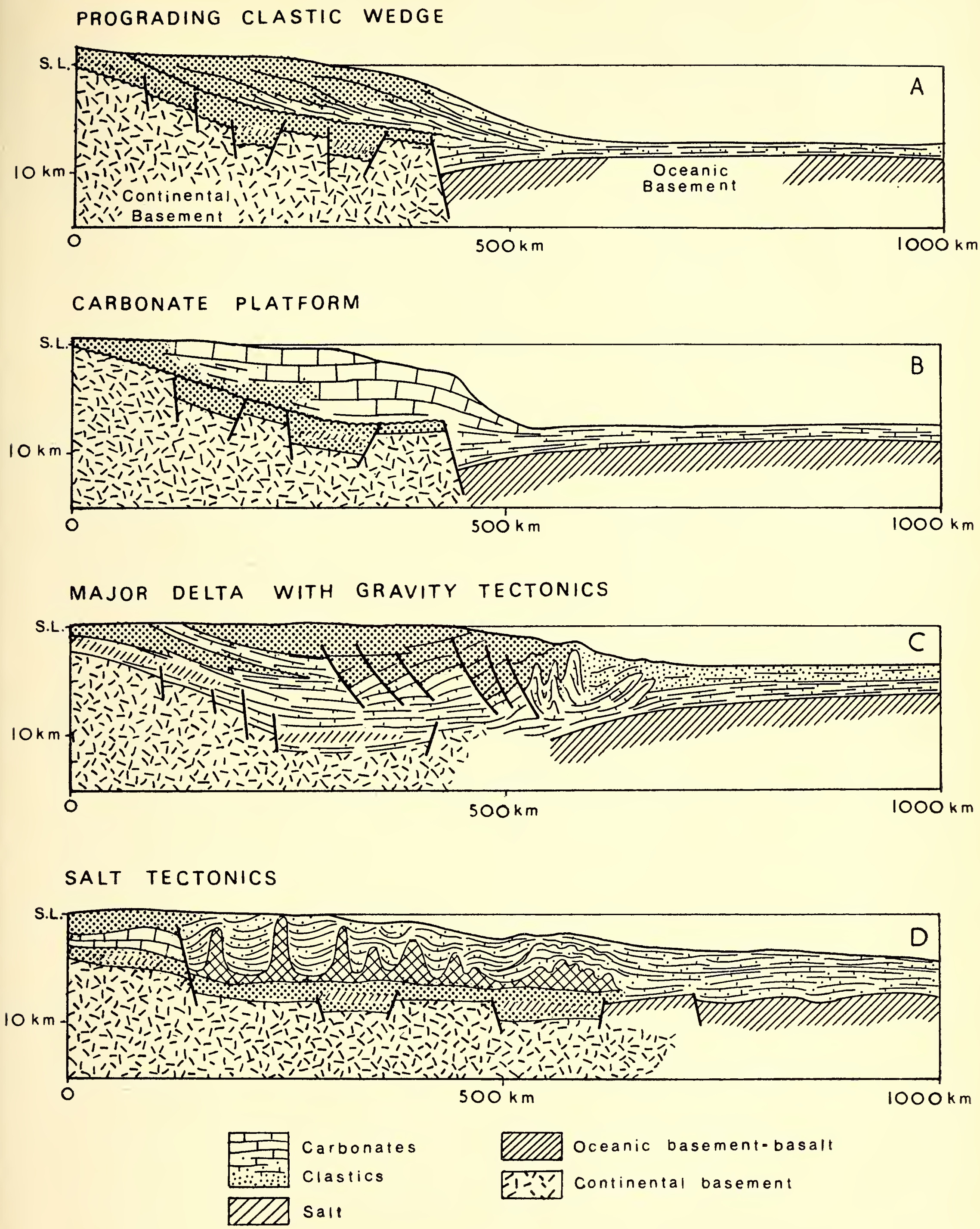

FIGURE 3.—Sections illustrating tectonic modifications of continental margins.

Coal, whether black or brown, is the dominant fuel for central power generation and is likely to remain so for at least several decades. Also as will be shown, the reserves of coal surpass those of other fuels—so it is convenient that the energy comparison of the various fuels should be made in terms of black coal equivalent.

The writer welcomes the opportunity of expressing his own views on this important subject and presenting an energy comparison tabulation which at least in his own view is more realistic and corresponds to the situation obtaining in the time interval 1975–80. See Table II.

A few comments on the above figures will serve to highlight and justify some differences between the two tabulations.

The figures given for coal, black and brown, are likely if anything to err on the conservative side. Possible recoverable reserves of brown coal in Victoria, for instance, may prove to be as high as 30,000 million tons of minable coal.

At the time of writing (mid-1973), natural gas reserves of the order of 140 trillion standard cubic feet are in sight (i.e., 140×10^{12} SCF) The Gippsland offshore gas fields alone have reserves of the order of 14 trillion SCF, whilst the reserves discovered to date on the North West Shelf are expected to be many times greater.

A conspicuous weakness in the Australian energy position is the low figure for the reserves of crude oil. Indeed this is the Achilles heel of the Australian energy situation and should prompt further intensive search for this vital fuel. The situation could easily be reversed if further exploration on the North West Shelf should prove that the area is not entirely a natural gas province, a geological contingency which in the opinion of the author is not outside the bounds of possibility.

It will be noted that the reserves of U_3O_8 have been more than doubled in the second tabulation but the energy expressed in terms of black coal equivalent has been revised severely downwards. This has been done because all available evidence indicates that commercial fast breeder reactors capable of utilizing up to 70% of Uranium atoms are unlikely to be available before 1995. Considerable engineering, metallurgical and ecological problems have still to be surmounted before it can be said that the breeder reactor is a commercial reality.

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A fact worthy of attention, emerging from the second tabulation is that the energy values of black coal, brown coal, natural gas and uranium are all of the same order of magnitude. This prompts the observation that rational exploitation policies of all energy sources will be necessary to solve Australia's forthcoming energy problems.

If the writer can be permitted a presidential prognostication it is that the 140 trillion cubic feet for natural gas will prove to be a gross underestimate—and that the present and impending breakthrough in oil and gas exploration and production technology will allow production from significantly deeper water (perhaps 300 to 600 metres of water).

Looking even further into the future, i.e. the post 2000 A.D. epoch, it is confidently expected that the advent of fast breeders, nuclear fusion and perhaps, most important of all, solar energy will present themselves as timely energy alternatives. The author is optimistic that Australian fossil fuel reserves will prove adequate to tide over the interim period before solar energy and nuclear fusion become available, with the important proviso that Australia does not squander her resources to an energy hungry world.

Acknowledgements

Thanks are extended to George Melville for drafting the illustrations and to Professor F. C. Beavis for reviewing the manuscript. The author, however, accepts full responsibility for views expressed in this paper.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 17–30, 1974

Sedimentology of Permian Rocks near Ravensworth, N.S.W., Northern Sydney Basin

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Abstract—Permian rocks near Ravensworth,, N.S.W. form part of the northern margin of the Sydney Basin, a Permo-Triassic structural basin in central eastern N.S.W. They consist of marine lithic arenites, conglomerates and siltstone of the Maitland Group, conformably overlain by interbedded mudstones, siltstones, sandstones, conglomerates and coal seams of the Singleton Coal Measures.

The sedimentary succession reflects changing depositional environments. Initially, marine sedimentation characterized by littoral and shallow neritic deposition (Branxton Formation) gave way to open shelf deposition (Mulbring Siltstone). Paralic sedimentation associated with coal swamp and meandering stream deposition (Singleton Coal Measures) followed. Tectonic instability related to movements along the Hunter Thrust initiated piedmont conditions with braided stream deposition in the Late Permian (upper portion of the Goorangoola Formation).

Maitland Group marine sedimentation appears to have been dominated by northwesterly directed longshore currents. The fluviatile-lacustrine sedimentation of the Singleton Coal Measures was associated with a northwest flowing drainage system, whereas the Late Permian braided stream deposition was due to south-south-west directed palaeocurrents.

Changes in the nature of sedimentation and palaeocurrent trends in the Singleton Coal Measures near Ravensworth are directly relatable to tectonic instability associated with the development of the Hunter Thrust. Such instability has probably controlled the nature, direction and rate of sediment influx along the entire northern margin of the Sydney Basin in the Late Permian.

Introduction

This paper stems from work undertaken as part requirement of a B.Sc.(Hons.) degree at the University of Newcastle in 1971. It attempts to integrate new data on lithology, sediment provenance, lithosome geometry, sedimentary structures and palaeocurrent trends in order to elucidate environmental aspects of Late Permian sedimentation along the northern margin of the Sydney Basin.

The Ravensworth district is located midway between Singleton and Muswellbrook, 96 km. northwest of Newcastle. It is situated on the eastern flank of the Muswellbrook Anticline and is bounded to the north by the Hunter Thrust. The region contains Late Permian strata which to the north are in faulted contact with rocks of Carboniferous age (Figure 1). The oldest Permian rocks crop out in a zone between the Hebden and Hunter Thrust Faults, and belong to the Maitland Group which contains marine sedimentary rocks of the Branxton Formation and Mulbring Siltstone (Figure 2). The Branxton Formation comprises fine, medium and coarse grained lithic arenites, pebbly arenites and pebble conglomerate with minor cobble zones. The Mulbring Siltstone is typically a massive light grey to green siltstone with minor arenaceous phases.

The Maitland Group is conformably overlain by the Singleton Coal Measures which are equivalent in age to both the Tomago and Newcastle Coal Measures. The Singleton Coal Measures contains three formations: the Saltwater Creek Formation, predominantly sandstone, siltstone and minor shale; the Vane Formation comprising sandstones, shales, mudstones and coal seams; and the Goorangoola Formation, consisting of sandstone, irregular coal seams and minor mudstones and shales which pass upward into sandstones and conglomerates.

The recognition and delineation of stratigraphic units is difficult because of poor outcrop, poor lateral continuity of the strata and the lack of any distinctive marker horizons. The chronological development of stratigraphic nomenclature and salient lithological characteristics of the stratigraphic units in the Ravensworth area are summarised in Table 1. Robinson (1969), using subsurface information revised the stratigraphy of the Singleton Coal Measures employing recognisably persistent coal seams as formation boundaries (Figure 2). Mapping outcrops of the coal seams is difficult because of poor exposure, and in the present study, projected seam outcrops from Booker (1953) were used in the construction of the geological map. The nomenclature employed

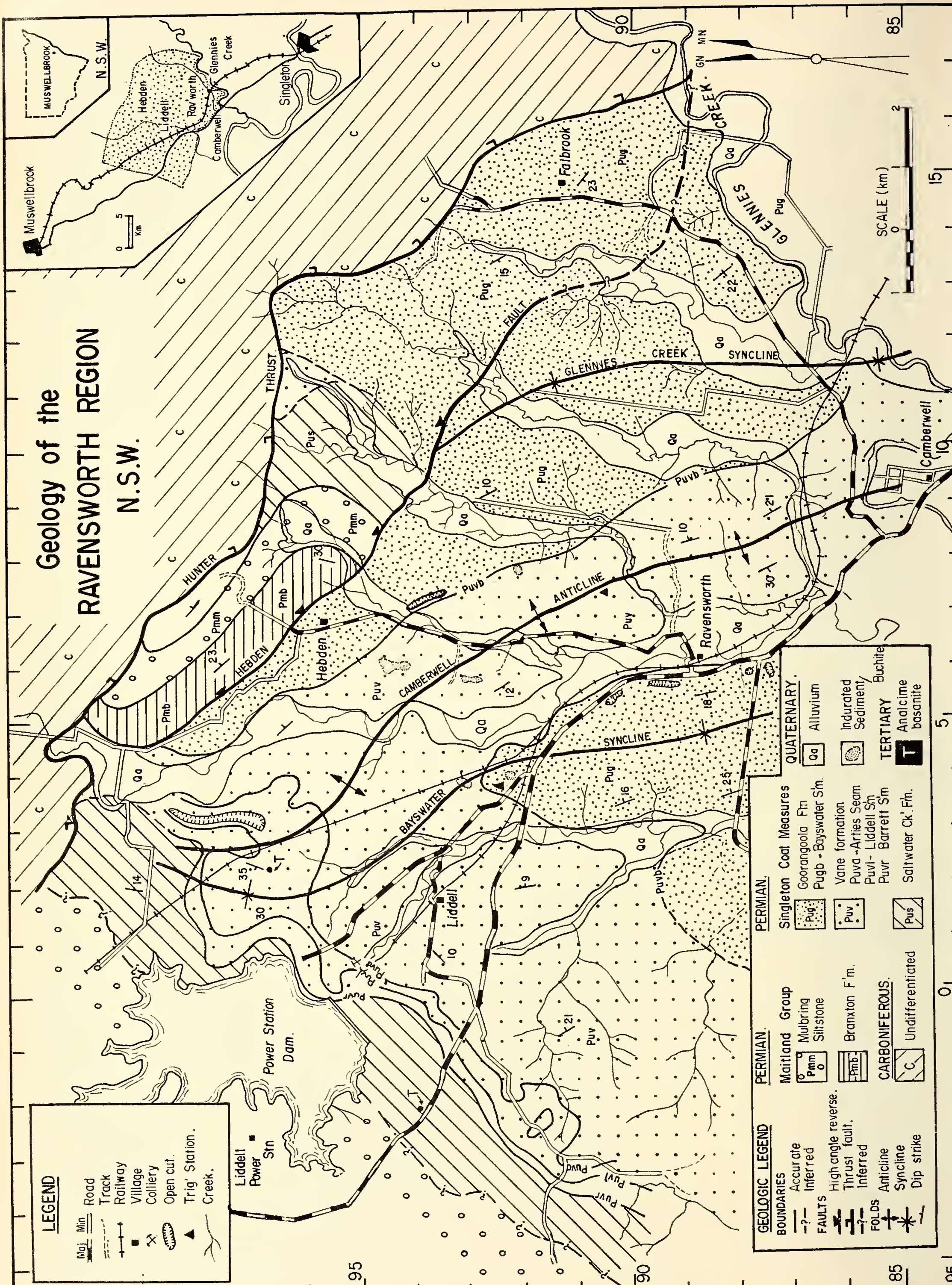

FIGURE 1.—Geological Map of the Ravensworth region, New South Wales. All formation boundaries in the Singleton Coal Measures are projected seam outcrops from Booker (1953).

by Robinson, although suitable for subsurface mapping, is difficult to apply to surface studies because of poor stratigraphic control.

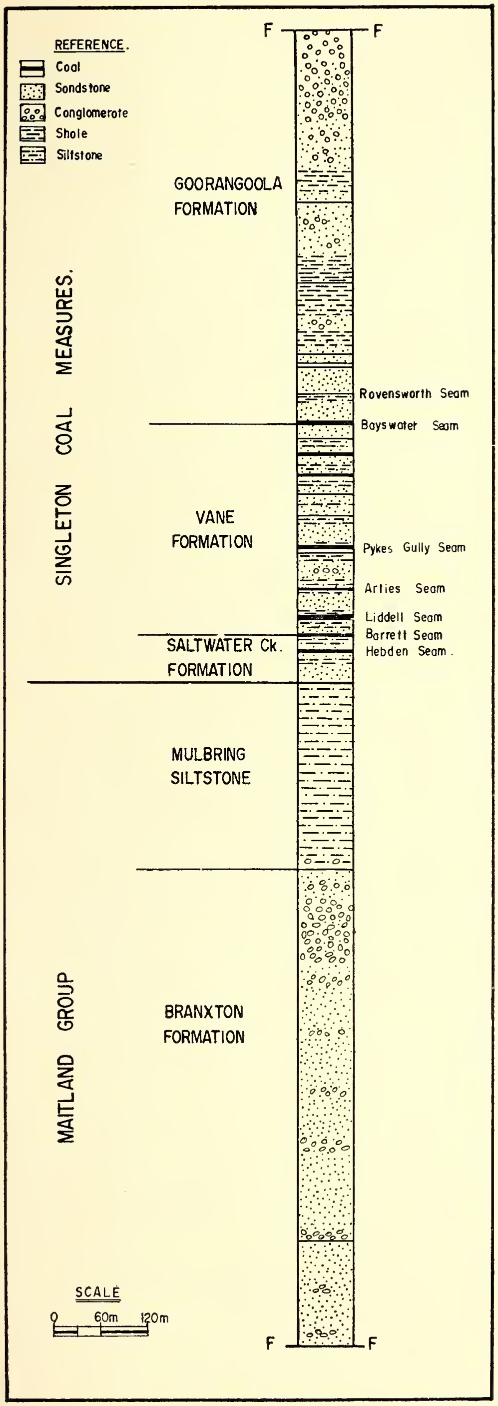

FIGURE 2.—Stratigraphic column of Permian rocks in the Ravensworth area.

All grid references cited refer to the Camberwell (denoted by suffix " C ") and Muswellbrook (denoted by suffix " M ") 1 : 63, 360 military sheets. The terminology used in this paper is as follows:

1. Arenite classification is that of McBride (1963).
2. Particle size classification is based on the Wentworth Grade Scale (Krumbein and Sloss, 1963. Table 4.1, p. 96).
3. Cross stratification nomenclature is that of Allen (1963).

Petrology

Rudites: The rudites are generally poorly sorted, pebble to cobble orthoconglomerates with rounded to well rounded clasts of moderate to high sphericity. The rocks are typically light to mid-grey and comprise clasts of quartzite, quartz, acid and intermediate volcanics, chert, jasper, arenite and lutite set in a generally dense arenaceous or argillaceous matrix.

Pebble lithology analyses, based on random samples of 100 pebbles within a 2 square metre sampling grid show that compositional variations occur in rudites throughout the stratigraphic section (Figure 3). The Vane and lower portion of the Goorangoola Formation contain a higher proportion (40–45%) of quartz/quartzite clasts than other rudites in the area. Branxton Formation conglomerates are characterized by dropstone clasts of metamorphic lithologies and those of the upper portion of the Goorangoola Formation by a higher proportion of clasts of intermediate volcanic (40%).

Generalized descriptions of pebble shape, size and morphology are given in Table 2. Pebble shape analysis after Zing (1935; cited in Krumbein and Sloss, 1963, p. 107) showed that quartz and quartzite clasts are spherical or cubic, sedimentary lithic clasts are oblate and volcanic clasts are oblate or cylindrical.

Arenites: Arenites within the area investigated are typically fine to coarse grained, compositionally and texturally immature lithic sandstones (Table 3). The immaturity is reflected in the low proportion of quartz, the high proportion of lithic fragments, the angularity and low to moderate sphericity of the clastic mineral grains.

Modal compositions are plotted in Figure 3, where triangular diagrams show the compositional variation of these rocks for stratigraphic units in which arenites are conspicuous elements. Arenites in the Branxton Formation contain a high or proportion of volcanic rock fragments than sedimentary rock fragments and mineral

TABLE 1
Stratigraphic Nomenclature and Formation Lithology

Booker (1953)		Veevers (1960)		Robinson (1969)	Thickness (metres)	Description
Tomago and Newcastle Coal Measures	Rixs Creek Formation	Singleton Coal Measures	Rixs Creek Formation	Goorangoola Formation	230 m. from bore data but up to 400 m.	Sandstone, shales, mudstones and irregular coal seams which pass upward into sandstone and conglomerate.
				Vane Formation	303 m.	Sandstones, shales, mudstones, coal seams and minor conglomerates.
				Saltwater Creek Formation	70 m.	Sandstone, siltstone with minor shales, conglomerates and an irregular coal seam (Hebden Seam).
	Bayswater Formation	Maitland Group	Ponds Creek Formation	Mulbring Siltstone	240 m.	Grey-green siltstone with minor arenaceous phases (glacial erratics in lower 15 m.).
Maitland Group	Mulbring Siltstone		Mulbring Siltstone			
	Branxton Formation		Branxton Formation	Branxton Formation	605 m.	Fine, medium and coarse grained lithic arenites, pebbly arenite and pebble conglomerates with minor cobble phases.

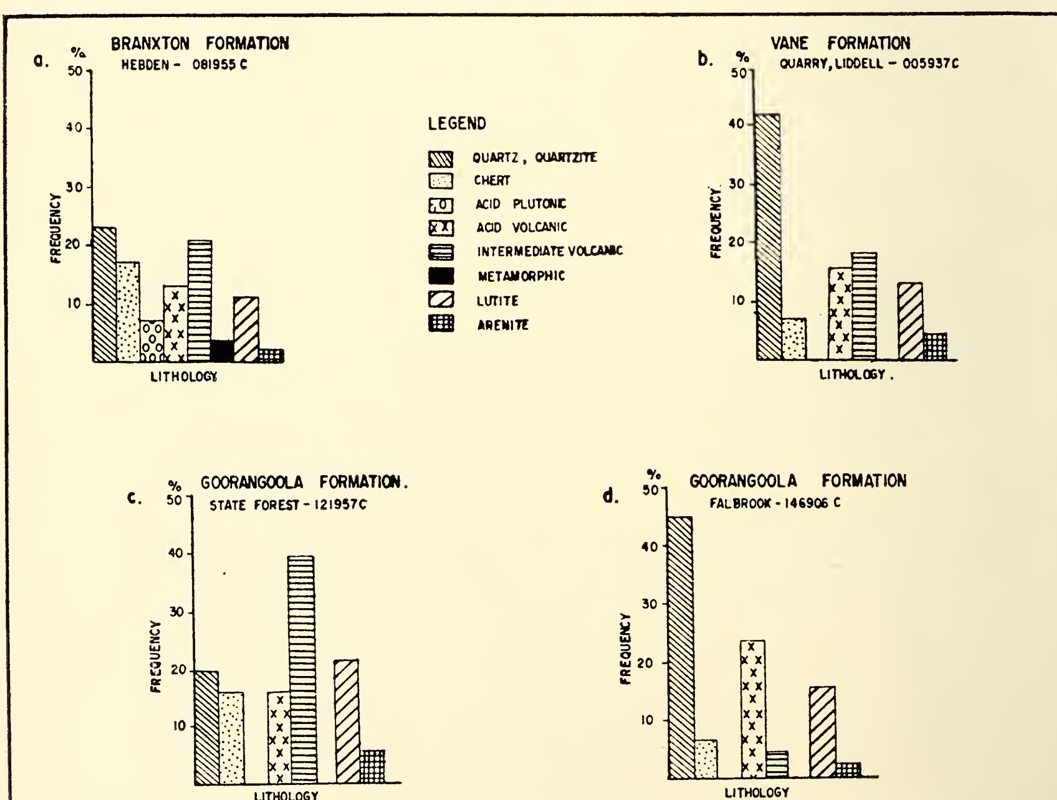

FIGURE 3 —Pebble phenoclast lithology histograms. Each histogram represents a sample of 100 pebbles randomly selected from a 2 square metre sampling grid.

TABLE 2
Textural and Compositional Features of Rudites

Formation	Size Range of Clasts	Gross Rudite Composition	Sorting	Roundness	Clast Lithology
Goorangoola Formation (upper section)	pebble to boulder (range : 2–48 cm.)	polymictic	unsorted	angular to subangular	intermediate volcanics (35–40%), lutite (18–23%), quartz/quartzite (15–20%), chert (13–18%) ; acid volcanic (15–18%), arenite (4–7%).
Goorangoola Formation (lower section)	granule to cobble (range : 2 mm.–16 cm.)	polymictic	poor sorting	rounded to subrounded	quartz/quartzite (35–45%), acid volcanics (15–23%), lutite (12–15%), chert/jasper (5–8%), intermediate volcanics (4–6%), arenite (2–3%).
Vane Formation	granule to pebble (range : 2 mm. –13 cm. ; average : 2 cm.)	polymictic	poor sorting	rounded to subrounded	quartz/quartzite (35–40%), acid volcanics (15–23%), acid volcanics (15%), lutite (10–13%), chert/jasper (5–8%), arenite (3–5%).
Saltwater Creek Formation	generally pebble size with minor cobble zones.	polymictic	unsorted	rounded to subrounded	quartz/quartzite, acid and intermediate volcanics, chert, lutite and arenite.
Mulbring Siltstone			no rudites		
Branxton Formation	granule to cobble	polymictic	unsorted	subrounded to subangular	quartz/quartzite (20–23%), intermediate volcanic (18–21%), chert (15–18%), acid plutonic (10–13%) metamorphic (3–5%), arenite (2–3%).

grains ; those of the Singleton Coal Measures show a higher proportion of sedimentary grains.

Lutites : Lutites are poorly exposed because of weathering. Except for some minor " silty " arenites in the lower portion of the Branxton Formation, the lutites of the Maitland Group are essentially confined to the Mulbring Siltstone except for some minor " silty " arenites in the lower portion of the Branxton Formation. The Mulbring Siltstone is a grey-green, massive, puggy siltstone which contains angular, elongate quartz, plagioclase, minor microcline and subrounded calcilutite fragments in a dense argillaceous matrix with minor sericite and calcite cement. Dropstones, comprising quartz-fedlspar porphyry, toscanite, hornfels, phyllite and granite of cobble and boulder size (up to 1 metre in diameter) are common in the lower 15 metres.

The Singleton Coal Measures also contain lutites, principally siltstone, mudstone, shale and claystone ; these lithologies are most common in the Vane Formation. The siltstones are generally light grey, massive, relatively even grained and often transitional from mudstone to fine grained sandstone. The siltstones comprise grains of subangular to subrounded quartz and plagioclase, subrounded to rounded lithic sedimentary rocks and carbonaceous material. Claystones are common as bands within coal seams. They are soft and waxy, exhibit a colour range from white to pale brown, and are probably tuffaceous (Booker, 1960).

Provenance

The composition of detrital components in arenites and rudites indicates varying provenance for the Permian strata in the region (Table 4). During Maitland Group sedimentation a lithological change in source terrain is evidenced by a difference in the detrital composition of arenites in the Branxton Formation and those in the Mulbring Siltstone. The Branxton Formation has a volcanic provenance with minor granitic and pegmatitic sources, whereas a predominantly sedimentary source is indicated for the Mulbring Siltstone. Additionally, Maitland Group rocks contain dropstones of metamorphic and igneous lithologies, and these evidently reflect ice rafting from areas of like composition.

Provenance during deposition of the Singleton Coal Measures was relatively uniform and associated with a sedimentary source. An

TABLE 3

Textural and Compositional Features of Arenites

Formation	Predominant Sandstone Type	Grainsize	Roundness	Sphericity	Matrix	Cement	Grain Composition
Goorangoola Formation (upper section)	litharenite	medium to coarse	subangular	elongate to equant	—	(10–15%) ferruginous (limonite, goethite) chlorite	lutite/arenite (35–40%); volcanic (1–5%), quartz (25–35%), plagioclase (5–7%).
Goorangoola Formation (lower section)	feldspar litharenite	medium to coarse	subangular to subrounded	elongate to equant	(5%) fine grained phenoclast material	limonite, calcite goethite	mudstone/siltstone (45–50%), acid and intermediate volcanics (1–5%), quartz (10–20%), plagioclase (10–15%).
Vane Formation	litharenite and feldspar litharenite	fine to coarse	subangular to subrounded	elongate to equant	(7%) quartz, sedimentary fragments	calcite (primary) siderite, limonite, goethite minor haematite chlorite	mudstone/siltstone (45–55%), acid and intermediate volcanics (1–5%), quartz (10–20%), plagioclase (10–13%), biotite (1–2%), opaques (1%).
Saltwater Creek Formation	Much higher silt content than Vane Formation arenites, not unlike the Mulbring Siltstone in places						
Mulbring Siltstone	" silty " arenite	fine	subangular to subrounded	elongate to equant	—	chlorite	quartz, chloritized and kaolinized feldspar muscovite, minor sedimentary lithic fragments.
Branxton Formation	feldspar litharenite	medium to coarse	subangular	elongate to equant	(5–10%) quartz, lithic volcanic fragments	(9–12%) ferruginous (limonite) minor chlorite dawsonite (?)	lithic volcanic fragments (30–40%), mudstone and chert fragments (9–13%), quartz (15–20%) feldspar (15%).

TABLE 4
Sediment Provenance

Formation	Provenance	Indicator
Singleton Coal Measures (upper section)	*Volcanic*	marked increase in the proportion of volcanic phenoclasts in rudites. (35–40% of clasts.)
Singleton Coal Measures (lower section)	*Sedimentary*	high proportion of sedimentary lithic fragments (45–50% of detrital grains).
Mulbring Siltstone	*Sedimentary*	sedimentary lithic fragments.
Branxton Formation	1. *Volcanic.* 2. Minor granite and pegmatite source.	1. high proportion of volcanic rock fragments in arenites (50–60% of detrital grains) and rudites. 2. quartz with inclusions ; graphic intergrowths ; microcline and plagioclase.

increase in intermediate and acid volcanic rudite phenoclasts in the upper portion of the Goorangoola Formation reflects a change from a sedimentary to a volcanic provenance.

Sedimentary Structures

Other than bedding, sedimentary structures within the Maitland Group are rare. Alpha, heterogenous " alpha " and epsilon cross stratification are present in the lower section of the Braxton Formation. Lithologically homogeneous alpha cross stratification is formed by the migration of solitary sand banks (Potter and Pettijohn, 1963) ; the origin of heterogeneous " alpha " cross bedding is problematical and this structure, although not uncommon elsewhere in the Sydney Basin in Triassic rocks, is yet to be described in detail in the literature (Conaghan, pers. comm., 1973). Epsilon cross bedding is commonly generated on muddy intertidal flats forming from the lateral migration of meanders in channels (Potter and Pettijohn, 1963). The upper section of the Branxton Formation is characterized by rapid lateral facies changes with interfingering of arenites and rudites, expressed by sandstone lenses and wedges within cobble conglomerate zones. The sedimentary features of the Branxton Formation (Table 5) suggest that the lower and upper parts of the Branxton Formation were deposited in tidal flat and shallow neritic/shoreface environments respectively.

Within the Singleton Coal Measures cross-stratification is the most common sedimentary structure. Ripple marks, channels and other small scale sedimentary structures, such as flame structures, convoluted foresets, ball-and-pillow structures and load casts are also present.

The Saltwater Creek and Vane Formations are characterized by alpha, beta, epsilon and nu cross-stratification. Lensing of the interseam sediments is common. Booker (1953) described the depositional sequence as " a series of interlocking lenses ". Lateral facies changes are marked and abrupt : arenites up to 4 metres thick taper to 1 metre within a distance of 9 metres. Seam splitting is also frequent. Splits occur as thin " rider " seams which diverge from the main seam at angles of 30° to 40°. Strata within the split " shadow " the divergent splitting seam as large scale foresets. These foresets are up to 7 metres in height and up to 200 metres in length. Britten (1970, 1972) considered that these foresets are the result of " mobile differential compaction ", where seam splitting is dependent on the direction and rate of sedimentary fill into the postulated coal swamps.

The stratigraphic interval between the Bayswater and Ravensworth Seams, in the lower portion of the Goorangoola Formation contains pi cross-stratification, and channel-like troughs. These structures presumably reflect a distinct change in the hydraulic regimen from that prevailing during deposition of the Vane Formation. A channel, exposed in a creek bank (024865C) is approximately 50 metres in width and has the asymmetrical profile characteristic of meandering streams. Rare imbricated pebbles within the channel-fill indicate the palaeocurrents responsible for channel infilling flowed from north to south. Linear channel structures exposed in a railway cutting (038920C) are up to two metres deep, 25 metres in width and are infilled with massive sandstone. The massive sandstone is inferred to be the product of upper to transition flow regime conditions and together with the basal erosion surfaces of the channels suggests episodic periods of high velocity channelized flow (Coleman, 1969). The lower bounding surfaces of the channel truncate sandstone with pi cross

TABLE 5
Palaeoenvironment Data

	Lithosome Geometry	Lithology	Sedimentary Structures	Palaeocurrents	Fossils
Singleton Coal Measures (upper portion)	prism shapes; (wedge shape cross section)	coarse clastics: cobble conglomerate with boulder conglomerate phases; coarse sandstones	epsilon, alpha and eta cross bedding (rare)	unidirectional (vector magnitude: 8.18)	macerated plant debris
Singleton Coal Measures (lower portion)	varies from tabular to prism shapes, with shoestring sands.	sandstone, siltstone, shale, coal and minor conglomerates	(i) alpha cross bedding and channel-like troughs. (ii) alpha, beta, nu, epsilon cross bedding.	unimodal (vector magnitude: 5.53).	macerated plant debris
Mulbring Siltstone	tabular	siltstone, with minor arenaceous phases	—	—	micro-fossils (ostracods, formini-era).
Branxton Formation (upper portion)	prism shapes, with shoestring sands and conglomerates	pebble and cobble conglomerate, with coarse sandstones	—	limited data irregular pattern)	brachiopods
Branxton Formation (lower portion)	tabular, with minor shoestring sands	fine and medium sandstones, with minor pebble conglomerates	alpha and epsilon cross bedding (rare)	limited data (appears unidirectional)	brachiopods

stratification. The channel trends are parallel to palaeocurrent trends as defined by azimuths of cross bedding foresets and presumably indicate a palaeoslope control. The pi cross stratified units are formed of interfering grouped sets, individually large in scale, and have plunging, scoop shaped lower erosional surfaces. They have an average width of 3 metres and trough amplitudes of 0·4 metres to 0·7 metres.

Ripple marks were observed at two localities in the Goorangoola Formation (13886C and 059876C); they plot within the "windformed" zone on diagrams of Tanner (1966).

The upper section of the Goorangoola Formation contains alpha, epsilon and eta cross-stratification. Epsilon foresets (up to 3 metres in height) are present in pebble conglomerate exposed in the bank of Glennies Creek (145884C).

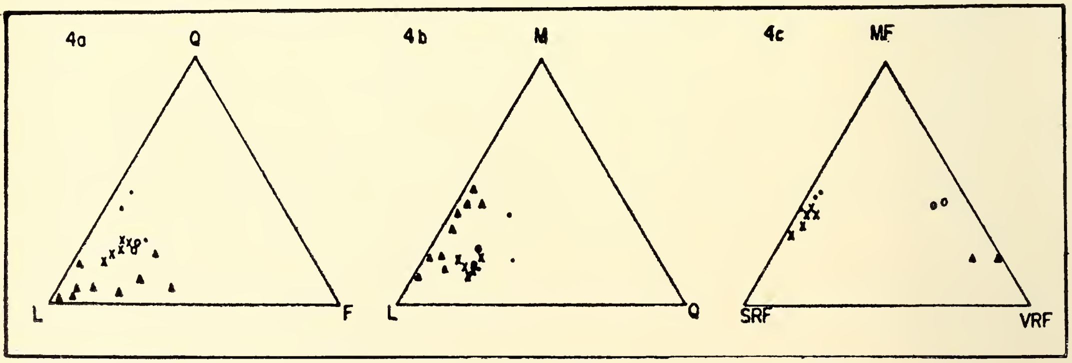

FIGURE 4.—Arenite composition (based on point count analyses)
4A. LQF (Lithic-Quartz/Chert-Feldspar) Diagram.
4B. MLQ (Matrix/Cement-Lithic/Feldspar-Quartz) Diagram.
4C. MF–SRF–VRF (Mineral Fragments-Sedimentary Lithic Fragments-Volcanic Lithic Fragments) Diagram.
O Branxton Formation; x Vane Formation; ● Goorangoola Formation; ▲ Carboniferous (from Hansen, 1968).

Palaeocurrent Trends

The palaeocurrent trends within the Branxton Formation (Figure 5) may suggest a complex interplay of currents associated with the variable marine inshore or littoral environment envisaged for this formation. The predominance of a northwesterly trend (mean azimuth 324°) possibly reflects the influence of longshore currents in this inshore zone.

The Singleton Coal Measures show distinct palaeocurrent trends for the Vane and Goorangoola Formations. The Vane Formation has a mean vector palaeocurrent direction (Pincus, 1956; Curray, 1956) of 304° and a resultant vector magnitude (Curray, 1956) of 5·53. Current directions range from 0° to 330°. These trends (Figure 6) suggest a moderate to high sinuosity, meandering stream pattern with a general westerly flow direction. In the vicinity of Liddell the palaeocurrent trends diverge to the north and south, possibly indicating the presence of a local high.

Palaeocurrent trends for the Goorangoola Formation (Figure 7) show a change in flow direction from that observed in the Vane Formation. The trends define a unidirectional current pattern perhaps related to a braided stream system associated with alluvial fan development. The mean vector direction is 213° and the "resultant vector magnitude" (Curray, 1956) is 9·18. Flow directions range from 125° to 260°.

Palaeoenvironments

The lenticular nature, textural immaturity and the presence of marine fossils and dropstones in the Branxton Formation (Table 5) indicates an extremely variable marine environment

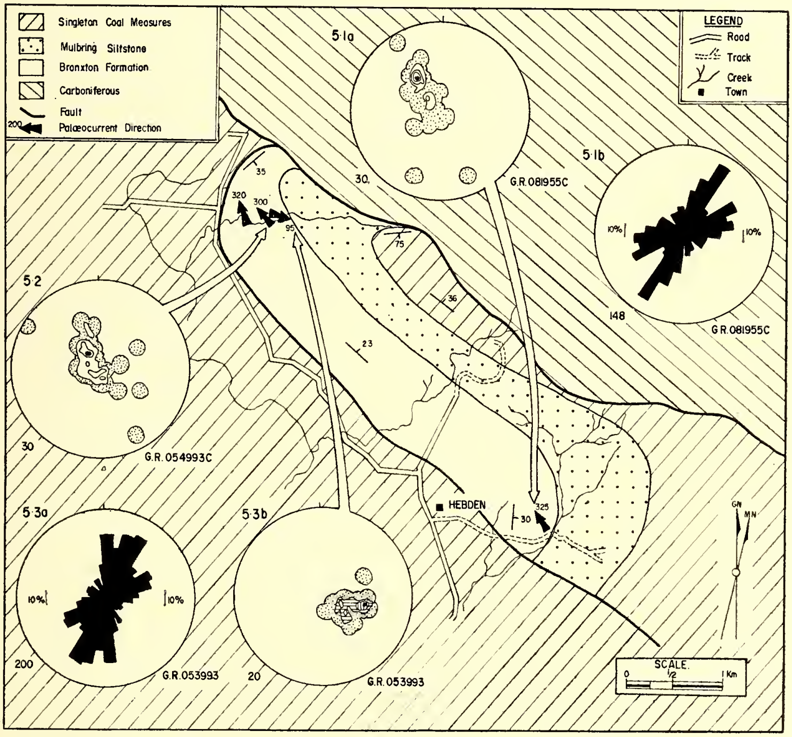

FIGURE 5.—Palaeocurrent Data, Branxton Formation.

5.1a Pebble imbrication 23·2%, 20%, 16·5%, 13·3%.
5.1b Pebble long axes (apparent).
5.2 Pebble imbrication 20%, 16·5%, 10%.
5.3a Pebble imbrication 35%, 25%, 20%.
5.3b Pebble long axes (apparent).
All contours per 1% area.

Note 1. Pebble imbrication diagrams are contoured poles to oblate clasts. Bedding is horizontal in all diagrams.
2. Apparent pebble long axes (measured on bedding planes or surfaces close to bedding).

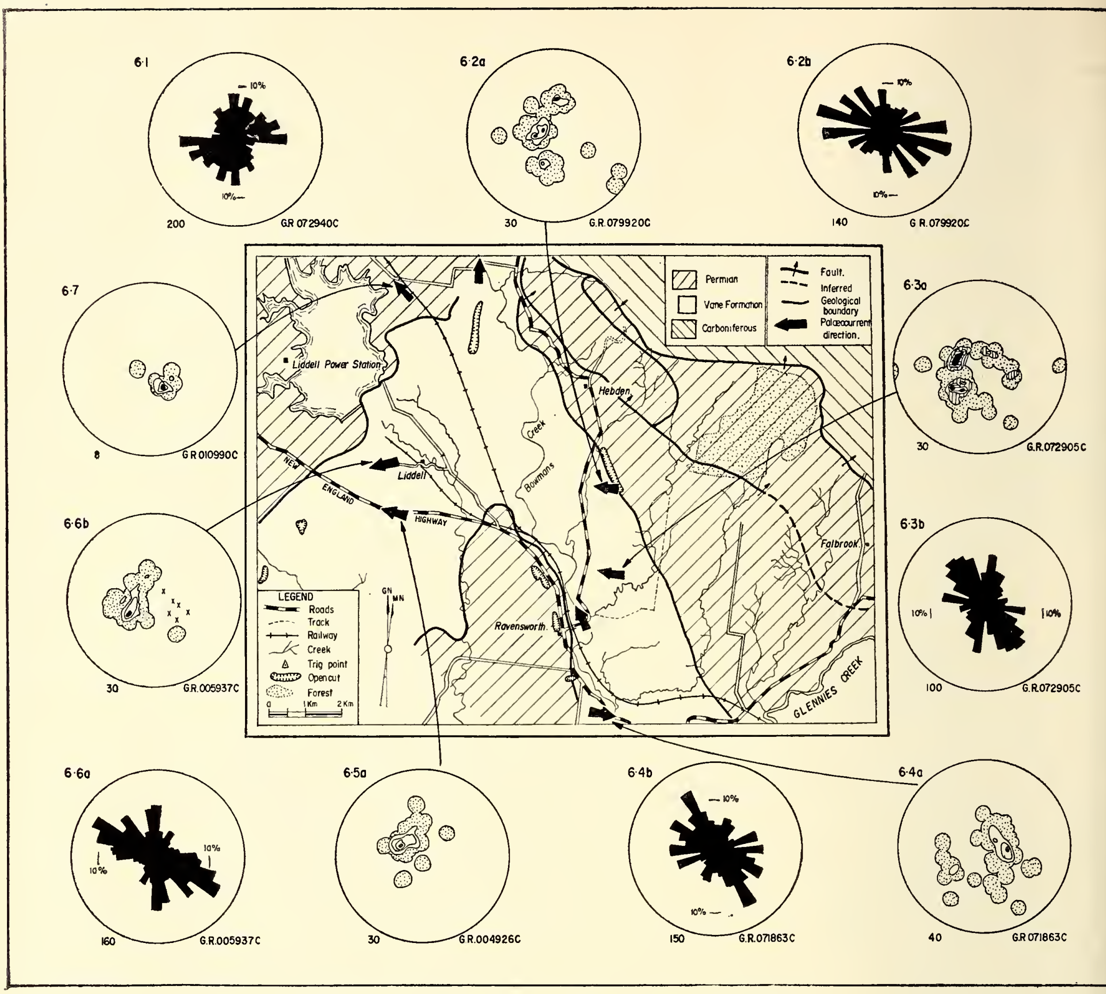

FIGURE 6.—Palaeocurrent Data, Vane Formation.

6.1 Fossil leaf orientation (long axes).
6.2a Pebble imbrication 16·5%, 13·3%. 10%.
6.2b Pebble long axes (apparent).
6.3a Pebble imbrication 16·5%, 13·3%, 10%.
6.3b Pebble long axes (apparent) (GR.072905C).
6.4a Pebble imbrication 17·5%, 15%, 10%.
6.4b Pebble long axis (apparent).
6.5 Pebble imbrication 33%, 30%, 23·2%, 16·5%.
6.6a Pebble long axes (apparent).
6.6b Pebble imbrication 27%, 20%, 16%.
6.7 Cross-stratification (poles to foresets).
All contours per 1% area.

associated with glacial or periglacial conditions. Deposition took place in a variable nearshore or littoral environment ranging from a shallow water intertidal zone in the lower portion to a strandline zone in the upper portion. Alpine glaciation is thought to have been established on a northwest-southeast trending mountain range to the south (Dulhunty, 1964; Crowell and Frakes, 1971).

These muddy strandline conditions are in complete contrast to the environment of deposition of the overlying Mulbring Siltstone. Raggatt (1938) considered that the Siltstone was deposited partly at least under shallow water conditions containing floating ice. The presence of cold-water calcareous foraminifera and ostracods also point to a cold shallow-water environment, whereas the development of glendonites indicates tranquil water and the presence of pyrite nodules reflect neutral or alkaline conditions (Reynolds, 1956). The absence of erratics in the upper portion of the Siltstone reflects a decline of ice rafting activity.

The Saltwater Creek Formation is characterized by a marine regression and the establishment of a fluviatile-lacustrine environment. Environments probably fluctuated between marine intertidal and peat swamp conditions. Raggatt (1938) suggests that the change in conditions was gradual and not abrupt.

The Vane Formation was deposited under fluviatile-lacustrine conditions in a meandering

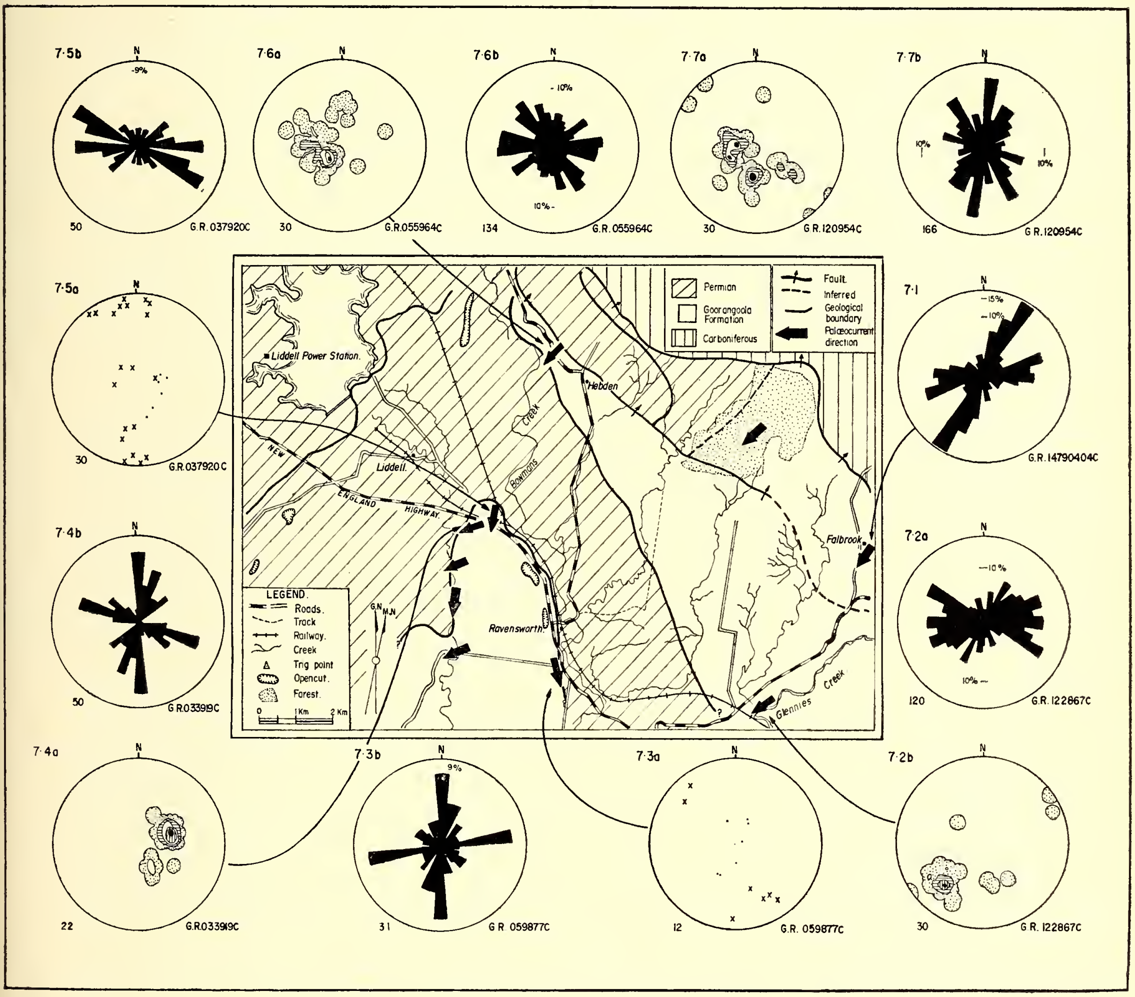

FIGURE 7.—Palaeocurrent Data, Goorangoola Formation.

7.1 Pebble long axes (apparent).
7.2a Pebble long axes (apparent).
7.2b Pebble imbrication 35%, 30%, 23·2%, 16·5%.
7.3a X Trough cross-stratification axes ; ● poles to foresets.
7.3b Fossil log casts (long axes).
7.4a Cross stratification (poles to sf) 41, 31, 22·3, 13·6%.
7.4b Fossil log casts (long axes).
7.5a X Trough cross-stratification axes ; ● poles to foresets.
7.5b Fossil log casts (long axes).
7.6a Pebble imbrication 27%, 23·2%, 13·3%, 10%.
7.6b Pebble long axes (apparent).
7.7a Pebble imbrication 16·5%, 13·3%, 10%.
7.7b Pebble long axes (apparent).
All contours per 1% area.

stream environment. Fine sandstones, siltstones and claystones represent overbank floodplain deposits, whereas the coarse sandstones, pebbly sandstones and conglomerates characterize the main channel deposits. Peat accumulation presumably occurred in abandoned river channels (oxbow lakes) and backswamps. The extent of coal seam development was controlled largely by the nature, the rate and direction of sedimentary fill and the location of the channel zones within the floodplain. Duff (1967) points out that there are two alternating environments involved—one where peat and fine clastics accumulated and the other where coarse clastics are deposited.

The origin of the coal, however, remains uncertain. The lack of seat earths has been considered to indicate an allochthonous origin for coal within eastern Australia (Duff, 1967). Duff suggested two models for coals which lack recognisable associated seat earths:

(1) " Drift Theory ", where vegetable debris is washed into the area of deposition.
(2) " Modified Drift Theory ", where vegetation grows on floating peat.

He also suggested that the deciduous character of southern hemisphere glossopterids, combined with the possibility that rooting took place on vegetable ooze rather than clay or sand, may explain the lack of seat earths.

The occurrence of vertical tree stems and vertically oriented " *Vertebraria* ", considered to be glossopterid rootlets, in the Hebden Open Cut Mine (072940C) indicates that some vegetation grew in zones of peat accumulation in this area.

Cyclic sedimentation, often characteristic of coal measure sedimentation was first recognized in the Singleton-Muswellbrook coalfield by Booker (1953). Veevers (1960) defined three major cycles compounded of minor cycles consisting essentially of sandstone, siltstone, shale and coal in ascending order. Duff (1967), however, concluded that there was a variety of cycle types in the Singleton Coal Measures with no particular one dominant. Analysis of borehole data after Duff (1967), in the Hebden region (Figure 8) also shows no obvious cyclicity. The overall sedimentation rhythms have generally been obliterated by cumulative cycle development. The complex cycles commonly observed are an expression of the superposition of several reduced or incomplete cycles, which results from continual channel switching of the alluvial drainage system.

Marked changes in palaeocurrent trends and sedimentary structures suggest a change in depositional environment for the Goorangoola Formation. A southerly flowing braided stream system developed on a terrestrial piedmont in front of an uplifted Carboniferous source area to the north. The uplift, caused by movements along the Hunter Thrust was initially gradual and prolonged, punctuated by sporadic phases

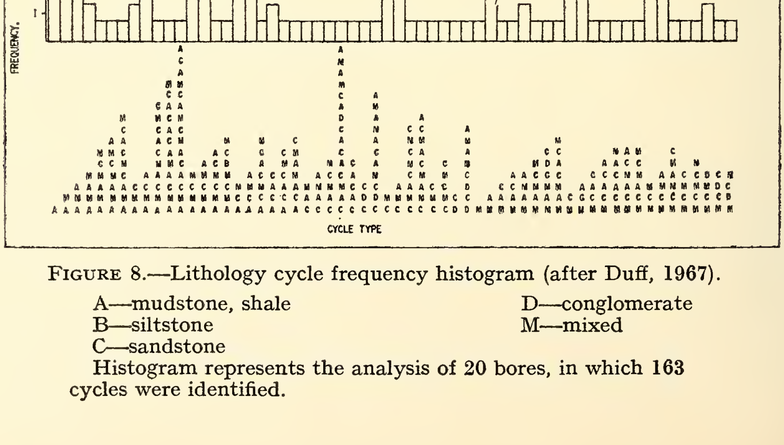

FIGURE 8.—Lithology cycle frequency histogram (after Duff, 1967).

A—mudstone, shale
B—siltstone
C—sandstone
D—conglomerate
M—mixed

Histogram represents the analysis of 20 bores, in which 163 cycles were identified.

of rapid uplift. Such phases probably caused flooding and swift drainage in parts of the area. The strata between the Bayswater and Ravensworth Seams, characterized by linear scour-channels and pi cross-stratification reflect a period of flooding.

Increased uplift resulted in the development of extensive conglomerate sheets. These conglomerates generally become more coarse to the north, and form part of the outcrop along the western bank of Glennies Creek, north of the village of Glennies Creek.

Conclusions

The Permian strata in the Ravensworth region form part of the northern margin of the Sydney Basin. Duff (1967) considers that the Basin corresponds to a depositional model of an intermontane basin with an outlet to the sea.

Dulhunty (1964) provides a general palaeogeographic description of the Basin. He considered that the Sydney Basin in the late Early Permian (Kungurian-Kazanian) was a marine embayment bordered to the southwest by a northwest-southeast mountain range carrying permanent snowfields and glaciers. Towards the close of the Permian (Tatarian) a waning of glaciation and a marine regression led to the development of freshwater lakes and swamps where alluvial sediments and peat beds were deposited.

Sedimentation in the Ravensworth area reflects this changing palaeogeography and has been characterized by marine strandline, fluviatile-lacustrine and alluvial fan—piedmont deposition. Depositional facies models (Figure 9) derived from the stratigraphic geometry, the sedimentary lithology and the palaeocurrent

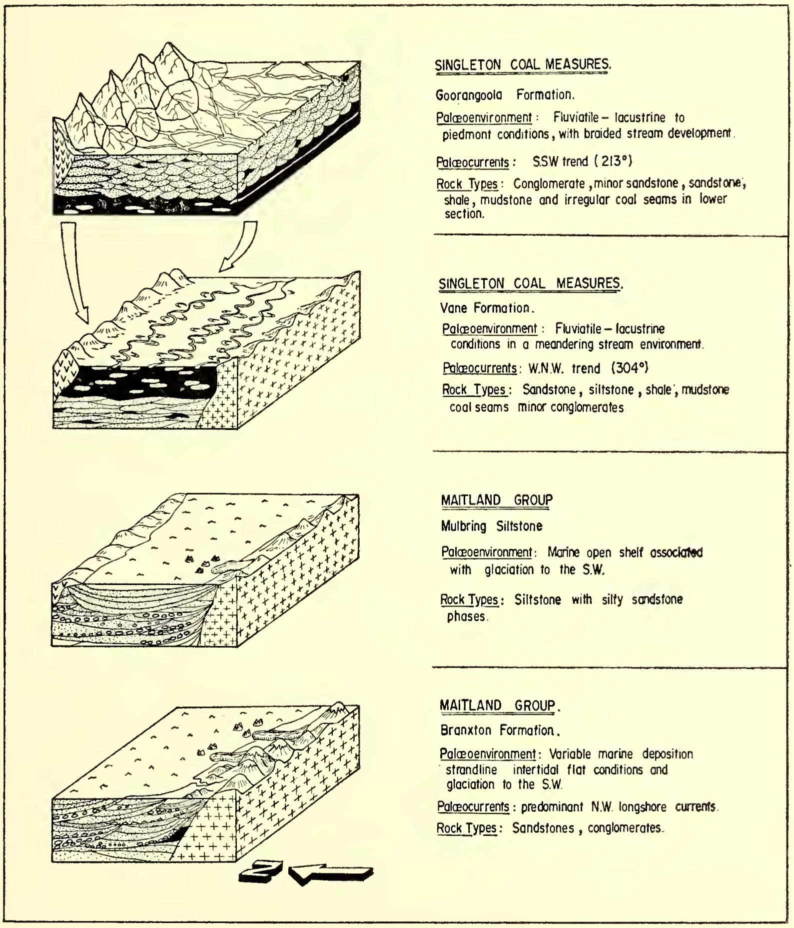

FIGURE 9.—Schematic depositional facies models. The diagrams represent hypothetical models adapted from Allen (1964) of successive depositional environments from the late Early Permian to the Late Permian for rocks in the Ravensworth area.

data for each stratigraphic unit pictorially depict these changing depositional environments. The models exist within the regional framework of the intermontane basin proposed by Duff (1967).

Booker (1960) considered a number of agencies responsible for such depositional changes in the Sydney Basin, of which climate, sea level changes and tectonic instability are the most important. The changes in the nature of sedimentation and palaeocurrent trends in the Singleton Coal Measures near Ravensworth are directly related to movements along the Hunter Thrust. Tectonic instability associated with this progressively developing structure very probably controlled the nature, direction and rate of sediment influx along the northern margin of the Sydney Basin during the Late Permian.

Acknowledgements

The author acknowledges use of facilities at the University of Newcastle and the advice and assistance given by Professor B. Nashar, Mr. B. Engel, Dr. K. Moelle, Dr. C. Diessel and Mr. B. Vitnell during the course of the work. Thanks are extended to Liddell Colliery, Hebden Mining Company, Foybrook Open Cut and Liddell State Mine managements for access onto their property, and to Mr. R. Britten for some drilling information.

Finally, the author would like to thank Dr. P. J. Conaghan for some invaluable suggestions during the preparation of this paper and for criticism of the final draft. All diagrams were drafted at Macquarie University, under the supervision of Mr. K. Kendall.

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(Received 18 July 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 31–34, 1974

Vesuvianite Hornfels at Queanbeyan, N.S.W.: The Nature and Status of a So-called Periclase Rock

T. G. Vallance

ABSTRACT—A contact metamorphic product, described in the literature as a periclase rock, occurs in a situation highly unusual for periclase. Re-examination of the locality and original material shows the earlier diagnosis to be in error. Vesuvianite (a=15·57Å, c=11·84Å) is, in fact, the principal phase present in the rock which also carries minor wollastonite and calcite. Vesuvianite appears to be stabilized in calcareous rocks at medium grades of contact metamorphism only where the vapour phase has a high H_2O content. Relatively hydrous metamorphism is typical of other contact zones in the Queanbeyan area.

Introduction

In her account of the geology of the Queanbeyan district, Phillips (1956) reported an occurrence of periclase rock at a contact between intrusive dacite and Middle Silurian limestone some 5 km south of the town. She described the material as extremely fine-grained and consisting of four minerals. " The predominating periclase occurs as a granular isotropic mass in which is scattered a small proportion of flaky brucite. The other minerals are hydromagnesite and calcite, the latter generally veining the periclase " (Phillips, 1956, p. 123). Formation of the periclase was attributed to a dedolomitization reaction operating during thermal metamorphism.

Local metamorphic features associated with silicic intrusive rocks, variously termed dacites or quartz-feldspar porphyries and perhaps better named porphyritic microgranodiorites, are known at several localities in the Queanbeyan area. In these other cases, however, the metamorphic situation is recognized as relatively low- to medium-grade, from albite-epidote hornfels to hornblende hornfels facies. Even in carbonate rocks it is common to find hydrous phases stabilized. At London Bridge, 18 km south-south-east of Queanbeyan, for instance, contact limestones carry the association calcite-epidote-tremolite with, locally, the hydrous borosilicate axinite (Vallance, 1966).

Stability and Occurrence of Periclase

Generation of periclase by dedolomitization requires rather elevated temperatures even at low pressures, and for such solid=solid+vapour reactions increased vapour pressure leads to higher reaction temperatures. According to Harker and Tuttle (1955) at 250 bars ($P_{CO_2}=P_{total}$) adjustment does not proceed for pure dolomite below about 700° C. With a mixed vapour phase (CO_2+H_2O) reaction temperatures are decreased, but as mole fraction H_2O (X_{H_2O}) in the vapour rises towards unity the equilibrium curve for the reaction passes into a region of brucite stability. Brucite itself dehydrates to periclase plus H_2O at about 530° C where $P_{total}=P_{H_2O}=250$ bars (Fyfe, 1958). Periclase is nowhere stable much below this temperature.

In natural situations, there is commonly sufficient water available even in carbonate rocks to ensure hydration of periclase to brucite, if not during waning stages of metamorphism then under post-metamorphic conditions. Pseudomorphs of brucite after periclase are unexceptional in higher-grade (normally, pyroxene hornfels facies) contact dolomites; periclase itself is a rare mineral. Good examples of brucite after periclase from the contact aureole at Ben Bullen, N.S.W., have been described by Joplin (1935).

Even if periclase had been generated in the case reported by Phillips (1956), its persistence there would be quite extraordinary. Not only was the terrain, including the dacites and related volcanic material, involved in a low-grade regional metamorphic event (Stauffer, 1967) but a granitic body (the Barrack Creek Adamellite) invaded the country near the so-called periclase rock.

Nature of the Contact Rocks

The material identified by Phillips as periclase rock (her sample 337; University of Sydney Collection No. 21887) comes from a contact zone in the southernmost limestone lens in Portion 103, Parish of Googong (incorrectly given as

Parish of Queanbeyan in Phillips's paper). Quarrying operations in the vicinity have been extended since the time of Phillips's study and the particular occurrence is now obscured by spoil. Limestone samples from the locality (about grid ref. 241 282, Canberra 1 : 63360 sheet) are distinctly recrystallized to fine-grained marbles, most of them displaying evidence of a schistosity. Staining of these marbles reveals that they are predominantly calcite rocks. Dolomite rarely exceeds about 15% by volume of the total carbonate and occurs typically as fractured porphyroblasts in recrystallized calcite mosaics or as trails of angular grains that serve to emphasize schistosity. The only other phases found commonly with the carbonates are minor pale green to colourless chlorite and scattered pyrite euhedra. No dolomite rocks have been recognized here and, indeed, an analysed sample (Table 1, column A) from the same general locality is not distinctly magnesian.

Re-examination of Phillips's collection confirms broadly the existence of contaminated dacite, in which diopside-hedenbergite plus wollastonite are generated, as an intermediate between normal dacite and the massive, pale yellow-green " periclase rock " (21887). The composition of the latter (Table 1), however, bears little resemblance to what it should be were the mineral association stated by Phillips present. The rock is clearly a calc-silicate hornfels containing some Ca-aluminosilicate phase. Examination of thin sections shows that a single phase constitutes more than 90% of the rock. This phase is practically isotropic with a mean refractive index 1.722 and must be that termed periclase. The refractive index is too low for periclase and, in addition, X-ray study shows the mineral has tetragonal symmetry agreeing with vesuvianite with cell dimensions a=15·57Å and c=11·84Å. The " flaky " phase that Phillips may have confused with brucite is fibrous wollastonite. Its presence has been confirmed by diffractometry on light fractions concentrated by centrifuging in diluted methylene iodide. No sign has been found of either brucite or the third phase, hydromagnesite, mentioned by Phillips. A thin chalk-white crust on the rock may have been mistaken for hydromagnesite but X-ray study shows it to consist almost entirely of vesuvianite, indistinguishable from the pale yellow-green vesuvianite.

There are, in fact, only three phases present, namely, vesuvianite with minor wollastonite and calcite. A modal check reveals almost 4·5% wollastonite present and the composition of vesuvianite quoted in Table 1 is calculated from the bulk analysis assuming ideal $CaSiO_3$ and $CaCO_3$. The formula derived from this calculated composition agrees generally with data listed by Deer, Howie and Zussman (1962), though it departs, as do many analysed vesuvianites, from ideal

$$Ca_{10}(Mg.Fe)_2(Al.Fe)_4Si_9O_{34}(OH.F)_4.$$

TABLE 1

	A	Rock 21887	Calculated Vesuvianite (21887)	Formula : 76 (O.OH.F)		
SiO_2	1·02*	37·73	37·8	Si	18·16	18·16
Al_2O_3	0·64	11·85	14·4	Al	8·15	9·71
Fe_2O_3		3·55	4·3	Fe^{3+}	1·56	
FeO	—	0·63	0·8	Ti	0·14	
MnO	0·24	0·05	0·06	Fe^{2+}	0·31	3·12
MgO	0·69	3·05	3·7	Mn	0·02	
CaO	54·25	38·90	36·5	Mg	2·65	
Na_2O	—	0·12	0·14	Ca	18·80	
K_2O	—	0·03	0·04	Na	0·13	18·95
H_2O+	—	1·54	1·87	K	0·02	
H_2O-	—	0·07	—	OH	5·99	5·99
TiO_2	—	0·31	0·4			
P_2O_5	—	0·03	—			
CO_2	43·47	2·05	—			
Total	100·31	99·91	100·01			

* " Gangue."

A—Limestone, Portion 114, Parish of Googong (Carne and Jones, 1919 ; assay 447).

21887—Vesuvianite-wollastonite-calcite hornfels, Portion 103, Parish of Googong, County of Murray (grid ref. 241 282, Canberra 1 : 63360 sheet). Anal. : T. G. Vallance.

Discussion

Vesuvianite has not been noted previously in contact zones in this area and the occurrence of wollastonite here might suggest somewhat higher temperatures than in other local cases. As we shall see, however, temperatures need not have been exceptional. The subvolcanic character of the intrusive rocks points to contact metamorphism being achieved at distinctly low pressure. Data on thickness of cover during metamorphism are lacking, but a total pressure not exceeding 500 bars and probably nearer 250 bars is considered reasonable.

Definition of the stability field of vesuvianite is still quite uncertain, though it is clear it must be confined by reactions involving a H_2O-bearing vapour phase and hence be influenced by critical concentrations of CO_2 in relations of the type (for end-member Mg.Al-vesuvianite):

15 vesuvianite + 98 CO_2 = 6 tremolite + 20 clinozoisite + 98 calcite + 27 quartz + 14 H_2O .... (1)

3 vesuvianite + 16 CO_2 = 6 diopside + 4 clinozoisite + 16 calcite + 3 quartz + 4 H_2O .... (2)

3 vesuvianite + 11 CO_2 = 6 diopside + 3 clinozoisite + 3 grossularite + 11 calcite + 5 H_2O .... (3)

1 vesuvianite + 4 CO_2 = 2 diopside + 1 anorthite + 1 grossularite + 4 calcite + 2 H_2O .... (4)

Ito and Arem (1970), in fact, failed to produce vesuvianite in any synthetic experiments with a mixed vapour phase though, for reasons obscure to the author, they predict vesuvianite should be stable " in a narrow overlap region in which pure calcite and quartz react to form wollastonite . . . under CO_2 pressure . . . even if the activity of CO_2 is considerable ". It is impossible to evaluate X_{CO_2} from the information given by Ito and Arem, but their use of ascorbic acid (which would yield $X_{CO_2}=0 \cdot 6$) plus $CaCO_3$ and hydrous gels in the mixes suggests X_{CO_2} cannot have exceeded $0 \cdot 6$ and may well have been much lower.

Equations (1), (2), (3) and (4), arranged in order of increasing temperature, suggest increasing tolerance of vesuvianite to CO_2 in that sense. Vesuvianite is expected to be on the higher-temperature side in each case which should have a T–X equilibrium curve with inflected positive slope towards $X_{CO_2}=1$ (Greenwood, 1967*a*). The solid phases in (4) suggest this possible reaction straddles the curve for calcite + quartz = wollastonite + CO_2. Stability relations of vesuvianite and grossularite are of especial interest. These two phases occur together commonly in nature and the T–X field of end-member grossularite has been defined by Gordon and Greenwood (1971).

The simple dehydration arrangement vesuvianite = grossularite + H_2O plotted schematically by Agrell (1965, fig. 1) cannot obtain for natural vesuvianites, even end-member Mg.Al-vesuvianite. Equations such as:

vesuvianite + SiO_2 + 2CO_2 = 2 diopside + 2 grossularite + 2 calcite + 2 H_2O .... (5)

vesuvianite + 3 SiO_2 = 2 diopside + 2 grossularite + 2 wollastonite + 2 H_2O .... (6)

express more likely limits. Equation (5) represents a special case where product-vapour balances reactant-vapour and vesuvianite occurs on the low-CO_2 side of a vertical T–X curve. T–X curves for (5) and (6) intersect at an invariant point on the wollastonite reaction curve (Trommsdorff, 1968) and (6) effectively defines upper temperature limits for vesuvianite plus excess silica. These limits must lie below those of the reaction: grossularite + SiO_2 = anorthite + 2 wollastonite which is independent of vapour composition and has been studied experimentally by Newton (1966).

In cases with no excess silica vesuvianite must be less restricted with regard to T and X_{CO_2} but even here vesuvianite appears limited on the higher X_{CO_2} side by grossularite-stable fields at moderate temperatures. Either (4) or both (3) and (4) must pass into a T–X region with X_{CO_2} greater than that for (5) but less than that of a grossularite + CO_2 reaction (Gordon and Greenwood, 1971) at the same temperature. As Trommsdorff (1968) has shown, the T–X curve for the reaction:

1 vesuvianite + 1 wollastonite + 3 CO_2 = 2 diopside + 2 grossularite + 3 calcite + 2 H_2O .... (7)

emerges from the invariant point shared by (5) and (6). Thus the assemblage vesuvianite + wollastonite appears restricted to a more hydrous part of the vesuvianite field.

Ito and Arem (1970) report generation of melilite (of unstated composition) + monticellite + wollastonite (+ vapour) from mixtures of vesuvianite composition at about 640° C at $P_{total}=P_{H_2O}=500$ bars (and, by extrapolation, about 610° C at 250 bars). These authors also show that synthesis temperatures for a given pressure are lowered by the presence of Na and appear to have stabilized vesuvianite at 350° C (500 bars) in such a case. In the absence of experimental data on reversed reactions, these results are quoted as a guide to stability of

Mg.Al-vesuvianite where mole fraction H_2O is unity.

As it seems clear that vesuvianite is restricted at medium metamorphic temperatures to an even narrower range of X_{CO_2} than grossularite, the reaction calcite+quartz to yield wollastonite associated with vesuvianite must proceed at temperatures well below that of the simple decarbonation in pure CO_2 (cf. Greenwood, 1967*b*). The Queanbeyan hornfels appears to have formed in what must be a narrow field above the temperatures of the calcite+quartz reaction and limited in terms of X_{CO_2} by (7) but outside the extremely hydrous situation where xonotlite is stabilized in place of wollastonite (cf. Vallance, 1973). The rock was evidently derived from a carbonate parent, but the present mineralogy points to a water-rich environment at temperatures of the order of 450° C, well within the hornblende hornfels facies (Turner, 1968).

The revised mineral assemblage in the Queanbeyan hornfels is in reasonable accord with experience of other contact metamorphic zones in the area. This particular example seems to have generated allochemically. Dilution of CO_2 by H_2O during progress of decarbonation reactions presumably was related to addition of magmatic water, but the presence of contaminated dacite and the apparent absence of rocks, such as calcareous shales, that could yield vesuvianite isochemically point to transfer of other components as well as water from the intrusive body. Until the outcrop is accessible once more, this aspect remains unresolved.

As an addendum, attention is drawn to the existence at Canberra, about 14 km to the north-west, of metamorphosed calcareous shales. Four of these hornfelses, denoted " calcareous rocks from Canberra (limestone with silicate of lime) ", have been chemically analysed (Department of Mines, N.S.W., 1911, p. 188). The analysed samples (which cannot now be found) almost certainly came from Red Hill, where Upper Silurian calcareous shales and associated volcanic sediments have been locally metamorphosed by another of the numerous subvolcanic intrusions of the region. Calc-silicate rocks collected at Red Hill by the author include types with colourless, anomalously-birefringent Ca-garnet + diopside + quartz. Vesuvianite has not been seen here (nor has " silicate of lime ") ; grossularite appears to have formed instead, reflecting more siliceous bulk compositions. Again, a distinctly hydrous metamorphism of carbonate rocks at only moderate temperatures is indicated.

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(Received 9 May 1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 35–40, 1974

The Seismicity of New South Wales

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ABSTRACT—Riverview College Observatory in Lane Cove has been recording ground motion in the neighbourhood of Sydney from earthquakes since 1909. The largest ground motion measured in this time has been of half-amplitude 500 microns and of period approximately 1 sec. There have been six earthquakes in New South Wales in this time of Wood-Anderson magnitude 5·5 or greater. Two of these have occurred in the Dalton-Gunning region and two have occurred near the southern and western boundaries of the Sydney Basin. Sydney itself and the South Coast of New South Wales have been much less seismic than these two regions. However, in evaluation of seismic risk, even in less seismic regions, allowance must be made for faults, ground with poor bearing capacity and potential landslide areas.

Introduction

The earthquake felt in Sydney (Modified Mercalli intensity IV) at 5.10 a.m., E.S.T., 10th March, 1973, served as a reminder that a study needed to be made of the ground motion caused in Sydney by past earthquakes before any estimate can be made of the likely effects of future earthquakes.

In this paper a brief summary of the more significant earthquakes felt in New South Wales between 1788 and 1909 is given. Since 1909, seismographs have been operating at Riverview College Observatory in Lane Cove and estimates of the Wood-Anderson magnitudes of the larger earthquakes felt in New South Wales between 1909 and 1973 are presented. Finally, some observations on earthquake risk in southeastern New South Wales are made.

Earthquakes in New South Wales from 1788–1909

Within a month of the founding of the colony of New South Wales in 1788, a small earthquake was felt at Port Jackson (Clarke, 1869). Another earthquake was felt in Parramatta in 1801 (Cotton, 1921). An earthquake which was felt in Prospect in 1809 was reported to have " changed well water from fresh to salt " (Clarke, 1869), and there exists an anonymous account of an earthquake near Lake George in 1828 (Doyle, *et al.*, 1968*b*). Explorers, for example, Sturt, also felt earthquakes in western New South Wales (Clarke, 1869).

Further earthquakes were felt in Sydney in 1837, in Maitland and Parramatta in 1841, and in St. Leonards and Maitland in 1868. As a result of the earthquake in 1868, a clock in East Maitland " which had not gone for months and could not be coaxed or forced to go . . . since midnight last night has continued to oscillate . . . and is apparently as reliable a time-teller as in its most palmy days " (Clarke, 1869). The Report of the Australasian Association for the Advancement of Science of 1892 mentions earthquakes felt at Coonamble (Rossi-Forel intensity VI) in 1880, and at Yass (Rossi-Forel intensity VII-VIII) in 1886 (Morton, 1893).

Clarke (1869) observed that the few earthquakes " that have been rescued from oblivion are sufficient to justify the belief that numerous others have passed unrecorded ", and the seismicity of New South Wales between 1788 and 1909 appears to have been quite similar to that since 1909.

Seismographs at Riverview

Mainka and Wiechert seismographs began operating at Riverview in 1909. The response of these seismographs to ground motion at various periods is calculated from their free period, static magnification, viscous damping and pen friction (Byerly, 1933). Galitzin seismographs began operating at Riverview in 1941. The response of these seismographs to ground motion at various periods is calculated from their free period and synchronous magnification (Sohon, 1932). The responses of the Mainka, Wiechert and Galitzin seismographs at Riverview are shown in Figure 1. Also shown in Figure 1 is the response of a standard Wood-Anderson seismograph of free period 0·8 sec., static magnification 2,800, and viscous damping parameter 0·8 (Richter, 1935, 1958). It can be seen from Figure 1 that, for ground motion at a period of 0·9 sec., the magnification of the

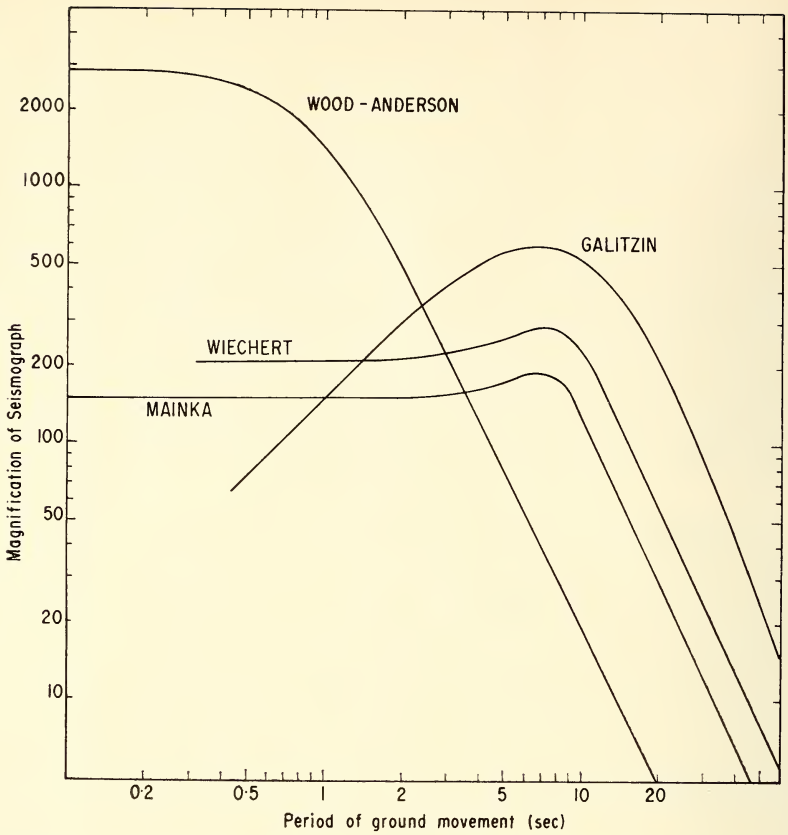

FIGURE 1.—Response to ground motion of a standard Wood-Anderson seismograph and of the Mainka, Wiechert and Galitzin seismographs at Riverview.

Mainka seismograph (approximately 150) is one-tenth that of a standard Wood-Anderson seismograph (approximately, 1,500).

The magnifications of Benioff and Sprengnether seismographs of the Worldwide Standard Seismograph Network which began operating at Riverview in 1962, are readily available (Geotech, 1962 ; University of Michigan, 1966).

Wood-Anderson Magnitudes

Burke-Gaffney (1951) estimated Wood-Anderson magnitudes of earthquakes in New South Wales from seismograms made at Riverview. He observed the period of the motion of largest amplitude on the seismogram and compared the magnification with that of a standard Wood-Anderson seismograph at that period. He then used the table of Richter (1935, 1958) for California to calculate the Wood-Anderson magnitude.

In this paper, Burke-Gaffney's procedure has been modified in three ways.

First, more attention has been paid to motion on the seismograms at periods of less than one second. Since 1962 the Benioff seismographs at Riverview have shown that earthquakes, at least in the eastern part of New South Wales, cause considerable ground motion at these periods. Figure 1 shows that the Wood-Anderson seismograph has a relatively high magnification at these periods.

Second, the Wood-Anderson magnitudes for earthquakes at distances greater than 100 km. from Riverview have been reduced by the amounts shown in Table 1. This is because Cooney (1962) shows a radius of perceptibility for the earthquake of 21st May, 1961, near Robertson, New South Wales, of approximately 300 km., while Richter (1958) gives a radius of perceptibility in California for an earthquake of similar size of approximately 200 km. Thus, there appears to be less attenuation of local earthquake motion in New South Wales than there is in California. Similar effects have been found by White (1968) in South Australia, and by Nuttli (1973) in the eastern United States. The reductions of Wood-Anderson magnitudes shown in Table 1 are approximate estimates based on comparison of magnitudes of earthquakes calculated at Riverview with those calculated in Canberra at the Australian National University (Department of Geophysics and Geochemistry) and at the Bureau of Mineral Resources (Geology and Geophysics).

TABLE 1
Reduction of Wood-Anderson Magnitudes

Distance of Epicentre (km)	Units of Magnitude
100–249	0·1
250–499	0·2
500–	0·3

Third, the static magnification of actual Wood-Anderson seismographs is often nearer 2,000 than 2,800 (D. Denham, personal communication). Hence, 0·1 has been subtracted from Wood-Anderson magnitudes calculated using the curve shown for the Wood-Anderson seismograph in Figure 1.

Earthquakes in New South Wales since 1909

Earthquakes in New South Wales of Wood-Anderson magnitude, four or greater recorded at Riverview since 1909, are tabulated in Table 2 and plotted in Figure 2.

The epicentres and origin times of the first 15 earthquakes of Table 2 are those of Burke-Gaffney (1951) with the exception of two : the epicentre of the earthquake of 22nd May, 1932, has been placed near the town of Narromine, where it was felt, and the epicentre of the earthquake, 10th March, 1949, has been moved 0·1° westward into a well-defined meizoseismal area (Joklik, 1951).

The Wood-Anderson magnitudes of the earthquakes in Table 2 are based on ground motions recorded at Riverview. A magnitude of 4·5 of the earthquake of 10th March, 1949, found by Burke-Gaffney (1951), is inconsistent with the Modified Mercalli intensity of VIII estimated near the town of Dalton (10 km. northwest of Gunning and 50 km. west of Goulburn) by Joklik (1951), or even with an intensity of VII, which would appear a more accurate estimate from the effects described. Wiechert seismograms indicate that there was ground motion at Riverview of half-amplitude 170 microns and of period approximately 1 sec. The distance to the epicentre was approximately 220 km. This ground motion and epicentral distance imply a Wood-Anderson magnitude of approximately 5·5, which is more consistent with the above intensities. Hence, the magnitude of the earthquake of 10th March, 1949, has been increased to 5·5 in Table 2. A body wave magnitude of 5·3 is given by the United States Coast and Geodetic Survey for this earthquake.

The epicentres and origin times of the four earthquakes near the town of Gunning in 1952 are those of the Bureau of Mineral Resources (Geology and Geophysics) in Canberra (cf. Joklik and Casey, 1952).

The epicentres and origin times of the two earthquakes in the Snowy Mountains region in 1958 and 1959 are those of Cleary, *et al.* (1964). The magnitude of 5·3 given in Table 2 for the earthquake of May 18, 1959 is 0·3 higher than that given by Cleary, *et al.* (1964). This earthquake is of some importance since its epicentre is within a few kilometres of the large Eucumbene and Jindabyne dams. Cleary, *et al.*

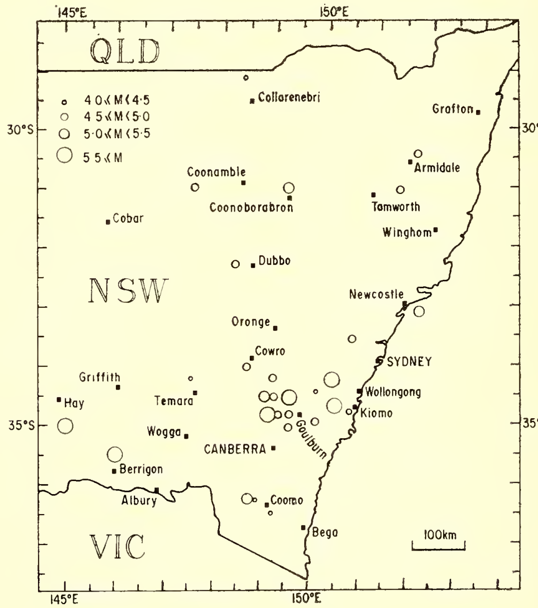

FIGURE 2.—Earthquakes in New South Wales, 1909–1973.

(1964) note that the earthquake occurred before the filling of Lake Eucumbene had proceeded to any significant extent. Hence, it is unlikely to have been caused by the weight of water in that lake.

TABLE 2
Earthquakes in New South Wales, 1909–1973

Date	Time (G.C.T.) h m s	Epicentre °S	Epicentre °E	Mag. M_L	Region
1919, August 15	10 21 21	33·5	150·7	4·6	Kurrajong, Sydney
1921, May 30	14 51 59	35·0	145·0	5·5	Hay, Tocumwal
1925, December 18	10 47 10	33·0	152·0	5·2	Sydney, Wingham
1930, October 27	02 03 51	34·5	149·0	5·0	Boorowa
1932, May 22	10 46 28	32·3	148·3	4·5	Narromine, Dubbo
1933, January 11	20 10 51	34·8	149·5	4·8	Gunning
1934, January 30	20 27 54	34·8	149·5	4·7	Gunning
1934, November 10	23 47 40	34·9	150·0	4·8	Goulburn, Canberra
1934, November 18	21 58 41	34·5	149·5	5·6	Gunning
1934, November 21	06 32 06	34·5	149·2	4·8	Crookwell
1938, March 24	20 03 33	35·5	146·0	5·5	Berrigan
1938, June 27	22 38 47	30·4	151·8	4·7	Armidale, Guyra
1947, May 5	04 43 48	35·0	149·5	4·5	Goulburn, Canberra
1947, September 25	10 56 27	34·0	148·6	4·6	Cowra, Orange
1949, March 10	22 30 33	34·8	149·2	5·5	Dalton, Gunning
1952, September 7	05 41 14	34·8	149·3	4·7	Gunning, Yass
1952, November 18	10 03 06	34·8	149·3	4·4	Gunning, Yass
1952, November 19	01 59 16	34·8	149·3	4·9	Gunning, Yass
1952, November 22	07 57 20	34·8	149·3	4·6	Gunning, Yass
1958, September 1	11 18 02	36·4	149·2	4·0	Rock Flat, Cooma
1959, May 18	06 12 59	36·2	148·7	5·3	Berridale, Cooma
1959, October 12	21 23 40	31·0	151·5	4·7	Uralla, Tamworth
1961, May 16	06 52 54	31·0	147·5	4·8	Coonamble
1961, May 21	21 40 01	34·6	150·4	5·6	Bowral, Robertson
1962, September 29	01 31 35	34·4	150·0	4·2	Bowral, Moss Vale
1968, March 8	11 48 46	34·2	149·1	4·6	Cowra, Orange
1968, July 8	11 50 13	34·7	150·7	4·0	Kiama, Moss Vale
1968, December 31	16 08 33	31·0	149·3	5·0	Coonabarabran
1970, August 8	16 05 53	29·1	148·4	4·0	Collarenebri
1971, June 21	01 11 41	36·2	148·8	4·1	Berridale, Cooma
1971, November 3	20 05 38	34·8	149·2	4·3	Gunning, Dalton
1972, February 25	15 22 34	34·2	147·5	4·0	Temora
1973, March 9	19 09 15	34·2	150·3	5·5	Burragorang Valley

The epicentres and origin times of the earthquakes of 12th October, 1959, and 16th May, 1961, are those of Doyle, *et al.* (1968*b*). The epicentre and origin time of the earthquake of 21st May, 1961, near Bowral and Robertson is that of Cooney (1962). However, Cleary and Doyle (1962) give an epicentre approximately 10 km. nearer Sydney, which fits the meizoseismal region better. This earthquake caused ground motion at Riverview of half-amplitude 500 microns and of period approximately 1 sec. The epicentre and origin time of the earthquake of 29th September, 1962, west of Bowral, are those of Doyle, *et al.* (1968*a*).

The epicentres and origin times of the last eight earthquakes in Table 2 have been calculated at the Australian National University (Department of Geophysics and Geochemistry) in Canberra. The epicentre of the earthquake of 9th March, 1973, is under the south end of Lake Burragorang. This earthquake may have been caused partly by the weight of the water in the lake. It was of similar magnitude to the earthquake of 21st May, 1961, and caused ground motion at Riverview of half-amplitude 500 microns and of period approximately 1 sec.

Seismic Risk in New South Wales

Prior to 1962, when a set of instruments of the Worldwide Standard Seismograph Network began operating at Riverview, earthquakes of Wood-Anderson magnitude less than 4·5 occurring more than 300 km. from Sydney were unlikely to be detected at Riverview. Hence, Table 2 and Figure 2 are incomplete representations of the seismicity of northern and western New South Wales, and, at present, little can be said about the seismic risk in particular sections of these regions.

From the observed distribution of epicentres shown in Figure 2, it appears that most of the seismicity in southeastern New South Wales occurs in the Dalton-Gunning region and near the southern and western boundaries of the

Sydney Basin. Other regions, for example, Sydney itself and the South Coast, are much less seismic. For the Dalton-Gunning region, Cleary (1967) found that most of the seismic activity from 1958 to 1961 occurred near the boundaries of a granite wedge which was overriding the surrounding country in a south-easterly direction. For the Snowy Mountains region, which was also an area of detailed study, Cleary, *et al.* (1964) found that between 1958 and 1962 small earthquakes occurred more or less randomly. For the Sydney Basin region and the region of the South Coast, Doyle, *et al.* (1968*a*) found that most of the earthquakes between 1959 and 1967 occurred near the southern and western boundaries of the Sydney Basin.

With any estimate of seismic risk, two reservations need to be made. First, Richter (1958) states that earthquakes recorded over two or three centuries are not an adequate basis for estimating the seismicity of any region. Second, he adds that stratigraphic and geomorphic evidence also needs to be used. This can rarely be done entirely satisfactorily, since active faults do not always have conspicuous surface manifestations. Hence, most estimates of seismic risk involve unavoidable assumptions. Steinbrugge (1968) also notes that allowance must be made in any seismic region for geological hazards, such as faults, ground with poor bearing capacity, and potential landslide areas. An example of all of these geological hazards occurs near the town of Picton within the Sydney Basin. The Nepean Fault dips westward towards the more seismically active region near the western edge of the Sydney Basin. It may be active. Also, the alluvial valley near Picton contains ground of poor bearing capacity. Finally, the slopes around Picton are potential landslide areas.

Conclusion

Ground motion at Riverview College Observatory in Lane Cove caused by earthquakes in New South Wales between 1909 and 1973 has been measured and estimates of the Wood-Anderson magnitudes of these earthquakes have been made. The largest ground motion measured in Sydney from earthquakes has been of half-amplitude 500 microns and of period approximately 1 sec. Six earthquakes in New South Wales of Wood-Anderson magnitude 5·5 or greater have been recorded between 1909 and 1973. Two of these have occurred in the southwestern part of the State, two have occurred in the Dalton-Gunning region, and two have occurred near the southern and western boundaries of the Sydney Basin. The South Coast of New South Wales and Sydney itself have been comparatively less seismic. However, even in less seismic regions allowance must be made for faults, ground with poor bearing capacity, and potential landslide areas.

Acknowledgements

The author is indebted to Dr. David Denham of the Bureau of Mineral Resources (Geology and Geophysics) in Canberra, to Dr. John Cleary of the Australian National University (Department of Geophysics and Geochemistry), and to Mr. P. F. Rheinberger of Riverview College Observatory for help and advice.

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(Received 27 July 1973)

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BAXTER, Sir John Philip, K.B.E., C.M.G., O.B.E., Ph.D., F.A.A., Australian Atomic Energy Commission, 1 Kelso Street, Enfield, 2136 (1950).

BROWNE, William Rowan, D.Sc., F.A.A., 363 Edgecliff Road, Edgecliff, 2022 (1913 : P23 ; President 1932).

BURNET, Sir Frank Macfarlane, O.M., Kt., D.Sc., F.R.S., F.A.A., c/o Department of Microbiology, University of Melbourne, Parkville, Victoria, 3052 (1949).

FIRTH, Raymond William, D.Litt., M.A., Ph.D., Professor of Anthropology, University of London, 33 Southwood Avenue, London, N.6, 5.SA, England.

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O'CONNELL, Rev. Daniel J., S.J., D.Sc., Ph.D., F.R.A.S., Borgo S. Spirito 5, 00193 Rome, Italy (1953).

OLIPHANT, Sir Marcus L., K.B.E., Ph.D., B.Sc., F.R.S., F.A.A., Emeritus Professor, Research School of Physical Sciences, Australian National University, Canberra, A.C.T., 2600 (1948).

ROBINSON, Sir Robert, M.A., D.Sc., F.R.S., F.C.S., F.I.C., Professor of Chemistry, Oxford University, England (1948).

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ADAMSON, Colin Lachlan, B.Sc., 43 Holt Avenue, Cremorne, 2090 (1944).

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*ALBERT, Adrien, D.Sc., F.A.A., Professor of Medical Chemistry, Australian National University, Canberra, A.C.T., 2600 (1938 : P4).

ANDERSON, Geoffrey William, B.Sc., c/o Box 30, P.O Chatswood, 2067 (1948).

ANDREWS, Helen Elizabeth, B.Sc., 33 Hillcrest Avenue, Gladesville, 2111 (1970).

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ASHLEY, Paul Michael, B.Sc., 2 Fernhill Avenue, Epping, 2121 (1970).

ATKINS, Francis Edward, B.A., 70 Cook Road, Centennial Park, 2021 (1973).

*AUROUSSEAU, Marcel, M.C., B.Sc., 229 Woodland Street, Balgowlah, 2093 (1919 : P2).

BADHAM, Charles David, M.B., B.S., D.R. (Syd.), M.C.R.A., " New Lodge ", 16 Ormonde Parade, Hurstville, 2220 (1962).

*BAKER, Stanley Charles, Ph.D., Associate Professor, Department of Physics, University of Newcastle, 2300 (1934 : P4).

BANFIELD, James Edmund, M.Sc., Ph.D. (Melb.), Department of Organic Chemistry, University of New England, Armidale, 2350 (1963).

BANKS, Maxwell Robert, B.Sc., Department of Geology, University of Tasmania, Hobart, Tasmania, 7000 (1951).

BARKAS, John Pallister, B.Sc., Department of Geology and Geophysics, University of Sydney, Sydney, 2006 (1972).

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BEADLE, Noel Charles William, D.Sc., Professor of Botany, University of New England, Armidale, 2350 (1964).

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BEAVIS, Francis Clifford, M.A., B.Sc., Ph.D., F.G.S., School of Applied Geology, University of N.S.W., P.O. Box 1, Kensington, 2033 (1973).

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BLAYDEN, Ian Douglas, B.Sc.(Hons.), 73 Abingdon Road, Roseville, 2069 (1966).

BOOKER, Frederick William, D.Sc., 11 Boundary Street, Roseville, 2069 (1951 : P1).

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BRANAGAN, David Francis, M.Sc., Ph.D., Department of Geology and Geophysics, University of Sydney, 2006 (1967 : P3).

BRENNAN, Edward, B.E.(App. Geology), P.O. Box 5, Mount Morgan, Queensland, 4714 (1962).

BRIDGES, David Somerset, 19 Mount Pleasant Avenue, Normanhurst, 2076 (1952).

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BROWN, Desmond J., D.Sc., Ph.D., Department of Medical Chemistry, Australian National University, Canberra, A.C.T., 2600 (1942).

BROWN, Frederick William, F.A.S.A., A.C.I.S., 32A Beach Street, Blakehurst, 2221 (1971).

BROWN, John Percival, 40 Woolgoolga Street, North Balgowlah, 2093 (1969).

BROWN, Kenneth John, A.S.T.C., A.R.A.C.I., 3 Karda Place, Gymea, 2227 (1963).

BROWNE, Ida Alison, D.Sc., 363 Edgecliff Road, Edgecliff, 2227 (1935 : P12 ; President 1953).

BRUCE, Colin Frank, D.Sc., 17 Redan Street, Mosman, 2088 (1964).

BRUCE-SMITH, James Richard, M.Ag.Sc. (N.Z.), Ph.D. (U.N.E.) (1973).

BRYAN, John Hamilton, B.Sc.(Hons.), c/o Clifford McElroy & Associates, P.O. Box 387, Milson's Point, 2067 (1968).

BUCHWALD, Viliam Teodor, M.Sc., Ph.D., Professor of Applied Mathematics, School of Mathematics, University of New South Wales, 2033 (1973).

BUDD, William Francis, Ph.D., Dip.Ed., Antarctic Division, Department of Science, 568 St. Kilda Road, Melbourne, 3000 (1971).

BULLEN, Keith Edward, D.Sc., F.R.S., F.A.A., Professor of Applied Mathematics, University of Sydney, 2006 (1946 : P3).

BURG, Raymond Augustine, Department of Mines, N.S.W. ; p.r. 17 Titania Street, Randwick, 2031 (1960).

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BURNS, Bruce Bertram, D.D.S., Suite 607, T. & G. Building, Park Street, Sydney, 2000 (1961).

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CAMERON, John Craig, M.A., B.Sc. (Edin.), D.I.C., 15 Monterey Street, Kogarah, 2217 (1957 : P1 ; President 1972).

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CAVILL, George William Kenneth, Ph.D., D.Sc., Professor of Organic Chemistry, University of New South Wales, Kensington, 2033 (1944).

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*CHURCHWARD, John Gordon, B.Sc.Agr., Ph.D., 12 Glen Shian Lane, Mount Eliza, Victoria, 3930 (1935 : P2).

CLANCY, Brian Edward, M.Sc., Australian Atomic Energy Commission, Lucas Heights, 2232 (1957)

CLAYTON, Norman Arthur, F.C.A.A., 87 Albert Drive, Killara, 2071 (1972).

CLOUSTON, John Gannon, M.Sc., Ph.D., F.A.I.P., 24 Bunyala Street, Carss Park, 2221 (1974).

COALSTAD, Stanton Ernest, B.Sc., 16 Station Street, Marrickville, 2204 (1961).

COHEN, Samuel Bernard, M.Sc., 46 Wolseley Road, Point Piper, 2027 (1940).

COLE, Edward Ritchie, B.Sc., Associate Professor of Organic Chemistry, University of New South Wales, Kensington, 2033 (1940 : P2).

COLE, Joyce Marie (Mrs.), B.Sc., 7 Wolsten Avenue, Turramurra, 2074 (1940 : P1).

COLLIER, Margaret A., 135 Highfield Road, Lindfield, 2070 (1973).

COLLETT, Gordon, B.Sc., 16 Day Road, Cheltenham, 2119 (1940).

COLLINS, Angus Robert, B.Sc., 16 Hull Road, Beecroft, 2119 (1969).

CONAGHAN, Hugh Francis, M.Sc., Department of Mines, N.S.W. ; p.r. 104 Lancaster Avenue, West Ryde, 2114 (1960).

CONOLLY, John Robert, B.Sc. (Syd.), Ph.D. (N.S.W.), B.P. Alaska Inc., 270 Park Avenue, New York, N.Y. 10017, U.S.A. (1963 : P4).

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CORTIS-JONES, Beverley, M.Sc., 65 Peacock Street, Seaforth, 2092 (1940).

COX, Charles Dixon, B.Sc., 51 Darley Street, Forestville, 2087 (1964).

CRAWFORD, Edwin John, B.E., 7A Battle Boulevarde, Seaforth, 2092 (1955).

CREELMAN, Robert Aughterlonie, B.A., 28 Vimiera Road, Eastwood, 2122 (1973).

*CRESSWICK, John Arthur, 101 Villiers Street, Rockdale, 2216 (1921 : P1).

CROFT, James Bernard, B.E., Ph.D., The Hunter Valley Research Station, P.O. Box 23, Tighes Hill, 2297 (1956).

CROOK, Keith Alan Waterhouse, Ph.D., Geology Department, Australian National University, Canberra, A.C.T., 2600 (1954 : P9).

CRUIKSHANK, Bruce Ian, B.Sc.(Hons.), 16 Arthur Street, Punchbowl, 2196 (1965).

DAVIES, George Frederick, 57 Eastern Avenue, Kingsford, 2032 (1952).

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DEAN-JONES, Gregory Lloyd, B.A., 124 Midson Road, Epping, 2121 (1973).

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DOUGLAS, Ian, B.Litt., M.A., Ph.D., Professor of Geography, University of New England, Armidale, 2351 (1972).

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ELLISON, Dorothy Jean, M.Sc., 45 Victoria Street, Roseville, 2069 (1949).

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EMMERTON, Henry James, B.Sc., 37 Wangoola Street, East Gordon, 2072 (1940).

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FLOOD, Peter Gerard, B.Sc.(Hons.), Department of Geology, University of Queensland, St. Lucia, 4067 (1969).

FOLDVARY, Gabor Zoltan, B.Sc., 267 Beauchamp Road, Matraville, 2036 (1965 : P1).

FORD, George William Kinvig, M.A. (Cantab.), 133 Wattle Road, Janalli, 2226 (1974).

FRENCH, Oswald Raymond, 6 Herberton Avenue, Hunters Hill, 2110 (1951).

FRIEND, James Alan, Ph.D., Professor of Chemistry, University of West Indies, St. Augustine, Trinidad, W.I. (1944 : P2).

GALLOWAY, Malcolm Charles, B.Sc., 46 Duntroon Avenue, Roseville, 2069 (1960 : P1).

GARRETTY, Michael Duhan, D.Sc., Box 763, G.P.O., Melbourne, Victoria, 3001 (1935 : P2).

GASCOIGNE, Robert Mortimer, Ph.D., Department of Philosophy, University of New South Wales, Kensington, 2033 (1939 : P4).

GELLERT, Emery, Dr.phil. (Basle), 38 Toorak Avenue, Wollongong, 2500 (1968).

GIBBONS, George Studley, M.Sc., 8 Marsh Place, Lane Cove, 2066 (1966 : P1).

GIBSON, Neville Allan, Ph.D., 103 Bland Street, Ashfield, 2131 (1942 : P6).

*GILL, Stuart Frederic, 45 Neville Street, Marrickville, 2204 (1947).

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GOLDING, Henry George, M.Sc., Ph.D., School of Applied Geology, University of New South Wales, Kensington, 2033 (1953 : P5).

GOODWIN, Robert Henry, B.Sc., M.Sc. (1968 : P1).

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GRIFFIN, Derek K., B.Sc., 21 Myra Street, Wahroonga, 2076 (1969).

GRIFFIN, Russell John, B.Sc. (No Address.) (1952).

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GRODEN, Charles Mark, M.Sc., Box 13, Post Office, Lindfield, 2070 (1957).

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HACKETT, Ian Harry, B.Sc. (Chem.Eng.), 5 Wyralla Avenue, Epping, 2121 (1968).

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Harper, Arthur Frederick Alan, M.Sc., National Standards Laboratory, University Grounds, City Road, Chippendale, 2008 (1936 : P1 ; President 1959).
Haydon, Sydney Charles, M.A., Ph.D., F.Inst.P., Professor of Physics, University of New England, Armidale, 2351 (1965).
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Jordan, Vilhelm Lassen, Ph.D., Gevninge, 4000, Roskilde, Denmark (1973 : P1).
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Kimble, Jean Annie, B.Sc., 2/163 Homer Street, Earlwood, 2206 (1943).
King, Haddon Forrester, B.App.Sc. (Min.Eng.), P.O. Box 47, Kallista, Victoria, 3791 (1973).
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Krysko v. Tryst, Maren (Mrs.), B.Sc., Grad.Dip., A.M.Aus.I.M.M., School of Applied Geology, University of New South Wales, Kensington, 2033 (1959).

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Lawrence, Laurence James, D.Sc., Ph.D., Associate Professor, School of Applied Geology, University of New South Wales, Kensington, 2033 (1951 : P4).
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*Lemberg, Max Rudolph, D.Phil., F.R.S., F.A.A., Assistant Director, Institute of Medical Research, Royal North Shore Hospital, St. Leonards, 2065 (1936 : P3 ; President 1955).
Lions, Jean Elizabeth (Mrs.), B.Sc., 93a Mona Vale Road, Pymble, 2073 (1940).
Lockwood, William Hutton, B.Sc., Institute of Medical Research, Royal North Shore Hospital, St. Leonards, 2065 (1940 : P1).
Lovering, John Francis, Ph.D., Professor of Geology, University of Melbourne, Parkville, Victoria, 3052 (1951 : P4).
Low, Angus Henry, Ph.D., Associate Professor, Department of Applied Mathematics, University of New South Wales, Kensington, 2033 (1950 : P4 ; President 1967).
Lowenthal, Gerhard C., Ph.D., M.Sc., 17 Gnarbo Avenue, Carss Park, 2221 (1959).
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Lyle, Valda Emma Louise, A.I.P.S.A., 26 White Street, Balgowlah, 2093 (1973).
Lyons, Lawrence Ernest, Ph.D., Professor of Chemistry, University of Queensland, St. Lucia, Brisbane, 4067 (1948 : P3).

MacColl, Allan, M.Sc., Department of Chemistry, University College, Gower Street, London, W.C.1, England (1939 : P4).

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McCullagh, Morris Behan (1950).

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McGregor, Gordon Howard, 4 Maple Avenue, Pennant Hills, 2120 (1940).

McKay, Maxwell Herbert, M.A., Ph.D., Professor of Mathematics, University of Papua and New Guinea, Boroko, T.P.N.G. (1956 : P1).

McKern, Howard Hamlet Gordon, M.Sc., F.R.A.C.I., Museum of Applied Arts and Sciences, Harris Street, Broadway, 2007 (1943 : P12 ; President 1963).

McLean, Ross Alastair, B.Sc., Ph.D., Department of Geology and Geophysics, University of Sydney, 2006 (1973).

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McMahon, Patrick Reginald, Ph.D., Professor of Wool Technology, University of New South Wales, Kensington, 2033 (1947).

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Magee, Charles Joseph, D.Sc.Agr., 57 Florida Road, Palm Beach, 2108 (1947 : P2 ; President 1952).

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Martin, Peter Marcus, M.Sc.Agr., Ph.D., Dip.Ed., Deputy Principal, Hawkesbury Agricultural College, Richmond, 2753 (1968).

Mawson, Ruth, B.A., School of Earth Sciences, Macquarie University, North Ryde, 2113 (1973).

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Millership, William, M.Sc., 18 Courallie Avenue, Pymble, 2073 (1940).

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Moelle, Konrad Heinrich Richard, Absolutorium (Innsbruck), Ph.D. (Innsbruck), University of Newcastle ; p.r. 2 Hillcrest Road, Merewether, 2308 (1967).

Moore, Laurence Frederick, B.A. (N.E.), 10A Boundary Road, Parramatta, 2150 (1967).

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Morris, Sidney Allen, Ph.D., Department of Mathematics, University of New South Wales, Kensington, New South Wales, 2033 (1973 : P1).

Morrissey, Matthew John, M.B., B.S., 152 Marsden Street, Parramatta, 2150 (1941).

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Mosher, Kenneth George, B.Sc., 9 Yirgella Avenue, Killara, 2071 (1948).

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Napper, Donald Harold, M.Sc. (Syd.), Ph.D. (Cantab.), Department of Physical Chemistry, University of Sydney, 2000 (1973).

Nashar, Beryl, Ph.D., Professor of Geology, University of Newcastle, 2308 ; p.r. 15 Princeton Avenue, Adamstown Heights, 2289 (1946 : P2).

*Naylor, George Francis King, Ph.D., Department of Psychology and Philosophy, University of Queensland, St. Lucia, Brisbane, 4067 (1930 : P7).

*Neuhaus, John William George, M.Sc., 32 Bolton Street, Guildford, 2161 (1943 : P1 ; President 1969).

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*Noble, Robert Jackson, Ph.D., 32A Middle Harbour Road, Lindfield, 2070 (1920 : P4 ; President 1934).

O'Farrell, Antony Frederic Louis, A.R.C.Sc., B.Sc., Professor of Zoology, University of New England, Armidale, 2351 (1961).

O'Halloran, Peter Joseph, B.Sc., Dip.Ed., M.Sc., 52 Bindaga Street, Aranda, A.C.T., 2614 (1968).

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Packham, Gordon Howard, Ph.D., Department of Geology and Geophysics, University of Sydney, 2006 (1951 : P4).

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Pearson, Robert John Butler, 25 Burling Avenue, Fairy Meadow, 2519 (1969).

*Penfold, Arthur Ramon, Flat 516, Baroda Hall, 6A Birtley Place, Elizabeth Bay, 2011 (1920 : P82 ; President 1935).

Perry, Hubert Roy, B.Sc., 74 Woodbine Street, Bowral, 2576 (1948).

PETERSON, George Arthur, B.Sc., B.E., 55 Roseville Avenue, Roseville, 2069 (1966).

PHILIP, Graeme Maxwell, M.Sc. (Melb.), Ph.D. (Cantab.), F.G.S., Professor of Geology and Geophysics, University of Sydney, 2006 (1964 : P1).

PHILLIPS, Marie Elizabeth, Ph.D., 16 Lawley Place, Deakin, A.C.T., 2600 (1938).

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PRIESTLEY, John Henry, M.B., B.S., B.Sc., 137 Dangar Street, Armidale, 2350 (1961).

PROKHOVNIK, Simon Jacques, M.A., B.Sc., School of Mathematics, University of New South Wales, Kensington, 2033 (1956 : P4).

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PUTTOCK, Maurice James, B.Sc.(Eng.), M.Inst.P., C.S.I.R.O. National Standards Laboratory, University Grounds, City Road, Chippendale; p.r. 2 Montreal Avenue, Killara, 2071 (1960 : P1 ; President 1971).

*QUODLING, Florrie Mabel, Ph.D., B.Sc., 145 Midson Road, Epping, 2121 (1935 : P5).

RADE, Janis, M.Sc., Box 28A, 601 St. Kilda Road, Melbourne, 3004 (1953 : P6).

RAMM, Eric John, Australian Atomic Energy Commission, Lucas Heights, 2232 (1959).

RANNEFT, Theodoor Seth Meijer, A.B. (Cornell), 813 Caltex House, 167 Kent Street, Sydney, 2000 (1972).

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*RAYNER, Jack Maxwell, O.B.E., B.Sc., 5 Tennyson Crescent, Forrest, Canberra, A.C.T., 2603 (1931 : P1).

READ, Harold Walter, B.Sc. (1962 : P1).

REICHEL, Alex, Ph.D., M.Sc., Department of Applied Mathematics, University of Sydney (1957 : P4).

RHODES, Jill Mina, B.Sc. (N.Z.) (1971).

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RITCHIE, Arthur Sinclair, M.Sc., Associate Professor of Geology, University of Newcastle, 2308 (1947 : P2).

RITCHIE, Ernest, D.Sc., F.A.A., Professor of Chemistry, Chemistry Department, University of Sydney, 2006 (1939 : P19).

ROBBINS, Elizabeth Marie (Mrs.), M.Sc., 21 Palm Street, St. Ives, 2075 (1939 : P3).

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ROBERTSON, William Humphrey, B.Sc., c/o Sydney Observatory, Sydney, 2000 (1949 : P31).

ROBINSON, David Hugh, A.S.T.C., Chemist, 12 Robert Road, West Pennant Hills, 2120 (1951).

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*SHARP, Kenneth Raeburn, B.Sc., Engineering Geology Branch, Snowy Mountains Authority, North Cooma, 2629 (1948).

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SHERRARD, Kathleen Margaret (Mrs.), M.Sc., 43 Robertson Road, Centennial Park, 2021 (1936 : P6).

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SLADE, Milton John, B.Sc., Dip.Ed. (Syd.), M.Sc (N.E.), Armidale Teachers' College, Armidale, 2350 (1952).

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SMALL, David Hayes, B.A. (Macquarie), 20 Gladys Street, Rydalmere, 2116 (1972).

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SMITH-WHITE, William Broderick, M.A., Associate Professor of Mathematics, University of Sydney, 2006 (1947 : P4 ; President, 1962).

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STAER, Ronald Robert, F.R.A.S., 29 Maple Avenue, Pennant Hills, 2120 (1972).

STANTON, Richard Limon, Ph.D., Associate Professor of Geology, University of New England, Armidale, 2351 (1949 : P2).

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THOMSON, Vivian Endel, B.Sc., 1/171–177 Rokeby Road, Howrah, Tasmania, 7018 (1960).

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TILLEY, Philip Damien, B.A., Dr.Phil., Department of Geography, University of Sydney, 2006 (1967).

TOMPKINS, Denis Keith, Ph.D., M.Sc., 14 Warrowa Road, Pymble, 2073 (1954 : P1).

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VAGG, Robert Sylvester, M.Sc. (N.S.W.), Ph.D., (Macq.), A.R.A.C.I., School of Chemistry, North Ryde, 2113 (1973).

VAGG, William James, B.Sc., Ph.D., 9 Cooleen Street, Blakehurst, 2221 (1973).

VALLANCE, Thomas George, Ph.D., Associate Professor, Department of Geology and Geophysics, University of Sydney, 2006 (1949 : P4).

VAN DIJK, Dirk Cornelius, D.Sc.Agr., c/o C.S.I.R.O., Division of Soils, Cunningham Laboratory, St. Lucia, Queensland, 4067 (1958).

VEEVERS, John James, Ph.D., School of Earth Sciences, Macquarie University, North Ryde, 2113 (1953).

VERNON, Ronald Holden, Ph.D., M.Sc., School of Earth Sciences, Macquarie University, North Ryde, 2113 (1958 : P1).

VICKERY, Joyce Winifred, M.B.E., D.Sc., 15 The Promenade, Cheltenham, 2119 (1935).

VOISEY, Alan Heywood, D.Sc., G.P.O. Box 3582, Sydney, 2001 (1933 : P13 ; President 1966).

*WALKOM, Arthur Bache, D.Sc., 5/521 Pacific Highway, Killara (1919 and previous membership 1910–1913 : P2 ; President 1943).

WALSH, Elizabeth Ann, B.Sc., Dip.Sc., 19 Francis Street, Strathfield West, 2140 (1972).

WARD, Colin Rex, Ph.D., B.Sc.(Hons.), School of Physical Sciences, N.S.W. Institute of Technology, Broadway, 2007 (1968 : P1).

WARD, Judith (Mrs.), B.Sc., 16 Mortimer Avenue, Newtown, Hobart, Tasmania, 7008 (1948).

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WASS, Robin Edgar, Ph.D. (Syd.), B.Sc.(Hons.) (Qld.), Department of Geology and Geophysics, University of Sydney (1965 : P1).

WATTON, Edward Charlton, Ph.D., B.Sc.(Hons.), A.S.T.C., Associate Professor of Chemistry ; p.r. 17 Malory Avenue, West Pymble, 2073 (1963).

WEBBY, Barry Deane, Ph.D., M.Sc., Department of Geology and Geophysics, University of Sydney, 2006 (1966).

WEST, Norman William, B.Sc., c/o Department of Main Roads, Sydney, 2000, p.r. 3/17 Claude Avenue, Cremorne, 2090 (1954).

WESTHEIMER, Gerald, B.Sc. (Syd.), Ph.D., F.S.T.C., Professor of Physiology, University of California, 2575 Life Sciences Building, Berkeley, California, 94720, U.S.A. (1949).

WHEELHOUSE, Frances, School of Biological Sciences, University of New South Wales, Kensington, 2033 (1968).
WHITLEY, Alice, M.B.E., Ph.D., 39 Belmore Road, Burwood, 2134 (1951).
WHITLEY, Gilbert Percy, F.R.Z.S., Honorary Associate of the Australian Museum, College Street, Sydney, 2000 (1963).
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WILKINSON, John Frederick George, M.Sc. (Qld.), Ph.D. (Cantab.), Professor of Geology, School of Earth Sciences, Macquarie University, North Ryde, 2113 (1961 : P1).
WILLIAMS, Benjamin, 30 Croft Road, Eleebena, 2280 (1949).
WILLIAMS, Lyall Richard, B.Sc., Ph.D., School of Chemistry, Macquarie University, North Ryde, 2113 (1973 : P1).
WILLIAMS, Peter Allan, B.A.(Hons.), School of Chemistry, Macquarie University, North Ryde, 2113 (1973).
WILLIAMSON, William Harold, M.Sc., 6 Hughes Avenue, Ermington, 2033 (1949 : P1).
WILSON, Christopher John Lascelles, B.Sc., Ph.D., Department of Geology, University of Melbourne, (1967 : P1).
WINCH, Denis Edwin, Ph.D., M.Sc., University of Sydney, 2006 (1968).
*WOOD, Harley Weston, D.Sc., M.Sc., Government Astronomer, Sydney Observatory, Sydney, 2000 (1936 : P16 ; President 1949).
WRIGHT, Anthony James, Ph.D., B.Sc., Department of Geology, Wollongong University College, Wollongong, 2500 (1961).
WRIGHT, Leslie Arthur, B.A.(Arch.) (Hons.), B.Sc.(Eng.), Dip.Arch., F.R.I.B.A., M.I.E.(Aust.), M.A.P.I., 17 Richmond Avenue, St. Ives, 2075 (1973).
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GUNTHORPE, Robert John, B.Sc.(Hons.), James Cook University of North Queensland, Townsville, 4810. (1965).
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LE FEVRE, Catherine Gunn, D.Sc. (Lond.), 6 Aubrey Road, Northbridge, 2063 (1961).

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STOKES, Jean Mary (Mrs.), M.Sc., 45 Garibaldi Street, Armidale, 2350 (1961).
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WADLEY, David Alastair, Department of Human Geography, Research School of Pacific Studies, Australian National University, Canberra, A.C.T., 2600 (1970).

Obituary

1971-1972

Rupert Boswood SCAMMELL (1920).
Thomas IREDALE (1943).

1973-1974

Robert FISHER (1940).

1972-1973

Sir Charles Bickerton BLACKBURN (1960).
Sir Lawrence BRAGG (1960).
Clive Melville HARRIS (1948).
Robert Kenneth MURPHY (1915).
Oscar Ulric VONWILLER (1929).
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71-79 ARUNDEL ST., GLEBE, N.S.W., 2037
1974

Journal and Proceedings of the

Royal Society of New South Wales

VOLUME 107 1974 PARTS 3 and 4

Published by the Society
Science House, Gloucester and Essex Streets, Sydney
Issued 22nd January, 1975

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Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 49–66, 1974

Proper Motions of Variable Stars in the Sydney Astrographic Zone

K. P. Sims

ABSTRACT—The relative proper motions ($\lambda_\alpha \cos \delta, \lambda_\delta$) of 30 stars determined photographically are given together with absolute measures ($\mu_\alpha \cos \delta$, μ_δ) found by applying corrections for the parallactic motion of the reference stars and for the effects of differential galactic rotation.

The stars whose proper motions are measured form part of a programme on variable stars brighter than 12·0 at maximum. The programme stars are those within the Sydney Astrographic Zone listed by L. Plaut and G. Van Herk in response to resolutions adopted at the Symposium for Co-ordination of Galactic Research in 1953.

Originally these lists contained 221 variables in the Sydney Zone but for only about 90 of them do old epoch plates exist with the image of the variable well-defined and within 45′ of the plate centre. This latter much reduces the coma which could well introduce effects in magnitude and colour.

The new epoch plates (Ilford Zenith Astronomical) have a colour sensitivity similar to the plates used for the old ones. Photographs have been taken with the same standard astrographic objective lens and with the same plate centres as before. Exposure times of 5 min. and 3 min. for a catalogue plate and 10 min. for a chart plate with a single image give, in general, images of density comparable with that on the earlier plates. Chart plates with two exposures separated in declination, were matched by using two exposures of 10 min. duration or by taking two separate plates on the same night.

In order to reduce the effects of parallax and refraction the aim was to match the hour-angle and date of the old plate. Since the radius of the reference field is always half a degree or less, the differential refraction, as given in the discussion of refraction by H. W. Wood (1956) is small enough to be neglected. Differences in date in a few cases may be as large as 0·3 year. Since the variable and reference stars are distant objects, error from difference of parallax would be small enough in the position measures to be neglected.

A

Measurement

In general the same set of 16 to 20 reference stars symmetrically placed around the variable were used for all catalogue or chart plate pairs. Reference stars close to reseau lines on the old epoch plates were avoided and if this applied to the variable the plate was rejected as unsuitable for measurement. The reference stars were basically chosen so that their mean magnitude approached 11·5 to 12·0 for catalogue plates and 12·5 to 13·0 for chart plates.

Measurement of the plate, in direct and reverse directions, was made in rectangular coordinates on a long screw measuring machine by Hilger and Watts. The image of the variable was measured at the beginning, middle and end for each position of the plate carriage. A difference of these measures exceeding 3 microns was regarded as indicating plate movement and in these cases the plate was remeasured. A new plate was set for measurement with an orientation to correspond to the measures on the earlier plate. Periodic and progressive corrections of the screw were applied.

Reduction of Measures

If the old and new plates are designated by o and n and X^o, Y^o are the rectangular measures of reference stars parallel to the original reseaux relative to the variable on the old plate the corresponding rectangular coordinate measures (X^n, Y^n) on the new plate are related to the old by equations of the type.

$$\tau\Delta X = Mx + aX^o + bY^o + c \quad \ldots\ldots \quad (1)$$
$$\tau\Delta Y = My + dX^o + eY^o + f$$

where ΔX, ΔY is the relative annual measured motion of the reference star in rectangular co-ordinates, $Mx = X^n - X^o$, $My = Y^n - Y^o$, a, b, c, d, e and f are plate constants and τ is the epoch difference. A coma term, corresponding to a term $H(m-m_1)\ x$ in the x coordinate, appears in positional solutions for the astrographic plates. Here it is omitted because the measures are relative with the same star occurring at the same position on each plate of a pair and because the distribution of the reference stars reduces its effect on the motion of the variable. The magnitude term $J(m-m_1)$ which appears in positional astrographic work has been looked for in the present work but no real evidence of such an effect has been found.

Since the variable has been chosen as the centre of the measured area, its rectangular annual motion relative to the mean motion of the reference stars would be given by

$$\tau\Delta X_v = c \qquad \tau\Delta Y_v = f \qquad \ldots \ldots \ldots \ldots (2)$$

The equatorial proper motion measures ($\lambda_\alpha \cos\delta$, λ_δ) of the variable can be expressed in terms of the motion $\Delta\xi$, $\Delta\eta$ in standard cor-ordinates by means of the formulae.

$$\lambda_\alpha \cos\delta = \Delta\xi + \Delta\eta . \xi \tan Da$$
$$\lambda_\delta = \Delta\eta - \Delta\xi . \xi \tan Da$$

Taking ξ, η in millimetres, $\lambda_\alpha \cos\delta$, λ_δ in seconds of arc and the focal length $f=3437\cdot747$ mm the formulae become

$$\tau\lambda_\alpha \cos\delta = \Delta X_v\{60(1+A)+GD\} + \Delta Y_v\{60B+G(1+E)\} \quad \ldots (3)$$
$$\tau\lambda_\delta = \Delta X_v\{60D-G(1+A)\} + \Delta Y_v\{60(1+E)-GB\}$$

where $G=0\cdot01745\ \xi_v \tan Da$, Da being the declination of the plate centre and A, B, D, E are constants of the old epoch plate as given in the Sydney Astrographic Catalogue.

In cases where the old epoch plate was not included in the catalogue or was a chart plate, the constants B and D were determined by the process outlined in work on double stars by W. H. Robertson (1953). The constants A and E have both been assumed to be $0\cdot0048$ for plates taken near to 1900 and $0\cdot0044$ for plates taken in the period 1920–30.

The relative proper motions of the reference stars were then determined by substituting the values of the plate constants, a, b, c, d, e and f in equation (1). These were then examined and any stars whose relative proper motion exceeded $0''\cdot05$/yr were then excluded and the process repeated without them. A limit $0''\cdot05$/yr although arbitrary has been used in other proper motion investigations and since large relative proper motions would have a disproportionate influence on the plate constants and on the mean proper motion of the reference sample some kind of limit seems necessary. The mean parallax of the reference stars (and hence the parallactic motion) is affected by the rejection of reference stars and to adjust for this, the procedure described by J. H. Oort (1936) has been followed.

Assessment of the standard error ε_x, ε_y associated with the derived relative proper motion of the variable and the intrinsic proper motion dispersion σ_x, σ_y as they appear in Table II has been made, in units of $0''\cdot001$/yr, from the formulae

$$\varepsilon_x = \left\{\varepsilon_m^2 + \frac{\Sigma\Delta X^2}{N(N-3)}\right\}^{\frac{1}{2}},$$
$$\sigma_x = \left\{\frac{\Sigma\Delta X^2}{N-3} - \varepsilon_m^2\right\}^{\frac{1}{2}}$$
$$\varepsilon_y = \left\{\varepsilon_m^2 + \frac{\Sigma\Delta Y^2}{N(N-3)}\right\}^{\frac{1}{2}},$$
$$\sigma_y = \left\{\frac{\Sigma\Delta Y^2}{N-3} - \varepsilon_m^2\right\}^{\frac{1}{2}}$$

as given by S.V.M. Clube (1968), where ΔX, ΔY is the measured relative proper motion of the reference star, ε_m the error associated with the process of measurement, N is the number of reference stars; $\frac{\Sigma\Delta X^2}{N-3}, \frac{\Sigma\Delta Y^2}{N-3}$ is a measure of the dispersion amongst the reference stars.

For stars having only one single plate pair, each with two images, the value of the measuring error has been derived from the difference between the measures and averages $0''\cdot0031$/yr in $\lambda_\alpha \cos\delta$ and $0''\cdot0025$/yr in λ_δ for a 60-year epoch difference. Where two or more plate pairs are available the measuring error has also been assessed from the differences between the plate pair measures which, for a 60-year epoch difference, averages $0''\cdot0026$/yr in $\lambda_\alpha \cos\delta$ and and $0''\cdot0021$/yr in λ_δ.

The standard error associated with the relative proper motion of a variable star averages $0''\cdot0042$/yr in $\lambda_\alpha \cos\delta$ and $0''\cdot0032$/yr in λ_δ for a result dependent upon one pair of plates. For stars having two or more plate pairs, the standard error has to be correspondingly reduced.

Positions of the variable stars and the reference stars were derived from the plates. This is straightforward for catalogue plates. For other plates, stars from the catalogue were included in the measuring process to provide data for transforming these measures to the system of the Catalogue plate enabling the standard co-ordinates to be calculated.

Reduction of Relative Measures to Absolute

In the absence of sufficient faint reference stars with known motions, the reduction of relative proper motion measures ($\lambda_\alpha \cos \delta$, λ_δ) to absolute proper motion measures ($\mu_\alpha \cos \delta$, μ_δ) have been effected via the formulae

$$\mu_\alpha \cos \delta = \lambda_\alpha \cos \delta + P_\alpha \cos \delta + Q$$
$$\mu_\delta = \lambda_\delta + P_\delta + Q'$$

where $P_\alpha \cos \delta$, P_δ represent equatorial corrections for the parallactic motion of the reference stars and Q, Q' the equatorial corrections for the effect of galactic rotation on the reference stars.

The corrections for parallactic motion of the reference stars have been obtained by

(*a*) determining the mean parallax $\bar{p}_m$ of the reference group from the mean magnitude by using the relationship.

$$\log \bar{p}_m = \log \bar{p}_{12} - 0{\cdot}115(m_{pg} - 12) \ldots\ldots \quad (4)$$

as given by L. Binnendijk (1943). Values of $\log \bar{p}_{12}$ were taken from Table 10 of this work. Mean parallaxes obtained in this way are designated p_1.

(*b*) ascertaining the mean parallax $\bar{p}_m$ of the reference stars from the number of stars N_m brighter than the mean magnitude of the reference stars within one square degree of the variable using Binnendijk's relationship.

$$\log \bar{p}_m = 0{\cdot}98 - 0{\cdot}36 \log N_m$$

Such parallaxes are called p_2.

Both techniques involve knowledge of the mean magnitude of the reference stars and this has been achieved by photographic comparisons with stars of the nearest *E* region (centred at declination —45°) using the Taylor, Taylor and Hobson astrometric lens (scale 1 mm=116″) which gives uniformly good images all over the plate. The photographic magnitude $S'P_g$ of the *E* region stars were those given by A. W. J. Cousins and R. H. Stoy (1962). To guard against changes in transparency two exposures of the variable star field, one each side of the *E* region exposure, were made. If a change was detected the plate was rejected.

In cases when two magnitude plates were taken a comparison of their magnitude difference yielded a standard error near 0·07 magnitude for the mean magnitude of the reference group and 0·19 magnitude for an individual magnitude.

The mean magnitude of the reference stars then give P_1, for the reference stars from (4) and a corresponding mean secular parallax and corrections $P_\alpha \cos \delta$, P_δ for a parallactic motion of the reference stars.

The alternative procedure of using star counts to derive a mean parallax p_2 was also used. In practise the counts of stars brighter than or equal to the mean magnitude of the reference group were made on plates taken for magnitude measurement over an area of four square degrees centred around the variable and an average taken. Differences between counts arise from uncertainty in the magnitude, that is as to whether or not a star should be countered, and imply an error of up to 0″·0001 in p_2.

A plot of p_1 against p_2 in Figure 1 shows a reasonable correlation for galactic latitudes less than 15°. For galactic latitudes lying between 15° and 60° p_1 tends to systematically exceed p_2.

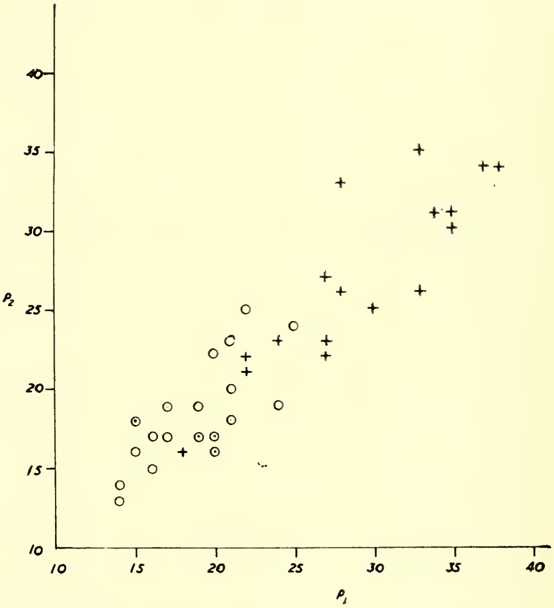

FIGURE 1.—Stars with open circle have $b<15°$. Stars with plus sign have $15°>b<60°$.

Corrections for the effect of galactic rotation on the reference stars have been derived using l^{II}, b^{II} galactic coordinates and galactic constants $A=+15$ kms/sec/kpc $B=-10$ kms/sec/kpc. For convenience, tables were prepared using the customary formulae with the right ascension of the ascending node for equinox 1900·0 being taken as 281°·65 and the inclination of the galactic plane to the equator 62°·20′. These corrections differ only slightly from those given by A. Blaauw and J. Delhaye (1949). The galactic coordinates l^{II}, b^{II} of the variable for equinox 1900·0 were computed with the same data.

Motions of some of the variable stars in this paper were already published in either Royal Observatory Bulletin No. 161 or 136 or Annals of the Cape Observatory, Vols. 19–20. The differences Sydney minus the other results are given in Table I in units of 0″·0001/yr.

There may be a systematic difference between my results and those of the Cape.

The degree to which the conversion of relative proper motions to absolute by using statistically derived mean parallaxes is liable to systematic error should possibly be considered.

A. R. Klemola and S. Vasilevskis (1971) in a preliminary investigation for determining the proper motions of faint stars relative to galaxies compare their mean secular parallaxes with those of Binnendijk who used a solar motion of 20 kms/sec. They achieve good agreement for

TABLE I

Star	Source	$\Delta\mu_\alpha \cos\delta$	$\Delta\mu_\delta$
I U Car ..	R.O.B. 161	+110	−4
DK Vel ..	R.O.B. 161	−21	−48
BI Cen ..	R.O.B. 161	−29	+16
TY Pav ..	R.O.B. 161	+55	+239
TY Pav ..	R.O.B. 136	−155	−151
W Hor ..	Cape	+153	−31
R Dor ..	Cape	+112	−11
I W Car ..	Cape	+108	+107
CM Vel ..	Cape	+92	+142
RR Car ..	Cape	+5	+16
BZ Car ..	Cape	−75	+95
V369 Cen ..	Cape	+100	+220
S Phe ..	Cape	+51	+78
S Pav ..	Cape	+10	+58
V Hor ..	Cape	−40	−139

the magnitude range 11–12 for middle and high galactic latitudes with only small difference at low galactic latitudes. Beyond magnitude 12 the discrepancies occur at all galactic latitudes and amount to 0″·003 to 0″·004/yr for magnitude 13. At fainter magnitudes the discrepancies become more marked. A higher value of solar speed may be indicated for faint hight latitude stars.

Then Z. Aslam (1971) who has made a re-examination of the material used by Binnendijk believes that as a result of an incorrect weighting system Binnendijk's average parallaxes are under-estimated by about 15%. The revised mean parallaxes would produce a somewhat better agreement with the Lick data although discrepancies would still exist. Evidence is also presented which indicates that the $\log N_m$, m relation varies with location in the sky and that since equations (4) and (5) imply a linear relationship between $\log N_m$ and m, equations (4) and (5) might not be applicable to all regions of the sky. This could explain the discrepancies pointed out in Figure 1.

Although the available evidence seems to indicate a need to increase Binnendijk's mean parallaxes, further observational data seem to be needed before any correction could be confidently applied. For southern hemisphere fields any doubt about regional difference must require re-evaluation. In view of this, the procedure has been to derive mean parallaxes from equation (4) leaving to the future any adjustment that may be needed. For this reason no errors are given for the absolute proper motion of the variable as given in Table 3.

The results of the measured relative proper motions and their reduction to absolute are given in Tables II and III.

Table II gives:

(*a*) the name of the star,

(*b*) the plate centre for equinox 1900·0,

(*c*) the plate pair or pairs,

(*d*) the epoch of each plate,

(*e*) the hour angle of each plate at mid exposure,

(*f*) the measured relative proper motion of the variable in units of 0″·0001/yr.

Table III gives:

(*a*) the name of the star,

(*b*) for 1900·0 α, δ, l^{II}, b^{II} and type of variable,

(*c*) Nm the number of stars per square degree around the variable with $m \leqslant$ mean m_{pg} of the reference stars,

(*d*) m_{pg} the mean photographic magnitude of the reference group or groups,

(*e*) the intrinsic dispersion of the proper motions of reference stars σ_x, σ_y.

(*f*) For each reference star the Catalogue number when available, the standard coordinates relative to the plate centre ξ, η in reseau intervals of 5′ and the relative proper motion,

(An asterisk before the catalogue number represents a rejected star.)

(*g*) the photographic magnitude of each reference star,

(*h*) the mean parallaxes p_1, p_2,

(*i*) the relative proper motion $\lambda_\alpha \cos\delta$, λ_δ of the variable in units of 0″·0001/yr together with the associated standard error,

(*j*) the absolute proper motion $\mu_\alpha \cos\delta$, μ_δ of the variable in units of 0″·0001.

TABLE II

Star	Plate Centre	Plate Pair	Date	H.A.	Relative Proper Motion in units of 0".0001/yr in			
					1st Image	2nd Image	1st Image	2nd Image
RS Hor	2^h32^m -63°	N1502 4621Sa	1926.826 1965.781	18^mE 12^mE	+ 11	+ 43	− 4	− 33
		890rh 4622Sa	1901.855 1965.781	47^mW 6^mW	+ 4		+ 10	
W Hor	2^h42^m -55°	1991s 4629Sa	1894.733 1965.803	39^mE 3^mE	− 52	− 93	− 13	+ 23
V Hor	3^h06^m -59°	1118rh 3299Sa	1902.970 1961.744	44^mW 17^mW	+ 62		− 277	
R Dor	4^h32^m -62°	2064s 2041Sa	1894.792 1958.748	41^mE 14^mE	− 602	− 668	− 826	− 787
IU Car	6^h54^m -59°	N1002 5238Sa	1924.083 1968.121	24^mW 4^mE	− 25		+ 281	
		2828s 5237Sa	1896.176 1968.121	6^mE 20^mE	− 36		+ 320	
		1116rh 3974Sa	1902.921 1963.864	39^mW 1^mE	− 21		+ 290	
DK Vel	9^h18^m -53°	3177s 4369Sa	1897.015 1965.220	3^mW 20^mW	+ 36		− 51	
		674rh 4392Sa	1901.195 1965.299	1^mW 8^mW	+ 6		− 29	
		647rh 4368Sa	1901.043 1965.220	24^mE 6^mW	+ 27		− 29	
IW Car	9^h28^m -63°	N1193 5029Sa	1925.291 1967.335	33^mW 2^mW	+ 163	+ 95	+ 37	− 16
		1321s 5279Sa	1894.228 1968.267	5^mE 6^mW	+ 166		+ 45	
SZ Car	9^h52^m -60°	244rh 4979Sa	1900.184 1967.220	32^mE 9^mE	− 70	− 59	+ 46	+ 7
RR Car	9^h54^m -59°	1405s 4070Sa	1894.288 1964.261	43^mE 1^mE	− 73	− 11	+ 84	+ 49
CM Vel	10^h06^m -53°	810s 2153Sa	1893.195 1959.280	10^mW 11^mE	+ 46	+ 56	− 24	− 13
		682rh 4414Sa	1901.223 1965.324	13^mW 5^mE	+ 27		− 23	
CL Car	10^h48^m -61°	1246s 5230Sa	1894.097 1968.097	7^mW 5^mE	− 8	− 7	+ 21	+ 12
BZ Car	10^h48^m -61°	1246s 5230Sa	1894.097 1968.097	7^mW 5^mE	+ 13	+ 10	+ 33	+ 58
		N1064 5291Sa	1924.310 1968.305	34^mW 5^mW	+ 53	+ 27	− 11	+ 41
TX Car	10^h54^m -59°	2841s 5287Sa	1896.179 1968.291	5^mW 5^mE	− 163		+ 68	
		3330s 5035Sa	1897.327 1967.338	3^mW 5^mW	− 139		+ 31	
RS Cen	11^h20^m -61°	1248s 5554Sa	1894.098 1969.155	4^mE 14^mW	− 103	− 130	+ 36	+ 18
		N1053 5307Sa	1924.278 1968.316	22^mW 3^mW	− 176	− 112	+ 94	+ 81
BI Cen	11^h42^m -59°	537rh 3467Sa	1909.305 1962.406	17^mW 17^mW	− 58		− 14	
		3340s 3491Sa	1897.330 1962.428	14^mE 17^mW	− 112		− 53	
		2885s 5255Sa	1896.269 1968.247	39^mW 15^mW	− 39		− 5	
W Cen	11^h54^m -59°	3332s 5309Sa	1897.327 1968.316	25^mW 10^mW	− 278		+ 76	
		2859s 3371Sa	1896.193 1962.163	21^mW 22^mW	− 272		− 8	

TABLE II (continued)

Star	Plate Centre	Plate Pair	Date	H.A.	Relative Proper Motion in units of 0".0001/yr in			
					1st Image	2nd Image	1st Image	2nd Image
V369 Cen	12^h12^m -54^o	1309s 1694Sa	1894.220 1958.245	22^mW 3^mE	− 30	− 38	+ 9	+ 11
		C1608 6010Sa	1927.403 1970.327	30^mE 5^mE	+ 24	− 35	− 5	− 89
U Cru	12^h30^m -57^o	1393s 5099Sa	1894.283 1967.694	18^mW 16^mW	+ 108	+ 116	+ 2	− 29
		2843s 4511Sa	1896.185 1965.497	3^mE 35^mW	+ 121		− 72	
U Cen	12^h24^m -54^o	280rh 5293Sa	1900.220 1968.302	3^mW 5^mW	+ 81	+ 130	+ 170	+ 170
Al Cen	12^h30^m -54^o	361rh 3026Sa	1900.332 1961.351	40^mW 10^mE	+ 71	+ 77	− 98	− 94
		815s 5256Sa	1893.195 1968.247	14^mE 12^mE	+ 64	+ 41	− 81	− 55
		360rh 3075Sa	1900.332 1961.453	27^mE 42^mW	+ 82		− 82	
		3307s 5257Sa	1897.272 1968.247	17^mW 9^mW	+ 95		− 75	
KQ Cen	14^h16^m -63^o	735rh 3083Sa	1901.374 1961.455	37^mW 5^mW	+ 83		+ 42	
		2908s 5272Sa	1896.289 1968.254	33^mW 2^mE	+ 99		+ 72	
R Cir	15^h18^m -57^o	1399s 5269Sa	1894.284 1968.251	11^mE 10^mW	+ 185		+ 74	
		1033rh 3155Sa	1902.568 1961.543	9^mW 5^mE	+ 107		+ 33	
TY Pav	17^h36^m -62^o	C2109 5797Sa	1929.658 1969.628	15^mW 7^mE	− 294	− 230	− 111	− 121
RZ Pav	17^h42^m -59^o	3422s 4254Sa	1897.492 1964.595	22^mW 6^mE	− 75		− 110	
		828rh 4255Sa	1901.623 1964.595	58^mW 15^mW	− 35		− 60	
BM Pav	19^h20^m -63^o	3714s 3892Sa	1898.549 1963.688	65^mW 15^mW	− 23		+ 154	
		771rh 5346Sa	1901.472 1968.423	4^mW 0^m	− 46		+ 150	
S Pav	19^h44^m -60^o	1741s 5388Sa	1894.529 1968.502	32^mE 4^mE	+ 317	+ 238	− 269	− 265
		C1894 6376Sa	1928.694 1971.631	16^mW 2^mE	+ 240	+ 276	− 294	− 252
W Ind	21^h06^m -53^o	3085s 3929Sa	1896.740 1963.770	23^mW 3^mW	+ 263		− 93	
		1011s 5396Sa	1893.549 1968.541	11^mE 12^mE	+ 323		− 98	
BU Pav	21^h18^m -64^o	1758s 5419Sa	1894.541 1968.707	63^mE 17^mE		− 132		− 10
		N920 3930Sa	1923.664 1963.770	50^mW 5^mW	− 126	− 172	+ 93	+ 50
Y Ind	21^h42^m -53^o	485rh 5420Sa	1900.634 1968.703	41^mW 19^mE	− 170		+ 18	
		3808s 2481Sa	1898.762 1959.836	26^mE 36^mW	− 111		− 7	
S Phe	23^h54^m -57^o	1037s 3611Sa	1893.598 1962.563	30^mW 20^mW	− 32		− 7	
		3137s 3975Sa	1896.844 1963.880	30^mW 5^mW	− 59		− 48	

Table III

RS HOR

$2^h33^m27^s.28$ $284^\circ.33$ M

$-63^\circ01'\ 06''.9$ $-50^\circ.60$

N_m = 23

12.26, 13.07

σ_x = 168, 107; σ_y = 163, 113

Cat No.	ξ	η	Δx	Δy
118	+ 8.691	+ 2.955	- 155	- 19
144	+ 8.511	+ 8.160	+ 322	+ 368
157	+ 8.086	+ 6.009	+ 37	+ 19
134	+ 8.076	+ 5.118	- 161	- 234
-	+ 5.680	+ 6.395	- 59	- 121
66	+ 10.657	- 3.399	- 354	+ 73
59	+ 8.267	- 4.286	- 85	- 115
42	+ 5.734	- 6.196	+ 80	+ 19
45	+ 3.756	- 6.622	+ 223	- 176
46	+ 3.650	- 6.265	+ 173	+ 186
132	- 1.141	+ 4.391	+ 139	+ 11
139	- 1.694	+ 5.370	+ 36	- 8
150	- 2.231	+ 7.394	- 121	- 190
123	- 3.762	+ 2.153	- 12	+ 130
67	+ 1.760	- 2.988	- 116	- 130
68	+ 1.181	- 3.497	+ 104	- 142
84	+ 0.290	- 1.664	- 102	+ 26
52	- 0.587	- 5.741	- 62	+ 48
72	- 4.843	- 3.245	+ 133	+ 211
*151	- 5.133	+ 7.202	+ 153	+ 649

Cat No.	ξ	η	Δx	Δy
110	+ 6.813	+ 1.531	- 96	- 289
119	+ 6.404	+ 2.574	+ 55	- 5
-	+ 5.764	+ 2.371	- 93	- 1
-	+ 5.523	+ 1.316	+ 60	+ 90
112	+ 5.019	+ 2.231	+ 94	+ 16
-	+ 7.615	- 4.293	+ 24	- 141
42	+ 5.734	- 6.190	+ 108	+ 63
78	+ 5.601	- 2.287	- 47	+ 78
-	+ 3.641	- 1.338	- 108	+ 187
113	+ 2.210	+ 1.728	- 121	+ 8
-	+ 1.148	+ 2.108	- 88	- 53
-	- 0.969	+ 1.168	+ 187	+ 56
-	- 2.114	+ 2.544	+ 8	+ 67
-	- 2.624	+ 5.147	- 7	+ 100
115	- 2.819	+ 1.510	+ 1	+ 12
-	+ 3.731	- 3.400	+ 169	+ 64
-	+ 3.236	- 0.718	- 41	+ 119
-	+ 2.447	- 2.394	- 241	- 188
69	+ 0.402	- 3.367	+ 93	- 64
84	+ 0.291	- 1.663	- 39	- 28
-	- 4.747	- 2.122	+ 77	- 92

Magnitudes of Reference Stars

(a) 12.2; 12.4; 11.9; 12.2; 12.0; 11.9; 11.6; 12.6; 12.1; 12.1; 12.6; 12.4; 12.6; 12.1; 12.7; 12.4; 13.0; 12.7; 12.1:

(b) 12.6; 12.5; 13.3; 13.1; 13.3; 13.3; 13.3; 12.6; 13.4; 13.4; 13.4; 13.2; 13.4; 12.8; 13.2; 13.1; 13.3; 13.2; 12.2; 12.6; 13.0:

p_1 = 0.0034, 0.0028 p_2 = 0.0031, 0.0026

Relative Proper Motion of RS Hor is

(1) $\lambda_\alpha \cos\delta = -15 \pm 45$

$\lambda_\delta = -3 \pm 40$

(2) $\lambda_\alpha \cos\delta = -4$

$\lambda_\delta = -11$

Absolute Proper Motion of RS Hor is

(1) $\mu_\alpha \cos\delta = +85$

$\mu_\delta = +51$

(2) $\mu_\alpha \cos\delta = +93$

$\mu_\delta = +42$

W HOR

$2^h41^m09^s.64$ $273^\circ.49$ SRa.

$-54^\circ43'\ 24''.0$ $-55^\circ.89$

N_m = 26

12.34

σ_x = 197 σ_y = 186

Cat No.	ξ	η	Δx	Δy
209	+ 6.411	+ 5.862	- 128	- 153
225	+ 4.180	+ 6.663	+ 68	+ 132
194	+ 3.789	+ 4.238	- 43	+ 117
196	+ 1.877	+ 4.650	- 7	+ 19
183	+ 1.069	+ 3.420	+ 134	- 29
213	+ 0.395	+ 5.478	+ 70	+ 5
125	+ 5.528	- 0.060	- 45	+ 120
150	+ 1.404	+ 1.969	- 190	+ 2
117	+ 1.045	- 1.495	- 58	- 119
173	- 1.029	+ 2.497	+ 227	- 119
228	- 3.111	+ 6.521	+ 94	- 28
214	- 3.132	+ 5.743	+ 244	+ 88
215	- 3.243	+ 5.499	+ 272	+ 181
217	- 8.393	+ 5.916	- 131	- 315
203	- 9.771	+ 4.515	- 298	- 465
218	- 10.065	+ 5.828	- 276	+ 448
128	- 1.977	- 0.320	+ 91	- 152
152	- 3.314	+ 1.712	- 137	+ 2
153	- 3.866	+ 1.765	- 200	+ 41
141	- 4.775	+ 0.408	- 42	+ 52
120	- 6.677	- 1.469	+ 257	+ 39
156	- 7.152	+ 1.349	+ 123	+ 109
*99	+ 4.167	- 3.369	- 792	- 414
*110	+ 3.897	- 2.502	+ 36	+ 805

Magnitudes of Reference Stars

12.2; 11.7; 12.0; 12.1; 12.1; 12.1; 12.4; 12.2; 13.2; 12.6; 12.6; 12.8; 11.7; 11.7; 11.7; 12.0; 12.6; 12.6; 12.2; 13.2; 13.0; 12.2.

p_1 = 0.0035 p_2 = 0.0030

Relative Proper Motion of W Hor is

$\lambda_\alpha \cos\delta = -72 \pm 60$

$\lambda_\delta = +5 \pm 51$

Absolute Proper Motion of W Hor is

$\mu_\alpha \cos\delta = +23$

$\mu_\delta = +49$

V HOR

$3^h01^m00^s.52$ $276^\circ.46$ SRb

$-59^\circ19'\ 21''.7$ $-50^\circ.87$

N_m = 50

13.16

σ_x = 119 σ_y = 79

Cat No.	ξ	η	Δx	Δy
-	- 2.165	- 1.929	+ 125	+ 84
-	- 3.374	- 1.348	- 114	- 120
-	- 4.775	- 2.643	- 18	- 31
-	- 6.583	+ 0.111	- 159	- 120
-	- 6.963	+ 0.107	+ 304	+ 96
38	- 4.938	- 8.252	+ 8	- 64
-	- 5.705	- 8.258	- 123	- 31
-	- 6.107	- 7.172	+ 31	+ 105
-	- 6.189	- 4.376	- 56	- 33
-	- 6.506	- 6.079	+ 40	+ 74
-	- 6.965	- 4.904	+ 8	- 29
-	- 8.579	- 2.909	+ 5	+ 59
-	- 8.897	- 1.214	- 15	+ 111
-	- 9.890	- 2.641	+ 41	+ 16
119	- 10.598	- 0.492	- 56	- 26
-	- 10.802	- 1.957	- 77	+ 136

Table III (continued 2)

Cat No.	ξ	η	Δx	Δy
–	– 11.509	– 0.261	– 143	– 196
–	– 8.079	– 4.736	– 53	+ 16
39	– 8.861	– 8.203	– 68	– 92
–	– 9.876	– 5.630	+ 7	+ 90
–	– 10.266	– 6.054	– 19	+ 32
–	– 10.406	– 4.756	+ 332	– 84

Magnitudes of Reference Stars

13.0; 13.4; 13.2; 13.0; 13.0; 12.9; 12.8; 13.0; 13.4; 13.4; 13.0; 13.4; 13.2; 13.0; 13.4; 13.4; 13.4; 13.6; 13.5; 13.6; 13.5; 12.8.

p_1 = 0.0027 p_2 = 0.0023

Relative Proper Motion of V Hor in

$$\lambda_\alpha \cos\iota = +62$$
$$\lambda_\delta = -277$$

Absolute Proper Motion of V Hor in

$$\mu_\alpha \cos\delta = +150$$
$$\mu_\delta = -219$$

R DOR

$4^h 35^m 35^s.25$ $272^\circ.65$ SRb

$-62^\circ 16' 30''.3$ $-39^\circ.34$

N_m = 17

11.73

$\sigma_x = 99$ $\sigma_y = 111$

Cat No.	ξ	η	Δx	Δy
93	+ 10.390	+ 1.484	– 106	– 79
51	+ 10.094	– 3.148	– 20	+ 152
80	+ 6.784	+ 0.861	– 172	– 77
81	+ 6.579	+ 0.930	+ 156	– 65
60	+ 5.208	– 2.576	+ 38	– 4
–	+ 9.664	– 5.511	– 8	– 131
22	+ 8.814	– 7.591	– 21	+ 119
23	+ 8.723	– 6.957	+ 13	+ 35
31	+ 7.016	– 6.055	+ 139	+ 13
40	+ 6.426	– 5.856	– 21	+ 38
82	+ 4.254	+ 0.375	+ 21	+ 92
84	+ 2.488	+ 0.590	+ 188	+ 222
61	+ 2.104	– 2.383	– 113	– 26
70	+ 0.976	– 0.411	+ 79	– 26
98	– 1.096	+ 1.178	– 58	– 189
33	+ 3.860	– 6.140	– 92	– 21
41	+ 3.407	– 5.145	+ 149	– 174
15	+ 2.643	– 9.044	– 143	+ 161
48	– 0.515	– 4.137	– 54	+ 62
28	– 3.302	– 7.123	+ 74	– 104

Magnitudes of Reference Stars

11.8; 11.7; 12.2; 12.2; 11.6; 12.0; 11.6; 11.4; 12.2; 12.2; 12.2; 12.3; 12.0; 11.6; 12.2; 11.6; 11.6; 10.4; 11.7; 11.2.

p_1 = 0.0037 p_2 = 0.0034

Relative Proper Motion of R Dor in

$$\lambda_\alpha \cos\delta = -635 \pm 60$$
$$\lambda_\delta = -806 \pm 45$$

Absolute Proper Motion of R Dor in

$$\mu_\alpha \cos\delta = -578$$
$$\mu_\delta = -691$$

IU CAR

$6^h 51^m 41^s.42$ $269^\circ.57$ R Rab

$-59^\circ 28' 12''.4$ $-22^\circ.89$

N_m = 19, 65

11.62, 12.52

σ_x = 80, 104 σ_y = 158,129

Cat No.	ξ	η	Δx	Δy
169	+ 2.164	– 1.319	– 52	– 158
154	+ 0.928	– 1.823	+ 55	+ 31
126	+ 0.779	– 3.608	+ 4	– 133
140	+ 0.424	– 2.771	– 58	+ 276
127	+ 0.144	– 4.297	+ 88	+ 88
129	– 3.106	– 3.440	– 27	– 147
69	+ 1.923	– 7.865	+ 145	– 104
71	+ 1.691	– 7.730	+ 56	+ 100
50	+ 1.415	– 8.967	– 4	– 71
33	+ 1.373	– 9.529	– 44	+ 70
103	– 0.207	– 5.928	– 124	– 148
21	– 1.451	– 10.837	– 37	+ 190
143	– 3.991	– 3.311	+ 19	+ 93
156	– 6.217	– 1.372	– 103	– 33
146	– 7.306	– 3.135	+ 12	– 63
159	– 8.671	– 2.289	+ 90	+ 179
149	– 9.448	– 3.032	– 30	– 140
90	– 5.092	– 6.757	– 77	– 153
72	– 6.951	– 7.525	– 167	– 197
38	– 6.960	– 9.573	+ 97	+ 354
73	– 7.287	– 7.577	+ 26	– 61
54	– 8.806	– 9.079	+ 130	+ 16
* 56	– 9.062	– 8.855	– 586	– 206
*174	– 6.521	– 1.158	+ 48	– 960

–	+ 3.147	– 1.471	– 94	+ 45
140	+ 0.422	– 2.770	– 21	+ 106
–	+ 0.122	– 1.559	– 48	– 126
–	+ 0.008	– 0.480	+ 72	– 34
–	– 3.377	– 4.394	+ 22	– 58
68	+ 2.203	– 7.657	– 31	– 8
–	+ 1.819	– 7.292	– 27	–. 35
89	+ 0.146	– 7.150	+ 272	+ 193
18	+ 0.189	– 11.026	– 104	– 56
34	– 0.383	– 9.568	– 47	– 28
142	– 3.869	– 2.504	– 111	+ 74
116	– 6.284	– 4.966	+ 15	+ 154
–	– 6.322	– 2.636	+ 38	+ 28
–	– 6.991	– 5.086	– 8	+ 29
117	– 8.972	– 4.559	+ 135	+ 218
52	– 4.116	– 8.601	+ 36	– 51
37	– 5.866	– 10.179	– 80	– 139
92	– 6.877	– 7.061	– 119	+ 172
40	– 7.570	– 9.450	+ 7	– 177
–	– 8.639	– 8.699	+ 88	+ 125

Magnitudes of Reference Stars

(a) 11.1; 11.3; 11.0; 12.1; 11.3; 12.1; 12.4; 12.5; 11.8; 11.7; 11.4; 11.4; 11.5; 11.0; 11.3; 11.9; 11.6; 11.7; 12.2; 11.7; 11.7; 11.5.

(b) 12.6; 11.8; 12.4; 12.6; 12.4; 12.6; 12.4; 12.4; 12.6; 12.6; 12.0; 12.6; 13.3; 13.1; 12.7; 12.4; 12.6; 12.6; 12.6; 12.7.

p_1 = .0028, .0022 p_2 = 0.0033, 0.0022

Table III (continued 3)

Relative Proper Motion of IU Car in

(1) $\lambda_\alpha \cos\delta = -25 \pm 49$

$\lambda_\delta = -281 \pm 57$

(2) $\lambda_\alpha \cos\delta = -30 \pm 25$

$\lambda_\delta = +307 \pm 33$

Absolute Proper Motion of IU Car in

(1) $\mu_\alpha \cos\delta = -59$

$\mu_\delta = +374$

(2) $\mu_\alpha \cos\delta = -62$

$\mu_\delta = +397$

DK VEL

$9^h 14^m 05^s.45$	274.01	RRc
$-52°39' 54''.7$	-2.69	
	$N_m = 130$	
	12.41	

$\sigma_x = 127$ $\sigma_y = 127$

Cat No.	ξ	η	Δx	Δy
801	- 3.330	+ 6.045	- 43	+ 109
782	- 3.490	+ 5.218	- 25	+ 36
-	- 4.360	+ 6.503	- 25	+ 81
841	- 5.695	+ 7.175	- 74	+ 124
-	- 6.404	+ 4.893	- 31	- 200
695	- 3.028	+ 3.647	- 49	+ 40
699	- 4.159	+ 3.763	- 12	+ 58
700	- 4.660	+ 2.937	+ 304	- 257
656	- 5.676	+ 2.244	- 9	+ 12
-	- 5.836	+ 3.228	- 35	- 4
808	- 7.889	+ 5.927	- 30	+ 94
-	- 8.161	+ 4.715	- 89	+ 68
-	- 8.601	+ 6.222	- 87	- 21
-	- 8.798	+ 4.896	+ 177	- 134
-	- 9.065	+ 4.146	+ 96	- 151
711	- 7.725	+ 3.191	+ 91	- 2
-	- 8.000	+ 1.868	+ 11	- 72
-	- 8.165	+ 2.396	- 249	+ 286
712	- 8 394	+ 2.910	- 29	- 2
-	- 9.795	+ 2.187	- 18	- 50

Magnitude of Reference Stars

12.6; 12.7; 13.1; 12.5; 11.9; 11.7; 12.3;
11.1; 12.1; 12.9; 10.7; 13.3; 13.1; 11.9;
13.1; 12.1; 12.7; 12.7; 12.1; 12.9.

$p_1 = 0.0017$ $p_2 = 0.0017$

Relative Proper Motion of DK Vel in

$\lambda_\alpha \cos\delta = +23 \pm 28$

$\lambda_\delta = -36 \pm 28$

Absolute Proper Motion of DK Vel in

$\mu_\alpha \cos\delta = -61$

$\mu_\delta = +12$

IW CAR

$9^h 24^m 32^s.39$	282.43	RVb
$-63°11' 42''.0$	$-9°.23$	
	$N_m = 51$	
	11.81, 12.06	

$\sigma_x = 86$ $\sigma_y = 77$

Cat No.	ξ	η	Δx	Δy
439	- 0.682	- 2.691	- 40	- 8
440	- 1.720	- 1.062	+ 76	+ 13
441	- 2.445	- 1.307	- 8	- 37
398	- 3.002	- 2.181	+ 188	- 34
500	- 3.141	- 0.128	- 120	- 2
349	+ 0.098	- 3.497	+ 92	- 24
207	+ 0.013	- 6.518	- 2	- 24
399	- 3.048	- 2.688	- 232	- 13
217	- 3.470	- 6.746	- 80	+ 96
265	- 3.647	- 5.549	+ 20	+ 9
445	- 7.727	- 1.468	+ 26	+ 164
504	- 7.730	- 0.854	- 104	+ 40
449	- 8.305	- 1.454	- 26	+ 68
549	- 8.628	+ 0.888	- 118	- 55
450	- 8.824	- 1.469	+ 6	- 4
359	- 5.770	- 3.962	- 8	+ 18
273	- 5.811	- 5.478	- 124	+ 8
274	- 6.665	- 5.562	+ 96	+ 12
318	- 6.819	- 4.516	- 8	- 14
276	- 6.924	- 5.850	+ 236	- 312
438	+ 0.709	- 1.260	- 1	- 24
492	- 0.620	- 0.507	+ 91	- 67
395	- 1.357	- 2.162	+ 98	- 75
350	- 1.176	- 3.932	- 15	- 7
311	- 1.630	- 4.212	- 62	- 15
314	- 3.261	- 4.949	+ 37	- 47
352	- 3.663	- 3.419	- 29	+ 274
502	- 5.506	- 0.577	- 70	- 58
544	- 7.115	+ 0.329	- 36	+ 40
405	- 5.151	- 2.688	- 93	+ 75
271	- 5.366	- 5.480	+ 164	- 61

Magnitudes of Reference Stars

12.0; 11.9; 12.0; 11.7; 12.0; 11.8; 11.8;
12.0; 11.7; 12.0; 11.9; 11.3; 11.7; 11.6;
11.2; 12.4; 12.0; 12.1; 12.0; 12.0; 11.9;
12.1; 12.3; 12.4; 12.4; 12.1; 12.1; 12.6;
12.4; 12.2; 12.3.

$p_1 = 0.0021$ $p_2 = 0.0023$

Relative Proper Motion of IW Car in

$\lambda_\alpha \cos\delta = +154 \pm 41$

$\lambda_\delta = +33 \pm 40$

Absolute Proper Motion of IW Car in

$\mu_\alpha \cos\delta = +58$

$\mu_\delta = +87$

RR CAR

$9^h 54^m 50^s.06$	282.11	SRb
$-58°23' 01''.1$	$-3°.18$	
	$N_m = 122$	
	11.75	

$\sigma_x = 46$ $\sigma_y = 47$

Cat No.	ξ	η	Δx	Δy
2906	+ 3.965	+ 8.288	- 55	+ 4
2907	+ 3.838	+ 8.081	- 90	- 22
3041	+ 2.730	+ 8.900	+ 90	- 82
3140	+ 2.011	+ 9.958	- 123	+ 120
2919	+ 1.885	+ 8.376	+ 220	- 50
2530	+ 4.292	+ 5.512	- 33	+ 28
2782	+ 3.994	+ 6.929	- 61	- 26
2650	+ 3.605	+ 6.378	+ 20	+ 10
2652	+ 2.953	+ 6.139	+ 47	- 25
2656	+ 2.362	+ 6.069	- 14	+ 38
2922	+ 1.116	+ 8.102	- 16	- 12
2804	+ 0.903	+ 7.843	- 9	+ 6
3051	+ 0.782	+ 9.652	- 5	+ 36
3053	- 0.201	+ 9.117	- 36	+ 24
2812	- 0.635	+ 7.774	+ 24	- 28
2661	+ 1.039	+ 6.427	- 28	- 106
2805	+ 0.733	+ 7.154	- 5	+ 48
2402	+ 0.019	+ 4.433	+ 22	- 35
2669	- 0.688	+ 6.077	+ 7	+ 54
2820	- 1.277	+ 6.954	+ 48	+ 10

Table III (continued 4)

Magnitudes of Reference Stars

11.8; 11.8; 11.8; 11.6; 11.9; 11.7; 11.7; 11.8; 11.6; 11.7; 12.2; 11.8; 11.8; 11.8; 11.7; 11.7; 11.8; 11.7; 12.0; 11.6.

p_1 = 0.0020 p_2 = 0.0017

Relative Proper Motion of RR Car in

$\lambda_\alpha \cos\delta = -42 \pm 54$

$\lambda_\delta = +66 \pm 32$

Absolute Proper Motion of RR Car in

$\mu_\alpha \cos\delta = -145$

$\mu_\delta = +106$

SZ CAR

$9^h56^m41^s.65$ $283^\circ.12$ SRb

$-59^\circ44'\ 17''.7$ $-4^\circ.12$

N_m = 102

11.59

σ_x = 91 σ_y = 30

Cat No.	ξ	η	Δx	Δy
1976	+ 9.096	+ 4.353	− 22	+ 14
1978	+ 8.794	+ 4.590	+ 26	0
1805	+ 8.360	+ 3.632	− 20	+ 9
1993	+ 7.500	+ 4.187	− 38	+ 44
1815	+ 7.358	+ 3.258	− 2	+ 4
1500	+ 9.756	+ 0.934	+ 40	− 40
1635	+ 8.697	+ 2.630	− 4	− 58
1368	+ 7.830	− 0.062	− 8	− 42
1641	+ 7.750	+ 2.289	− 8	+ 26
1372	+ 7.395	+ 0.484	+ 30	+ 29
1999	+ 6.557	+ 4.800	− 9	− 26
2001	+ 6.352	+ 4.190	− 4	+ 6
2004	+ 6.197	+ 4.805	− 104	− 10
1834	+ 4.689	+ 3.546	− 116	+ 25
2016	+ 4.145	+ 4.802	+ 285	− 65
1650	+ 6.472	+ 1.924	+ 3	+ 4
1652	+ 6.257	+ 2.038	− 54	+ 2
1386	+ 5.708	+ 0.665	− 19	+ 72
1662	+ 5.226	+ 2.717	+ 90	− 34
1393	+ 3.631	+ 0.585	− 70	+ 29

Magnitudes of Reference Stars

11.2; 11.2; 11.6; 11.7; 11.2; 11.5; 11.7; 11.8; 11.8; 11.6; 11.5; 11.0; 11.8; 11.8; 11.6; 11.6; 11.0; 11.8; 11.2; 11.6.

p_1 = 0.0021 p_2 = 0.0018

Relative Proper Motion of SZ Car in

$\lambda_\alpha \cos\delta = -64 \pm 23$

$\lambda_\delta = +25 \pm 26$

Absolute Proper Motion of SZ Car in

$\mu_\alpha \cos\delta = -171$

$\mu_\delta = +66$

CM VEL

$10^h03^m50^s.34$ $279^\circ.82$ SRa

$-52^\circ46'\ 16''.2$ $+2^\circ.10$

N_m = 90, 154

11.87 12.80

σ_x = 72, 38 σ_y = 62, 41

Cat No.	ξ	η	Δx	Δy
1035	− 0.427	+ 5.340	− 54	0
1036	− 0.737	+ 5.054	+ 57	+ 82
1038	− 1.199	+ 5.521	+ 4	+ 14
1081	− 1.504	+ 6.251	− 40	− 32
1043	− 2.560	+ 5.350	− 42	+ 2
790	+ 0.699	+ 0.487	− 80	+ 56
884	− 0.919	+ 1.984	− 17	+ 36
885	− 1.235	+ 3.055	+ 172	− 98
792	− 2.464	+ 0.792	− 60	+ 16
890	− 3.214	+ 2.357	+ 62	− 78
995	− 4.833	+ 4.150	− 23	0
1090	− 5.494	+ 6.254	+ 4	− 5
1131	− 6.181	+ 7.174	− 11	+ 16
1091	− 6.274	+ 6.474	+ 40	− 4
1054	− 6.871	+ 5.067	+ 64	− 76
794	− 4.801	+ 0.623	− 30	+ 4
754	− 5.450	− 0.875	+ 108	− 96
799	− 6.154	− 0.030	− 110	− 18
800	− 6.161	+ 0.574	− 44	+ 48
895	− 6.616	+ 2.550	+ 2	+ 132
−	− 0.716	+ 4.627	+ 44	+ 30
−	− 0.932	+ 3.587	+ 40	− 71
1042	− 2.218	+ 5.487	+ 63	+ 1
992	− 3.390	+ 4.251	− 42	− 12
1084	− 3.467	+ 5.968	+ 27	+ 9
834	− 0.500	+ 1.182	− 8	− 32
750	− 0.464	− 0.374	+ 5	+ 40
751	− 2.687	− 0.880	− 95	+ 78
889	− 3.085	+ 2.157	− 5	− 85
−	− 3.483	+ 1.245	− 35	+ 36
1048	− 4.798	+ 5.780	− 25	+ 81
996	− 5.186	+ 4.319	− 21	− 8
−	− 5.227	+ 3.304	− 49	− 9
946	− 5.274	+ 3.477	− 3	− 27
−	− 6.382	+ 4.666	− 40	0
698	− 4.689	− 1.201	+ 66	+ 11
−	− 5.182	+ 1.561	+ 7	− 41
797	− 5.281	+ 0.096	+ 16	− 45
756	− 6.346	− 0.855	− 30	− 32
−	− 8.337	+ 0.984	+ 74	+ 67

Magnitudes of Reference Stars

(a) Catalogue plate: 11.8; 11.6; 12.4; 12.5; 12.3; 12.2; 11.4; 11.0; 12.6; 12.0; 12.4; 11.4; 12.0; 12.2; 11.4; 11.6; 11.8; 12.0; 11.5; 11.4

(b) Chart plate: 12.8; 13.2; 12.8; 12.7; 12.6; 12.4; 12.8; 13.2; 12.6; 13.4; 12.4; 13.0; 13.0; 13.0; 12.8; 12.6; 12.8; 12.6; 12.5; 13.0.

p_1 = 0.0019, 0.0015 p_2 = 0.0019, 0.0016

Relative Proper Motion of CM Vel in

(1) $\lambda_\alpha \cos\delta = +51 \pm 20$

$\lambda_\delta = -18 \pm 18$

(2) $\lambda_\alpha \cos\delta = +27$

$\lambda_\delta = -23$

Absolute Proper Motion of CM Vel in

(1) $\mu_\alpha \cos\delta = -52$

$\mu_\delta = +15$

(2) $\mu_\alpha \cos\delta = -63$

$\mu_\delta = +9$

CL CAR

$10^h50^m0^s2.58$ 289.22 SRb

$-60^\circ33'\ 33''.8$ $-1^\circ.38$

N_m = 85

11.05

σ_x = 59 σ_y = 59

Table III (continued 5)

Cat No.	ξ	η	Δx	Δy
2404	+ 5.225	+ 7.241	− 8	+ 52
2278	+ 5.077	+ 6.411	+ 94	+ 24
2281	+ 4.810	+ 6.537	− 65	− 5
2415	+ 3.539	+ 7.333	+ 8	− 32
2170	+ 3.495	+ 5.548	− 4	+ 36
2017	+ 6.183	+ 4.397	+ 24	+ 23
2020	+ 6.022	+ 4.463	+ 36	− 28
2029	+ 4.107	+ 4.653	+ 4	− 52
1892	+ 3.773	+ 3.826	− 62	− 5
1766	+ 3.292	+ 2.382	− 28	− 9
2424	+ 2.508	+ 7.936	+ 76	− 43
2425	+ 2.487	+ 7.520	− 50	+ 50
2296	+ 1.661	+ 6.068	+ 4	− 64
2179	+ 1.652	+ 5.642	− 30	− 2
2430	+ 1.485	+ 7.599	− 26	− 12
1771	+ 2.010	+ 2.312	+ 4	− 16
2040	+ 1.851	+ 4.051	− 96	+ 112
1901	+ 1.145	+ 3.754	− 26	− 30
2043	+ 0.809	+ 4.632	− 20	− 32
1902	+ 0.357	+ 3.845	+ 163	− 1

Magnitudes of Reference Stars

10.8; 11.4; 10.4; 11.6; 11.2; 12.0; 11.8; 11.0; 11.7; 11.2; 11.2; 11.6; 11.0; 11.2; 10.5; 10.8; 10.6; 10.7; 10.8; 10.6.

p_1 = 0.0024 p_2 = 0.0019

Relative Proper Motion of CL Car in

$$\lambda_\alpha \cos\delta = -8 \pm 13$$
$$\lambda_\delta = +16 \pm 17$$

Absolute Proper Motion of CL Car in

$$\mu_\alpha \cos\delta = -133$$
$$\mu_\delta = +35$$

BZ CAR

$10^h50^m11^s.65$ 289°65 SRb

$-61°30' 35''.8$ $-2°.23$

N_m = 74

11.53

σ_x = 114 σ_y = 90

Cat No.	ξ	η	Δx	Δy
606	+ 5.554	− 5.690	+ 11	+ 6
751	+ 5.147	− 4.875	+ 39	− 1
622	+ 3.683	− 5.252	+ 37	− 26
623	+ 3.535	− 5.051	+ 14	+ 16
373	+ 5.474	− 7.278	+ 12	+ 17
374	+ 5.396	− 7.589	− 25	+ 27
379	+ 3.962	− 7.408	− 33	− 25
380	+ 3.782	− 6.952	− 39	− 62
381	+ 3.454	− 7.542	− 15	+ 48
626	+ 3.022	− 5.049	− 11	− 20
769	+ 2.561	− 4.792	− 20	+ 99
633	+ 2.161	− 5.496	+ 142	+ 17
776	+ 1.775	− 4.222	+ 39	− 34
784	+ 0.975	− 4.111	+ 31	− 58
387	+ 2.272	− 6.969	− 31	− 18
499	+ 1.498	− 6.581	+ 144	− 100
394	+ 1.448	− 7.484	− 120	+ 109
501	+ 1.413	− 6.620	+ 167	+ 53
503	+ 1.053	− 6.705	− 63	− 49
*612	+ 4.933	− 5.681	+ 740	− 180

Magnitudes of Reference Stars

11.6; 11.4; 12.1; 11.6; 12.0; 12.1; 12.1; 12.0; 11.6; 10.9; 11.3; 11.3; 11.4; 11.6; 11.4; 11.8; 11.3; 11.4; 11.8.

p_1 = 0.0021 p_2 = 0.0020

Relative Proper Motion of BZ Car in

$$\lambda_\alpha \cos\delta = +21 \pm 31$$
$$\lambda_\delta = +36 \pm 27$$

Absolute Proper Motion of BZ Car in

$$\mu_\alpha \cos\delta = -85$$
$$\mu_\delta = +55$$

TX CAR

$10^h54^m51^s.10$ 288.91 RR ab

$-58°32' 48''.4$ $+0°.71$

N_m = 454

12.89

σ_x = 95 σ_y = 67

Cat No.	ξ	η	Δx	Δy
2789	+ 2.676	+ 5.900	− 36	+ 62
2953	+ 2.252	+ 6.708	+ 10	− 16
2795	+ 1.823	+ 6.059	− 16	− 74
2959	+ 1.626	+ 6.385	+ 182	− 98
3127	+ 1.569	+ 7.981	− 54	+ 65
−	+ 2.589	+ 4.489	+ 32	+ 32
2790	+ 2.542	+ 5.130	− 22	+ 56
2484	+ 2.478	+ 4.048	− 21	+ 38
−	+ 1.878	+ 4.852	+ 44	− 70
2647	+ 1.555	+ 4.291	− 118	+ 5
2803	+ 0.960	+ 5.936	+ 10	+ 72
−	+ 0.782	+ 7.616	+ 14	+ 23
−	+ 0.186	+ 7.110	− 28	+ 43
2815	− 0.163	+ 6.040	− 55	− 24
3152	− 1.150	+ 5.406	− 20	− 17
−	+ 0.694	+ 3.764	+ 88	− 3
2504	+ 0.422	+ 3.770	− 38	− 12
−	+ 0.373	+ 5.001	− 16	+ 18
−	+ 0.267	+ 5.167	+ 6	0
2657	− 0.337	+ 4.714	+ 46	− 64

Magnitudes of Reference Stars

13.0; 12.8; 13.0; 13.0; 12.6; 12.9; 13.0; 13.0; 13.1; 12.9; 12.6; 12.8; 12.8; 12.6; 13.0; 12.9; 13.0; 13.1; 13.0; 13.1.

p_1 = 0.0014 p_2 = 0.0001

Relative Proper Motion of TX Car in

$$\lambda_\alpha \cos\delta = -151 \pm 26$$
$$\lambda_\delta = +50 \pm 28$$

Absolute Proper Motion of TX Car in

$$\mu_\alpha \cos\delta = -244$$
$$\mu_\delta = +67$$

RS CEN

$11^h16^m05^s.46$ 292°.43 M

$-61°19' 46''.7$ $-0°.87$

N_m = 146

11.62

σ_x = 69 σ_y = 40

Cat No.	ξ	η	Δx	Δy
966	− 2.026	− 2.795	− 24	− 28
1097	− 2.590	− 1.621	+ 47	− 33
969	− 2.841	− 2.619	+ 24	− 12
850	− 3.574	− 3.414	− 10	− 4
972	− 4.604	− 2.780	+ 100	0
538	− 1.975	− 6.401	− 12	− 16
742	− 3.770	− 4.671	− 29	+ 62
649	− 3.861	− 4.982	− 25	+ 15

Table III (continued 6)

Cat No.	ξ	η	Δx	Δy
650	− 3.862	− 5.553	− 50	− 13
744	− 4.567	− 4.504	− 21	+ 14
978	− 6.055	− 2.237	− 15	+ 19
981	− 6.585	− 2.510	− 37	− 2
1116	− 6.863	− 1.572	− 15	+ 41
1118	− 7.536	− 1.614	− 19	0
985	− 7.849	− 2.766	− 54	+ 37
753	− 6.814	− 4.671	− 19	+ 29
553	− 7.106	− 6.454	+ 37	− 7
667	− 8.432	− 5.808	+ 1	− 5
668	− 8.726	− 5.758	− 43	+ 4
670	− 9.092	− 5.120	+ 126	− 93

Magnitudes of Reference Stars

11.4; 11.6; 11.4; 11.2; 11.7; 11.4; 11.3;
11.6; 11.1; 12.0; 12.2; 11.9; 12.0; 11.5;
11.7; 11.4; 11.6; 12.1; 12.1; 12.0.

p_1 = 0.0020 p_2 = 0.0016

Relative Proper Motion of RS Cen in

$$\lambda_\alpha \cos\delta = -130 \pm 24$$
$$\lambda_\delta = +58 \pm 37$$

Absolute Proper Motion of RS Cen in

$$\mu_\alpha \cos\delta = -244$$
$$\mu_\delta = +65$$

BI CEN

$11^h41^m03^s.53$ $294^\circ.67$ RRab

$-58^\circ49'\ 20''.6$ $+2^\circ.44$

N_m = 253

13.25

σ_x = 50 σ_y = 56

Cat No.	ξ	η	Δx	Δy
−	+ 1.618	+ 4.185	+ 29	+ 57
−	+ 0.443	+ 2.873	− 14	− 44
−	− 0.596	+ 2.911	− 31	+ 16
−	− 0.625	+ 4.179	− 9	− 44
−	− 0.936	+ 3.184	− 10	+ 30
−	+ 2.270	+ 0.515	+ 39	− 30
−	+ 1.013	+ 0.384	− 50	+ 20
−	+ 0.460	+ 2.067	+ 27	− 20
−	+ 0.446	+ 1.401	+ 4	+ 13
−	− 1.175	+ 0.261	+ 16	+ 1
−	− 1.691	+ 3.336	+ 47	+ 42
−	− 1.808	+ 3.471	− 55	+ 1
−	− 2.620	+ 2.536	+ 10	− 17
−	− 2.641	+ 3.804	+ 16	− 37
−	− 3.310	+ 0.631	+ 15	− 4
−	− 1.554	+ 0.191	+ 18	− 11
−	− 1.879	+ 1.668	+ 1	+ 3
−	− 2.184	+ 1.884	− 24	+ 49
−	− 2.632	+ 0.132	− 96	− 28
−	− 3.344	+ 1.169	+ 67	0

Magnitudes of Reference Stars

13.4; 13.4; 13.0; 13.4; 13.4; 13.4; 13.4;
13.4; 12.8; 13.2; 13.2; 13.2; 13.0; 13.4;
13.2; 13.4; 13.5; 13.2; 13.4; 13.4.

p_1 = 0.0014 p_2 = 0.0013

Relative Proper Motion of BI Cen in

$$\lambda_\alpha \cos\delta = -70 \pm 28$$
$$\lambda_\delta = -24 \pm 22$$

Absolute Proper Motion of BI Cen in

$$\mu_\alpha \cos\delta = -159$$
$$\mu_\delta = -14$$

W CEN

$11^h50^m01^s.62$ $295^\circ.77$ M

$-58^\circ41'\ 51''.3$ $+2^\circ.84$

N_m = 266

13.23

σ_x = 101 σ_y = 40

Cat No.	ξ	η	Δx	Δy
−	− 3.646	+ 4.840	+ 182	+ 57
−	− 4.787	+ 4.093	− 104	− 20
−	− 5.736	+ 4.440	− 82	− 2
−	− 5.970	+ 5.518	− 94	− 14
806	− 6.079	+ 4.388	− 40	− 24
−	− 3.487	+ 2.727	− 113	− 42
−	− 4.452	+ 3.559	+ 327	+ 6
−	− 4.992	+ 2.555	− 58	+ 9
−	− 5.566	+ 2.147	− 12	+ 58
713	− 5.780	+ 2.531	− 4	− 24
808	− 6.507	+ 4.741	− 56	− 22
−	− 6.794	+ 4.315	− 64	+ 46
−	− 6.885	+ 5.169	+ 54	+ 16
−	− 8.015	+ 5.153	+ 124	− 33
−	− 8.109	+ 4.185	+ 80	0
−	− 6.276	+ 3.372	− 44	− 32
−	− 6.429	+ 3.456	− 20	+ 2
−	− 6.804	+ 3.114	− 58	0
−	− 6.920	+ 2.247	− 2	+ 36
−	− 7.013	+ 3.017	− 31	− 25

Magnitudes of Reference Stars

13.4; 13.4; 13.4; 13.4; 12.8; 13.2; 13.2;
13.4; 12.5; 12.8; 13.2; 13.4; 13.2; 13.2;
13.2; 13.4; 13.2; 13.4; 13.2; 13.4.

p_1 = 0.0014 p_2 = 0.0013

Relative Proper Motion of W Cen in

$$\lambda_\alpha \cos\delta = -275 \pm 4$$
$$\lambda_\delta = +34 \pm 53$$

Absolute Proper Motion of W Cen in

$$\mu_\alpha \cos\delta = -364$$
$$\mu_\delta = +31$$

V369 CEN

$12^h09^m42^s.30$ 297.65 SR

$-54^\circ15'\ 51''.6$ $+7^\circ.68$

N_m = 118

12.03, 12.35

σ_x = 149 σ_y = 109

Cat No.	ξ	η	Δx	Δy
408	+ 0.461	− 2.064	− 134	− 70
413	− 1.277	− 1.908	+ 124	+ 6
366	− 2.441	− 2.646	+ 56	− 46
370	− 3.614	− 2.934	+ 31	− 26
239	− 0.764	− 5.639	− 4	− 89
199	− 1.155	− 7.021	− 213	+ 238
316	− 1.858	− 3.368	− 2	− 111
156	− 2.815	− 7.766	+ 123	+ 142
373	− 5.307	− 2.709	+ 144	− 2
425	− 6.052	− 1.939	+ 75	− 2
427	− 7.339	− 1.238	− 95	+ 59
378	− 8.875	− 2.873	− 285	+ 98
324	− 6.441	− 3.836	+ 27	+ 8
277	− 6.461	− 4.505	+ 94	− 6
208	− 5.907	− 6.892	− 46	− 14
254	− 7.877	− 5.169	+ 26	− 136
454	− 0.495	− 0.390	− 137	+ 8
364	− 1.820	− 2.330	+ 68	− 4
500	− 2.409	− 0.038	− 50	+ 77

Table III (continued 7)

Cat No.	ξ	η	Δx	Δy
311	+ 0.494	− 3.915	− 172	+ 113
238	− 0.394	− 5.121	+ 176	− 72
318	− 2.035	− 3.661	− 39	− 26
421	− 4.825	− 1.460	+ 36	− 69
462	− 5.173	− 0.796	+ 208	+ 4
426	− 6.293	− 1.208	− 92	− 88
428	− 8.555	− 2.028	+ 3	+ 90
246	− 4.307	− 5.407	− 27	+ 74
206	− 4.951	− 6.569	− 108	+ 78
273	− 5.396	− 4.567	+ 39	− 88
250	− 6.045	− 5.446	+ 48	+ 64
328	− 7.687	− 4.908	+ 40	− 99

Magnitudes of Reference Stars

(a) 12.0; 11.8; 12.4; 11.8; 12.0; 11.6; 11.9; 12.2; 11.9; 12.0; 12.0; 12.4; 12.3; 11.6; 12.2; 12.7.

(b) 12.4; 12.4; 12.2; 12.6; 11.8; 11.9; 12.6; 12.0; 12.8; 12.6; 12.5; 12.5; 12.2; 12.7; 12.4; 12.0; 12.4; 12.6; 12.6.

$p_1 = 0.0019$ $p_2 = 0.0017$

Relative Proper Motion of V369 Cen in

$\lambda_\alpha \cos\delta = -23 \pm 43$

$\lambda_\delta = -13 \pm 46$

Absolute Proper Motion of V369 Cen in

$\mu_\alpha \cos\delta = -130$

$\mu_\delta = -30$

U CRU

$12^h26^m49^s.47$ $300^\circ.37$ M

$-57^\circ01' 51''.0$ $+5^\circ.20$

N_m = 93, 200

12.51, 13.25

σ_x = 110, 92 σ_y = 36, 61

Cat No.	ξ	η	Δx	Δy
853	− 2.106	+ 0.780	+ 32	+ 46
922	− 2.511	+ 1.867	− 170	− 22
988	− 2.836	+ 2.768	+ 32	− 47
1034	− 4.378	+ 2.975	− 42	+ 62
858	− 4.664	+ 0.923	+ 8	+ 13
708	− 1.665	− 1.329	− 44	+ 7
713	− 3.060	− 1.855	+ 2	+ 18
788	− 3.839	− 0.575	− 2	+ 19
793	− 4.593	− 0.715	+ 136	− 20
650	− 4.821	− 2.337	+ 78	+ 48
934	− 6.290	+ 1.199	+ 29	+ 65
937	− 6.984	+ 1.380	+ 86	+ 14
1000	− 7.098	+ 2.001	− 20	− 34
866	− 8.771	+ 0.590	+ 54	− 36
943	− 9.329	+ 1.139	+ 84	+ 21
580	− 6.026	− 3.637	− 27	+ 26
730	− 7.117	− 1.721	+ 34	− 40
734	− 7.446	− 1.051	− 74	+ 33
655	− 8.014	− 2.238	− 274	+ 101
806	− 8.374	− 0.675	+ 120	− 66
−	− 2.100	+ 3.044	− 113	− 27
−	− 2.924	+ 1.777	− 41	− 70
−	− 3.655	+ 0.613	− 20	+ 13
−	− 4.399	+ 1.549	+ 135	+ 108
859	− 4.973	+ 0.530	+ 162	− 29
710	− 2.306	+ 1.077	+ 5	− 64
−	− 3.353	− 1.168	− 44	− 12
−	− 3.419	− 2.568	− 3	+ 71
790	− 4.379	− 1.024	− 44	+ 38
−	− 4.712	− 1.835	− 61	− 29
−	− 5.721	+ 1.351	− 9	+ 38
−	− 5.782	+ 0.174	− 10	− 69
−	− 6.122	+ 3.106	+ 25	− 25
−	− 7.017	+ 0.245	− 86	+ 74
941	− 8.206	+ 1.787	− 46	− 11
−	− 5.616	− 1.328	+ 109	− 8
−	− 6.148	− 2.320	− 35	− 35
726	− 6.213	− 1.462	+ 27	− 67
803	− 7.317	− 0.823	+ 124	+ 10
−	− 8.330	− 1.639	− 85	+ 93

Magnitudes of Reference Stars

(a) Catalogue plate: 12.8; 12.8; 12.2; 12.5; 12.4; 12.3; 12.6; 12.6; 12.4; 12.6; 12.3; 12.3; 12.7; 12.6; 12.4; 12.6; 12.6; 12.2; 12.5; 13.0.

(b) Chart plate: 13.5; 13.5; 13.4; 13.0; 13.2; 13.2; 13.4; 13.2; 13.2; 13.2; 13.2; 13.1; 13.2; 13.1; 12.9; 13.4; 13.4; 13.2; 13.2; 13.2.

$p_1 = 0.0017, 0.0014$ $p_2 = 0.0019, 0.0014$

Relative Proper Motion of U Cru in

(1) $\lambda_\alpha \cos\delta = +112 \pm 27$

$\lambda_\delta = -14 \pm 31$

(2) $\lambda_\alpha \cos\delta = +121$

$\lambda_\delta = -72$

Absolute Proper Motion of U Cru in

(1) $\mu_\alpha \cos\delta = +15$

$\mu_\delta = -34$

(2) $\mu_\alpha \cos\delta = +35$

$\mu_\delta = -88$

U CEN

$12^h27^m58^s.46$ $300^\circ.31$ M

$-54^\circ06' 27''.3$ $+8^\circ.12$

N_m = 60

12.00

σ_x = 63 σ_y = 55

Cat No.	ξ	η	Δx	Δy
465	+ 9.862	+ 2.096	− 72	+ 18
349	+ 9.799	− 0.534	+ 28	0
306	+ 9.046	− 1.206	− 62	+ 44
350	+ 8.837	− 0.963	− 48	+ 21
393	+ 7.157	+ 0.765	− 28	− 12
266	+10.038	− 2.789	+ 25	− 48
270	+ 8.908	− 2.674	− 67	− 37
198	+ 8.577	− 4.585	+ 120	+ 60
311	+ 7.440	− 1.878	+ 48	− 35
313	+ 7.302	− 1.642	+ 56	− 11
396	+ 6.814	+ 0.528	+ 34	+ 60
468	+ 6.340	+ 2.341	− 117	− 3
315	+ 6.042	− 1.166	+ 79	+ 72
400	+ 3.947	+ 0.776	+ 102	− 46
440	+ 3.442	+ 1.387	+ 82	− 11
273	+ 6.237	− 2.638	− 64	+ 31
321	+ 4.816	− 1.603	− 173	+ 76
234	+ 4.253	− 3.398	+ 76	+ 16
322	+ 3.763	− 1.551	+ 7	− 30
239	+ 3.094	− 3.208	− 26	− 19

Magnitudes of Reference Stars

12.0; 12.4; 11.8; 12.2; 12.2; 11.3; 11.6; 11.0; 12.4; 12.2; 12.4; 11.6; 11.5; 12.7; 12.2; 12.3; 12.3; 11.4; 11.8; 12.6.

$p_1 = 0.0020$ $p_2 = 0.0022$

Table III (continued 8)

Relative Proper Motion of U Cen in

$\lambda_\alpha \cos\delta = +106 \pm 42$

$\lambda_\delta = +170 \pm 13$

Absolute Proper Motion of U Cen in

$\mu_\alpha \cos\delta = -1$

$\mu_\delta = +144$

AL CEN

$12^h30^m32^s.82$ $300^\circ.65$ SRa

$-53^\circ03'\ 02''.3$ $+9^\circ.21$

N_m = 44, 129

11.43, 12.84

σ_x = 65, 124 σ_y = 88, 84

Cat No.	ξ	η	Δx	Δy
209	+ 5.359	+ 1.557	+ 2	− 34
211	+ 3.736	+ 1.823	+ 54	− 7
210	+ 3.652	+ 1.607	− 28	− 85
200	+ 3.259	+ 0.223	− 27	+ 18
202	+ 2.098	+ 0.361	+ 49	+ 271
178	+ 6.216	− 1.046	+ 12	− 36
159	+ 5.152	− 1.498	+ 10	− 85
109	+ 3.052	− 4.786	+ 61	− 42
131	+ 2.518	− 3.582	− 57	− 24
132	+ 2.480	− 3.901	− 55	+ 29
222	+ 0.645	+ 2.154	+ 27	+ 5
203	+ 0.206	+ 0.750	− 66	− 48
185	− 0.534	− 0.155	− 77	− 58
212	− 3.776	+ 1.235	− 21	− 12
213	− 4.193	+ 1.219	+ 91	− 44
146	− 0.751	− 2.772	− 75	+ 128
162	− 1.101	− 1.832	+ 148	+ 22
148	− 2.483	− 2.752	− 42	+ 54
150	− 3.368	− 2.265	+ 52	− 15
166	− 5.767	− 1.890	− 32	− 36
−	+ 3.530	+ 1.244	− 138	0
−	+ 2.803	+ 0.863	− 22	+ 16
−	+ 2.432	+ 0.170	− 62	+ 60
−	+ 2.233	+ 2.743	+ 28	− 44
−	+ 1.966	+ 2.272	+ 168	− 74
−	+ 4.717	− 1.176	+ 70	+ 51
−	+ 4.636	− 2.507	− 207	+ 68
−	+ 3.552	− 0.964	− 94	+ 14
−	+ 2.268	− 1.756	+ 183	− 106
−	+ 1.738	− 2.892	+ 72	+ 15
−	+ 0.843	+ 0.902	− 246	+ 124
−	+ 0.504	− 0.357	+ 15	− 48
−	+ 0.230	− 0.455	+ 94	+ 142
−	− 0.757	+ 3.170	+ 102	− 85
−	− 1.783	+ 0.669	+ 60	− 88
−	+ 0.748	− 3.274	− 94	+ 40
−	+ 0.165	+ 1.626	− 30	+ 15
−	+ 0.021	− 1.652	0	− 41
−	− 0.775	− 3.369	+ 22	+ 56
−	− 2.561	− 1.993	+ 76	− 114

Magnitude of Reference Stars

(a) 11.7; 11.8; 11.8; 11.2; 11.7; 11.6; 10.7; 11.2; 11.6; 11.0; 11.6; 10.8; 11.5; 11.6; 11.7; 11.2; 11.4; 11.8; 11.4; 11.3.

(b) 12.6; 12.6; 12.6; 12.3; 12.5; 12.7; 13.0; 12.9; 12.9; 12.7; 12.9; 13.4; 13.2; 12.7; 12.9; 12.9; 12.7; 13.0; 13.2; 13.0.

p_1 = 0.0025, 0.0016 p_2 = 0.0024, 0.0017

Relative Proper Motion of Al Cen in

(1) $\lambda_\alpha \cos\delta = +61 \pm 19$

$\lambda_\delta = -80 \pm 25$

(2) $\lambda_\alpha \cos\delta = +88 \pm 32$

$\lambda_\delta = -78 \pm 21$

Absolute Proper Motion of Al Cen in

(1) $\mu_\alpha \cos\delta = -59$

$\mu_\delta = -112$

(2) $\mu_\alpha \cos\delta = -5$

$\mu_\delta = -98$

KQ CEN

$14^h17^m37^s.85$ $313^\circ.01$ SR

$-63^\circ32'\ 32''.1$ $-2^\circ.97$

N_m = 172

12.55

σ_x = 98 σ_y = 44

Cat No.	ξ	η	Δx	Δy
−	+ 5.436	− 5.188	+ 32	− 97
−	+ 4.109	− 4.526	+ 230	+ 45
−	+ 3.780	− 4.450	− 100	+ 22
−	+ 3.421	− 6.152	− 56	− 14
98	+ 3.083	− 5.642	+ 6	− 38
−	+ 6.742	− 6.882	− 128	− 42
−	+ 4.485	− 7.855	+ 52	− 26
−	+ 3.664	− 8.323	− 97	− 2
80	+ 3.442	− 6.938	− 36	+ 26
−	+ 2.962	− 7.174	+ 97	+ 47
−	+ 1.962	− 4.633	− 14	− 34
−	+ 1.712	− 5.142	− 2	+ 22
−	+ 1.042	− 4.650	− 69	− 10
−	+ 0.846	− 5.585	− 24	+ 16
−	− 1.672	− 5.674	− 1	+ 7
−	+ 2.110	− 7.526	+ 2	− 18
85	+ 0.836	− 6.665	− 72	+ 20
−	+ 0.371	− 8.245	+ 24	− 24
−	+ 0.330	− 7.335	+ 54	− 5
−	− 2.324	− 7.348	+ 102	+ 22

Magnitudes of Reference Stars

12.9; 13.1; 12.8; 12.5; 11.4; 12.2; 12.8; 13.1; 12.2; 12.6; 13.1; 13.1; 12.6; 12.2; 13.1; 12.9; 10.0; 13.1; 13.1; 13.1.

p_1 = 0.0016 p_2 = 0.0015

Relative Proper Motion of KQ Cen in

$\lambda_\alpha \cos\delta = +91 \pm 27$

$\lambda_\delta = +57 \pm 21$

Absolute Proper Motion of KQ Cen in

$\mu_\alpha \cos\delta = +23$

$\mu_\delta = +63$

R CIR

$15^h20^m02^s.83$ $322^\circ.62$ SR

$-57^\circ22'\ 32''.8$ $-0^\circ.95$

N_m = 42, 100

11.39, 12.76

σ_x = 102, 60 σ_y = 74, 90

Cat No.	ξ	η	Δx	Δy
297	+ 6.252	+ 0.516	+ 113	− 55
212	+ 5.936	− 2.946	− 125	+ 106

Table III (continued 9)

Cat No.	ξ	η	Δx	Δy
160	+ 4.663	- 4.312	- 92	+ 20
274	+ 3.577	- 0.368	- 28	+ 15
214	+ 3.438	- 2.102	+ 104	+ 54
128	+ 9.313	- 5.594	+ 261	+ 80
159	+ 8.264	- 4.937	- 21	- 163
93	+ 4.585	- 7.417	- 36	+ 21
51	+ 4.141	- 9.270	- 174	- 78
276	+ 2.689	- 0.100	- 52	- 125
188	+ 2.011	- 3.011	- 46	- 38
215	+ 1.197	- 2.028	+ 52	+ 16
218	- 1.362	- 2.921	+ 72	+ 7
141	+ 1.909	- 5.381	- 53	+ 26
142	+ 1.541	- 5.903	- 23	+ 7
144	+ 0.462	- 5.315	+ 61	- 35
99	- 0.218	- 7.139	+ 35	+ 128
167	- 2.308	- 4.816	- 48	+ 15
* 94	+ 3.554	- 7.899	- 780	-1150
*193	- 0.424	- 3.107	+ 776	- 15
184	+ 6.154	- 3.166	- 83	+ 54
-	+ 5.880	- 3.923	+ 78	+ 8
-	+ 4.923	- 3.182	- 36	+ 60
-	+ 4.318	- 3.875	- 74	- 68
-	+ 3.914	- 2.996	- 7	- 8
-	+ 6.360	- 5.087	+ 114	- 238
-	+ 6.090	- 5.065	- 32	- 6
-	+ 4.884	- 5.193	- 10	+ 89
-	+ 5.728	- 5.766	- 33	- 52
-	+ 4.856	- 6.408	+ 93	+ 161
-	+ 2.069	- 4.054	+ 6	- 28
190	+ 1.677	- 3.265	+ 42	- 58
-	+ 1.023	- 3.167	- 54	- 92
-	+ 0.631	- 4.302	- 44	- 59
-	+ 0.240	- 3.558	+ 181	+ 190
-	+ 2.580	- 7.088	- 38	+ 2
96	+ 1.855	- 7.868	- 52	+ 90
-	+ 1.697	- 6.309	- 72	- 86
-	+ 1.174	- 6.170	+ 23	+ 38
* -	- 0.689	- 5.401	+ 656	+1294

Magnitudes of Reference Stars

(a) 11.6; 10.8; 11.2; 11.4; 11.8; 10.6;
11.2; 11.6; 10.8; 10.8; 11.6; 12.2;
11.8; 11.2; 11.8; 11.6; 11.4; 12.1.

(b) 12.3; 12.9; 13.2; 13.2; 12.7; 12.7;
12.9; 12.3; 12.5; 13.2; 12.7; 12.5;
13.4; 12.9; 12.7; 13.2; 12.5; 13.2;
12.1.

p_1 = 0.0022, 0.0015 p_2 = 0.0025, 0.0018

Relative Proper Motion of R Cir in

(1) $\lambda_\alpha \cos\delta = +185$

$\lambda_\delta = +74$

(2) $\lambda_\alpha \cos\delta = +158$

$\lambda_\delta = +66$

Absolute Proper Motion of R Cir in

(1) $\mu_\alpha \cos\delta = +124$

$\mu_\delta = -8$

(2) $\mu_\alpha \cos\delta = +113$

$\mu_\delta = +7$

TY PAV

$17^h39^m18^s.85$ $330^\circ.35$ RR

$-62^\circ33'38''.6$ $-17^\circ.09$

N_m = 70

12.13

$\sigma_x = 85$ $\sigma_y = 126$

Cat No.	ξ	η	Δx	Δy
-	+ 7.739	- 2.678	+ 46	- 40
93	+ 7.703	- 4.414	+ 45	- 40
81	+ 7.198	- 5.759	+ 149	+ 57
-	+ 6.548	- 6.343	- 180	- 54
83	+ 6.004	- 5.660	- 42	+ 104
95	+ 5.134	- 4.047	+ 30	+ 106
21	+ 7.648	- 9.249	- 12	- 316
-	+ 7.520	- 7.766	+ 140	+ 78
-	+ 6.795	- 7.144	- 38	+ 72
-	+ 5.897	- 9.166	+ 12	+ 26
-	+ 5.690	- 7.149	- 124	- 9
-	+ 5.654	- 9.698	- 15	+ 14
97	+ 4.003	- 4.856	- 62	0
68	+ 3.669	- 6.290	- 84	+ 67
-	+ 3.248	- 3.709	+ 70	- 274
69	+ 2.803	- 6.477	- 198	+ 69
98	+ 2.430	- 4.893	- 12	- 101
127	+ 1.099	- 2.965	+ 252	+ 110
42	+ 3.536	- 8.230	- 56	+ 254
43	+ 3.199	- 8.969	- 28	- 16
-	+ 2.813	- 9.148	- 14	- 140
44	+ 2.397	- 8.228	- 62	- 148
60	+ 0.501	- 7.939	+ 128	+ 193
-	+ 0.347	- 7.051	+ 52	- 9

Magnitudes of Reference Stars

11.6; 12.5; 12.0; 12.6; 11.8; 12.2; 12.6;
11.4; 12.4; 12.6; 12.8; 12.5; 12.4; 12.1;
12.4; 12.1; 11.4; 12.1; 12.0; 12.2; 12.2;
12.1; 11.8; 12.6.

p_1 = 0.0022 p_2 = 0.0021

Relative Proper Motion of TY Pav in

$\lambda_\alpha \cos\delta = -262 \pm 45$

$\lambda_\delta = -116 \pm 28$

Absolute Proper Motion of TY Pav in

$\mu_\alpha \cos\delta = -265$

$\mu_\delta = -211$

RZ PAV

$17^h40^m09^s.51$ $334^\circ.17$ M

$-58^\circ41'22''.2$ $-15^\circ.38$

N_m = 148

12.85

$\sigma_x = 63$ $\sigma_y = 170$

Cat No.	ξ	η	Δx	Δy
-	- 0.075	+ 3.928	+ 68	+ 269
-	- 0.759	+ 6.372	+ 21	- 16
-	- 1.545	+ 4.780	- 89	- 110
-	- 2.157	+ 6.756	- 51	- 115
-	+ 1.399	+ 0.824	+ 38	- 94
-	- 0.119	+ 2.430	+ 38	- 16
-	- 0.355	+ 1.786	+ 67	- 116
-	- 0.743	+ 0.832	- 80	- 62
157	- 1.815	+ 1.757	- 66	+ 314
-	- 4.296	+ 6.192	- 9	+ 28
-	- 4.659	+ 4.305	- 30	+ 128
-	- 5.713	+ 3.599	+ 6	- 90
-	- 6.408	+ 4.701	+ 111	- 14
-	- 3.070	+ 2.248	0	- 58
-	- 4.216	+ 2.413	+ 9	- 38
-	- 4.328	+ 0.942	- 12	- 50
-	- 6.267	+ 2.549	- 21	+ 39

Magnitudes of Reference Stars

13.5; 12.4; 12.8; 12.8; 12.8; 13.2; 12.4;
13.0; 12.0; 13.0; 12.8; 13.4; 13.0; 13.0;
13.2; 13.2; 12.4.

p_1 = 0.0018 p_2 = 0.0016

Table III (continued 10)

Relative Proper Motion of RZ Pav in

$\lambda_\alpha \cos\delta = -55$

$\lambda_\delta = -85$

Absolute Proper Motion of RZ Pav in

$\mu_\alpha \cos\delta = -55$

$\mu_\delta = -163$

BM PAV

$19^h19^m05^s.77$ $333^\circ.63$ SR

$-63^\circ00'46''.4$ $-28^\circ.07$

$N_m = 51$

12.60

$\sigma_x = 91$ $\sigma_y = 91$

Cat No.	ξ	η	Δx	Δy
–	+ 2.755	+ 1.353	– 38	– 10
–	+ 1.013	+ 5.385	– 1	+ 128
–	+ 0.909	+ 0.768	+ 64	– 110
115	+ 0.673	+ 2.814	+ 100	– 175
–	– 1.139	+ 0.666	– 38	+ 124
–	+ 3.679	– 1.051	– 116	+ 22
–	+ 2.482	– 2.525	– 18	– 100
–	+ 1.022	– 1.600	+ 164	– 50
–	+ 0.123	– 1.755	– 76	+ 81
63	– 0.947	– 3.875	– 42	+ 86
–	– 2.046	+ 1.545	– 4	– 14
–	– 3.255	+ 4.226	– 34	– 82
116	– 3.642	+ 2.320	+ 73	+ 32
–	– 3.532	+ 1.433	– 70	+ 46
–	– 4.698	+ 1.462	– 54	+ 58
–	– 1.652	– 1.863	+ 31	– 78
–	– 2.248	– 2.274	+ 26	– 50
–	– 4.317	– 2.200	+ 64	+ 110
–	– 6.183	– 1.440	– 32	+ 22
* –	– 3.305	+ 0.495	– 868	+1088

Magnitudes of Reference Stars

13.1; 12.9; 12.7; 12.3; 12.9; 12.5; 12.3; 12.7; 12.7; 11.6; 12.9; 12.9; 12.7; 12.1; 12.7; 12.7; 12.7; 12.1; 12.9.

$p_1 = 0.0024$ $p_2 = 0.0023$

Relative Proper Motion of BM Pav in

$\lambda_\alpha \cos\delta = -34 \pm 30$

$\lambda_\delta = +152 \pm 21$

Absolute Proper Motion of BM Pav in

$\mu_\alpha \cos\delta = +6$

$\mu_\delta = +60$

S PAV

$19^h46^m47^s.07$ $338^\circ.02$ SRa

$-59^\circ27'13''.7$ $-31^\circ.05$

$N_m = 16, 32$

11.52, 12.17

$\sigma_x = 107, 143$ $\sigma_y = 115, 173$

Cat No.	ξ	η	Δx	Δy
287	+ 6.624	+ 10.790	+ 28	+ 26
272	+ 6.018	+ 9.303	+ 101	+ 170
244	+ 5.853	+ 7.648	– 143	– 46
295	+ 5.249	+ 11.874	– 37	– 204
179	+ 5.804	+ 2.049	+ 46	– 63
181	+ 4.819	+ 1.505	– 72	+ 64
182	+ 4.449	+ 1.868	+ 44	– 34
274	+ 3.301	+ 9.990	+ 30	– 29
245	+ 2.791	+ 7.975	+ 256	– 218
234	– 0.005	+ 6.951	– 143	– 75
290	– 1.286	+ 11.096	– 77	+ 167
279	+ 1.823	+ 9.814	– 5	– 39
219	+ 4.034	+ 5.213	– 97	+ 147
209	+ 3.131	+ 4.349	– 86	+ 44
162	+ 2.163	+ 0.024	+ 77	– 78
211	+ 0.755	+ 4.277	+ 117	+ 44
183	– 0.051	+ 1.362	+ 28	– 52
243	+ 8.622	+ 8.146	+ 227	– 64
270	+ 7.533	+ 10.090	+ 75	– 28
261	+ 5.761	+ 9.174	– 328	+ 356
207	+ 8.144	+ 4.690	– 45	– 100
232	+ 0.672	+ 6.849	+ 25	– 93
246	+ 0.605	+ 7.893	– 61	– 55
277	+ 0.774	+ 9.279	– 22	+ 349
202	+ 2.554	+ 3.315	+ 11	+ 172
194	+ 1.879	+ 2.463	– 31	– 61
231	+ 1.511	+ 6.237	– 187	+ 109
*260	+ 6.885	+ 8.283	– 274	+ 854
*217	+ 6.922	+ 5.334	–1115	+1630
*218	+ 6.783	+ 5.420	–1128	+1701

Magnitudes of Reference Stars

(a) 10.8; 11.4; 11.8; 11.8; 11.8; 12.2; 11.4; 11.7; 11.6; 10.0; 11.6; 11.7; 11.0; 12.0; 11.6; 12.3; 11.8.

(b) 12.6; 12.2; 11.9; 12.7; 12.6; 11.8; 12.0; 11.4; 11.8; 11.5; 12.6; 12.4; 12.5; 12.0; 12.4; 12.2; 12.8; 12.3.

$p_1 = 0.0033, 0.0027$ $p_2 = 0.0035, 0.0027$

Relative Proper Motion of S Pav in

(1) $\lambda_\alpha \cos\delta = +277 \pm 56$

$\lambda_\delta = -267 \pm 28$

(2) $\lambda_\alpha \cos\delta = +258 \pm 40$

$\lambda_\delta = -273 \pm 50$

Absolute Proper Motion of S Pav in

(1) $\mu_\alpha \cos\delta = +333$

$\mu_\delta = -376$

(2) $\mu_\alpha \cos\delta = +308$

$\mu_\delta = -367$

W INDI

$21^h07^m14^s.81$ $344^\circ.49$ SRc

$-53^\circ26'17''.4$ $-42^\circ.59$

$N_m = 56$

12.82

$\sigma_x = 170$ $\sigma_y = 115$

Cat No.	ξ	η	Δx	Δy
–	+ 7.997	– 3.326	+ 478	– 61
–	+ 6.028	– 2.153	– 170	+ 70
–	+ 5.839	– 1.563	– 119	+ 80
–	+ 5.806	– 3.544	– 11	– 44
–	+ 5.407	– 4.048	– 170	+ 15
–	+ 3.617	– 1.206	+ 26	+ 42
–	+ 7.575	– 5.953	+ 120	+ 70
–	+ 6.756	– 8.765	– 98	+ 8
–	+ 5.929	– 6.872	– 2	– 184
–	+ 3.526	– 7.669	– 30	+ 22
–	+ 2.842	– 5.716	– 72	+ 5
–	+ 2.676	– 6.357	+ 42	– 17
–	+ 1.899	– 2.940	+ 76	– 30
–	+ 1.379	– 3.589	+ 7	– 25
–	+ 0.057	– 3.921	+ 44	+ 130
–	– 1.283	– 1.987	– 64	– 8
–	– 2.127	– 3.914	– 23	– 78
–	– 2.266	– 4.614	– 76	– 90
–	+ 1.824	– 7.019	+ 231	+ 289
–	+ 1.758	– 6.702	– 124	– 61
–	+ 0.747	– 5.837	+ 200	– 112
–	+ 0.660	– 7.455	+ 24	+ 16
–	+ 0.649	– 7.918	– 173	+ 62
–	– 3.115	– 6.134	– 118	– 92

Magnitudes of Reference Stars

12.6; 12.8; 12.7; 13.2; 12.8; 13.3; 12.6; 12.8; 12.8; 13.2; 12.8; 12.8; 13.0; 12.8; 12.7; 12.6; 12.9; 12.9; 13.1; 13.0; 11.9; 12.8; 12.8; 12.8.

Table III (continued 11)

$p_1 = 0.0027$ p_2 0.0022

Relative Proper Motion of W Indi in

$$\lambda_\alpha \cos\delta = +297 \pm 50$$
$$\lambda_\delta = -96 \pm 24$$

Absolute Proper Motion of W Indi in

$$\mu_\alpha \cos\delta = +376$$
$$\mu_\delta = -179$$

BU PAV

$21^h13^m59^s.76$	$330^\circ.87$	SR
$-63^\circ45'\ 22''.1$	-40.64	

$N_m = 17,\ 22$

11.48, 11.76

$\sigma_x = 138,\ 210$ $\sigma_y = 128,\ 180$

Cat No.	ξ	η	Δx	Δy
135	+ 1.262	+ 4.999	− 66	− 216
130	− 1.774	+ 4.378	+ 216	− 138
151	− 1.946	+ 7.536	− 148	+ 227
126	− 2.062	+ 3.900	− 111	+ 96
137	− 4.012	+ 5.859	+ 172	− 162
86	− 0.109	− 1.485	+ 38	− 120
108	− 1.660	+ 1.299	+ 308	+ 198
88	− 2.370	− 1.667	− 53	+ 115
109	− 3.408	+ 1.748	− 144	− 19
95	− 3.555	− 0.043	− 7	− 63
138	− 5.482	+ 5.215	+ 187	+ 258
147	− 6.845	+ 6.884	+ 92	− 196
132	− 8.204	+ 4.262	− 113	+ 122
139	− 8.357	+ 5.678	+ 175	− 224
140	− 10.467	+ 5.326	− 417	+ 283
103	− 5.850	+ 0.126	+ 42	− 144
74	− 6.118	− 3.888	+ 195	+ 2
110	− 6.962	+ 1.991	− 382	+ 241
80	− 10.458	− 2.391	+ 25	− 24
94	− 11.495	− 1.203	+ 201	− 203
−	+ 2.544	+ 6.896	− 281	+ 23
−	− 3.839	+ 5.091	− 184	+ 91
−	+ 2.051	− 1.231	− 20	− 112
−	− 7.013	+ 8.171	+ 70	+ 147
−	− 7.201	+ 6.366	+ 46	− 7
−	− 7.567	+ 4.714	− 37	+ 97
−	− 6.355	− 1.734	− 194	− 69
−	− 7.334	− 0.742	− 174	− 60
−	− 8.129	+ 0.082	+ 121	+ 95
* −	+ 0.541	+ 3.224	− 605	− 311

Magnitudes of Reference Stars

(a) 11.8; 12.0; 11.2; 11.0; 11.4; 11.9; 11.9; 12.0; 11.8; 11.6; 10.9; 11.2; 12.2; 11.2; 11.3; 10.9; 11.2; 11.8; 11.0; 11.6.

(b) 11.8; 12.2; 12.1; 11.0; 12.1; 11.6; 12.0; 11.9; 11.8; 12.2; 12.0; 11.6; 11.2; 11.9; 12.2; 12.3; 12.1; 11.0; 11.2; 12.2; 11.5; 11.0; 12.0; 12.8.

$p_1 = 0.0038,\ 0.0035$ $p_2 = 0.0034,\ 0.0031$

Relative Proper Motion of BU Pav in

(1) $\lambda_\alpha \cos\delta = -136$
$\lambda_\delta = +72$

(2) $\lambda_\alpha \cos\delta = -132 \pm 43$
$\lambda_\delta = -10 \pm 41$

Absolute Proper Motion of BU Pav in

(1) $\mu_\alpha \cos\delta = -40$
$\mu_\delta = -21$

(2) $\mu_\alpha \cos\delta = -44$
$\mu_\delta = -96$

Note: Both plate pairs have 14 reference stars in common.

Y IND

$21^h37^m06^s.97$	$343^\circ.30$	M
$-53^\circ11'\ 07''.6$	$-46^\circ.98$	

$N_m = 41$

12.65

$\sigma_x = 158$ $\sigma_y = 120$

Cat No.	ξ	η	Δx	Δy
85	− 3.302	− 0.639	− 190	+ 68
91	− 3.476	+ 0.506	+ 3	+ 63
77	− 4.807	− 2.138	− 17	+ 202
−	− 5.256	− 1.194	− 105	− 52
105	− 5.382	+ 1.616	+ 130	− 179
93	− 7.335	+ 0.687	− 113	− 70
−	− 4.598	− 3.591	− 158	+ 123
57	− 5.058	− 4.526	+ 189	− 130
−	− 7.072	− 3.259	+ 24	+ 172
78	− 8.069	− 2.890	− 60	− 38
−	− 8.330	− 4.133	+ 180	− 63
36	− 8.390	− 6.253	+ 114	− 94
−	− 9.398	− 1.484	+ 10	− 56
−	− 9.950	+ 1.729	0	− 48
88	− 10.360	− 0.959	− 164	+ 90
−	− 11.242	− 1.637	+ 337	+ 92
−	− 11.557	− 1.939	+ 52	− 75
−	− 11.631	− 0.385	+ 59	− 38
46	− 9.102	− 5.239	− 403	+ 279
−	− 9.860	− 5.220	− 82	− 64
−	− 10.286	− 4.872	+ 145	− 38
58	− 10.586	− 4.172	− 46	+ 52
−	− 11.767	− 3.820	+ 144	− 90
−	− 11.957	− 3.077	− 56	− 104

Magnitudes of Reference Stars

12.7; 13.1; 12.2; 13.0; 12.0; 13.0; 12.8; 12.6; 13.2; 12.0; 12.6; 12.2; 13.2; 13.2; 12.8; 12.2; 13.1; 12.2; 12.4; 13.0; 13.2; 12.0; 13.4; 12.0.

$p_1 = 0.0030$ $p_2 = 0.0025$

Relative Proper Motion of Y Indi in

$$\lambda_\alpha \cos\delta = -140 \pm 49$$
$$\lambda_\delta = +6 \pm 29$$

Absolute Proper Motion of Y Indi in

$$\mu_\alpha \cos\delta = -44$$
$$\mu_\delta = -99$$

S PHE

$23^h53^m54^s.02$	$316^\circ.97$	SR
$-57^\circ07'\ 56''.6$	$-59^\circ.09$	

$N_m = 36$

12.70

$\sigma_x = 184$ $\sigma_y = 112$

Cat No.	ξ	η	Δx	Δy
−	+ 5.800	+ 1.554	− 374	− 62
−	+ 5.706	+ 3.398	+ 206	+ 53
−	+ 2.631	+ 5.238	+ 48	+ 52
−	+ 1.955	+ 5.166	+ 66	− 107
−	+ 1.131	+ 3.175	+ 16	− 125
−	+ 6.266	− 1.862	+ 100	+ 166
−	+ 2.899	− 3.004	+ 148	+ 68
−	+ 1.917	− 3.719	− 18	− 187
−	+ 1.862	− 3.776	− 189	+ 143
−	+ 0.871	− 0.337	+ 3	− 146
−	− 0.987	+ 3.675	+ 84	− 62
−	− 1.366	+ 0.623	+ 40	+ 34
−	− 1.946	+ 2.781	− 144	+ 86
−	− 4.140	+ 3.977	+ 72	+ 154
−	− 6.255	+ 1.132	+ 170	− 96
−	− 2.744	− 2.665	+ 48	+ 48
−	− 3.297	− 1.672	− 76	+ 6
−	− 3.509	− 1.802	+ 202	+ 1
−	− 4.384	− 2.100	− 399	− 22
* −	− 6.299	− 2.641	− 564	− 298

Magnitudes of Reference Stars

12.6; 12.8; 12.8; 12.2; 12.4; 12.6; 13.0; 12.9; 12.5; 12.7; 12.8; 12.8; 13.0; 12.9; 13.0; 12.5; 13.0; 12.4; 12.6; 12.8.

$p_1 = 0.0033$ $p_2 = 0.0026$

Relative Proper Motion of S Phe in

$$\lambda_\alpha \cos\delta = -46 \pm 42$$
$$\lambda_\delta = -28 \pm 26$$

Absolute Proper Motion of S Phe in

$$\mu_\alpha \cos\delta = +71$$
$$\mu_\delta = -52$$

I woulk like to thank Dr. H. Wood for advice and criticism and Misses W. Bellamy, R. Stanfield, A. Davis, R. Bleakley and E. Wiegold for assistance in measurement and in some of the computations.

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(Received 3.12.1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 67–75, 1974

The Influence of Soil Composition on the Vegetation of the Coolac Serpentinite Belt in New South Wales

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Abstract—Plants and soils from the Coolac Serpentinite Belt, New South Wales, were analysed for calcium, cobalt, chromium, copper, iron, potassium, magnesium, manganese, nickel and zinc, in order to establish plant-soil relationships for this area and also to evaluate those principal compositional factors of the soil, which affected plant distributions. Species analysed were: *Casuarina stricta, Ricinocarpos bowmanii,* and *Xanthorrhoea australis.*

Relationships for pairs of elements in soils showed a strong mutual association of elements of the iron family (cobalt, chromium, iron, manganese and nickel). Correlation analysis of vegetation alone, showed mutual antagonism to uptake of calcium and potassium and also iron and potassium. The only highly significant plant-soil association is for zinc in *C. stricta* and none of the other species therefore appeared to be useful in biogeochemical prospecting.

Discriminant analysis of the soil data, showed that *X. australis* strongly favours soils high in magnesium and low in copper, whereas the distribution of *C. stricta* appeared to be controlled mainly by the high potassium and nickel values in the soils. There is little evidence for any soil factors controlling the distribution of *R. bowmanii.*

Introduction

There is a very extensive literature on the so-called " serpentine problem " (Brooks, 1972; Krause, 1958; Kruckeberg, 1954; Lee *et al.*, 1974; Lyon *et al.*, 1968, 1970, 1971; Paribok and Alekseyeva-Popova, 1966; Robinson *et al.*, 1935; Rune, 1953; Sarosiek, 1964; Walker, 1954; Walker *et al.*, 1955). This problem arises from the general infertility of serpentine soils and is believed to be due to three main causes. According to Robinson *et al.* (1935), Rune (1953), and Louanamaa (1956), the infertility of serpentine soils arises from the toxic levels of chromium and nickel. Other workers such as Walker (1954), Kruckeberg (1954) and Walker *et al.* (1955), consider that the main limiting factor is the low level of available calcium and this is further aggravated by the antagonistic effect of high magnesium levels which hinder uptake of calcium by vegetation. The third factor is said to be the low levels of essential nutrients in serpentine soils (Paribok and Alekseyeva-Popova, 1966; Robinson *et al.*, 1935). Other workers (Sarosiek, 1964) consider that successful colonizers of serpentine soils have been able to adapt simultaneously to all and not merely one or several of the unfavourable factors of a serpentine environment.

In September 1973, an investigation was carried out on a serpentine flora near Tumut, New South Wales. The purpose of this study was the examination of plant-soil relationships in the area in order; (a) to search for nickel accumulators (Brooks, 1972; Severne and Brooks, 1972); (b) to determine the suitability of the flora for biogeochemical prospecting (Brooks, 1972); and above all, (c) to determine the soil factors primarily responsible for the distribution of typical members of the serpentine community, with a view to attempting to solve the serpentine problem for this particular area. The results of the investigation are reported in this paper.

The Coolac Serpentinite Belt

Location and physiography

The Coolac Serpentinite Belt (Adamson, 1957; Ashley *et al.* 1971; Boots, 1968; Golding, 1966, 1969; Veeraburus, 1963) is located some 450 km. southwest of Sydney near the township of Tumut. The belt is a continuous outcrop of ultrabasic rocks over a distance of 55 km. in a north-south direction and with an average width of 1 km.

The region traversed by the belt is broadly divisible into three physiographic zones (Ashley *et al.*, 1971). The eastern zone consists largely of a dissected plateau with an elevation of about 900 m. and is underlain by Burrinjuck granite. The central zone, the Coolac Serpentinite Belt, is a zone of major tectonism which largely coincides with ridges and scarps of the Mooney Mooney Range in the north and the Honeysuckle Range in the south. The western zone is underlain by lower palaeozoic sedimentary volcanics and low-grade metamorphic rocks, folded about sub-meridional axes and locally intruded by porphyrites and in the south, by Bogong granite.

The study area is located in the southern half of the serpentinite belt in the Honeysuckle Range where it is traversed by Brungle Creek.

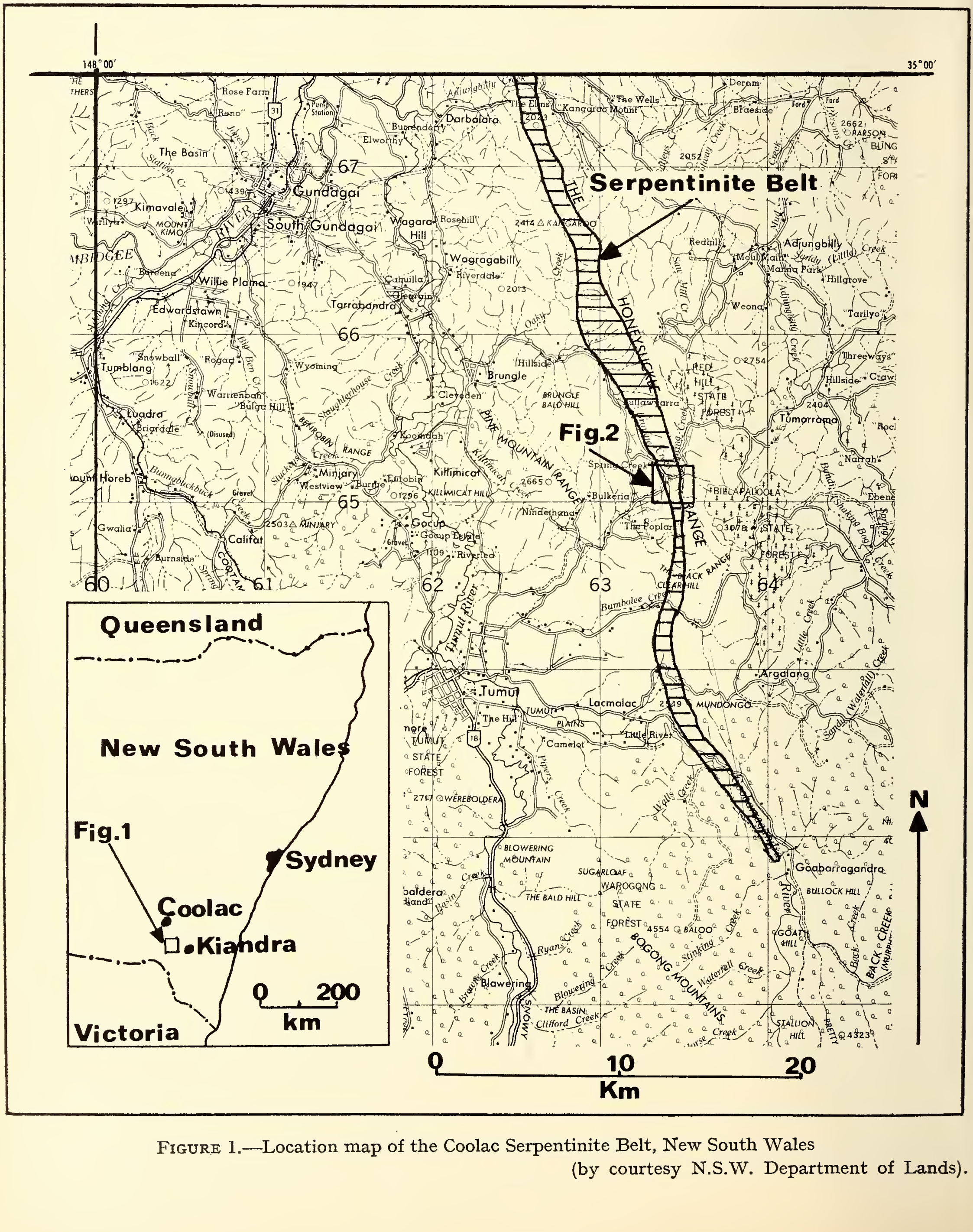

FIGURE 1.—Location map of the Coolac Serpentinite Belt, New South Wales (by courtesy N.S.W. Department of Lands).

Geology

The dominant rocks of the Coolac Serpentinite Belt (Ashley *et al.*, 1971; Golding, 1969) are serpentinite and partly-serpentinized harzburgite. There are also widespread pockets of wehlite, lherzolite, clinopyroxenite and chromite, together with narrow discontinuous dykes of rodingitic rocks.

Along the eastern contact with the Burrinjuck Granite, there is a zone of brecciated granite up to several meters wide abutting peridotite in the Honeysuckle Range. The most common rock type forming the granite, is massive to foliated biotite granodiorite, grading to adamellite.

The western margin of the serpentinite belt is flanked by the Honeysuckle Beds which are a discontinuous series of low-grade metabasaltic and spilitic rocks with quartzofeldspathic metasediments and rare porphyritic metadacite.

Climate

The study area has a cool temperate climate with mild to warm summers and cold winters. Mean summer and winter temperatures are 21° C in January and 5° C in July. The mean annual rainfall is 1023 mm with a maximum of 108 mm in July and a minimum of 57 mm in February. Frosts are widespread and can occur over approximately half the year.

Vegetation

The outline of the Coolac Serpentinite Belt is well defined in those areas where the original vegetation still remains. To the east of the study area (Figure 2), the Burrinjuck Granite supports a comparatively dense eucalypt woodland with a dominance of *Eucalyptus melliodora.* At the boundary with the serpentinite, there is a sharp change of vegetation with no species (except for a few grasses) being common to both geological formations. At this contact, the eucalypt woodland gives way to a typically xerophytic vegetation assemblage with a paucity of numbers of species, diminution of total cover (from 100% to about 40%) and with the appearance of species with needle-like leaves.

Table 1 is a list of the major species encountered upon the serpentinite belt. It does not include herbs or grasses.

The most typical plants of the serpentine flora are: *Casuarina stricta, Ricinocarpos bowmanii,* and *Xanthorrhoea australis.*

South of Brungle Creek and to the west of the belt, there is no clear-cut vegetation boundary because the original cover has been cleared and

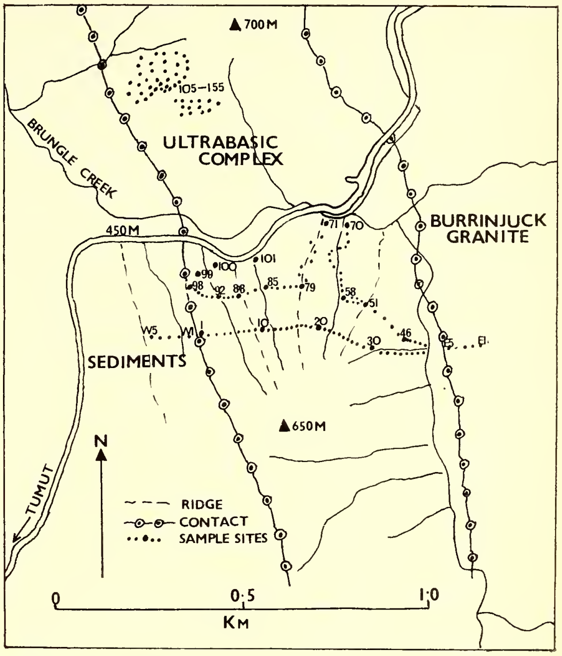

FIGURE 2.—Detailed map of the Brungle Creek area, Coolac Serpentinite Belt, New South Wales.

replaced with pasture. It is interesting to observe however, that the boundary between pasture and uncleared bush, corresponds exactly with the geological boundary. Presumably the ultrabasic area was never cleared because of the difficulty of growing suitable pasture grasses upon it.

X. australis was found only to the north of Brungle Creek and not a single specimen was

TABLE 1

List of Major Plant Species Growing upon the Coolac Serpentinite Belt

Species	Family	Relative Abundance
Acacia decora Reichb.	leguminaceae	4
Acacia implexa Benth.	leguminaceae	2
Banksia marginata Cav.	proteaceae	1
Casuarina stricta Ait.	casuarinaceae	4
Clematis microphylla D.C.	ranunculaceae	3
Exocarpus cupressiformis Labill. ..	santalaceae	1
Ricinocarpos bowmanii F. Muell.	euphorbiaceae	5
Stackhousia sp. ..	stackhousiaceae	1
Xanthorrhoea australis R. Br.	xanthorrhoeaceae	4

5—extremely abundant; 4—abundant; 3—fairly abundant; 2—uncommon; 1—rare.

recorded in the south of the test area. To the north, there is some evidence of clearance of the original vegetation cover, but nevertheless *R. bowmanii* and *C. stricta* are still to be found in abundance.

Xanthorrhoeas and casuarinas seem to be typical of serpentine floras in Australia as they are found in ultrabasic belts in other parts of the country including Baryulgil in northern New South Wales. Casuarinas are also typical of ultrabasic areas throughout Oceania as for example in New Caledonia (Baumann-Bodenheim, 1956 ; Jaffré, 1973) and in the Solomon Islands (Krause, 1958).

Methods

Collection and treatment of samples

Plants and soils were collected according to the sampling pattern shown in Figure 2. Leaves (about 100 g) were removed from different parts of each specimen by means of pruning shears and were stored in numbered polythene bags. A soil sample (100 g) was taken from the B horizon below each plant sampled, and was also stored in a numbered polythene bag. Rock chip samples were also collected.

Plant samples were washed, dried at 105° C, weighed, and then ashed at 500° C in pyrex beakers by means of a muffle furnace. The weight of the ash was recorded in order to obtain a factor to convert concentration data from an ash-weight to a dry-weight basis if desired.

Soil samples were air dried and sieved to —80 mesh particle size by means of a nylon sieve.

Rock chips were ground in a " Tema " disc mill to —100 mesh size.

Chemical analysis

Plant ash samples (0·1 g) were dissolved in 15 ml of 2M hydrochloric acid prepared from redistilled, constant-boiling, analytical-grade reagent. The containers were immersed in boiling water for 10 min. in order to ensure complete dissolution of the plant ash.

Soil and rock samples (0·1 g) were treated with 10 ml. of a 1 : 1 mixture of concentrated A.R. grade hydrofluoric and nitric acids. The mixtures were taken to dryness in 50 ml squat polypropylene beakers immersed in a water bath maintained at 100° C. The residues were redissolved in 10 ml. of 2M hydrochloric acid prepared as above.

All solutions were analysed by flame photometry for potassium and by atomic-absorption spectrophotometry for : calcium, chromium, cobalt, copper, iron, magnesium, manganese, nickel and zinc.

Analyses were carried out by use of a Varian-Techtron AA5 instrument. Possible effect of phosphate interference upon calcium determinations was avoided by the addition of lanthanum chloride to the solutions.

Statistical analysis

Elemental associations were determined by computing Pearson Product Moment Correlation Coefficients for various pairs of variables. All data were logarithmically transformed since visual observation of the data showed that distributions are closer to a log-normal rather than normal mode. In assessing the significance of correlation coefficients, the convention used is that of Brookes *et al.* (1966) : namely** =very-highly significant ($p<0 \cdot 001$) ; and *=highly significant ($0 \cdot 001<p<0 \cdot 01$). Values of the correlation coefficient with significances less than 99% ($p<0 \cdot 01$) have not been listed.

Discriminant analysis was carried out by classifying each soil sample into one of three groups depending on which of the three species of vegetation was growing in it. A discriminant function of the form : $Z=1_1X_1+1_2X_2 \ldots 1_kX_k+$CONSTANT, was then calculated for each soil group where : Z is the score of the discriminant function, $X_1 \ldots X_k$ are the variablse measured (elemental concentrations in soils), and $1_1 \ldots 1_k$ are appropriate coefficients. The coefficients were selected so that the differences of values of Z were maximized. The extent of this degree of discrimination was measured by the so-called Mahalanobis D^2 statistic (Mahalanobis, 1936), which is in effect a measure of the " distance " between the groups. A similar procedure was used by Nielsen *et al.* (1973) for evaluation of geobotanical and biogeochemical data from Western Australia.

All statistical calculations were carried out by means of a Univac 1108 computer with programmes written in Fortran.

Results and Discussion

Elemental relationships in soils

Table 2 summarizes the data for elemental concentrations in soils of the serpentinite belt. Data for a small number of rocks are also included for comparison. The general levels for most elements are in the expected range for serpentine soils developed in temperate climates and correspond very closely for values obtained in New Zealand (Lee *et al.*, 1974). Cobalt, chromium, nickel and magnesium have the usual high values and the macronutrients calcium and potassium are characteristically low.

TABLE 2

The Elemental Content of Serpentine Rocks and Soils of the Coolac Serpentinite Belt

Element	Soils (138 samples)		Rocks (12 samples)
	Geometric Mean	Standard Deviation Range	Geometric Mean
Co (ppm) ..	205	172–246	119
Cr (ppm) ..	1,496	1,176–1,903	1,706
Cu (ppm) ..	22	13–37	19
K (ppm) ..	1,582	1,241–2,015	252
Mn (ppm) ..	1,654	1,404–1,948	913
Ni (ppm) ..	1,984	1,660–2,373	2,167
Zn (ppm) ..	54	47–62	66
Ca (%)	0·49	0·40–0·61	2·80
Fe (%)	10·27	8·87–11·91	6·56
Mg (%)	7·58	6·43–8·93	18·80

Interelemental relationships in soils alone, are summarized in Table 3 in terms of values for correlation coefficients and their degrees of significance for various pairs of variables.

As may be expected, there is strong mutual correlation of elements which are indicators of the basic character of rocks and soils (magnesium and members of the iron group of the periodic table). Iron has a strong positive correlation with cobalt, chromium, manganese and nickel. Magnesium is inversely correlated with the nutrients copper and potassium. This is an important factor in assessing the fertility of these soils. In this are at least, it appears that the higher the magnesium content, the lower the concentration of the above nutrients. When this factor is compounded by the known mutual antagonism of calcium and magnesium in plant nutrition (Mulder, 1953), it is clear that this environment will be particularly hostile to growth of vegetation.

TABLE 3

Elemental Correlations in Plants and Soils

	Ca	Cr	Cu	Fe	K	Mg	Mn	Ni	Zn
					Soils (138)				
Ca	—	—	—	−0·41**	—	—	—	—	—
Co	−0·47**	0·54**	—	0·79**	—	0·33**	0·63**	0·70**	—
Cr	−0·33**	—	−0·35**	0·63**	—	—	0·36**	0·42**	0·31*
Cu	—	—	—	−0·26*	—	−0·26*	—	—	0·43**
K	−0·32*	—	—	—	—	−0·36**	—	−0·25*	0·25*
Mn	−0·29*	—	—	0·63**	—	—	—	0·28*	0·34**
Ni	−0·44**	—	—	0·48**	—	0·33**	—	—	—
Zn	—	—	—	0·26*	—	—	—	—	—
					C. stricta (46)				
Ca	—	—	—	—	−0·41*	—	—	—	—
Cr	—	—	—	0·81*	—	—	—	0·37*	—
Cu	—	—	—	—	—	—	—	0·67**	0·37*
Zn	—	—	—	—	0·37*	—	—	—	—
					R. bowmanii (42)				
Ca	—	—	—	—	−0·49**	—	—	—	—
Cr	—	—	—	0·77**	—	—	—	—	—
Cu	—	—	—	—	—	0·50**	—	0·70**	—
Mn	—	—	—	—	—	—	—	—	0·45*
Ni	—	—	—	—	—	0·63**	—	—	—
Zn	—	—	—	—	—	—	—	—	0·46*
					X. australis (43)				
Ca	—	—	—	—	−0·41*	—	—	—	—
Cr	—	—	—	0·66**	—	—	—	—	—
Cu	—	—	—	—	0·44*	—	—	—	—
Fe	—	—	—	—	−0·49**	—	—	—	—
Mn	—	—	—	—	—	—	—	0·39*	—
Zn	—	—	—	—	—	0·47**	—	—	—

** Very highly significant ($p<0·001$).

* Highly significant ($0·01>p>0·001$).

TABLE 4

The Elemental Content of the Ash of Plants of the Coolac Serpentinite Belt

Species	No.	Ash Wt.-Dry Wt. Factor	Element	Geometric Mean	Standard Deviation
C. stricta ..	46	0·041	Cr (ppm)	42	27–65
			Cu (ppm)	74	50–109
			Fe (ppm)	4,650	2,831–7,636
			Mn (ppm)	1,561	1,067–2,284
			Ni (ppm)	474	334–672
			Zn (ppm)	609	418–888
			Ca (%)	22·1	17·6–27·7
			K (%)	5·3	3·6–7·9
			Mg (%)	8·4	6·1–11·6
R. bowmanii ..	42	0·036	Cr (ppm)	48	30–79
			Cu (ppm)	148	103–212
			Fe (ppm)	6,920	4,678–10,239
			Mn (ppm)	1,941	1,361–2,769
			Ni (ppm)	751	503–1,121
			Zn (ppm)	307	237–396
			Ca (%)	21·3	15·9–28·6
			K (%)	4·6	3·3–6·5
			Mg (%)	7·6	5·3–10·8
X. australis ..	43	0·021	Cr (ppm)	27	19–39
			Cu (ppm)	77	62–95
			Fe (ppm)	2,448	1,519–3,946
			Mn (ppm)	1,715	1,118–2,631
			Ni (ppm)	271	179–409
			Zn (ppm)	519	320–843
			Ca (%)	13·4	9·7–18·4
			K (%)	6·4	4·1–9·9
			Mg (%)	14·0	10·2–19·2

Elemental relationships in vegetation

Table 4 lists elemental concentrations in plants from the Coolac Serpentinite Belt.

Correlation coefficients and significance value are also shown in Table 3 for interelemental relationships in vegetation considered separately. Relationships are far fewer than in soils but there is a general trend towards positive correlation of iron and chromium and for copper and nickel.

There is an inverse relationship (i.e. mutual antagonism) between calcium and potassium in all three species. Iron is also strongly antagonistic to potassium in *X. australis*. This same element is also weakly antagonistic to potassium in *C. stricta* ($0{\cdot}05 > p > 0{\cdot}01$—data not shown in Table 3).

Plant-soil relationships for individual elements

Plant-soil relationships for individual elements were studied with a two-fold purpose: (a) to determine whether any of the vegetation species would be suitable for biogeochemical prospecting (Brooks, 1972), and (b) to ensure that inter-elemental relationships discussed above, were in fact real antagonisms or stimulations and not merely a reflection of associations already existing in the soils alone. For example, the strong antagonism between calcium and potassium in all three species, would not be a real effect if an inverse relationship already existed between these two elements in the soil and if in addition, there were direct plant-soil relationships for calcium and potassium considered separately. Inspection of Table 3 shows that there is indeed a weak calcium-potassium association in soils, but there is no significant plant-soil relationship for either of these elements in any of the three species studied. The relationship in soils therefore cannot be transmitted to the vegetation and the mutual antagonism found in the plants must be real for this pair of elements.

Correlation analysis showed that with one exception, there are no highly-significant ($0{\cdot}01 > p > 0{\cdot}001$) plant-soil relationships for any element in any species. The exception is for zinc in *C. stricta* for which the value of the correlation coefficient is 0·46*. With this exception therefore, none of the species is suitable as an alternative to soil sampling in geochemical prospecting work. The suitability of the plants for biogeochemical prospecting has not of course, been fully evaluated since the criterion of acceptability is how well vegetation reflects bedrock values compared with soils used for the same purpose. A complete analysis of bedrock values was outside the scope of this investigation because of the difficulty of obtaining meaningful samples of the bedrock.

Evaluation of soil factors affecting plant distributions

Discriminant analysis was used to characterize the specific compositional characteristics of the group of soils in which each plant species is growing. The procedure has been described above. Having obtained from the discriminant (regression) equation, the overall chemical characteristics of each soil group, the model was tested by using it to assign each soil sample to a specific group and then comparing the theoretical result with the actual assignation. A high score in this procedure, would indicate the correctness of the model pioposed and would enable an evaluation of the compositional factors affecting the distribution of each plant species.

Table 5 lists the elemental content of each of the three groups of soils and a preliminary visual inspection shows that soils supporting *X. australis* usually have appreciably lower copper and nickel contents and a higher magnesium concentration than the serpentine soils as a whole. The other two groups are less well differentiated from each other.

Table 6 shows that as might be expected, the best overall discrimination is obtained by using all ten elemental concentrations (D^2=246·9). If calcium, cobalt, chromium, iron and manganees are neglected (since they have approximately the same mean concentrations in all three soil groups), the overall discrimination is poorer (D^2=154·9), though that for group 3 is improved and for group 2 is worsened. Further discrimination tests were carried out using various combinations of three, taken from the five best discriminators.

Easily the best discrimination for group 1 (*C. stricta*) was obtained with the trio copper-potassium-zinc (62%). Inspection of Table 5 shows that this group is separated almost completely from group 3 (*X. australis*) by its higher copper content. It also has the highest potassium and nickel content of any group.

Discrimination for group 2 (*R. bowmanii*) is never very good. The best results were obtained with copper-nickel-magnesium (41%). Since a random assignation of soils would in any case give a discrimination of 33%, it cannot be said that successful discrimination of group 2 has been achieved.

Examination of the data for group 3 (*X. australis*), shows a very successful degree of discrimination which includes 92% for potassium-magnesium-nickel and 88% for copper-nickel-magnesium. Magnesium, which occurs in both combinations, has substantially the highest value in group 3. *X. australis* also seems to favour soils with the lowest copper, nickel and potassium values. The low copper concentration alone, is almost sufficient to discriminate group 3 from the others.

The role that magnesium plays in controlling the distribution of *X. australis* is further indicated in Table 4, which shows that the mean magnesium content of ashed leaves of this species (14·0%) is nearly double that of the others. The propensity of plant indicators to

TABLE 5

The Elemental Content of Three Soil Groups from the Coolac Serpentinite Belt

Element	1 *C. stricta* (45)		2 *R. bowmanii* (44)		3 *X. australis* (49)	
	G. Mean	Std. Dev.	G. Mean	Std. Dev.	G. Mean	Std. Dev.
Co (ppm) ..	205	166–253	207	169–253	204	180–231
Cr (ppm) ..	1,444	1,109–1,882	1,495	1,104–2,023	1,545	1,357–1,760
Cu (ppm) ..	27	17–41	28	18–45	15	10–22
K (ppm) ..	1,660	1,277–2,157	1,581	1,207–2,070	1,515	1,255–1,828
Mn (ppm) ..	1,640	1,324–2,030	1,623	1,373–1,918	1,694	1,541–1,863
Ni (ppm) ..	2,107	1,754–2,530	2,056	1,727–2,445	1,819	1,573–2,103
Zn (ppm) ..	57	49–65	56	49–64	51	46–56
Ca (%) ..	0·47	0·38–0·58	0·48	0·37–0·62	0·52	0·45–0·60
Fe (%) ..	9·96	8·54–11·62	10·21	8·57–12·18	10·62	9·59–11·77
Mg (%) ..	7·27	6·06–8·72	7·30	6·32–8·43	8·15	7·08–9·38

TABLE 6

Values for the Mahalanobis D^2 Statistic and the Degree of Discrimination (number of correct assignations) for Soil Groups Associated with Individual Plant Species

Variables	D^2	1 (*C. stricta*)	2 (*R. bowmanii*)	3 (*X. australis*)	Total
Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Ni, Zn	246·9	24	22	45	91
Cu, K, Mg, Ni, Zn	154·9	27	15	44	86
Cu, Ni, Mg	122·8	23	18	43	84
Cu, K, Ni	119·1	28	16	41	85
Cu, Ni, Zn	90·3	21	13	38	72
Mg, Ni, Zn	87·4	25	14	39	78
K, Mg, Ni	72·3	24	12	45	81
Cu, Mg, Zn	63·1	21	11	40	72
Cu, K, Zn	61·2	20	19	38	77
Cu, K, Mg	53·5	21	16	39	76
K, Ni, Zn	51·7	25	12	37	74
K, Mg, Zn	38·8	21	14	36	71
Total number of soils	—	45	44	49	138

accumulate the element or elements which they indicate, has been well established in the literature, particularly for serpentine plants and especially for nickel (Severne and Brooks, 1972) and magnesium (Lee *et al.* 1974). For example, Lee *et al.* (1974) in studies on the Dun Mountain Serpentinite Belt, New Zealand, have shown that the serpentine endemics *Myosotis monroi* and *Pimelea suteri* have a two-fold higher magnesium content (16·3% and 14·9% respectively) than any other plants of the area.

X. australis is also characterized by a lower calcium content than the other species. This is in accordance with the general principle that plant species with the lowest calcium/magnesium ratios are the most successful colonizers of serpentine environments (Krause, 1958).

Conclusions

It is concluded that the Coolac Serpentinite Belt is a typical ultrabasic environment with the usual strong associations of elements of the iron group of the periodic table. The soils are characteristically low in the macronutrients calcium and potassium.

None of the plants studied seems to be suitable for biogeochemical prospecting for elements such as chromium, copper and nickel. All three species showed typical mutual antagonism patterns for uptake of calcium and potassium thus aggravating other hostile features of this environment.

Soil chemical factors do not appear to affect the distribution of *R. bowmanii* to any extent, whereas the distribution of *C. stricta* appears to be controlled largely by higher potassium and nickel values. It is concluded however, that the distribution of *X. australis* is strongly influenced by the chemical composition of the soil, particularly with regard to the magnesium content. It seems that this species may be tolerant to high magnesium levels in the soil. This tolerance to magnesium is reflected in the very high concentrations of this element in the plant ash, a level that is at least twice as high as in other species studied. High uptakes of magnesium are typical of serpentine endemics and although *X. australis* cannot be considered endemic in serpentines in New South Wales, it is nevertheless, a characteristic plant of ultrabasic complexes in this state and is probably a useful indicator plant in this connection. The species will merit further investigations into its role as an indicator.

Acknowledgements

The authors wish to thank Professor L. E. Smythe and the School of Chemistry of this University, for transport and research facilities to support this investigation; Dr. T. Howard and Mr. J. T. Waterhouse of the School of Botany of this University and also the staff of the Herbarium of the Royal Botanic Gardens, Sydney, for identification of plant species; Dr. H. G. Golding of the School of Applied Geology of this University for valuable advice and identification of rock samples; Mr. G. Windsor of the Forestry Commission of New South Wales, Tumut, for maps and other information; and Mr. G. N. Baur of the New South Wales Forestry Commission, Sydney, for providing climatological data.

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(Received 3.12.1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 76–86, 1974

The Carboniferous Non-Marine Stratigraphy of the Paterson-Gresford District, New South Wales

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Abstract—Non-marine units in the Paterson-Gresford district comprise part of the Flagstaff Sandstone and the classical succession of Gilmore Volcanics, Mt. Johnstone Formation, Paterson Volcanics and Seaham Formation. The units range in age from late Early Carboniferous to Late Carboniferous, and were deposited on a piedmont plain which gradually prograded northwards into a marine area of deposition. The Gilmore Volcanics are subdivided into the Newtown and Mowbray Formations (new names). Ignimbrites in the lower part of the sequence have been mapped out and defined as members. A non-marine portion of the Flagstaff Sandstone contains the Mount Rivers Ignimbrite Member (new name), the Newtown Formation the Martins Creek and Vacy (new name) Ignimbrite Members, and the Mowbray Formation the Breckin and Lambs Valley (new names) Ignimbrite Members. Erosion of the Lambs Valley Ignimbrite at the top of the Mowbray Formation and a change in sediment colour from red or purple in the Mowbray Formation, to yellow in the Mt. Johnstone Formation indicates a hiatus between the two units. Rocks in the Paterson-Gresford District are folded into basinal structures in the south-west near the Hunter Thrust, and into more open north-westerly trending folds in the north-east. Faults, which mainly have a steep reverse component, extend north-eastwards normal to the Hunter Thrust but swing towards the north at Gresford.

Introduction

The Paterson-Gresford district is located in the Lower Hunter Valley, New South Wales, between the townships of Paterson and Gresford (Figure 1). Paterson is situated on the Paterson River 15 km north of Maitland, and the village of Gresford lies between the Paterson and Allyn Rivers 20 km farther to the north. Recent geological mapping in the district has clarified stratigraphic relationships within the Carboniferous sequence, and has revised previous mapping by Sussmilch and David (1920), Osborne (1922, 1950) and Roberts (1961).

The Carboniferous rocks of the Paterson-Gresford district comprise an Early Carboniferous marine sequence which intertongues with and is overlain by a terrestrial sequence ranging in age from late Early to Late Carboniferous. They now constitute a belt of basins and folds, trending in a north-westerly direction, which are dislocated by faults extending in a north-easterly direction normal to the Hunter Thrust. This paper describes the terrestrial part of the Carboniferous succession and includes the definition of a number of new units. The Mount Rivers Ignimbrite Member is described from a non-marine part of the Flagstaff Sandstone, and the Gilmore Volcanics are subdivided into the Newtown and Mowbray Formations. The Newtown Formation contains the Vacy Ignimbrite Member, and the Mowbray Formation the Lambs Valley and Breckin Ignimbrite Members.

Stratigraphy

The carboniferous sequence in the Paterson-Gresford district has been described by Osborne (1922) and Roberts (1961). A summary of the stratigraphic succession was given by Campbell

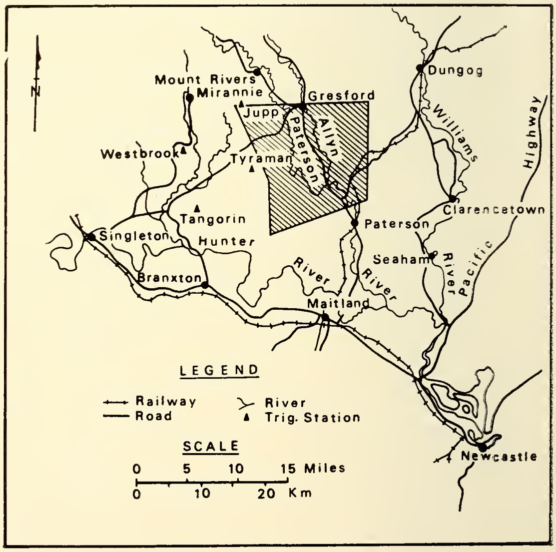

Figure 1.—Locality map.

et al. (*in* Packham, 1969). This paper deals with the succession above the Bonnington Siltstone and is concerned mainly with the subdivision of the Gilmore Volcanics and the definition of Ignimbrite Members within the terrestrial portion of the Flagstaff Sandstone and within the Newtown and Mowbray Formations.

Early Carboniferous units, of predominantly marine origin, were defined from the Gresford district by Roberts (1961). The lithological characters of these formations may be summarized as follows:

Flagstaff Sandstone: 1,250 m. Coarse lithic sandstone. South-east of Gresford three sedimentary units are recognized within the formation:

(1) lithic sandstone and pebbly lithic sandstone, siltstone and impure limestone (at the base of the succession);

(2) interbedded mudstone and lithic sandstone;

(3) massive lithic sandstone with interbedded ignimbrite (Mt. Rivers Ignimbrite Member) or devitrified ash fall tuff.

Bonnington Siltstone: 265 m. Hard blue-grey siltstone, mudstone and minor limestone.

Ararat Formation: 730 m. Fine to coarse lithic sandstone with subordinate mudstone, oolitic limestone and conglomerate. South of Gresford the formation contains the Glenroy, Gresford and Trevallyn Conglomerate Members. An ignimbrite underlies the uppermost (Trevallyn) conglomerate.

Bingleburra Formation: 350 m+. Regularly bedded mudstone, silty sandtone, and minor limestone (base of sequence).

In the Paterson-Gresford district the Flagstaff Sandstone is overlain by the non-marine Wallaringa Formation and succeeding terrestrial units (Figure 2). Farther northwards, away from the influence of prograding terrestrial sedimentation, the Flagstaff Sandstone is overlain by an unnamed marine unit of late Visean age (Roberts and Oversby, 1973).

Sediments in the blocks bounded by the Bingleburra and Camyr Allen Fault System were previously identified as Bingleburra Formation (Roberts, 1961). A re-assessment of the stratigraphy of the Gresford district by Roberts during 1970, and by Hall during 1972 indicates that these rocks were mis-correlated. The Bingleburra Formation is restricted to a narrow band of outcrop in the east, where it is faulted against a sliver of Bonnington Siltstone along the Bingleburra Fault. The Ararat Formation contains three conglomerate markers; it overlies the Bingleburn Formation and passes upwards into the Bonnington Formation. A fault extending between the Camyr Allen Fault System and the Bingleburra Fault appears to repeat the Bonnington Siltstone west of the Gresford-Vacy Road. Stratigraphic details of marine units in the Gresford district will be given in a forthcoming paper (Roberts, in preparation).

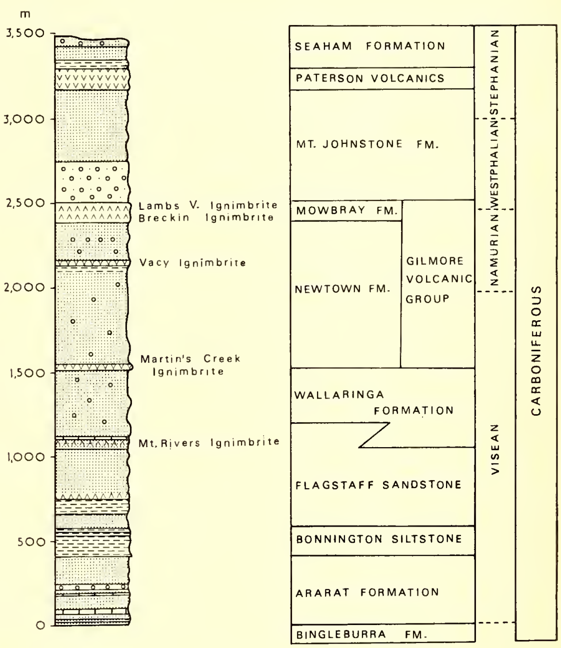

FIGURE 2.—Composite stratigraphic column showing formations in the Paterson Gresford district.

Flagstaff Sandstone

In the type section in the Lewinsbrook Syncline, 10 km north-east of Gresford, the Flagstaff Sandstone consists of coarse grained thickly bedded green lithic sandstone, some of which is tuffaceous, and minor grey siltstone (Roberts, 1961); the unit is 1,250 m thick. North of Gresford the Flagstaff Sandstone lies between the Bonnington Siltstone and an unnamed unit which in the Salisbury district contains brachiopods of the *Rhipidomella fortimuscula* Zone (Roberts and Oversby, 1973).

The lowermost beds of Flagstaff Sandstone in the Paterson-Gresford district are exposed in the core of the Hilldale Anticline at Greenhills near Hilldale. These sediments comprise coarse grained lithic sandstone, grey siltstone, and impure limestone (Roberts, 1964). Fossils from the lowermost beds were originally assigned to the *Orthotetes australis* Zone by Roberts (1965). Recent biostratigraphical investigations in the Salisbury and Brownmore districts, 30 km to the north, indicate that this fauna is either transitional with or is the lowermost part of the *Delepinea aspinosa* Zone (Roberts, 1975). The *aspinosa* Zone is positively identified from slightly higher in the sequence at Greenhills by the presence of the index species and *Productina* sp.

On the southern limb of Hilldale Anticline the lowermost unit of Flagstaff Sandstone is overlain by interbedded mudstone and sandstone mapped as Member A, an informal unit, of the Flagstaff Sandstone. Member A forms subdued countryside beneath the steep scarp of Mt. Ararat, and has been identified in the valleys of the Paterson and Allyn Rivers, north-west and north of Gresford (Roberts, Gresford 1 : 50,000 geological map in preparation). Member A is overlain by thickly bedded green and brown lithic sandstone and conglomerate which near Gresford contains the Mount Rivers Volcanic Member, and at Mt. Ararat devitrified ash fall tuffs. Brachiopods from the lower part of the *Delepinea aspinosa* Zone are present in Member A at Toryburn (Dungog 595855).

West and south-west of Gresford, Member A is overlain by yellow-brown lithic sandstone, conglomerate, plant-bearing siliceous siltstone and two ignimbrites. The ignimbritic part of the succession is mapped as the Mount Rivers Ignimbrite Member of the Flagstaff Sandstone. The welded nature of the ignimbrites and quantity of plant debris in some of the associated siltstone indicate a terrestrial environment of deposition. The ignimbrites are restricted to the north-western part of the Gresford-Paterson district (Figure 1). In this area the boundary between the Flagstaff Sandstone and the Wallaringa Formation is taken at the transition between greenish-yellow and red lithic sandstone. In the south-east, the boundary is taken at the base of a distinctive green and red water distributed lithic tuff.

Age of the Flagstaff Sandstone

Brachiopod faunas from the Flagstaff Sandstone belong to the *Delepinea aspinosa* Zone (Roberts, 1975 ; Jones, Campbell and Roberts, 1973). The oldest fauna, from the core of the Hilldale Anticline at Greenhills may be transitional between the *Orthotetes australis* and *Delepinea aspinosa* Zones, but it is almost immediately overlain by a fauna which can definitely be assigned to the *aspinosa* Zone (Roberts, 1975).

The *aspinosa* Zone is dated as Cu III_α in terms of the German ammonoid zones (Jones, Campbell and Roberts, 1973). The Flagstaff Sandstone can therefore be informally correlated with the middle to late Visean. Roberts and Oversby (1973) termed the unit middle Visean for the purpose of palaeogeographic reconstructions, but did not imply a direct correlation with the Visean zones of Belgium.

Most faunas from the Paterson-Gresford district represent a level low in the *aspinosa* Zone. This suggests that non-marine sedimentation commenced earlier in this district than in the Wallarobba district, 7 km north-east of Hilldale, where faunas from the upper part of the zone are preserved below the Wallaringa Formation.

Mount Rivers Ignimbrite Member

Derivation: Mount Rivers Township (Camberwell 498977).

Type Section: Camberwell 431972 (White, 1969).

Thickness: 71 m.

Lithology: According to White (1969) the Mount Rivers Member comprises a basal dacitic ignimbrite (4 m) overlain by volcanic breccia (12 m), light brown siliceous siltstone and chert (15 m), medium to coarse grained micaceous sandstone with minor siltstone and chert (36 m) and further dacitic ignimbrite (4 m).

Regional variation: In the western part of the Gresford district two ignimbrites are recognized within the Mount Rivers Member. Both ignimbrites lens out northwards and eastwards, and are replaced by siliceous siltstone containing a large proportion of devitrified glass. The siltstone is interpreted as an ash fall which was devitrified when deposited in water. The lowermost ignimbrite is mapped from the western side of the Webbers Creek Fault to the vicinity of Gresford, where it passes into siltstone. North of Gresford the uppermost ignimbrite, previously mapped as Martins Creek Andesite (Roberts, 1961), is present around the southern parts of Colstoun (Dungog 544938), and passes northwards into a devitrified silty sediment. Around Vacy the Mount Rivers Member is represented by a water distributed lithic tuff.

Petrology: In hand specimen the Mount Rivers Ignimbrite has a red-brown vitric groundmass containing euhedral biotite crystals and rare quartz and feldspar crystals. Collapsed pumice fragments are present as pale glassy inclusions.

Under the microscope the ignimbrite ranges from partly to completely welded and displays eutaxitic and axiolitic textures, although these are frequently obscured by devitrification. The groundmass is coloured red because of haematite derived from the weathering of small grains of magnetite; it contains crystals of plagioclase (Ab_7An_3), minor resorbed quartz, orthoclase and biotite. The biotite exhibits kink-bending, and the feldspar is highly sericitized and has an undulose extinction. These features indicate a substantial degree of placticity and hydrothermal action during cooling. An explosive eruption is suggested by the fragmentation of the crystals.

Age: The Mount Rivers Ignimbrite Member lies 180 m stratigraphically above mudstone containing brachiopods typical of the lower part of the *Delepinea aspinosa* Zone (Roberts, personal communication). It is overlain by units including the Martins Creek Ignimbrite, the latter having been dated radiometrically as 319 ± 9 my (Harland *et al.*, 1964).

Wallaringa Formation

The Wallaringa Formation was defined in the Wallarobba district and named after "Wallaringa" homestead by Roberts (1961). The base of the formation is defined by a transition in lithology from green lithic sandstone, typical of the Flagstaff Sandstone, to red zeolitic lithic sandstone. The top of the unit is taken at the base of the Martins Creek Ignimbrite Member of the Newtown Formation.

In a section measured in the Paterson-Gresford district, the Wallaringa Formation lacks the basal Wallarobba Conglomerate Member found in parts of the Wallarobba district, and overlies either the Mount Rivers Ignimbrite Member or thinly bedded greenish-yellow lithic sandstone of the Flagstaff Sandstone. In the latter case in the south-eastern part of the district, the basal beds of the Wallaringa Formation usually contain sediments laterally equivalent to the Mount Rivers Ignimbrite (Figure 3) which consist of brightly coloured angular coarse-grained lithic agglomerate cemented by zeolite. Red zeolitic vitric tuff is interbedded in the Wallaringa Formation west of Gresford.

Cyclic sedimentation showing sequences of fining upwards, similar to that described by Rattigan (1967) from Balickera, is present in the Wallaringa Formation in the Paterson-Gresford district. The cycle consists of a basal boulder conglomerate up to 1 m in thickness, coarse to fine grained red lithic sandstone up to 2 m in thickness, and blue-grey to purple silty mudstone up to 1 m in thickness (Figure 4) Sedimentary structures, mainly within the

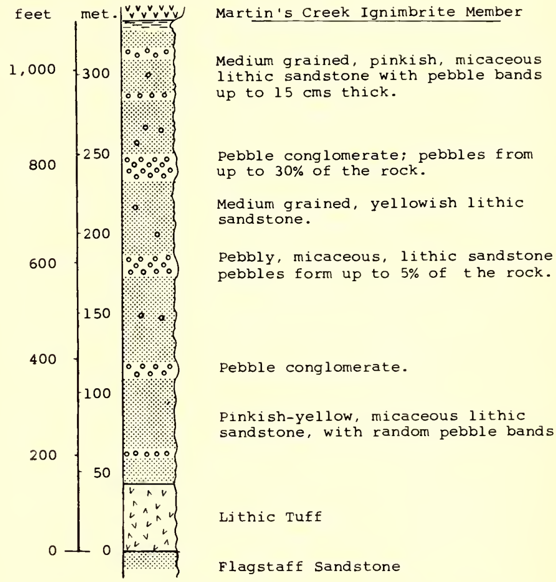

FIGURE 3.—The Wallaringa Formation measured on the eastern side of the Martins Creek-Hilldale road, north of Martins Creek.

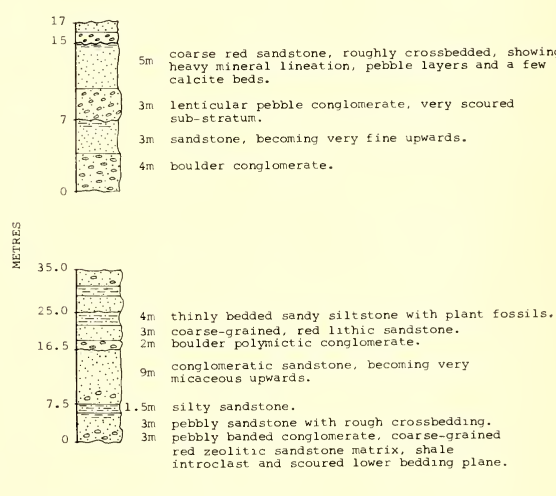

FIGURE 4.—Sedimentary cycles in the Wallaringa Formation on the Gresford-Singleton Road, west of Mt. Tyraman.

conglomerates, include large scale cross stratification of trough or channel type, heavy mineral lineation, scour and fill, pebble imbrication, and rafted mudstone clasts. Individual cycles are not continuous over wide areas, but the cyclical nature of the formation is constant throughout the area.

Petrology : Sandstones in the Wallaringa Formation contain grains which are fine to coarse (4 to 0·1 mm), subangular, and poorly to moderately sorted. The grains consist of quartzo-feldspathic volcanics often showing eutaxitic and spherulitic structures, plagioclase (Ab_7An_3) and orthoclase, and minor embayed crystals of volcanic quartz, biotite, hornblende, magnetite and apatite ; they are cemented by chlorite and heulandite. The red colour of the sandstones distinguishes them from the predominantly green sediments of marine origin. The colour is derived from clay-sized haematite which commonly adheres to grain surfaces and stains the zeolite cement. The haematite may have been derived from either contemporaneous weathering of magnetite, or the progressive alteration of mafic constituents and the redistribution of iron from decomposing grains by oxygenated pore waters during diagenesis (Blatt *et al.*, 1971). Abundant microscopic magnetite grains in the groundmass of most volcanic rocks provide a source for the magnetite in the sediments. The presence of magnetite grains in the yellow to green marine Flagstaff Sandstone tends to support the weathering hypothesis.

Age: The Wallaringa Formation overlies the Flagstaff Sandstone, which contains the *Delepinea aspinosa* Zone, and is overlain by the Martins Creek Ignimbrite dated radiometrically as 319±9 my (Harland *et al.*, 1964). The formation is late Visean in age.

Gilmore Volcanic Group

The Volcanic Stage of the Kuttung Series, defined from Mt. Gilmore by Osborne (1922), was renamed the Gilmore Volcanics by Roberts (1961). Rattigan (1967), from work in the Balickera Tunnel, recognized two formations within the Gilmore Volcanics, and raised the status of the unit to a group. The type section of the Gilmore Volcanics extends from the Williams River opposite Clarencetown, south-eastwards to the distal part of the Gilmore Range, and is 884 m in thickness (Osborne, 1922). The sequence consists of a lower unit, 384 m in thickness, of conglomerate, lithic sandstone and interbedded pitchstone, rhyolite, keratophyre and andesite, overlain by 500 m of rhyolite, dacite and felsite with interbeds of conglomerate (Osborne, 1922). The Group conformably overlies the Wallaringa Formation, and is overlain, with possible disconformity, by the Mount Johnstone Formation.

In the Paterson-Gresford district the Gilmore Volcanic Group contains two formations, the Newtown and Mowbray Formations (new names). The Newtown Formation consists of lithic sandstone and two ignimbrite members, the basal Martins Creek Ignimbrite, and the Vacy Ignimbrite. The Mowbray Formation is predominantly volcanic and contains the basal Breckin Ignimbrite Member, and the uppermost Lambs Valley Ignimbrite Member.

Radiometric dating of the Martins Creek Ignimbrite indicates that the base of the Gilmore Volcanics Group has an age of 319±9 my (Harland *et al.*, 1964).

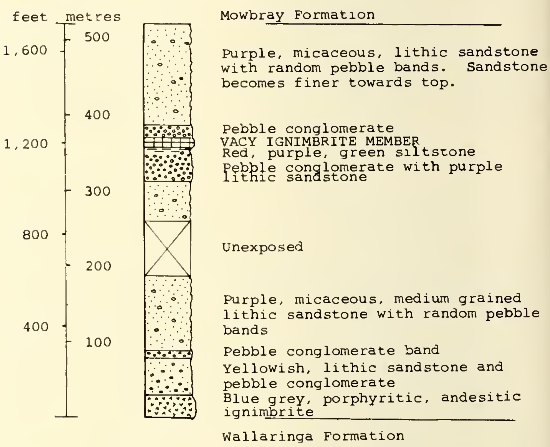

FIGURE 5.—The type section of the Newtown Formation.

Newtown Formation

Derivation : " Newtown " homestead (Paterson 602800).

Type section : Measured from a prominent ridge 1 km east of the Allyn River (Paterson 612805) to Breckin (584796).

Thickness : 565 m in the type section.

The Newtown Formation is comprised predominantly of sedimentary rocks, consisting of reddish-purple micaceous lithic sandstone and pebble conglomerate, with interbedded volcanics. The volcanics include the Martins Creek Ignimbrite Member, an unnamed hypersthene andesite pitchstone of limited areal extent, and the Vacy Ignimbrite Member (Figure 5). Sandstones of the Newtown Formation are distinguished from those of the Wallaringa Formation and Flagstaff Sandstone by their characteristic purple colour.

The base of the formation is identified at the base of the Martins Creek Ignimbrite, and the upper boundary is taken at the Breckin Ignimbrite Member of the Mowbray Formation (Figure 2).

Martins Creek Ignimbrite Member

Roberts (1961) mapped the Martins Creek Andesite as a member of the Gilmore Volcanics in the Gresford district. The unit is renamed the Martins Creek Ignimbrite Member because of shard structures which indicate a partly to thoroughly welded ignimbrite. Stratigraphically, the Martins Creek Ignimbrite overlies sandstone of the Wallaringa Formation ; it is overlain by reddish-purple lithic sandstone of the Newtown Formation. The maximum thickness of the ignimbrite in the Paterson-Gresford district is 35 m, measured on a ridge 1 km east of " Newtown ". The apparent greater thickness at Martins Creek quarry results from repetition by a westerly dipping fault ; the maximum thickness at the quarry is 30 m.

Numerous lithological variations within the ignimbrite were observed in a diamond drill core from Martins Creek quarry. The log of DDH 5 from the top of the hole is : typical grey-blue andesitic ignimbrite with phenocrysts of oligoclase-andesine (Ab_7An_3) enclosing nuclei of hornblende, magnetite or chlorite, and hornblende in a partially welded devitrified shard-rich matrix (10 m) ; grey-blue andesitic ignimbrite with phenocrysts of oligoclase-andesine with nuclei of hornblende magnetite and chlorite, hornblende, and quartz in a partially welded devitrified shard-rich matrix (6 m) ; altered red-green andesitic ignimbrite with phenocrysts of oligoclase, orthoclase, hornblende and quartz in a partially welded devitrified shard-rich matrix (15 m) ; and a basal black glassy ignimbrite with phenocrysts of oligoclase with replaced centres, hornblende and quartz in a welded devitrified shard-rich matrix (2 m).

Sediments of the Newtown Formation: Two hundred metres of reddish-purple micaceous lithic sandstone are present between the Martins Creek and Vacy Ignimbrite Members. The sandstones are fine to coarse grained (0·1 to 3 mm), contain grains which are subangular and poorly sorted, and are composed dominantly of lithic fragments ; these comprise ash flow tuffs, intermediate to acid volcanics, siltstone and foliated sediments. Oligoclase (Ab_7An_3) and orthoclase are corroded and sericitized, and quartz grains are pitted, cracked and contain inclusions of magnetite and muscovite. The cement is colourless acicular zeolite (possibly laumontite or heulandite).

Volcanic units within the Newtown Formation are frequently overlain by pebble bands ; a porous pebbly lithic sandstone containing clasts of ash-flow tuff and crystalline volcanics up to 3 cm in diameter overlies the Martins Creek Ignimbrite ; and a conglomerate containing intermediate to acid ash-flow tuff pebbles overlies the Vacy Ignimbrite. The volcanic members are underlain by reddish-purple and green silstones composed of quartz, feldspar and rock fragments and containing plant remains. Siltstone is found beneath the Martins Creek Ignimbrite in drill holes at Martins Creek quarry, and beneath the Vacy Ignimbrite in road cuttings west of Kealy's Bight on the Paterson River.

Pitchstone: A flow of hypersthene andesite pitchstone crops out prominently 300 m west of Martins Creek, and lies stratigraphically beneath the Vacy Ignimbrite Member. The pitchstone contains phenocrysts of zoned andesine, and small crystals of hypersthene, augite and magnetite in a glassy matrix. The pitchstone crops out only in a fault block between the Brownmore and Hilldale Faults west of Martins Creek.

Vacy Ignimbrite Member

Derivation: The village of Vacy (Paterson 593765).

Type section: Paterson 632767 in a railway cutting beneath an overhead bridge on the Paterson-Dungog road.

Thickness: 5 m.

The Vacy Ignimbrite contains a basal red micaceous ignimbrite with crystals of oligoclase (Ab_7An_3), orthoclase, quartz, biotite and magnetite in a devitrified partially welded shard-rich matrix. Axiolitic textures and complete spherulites are present within the matrix. Overlying the basal unit is a white micaceous ignimbrite with crystals of oligoclase (Ab_7An_3), orthoclase, quartz and biotite in a devitrified partially welded shard-rich matrix. The uppermost unit consists of grey micaceous ignimbrite of dacitic composition with eutaxitic and axiolitic textures.

The Vacy Ignimbrite has a constant thickness of 5 m in the Paterson-Vacy district, but becomes thinner to the north and west. In the vicinity of Mt. Tyraman on the Gresford-Singleton road, the Ignimbrite degenerates into red micaceous siltstone interbedded with coarse and fine grained purple lithic sandstone. The member is absent west of Myall Creek.

A sequence of reddish-purple lithic sandstone and conglomerate, 149 m thick, overlies the Vacy Ignimbrite Member.

Mowbray Formation

Derivation : " Mowbray " homestead (Paterson 616756).

Type section : Paterson 627763 to 614751 from near the Paterson-Dungog overbridge across the North Coast Railway, south-westwards to the Paterson River.

Thickness : 198 m in the type section.

The Mowbray Formation consists of ignimbrites, reddish-purple sandstone, lithic tuff, and conglomerate (Figure 6). The unit conformably overlies the Newtown Formation and is overlain, possibly disconformably, by the Mt. Johnstone Formation. Two members within the Mowbray Formation are named the Breckin and Lambs Valley Ignimbrite Members (new names) ; they mark the base and top of the formation.

Breckin Ignimbrite Member

Derivation : Breckin, 153 m (Paterson 583798).

Type section : Breckin (Paterson 593795).

Thickness : 20 m in the type section.

The Breckin Ignimbrite Member consists of a basal grey andesitic ignimbrite containing crystals of oligoclase to andesine, orthoclase, hornblende and biotite in a welded matrix of devitrified glass shards. The grey ignimbrite reaches a thickness of 12 m on Lees Mountain, but becomes thinner towards the south and is 2 m thick near Martins Creek. The upper part of the member is red and contains crystals of oligoclase (Ab_7An_3), hornblende and biotite in a welded matrix of devitrified glass shards. The red ignimbrite reaches a thickness of 8 m in the type section of the Mowbray Formation but becomes thinner northwards, and is 3 m thick west of Kealeys Bight, and 6 m thick on Lees Mountain.

In the Vacy area, the Breckin Ignimbrite is overlain by pebbly lithic sandstone, conglomerate and ignimbrites. The ignimbrites have a limited areal extent, and include a rhyolitic ignimbrite, 25 m thick, which is mainly light brown in colour but becomes white at the top. In thin section the ignimbrite contains crystals of corroded sericitized oligoclase (Ab_7An_3) and orthoclase, quartz containing vesicles and inclusions, altered laths of biotite, and magnetite in a nearly completely welded devitrified matrix. The ignimbritic sequence is overlain by lithic tuff, 62 m thick, containing angular water-born rock fragments, feldspar, quartz and biotite in a matrix of glass shards and zeolite. Interbedded with the lithic tuff is a highly fractured zeolitized brown to white ignimbrite of rhyodacitic composition. The sequence of lithic tuffs is overlain by the Lambs Valley Ignimbrite Member (Figure 6). In the Tyraman-Myall Creek area the ignimbritic sequence is replaced by water distributed volcanic breccias and agglomerate.

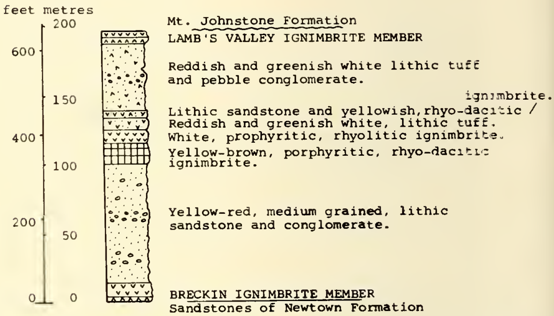

FIGURE 6.—The type section of the Mowbray Formation.

Lambs Valley Ignimbrite Member

Derivation : Lambs Valley (Singleton 1 : 63360 sheet).

Type section : Singleton 482752 from Lambs Valley Creek westwards along Lambs Valley Creek road.

Thickness : 49 m.

The Lambs Valley Ignimbrite Member contains two ignimbritic horizons. The basal unit is a white dellenitic porphyritic ignimbrite with highly sericitized and corroded crystals of orthoclase, zoned oligoclase, embayed and corroded quartz, magnetite and small distorted flakes of biotite in a welded devitrified shard-rich matrix. The ignimbrite has a thickness of 21 m in Lambs Valley and 20 m on Lees Mountain. It becomes thinner southwards, and in the type section of the Mowbray Formation is 8 m thick. The basal ignimbrite is overlain by a purple dellenitic ignimbrite containing crystals of orthoclase, oligoclase, quartz and biotite in a welded devitrified eutaxitic matrix. When weathered, the purple ignimbrite turns to a lime-green colour. The purple ignimbrite has a maximum thickness of 27 m in Lambs Valley ; west of Martins Creek it is 10 m thick.

Both ignimbrites pass westwards into water-distributed volcanic breccias. In the area around Mt. Tyraman the breccias vary between 40 and 100 m in thickness. Elsewhere in the Gresford district, relics of a white ignimbrite overlie the purple ignimbrite. Both of these data suggest a disconformity between the Mowbray and Mt. Johnstone Formations.

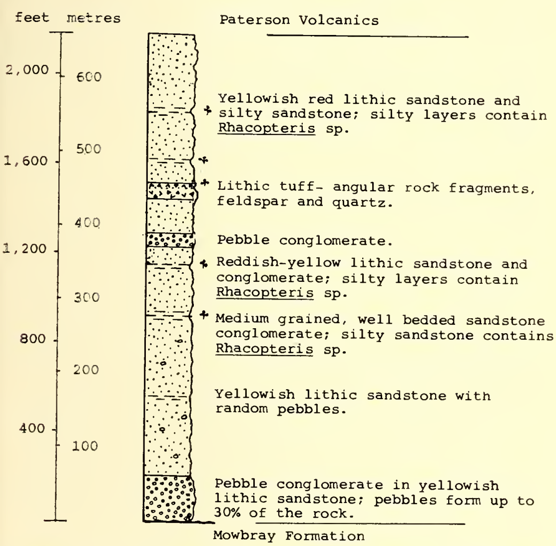

FIGURE 7.—The type section of the Mt. Johnstone Formation.

Mt. Johnstone Formation

The Mt. Johnstone Formation, originally termed Mt. Johnstone Beds, was defined from Mt. Johnstone near Paterson by Sussmilch and David (1920). The section given by Sussmilch and David is faulted and is replaced as type section by one measured from the Paterson River (Paterson 613753) to Mt. Johnstone (Paterson 598738).

The Mt. Johnstone Formation consists of yellowish-brown lithic sandstone, pebble conglomerate, and siltstone. The formation disconformably overlies the Mowbray Formation and is conformably overlain by the Paterson Volcanics. In the Paterson-Vacy area the Mt. Johnstone Formation contains a basal pebble conglomerate with clasts of acid and intermediate volcanics similar in lithology to the remnant volcanic in the uppermost part of the Lambs Valley Member (Figure 7). The conglomerate grades upwards into coarse to medium grained well bedded reddish lithic sandstone with thin stringers of pebble conglomerate. The sandstone is comprised of poorly sorted angular grains of intermediate to acid ignimbrites,minor quartz, and feldspar cemented by iron stained laumontite ; heavy minerals include magnetite and titanomagnetite. Above a distinctive lithic tuff, 425 m from the base of the formation, the sediments become finer grained and comprise siltstone containing *Rhacopteris* sp., silty sandstone, green fine grained lithic sandstone, and yellow medium grained lithic sandstone.

Regional variation: The coarse and fine sequences observed in the type section are also present at Tyraman (Figure 8). The basal 280 m contains at least three polymictic pebble conglomerate horizons separated by coarse grained yellow lithic sandstone and occasional

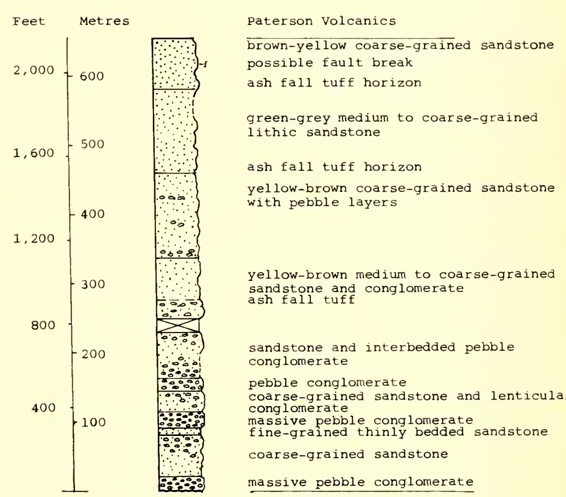

FIGURE 8.—The Mt. Johnstone formation measured at Mt. Tyraman.

pebble conglomerate lenses, and grades upwards into fine grained sandstone ; plant-bearing siliceous siltstone is present in the upper part of the unit. The uppermost 370 m at Mt. Tyraman consists of medium grained yellow lithic sandstone containing small lenses of pebble conglomerate, which grades upwards into fine grained sandstone and siliceous siltstone. In the Myall Creek area there is a similar but expanded sequence, 790 m thick.

At Balickera, Rattigan (1967) divided the two sequences into formations, the Balickera Conglomerate and the Italia Road Formation. The Balickera Conglomerate (420 m) is a polymictic boulder conglomerate containing two prominent members of grey pumiceous rhyolitic tuff. The Italia Road Formation consists of lithic sandstone, shale, coal and chert which were deposited in cycles. Thin ignimbrites and bentonites are also present in the formation (Rattigan, 1967).

Age: The overlying Paterson Toscanite has been dated radiometrically as 298 my (Harland *et al.*, 1964), and is considered by Jones, Campbell and Roberts (1973) to be early Stephanian in age. The Mt. Johnstone Formation cannot be accurately dated, but probably spans the Namurian and Westphalian.

Paterson Volcanics

The Paterson Volcanics were originally termed the Paterson Rhyolite by Sussmilch and David (1920). Engel *et al.* (in Packham, 1969) gave the unit formational status and changed the name to Paterson Toscanite. Subsequently, the unit has been termed Paterson Volcanics (Jones, Campbell and Roberts, 1973). The Paterson Volcanics consist of two ignimbrites which in some areas are separated by a sedimentary lens. The formation lies conformably between the Mt. Johnstone and Seaham Formations and is 88 m in thickness. The basal ignimbrite is a brown to grey toscanite with crystals of oligoclase (Ab_7An_3), orthoclase, quartz, hornblende and hypersthene in a partially devitrified welded eutaxitic matrix. At Vacy, sediments overlying the lowermost ignimbrite comprise medium grained red lithic sandstone ; at the southern margin of the Moonabung Basin there is an oligomictic boulder conglomerate ; and in the Sharps Mountain district the sediments comprise up to 60 m of coarse grained grey-green to brown lithic sandstone. The sedimentary lens is absent at Tyraman. The upper ignimbrite is a grey dellenite with crystals of oligoclase (Ab_7An_3), orthoclase, quartz, hornblende and biotite in a massive welded shard rich matrix. At Paterson, the volcanics are 88 m thick (Engel *et al.*, 1969).

Seaham Formation

The Seaham Formation, originally termed the Seaham Glacial Beds, was first described from the vicinity of Seaham township by Sussmilch and David (1920). A section measured at Seaham contains about 80 m of fluvioglacial conglomerate, varve shale, tillite, lithic sandstone, mudstone, and tuffaceous deposits (Engel *et al.*, in Packham, 1969). The Seaham Formation conformably overlies the Paterson Volcanics, and is conformably overlain by the Lochinvar Formation.

In the Paterson-Gresford district only a little more than 150 m of the Seaham Formation is preserved. The sediments comprise coarse-grained pebbly lithic sandstone and pebble conglomerate containing interbeds of siliceous siltstone with abundant *Rhacopteris* sp. (Figure 9). Varved shales overlie the Paterson Volcanics in the southern part of Lambs Valley and the formation has also been mapped in the Moonabung Basin and in a northerly extension of the Cranky Corner Basin adjacent to the Webbers Creek Fault (Figure 1). A complete section through the Seaham Formation is present on the western side of Lambs Valley between the Paterson Volcanics and Permian outliers in the Cranky Corner Basin.

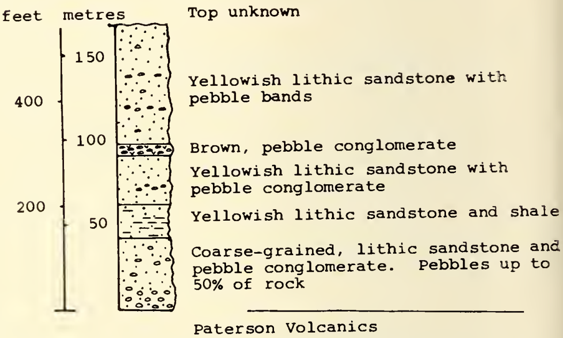

FIGURE 9.—The Seaham Formation measured in the fault block west of Mt. Johnstone.

Structural Geology

The Paterson-Gresford district is situated north of the Hunter Fault System on the margin of a belt of structural basins formed during the Hunter-Bowen Orogeny. Parts of three basins, the Mirannie, Cranky Corner-Gresford, and Moonabung Basins, are present along the south-western margin of the Paterson-Gresford district. The basins are separated from one another by a set of major north-easterly trending faults. North-east from the belt of basins is a series of broad fold axes striking north-west, parallel with the basin belt, which are dislocated by the same set of faults. Immediately north of the area portrayed in the geological map fold axes and faults become parallel with one another, and strike in a north-south direction.

The north-westerly trending fold axes comprise the Hilldale Anticline (Roberts, 1961), which strikes N35°W and plunges at 5° to the east, and a parallel syncline. The syncline passes through Mt. Ararat and before faulting may have been a southerly extension of the Ararat Syncline mapped at Bingleburra by Roberts

(1961). The syncline is separated from the Wallarobba Syncline to the east of this area by two major faults, the Brownmore and Hilldale Fault Systems.

Major fault systems in the Paterson-Gresford district post-date folding, and originate from the Hunter Fault System. In the southern part of the region near Paterson the faults strike north-easterly, but towards Gresford they swing to a more northerly orientation. All of the major faults are interpreted as high angle reverse faults.

The Webbers Creek Fault originates at the Hunter Fault System, flanks the southern and eastern margins of the Mirannie Basin and cuts the north-western flank of the Cranky Corner Basin. The fault plane is visible at The Pass on the Singleton-Gresford road. The Camyr-Allen Fault System (Roberts, 1961) bifurcates into the Webbers Creek and Bingleburra Faults in the south, and extends northwards from Gresford, where it has a throw of approximately 2,000 m. The Bingleburra Fault, mapped in part by Roberts (1961), has a maximum throw of 2,000 m indicated by the displacement oi the Martins Creek Ignimbrite west of Mt. Breckin. The throw descrease to 1,000 m near Mt. George. At Lewinsbrook, 5 km southeast of Gresford, a wedge of Bonnington Siltstone appears to be caught in a splay of the Bingleburra Fault. The Brownmore Fault system extends sub-parallel to the Hilldale Fault System and is linked with the Vacy Fault System. The Brownmore Fault has a throw of 50 m at Martins Creek. Dextral movement of the fault has produced a rotation of strike from 315° to 343° in a fault block 1 km north-west of Martins Creek, and drag folds in the Mowbray Formation. The Vacy Fault System, which dissects the Mt. Johnstone and Moonabung Basin structure, has a maximum throw of 200 m east of Hilldale. The Hilldale Fault, originally identified by Osborne (1922) from the railway cutting east of Hilldale, has a throw varying from 150 m near Paterson to 460 m near Mt. Douglas, 4·5 km south of Hilldale.

Palaeogeography

The Early Carboniferous palaeogeography of the southern New England Belt, which includes the Paterson-Gresford district, has recently been described by Roberts and Oversby (1973) and will be considered only breifly in this paper.

In the late Tournaisian and earliest Visean, shelf muds (Bingleburra Formation) accumulated in the Gresford district. Volcanism in the south during the early Visean caused sandy sediment to prograde into the marine shelf. The sand was interbedded with marine mud and calcareous sediment in the north, and with terrestrial welded ignimbrite and gravel wedges in the south ; all of these units now comprise the Ararat Formation. Vast amounts of volcanic ash fell into the marine shelf during the middle Visean, and when mixed with silt gave rise to the Bonnington Siltstone. Marine conditions prevailed over the area during the early part of the late Visean, with interbedded mud and sand (Member A of the Flagstaff Sandstone) being deposited probably behind a barrier bar complex. Sand in the barrier bar complex comprises the sand-rich type section of the Flagstaff Sandstone situated 10 km north-east of Gresford. An increase in the influx of sand, presumably from volcanism and uplift in a south-western source area caused a marine regression slightly later in the Visean. Welded ignimbrites (Mount Rivers Member) and plant-bearing silt were deposited with sand on a terrestrial region west and north-west of Gresford, while to the east at Mt. Ararat similar sands containing devitrified ash layers were deposited in a marine environment. Both the terrestrial and marine sands are referred to the Flagstaff Sandstone.

Volcanism and uplift in the south during the late Visean caused coarse terrestrial debris to be deposited on a piedmont plain. Meandering streams flowing across the piedmont caused cyclicity in the alluvial sediments (Wallaringa Formation) and left lag deposits in channels (Wallarobba Conglomerate). Increased volcanism in the same sedimentological setting resulted in the accumulation of the Newtown and Mowbray Formations. The red sediments in the Wallaringa, Newtown and Mowbray Formations which derive their colour from haematite, may have formed in a moist warm climate ; palaeomagnetic data indicate a palaeolatitude of about 30° S during deposition of the Martins Creek Ignimbrite (Irving, 1964).

Regional uplift around the end of the Visean caused erosion of the Mowbray Formation. Red sediments which characterized most of the earlier terrestrial units were replaced by yellow-brown sediments which display a sequence of " fining upwards " and appear to be characteristic of flood plains (Mt. Johnstone Formation). Fine grained sediments in the upper part of the Mt. Johnstone Formation suggests derivation from a source area with a mature physiography. The abrupt colour change between the Mt. Johnstone and Mowbray Formations may indicate a significant hiatus in deposition. Volcanism in the early Stephanian (Paterson Volcanics) followed deposition of the Mt. Johnstone Formation. By this time climatic conditions were much cooler, as indicated by palaeolatitudes of slightly less than 50° S from the Paterson Volcanics and of nearly 70° S for the succeeding Seaham Formation (Irving, 1964). Sediments comprising the Seaham Formation were probably derived from a nearby glaciated upland region (Crowell and Frakes, 1971) which still contained active volcanoes. Varved shale and fine grained glacigene sediments were deposited in lakes south of Paterson, and gravel and sand were derived by glacial action from the upland region.

Acknowledgements

We wish to acknowledge the assistance of Miss P. Ryan and Mr. G. Melville in drafting the map and figures.

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(Received 17.12.73)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 87–89, 1974

The Phonolite-Trachyte Spectrum in the Warrumbungle Volcano, New South Wales, Australia

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Abstract—The spectrum of salic magmas ranging in composition from phonolite to trachyte from the Warrumbungle Shield Volcano is attributed to high-level, low pressure crystal fractionation. Field, petrographic, mineralogical and chemical evidence all support the derivation of the phonolite-trachyte spectrum by differentiation of a range of nepheline and hypersthene normative alkali basalt parental magmas respectively. Rare xenoliths in the Breadknife trachyte are interpreted as fragments of a crystal accumulate formed in a high-level magma chamber. Rejuvenation of volcanic activity resulted in disintegration and incorporation of the accumulate in the Breadknife trachyte. No evidence to support an upper mantle origin for the phonolite-trachyte spectrum has been recognized.

The Warrumbungle Volcano is a Middle Miocene continental alkaline shield volcano that occupies an almost circular area in excess of 1,200 sq. km in central western New South Wales, Australia. Rocks of the alkali basalt-trachyte phonolite assemblage forming the shield comprise three rock lineages.

I. A sodic undersaturated alkali basalt-hawaiite-mugearite-trachyte lineage.

II. A mildly potassic hypersthene normative trachybasalt - trachyandesite - tristanite - trachyte lineage.

III. A mildly potassic nepheline normative trachyandesite-high iron trachyandesite-nepheline bearing trachyte-phonolitic trachyte lineage.

High or Low Level Formation of Salic Magmas :

The rock lineages from the Warrumbungle Shield are characterized by the abundance of intermediate variants, the hawaiites and trachyandesites. In these rock lineages the degree of undersaturation of the parental liquids that is reflected by the basic and salic end members is also reflected by the intermediate lineage members. The norm of a clinopyroxene from a *hy* trachyandesite contains *hy* and the norm of a clinopyroxene from a *ne* trachyandesite contains *ne*. Coombs, (1963) ; Wilkinson (1966) ; Coombs and Wilkinson (1969).

The Chemistry of the vitric groundmass of basaltic lavas (Wilkinson, 1966 ; Coombs and Wilkinson, 1969) of felsic veins and schlieren in differentiated alkaline intrusives (Yagi, 1953 ; Wilkinson, 1958, 1965 ; Wilshire, 1967) demonstrate that low pressure fractionation of alkali basalts is capable of producing liquids of hawaiitic, mugearitic, benmoreitic, trachyandesitic, trachytic and phonolitic composition.

By contrast the occurrence of megacryst and lherzolitic xenoliths that are regarded (Green and Ringwood, 1967) as being derived from the upper mantle in phonolites (Pröscholdt and Thürach, 1895 ; de Rover, 1961 ; Wright, 1966), trachytes (Wright, 1969) hawaiites (Wilkinson and Binns, 1969 ; Binns, Duggan and Wilkinson, 1970) analcimites, trachybasalts and nephelinites (Binns, Duggan and Wilkinson, 1970) indicate that the full spectrum of evolved alkaline lavas may be generated in the upper mantle (Bailey, 1965 ; Bailey and Schairer, 1966 ; Wright, 1971).

A feature of the lavas from the Warrumbungle Shield is the absence of any high pressure phases such as megacrysts or lherzolite xenoliths that are indicative of low level formation under high pressures in the lower crust or upper mantle. The presence of several coarse grained segregations (up to 10 cm in length and 8 cm in width) in a high iron trachyandesite indicates that fractionation occurred under low pressures. These segregations consist of abundant olivine (Fa_{53}), plagioclase (An_{17}), titaniferous augite or salite, titanomagnetite, apatite and glass, the liquidus phases in an alkali olivine basalt at low pressures (Yoder and Tilley, 1962 ; Green and Ringwood, 1967).

The existence of high level magma chamber(s) are supported by the presence of numerous parasitic centres erupting material of diverse composition during the growth of the Warrumbungle Shield Volcano. Two of these centres are indicated from the available K/Ar age determinations (Dulhunty and McDougall, 1966 ; McDougall and Wilkinson, 1967). Additional evidence reflecting the existence of high level magma chamber(s) are the widespread scoria throughout the Warrumbungle Shield, the presence of siliceous sinter, the paucity of alkali basalts and the late eruption of valley filling mugearite flows. A combination of field, petrographic, mineralogical and chemical evidence supports the conclusion that the abundant intermediate and salic volcanics recognized in the Warrumbungle Shield were only produced when sufficient parental alkali basalt magma differentiated by processes of crystal fractionation at the low pressures of 9 kb or less in a high level magma chamber. Mineralogical evidence from the quartz-bearing trachytes indicates that

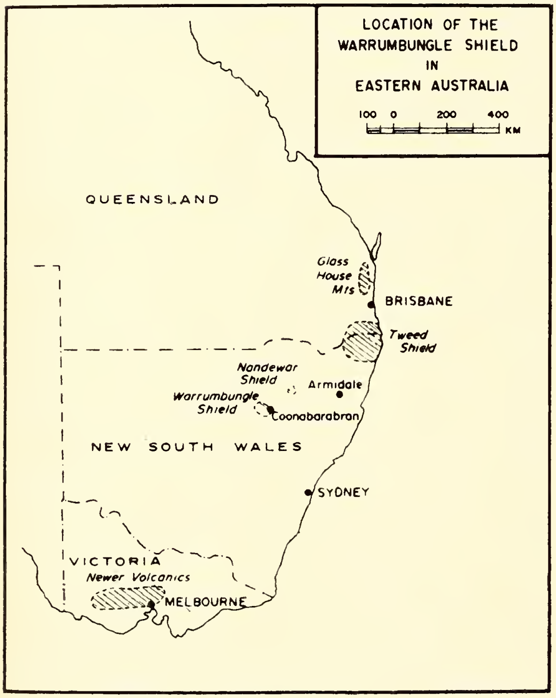

FIGURE 1.

with time the efficiency of the differentiation processes increased. Concomitant with an increase in the differentiation indices of the quartz-bearing trachytes is a change in the ferromagnesian content from arfvedsonite+minor aegirine augite→arfvedsonite→a ferromagnesian-free assemblage in the leucocratic trachytes of quartz+alkali feldspar+titanomagnetite.

Several elongated xenoliths (up to 12 cm in length and 4 cm in width) have been recognized in the Breadknife trachyte dyke, a dyke radiating from the volcanic neck of Crater Bluff. These xenoliths represent a stage in the volcanic history of the vent of Crater Bluff, when a slight amount of fractional crystallization occurred in a high level magma chamber resulting in some crystal accumulation. The crystal accumulation occurred prior to the final eruptive stage of Crater Bluff that culminated with the intrusion of the Breadknife dyke. Rejuvenation of the vent in the final eruptive stage resulted in fragmentation and incorporation of the crystal accumulate as xenoliths in the Breadknife trachyte. The process of crystal accumulation envisaged is similar but on a much smaller scale to that recorded by Upton *et al.* (1967), from Rodriguez Island, Indian Ocean.

The restriction of basaltic hornblende to the xenoliths where it partially and in some instances completely replaces aegirine-augite indicates that its formation is dependant upon local development of a relatively hydrous magma prior to an explosive phase. The replacement of pyroxene by amphibole indicates that the buildup of volatiles most probably occurred over a prolonged period of time. The development of basaltic hornblende in the xenoliths from the Breadknife trachyte is regarded as analogous to the formation of basaltic hornblende in the xenoliths from the Rodriguez lavas (Upton *et al.*, (1967) and to the formation of secondary amphibole in the Tristan xenoliths (Baker *et al.*, (1964). The fact that the Breadknife dyke has been intruded into agglomerates verifies the existence of an explosive phase from Crater Bluff and its subsiduary parasitic vent. Belougery Spire, prior to the intrusion of the Breadknife dyke.

In summary, it is concluded that the phonolite-trachyte spectrum in the Warrumbungle Shield Volcano was derived by fractional crystalization of parental alkali basalt magmas with varying degrees of saturation undersaturation at the relatively low pressures of 9 kb or less in a high level magma chamber. The mineralogy of the quartz-bearing trachytes indicates that the efficiency of the differentiation processes increased with time. Fractional crystallization in a high level magma chamber in the latter stages of volcanic activity during a period of quiescence resulted in slight crystal accumulation. The localized accumulation of volatiles in the upper level of this magma chamber prior to the explosive phase that preceded rejuvenation of the vent resulted in the formation of basaltic hornblende. Fragmentation and incorporation of the crystal accumulate as xenoliths in the Breadknife trachyte occurred during the rejuvenation of volcanic activity.

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(Received 8.4.1974)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 90–99, 1974

Structural Interpretation of New England Region

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Abstract—As a result of a geologic study of the New England Region it appeared that many terms for newly proposed structural units in this region are ill-founded and more the expression of guesswork than an evaluation of established geologic observations. The fact that the age and relative position within the sequence of all those low-grade metamorphic rocks which make up the bulk of the rock units and are so characteristic for the eastern portion of the New England Region, are unknown or just a matter of conjecture, is not sufficiently emphasized in many recent publications.

The New England Block and the Tamworth Fold Belt are the only two structural units which can be regarded as well defined and valid.

Introduction

A study of the geology of New England showed that in any structural interpretation the Mihi Fault (Figures 1 and 5) and the indentation (re-entrant) at Murrurundi would be of great significance. The Murrurundi re-entrant separates the Mooki Thrust and the Tamworth Fold Belt to the north from the Hunter Thrust to the southeast.

It was realized as a result of this investigation that the position within the stratigraphic sequence of each Palaeozoic rock unit would have to be closely scrutinized because too many rock units are shown on the published maps without any question marks or without any comments in the legend in spite of the fact that the age of the rock units or their relative position within the sequence is not known.

By referring repeatedly to the same opinion in a publication without going back to the source, a tendency arises to transform statements expressing some doubts into simple facts and thus many rock units of very questionable age have gradually become regarded as well established as to their age. Within a few years, the age of a certain formation—without any added evidence from fossils or radiometric age determination—moved from conjecture to fact.

Most of the current stratigraphic classification of the low-grade metamorphic rocks exposed in the New England region is based on circumstantial evidence. These rocks consist mainly of slate, phyllite, greywacke and some subordinate chert and jasper. Thus there is no direct evidence for the age of the following rock units :

- Woolomin Beds.
- Myra Beds.
- Nambucca slates and phyllites (or beds).
- Neranleigh-Fernvale Beds (area north of Coffs Harbour).

How complicated the situation is can best be seen when studying and comparing the geological maps 1 : 250,000 covering the New England region. Not one map agrees with the other on the age assignment or relative position of these low-grade metamorphic rocks.

On the Geological Map of New South Wales 1 : 1,000,000 (Pogson, 1972), thousands of square kilometres of the New England area are underlain by rocks which did not merit an informal name. On the map and legends these rock units are coded " S-Dz " and " S-D " and are referred to the Silurian-Devonian. Reference sheet 3 (Pogson, 1972) shows in the columnar sections that they might range up or down in the geologic sequence. Again here this pile of rock of uncertain age consists mainly of argillite, greywacke and phyllite.

The Nambucca Phyllites are referred to the Lower Palaeozoic by Voisey (1969). Voisey makes it quite clear that no diagnostic fossils have been found and that the stratigraphic position of these beds is doubtful. Packham (1973, p. 373) does not leave any doubt on the questionable age of these rock units. On the Geological Map of New South Wales 1 : 1,000,000 (Pogson, 1972) the Nambucca Beds are shown as unquestionable Permian, whereas the 1971 provisional edition of the 1 : 500,000 Geological Map of New England (Offenberg and Pogson, 1971) indicates that the Nambucca beds might range down into the Lower Carboniferous. Where is the proof that the Nambucca Beds are Permian ? As long as the Nambucca Beds, the Woolomin Beds and the Myra Beds cannot be exactly dated, any attempt at a structural interpretation of the area east of the Mihi Fault and north of the Hunter Thrust must be regarded as an assumption. Based on radiometric measurements, Green (1973) recently suggested that at least part of the Neranleigh-Fernvale

Group was probably as young as Lower Carboniferous.

Many palaeogeologic reconstructions and plate tectonic models based on the assumed age of rock units covering such a large area should not be taken seriously and might be misleading.

The kind of structural interpretation obtained based on conjecture is best demonstrated by the map 1 : 6,000,000 called " Structural Units of New South Wales " included in the Geological Map of New South Wales 1 : 1,000,000 (Pogson, 1972). Figure 4, shows the New England portion of this map. The colours of the original map are rendered here by black and white patterns. The way in which the finger-like lobes of the southeastern " Woolomin-Texas Block " are interlocked with some fingers of the Tamworth Synclinorial Zone or the tooth-like protuberances of the Nambucca Block is mechanically incongruous. The same can also be said when considering how some blue wedges of the Nambucca Block are dovetailed with isolated masses of the southern portion of the Woolomin-Texas Block.

When studying the New England region on the same map called " Structural units of New South Wales " (Pogson, 1972) the following questions might be asked :

(*a*) Where is the boundary between the Tamworth Synclinorial Zone and Kempsey Block ? (See Figure 4.)

(*b*) Where are the boundaries between the Demon Block, the " Brisbane Block " and the Emu Creek Block ?

(Note that " Brisbane Block " is a misnomer since the name Beenleigh Block has priority and the city of Brisbane lies on the edge of the D'Aguilar Block.)

The discussion of the validity of calling eleven structural units of New South Wales " Synclinorial Zones " lies beyond the scope of this paper.

Discussion of Some Structural Units and their Boundaries

Peel Fault (Figures 1 and 5)

For its history of exploration and terminology, see Packham (1969). Both the terms " Peel Fault " and " Peel Thrust " have been used in the literature and on maps. The more general term of " fault " is used here because the Peel Fault is typically a fault zone having had a long history of complex dip slip and horizontal movements. Depending on the cross section considered (Figure 3) the fault might have the nature of a normal fault or a reverse fault. Locally the strains caused by horizontal components might be dominant. The Peel Fault is characterized especially by lenses or wedges of ultramafic rocks emplaced as solid masses of various sizes along the trend of the fault. It was therefore described as the " Great Serpentine (Serpentinite) Belt of New South Wales " by earlier workers (Benson, 1912–1918, quoted by Voisey, 1969 ; Wilkinson, 1969). The Peel Fault is a distinctive geosuture, in the same class as the Owen-Stanley Fault of Papua, the New Caledonian Geosuture or the Alpine Fault of New Zealand (see Figure 3, cross sections).

From a point 35 km south of Bingara the trace of the Peel Fault is remarkably straight for some 153 km as far as Hanging Rock where the fault is covered by the Tertiary basalts of the Liverpool beds. East of Tamworth where the fault zone is obliterated by the intrusion of the Moonbi Porphyritic Adamellite, a plutonic body belonging to the New England Batholith, the Peel Fault is slightly displaced in a left sense by a north-south fault (see Figures 1, 3 and 5). For the last 40 km the Peel Fault has a bearing of 159° and is completely straight before it disappears under the Liverpool Beds at Hanging Rock (Figure 5). There is no suggestion that the trace of the fault might gradually curve toward east. The Tectonic Map of Australia and New Guinea (Geological Society of Australia, 1971) and the Geological Map of New South Wales, 1 : 1,000,000 (Pogson, 1972) show the above described feature clearly.

Twelve kilometres southeast of Hanging Rock, northwest of the village of Barry, some older rocks are again exposed under the cap of the Liverpool Beds and a questionable fault has been mapped in this area. However, the average trend of the fault changed to a bearing of 131°. Several outcrops of small masses of ultramafic rocks have been observed.

Nevertheless, it should be emphasized that the Tamworth 1 : 250,000 geological sheet (Offenberg, 1971) indicates only an inferred or probable fault.

At Boonara homestead (50 km southeast of Hanging Rock, see Figure 5) in the headwaters of the Manning River, a ten kilometre long lense of ultramafic rocks is gently curved towards the east and dissected by several faults. From this locality towards the east and northeast, many wedges and lenses of ultramafic rocks occur always associated with some fault zones (see Figures 1, 3, 5). The area between Port

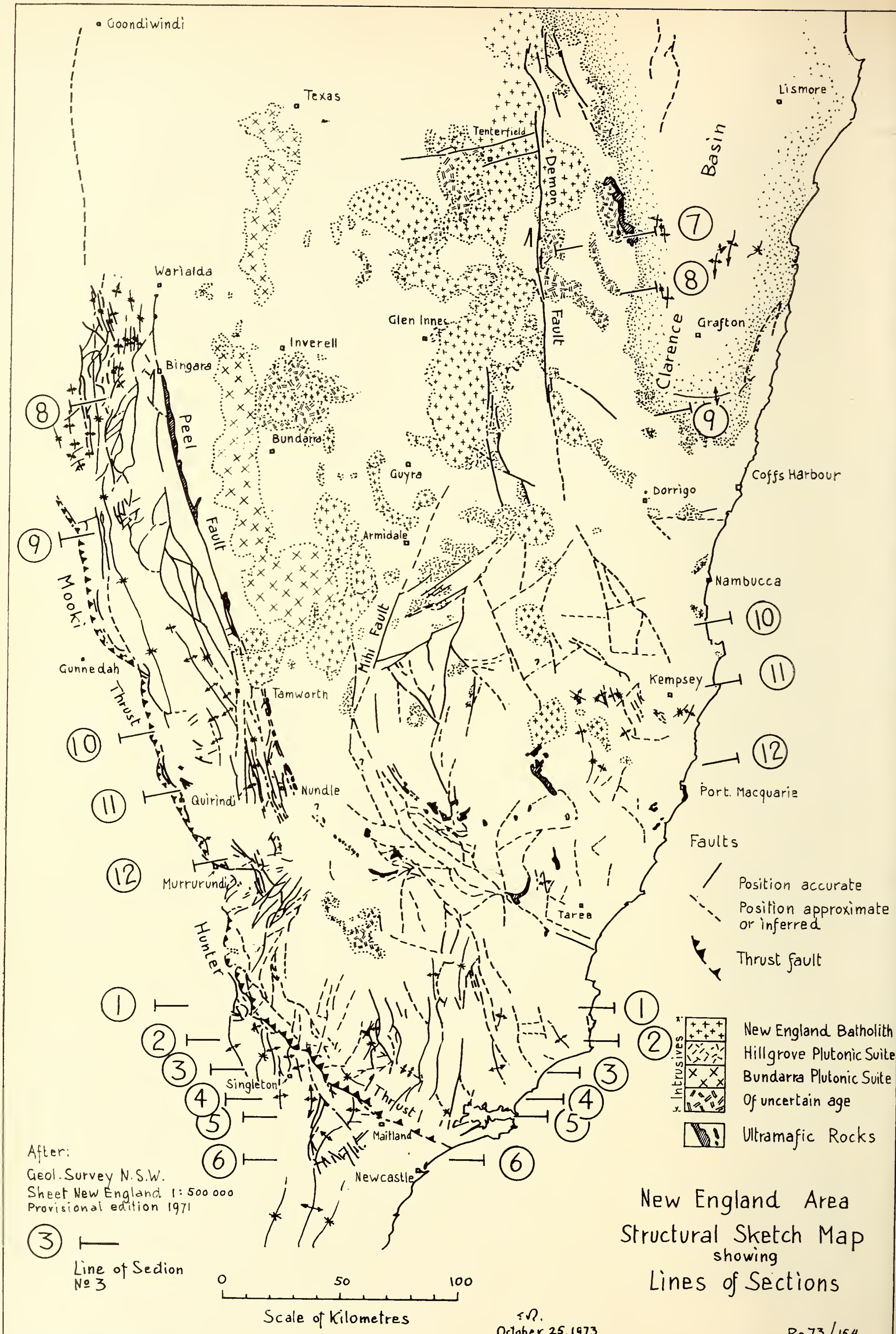
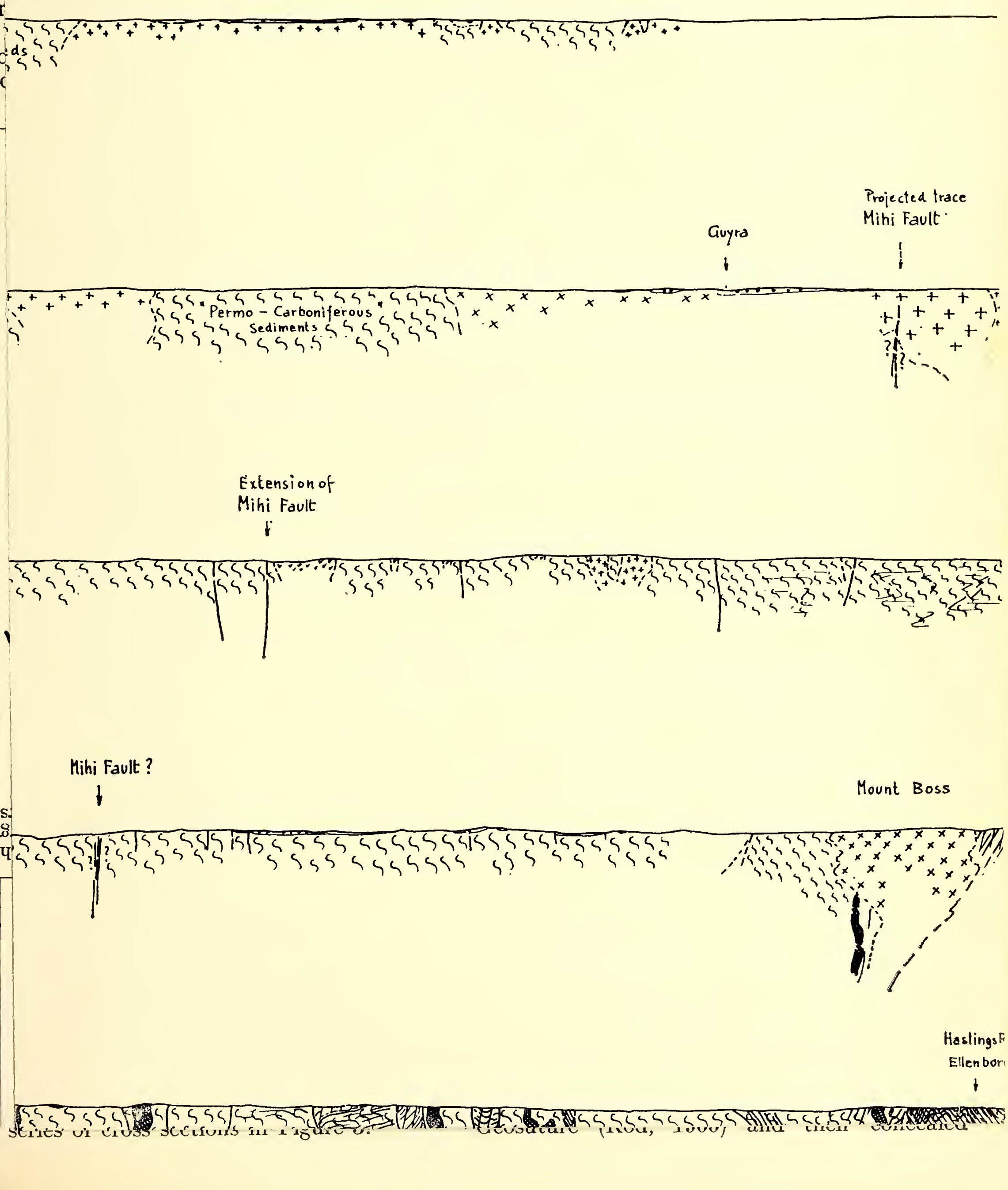


FIGURE 1.—Structural sketch map of New England area after New England and Sydney Basin 1 : 500,000 Geological Sheets (Offenberg and Pogson, 1971; Brunker and Rose, 1969). Cross sections numbers 1 to 6 are on Figure 2, and cross sections 7 to 12 on Figure 3.


Projected trace
Mihi Fault
Guyra
Permo – Carboniferous
Sediments
Extension of
Mihi Fault
Mihi Fault ?
Mount Boss

Macquarie and the upper Manning River seems to be built up by a group of imbricate structures. Until more is known about the age and correlation of the rock units in this area, and assumptions can be replaced by some facts, it is futile to attempt a structural interpretation. Judging from the published geological maps it cannot be stated that the ultramafic rocks are all arranged along one thrust zone which was deformed into loops in the manner as can be done with a string of pearls.

From the general character of the Peel Fault, from its topographic expression, arrangement of secondary faults and alignment of adjoining folds it can be regarded as certain that it has a horizontal component with a left sense of displacement.

Based on the same characteristics the attitude of the fault in general appears to be vertical or steeply dipping to either side. Some dips of 60° to the east have been reported locally. Thus it appears not to be a thrust fault in the usual sense of the word. Therefore an average dip of 32° to 40° toward the east as shown by Scheibner and Glen (1972, Figure 4) for the Peel Thrust seems to be unrealistic.

Moreover it is difficult to see how Scheibner (1972) could postulate "due to the relative

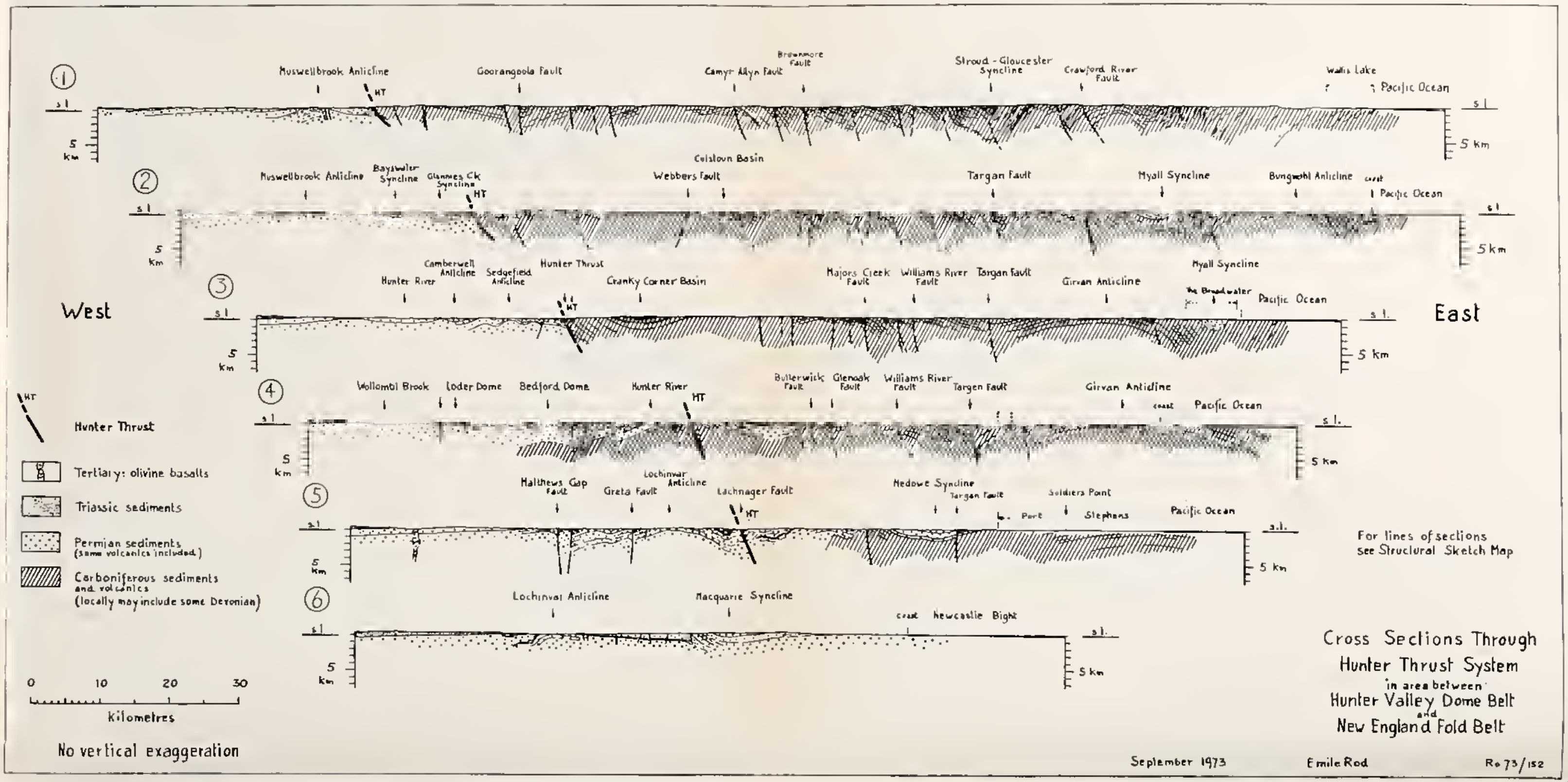


FIGURE 2.—Cross sections through Hunter Thrust system in area between Hunter Valley Dome Belt and New England Fold Belt. The sections were prepared from information on the Singleton and Newcastle 1 : 250,000 Geological Series Sheets (Rasmus and others, 1969; Rose and others, 1966).

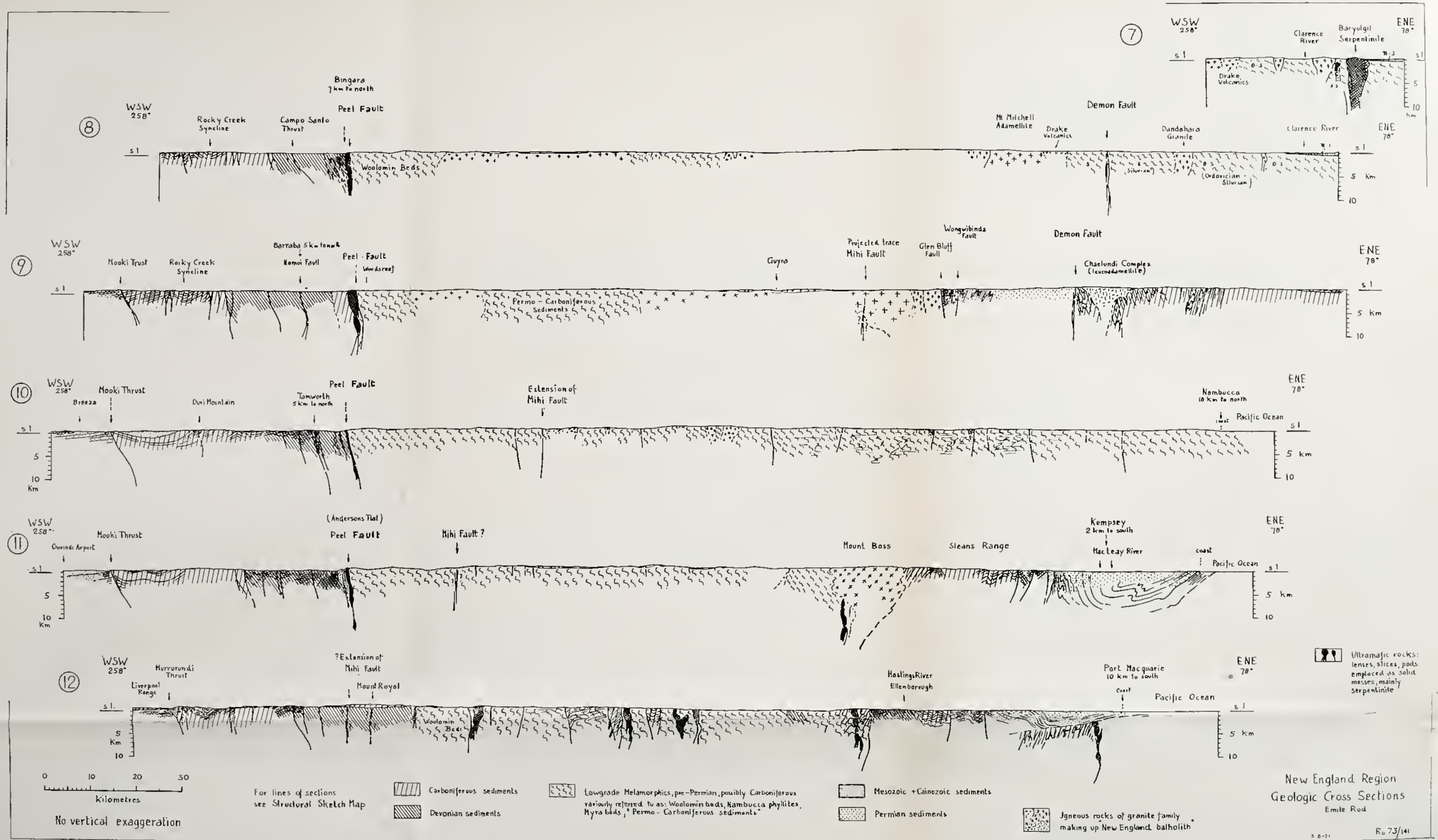


FIGURE 3.—Geologic cross sections through New England Region, prepared from information on the Tamworth, Hastings, Manilla, Dorrigo-Coffs Harbour, Inverell and Grafton 1 : 250,000 Geological Series Sheets (Offenberg, 1971; Brunker and others, 1970; Chesnut and others, 1970; Leitch and others, 1971; Chesnut and others, 1971; Brunker and others, 1969).

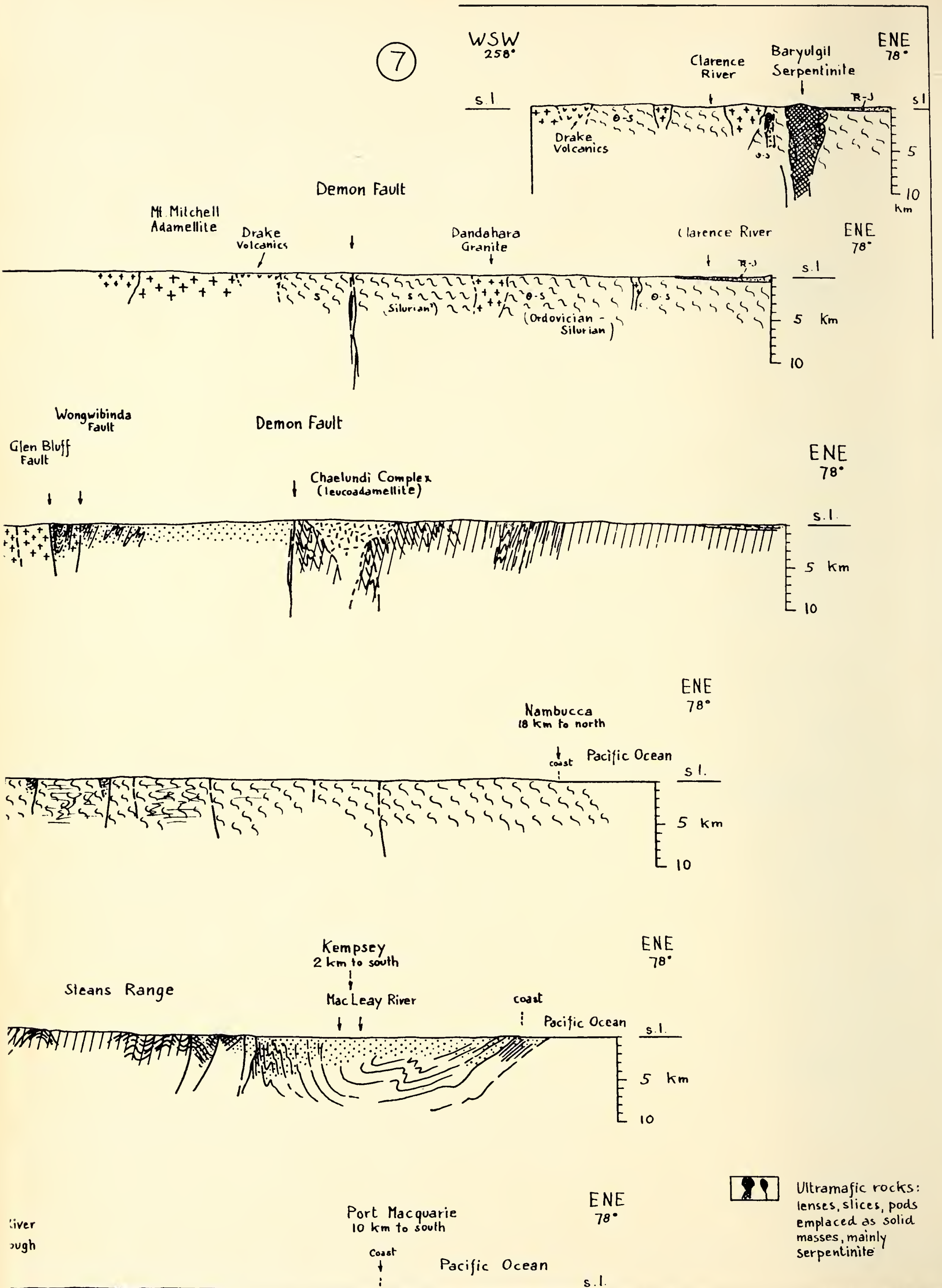


FIGURE 1.—Structural sketch map of New England area after New England and Sydney Basin 1 : 500,000 Geological Sheets (Offenberg and Pogson, 1971; Brunker and Rose, 1969). Cross sections numbers 1 to 6 are on Figure 2, and cross sections 7 to 12 on Figure 3.

rotation of the plates involved " a right displacement (he calls it " clockwise ") " amounting to 150 km in some sections ".

Mihi Fault (Figures 1 and 5)

When considering the sudden change in structural grain as it occurs at the latitude of the town of Murrurundi (Figures 1 and 5), it will be realized that this Murrurundi re-entrant must be of great structural significance. The folds and faults of the Tamworth Fold Belt exhibit a south-south easterly to southerly grain, whereas the dominant structural direction in the belt southeast of Murrurundi is southwesterly. This change in direction is one of the outstanding geologic features well illustrated on all geologic maps.

Several large, northeast trending faults east of Murrurundi are perfectly aligned with the projected extension of the Mihi Fault.

According to this working hypothesis which is illustrated in Figure 5, the Mihi Fault intersects the Peel Fault at an angle of 40° just about 8 to 10 km southeast of Hanging Rock. South and East of Armidale, where the Mihi Fault is well established, it has an average bearing of 22° and may be regarded as a steeply dipping strike-slip fault. Its sense of horizontal displacement can not be determined with certainty. A right sense of movement is probable and is here proposed as a working hypothesis.

Many plutonic bodies of the New England Batholith truncate the trace of the Mihi Fault. Therefore, movement along this fault ceased during the late Permian and faulting in this trend was not reactivated in later geologic time.

The Peel Fault appears to have been active already in Devonian to early Carboniferous time. Moreover, both the Peel Fault and the Mihi Fault originated very likely as a result of slightly different directions of the greatest principal stress. It does not seem that they belong to a conjugate set of master faults. Insufficient detailed observations have been published on both the Peel and Mihi faults making it impossible to elaborate any further on their relationship.

Other major faults in the area :

Mooki Thrust (Figures 1 and 5)

The Mooki Thrust is a well established structural feature forming the west boundary of the Tamworth Fold Belt. The nature and the general attitude of this thrust is illustrated in a series of cross sections in Figure 3.

The history of exploration and the terminology of both the Mooki and Hunter thrusts have been adequately discussed in the various contributions included in the volume on the " Geology of New South Wales " (Packham, 1969, ed.). The practice of Bembrick and others (1973) is followed here calling the thrust north of the Murrurundi re-entrant " Mooki Thrust " (or Thrust System) and the thrust to the southeast the " Hunter Thrust ". The general terminology shown in their Figures 1 and 4 is also adopted here (Bembrick, 1973).

Based on an analysis of the many folds and faults making up the Tamworth Fold Belt, it might be suggested that the Peel Fault and the Mooki Thrust are actually just the border faults of one 40 km and to 50 km wide fault zone now known under its three main component parts, namely the Peel Fault, Tamworth Fold Belt and Mooki Thrust. In the south, near Murrurundi, the Mooki thrust swings into the Murrurundi Fault.

Hunter Thrust (Figures 1 and 5)

The way the intensity of structural deformation gradually increases in the Hunter Valley Dome Belt toward northeast, in the direction of the Hunter Thrust, is well depicted on the Newcastle 1 : 250,000 Geological Series Sheet (Rose, 1966). The six cross sections of Figure 2, illustrate this relationship and should also make it clear that for such a highly dissected belt of folds forming an upthrust block of imbricated slices, the term " Synclinorial Zone " becomes meaningless.

Demon Fault (Figures 1, 3 and 5)

According to Shaw (1966) the Demon Fault has in its type area along Demon Creek a right displacement of 30 km. Reportedly some late Permian granites have been dissected so that the activity of the fault lasted at least into the early Mesozoic. The extension of the Demon Fault toward the south is questionable, especially as its relationship with a probable fault trending through Dorrigo toward northwest, and with the Bellinger Fault is not known. Any suggested connection of the Demon Fault with some inferred faults in the area of Kempsey should be regarded as highly speculative.

New England Block (Figure 5)

The triangular shaped custal block bounded by the Peel Fault, Mihi Fault and the Birrie Geosuture (Rod, 1966) and their concealed

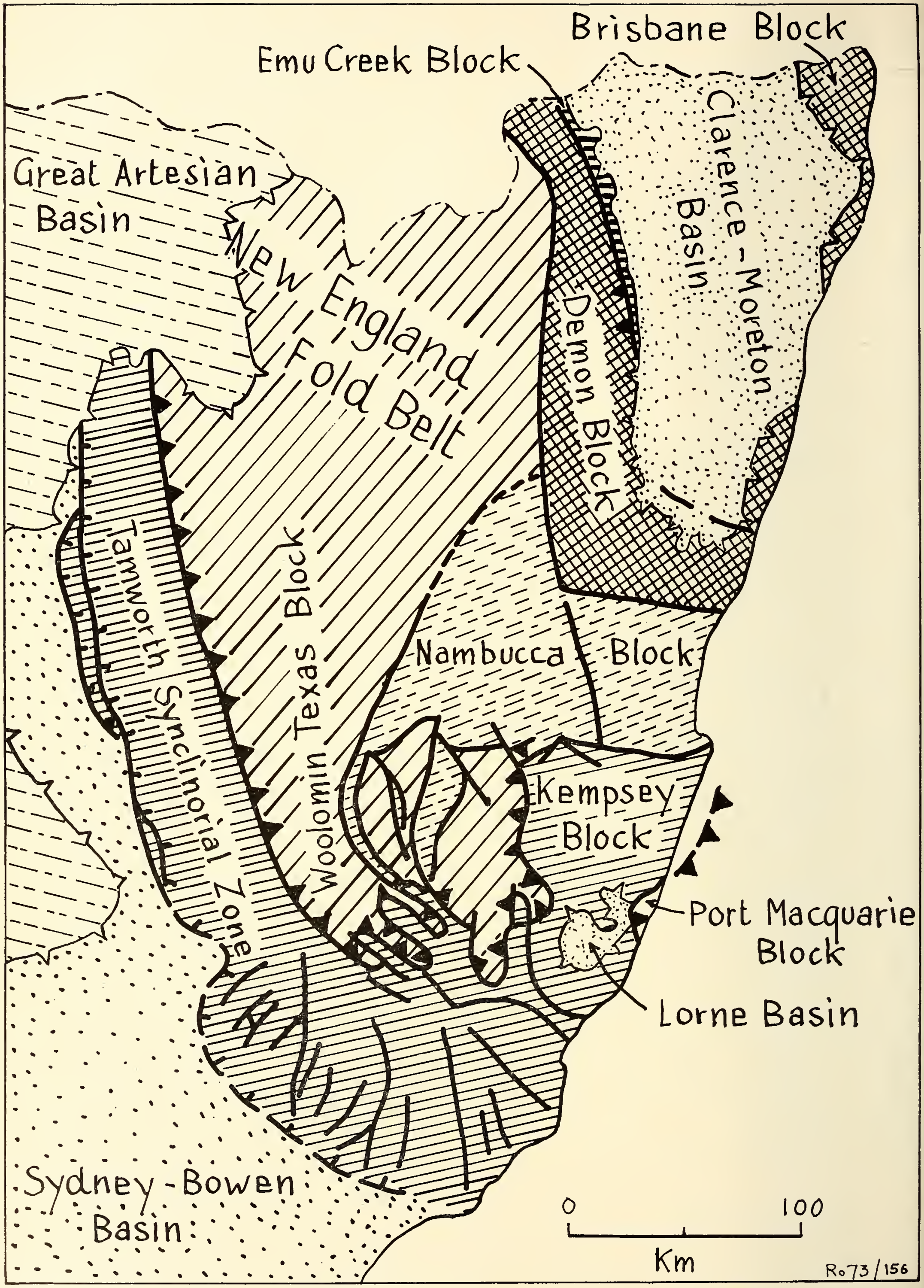


FIGURE 4.—Structural units of New England Region after portion of map called " Structural units of New South Wales " included in Geological Map of New South Wales 1 : 1,000,000 (Pogson, 1972). The colours of the original map have been rendered here by black and white patterns.

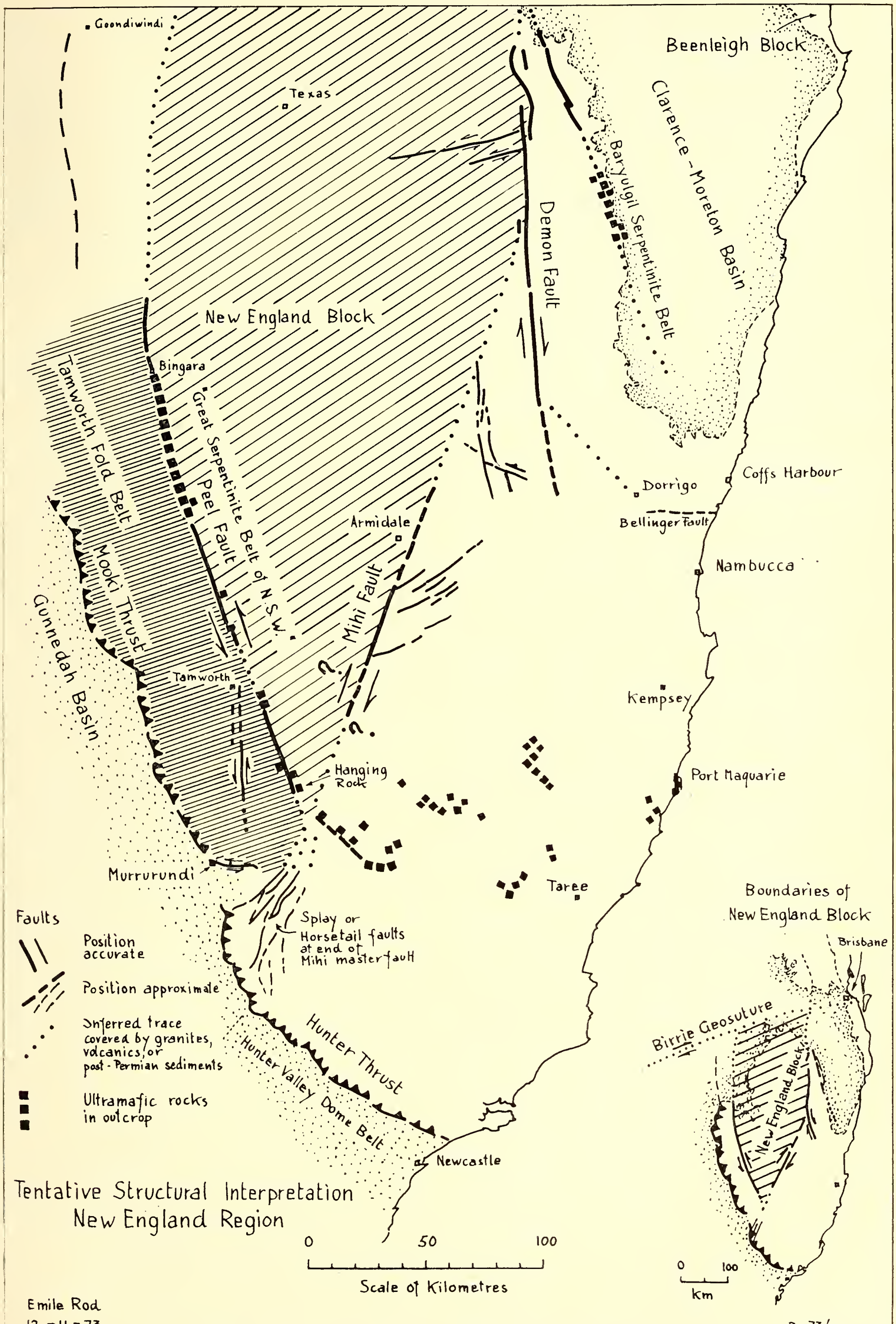


FIGURE 5.—Tentative structural interpretation of New England Region proposed in this paper.

extended traces (see Figure 5) is named the "New England Block". Previously, more or less the same structural unit was named the "New England Massif" (Hill and Denmead, 1960), or the "New England High" (Geological Society of Australia, 1971) Hill (1960) mentioned the Texas structural high as the "Queensland part of the New England massif". Moreover the term "New England Block" is widely used by geologists in Queensland. Swindon's map (1971) of the Regional Setting of the Moreton District spells it out clearly. Thus "New England" has priority over "Woolomin-Texas".

Blocks East of New England Block Named on Map "Structural Units of New South Wales" (Pogson, 1972)

On this map (see Figure 4) the following blocks were proposed:

Demon Block
Emu Block
Brisbane Block
Nambucca Block
Kempsey Block
Port Macquarie Block

None of these blocks has been well defined. They have either boundaries which are mechanically unreasonable or no clear boundaries at all. It is worthwhile to have a good look at this map which is rendered in black and white patterns as Figure 4 (after Pogson, 1972). As mentioned in the introduction, as long as the stratigraphy of all those low-grade metamorphic rocks so widely distributed in the area east of the New England Block has not been sorted out and settled, it is futile to attempt any structural analysis and subdivision. On Figure 5, this area was therefore left blank.

Beenleigh Block

As mentioned previously, the name "Brisbane" for this block is a misnomer because the city of Brisbane lies on the south east corner of the d'Aguilar Block. Moreover, Beenleigh would have priority (Swindon, 1971). It is possible that the faults associated with the north-northwesterly trending Baryulgil Serpentinite Belt might form the western boundary of this block (Figure 5).

Conclusion

A critical study of the geology of the New England Region, based mainly on the 1 : 250,000 Geological Series and the published information, reveals that, with the exception of the sedimentary basins which are well established (Sydney, Great Artesian, Clarence-Moreton and Lorne Basins) only the New England Block and the Tamworth Fold Belt can be regarded as properly defined structural units. As long as the stratigraphy of the many poorly described rock units consisting of low-grade metamorphic rocks, predominantly of argillite, phyllite, slate and greywacke, is unsettled, any further structural interpretation is in vain.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 100–113, 1974

Chance and Design: An Historical Perspective of the Chemistry* of Oral Contraceptives

A. J. Birch

Abstract—The requirement of total synthesis of sex and cortical hormones is discussed in the historical context of evolution of ideas and techniques leading to biologically active analogues. In particular, the desire to make 18- and 19-norsteroids led to development of the technique of metal-ammonia reductions and eventually to the 19-norsteroid hormones used as oral contraceptives. This history is considered against a background of the role of chance and design in scientific research in general and pharmaceutical research in particular.

Most scientists are too busy to analyse why they carry out scientific work in the way they do. If they pause to consider how creative new discoveries are made they probably think in terms of the scientific method. This method involves collecting facts, drawing logical deductions from them and testing these deductions by experiment. It is usually thought to define the respectable way to discovery. The destructive testing of hypotheses once they are initiated is vitally necessary, but the real stories behind the origins of genuinely new and creative scientific theories are rarely told, and they often do not accord with the orthodox " official " scientific approach. Although a creative scientist operates instinctively by leaps of imagination, he often feels bound to make obeisance before the official tablets. The authentic process of discovery is often rationalized in recounting to what it *should* have been, usually unconsciously. Sometimes the motives are more conscious and less admirable, designed to confer apparently greater insight on the discoverer. There is no apparent sin attached, since the primary objective is thought to be to reach the *facts* and providing these are stated the process by which they are reached is often thought to be unimportant in any case. The pathway may even be forgotten and be later recounted in terms of what *must* have happened.

The high regard for the truth, which is an absolute necessity in testing scientific theories, is often strangely missing in defining the origins of the theories. A particular manifestation is the omission of discussion of previous ideas. It is perhaps incredible but true that one highly-distinguished scientist, on being challenged on this score, replied " Am I not as good a scientist as he is; could I not have thought of this for myself? ".

This remark is not as egocentric and irrelevant as it sounds. From the viewpoint of completeness in presentation, all previous ideas should be acknowledged, but frequently these played no part in a particular crucial development, since the developer was unaware of them despite their presence in the literature. A true picture of the evolution of his ideas can therefore apparently falsify the " true " historical development of the subject, as shown by complete documentation. The size of the literature and the fallibility of abstractors guarantee large areas of ignorance. Furthermore, Journal referees who presumably know their fellow scientists, tend not to accept any statements relative to independence of ideas which cannot be demonstrably documented. That controversy is now barred under the heading of " polemics " is sometimes unfortunate, since resolutions of the origins of ideas have value quite apart from bolstering egos. On a more practical plane, demands by Journal editors and costs of publication are also factors leading to brief *logical* presentations of *facts*, presentations which not only obscure the intellectual processes involved but often falsify them.

Science is one of the most creative of intellectual activities, so falsifications, for whatever reasons, of processes of intellectual adventure, are very regrettable in cultural terms. They are also misleading for young scientists, who pursue invalid approaches, or despair, because their work does not proceed in the smooth logical manner they are often led, by reading the Journals, to believe it should.

A story tracing the origins of an idea can be told authentically only by the discoverer.

*The Liversidge Research Lecture, delivered before the Royal Society of New South Wales, 15th August, 1974.

However, to recount it thus requires an interest in and awareness of the nature of the processes as they occur, considerable intellectual honesty and detachment, and a good memory. With these requirements very consciously in mind and with a long continued interest in historical processes in science as well as in results, I recount my own contact with the course of development of synthetic sex hormone analogues.

I finished a D.Phil. degree course at Oxford, with Sir Robert Robinson, in late 1940 and was asked to join a group attempting to synthesize steroid hormones, the structural group to which the cortical and sex hormones belong. A report from the Polish underground had suggested that Luftwaffe pilots were being given cortical hormones, which are involved, for example, in shock conditions. I still have no idea whether this was true, or whether they would have been useful, but in consequence, the R.A.F. wanted reasonable quantities of substances biologically active as corticoids.

The molecules of the sex hormones and those from the adrenal cortex contain the same basic carbon skeleton (1), variations in the types of group present and in their positions leading to substances with different kinds of biological activities (Fieser and Fieser, 1959*a*). For example (1,R=CH_3, R′=OH) is the male sex hormone testosterone, and (1,R=CH_3, R′=$COCH_3$) is progesterone, one of the two types of female hormone. The molecules of cortical hormones are of the progesterone type but require for activity critical groups, containing oxygen atoms, at certain positions, such as 3, 11, 17, 21 (*cf.* 1) notably the last is needed in the 17-side chain as R′=$COCH_2OH$. Many compounds of these series have several types of biological activity although one usually preponderates, for example, a cortical hormone can also be androgenic, and androgens normally have the generalized anabolic action (stimulation of protein formation) in addition to their specialized effects on male sex organs and secondary sex characteristics.

At this time, the natural hormones were, and still now are, available only in minute amounts by extraction from animal glands. The original work on cortical molecular structures by Reichstein and Kendall (Fieser and Fieser, 1959*a*) met with great difficulties because of the rarity of the substances and because of their presence in complex mixtures of twenty or more related compounds. The development of partial synthesis, that is of chemical modification of steroids which are available naturally in large quantities, still awaited the advent of the remarkable Russell Marker and his diosgenin from Mexican yams.

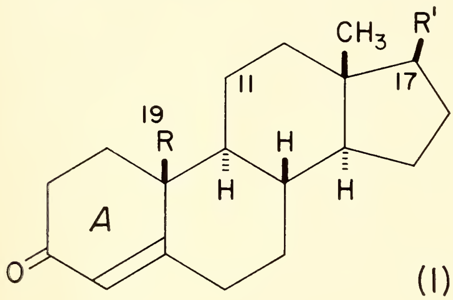
The answer, if any, then appeared to be a total synthesis, and it was a logical deduction that if the Germans had indeed succeeded in making a practical hormone, they were either producing the natural structure synthetically, or more likely were preparing a structurally simplified but biologically active analogue. The subject of sex hormone analogues was then much in mind because of recent work on stilboestrol (2, R=H), a replacement for the oestrogenic female hormone oestradiol (3, R=H).

The discovery of stilboestrol is an interesting illustration of the role of accident (Campbell *et al.*, 1938). When oestrone [the 17-ketone corresponding to (3, R=H) and the first oestrogenic hormone discovered] was shown to be a phenol, Sir Charles Dodds and Sir James Cook commenced examination of other "natural" phenols. Among those to be tested was anole (4, R=H) the phenol corresponding to anethole (4, R=CH_3) the readily available flavouring matter of aniseed.

According to the literature, drastic alkaline treatment of (4, R=CH_3) gives (4, R=H), and the product of such a reaction was tested without adequate purification. It was powerfully oestrogenic. The activity was then found to be concentrated in mother liquors from the pure phenol and was thought possibly to be due to a dimer of anole. Sir Robert Robinson, who then with Leon Goldberg collaborated on the chemical side, synthesized possible dimers, the first being stilboestrol (2, R=H) (Dodds *et al.*, 1939) which proved to be a very powerful hormone. It is still used in medicine and in veterinary practice. Later, Robinson rationalized the structural resemblance to oestradiol (3, R=H) by writing the formula of (2, R=H) as shown. This has led to the fairly general belief that it was synthesized because of this structural resemblance, although the authentic story is well documented.

A possible answer to the problem of supply of corticoids seemed to be the attachment of the highly characteristic cortical $COCH_2OH$ side-chain to a nucleus of the stilboestrol type. Even at that time there were considerable doubts about the validity of such an approach because it was becoming clear that many aromatic compounds, particularly phenols, are oestrogenic, and that oestrogenic activity is less linked to exact structure than any other hormonal activity. However, I was asked to make aromatic compounds of the general type, basically because they were easy to make.

About eighteen months of frustrating work led only and, not unexpectedly, to oestrogenic compounds. These would merely have feminized R.A.F. pilots, which was not exactly what was needed. I started in 1942 to rethink the problem on the basis of possible rational, rather than accidental, modifications of the skeleton which might assist synthesis by simplification and yet result in structures with some possibility of retaining biological activity. In pharmacological-structural relations usually there are no predictable certainties, merely finite probabilities of finding activity which make the synthetic operations worthwhile. To see what simplifications might conceivably be made with profit, let us look at the difficulties to be surmounted in a total synthesis of the natural compounds, multiplied in their effects if the synthesis needs to be employed for making quantities for practical use, rather than formally to prove a scientific point. This need for a practical synthesis was an aspect which the origins of the work had impressed on me long after the original war necessity had vanished and it led to a continued preoccupation with the possibility of a given route for large-scale production. In all probability, I could have carried out a formal total synthesis earlier but for this; for example, an abandoned procedure published in 1951 (Birch, 1951*a*) was completed by others (Narasimha Rao and Axelrod, 1965).



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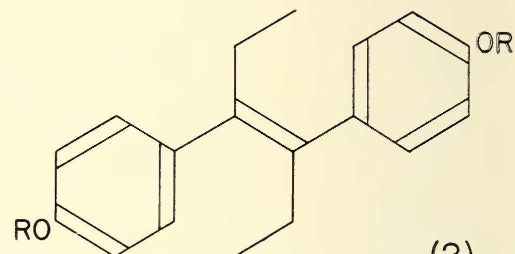

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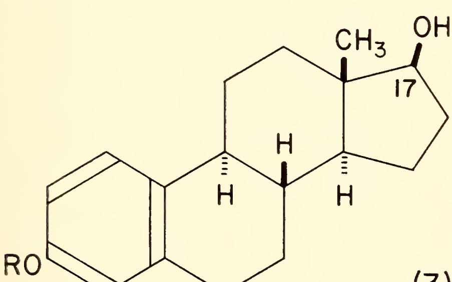

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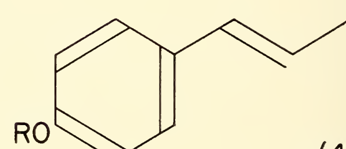


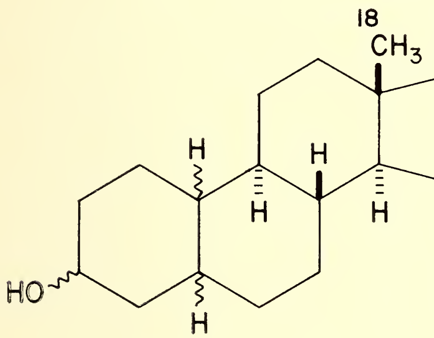
(4)

The first problem is that of stereoisomerism. There are a number of asymmetric centres, e.g. for testosterone (1, R=CH_3, R'=OH) there are 6, giving rise to the possibility of $2^6=64$ isomers with different shaped but otherwise identical molecules. Normally only one isomer is likely to be highly active (the normal series shown) (8) although progestational activity seems from the subsequent results to be less linked to exact shape than is androgenic activity. The subject of steric specificity in synthesis of cyclic systems was then in its infancy, and made notable advances only from about 1950, with Sir Derek Barton's work on conformational analysis. Some empirical correlations were then known (e.g. a relevant one was that the stable configuration of two six-membered fused rings is normally *trans*—as in the steroids). Much of the experimental work on steric specificities of reactions in complex molecules indeed grew out of the need for synthesis of steroids and other natural products.

A further synthetic difficulty was due to the presence of two *angular* CH_3 groups at 18- and 19- (e.g. 1, R=CH_3) the formation of which require the production of quaternary carbon atoms. This greatly limits tempting approaches through benzenoid precursors, made possible by the presence of the six-membered rings. Aromatic compounds are attractive because of the practical ease and known specificities of substitution and ring-closures. Reduction by direct or indirect addition of hydrogen to such benzenoid rings can lead to non-aromatic products [e.g. (5) from oestradiol (3, R=H)] (Discherl *et al.*, 1936), but the structural equivalent of addition of CH_3 rather than H required to produce the angular methyl group is more difficult, since it involves formation of new C-C rather than just C-H bonds. If CH_3 is present in the precursors it limits the number of possible synthetic procedures, although a possible one, the Robinson annelation, was known at the time. Robinson had also elaborated previously (Koebner and Robinson, 1938) a very simple route to (6) which seemed potentially capable of development for quantity production, particularly of corticoids, in view of the oxygenation at 3, 11, 17- [*cf.* corticosterone (7)]. Use of (6) would however, require elaboration of specific reduction processes. I had this route in mind, or one involving the precursors of (6), as a possible basis of our work. However, it was many years later before Subba Rao and I succeeded, as I note below, in completing such an approach.

The effect of structural, including steric, difficulties on total synthesis are shown by the historical sequence : equilenin (14, R=H) in 1937) (Backmann *et al.*, 1937) (two aromatic rings and only one angular CH_3 and two asymmetric centres), oestrone (3, R=H) in 1948 (Anner and Miescher, 1948) (one aromatic ring, one angular CH_3 and 4 asymmetric centres) and finally, the non-aromatic steroids in 1951 (Cardwell *et al.*, 1951) (no aromatic rings, two angular CH_3 and six or more asymmetric centres).

Which analogues to synthesize might be decided by starting with the natural structures and working away from them (mentally and on paper) by progressive stages, omitting structures causing difficulties in the syntheses. Compounds with the resulting structures would then have to be made and their activities examined to find at what point of structural alteration activity disappeared in a given biological series. The then known structural factors necessary for activity were first summarized. A clear requirement for high activity in all series except the oestrogens was known to be the presence of the cyclohexenone ring-A (e.g. in 1). Hydrogenation of this unsaturation normally leads in the product to lowering or loss of biological activity in any hormonal series. Another clear factor was stereochemistry. Despite a remarkable exception in the progestational series noted



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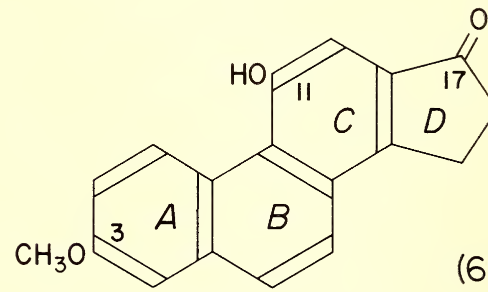

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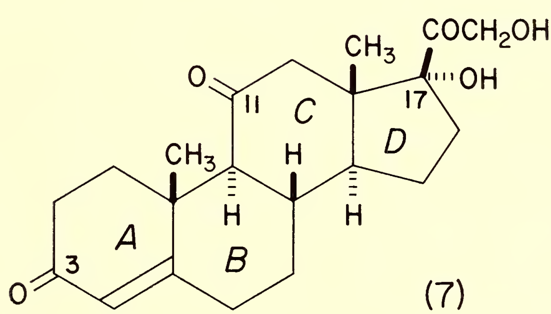
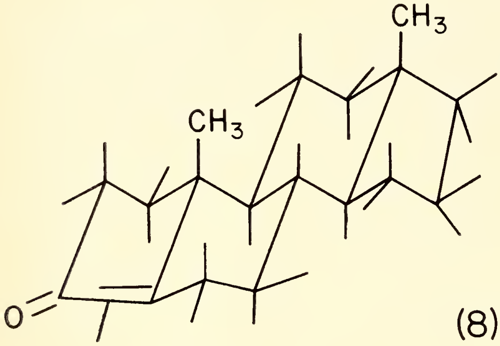


(7)

below, activity, which depends on the shape of the main skeleton, normally is found only when this is identical with the natural one [e.g. (8) is a three-dimensional model of testosterone (1, $R{=}CH_3$, $R'{=}OH$)). Even a minor steric alteration such as that of the 17-OH from β- (above) to α- (below) the ring system can abolish activity in the androgenic series.

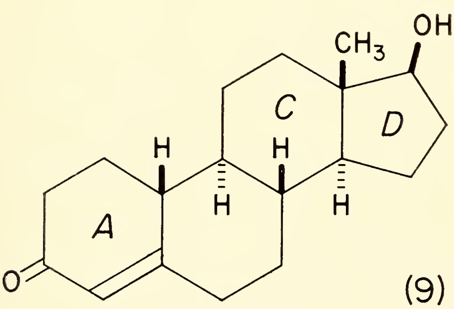


(8)

I decided from such considerations that a fairly direct method of making cyclohexenones from aromatic systems might be useful for ring-A synthesis. However, because of the practical difficulty of inserting the angular CH_3 at position 19-, the question then arose whether the presence of this group is really necessary. Omission of the 18-CH_3 would also be desirable to facilitate a synthesis using an aromatic precursor of ring-C.

On searching the literature I found one clue that the 19-CH_3 might be omitted. Oestradiol (3, R=H) had been catalytically hydrogenated (Dirscherl *et al.*, 1936) to an octahydro-derivative of undefined stereochemistry (5) which was weakly androgenic. Since this structural type of A-ring even with the complete skeleton and in the authentic stereochemical series would not be expected to confer high activity, it seemed to me of great interest to make the 19-nor analogue (9) of testosterone which contained the cyclohexenone A-ring (nor implies loss of one carbon, in this case the 19-CH_3 attached to carbon 10). My second objective was to omit the 18-CH_3, but this was liable to lead to stereochemical problems, since the C-D ring-junction is *trans* (e.g. in 9) and the stable junction is *cis*. Most syntheses would probably involve an intermediate carbonyl at the 17-position, which would permit equilibration of the stereoisomers and would almost certainly lead in consequence to the unnatural *cis* C-D junction. A six-membered D-ring would give a stable *trans* C-D junction. A practical objective was therefore to make 18, 19-bisnor-D-homotestosterone (10), retaining a good deal of the overall shape of the natural molecule.

This intuitive approach is a characteristic example, leading merely to a suggestion of what should be submitted to experimental test. Such intuitions cannot be exercized in the absence of some known facts ; frequently there are too many facts and the creativity lies in choosing which are significant in the context. In the present connection the cyclohexenone A-ring requirement was fairly obvious, but the Discherl hydrogenation result, which was critical to the decisions, was rather obscure and was deliberately sought in the form of any information available on hydrogenated oestrones. The work of Ehrenstein, discussed below, apparently did not start from this same point, since he mentions it in none of his publications, despite an implication to the effect by Fieser (Fieser and Fieser, 1959*b*).



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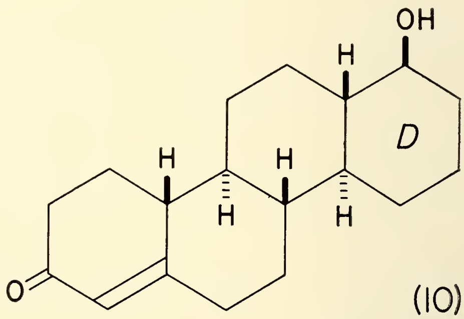


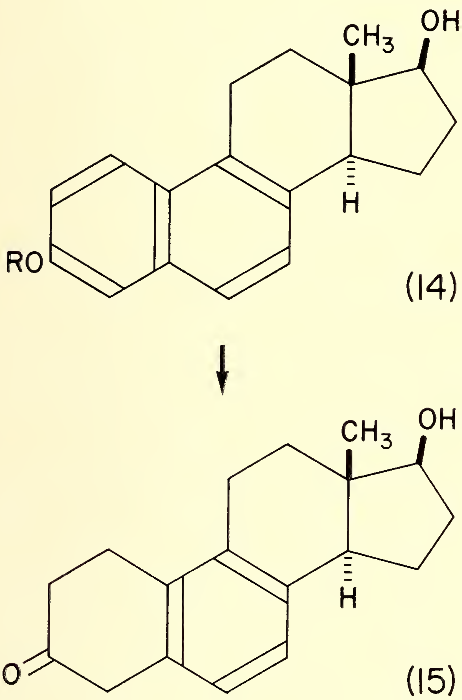
(10)

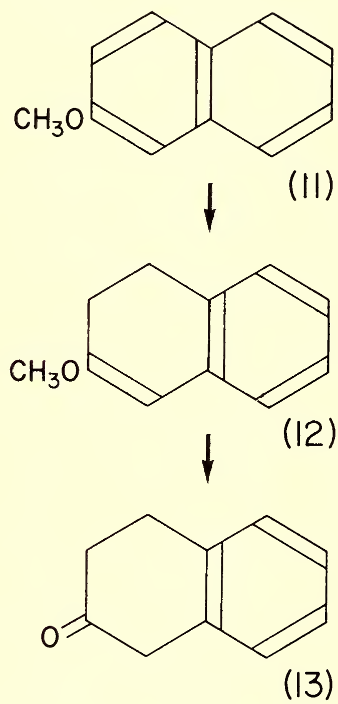
In 1942 oestrone was available only at a high price (about £25 per g) but it nevertheless seemed worthwhile to try to convert it into (9) to see whether androgenic activity resulted and whether consequently the further labour of total synthesis of this and other hormone analogues was justified. The initial synthetic problem was therefore how to obtain from the oestrone phenolic A-ring the required cyclohexenone A-ring. An objective which could more immediately be attacked experimentally, since the starting-material was available, was to modify the original approach via stilboestrol analogues to make corresponding cyclohexenones.

The reduction of aromatic rings had hitherto been by two methods: catalytic, using a transition metal and hydrogen gas, or by sodium and an alcohol. They both have severe drawbacks for the present requirements. Catalytic hydrogenations, such as used by Dirscherl,

compound interest: a four-stage synthesis at 80% per stage gives an overall molecular efficiency in the product of 41% and even two further similar stages reduce this to 26%. Yields of 80% per stage are normally very good, and a continued run of them would be unusual except in the very best synthetic sequences.

The sodium method cannot be used with monobenzenoid compounds, but its existence gave the clue to the solution of the problem. At this time Cornforth and Robinson were beginning their work on steroid total synthesis which culminated in 1951 (Cardwell *et al.*, 1951).



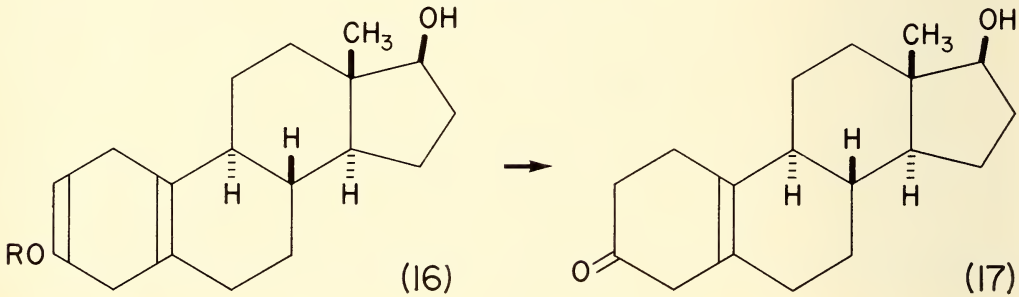


cannot usually be stopped short of saturation, stereochemistry is unpredictable and frequently resulting mixtures contain mostly *cis*-isomers, in this case undesirable. A further drawback is that oxygenated groups are frequently undesirably removed.

Although unsaturation could theoretically be reinserted after complete hydrogenation, this would almost certainly be an inefficient procedure and direct partial hydrogenation would clearly be better. In some respects, laziness can be equated with efficiency: the smaller the number of stages in a synthesis, the more likely is it to be efficient. Calculated on the basis of reverse

A key model process was the reduction by sodium and ethanol of 2-methoxynaphthalene (11) into a dihydro-derivative (probably mostly 12) which, as an enol-ether, was hydrolysed by acid to give the ketone (13) (Cornforth *et al.*, 1942). A similar reduction of equilenin methyl ether (14, R=CH_3) gave finally (15). I thought at the time that my problem would be solved if a similar process could have been carried out on an oestradiol ether (e.g. 3, R=CH_3) through (16), reaction of which with acid would yield first (17) and then the more stable 19-nortestosterone (9). Unfortunately, it was known that similar reductions of monobenzenoid compounds do not take place. This is now known to be because of the lower electron affinity of a benzene compared with a naphthalene ; the first stage of electron-addition to the aromatic ring does not take place. A search was then made of the literature, greatly assisted by a review then recently published (Campbell and Campbell, 1942) to see whether any chemical rather than catalytic reduction of monobenzenoid compounds had been reported other than the special case of benzoic acids which were well known to be reducible with sodium. Several very hopeful results were found.

In 1916 Dumanskii and Zvyerava (Dumanskii and Zvyerava, 1916) showed that benzene was converted into cyclohexa-1, 4-diene by an ammoniate of calcium, produced by the action of ammonia gas on the metal. Kazanskii



(16) (17)

(Kazanskii and Glushner, 1938) later examined the reaction further, but obtained mainly cyclohexene with some unidentified diene. Alkylbenzenes similarly were found to give chiefly l-alkylcyclohexenes. Unconjugated dienes could have been intermediates in the process since he also showed that these are further conjugated and reduced, e.g. cyclohexa-l, 4-diene gives cyclohexene. I had initially intended to examine control of this type of process in an attempt to isolate intermediates, but a more exciting prospect was based on an observation of C. B. Wooster (Wooster and Godfrey, 1937).

Sodium in liquid ammonia, which reacts with addition to naphthalenes, does not react with benzenes but Wooster found that if water or ethanol is added to such a solution containing benzene, toluene or anisole [methoxybenzene (18)] reduction occurs. The basic observation was " accidental ". Toluene was intended to be a solvent for adding other substances he wished to react with sodium in ammonia but which were insoluble in the reagent. He recovered the product by adding water, still in the presence of dissolved metal, and the hydrogen gas given off was found to be deficient by 2H for every molecule of toluene used as solvent. This deficiency also occurred with benzene and with anisole on similar treatment, and he correctly deduced that dihydro-aromatic products are formed, although he proved only the structure of the 1, 4-dihydrobenzene. Measurement of gas evolution was probably made originally to measure the metal consumption of his substrate, not of the admixed solvent, but the observation and deduction were crucial. Many workers would probably have dismissed the anomaly, since it was not closely related to the primary objective.

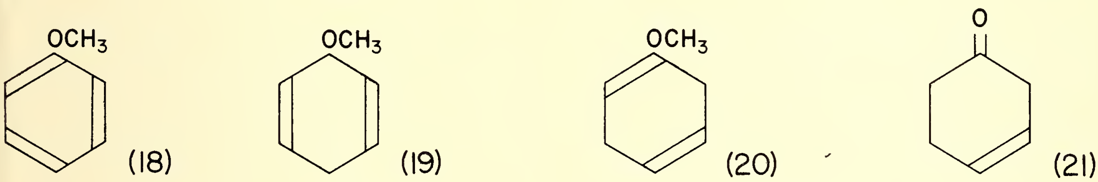
Wooster stated the anisole product to be " 1, 4-dihydroanisole " which is (19), and which on reaction with acid would probably give benzene. I thought it more likely to be 2, 5-dihydro-anisole (20), precisely the type of enol-ether required. Perhaps Wooster merely intended to indicate an opinion that the hydrogens had added *para-* to each other as with benzene. He published no more work in the area.

Accidentally, in connection with another projected steroid synthesis (Birch and Robinson, 1944*b*) I fortunately had a cylinder of ammonia in the laboratory. In 1942 it took three months or more to obtain a cylinder from ICI (Billingham) and I might otherwise well have decided not to bother to test the possibility in view of other urgent tasks. After reaction of anisole (methoxybenzene) with sodium and ethanol in ammonia, the product, which already had a different sharp smell, was reacted directly with Brady's reagent. This was calculated to hydrolyse any enol-ether and to form the 2, 4-dinitrophenylhydrazone of the cyclohexenone directly. There was an immediate orange precipitate [the derivative of (21)] which slowly changed to vermilion, rapidly on heating, to give the beautifully crystalline derivative of (22). It was a very satisfying moment.

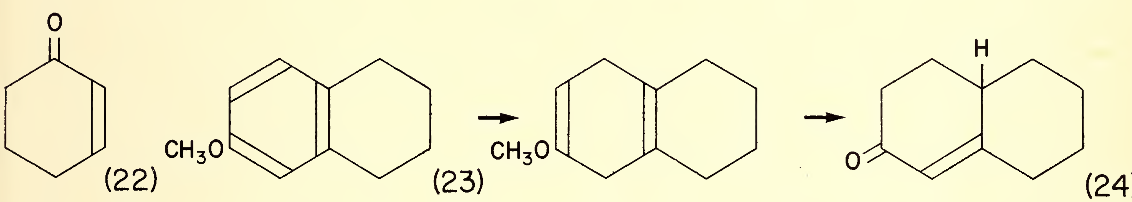
The scope and specificity of the reduction process was then further examined with available substituted anisoles. Among the reductions reported was that of (23), the simple model for oestrone methyl ether, shown to give (24) the model for 19-norsteroids. This was published in 1944 (Birch, 1944) without mention of steroid work for a number of reasons, one being that I hoped to continue the steroid line myself. However, thenceforth it must have been apparent to a steroid chemist " skilled in the art " who made the correct selection from the available literature what the application to steroids might be. Despite the large amount of work I carried out to generalize the procedure as a synthetic method, its genesis lay in steroid chemistry as outlined and it was not more or less accidentally later applied in that area. Its specificity and the simplicity and cheapness of the experimental procedure have led to wide use in sophisticated synthesis in other connections, e.g. (Birch and Subba Rao, 1972).

With the steroids themselves I had run into two types of problem : political and practical. The practical difficulties were the unavailability of oestrone, or rather of funds to buy it since I was officially still working on ring-opened analogues, and the insolubility in ammonia of the methyl ether, when I finally obtained 500 mg. Such low solubility was true also of hexoestrol dimethyl ether (25) which I wished to convert into (26). Insolubility defeated all reduction attempts. The political problems were concerned with whether I should have been carrying out such reductions at all. ICI (Dyestuffs Division, Blackley) which for some curious reason was connected with the organization of the project, was technically my employer. I was ordered to stop the reductions because of a cartel agreement with Dupont, who held a Wooster patent. I recall sorting this out at Blackley with the kind assistance of Dr. H. A. Piggott, on my first visit to Manchester in 1943, when the centre of the town was a smoking ruin, but continuation of the work was not viewed with favour.

In 1944 a tremendous impetus was given to the topic by M. Ehrenstein (Ehrenstein, 1944). His starting point was also the desire to simplify the skeleton but he set out to make 19-norprogesterone from the natural material digitoxigenin (27), which differs from most other natural steroids by having the 19-CH_3 oxidized to CHO. Simple mechanisms for its removal and replacement of H can therefore be devised. Although it was not known for certain at the time, the conversion procedures produce an unnatural C-D *cis* ring-junction and the $COCH_3$ at 17- consequently becomes stabilized in the unnatural α- instead of the β-configuration (28). The product initially obtained was amorphous and a mixture, but was claimed to be as biologically active as progesterone. Work much later, published in 1957 (Barber and Ehrenstein, 1957) reported obtaining the major product as pure (28) which, although of unnatural configuration (*cf.* 1), is more biologically active than progesterone itself. Because of the cost and rarity of digitoxigenin, the process is not a practical one, but the result led to an expectation that compounds of the natural stereochemical series would be of notable biological interest. Following this demonstration, a number of steroid chemists realized the desirability of making authentic 19-norprogesterone but were unable to devise methods to make it either by total or partial synthesis.



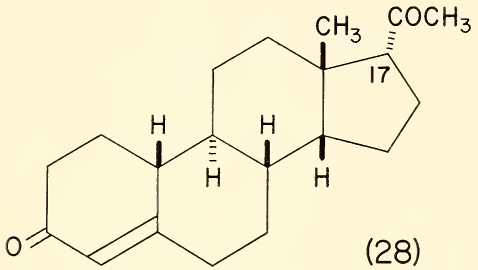
(18) (19) (20) (21)



(22) (23) (24)

Up to the end of the war, and for some time afterwards, partly in collaboration with Robinson, I was still pursuing methods which might be practical ones for the synthesis of oestrone. The closest approach, based on precursors of (6), was that of isoequilenin methyl ether (Birch *et al.*, 1945).

Our original wartime project had folded by this time and I was employed on research fellowships in Oxford which permitted me to undertake work independently of Robinson's interests. Accordingly, I was mainly engaged on examination of the reduction method, rather than with steroids which Robinson was still pursuing. Also I had no oestrone, and no research assistance. About 1946, William S. Johnson, then at Madison, wrote to me indicating that he had also made the appropriate deductions from the reduction work and was interested in making 19-norsteroids. With his usual generous approach, he desisted on learning of my progress. In 1947, following the first IUPAC Conference held after the war, I met Gilbert Stork (now at Columbia University) and explained my situation. With characteristic generosity he gave me 5 g of oestrone which he had obtained from industrial sources.



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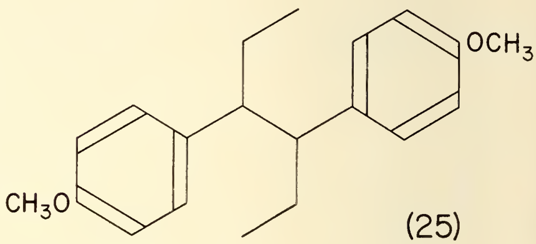

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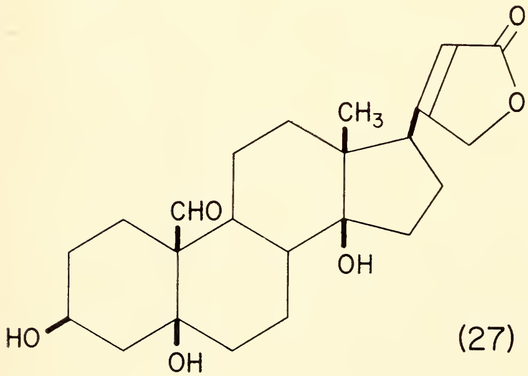

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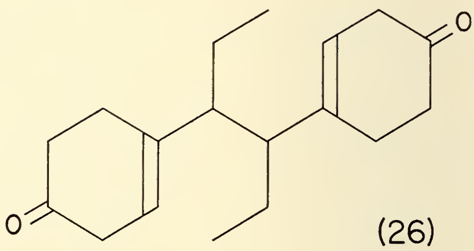


(26)

Efforts to reduce oestrone methyl ether [or oestradiol methyl ether (3, R=CH_3) into which it is converted initially by the reduction process] had been initially defeated by lack of solubility in ammonia. The ammonia was used direct from the cylinder, when it usually contains impurities such as iron which were later found to catalyse decomposition of the reducing agent. Only soluble compounds can compete with this loss. A. L. Wilds and N. A. Nelson, as the result of several years' study of the experimental conditions, evolved a technique using lithium instead of sodium which can cope with this impure ammonia. Using this technique (Wilds and Nelson, 1953), they were eventually able to reduce oestrone methyl ether. Providing purified ammonia is used, the original technique, particularly with sodium and tert-butanol (Birch, 1944), is effective and an industrial process (Colton *et al.*, 1957).

In the first synthesis of 19-nortestosterone I solved the problem in a different way. Alcohols are usually soluble in ammonia, and using the β-hydroxyethyl (1, R=CH_2CH_2OH) or glyceryl ethers of oestrone, reduction proceeded readily. The nature of the ether group is unimportant since it is removed by the acid hydrolysis. I was able also to make greater progress because, for the first time I received research assistance in the form of a collaboration with Dr. S. M. Mukherji, now Professor at Kanpur. With Stork's oestrone we were able to carry out the sequence (3, $R=OCH_2CH_2OH$ or $OCH_2CHOHCH_2OH$) to (16, $R=OCH_2CH_2OH$, etc.) to the βγ-unsaturated ketone (17) and thence to the objective (9) (Birch and Mukherji, 1949*a*) about July 1948. We also prepared (about May 1948) the dione (26) from hexoestrol dimethyl ether (Birch and Mukherji, 1949*b*). For structural reasons this undergoes only partial conjugation, and neither pure (26) nor the partially conjugated material has androgenic activity. This result appears to dispose finally of the initial ring-open approach based on stilboestrol.

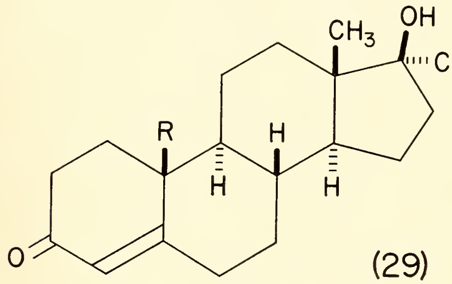
19-Nortestosterone was the first synthetic potent androgen (Birch, 1950*a*), in fact it was the first synthetic hormone other than an oestrogen if we neglect the weakly active compound of Dirscherl. Oestrone had been synthesized in 1948, so according to the rules of the game, anything made from it counted as synthetic. Unfortunately this biological activity was not known when the chemical work was published in 1950 (Birch and Mukherji, 1949*a*). The compounds (17) and (9) were both sent to ICI for testing but were withdrawn at the urgent request of Sir Robert Robinson and sent to Sir Charles Dodds at the Courtauld Institute. This action was unfortunate for two reasons : it delayed the testing by several years (until late 1950) and also publication of the chemical paper which finally was submitted without the biological results. It also removed the series from an industrial atmosphere where exploitation of the biological breakthrough might have been favoured. One ketone (17) was found to be slightly oestrogenic (Birch, 1950*a*), but 19-nortestosterone (9) has a marked androgenic activity although this is somewhat lower than that of testosterone.

In January 1949, I went to Cambridge as Smithson Fellow of the Royal Society. Lord Todd there generously obtained for me a grant in 1950 from the Nuffield Foundation and also gave me an exceptionally able Ph.D. student, Herchel Smith. By then it was probably basically too late for us to compete with industrial laboratories since both objectives and methods had become obvious. Our first objective was 19-norprogesterone followed by 19-norcortisone, as foreshadowed in the paper of 1949 (Birch and Mukherji, 1949*a*) and also in the Report of the Smithson Fellow (September 1950) in the Royal Society Yearbook 1951 (issued in January 1951) (Birch, 1951*b*). It is perhaps worth quoting (it first discusses making αβ-unsaturated cyclohexenones from phenol ethers). " Almost all of the active hormones of the cyclopentenophenanthrene group, including testosterone, progesterone and cortisone, contain such a cyclohexenone group, and the method thus provides a method of synthesizing analogues from aromatic starting materials. It cannot, however, directly provide the 19-methyl group and experiments have been carried out to determine whether this group is in fact necessary for physiological activity. The reduction of the α-oestradiol glyceryl or hydroxyethyl ether followed by acid hydrolysis and bond-migration with alkali has provided 10-nortestosterone* (*naming by the Editor, Chemical Society, now 19-nor). Since this compound is physiologically active, the methyl group is not necessary, at least in this case, and the method is being extended to make 10-nor derivatives of progesterone and desoxy-corticosterone ". These other 19-nor derivatives specifically, of natural configuration, were therefore conceived in print although not then made.

Physically, our starting material was still oestrone and we were in process of adding the $17\text{-}COCH_3$ via the $17\text{-}C{\equiv}CH$ when Carl Djerassi of Syntex, who had the aromatic progesterone already available, reported (Miramontes *et al.*, 1951) the reduction of its methyl ether by metal-ammonia solutions, using the Wilds-Nelson technique, to 19-norprogesterone, and also the high progestational activity of the product. This work is dated May 21st, 1951. Further industrial interest was evinced by Byron Riegel, then recently appointed research director of Searle, who visited Herchel Smith and me in Cambridge in, I think, 1950 to discuss our work and ideas.

It was in restrospect a mistake for us to drop the 17-acetylene work because our initial objective had been reached by others. The progestational activity of 17α-ethynyltestosterone (29, $R=CH_3$) was well known and the substance had been used medically because it is more active than natural progesterone, when given by mouth (Stavely, 1939). It was therefore logical to attach this known activating group to the 17-position in the 19-nor series and also to hope for oral activity. The Syntex work (Djerassi *et al.*, 1954) on (29, R=H) and the Searle work (Colton, 1955) for the isomer (30) are dated 1954. Both compounds are potent oral progestational agents, and were adopted as oral contraceptives, chiefly as the result of investigations by Gregory Pincus. It was well known that progesterone prevents ovulation but has to be injected. The compounds norethindrone, norethisterone (29, R=H) and norethynodrel (30) were, accidentally apart from the clue noted, highly active when given by mouth. It is of interest that initially traces of aromatic oestrogen were left, from incomplete reduction, which potentiate the activity and later were deliberately added (norinyl, enovid).

In another account of the industrial development (Djerassi, 1966), Djerassi makes the statement " The likelihood that the absence of the angular methyl group was associated with high biological activity became more remote when . . . Birch described the synthesis of 19-nortestosterone . . . which exhibited considerably lower androgenic activity than the



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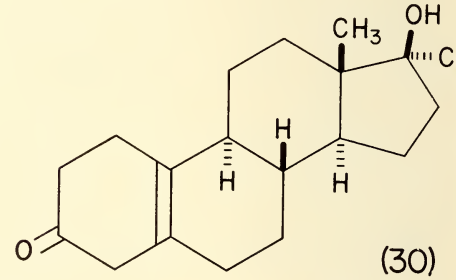


(30)

parent hormone ". This is a misunderstanding of the resulting situation. In fact Djerassi notes elsewhere (Djerassi *et al.*, 1954) after mentioning the lower activity of 19-nortestosterone " Since the mechanism of androgenic and progestational activity is not necessarily comparable it appeared of very considerable interest to synthesize 19-norprogesterone ". The importance of the 19-nortestosterone activity was that it indicated that the 19-nor series, the first with an altered carbon nucleus, showed very considerable activity in at least one hormonal series with highly structure-sensitive relationships. It was well-known that a change in activity produced by a particular structural alteration in one hormonal series is not usually parallel to change in another series. The matter of higher or lower activity in the progestational and cortical series was thus completely open, and it was clear that what was needed experimentally was to attach known activating groups for different hormonal series to the 17-position, followed by biological tests. In the 19-nor series compared with the natural series the progestational analogues were found to have higher activities, the anabolic analogues to be about as active, and the cortical analogues to have almost no activity. However important in other areas, the work would not have led to anything useful for fighter pilots.

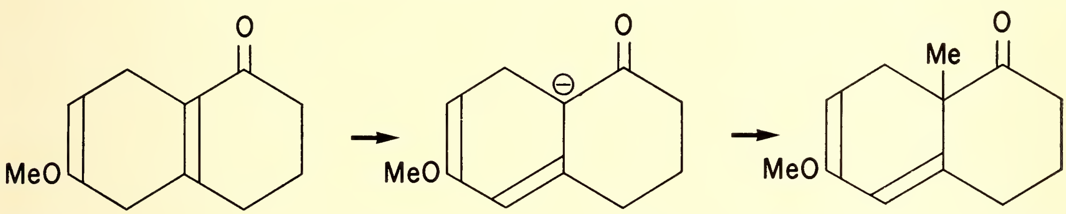
In telling this history there is an element of selection on the basis of what became important. Other ideas and lines of work to overcome synthetic problems discussed above were simultaneously conducted. The major lines concerned the introduction of angular methyl groups and the stereospecific synthesis of ring-A aromatic steroids with useful 17-substituents including new methods of closing rings. In line with my interest in general methods rather than in specific syntheses the reactions were initially more successful than the resulting syntheses. Three early methods of producing quaternary carbon atoms of scope beyond the original intention, emerged: (i) the methylanilinomethylene blocking group which I devised in 1943 (Birch and Robinson, 1944*a*) which permits substitution in the angle of rings at the CH centre of—$CHCOCH_2$—(rather than in the CH_2) which led in our hands to isoequilenin (Birch *et al.*, 1945); (ii) the copper-catalyzed addition of Grignard reagents (Birch and Robinson, 1943), developed from an observation of Kharasch (Kharasch and Tawney, 1941), which gave *cis*-9-methyldecalone from 2-octalone. The wrong stereochemistry of the process led to its neglect in the steroid connection, but later work, especially in the $LiCuR_2$ development, has had many uses; (iii) the alkylation of the correct enolate anions of αβ-unsaturated ketones, e.g. (31)→(32) (Birch *et al.*, 1952), developed from my initial work on this type of deconjugation process, the prototype being the conversion of cholest-4-en-3-one into cholest-5-en-3-one (Birch, 1950*b*), a necessary step in the total synthesis of cholesterol.

The ideas of stereochemical control were still rather primitive and based on equilibration of 6-6 ring junctions to the *trans* or steroid configuration. One example is the synthesis of (33) below, in which all of the asymmetric centres

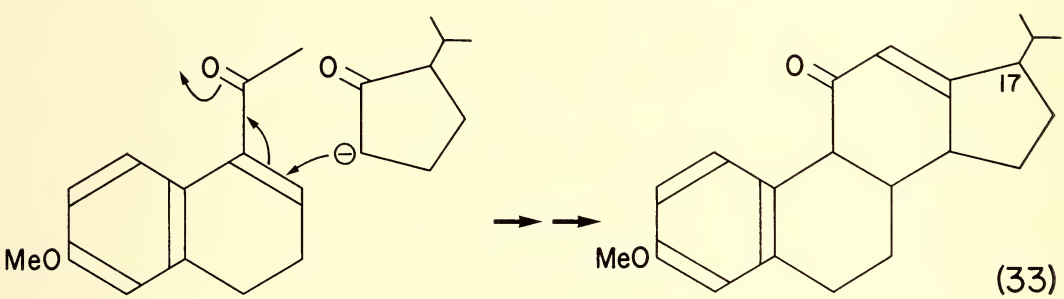
(8, 9, 14, 17) are equilibratable (adjacent or vinylic to carbonyl) (Birch and Robinson, 1944*b*). This is not pursued for two reasons: the problem of placing a useful group at 17- and the failure of additions to the unsaturated carbonyl system.

A ring-closure process which can only be briefly noted, but the discovery of which was also accidental in an interesting way, was the first use of polyphosphoric acid as a general cyclising agent for arylpropionic and butyric acids (Birch *et al.*, 1945). It was later rediscovered in an equally interesting and accidental manner (Snyder and Werber, 1950).

As a matter of some pride, although at present of no practical importance, in completing the original task I did eventually succeed in finding out how to insert the missing CH_3 groups and how to make use of intermediates in the original Robinson synthesis of (2). Inserting the 19-CH_3 turned out to be very simple (Birch *et al.*, 1964). The type of process used for (16) was employed to make (34) which on reaction with dichlorocarbene gave (35, R=Cl) which was reduced to (35, R=H), converted by acid into androstenedione (36). Since oestrone is now readily synthesized by a process due to Ananchenko and Torgov (Ananchenko and Torgov, 1959) in



(31) (32)



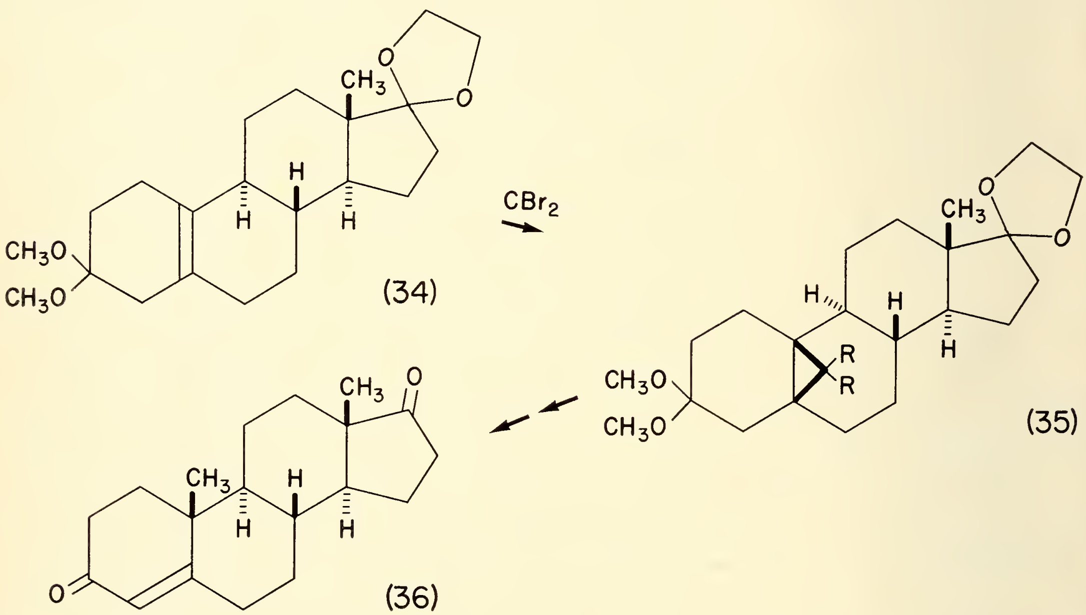
(33)

Also, Herchel Smith and I continued to make the 18-nor and 18, 19-bisnor and D-homo- series (Birch and Smith, 1956). Our work and that of others, particularly of Gilbert Stork (Stork *et al.*, 1959) showed that removal of the 18-CH_3 even with the correct stereochemistry is catastrophic for any kind of activity. Two out of the three of our original bases for action thus provied to be invalid. Much later Herchel Smith (Smith *et al.*, 1964), taking into account the loss of activity by removal of the 18-CH_3 and effectively standing the 19-nor result on its head, inserted an *extra* CH_3 on the 18-carbon (to give an ethyl group). The resulting series, related to norethindrone, proved to be the most highly progestational known, and the compound norgestrel forms a very successful low-dosage contraceptive pill.

Russia and to Herchel Smith in Manchester (Douglas *et al.*, 1963), this efficient procedure, or related ones, could be used for practical total syntheses of non-aromatic steroids. Our insertion of the 18-CH_3 and consequent synthesis of oestrone from precursors of (6) (Birch and Subba Rao, 1970) is of no practical interest compared to the Torgov-Smith procedure but completes the sequence back to the original Robinson synthesis with which we started in 1941.

What general points are there to make? One is the obvious role of accident, although to interpret Goethe and Pasteur, accident tends to favour only those who have the attitude of mind to take advantage of it. The creative process involves the choice of significant features from numbers of facts, and I have tried to indicate the conscious part of this process in the present connection. It is also a demonstration of the oblique nature of attainment of unpredictable objectives. The initial conscious objective, the synthesis of useful corticoids, was not achieved, but the need generated in that area was transferred to a new but related area. The requirement was to simplify synthesis, and a logical analysis of the situation led to a selection of literature results culminating in the metal-ammonia procedure. This in turn had much more general application, including at least one initially unexpected impact back in the steroid field due to its stereospecificity. The high oral activity in the progestational series of the new nucleus was accidental, although Ehrenstein's work was a good indicator of probable high activity. The fact that I was not encouraged initially to pursue this line of work is an indication of how difficult it was to foresee developments. No patents were taken out initially on 19-norsteroids chiefly because it appeared that they were likely to be much more expensive than the 19-Me series. Probably universities should be better organized to take advantage, materially, of breakthroughs of this type.

However, accidentally, I am pleased that, to quote a Chemical Society Christmas competition, the Birch Reduction ultimately became a birth reduction.



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(Received 17.7.1974)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 114–115, 1974

Extremally Disconnected Topological Groups

Sidney A. Morris and Alfred J. van der Poorten

Abstract—It is shown that a metrizable extremally disconnected topological space is discrete. This general result is applied to show that a non-discrete finitely generated nilpotent topological group with a subgroup topology is not extremally disconnected.

1. Introduction

Arhangelskii [1] has shown that every compactly generated extremally disconnected topological group is finitely generated (a topological space is said to be extremally disconnected if the closure of every open set is open). It is not clear, however, whether there exists a non-discrete finitely generated extremally disconnected topological group.

We show that if an extremally disconnected topological space is metrizable then it is discrete (indeed it is sufficient that the space have a countable basis of open sets at each point); this result does appear to be known in the folklore but no elegant proof seems accessible. We apply this general result to the investigation of extremally disconnected topological groups in order to conclude that a finitely generated nilpotent topological group with a subgroup topology is not extremally disconnected, unless it is discrete.

A topological group with an open basis at the identity consisting of subgroups, that is, with a subgroup topology, clearly is "rather disconnected" in the sense that each set in the open basis is open and closed. It therefore seems reasonable to search for examples of extremally disconnected groups among the subgroup topologies. The negative conclusions reached tend to suggest that a subgroup topology on any group will not be extremally disconnected unless it is discrete.

2.

Theorem: If X is a metrizable extremally disconnected topological space then it is discrete.

Proof: Since X is metrizable, for each point $x \varepsilon X$ there is a sequence $W_1, W_2, \ldots$ of open neighbourhoods of x such that $\overline{W}_1, \overline{W}_2, \ldots$ is a base of neighbourhoods at x. As X is extremally disconnected each $\overline{W}_i$ is open, so $\overline{W}_1, \overline{W}_2, \ldots$ is an open basis at x.

Without loss of generality we can therefore assume that $W_1, W_2, \ldots$ are open and closed sets, that they are an open basis at x and that $X = W_0 \supseteq W_1 \supseteq W_2 \supseteq \ldots$ Put $T_i = W_{i-1} \diagdown W_i$. So we have $W_{i-1} = W_i \cup T_i$, $W_i \cap T_i = \emptyset$ and T_i is open.

Let L be the even natural numbers, and M the odd natural numbers. Define $S = \bigcup_{l \varepsilon L} T_l$. We assert that (a) $\mathscr{C}S = \bigcup_{l \varepsilon M} T_l \cup \{x\}$ and (b) S is an open set whose closure is not open unless $\{x\}$ is open and X is thus discrete (where $\mathscr{C}S = X \diagdown S$ is the complement of the set S).

To see (a) simply note that X is the disjoint union $\bigcup_{n=1}^{\infty} T_n \cup \{x\}$. To see (b) note that if $\mathscr{C}S$ contains a non-trivial open set containing $\{x\}$ then $\mathscr{C}S \supseteq W_i$ for some i. So $\mathscr{C}S$ contains T_l for all $l > i$ which clearly contradicts the definition of S. Hence the interior of $\mathscr{C}S$ is $\bigcup_{l \varepsilon M} T_l$; so $\overline{S} = \bigcup_{l \varepsilon L} T_l \cup \{x\}$ (where $\overline{S}$ is the closure of S). Similar reasoning shows that $\overline{S}$ contains no non-trivial open set containing $\{x\}$ so $\overline{S}$ is not open unless $\{x\}$ itself is open. Consequently, if X is extremally disconnected then $\{x\}$ must be open. Since this argument holds for all $x \varepsilon X$ we see that X is discrete.

Remark: In the theorem "metrizable" can be replaced by "first countable".

3.

We apply the general result to topological groups with a subgroup topology.

Proposition: Every Hausdorff subgroup topology on a finitely generated nilpotent group G is metrizable.

Proof: G is metrizable if there exists a countable open basis at the identity. This is certainly the case if G has only countably many subgroups but any subgroup of a finitely generated nilpotent group is finitely generated (see [2; at p. 182]) and there are only a countable number of finite subsets of G.

Corollary : No non-discrete Hausdorff subgroup topology on a finitely generated nilpotent group is extremally disconnected.

Remarks :

1. In the proposition and its corollary the words " finitely generated nilpotent " can be replaced by " supersoluble" (see [2 ; at p. 212]).
2. Noting that a quotient group of an extremally disconnected group with a subgroup topology is extremally disconnected our results extend to a somewhat larger class of groups than is explicitly mentioned.

4.

The technique employed in the proof of the theorem can be adapted to prove more general propositions. We illustrate such a generalization by means of an example which shows incidentally that metrizability is certainly not a necessary condition for the result of the theorem.

Example : Let $F_2(X)$ be the vector space over the field F_2, of two elements with basis an uncountable set X ; and let the subspaces $F_2(X\setminus Y)$ where Y is a *finite* subset of X be an open basis at 0 for the topology of the additive group $F_2(X)$. Then $F_2(X)$ is not metrizable. Let $x_1,x_2, \ldots$ be a sequence of distinct elements of X and write

$$W_0=F_2(X),\ W_1=F_2(X\setminus\{x_1\}),\ W_2=F_2(X\setminus\{x_1,x_2\}), \ldots$$

Then $K=\bigcap_{n=1}^{\infty} W_n=F_2(X\setminus\{x_1,x_2, \ldots\})$ is not an open set in $F_2(X)$.

As in the proof of the theorem we write $T_i=W_{i-1}\setminus W_i$ and consider the sets $S=\bigcup_{l\varepsilon L} T_l$ and $\mathscr{C}S=\bigcup_{l\varepsilon M} T_2 \cup K$. We find that if $F_2(X)$ is extremally disconnected then we obtain the contradiction that K contains an open subgroup and so is open.

Acknowledgement

The authors wish to thank Dr. D. C. Hunt for his helpful comments.

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(Received 6.12.1973)

Journal and Proceedings, Royal Society of New South Wales, Vol. 107, pp. 116–121, 1974

Floppy Rulers and Light Pens—Reactor Mathematical Aids*

John Pollard

Abstract—Much of present day nuclear reactor mathematics is concerned with numerical methods which require the use of giant digital computers. Even as little as a quarter of a century ago sturdy rulers and ink pens were used as graphical aids to computation. These aids, or at least their computer analogues, still play a part in computation, although the present fashion is to use floppy rulers and light pens.

1. Preamble

If I were to tell you that I intend to talk about solution of the neutron reactor diffusion equation, even in the simplest form,

$$-\nabla . D\nabla\varphi+\sigma\varphi=-\frac{1}{v}\frac{\partial\varphi}{\partial t}$$

in the reactor material .. (1)

$$n.D\nabla\varphi+a\varphi=0$$

on the reactor boundary .. (2)

(where D, σ, v and a are known, n=outward normal and φ, the neutron flux, is required to be calculated as a function of space and time (t)) then I am sure you would not want to stay. I will, therefore, talk about minor matters that are, nevertheless, part of the procedure used in solving the above equations (for a somewhat more general form see Pollard 1974) when using a giant digital computer. We will use such everyday objects as rulers and pens, and computer analogues of these, to bring some focus on ideas of mathematics pertinent to the use of digital computers for nuclear reactor computation.

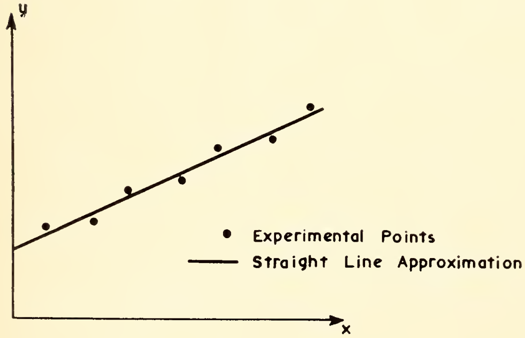

Figure 1.—A straight line fit to experimental data.

2. Sturdy Rulers

You are all familiar with the old foot ruler. Perhaps you have used one to draw in a line of best fit to some experimental data. The idea here is that the ruler is moved around on a plot of the data until the eye is satisfied with the fit as in Figure 1.

Maybe you have even tried to fit a straight line, or several straight lines, to some other continuous function as in Figure 2.

Well, a digital computer does not usually include as part of its working parts, so-called " hardware ", a ruler or an eye, so we must simulate these in order to use the machine for the type of approximation task briefly indicated so far.

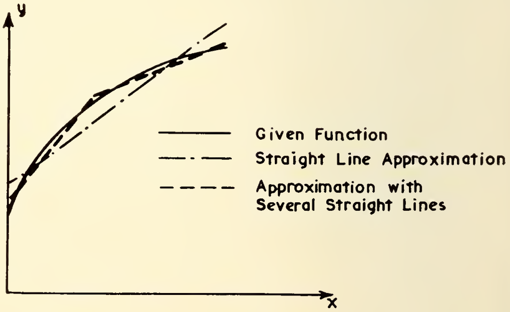

Figure 2.—A straight line fit to a given function.

2.1 *Sturdy ruler simulation*

Simulation of a ruler is easy as any father of a high school student knows. We simply have

$$y(x)=mx+c \quad .... (3)$$

with m=slope and c=intercept for the line. A digital computer can add and multiply, hence the above is easy to set as a task or " program " for the machine to calculate.

* Presidential Address delivered to the Royal Society of New South Wales at Science House, Gloucester Street, Sydney, on April 3, 1974.

2.2 *Simulation of the eye*

A mathematical analogue for an eye requires in its simplest form a measure of size of a function—that is, how big is a function? We extend the idea of size of a number x, which is simply the absolute value (magnitude) of the number, $|x|$. Mathematicians delight in the expressiveness of notation and since the size of a function $y(x)$ is a generalization of the absolute value we write for it $||y||$ and we call it a norm. Fortunately, when we make the generalization, many different norms exist. We might even say that our simulated eye sees things differently with different norms. One possible approach is to take the maximum value of the function $y(x)$ for a certain interval of x, say $[a, b]$, then

$$||y|| = \underset{x \varepsilon [a, b]}{\text{maximum}} |y(x)| \quad \ldots\ldots (4)$$

Figure 3 illustrates the idea involved here.

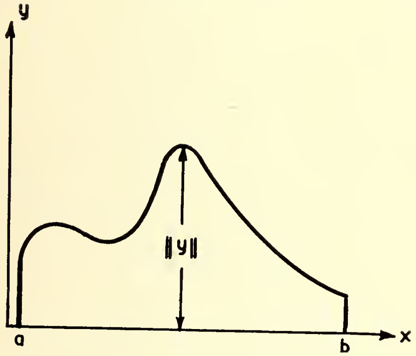

FIGURE 3.—A norm of a function.

Fairly readily we see that our norm $||y||$ given by equation (4) satisfies the desirable size properties (Kantorovich and Akilov, 1964).

1. (*a*) $||y|| > 0$, 1. (*b*) $||y|| = 0$ implies $y = 0$,
2. $||cy|| = c||y||$ for c a positive constant, and
3. $||y+z|| \leqslant ||y|| + ||z||$ (" triangle inequality ").

Using the above mathematical equipment we are able to measure the nearness of two functions $g(x)$ and $y(x)$ through the norm $||g-y||$, the size of the difference between the two functions. We may then simulate our eye fit by the mathematically precise, and computer feasible, process of calculating that $y_n(x)$ is closer to $g(x)$ than $y_m(x)$ when

$$||g-y_n|| < ||g-y_m|| \quad \ldots\ldots (5)$$

The best fit of a class of functions $y_m(x)$ to a given function $g(x)$ is then the particular function $y_n(x)$ for which

$$||g-y_n|| = \text{minimum (Meinardus, 1967)} \quad (6)$$

3. Ink Pens

Most of us are no doubt familiar with the idea of graphical display of data. At a glance, a graph is able to convey the general trend of behaviour of, say, a function $\varphi(t)$ plotted against t. Nowadays, it is fashionable and extremely useful to have graphs plotted automatically from results produced on a computer. Figures (4) to (6) illustrate the versatility of such automatic graph plotting. The results plotted are for the solution of a more general form of equation (1) from calculations on the AAEC reactor MOATA when a safety rod is suddenly dropped into the fuel in one half of the reactor in order to shut the reactor down, $\varphi(t) \to 0$ (Pollard, 1974). Figure 4 is a plot carried out by fifth form high school students at a recent AAEC Summer School (Barry *et al.*, 1974).

4. Floppy Rulers

In Figure 2 we notice that, as an approximation to the given function, we obtained a better fit, as measured by our norms, when two straight lines were used. We could obviously join together many straight lines, but the resulting many cornered approximation would not be acceptable to our human eye as it would lack smoothness. Draftsmen have been able to achieve this smoothness property in their drawing of curves by using thin beams of flexible wood or plastic called splines—these are our floppy rulers. Figure 7 shows the idea of using a spline to achieve a smooth fit to a set of exact data points, $g(x_i)$ with $x_1(=a) < x_2 < \ldots < x_n(=b)$.

4.1 *Floppy ruler simulation*

Now when the spline is only bent slightly to pass through the given points, the potential energy is proportional to

$$\int_a^b \left(\frac{d^2y}{dx^2}\right)^2 dx \text{ (Handscomb, 1966)} \quad \ldots\ldots (7)$$

and the shape taken up by the spline minimizes the above. Since mathematically $\frac{d^2y}{dx^2}$ (for small slopes $\frac{dy}{dx}$) is a measure of curvature, that is extent of bending, we could say that the spline enables a curve to be drawn through the points which minimizes curvature or is the smoothest curve through the points.

4.2 *Simulation of the eye with smoothness discernment*

In section 2.2 we sought a mathematical analogue of an eye based on the size of a function (equation (4)). Here we want to specify a smoothness measure—how about the candidate

$$||y||_2=\left\{\int_a^b\left(\frac{d^2y}{dx^2}\right)^2 dx\right\}^{\frac{1}{2}} \text{?} \quad \ldots . \quad (8)$$

through the given points and $y(x)$ is the spline through the points then

$$||y||_2<||g||_2 . \quad \ldots\ldots\ldots \quad (9)$$

In fact, if the given points are obtained from a smooth-looking function $g(x)$ then the spline fit is even smoother! We accept our candidate as an "eye" with suitable discrimination, although we must not take smoothness as an universally desirable property.

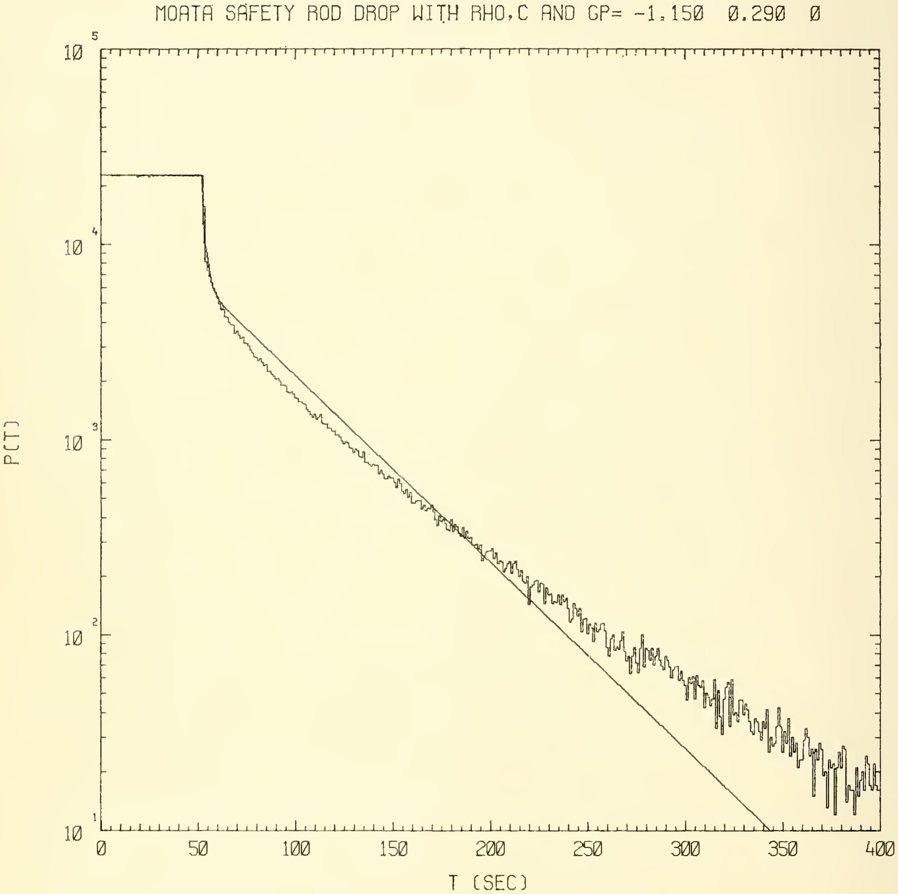

FIGURE 4.—MOATA flux $\varphi(t)$; approximation $\nabla=0$

Our desirable size properties (1) to (3) of section 2.2 are met, provided we accept the lapse that

(1. (*b*)) $||y||_2=0$ implies $y(x)=mx+c$ (an arbitrary straight line).

You could almost say that our new eye cannot see straight lines and, consequently, mathematicians term our candidate a pseudo-norm. In addition the minimum potential energy condition (7) tells us that if $g(x)$ is any curve

An interesting property of our spline $y(x)$ and pseudo-norm $||y||_2$ is that

$$||g-y||_2^2=||g||_2^2-||y||_2^2 \text{ (Holladay, 1957)}, \quad (10)$$

which immediately gives us condition (9):

$$||y||_2^2=||g||_2^2-||g-y||_2^2<||g||_2^2.$$

4.3 *Spline functions*

You might reasonably ask "what is this spline function $y(x)$?" It turns out (Ahlberg, Nilson and Walsh, 1967) that $y(x)$ is no at polynomial but rather consists of neighbouring smooth joining cubic polynomials with each cubic holding between neighbouring data points (" knots "), say corresponding to x_i and x_{i+1} and with a possible jump in $\frac{d^3y}{dx^3}$ at the knots. We have

$$y(x)=a_ix^3+b_ix^2+c_ix+d_i,\ x_i \leqslant x \leqslant x_{i+1} \quad .. \quad (11)$$

and the constants may be determined from the conditions

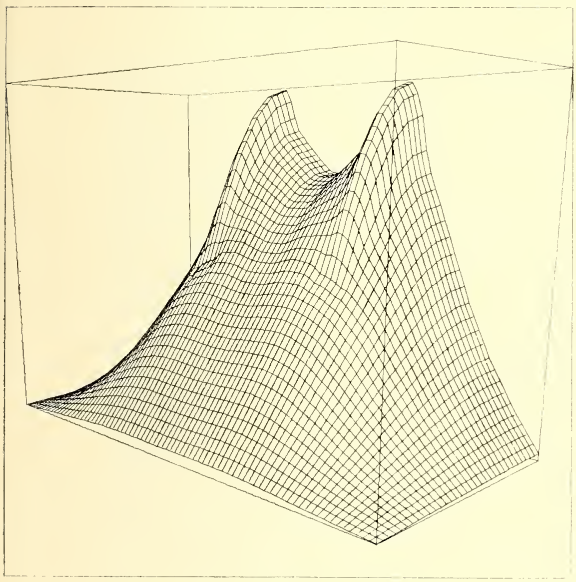

FIGURE 5.—MOATA flux $\varphi(x,y,t=0.)$

(1) continuity of y, $\frac{dy}{dx}$ and $\frac{d^2y}{dx^2}$ at the internal knots

(2) interpolation through the given data points

$y(x_i)=g(x_i)$, $i=1,2,\ldots,n$, and

(3) specification of two arbitrary end conditions, one at each end x_1 and x_n, say $\frac{d^3y}{dx^3}=0$.

Calculation of the coefficients is not a difficult task as the process may be reduced to solution of a tridiagonal set of equations, readily solvable using a forward elimination and backward substitution scheme (Ahlberg, Nilson and Walsh, 1967).

The advantage of spline approximation over polynomial approximation employing neighbouring straight lines, quadrics, etc., up to a polynomial of order $n-1$ through n data points, is its greater insensitivity to the dropping of data points and its ability to uniformly approximate not only the function but also the low order derivatives of the function.

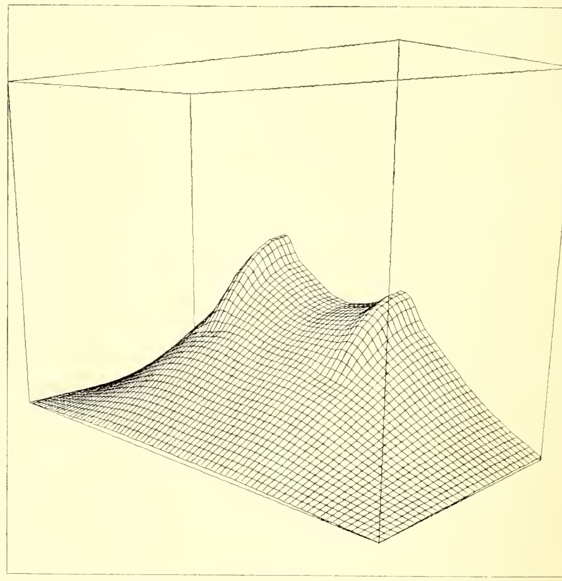

FIGURE 6.—MOATA flux $\varphi(x,y,t=1s)$.

A generalization of the spline approximation briefly outlined here, which attempts only to pass near experimentally inexact data points rather than to pass through each one, is used in reactor studies for producing smooth fits to

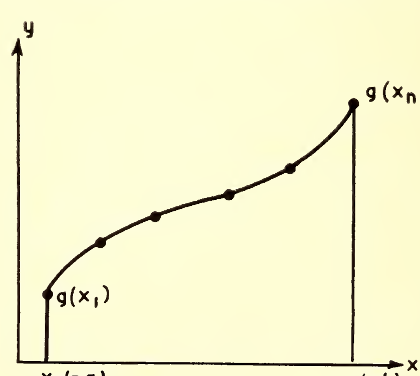

FIGURE 7. A spline fit to a set of exact data points.

basic cross section data σ as a function of reacting neutron energy (Parker, 1970). A further generalization of the idea to surface smoothing is used in vehicle body design and, indeed, one of the earliest applications for splines was in the "fairing" of ship lines (Theilheimer and Starkweather, 1961).

Figure 8 shows a spline fit to an idealized neutron resonance cross section

$$\sigma(x)=\frac{1}{1+x^2} \text{ with knots at } x=-8, -7, \ldots, 0, \ldots, 7, 8. \qquad (12)$$

In the plot the actual cross section $\sigma(x)$ and the spline fit essentially coincide. A comparison plot is also given of the (Lagrangian) polynomial of degree 16 that passes through the same knots —note that the off scale peaks are $\sigma=4\cdot8$ and $\sigma=-50$!

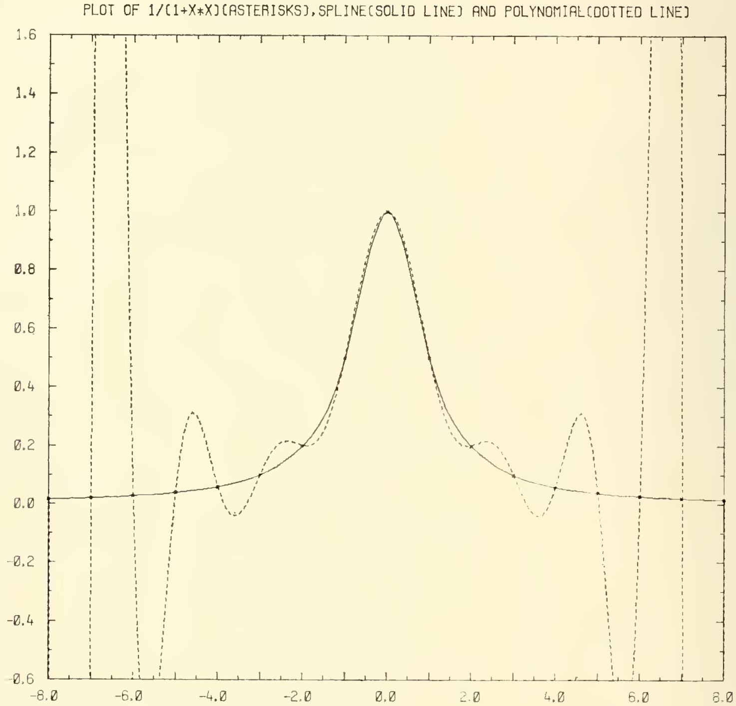

FIGURE 8.—An idealized neutron resonance cross section.

Full marks to floppy rulers—the advantage of the spline approximation over polynomial approximation is indeed marked for the example given. In general, the advantage is not as pronounced as indicated here.

5. Light Pens

In section 3 on Ink Pins we were introduced briefly to computer driven graph plotting. The graphs may also be produced on a cathode ray (TV) screen for viewing and may be photographed for later perusal. Here we meet a device, a light pen, which in essence may communicate to the computer by drawing actions carried out with the pen in near contact to the cathode ray screen. Some pens emit a light beam for user orientation, but communication to the computer is by the pen detecting the dynamic light changes of the phosphor glow on the screen with subsequent pulse signal transmission to the computer. Use of a light pen opens up a new mode of communication to a computer—we can communicate with each other through pictures!

Use of a TV screen and light pen enables new approaches to be adopted when using a computer. Draughtsmen can recall a drawing to be modified and quickly make the change using the light pen. Copies of the new drawing can then be obtained for distribution. Civil engineers can simulate driving along a road as yet still only in the planning stages. The blending of the road with the countryside can be assessed. Mechanical engineers can simulate the flight of aircraft. Body surface shapes can be quickly changed and new computer assessments tackled. Nuclear physicists can judge the smoothness of their fits to neutron cross sections, σ. New " knots " may be chosen and new fits obtained. This rapidly developing field of " computer graphics " offers not only picture presentation of already understood phenomena but, because of its interactive nature (men and computer working together), new insights can be gained into the phenomena being studied. The extensive book by Parslow and Green (1971) shows further applications covering a wide range of disciplines. Figure 9 is a photograph of the type of equipment being used for computer graphics work.

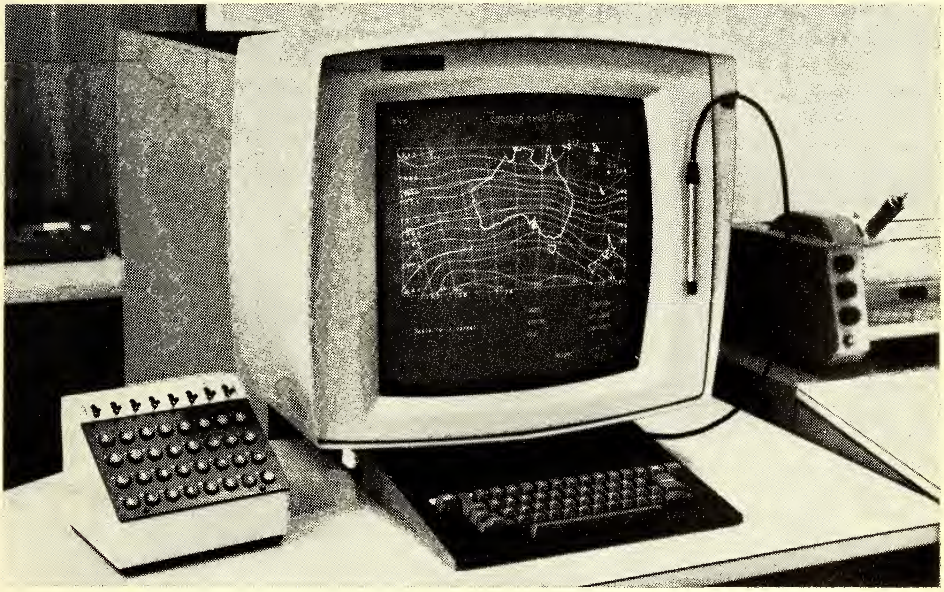

Figure 9.—The IBM2250 display.

6. What Next ?

It is to be expected that sometime during their school life present kindergarten children will use digital computers. The teaching aid could consist of a TV screen, light pen and typewriter, all connected to a computer. Not only mathematics, but perhaps unexpected subjects, geography, economics and geology, will use the teaching aid.

Acknowledgements

The slide and film presentation made use of material from the Australian Atomic Energy Commission Research Establishment (Lucas Heights), Meterological Bureau (Canberra) and International Business Machines (Canberra). Thanks are expressed to the people who made this material available.

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A.A.E.C. Research Establishment,
Lucas Heights,
New South Wales.

(Received 10.6.1974)

Review of Society's Activities

Royal Society of New South Wales Dinner*

Wednesday, 20th March, 1974

President and Members of the Royal Society of New South Wales, Ladies and Gentlemen :

Thank you for your invitation to my wife and myself to join you at your dinner tonight in The Sydney Opera House. I think that this arrangement is an imaginative one, and no doubt Sir Philip Baxter would have been a supporter of the idea. The Opera House gives excitement and charm to Sydney and is an outstanding feat of architecture and scientific construction—a feat which you have recognized in your publication last year. This story of The Opera House and its complexities is, I think, of considerable interest, and no doubt will become a valuable item in your library, particularly to future members who will wish to look back on the challenge of constructing a building which stretched technology in some respects to its limit.

I am also pleased to be here in the capacity of one of your two patrons, and am conscious of the close links between the Royal Society of New South Wales and the Governors of this State since you first formed the Philosophical Society of Australasia on the 4th July, 1821, and asked the incoming Governor, Major-General Sir Thomas Brisbane, on the 14th November of that year to accept the Presidency of the infant body. It is interesting to note that Brisbane had only arrived in the Colony a week before, on the 7th November, and he must have replied immediately to the Society's letter of the 14th, because he accepted two days later and attended his first meeting on the 2nd January, 1822. Today the rules of vice-regal patronage would prevent a governor accepting the invitation of such a newly formed body, no matter how learned its members and how estimable its aims.

Brisbane, of course, was noted for his interest in astronomy, an interest which he developed after nearly being involved in a shipwreck in 1795. In 1808 he built at Brisbane House, the second observatory in Scotland, and had been a member of the Royal Society of London since 1810. His friend, Arthur Wellesley, the Duke of Wellington, when asked about Brisbane on one occasion replied that he " kept the time of the army ". He was, however, a competent officer, and as Governor introduced a number of reforms in the Colony. He experimented in the growing of Virginian tobacco, Georgian cotton, Brazilian coffee and New Zealand dax, but without much success. He had much more success in commencing an observatory at Parramatta near his residence, and was obviously the man to be offered the Presidency of the Society. It is interesting that he equipped the observatory at his own expense, buying books and instruments, and engaging two astronomical assistants, Charles Rumker and James Dunlop. Brisbane took a detailed interest in your Society, to such an extent that when it was proposed that a commemorative tablet be erected at Kurnell to mark the point of landing of Cook, he made two special trips from Parramatta to Sydney, but on the first occasion, Botany Bay was too rough to risk a crossing from the north to the south shore, and so apparently the Governor and members of the Society had a picnic lunch and decided to return a week later. On this occasion the weather was favourable and the tablet was affixed to a rock on the shore above sea level. The inscription said : " Under the Auspices of British Science, these Shores were Discovered by James Cook and Joseph Banks, the Columbus and Myecaenas of their time. This spot once saw them ardent in the pursuit of knowledge. Now, to their memory, this tablet is inscribed in the first year of the Philosophical Society of Australasia ". I don't know whether the Plaque is still there, but I attended the Cook Bi-Centenary Celebrations at Kurnell in 1970 and did not remember any reference to the plaque.

The Founding Society was very firm in its rules, and laid down that each of its original seven members had to produce a monthly paper under penalty of £10 ; no refreshments were to be introduced except tea and coffee under penalty of £5 ; the Society was to meet every Wednesday at each other's house in Sydney in rotation, and if not present within a quarter of an hour of the time of seven o'clock, there was a fine of five shillings. Mr. Wollstonecraft was excused from one meeting because of attendance at a friend's funeral in the country, but was fined when he accepted the Governor's invitation to dine at Government House rather than fulfil his obligation to attend a meeting. Whether or not this reached the Governor's ears I do not know, but for the July meeting in 1822, the Governor invited all members of the Society to dinner to mark the anniversary.

The Philosophical Society of Australasia ceased to function early in 1823, apparently because colonial politics, particularly concerning free settlers and emancipists, and Brisbane's instructions following upon Commissioner Biggs' inquiry into affairs of the Colony left, in the words of a member, Barron field, " A baneful atmosphere of distracted politics " in which the Society " soon expired ". There was a revival on the 19th, January, 1850, when Charles Nicholson and Henry Grattan Douglass founded the Australian Philosophical Society with the object of encouraging such research as should help in developing the Colony's material resources. Obviously the Society's name was causing some difficulty, because in June of that year it was changed to " Australian Society ", and again in August to the " Australian Society for the encouragement of arts, science, commerce and agriculture ". It is no wonder that with a name like that the Society ceased to function after five years, in 1855.

Again, it was probably due to the encouragement of the then Governor that the Society was reformed as the Philosophical Society of New South Wales on the

* Address delivered by His Excellency the Governor of New South Wales, Sir Roden Cutler, V.C., K.C.M.G., K.C.V.O., C.B.E.

30th July, 1855. Sir William Denison, who was an engineer of some merit, read a paper at the first meeting entitled " The development of the railway system in England, with suggestions as to its application to the Colony of New South Wales ". He continued to write articles for the Philosophical Society, and indeed regarded this activity as compensating for what he described as the " work (of the Government) being taken out of my hands " by the formation of a Legislative Council. I should not have thought that my distinguished predecessor was a man of humour, but one of the papers which he read was " On the dental system of mollusca ". (It occurs to me that I might read this paper if I am ever asked again to the oyster farmers' luncheon.) He also took a great interest in the grounds of Government House and sought the advice of Professor John Smith of Sydney University, and one of the members of the Society's council, as to the composition of the soil in the Government House gardens and what fertilizers should be used. The Society holds a letter which Sir William Denison wrote to the Professor in October, 1858, in which he solemnly (and perhaps again without humour) sent " Dear Smith " several bags of soil and invited him to dine at Government House to discuss the matter.

The Philosophical Society of New South Wales was said to be in a " languishing condition " in 1865, and therefore in November of that year the members sought permission to change the name to " Royal Society of New South Wales ", and again this would have involved the Governor, Sir John Young, in obtaining Royal consent in September, 1866. In 1881 an Act of Parliament of New South Wales incorporated the Society. From that day the Society has continued its learned work and investigations, and I think that one of its most valuable functions has been the keeping of a library. The papers which are written by its members are carefully filed and are available with other books and documents for study and research.

The Royal Society of New South Wales may not be as widely known as it deserves, nor may its functions be fully understood. However, there is encouragement in the fact that in the last year your membership has increased by 60 to 402, and it must be remembered that the real value of your Society is in the learned qualifications of your membership, not in the total number. The medals which you award are held in high regard, and include the Clarke Medal, which has been given for the last 96 years for work in the field of natural sciences. There are others, such as the Walter Burfitt Medal for contributions to science and, since 1947, The James Cook Medal for contributions to science and human welfare in the southern hemisphere. The medal named after Edgeworth David is awarded to younger scientists for contributions in learning. These medals are a valuable source of encouragement to workers in these fields.

The purpose of the Society becomes increasingly important over the years, and in essence I should think your object is to make the public aware of the contributions of science and its influence on everyday affairs. The rapidly increasing fields of scientific study and the proliferation of scientific knowledge in recent years almost makes it an impossible task for the Society to keep the public informed. Scientific investigations and discoveries in the last 25 to 30 years have both excited public imagination and at the same time occasionally frightened the public. The Society's task is to bring a balance into people's assessment of the advantages and limitations of scientific progress. You need to encourage research and investigation, and occasionally express a word of warning.

It is, as I said, a pleasure to be with you tonight as one of your patrons. I compliment you on the work which you are doing. Thank you for the dinner and thank you for your good sense in not asking the Governor these days to read learned treatises for you.

Report of the Council for the Year Ended 31st March, 1974

Presented at the Annual General Meeting of the Society held on 3rd April, 1973 in accordance with Rule 18 (*a*).

At the end of the period under review the composition of the membership was 375 members, 21 associate members and nine honorary members.

During the year, 55 new members and five associate members were elected, and eight members were written off under Rule 5 (*b*).

It is with regret that we announce the loss by death of the following members :

Joseph James Fallon (1950).
William John Kirchner (1920).
Robert Fisher (1940).

Nine monthly meetings and two special meetings were held. The abstracts of addresses have been printed in the Notice Paper. The Proceedings of these will appear later in an issue of the *Journal and Proceedings.*

The members of Council wish to express their sincere thanks and appreciation to the 12 speakers who contributed to the success of these meetings, the average attendance being 45.

The Annual Dinner was held on the 20th March, 1974, at the Reception Hall, Sydney Opera House. The guest speaker was the Society's Patron His Excellency the Governor of New South Wales, Sir Roden Cutler, V.C., K.C.M.G., K.C.V.O., C.B.E., accompanied by Lady Cutler. The text of his speech is printed in full in this issue of *Journal.*

There were 150 members and guests present, the Honourable E. A. Willis, B.A., M.L.A., Minister for Education (accompanied Mrs. Willis) representing the Premier of New South Wales, Sir Robert Askin. Sir Philip Baxter, Honorary Member of the Society gave the vote of thanks to His Excellency.

Arrangements for the smorgasbord dinner were carried out by Executive Secretary, Mrs. Lyle and Mrs. D. F. Coleman of Sydney Chapter of Ikebana International was responsible for the Ikebana flower arrangement.

The Society's rooms were open during the Sydney Opera House Opening Fortnight in October and the Executive Secretary reported that 35 people called. Laurence Hargreaves' original drawings of the Flying Machine were of considerable interest.

Awards for 1973 were made as follows :

The Society's Medal : Prof. R. L. Stanton, M.Sc., Ph.D.

The Clarke Medal : Dr. M. R. Hatch.

The Edgeworth David Medal : Dr. C. S. Osmond.

A highly successful five-day Summer School was held during January when sixty fifth form students attended a series of laboratory workshops organized around the theme " Chemistry and Environment ".

The Society wishes to acknowledge the co-operation of the Chemical Education Committee of New South Wales and Macquarie University School of Chemistry for arranging the details of the programme and providing facilities and staff for the practical activities.

Students and staff of the School were each presented with a copy of the Society's Centenary Volume.

The Society's financial statement shows a net deficit of $5,041.

The New England Branch of the Society held five meetings and their activities will be included in the Proceedings to follow. The President, Dr. J. P. Pollard, addressed a meeting of the Branch in April.

A report of the Proceedings of the South Coast Branch will be included in the Proceedings of the Branch to follow.

The Section of Geology continued to hold regular meetings and its Annual Report is tabled.

The Council held 11 ordinary meetings. Attendances were as follows : Mr. D. S. Bridges 6 ; Mr. J. C. Cameron 11 ; Mr. E. F. Chaffer 8 ; Dr. B. F. Clancy Nil ; Dr. A. A. Day 8 ; Dr. E. E. Doherty Nil ; Mr. J. W. Humphries 10 ; Mrs. M. Krysko v. Tryst 8 ; Prof. L. J. Lawrence 6 ; Prof. R. J. W. Le Fevre 4 ; Dr. J. W. Pickett 9 ; Mr. W. H. Poggendorff 11 ; Mr. J. Pollard (in the Chair) 11 ; Mr. J. Puttock 8 ; Prof. W. B. Smith-White 6 ; Prof. W. Smith 6 ; Prof. R. L. Stanton Nil ; Dr. P. D. Tilley 6 ; Dr. A. J. Van Der Poorten 6 ; Prof. F. C. Watton 4.

The President represented the Society at : The Celebrations of the Captain Cook Landing at Kurnell and placed a wreath on the Banks Memorial ; at the Annual Dinner of the Chamber of Manufacturers of N.S.W., at the Annual Dinner of the Sydney Division of the Institution of Engineers Australia ; the Annual Dinner of the N.S.W. Division of Surveyors, Australia, at the State Reception for the delegates to the International Astronomical Congress and at the Opening of the Sydney Opera House by Her Majesty Queen Elizabeth II.

The Honorary General Secretary represented the President at a meeting of the International Association of Geology at the University of N.S.W. The President also attended meetings at the Board of Visitors of the Sydney Observatory and a meeting of the Donovan Astronomical Trust.

Eight parts of the *Journal and Proceedings* were published during the year. Volume 105, 1/2 (1972) was issued on 15th April, 1973, 3/4 on 15th September, Volume 106 (1973 1/2 on 15th November and 3/4 on 15th January, 1974). This brings the publication up to date.

Of particular interest was Volume 106, 1/2 of which was issued as the Sydney Opera House Commemorative Issue. Following a decision of Council to invite articles on the Opera House for an issue of the *Journal,* an approach was made to one of the Society's Honorary Members, Sir Philip Baxter, Chairman of the Opera House Trust. Names of interested authors were given to the Society by the Trust. This resulted in five manuscripts being presented covering some aspects of design and construction of the Opera House. Six hundred copies were printed. Following as publicity campaign these were sold and a further 300 copies printed. The Executive Secretary presented a bound copy to Sir Martin Charteris, Queen's Private Secretary, at Buckingham Palace.

Negotiations are proceeding with the National Library, Canberra for the publication of a cumulative index of the first 50 years of the *Journal and Proceedings*. A stocktake of back issues has been taken and efforts will be made to sell as many as possible before the move to the new Science House.

Gifts of surplus copies have been made, following negotiations with the Commonwealth Scientific Foundation, London, to institutions in Sri Lanka, India, Zambia and Malawi.

The Library.—The number of items received and processed was 2,502. These were periodicals received on exchange from 398 societies and institutions donations and by the purchase of periodicals in which $315 was expended.

Among the Institutions who made use of the Library through the Inter-Library Loan Scheme were :

New South Wales and Other State Government Departments : Geological Survey of New South Wales ; Metropolitan Water Sewerage and Drainage Board, Sydney ; N.S.W.—Department of Education ; N.S.W.—Department of Main Roads ; Queensland—Department of Primary Industries—Plant Pathology Library ; Victoria—Mines Department.

Commonwealth Government Departments : Bureau of Mineral Resources, Geology and Geophysics ; Atomic Energy Commission ; Research Laboratory of the Royal Australian Navy.

C.S.I.R.O. : Divisions of Animal Genetics ; Animal Physiology ; Applied Chemistry ; Fisheries and Oceanography ; Mineral Chemistry ; Textile Physics ; Food Research Library ; and National Standards Laboratory.

Universities and Colleges : Advanced Studies Library—Australian National University ; Avondale College Library, Cooranbong, N.S.W. ; Badham Library, University of Sydney ; Barr Smith Library, University of Adelaide ; Broken Hill University College ; Darling Downs Institute of Advanced Education ; Footscray Institute of Technology ; Geography Department Library, University of Sydney ; Geology Department Library, University of Sydney ; General Studies Library, Australian National University ; Macquarie University ; Mitchell College of Advanced Education ; Monash University ; New South Wales Institute of Technology, Gore Hill ; Newcastle Technical College ; Riverina College of Advanced Education ; University of Newcastle ; University of New England ; University of New South Wales ; University of Queensland ; Western Australian Institute of Technology ; Wollongong University College.

Companies : Australian Consolidated Industries Ltd., Sydney ; Australian Mineral Foundation Inc. South Australia ; Australian Oil Refining Pty. Ltd., Kurnell ; Australian Pharmaceutical Manufacturers Association, Sydney ; Colonial Sugar Refining Co. Ltd., Sydney ; Commonwealth Steel Co. Ltd., Sydney ; Conzinc Riotinto of Australia Ltd., Melbourne ; Esso Australia Ltd., Sydney ; Kennecott Explorations (Australia) Ltd., Sydney ; Peko-Wallsend Ltd., Sydney ; Roche Products Pty. Ltd., Sydney ; Shell Co. of Australia Ltd., Melbourne ; Union Carbide (Australia) Ltd., Rhodes, N.S.W.

Research Institutes : Prince Henry Hospital ; Royal North Shore Hospital.

Miscellaneous : Institution of Engineers, Sydney.

A total of 303 loans were made to the above and 50 to members of the Society. There were 50 requests for photocopying of articles with a total of 796 pages copied.

The Library has been completely dusted and a tax-deductible Library Fund has been established, representations being made to large companies who borrow from it for contributions.

New Science Centre Project : In order to perpetuate the name Science House, the name of the company formed jointly with the Linnean Society for the purpose of establishing a science centre was changed from Science Centre Pty. Ltd. to Science House Pty. Ltd. The change became possible after some earlier legal difficulties had been overcome.

The four Directors representing the Royal Society on the Board of Science House Pty. Ltd. are Mr. E. K. Chaffer, Mr. J. W. Humphries, Mr. M. J. Puttock (Vice-Chairman) and Prof. W. E. Smith.

After nearly two years of fruitless endeavour the proposal to purchase a site and erect a science centre thereon has been abandoned. Instead it is now proposed to purchase an existing building which can be suitably modified to fulfill the requirements of a science centre.

Currently, negotiations for the purchase of such a building have reached an advanced stage and in anticipation of a successful outcome, the Royal Society and the Linnean Society have each transferred to Science House Pty. Ltd., a substantial portion of the compensation monies received for the present Science House. The amount transferred by each Society was $400,000 together with interest earned. The balance, about $28,000 has been retained to meet contingencies.

The Council wishes to acknowledge the excellent work carried out during the year by the Executive Secretary, Mrs. Valda Lyle and by the Assistant Librarian, Mrs. Grace Proctor.

Honorary Treasurer's Report

There was a deficit for the period of $5,293 as against a surplus for the previous year of $1,597 resulting in a total decrease of $6,890 made up as follows :—

	$	$
Increase in general interest		1,246
Increase in sale of back numbers		405
Increase in subscriptions to journal		426
Increase in members subscriptions		561
Increase in government subsidy		251
Sale of "Sydney Opera House Commemorative Issue"		1,602
Increase in donations received		6
Increase in summer school surplus		6
		4,503
Less :		
Reduction in Science House surplus	3,347	
Reduction in sale of reprints	59	
Reduction in commission received	23	
Increase in salary costs	1,934	
Increase in printing costs	2,476	
Increase in rentals	2,191	
Increase in general expenses	1,363	
		11,393
Total decline		$6,890

At the end of the last financial year, due to the loss of income from Science House, and the intangible date of commencement of income from the new company Science House Pty. Ltd., budgets for three successive financial years were drawn up, allowing for a total deficit of $28,420, and for the year just ended a deficit of $8,491. That the year ended with a deficit of $5,293, in spite of increased salaries and the general effect of inflation is due in the main to sales of back numbers of the journal, an erratic source of income for which no budget allowance can be made. This means at least that we enter the second year of the triennium in a slightly better financial situation than anticipated.

J. W. PICKETT,
Hon. Treasurer.

Report of the South Coast Branch of the Royal Society of New South Wales

Officers :

President : B. Clancy.
Secretary : G. Doherty.
Council representative : G. Doherty.

A meeting was held at Jervis Bay on 28th April, 1973, but no further meetings were held during the past year. It is hoped to recommence regular activities shortly.

FINANCIAL STATEMENT, 1973—

Previous balance	$106.10
Accumulated interest	$12.03
Present balance	$118.13

29th March, 1974

G. DOHERTY,
Secretary.

Report of the New England Branch of the Royal Society of New South Wales

Officers :

Chairman : H. G. Royle.
Secretary-Treasurer : T. O'Shea.
Committee : R. L. Stanton, D. H. Fayle, N. H. Fletcher, I. Douglas.
Branch Representative on Council : R. L. Stanton.

The following meetings were held :

4th May, 1973 : Mr. J. Pollard, President, Royal Society of N.S.W. "Nuclear Reactors—Precambrian Times to Present Day".

7th June, 1973 : Mr. Z. J. Buzo, World Health Organization. "The Role of the Engineer in the Development of Water Resources and the Control and Elimination of Disease in Developing Countries."

12th July, 1973 : Dr. B. Tyson, McWilliams Wines, Sydney. "Wine and the Chemist."

12th October, 1973 : Professor C. M. Williams, Harvard University. "Everything You Wanted to Know about Insect Hormones and Were Afraid to Ask."

13th March, 1974 : Prof. M. W. Thring, University of London. "Energy in the 21st Century".

Financial Statement :

	$	$
Balance at University of New England	338.01	
Credit		
Interest to 29th June, 1973	5.78	
Interest to 28th December, 1973	5.05	
		348.84
Debit		
Expenses talk Mr. Buzo	29.00	
Expenses talk Professor Thring	25.00	
Advertising	7.50	
Purchase crockery	6.50	
Petty cash	7.50	
		75.50
Balance at 29th May, 1973		$273.34

29th March, 1974.

T. O'SHEA,
Secretary-Treasurer.

THE ROYAL SOCIETY OF NEW SOUTH WALES
BALANCE SHEET AS AT 28th FEBRUARY, 1974

1973 $		$	$
	RESERVES		
8,898	Library reserve		12,123
435,899	Resumption reserve—note 1		453,971
—	LIBRARY FUND		205
37,367	ACCUMULATED FUNDS		26,696
$482,164	NET FUNDS		$492,995
	Represented by:		
	CURRENT ASSETS		
602	Cash at bank and in hand	675	
—	Cash at bank—library fund	205	
—	Debtors for subscriptions—note 2	—	
428,500	Debtor for compensation	—	
828	Other current debtors and prepayments	892	
15,847	Deposits at call—note 3	30,318	
445,777			32,090
	Less:		
	CURRENT LIABILITIES		
340	Sundry creditors and accruals	674	
80	Subscriptions paid in advance	128	
9	Life members subscriptions—current portion	6	
420,000	Provision for specific commitments—note 4	—	
420,429			808
25,348	NET CURRENT ASSETS		31,282
	Add:		
	FIXED ASSETS—note 5		
1,771	Furniture and office equipment	1,868	
2	Lantern	2	
13,600	Library	13,600	
17	Pictures	16	
15,390			15,486
	INVESTMENTS—note 6		
9,680	Commonwealth bonds and inscribed stock	9,680	
9,600	Deposits at call—library reserve	12,123	
19,280			21,803
	ASSOCIATED CORPORATIONS—note 4		
—	Shares	1	
—	Advances and loans—unsecured	424,490	
—			424,491
	TRUST FUNDS—note 7		
7,000	Commonwealth bonds and inscribed stock	7,000	
2,704	Deposits at call	3,036	
9,704			10,036
	NON-CURRENT ASSETS		
2,219	Centenary volume	—	
420,000	Science centre project—note 4	—	
422,219			—
491,941			503,098
	Less:		
	NON-CURRENT LIABILITIES		
9,704	Trust funds—note 7	10,035	
73	Life members subscriptions—non-current portion	68	
9,777			10,103
$482,164	NET ASSETS		$492,995

THE ROYAL SOCIETY OF NEW SOUTH WALES
INCOME AND EXPENDITURE ACCOUNT
FOR YEAR ENDED 28th FEBRUARY, 1974

1973 $		$	$
1,848	NET SURPLUS (DEFICIT) for period before bad debts		(5,041)
	Less :		
1	INCREASE in provision for bad debts	175	
250	SUBSCRIPTIONS written off	77	
251			252
1,597	NET SURPLUS (DEFICIT) for period		(5,293)
	Add :		
438,000	COMPENSATION re resumption Science House		—
—	INTEREST on compensation investment		17,162
35,770	ACCUMULATED FUNDS brought forward from 1973		37,367
475,367	FUNDS AVAILABLE		49,236
	Less :		
438,000	TRANSFER to resumption reserve—note 1	17,162	
—	TRANSFER to library reserve	3,224	
—	CENTENARY VOLUME—stock written off	2,154	
438,000			22,540
$37,367	ACCUMULATED FUNDS—28th February, 1974		$26,696

(The above account and the balance sheet on the previous page are to be read in conjunction with the notes attached.)

(Signed) J. W. PICKETT, Hon. Treasurer. J. P. POLLARD, President.

AUDITOR'S REPORT TO THE MEMBERS

1. In our opinion : (*a*) The attached Balance Sheet and Income and Expenditure Account, together with the notes thereon, have been properly drawn up so as to correctly show the state of the Society's affairs at 28th February, 1974, and the surplus for the year ended on that date.

   (*b*) The accounting and other records have been properly kept in accordance with the Rules of the Society.

2. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

HORLEY & HORLEY,
Chartered Accountants.
Registered under the Public Accountants Registration Act 1945, as amended.

65 York Street,
Sydney.
27th March, 1974.

THE ROYAL SOCIETY OF NEW SOUTH WALES
NOTES ON ACCOUNTS—28th FEBRUARY, 1974

1. RESUMPTION RESERVE.

1973 $		$
438,000	Compensation from Sydney Cove Redevelopment Authority re the resumption of Science House	438,000
	Add :	
—	Refund of expenditure incurred to date re Science Centre Project	2,378
—	Interest on investment	17,162
438,000		457,540
	Less :	
2,102	Expenditure incurred to date re Science Centre Project	3,569
$435,898		$453,971

2. DEBTORS FOR SUBSCRIPTIONS

1973 $		$
655	Owing by members	830
	Less :	
655	Reserve for bad debts	830
$ —		$ —

3. DEPOSITS AT CALL.

1973 $		$
15,130	General funds	29,554
717	Long service leave fund	764
$15,847		$30,318

4. ASSOCIATED CORPORATIONS.

The Society is currently planning a joint venture with the Linnean Society for the establishment of a Science Centre for New South Wales and to facilitate this a company, Science House Pty. Limited, has been formed in which each Society has a 50% interest.

5. FIXED ASSETS.

The basis adopted for the valuation of fixed assets is :

Furniture and office equipment—cost less depreciation
Lantern —cost less depreciation
Library —1936 valuation
Pictures —cost less depreciation

6. INVESTMENTS.

1973 $		$
9,680	General funds	9,680
9,600	Library reserve	12,123
$19,280		$21,803

7. TRUST FUNDS.

	Clarke Memorial $	Walter Burfitt Prize $	Liversidge Bequest $	Ollé Bequest $
Capital	3,600	2,000	1,400	$ —
Revenue :				
Income for period	208	115	81	102
Less :				
Expenditure	175	—	—	—
	33	115	81	102
Balance from 1973	777	685	289	953
	$810	$800	$370	$1,055

THE ROYAL SOCIETY OF NEW SOUTH WALES
DETAILED INCOME AND EXPENDITURE ACCOUNT
FOR YEAR ENDED 28th FEBRUARY, 1974

1973 $			$
	INCOME		
3,015	Membership subscriptions—ordinary		3,440
9	—life members		9
23	Application fees		159
3,047			3,608
1,368	Subscriptions to journal		1,794
1,500	Government subsidy		1,750
$5,915	Total membership and journal income		$7,152
6,717	Science house management—share of surplus		3,370
2,088	Interest on general investments		3,334
313	Sale of reprints		254
2,413	Sale of back numbers		2,818
—	Sale of "Sydney Opera House Commemorative Issue"		1,602
23	Commission		—
17	Donations		23
—	Summer school surplus		6
$17,486	TOTAL INCOME		$18,559
	Less :		
	EXPENDITURE		
300	Accountancy		500
271	Advertising		500
132	Annual social		103
110	Audit		110
100	Branches of the Society		—
101	Cleaning		154
94	Depreciation		164
69	Electricity		76
38	Entertaining		81
135	Insurance		144
—	Legal expenses		83
429	Library purchases		315
258	Miscellaneous		762
439	Postages and telegrams		343
		$	
	Printing—Vol. 105, Parts 1–4	2,705	
	Vol. 106, Parts 1–2 "Sydney Opera House Commemorative Issue"	2,654	
	New cover design	60	
	Binding	105	
	Postages	508	
3,556			6,032
366	Printing, general and stationery		617
4,215	Rent		6,406
30	Repairs		123
4,815	Salaries and superannuation		6,749
180	Telephone		338
15,638	TOTAL EXPENDITURE		23,600
$1,848	NET SURPLUS (DEFICIT) FOR YEAR		($5,041)

Abstract of Proceedings

4th April, 1973

The one hundred and sixth Annual Meeting of the Society was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. C. Cameron was in the chair. There were present 53 members and visitors

John Robert Hardie was elected an Associate Member of the Society.

The Society's Medal for 1972 was presented to Mr. W. H. G. Poggendorff and Dr. Jonathan Stone and Dr. D. H. Napper were present to receive The Edgeworth David Medal for 1972, which was awarded jointly.

Messrs. Horley and Horley were re-elected Auditors for the Society 1973/74.

The incoming President, Mr. J. P. Pollard was installed and took the chair. The address " Sedimentary Basin Classification : with Specific Reference to Oil and Gas Occurrence in Australia " was delivered by the retiring President, Mr. J. C. Cameron, School of Applied Geology, University of New South Wales.

2nd May, 1973

The eight hundred and sixty seventh (867) Meeting of the Society was held in the Large Hall of Science House, on Wednesday, 2nd May, 1973.

The President, Mr. J. P. Pollard was in the chair. There were present 53 members and visitors.

Viliam Teodor Buchwald, Margaret A. Collier, Patrick De Deckker and Valda E. L. Lyle were elected to membership and the names of new members proposed : Jonathan Stone, Donald Harold Napper and Charles John Murray, were read for the first time.

The Council advised that it had elected Dr. Dorothy Hill to Honorary Membership of the Society at its meeting on 18th April.

The Clarke Medal for 1972 was presented to Mr. Haddon F. King, the citation read by Prof. L. J. Lawrence.

The Address : " Alchemy, Chemistry and Minerals " was delivered by Dr. D. J. Swaine, Division of Mineralogy, C.S.I.R.O., North Ryde.

6th June, 1973

The eight hundred and sixty eighth (868) Meeting of the Society was held in the Large Hall of Science House. The President, Mr. J. P. Pollard was in the chair and 36 members and visitors were present.

Jonathan Stone, Donald Harold Napper and Charles John Murray were elected members and the names of new members proposed: Timothy O'Shea, Haddon Forrester King, John Alfred Talent, Vidmantas Romualdas Labutis, Grainger Rabone Morris, Ervin Slansky and Dalway John Swaine were read for the first time.

A new Associate Member, Winifred Christian Hendry Swaine was presented to the Meeting.

The following papers were presented (by title only)

" A Method for the Exact Orientation of the Plane Table ", by A. D. Albani.

" Vesuvianite Hornfels at Queanbeyan ", by T. G.. Vallance.

" Potassium-Argon Basalt Ages and Their Significance in the Macquarie Valley ", by J. A. Dulhunty.

" Precise Observations of Minor Planets at Sydney Observatory During 1971 and 1972 ", by W. H. Robertson.

The address entitled " Traffic Safety : A Time for Reappraisal " was given by Dr. Michael Henderson, Executive Director of Traffic Safety, Traffic Safety Research Unit, Department of Motor Transport.

4th July, 1973

The eight hundred and sixty ninth (869) Meeting of the Society was held on Wednesday, 4th July, 1973.

The President, Mr. J. P. Pollard, was in the chair and 50 members and visitors were present.

The following new members were elected :

Timothy O'Shea, Haddon Forrester King, John Alfred Talent, Grainger Rabone Morris, Ervin Slansky, and Dalway John Swaine.

The meeting was advised by Council that David Joseph Gwynne was elected to associate membership at the Council Meeting on 27th May.

The address was given by Professor Hugh Muir, Professor of Physical Metallurgy and Head of the School of Metallurgy, University of New South Wales. Title of the address was " Why Metal Fails ".

1st August, 1973

The eight hundred and seventieth (870) Meeting of the Royal Society of New South Wales was held in the Large Hall, Science House.

The President, Mr. J. P. Pollard, was in the Chair and 36 members and visitors were present.

The following new members were elected :

Alberto D. Albani : Proposers M. Krysko v. Trust, J. C. Cameron.

Arthur John Birch : Proposers A. Albert, D. Brown.

Gregory Lloyd Dean-Jones : Proposers J. W. Pickett, S. J. Riley.

James Richard Bruce-Smith : Proposers R. Stanton, H. Royle.

Two papers were read by title only :

" A Note on Recurrence Sequences ", by A. J. Van der Poorten.

" Structural Analyses of the Woolgoolga District ", by R. J. Korsch.

The address " The Role of the Chemist in the Australian Wine Industry " was given by Mr. B. Tyson, Technical Manager, McWilliam's Wines and was followed by wine and cheese in the Edgeworth David Room.

20th August, 1973

A special meeting in conjunction with The Donovan Astronomical Trust was held in the Hall of Science House.

The speaker was Dr. J. Allen Hynek, Professor of Astronomy, Northwestern University, Illinois, U.S.A. a delegate to the International Astronomical Union Congress in Sydney, and the subject was " Television Astronomy ".

5th September, 1973

The eighth hundred and seventy first (871) meeting of the Royal Society of New South Wales was held in the Hall of Science House.

The Chairman, Mr. Pollard was in the Chair and there were present 45 members and visitors.

The following members were elected : William James Vagg, David Ross Gray, John Thomas Joyce, Robert Sylvester Vagg, Norman Thomas Barker, Peter Allan Williams, James Henry Green, and the Council advised the election to associate membership of Beatrice Elizabeth Riley.

Papers read by title only were :

" Occultations Observed at Sydney Observatory During 1972 ", by K. P. Sims.

" Slow Transport as a Criterion for Synchronizing Clocks ", by S. J. Prokhovnik.

" Sedimentology of Permian Rocks near Ravensworth ", by David R. Gray.

A Symposium on the Environment took place, with the following speakers :

Professor J. Green, Professor of Chemistry, Macquarie University, " Chemistry and the Environment ".

Mr. J. Steele, Assistant Director, Fauna, National Parks and Wildlife Service, " Fauna and the Environment ".

Professor Peter Spooner, School of Architecture, University of New South Wales, " Landscape and the Environment ".

3rd October, 1973

The eight hundred and seventy second (872) meeting of the Royal Society of New South Wales was held in the Hall of Science House.

There were present 20 members and visitors and the President, Mr. J. P. Pollard was in the Chair.

The following new members were elected : Francis Edward Atkins, Francis Clifford Beavis, Robert Brain, William E. Moser, William Trevor Tyrrell, John Scott, Leslie Arthur Wright, and Lyall Richard Williams.

Council advised of the receipt of the manuscript of the Clarke Memorial Lecture for 1973 " The Late Precambrian Glaciation, with Particular Reference to the Southern Hemisphere " and the following papers were presented by title only :

" The Sydney Opera House : The Contractor and Some Aspects of Stage III ", by H. R. Hoare.

" Roof Cladding of the Sydney Opera House ", by Michael Lewis.

" Acoustical Design Considerations of the Sydney Opera House ", by V. L. Jordan.

" The Design of the Concert Hall in the Sydney Opera House ", by Peter Hall.

" The Grand Organ in the Sydney Opera House ", by Ronald Sharp.

The address was given by Dr. R. S. Nielsen, Commission, Public Transport Commission of New South Wales, the subject being " Urban Transportation ".

23rd October, 1973

A special meeting of the Royal Society of New South Wales was held in the Hall of Science House, to celebrate the opening of the Sydney Opera House

The President, Mr. J. P. Pollard was in the chair and there were present 58 members and visitors.

The address " The Grand Organ in the Sydney Opera House " was given by Mr. Ronald Sharp, organ builder and was accompanied by slides and recorded music.

The vote of thanks to Mr. Sharp was given by Prof. H. Pollard, Division of Acoustics, School of Physics, University of New South Wales.

7th November, 1973

The eight hundred and seventy third (873) meeting of the Royal Society of New South Wales was held in the Hall, Science House.

The President, Mr. J. P. Pollard was in the chair and 35 members and visitors were present.

The following new members were elected : Mark Geoffrey Fisher, Peter Brian Hall, and Henry Roland Hoare.

Papers read by title only :

" The Seismicity of New South Wales ", by Lawrence Drake.

" Sympathomimetic Tertiary Amines ", by R. Buise and L. A. Williams.

" The Re-Deposition of Midden Material by Storm Waves ", by P. G. Hughes and M. E. Sullivan.

The Address " The Place of the Engineer in Society " was given by Professor J. W. Roderick, Dean of the Faculty of Engineering and Professor of Civil Engineering, University of Sydney.

5th December, 1973

The eight hundred and seventy fourth (874) meeting of The Royal Society of New South Wales was held in the Hall of Science House, 157 Gloucester Street, Sydney.

The President, Mr. J. P. Pollard, was in the chair and there were present 35 members and visitors.

The following were elected to membership : Rodney Edward Gould, Donald Keith Hughes, Wilhelm Lassen Jordan, Ronald William Sharp, Noel Charles Morgan, Philip Joseph Hughes.

The address was given by Dr. Harry Windsor, F.R.A.C.S. who discussed current trends in Heart Surgery and his recent visit to China, where he studied the use of acupuncture

Section of Geology

Abstracts of Meetings, 1973

Five meetings were held during 1973, the average attendance being 15 members and visitors.

16th MARCH (Annual Meeting):

(1) Election of office-bearers: Chairman, Dr. B. B. Guy; Hon. Secretary, Dr. E. V. Lassak.

(2) Address by Dr. B. B. Guy: " Aspects of Gossan Formation "

The minor element geochemistry of anomalous copper gossans and pseudogossans (" ironstones ") from an area 70 miles northwest of Mt. Isa, Queensland, has been investigated. Two main controls are considered to markedly influence this minor element geochemistry, viz:

(i) geochemistry of chalcopyrite and pyrite mineralization in the primary zone—pyrite being significantly enriched in Ag, As, Co, Ni, and Pb and depleted in Hg and Se, relative to chalcopyrite.

(ii) physical environment in the oxidized zone—element dispersal being influenced by the associated rocks—graphitic shales and dolomites, the former producing reducing environments, the latter alkaline environments.

Correlation and regression analysis of multi-element geochemistry data of surface ironstones is being used to distinguish gossans from pseudogossans, and pyritic from chalcopyritic sources for surface anomalies.

18th MAY (Exhibits Night):

Dr. G. Gibbons exhibited a specimen of prismatic Hawkesbury sandstone from Baulkham Hills, showing original cross-bedding and a specimen of Carboniferous conglomerate from Dungog. A pyritized limestone fragment within the conglomerate showed a weathering crust around it. All pyrite appeared to have been weathered to siderite.

Mr. I. Mumme exhibited a specimen of crystallized scholtzite from South Australia as well as slides of mining operations at the Jabiru uranium deposit in the Northern Territory.

Mr. J. Scott exhibited a specimen of green glass, possibly of volcanic origin, from the Northern Territory, as well as root concretions in sandstone from Yowals and fossil brachiopods from Suxxes Inlet.

Mrs. B. Clark exhibited a " sulphur bomb " from the eastern shore of Lake Eyre. The specimen consisted of a sulphur core with crystals of gypsum around it. The sulphur core was derived from gypsum by microbial action.

Mrs. R. Rowe exhibited worm casts from Kalbarri, W.A.

Dr. E. Lassak exhibited a specimen of petrified wood from the vicinity of Addis Ababa, Ethiopia.

20th JULY

Address by Dr. S. R. Sangameshwar: " The Economic and Barren Sulphide Deposits of the Flin Flon—Snow Lake Mineralized Belt, Canada ".

The Flin Flon—Snow Lake region comprises a belt of metamorphosed Precambrian volcanic and intrusive rocks over 100 miles long containing many base metal sulphide deposits with varying amounts of pyrite, pyrrhotite, arsenopyrite, chalcopyrite, sphalerite and galena. These are the " economic " deposits. In addition to these there are numerous " barren " sulphide deposits which are sometimes mineralogically similar but are composed mainly of iron sulphides.

A geochemical study of trace elements such as Ni, Co, Se and Te sulphur isotopes in sulphides of both " economic " and " barren " types has been made. The results suggest that these data may be useful in distinguishing between the two types of deposits in exploration programmes. Some comments are presented on the modes of formation of the two types of deposits.

21st SEPTEMBER (Exhibits Night):

Mrs. B. Clark exhibited the following specimens: lizard-like mudstone concretions from Longreach; a starfish fossil from Roma; ammonites from Normanton, trilobite resting trails from Alice Springs; and colour slides of the Henbury meteorite crater south of Alice Springs.

Mr. Percival exhibited a doubly terminated rock crystal from Kingsgate, fossils of a water plant from the Glenbourne Dam in N.S.W. and slides of fossils.

Mr. J. Scott exhibited a fragment of chalcedony-ironstone conglomerate from Yowa.

Dr. E. Lassak exhibited a selection of cut and polished gemstones from the collection of the Museum of Applied Arts and Sciences.

23rd November

Address by Mr. D. Nicholson: " Quaternary Deposits of the Port Stephens Area ".

Mr. Nicholson described in detail the geomorphology of the area and its depositional environment. Economic aspects, such as the occurrence of heavy mineral sands and of various types of clays, have also been discussed. The area is also rich in sand suitable for glass manufacture.

Citations

The Society's Medal for 1973

The Society's Medal is awarded to a member of the Society for " meritorious contributions to the advancement of science. This may include administration and organization of scientific endeavour ; and for services to the Society.

Richard Limon Stanton graduated Bachelor of Science of The University of Sydney in 1947, having been one of the pioneers of The New England University College where he had shone out as one destined to become a major contributor to geological science.

A spirit of adventure and a desire to see rocks and minerals at close quarters led him to suspend his academic career and accept the position of exploration geologist for Broken Hill South Ltd. He thereby gained extensive and detailed experience of occurrences and geological settings of the metalliferous deposits of eastern Australia. Armed with this knowledge he joined the staff of the Department of Geology of The University of Sydney in 1950. Interspersed with his field-work on the Palaeozoic rocks of central western New South Wales he carried out geological mapping of the British Solomon Islands and detailed studies of the New Caledonian chromites. Realising the influence of geological environments on ore genesis he was the first to recognize the part played by vulcanism in the formation of a special group of metalliferous deposits. He was later able to consolidate his field observations with microscopic and experimental work and the investigation of lead and sulphur isotopes.

He was awarded the Master of Science (1952) and Doctor of Philosophy (1955) degrees by The University of Sydney—and, in 1955, the Olle Research Prize by this Society. In 1956 he accepted a post-doctorate fellowship of the National Research Council of Canada to enable him to study what he judged to be volcanic arc environments in America, notably in New Brunswick. In addition, however, in close collaboration with Professor Hawley of Queen's University, Kingston, he was able to carry out intensive work on the important nickeliferous ores of Sudbury, Ontario.

On his return to Australia in 1958, he joined the staff of what had then become The University of New England and soon became Associate Professor, a position which, for personal reasons, he still holds in spite of persistent offers of overseas chairs.

Professor Stanton went abroad in 1964 as Royal Society and Nuffield Foundation Bursar to Imperial College, London and again in 1966 in response to a Fulbright award and Hoffman Fellowship to Harvard University. He was awarded the David Syme Research Prize by The University of Melbourne in 1972.

The author of over fifty scientific papers and a widely acclaimed book on " Ore Petrology " Professor Stanton has proved himself to be one of Australia's great geologists.

However, it is not only because of his outstanding contributions in geological research that the Society awards him its own medal but also because of his service to it over a number of years. He was involved in early discussions with the then president, Mr. H. Donegan with regard to the establishment of the New England Branch in 1961 and since this time has consistently maintained his early enthusiasm. He has kept it alive and flourishing. Professor R. L.Stanton is a very worthy recipient of this award. (A.H.V.)

The Clarke Medal for 1973

The Clarke Medal is awarded for distinguished work in the Natural Sciences done in or on the Australian Commonwealth and its territories. It is considered annually and is awarded in the fields of Geology, Botany and Zoology in rotation.

The award for 1973 goes to Dr. Marshall Hatch, currently a Senior Principal Research Scientist in the Division of Plant Industry, Canberra.

Dr. Hatch gained his first degree (B.Sc. Honours) at Sydney in 1955, and his Ph.D. in plant physiology in the Botany Department, Sydney in 1959. From 1955 until 1960 he held an appointment in the C.S.I.R.O. Plant Physiology Unit, Botany Department, University of Sydney, under the directorship of Dr. (now Sir) Rutherford Robertson.

In 1961 he held a post-doctoral appointment at the University of California at Davis, California, and from 1962 until 1969 held an appointment at the David North Plant Research Centre, C.S.R., Toowong, Queensland. In 1967 he held a Readership in the University of Queensland.

Whilst working at the David North Plant Research Centre, Hatch and his collaborator, Dr. Slack, became aware of work published by a Russian worker (Karpilov, 1960) and Hawaiian workers (Kortschak *et al.*, 1965) which suggested a different pathway for photosynthesis to that which was then currently accepted.

Hatch and Slack followed up this work, and formulated the first working biochemical model of the C_4 photosynthetic pathway. They then filled in the details of the process in terms of enzymes, and were able to partition the C_3 and C_4 pathways morphologically between mesophyll and vascular bundle-sheath tissues.

The C_3 pathway and the models proposed by Hatch and his co-workers, have provided striking insights into many aspects of plant science. Variation in the anatomical features of the leaf, discovered by the great German investigators of the last century, remained largely unexplained in functional terms until these models were elucidated. Since this pathway and its associated syndrome of characters appears in a number of groups of flowering plants, a fact which is itself a matter of much interest and investigation, it has been used to solve some particularly critical taxonomic problems and to evaluate phylogenetic relationships. Distributional characteristics of many groups—notably the tribes of Grasses—have taken on a new significance when correlated with the occurrence of the C_4 pathway and thus contributed further to our knowledge of Physiology, Plant Geography, Ecology and Plant Introduction techniques. Within these last four disciplines are many unsolved problems related to the C_4 pathway and it must be expected that long after the biochemical pathways are completely known, the impetous given by their discovery will continue through descriptive and experimental botany. (S. S.-W.).

Edgeworth David Medal 1973

The Edgeworth David Medal is awarded for distinguished contributions by young scientists, under the age of 35 for work done mainly in Australia or its territories or contributing to the advancement of Australian science.

The Council of the Royal Society of New South Wales has awarded the Edgeworth David Medal for 1973 to Dr. C. B. Osmond, a Senior Fellow in the Research School of Biological Sciences, Australian National University.

Dr. Osmond is an outstanding Plant Physiologist whose work in different research fields, performed mainly in Australia using Australian plants has attracted world-wide attention.

He has worked chiefly with plants from arid and saline environments where the significance of certain physiological processes can be more easily assessed. His publications fall into two main groups.

1. Studies in ion absorption.
2. Studies in Photosynthesis and Photorespiration in C_4 plants.

Dr. Osmond determined the mechanism of carbon fixation via the C_4 dicarboxylic acid pathway of photosynthesis in dichotyledonous plants. This photosynthesis is insensitive to atmospheric oxygen which is inhibitory to the process in other plants. Dr. Osmond's work has been directed to elucidating the process in C_4 plants. It represents a major advance in understanding the effective utilization of solar energy and depends essentially on his studies on ionic transport within and between leaf cells.

Dr. Osmond's achievements and his contacts abroad have contributed to substantial exchange of plant physiologists between Australia and a number of overseas countries. (W. S.-W.).

The Archibald D. Olle Prize

The Archibald D. Olle Prize may be awarded annually by the Council to a member of the Society who has submitted the best paper for publication in the Journal of the Society.

No award was made for the current year.

The James Cook Medal

The James Cook Medal may be awarded for outstanding contributions to Science and Human Welfare in and for the Southern Hemisphere.

No award was made for the current year.

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When several photographs are to be combined in one Plate, the arrangement desired for final reproduction should be clearly indicated.

Maps. Geological maps should not be larger when reduced than two pages of the printed journal. If a map does require two pages it is preferable to present it in two separate halves, each to be reduced to one-page size in the printed journal.

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