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1968-69

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JOURNAL AND PROCEEDINGS
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Journal and Proceedings, Royal Society of New South Wales, Vol. 102, pp. 1–4, 1969

Geology of the Talbragar Fossil Fish Bed Area

J. A. Dulhunty and J. Eadie

Abstract—Chert containing Jurassic plant and fish fossils occurs as loose blocks floating in soil derived by weathering from Jurassic Purlawaugh sediments overlain by remnants of Pilliga sandstone and underlain by Triassic Narrabeen sandstone. From field investigations it is concluded that the loose blocks of chert represent displaced erosional remnants, and all that is left, of an isolated lake-bed deposit now almost completely removed by erosion. The chert bed appears to have accumulated over a relatively short period of time, probably less than 250 years, and possibly as little as several seasons.

Introduction

The widely known occurrence of Jurassic fish fossils, generally referred to as the "Talbragar Fossil Fish Bed", is situated some 20 miles north-east from Gulgong, on Farr's Hill, in Portion 14, Parish of Bligh. Hard cherty shale containing Jurassic plant and fish fossils (Woodward, 1895; Wade, 1942) occurs as loose blocks floating in soil derived from weathering of soft argillaceous sedimentary rocks. The occurrence was originally described (David and Pittman, 1895) as Jurassic sediments infilling an erosion hollow in Triassic sandstone. Later it was established (Dulhunty, 1938) that the Fish Bed Chert was associated with an outlier of Jurassic sediments, then described as Munmurra sandstone and Comiala shales, but now known to be equivalent to the Pilliga sandstone and Purlawaugh Formation, outcropping over wide areas to the north (Offenberg, 1968; Offenberg, Rose and Packham, 1968). It was also suggested by Dulhunty that the chert may have been deposited in an erosion hollow in the Jurassic Pilliga sandstone. However, details of occurrence and relations to associated Jurassic sediments remained uncertain as all outcrops were largely concealed by deep soil on gently sloping hillsides.

Recently, a more exact understanding of the geology of occurrence of the Fish Bed Chert became necessary in connection with biological studies of the fossil fish, and an investigation, results of which are recorded in this paper, was undertaken by the present authors.

General Stratigraphy

The general stratigraphical sequence, in the vicinity of Farr's Hill, is indicated in the legend and map of Fig. 1. The oldest sedimentary rocks outcropping in the area are Triassic sandstones. They are continuous across the Main Divide, with sandstones of the Narrabeen Group to the east and north-east in the Goulburn River-Rylstone-Capertee region.

Younger Mesozoic sediments, lying upon the Triassic sandstone, have been extensively dissected and removed by erosion in the Farr's Hill area, and occur only as ridge-cappings and outliers. The lowest is a bed of blue-grey carbonaceous shale about 20 feet thick. It forms a well-marked horizon throughout most of the area, but is absent in the vicinity of the Fish Bed Chert, as shown in Fig. 1, having been removed by erosion immediately following deposition. The blue-grey shale is overlain by about 60 feet of alternating sandstone and shaley beds with predominating grey-white and yellow-grey coloration. Next in sequence come some 80 feet of ferruginous shales, mudstones and lithic sandstones, which produce rich red and brown soils with haematitic and limonitic concretions, and with which the Fish Bed Chert is associated. These ferruginous sediments have been traced north by means of outliers to the vicinity of Uarbry, where they become continuous with sediments of the Jurassic Purlawaugh formation in the Coolah-Binnaway-Coonabarabran region to the north-west. Above the Purlawaugh sediments, on top of Farr's Hill, there occur remnants of a coarse pebbly ferruginous quartz sandstone which has been correlated with the Pilliga sandstone overlying Purlawaugh sediments to the north.

Of the foregoing stratigraphical sequence the Pilliga sandstone and Purlawaugh sediments are Jurassic in age, and the basal Narrabeen Group sandstones are Triassic but, as indicated in Fig. 1, the exact ages of the two intervening series of beds have not yet been established.

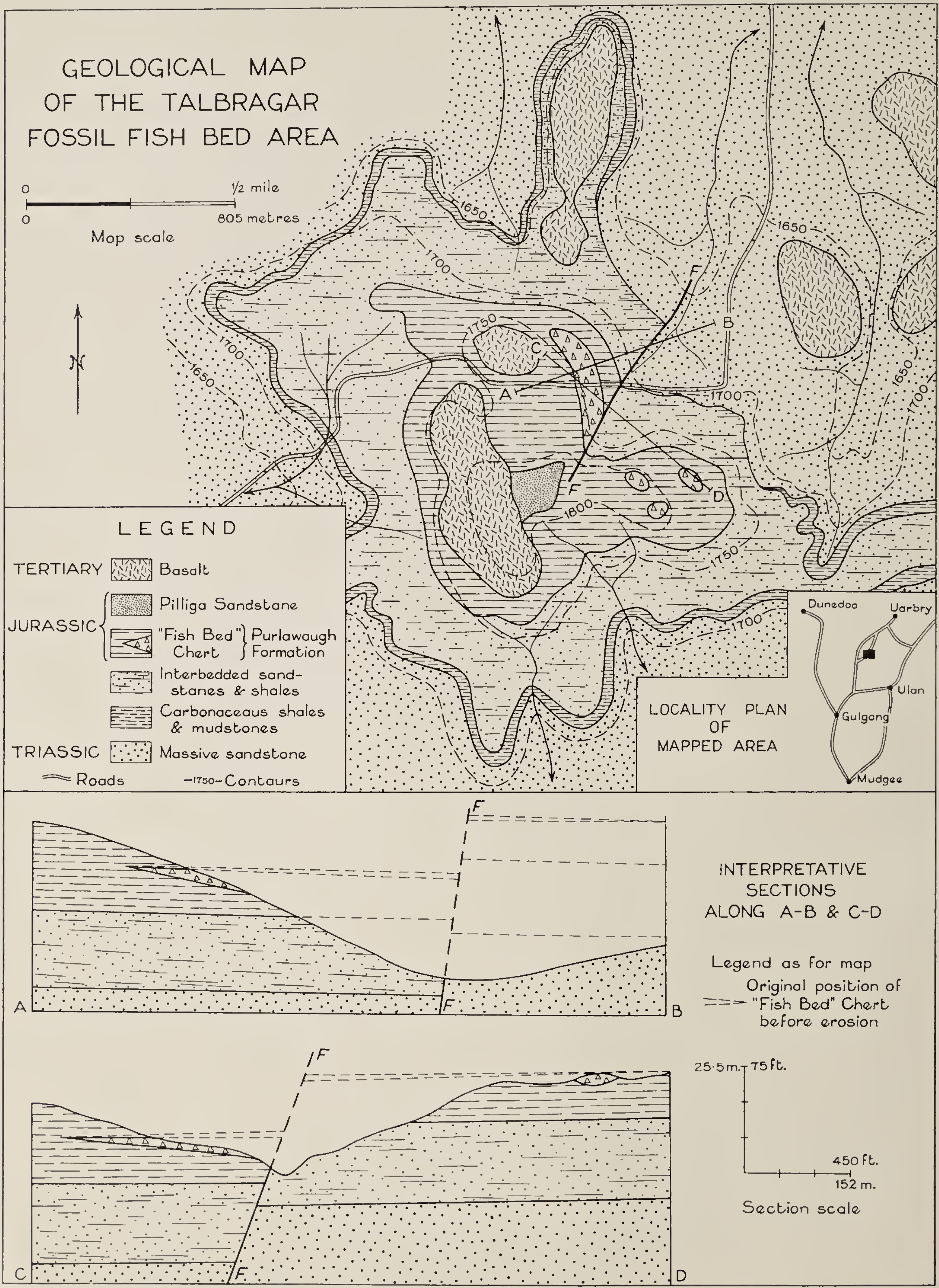
GEOLOGICAL MAP OF THE TALBRAGAR FOSSIL FISH BED AREA
0 ½ mile
0 805 metres
Map scale
N
LEGEND
TERTIARY Basalt
JURASSIC Pilliga Sandstone
"Fish Bed" Chert } Purlawaugh Formation
Interbedded sandstones & shales
Carbonaceous shales & mudstones
TRIASSIC Massive sandstone
Roads
-1750- Contours
1650
1700
1750
1800
A
B
C
D
F
LOCALITY PLAN OF MAPPED AREA
Dunedoo
Uarbry
Ulan
Gulgong
Mudgee
INTERPRETATIVE SECTIONS ALONG A-B & C-D
Legend as for map
Original position of "Fish Bed" Chert before erosion
25·5 m. 75 ft.
450 ft.
152 m.
Section scale

Fig. 1.

Mode of Occurrence of the Fish Bed Chert

The Fish Bed Chert is a hard, fine limonitic cherty-shale containing Jurassic plant and fish fossils perfectly preserved with moderate compression parallel to the bedding. It occurs as loose floating blocks lying in soil on a gently sloping hillside. The occurrence is limited to one main area on the north-eastern side of Farr's Hill and three very small areas on the eastern side, as illustrated in Fig. 1. The main area of occurrence extends for some 900 feet round the hillside, and is about 200 feet wide. The blocks of chert occur most abundantly near the centre of the area on its downhill side. To the north-west, round the hillside, the amount of chert rapidly decreases and then disappears completely to the north-western extremity of the area of occurrence. To the south-east, along the hillside, it also decreases until the area of occurrence terminates at the outcrop of a fault running from south-west to north-east down along a small creek. The fault with a vertical displacement of about 50 feet dislocates all beds outcropping immediately to the north-east of the Fish Bed Chert (see Fig. 1), but it does not extend south-west beyond the top of Farr's Hill.

The three very small areas in which Fish Bed Chert occurs, on the eastern side of Farr's Hill, are situated to the south-east of the fault at a level approximately 50 feet above that of the main area. No Fish Bed Chert, or any other material of similar or related lithology, occurs on the southern, south-western or western sides of Farr's Hill.

The blocks of Fish Bed Chert vary in size from small chips to rectangular slabs measuring as much as 18 inches across the bedding and 24 inches by 24 inches on surfaces parallel to the bedding, and weighing up to 300 and 400 pounds. They all cleave readily along the bedding and exhibit strong jointing at right angles. Nowhere do the blocks of chert occur *in situ*, nor are they arranged in any orderly manner. Small chips are scattered with their bedding at all angles to the horizontal, and the larger slabs are inclined in various directions, but mainly downhill, at angles of up to 20° and 30°.

The possibility of the chert blocks representing the outcrop of a continuous bed extending into Farr's Hill was investigated by sinking a shaft to a depth of 8 feet on the uphill side of the main area of occurrence, near the intersection of section lines A–B and C–D in Fig. 1. The shaft passed down through 18 inches of red-yellow surface soil, 18 inches of light cream-coloured clay with small fragments of fossiliferous chert up to 4 inches in diameter, 24 inches of fine cream-coloured clay with larger scattered blocks of chert up to 9 inches in diameter, and finally through 36 inches of white granular gritty clay without any trace of chert. The fragments and blocks of chert encountered in the shaft were generally smaller, softer, less ferruginous and less abundant than those occurring in the soil at the surface further downhill. The generally inferior nature of the chert occurrence penetrated in the shaft strongly suggests that the surface blocks of Fish Bed Chert do not become more abundant and closely packed underground to form a continuous bed passing into the hillside, as would be expected in the case of the outcrop of a normal flat-lying bed. Similarly, the very limited lateral extent of surface blocks round the hillside at the levels of the areas of occurrence does not indicate a continuous bed of chert extending any significant distance into the hill behind a surface outcrop.

Conclusions

In view of its special features of occurrence, it was concluded that the scattered blocks of Fish Bed Chert, lying on the side of Farr's Hill, represent the displaced erosional remnants, and all that is left of a small marginal section, or arc, of a lens-shaped lake-bed deposit originally situated to the north-east but now almost completely removed by erosion. This is illustrated by means of interpretative sections along lines A–B and C–D in Fig. 1, with reconstruction of the position of the original lens after faulting but before erosion to present surface topography. Based on this interpretation, it follows that excavation of the hillside is unlikely to yield any appreciable additional quantity of Fish Bed Chert.

The relatively small number of larger chert slabs, all of about the same thickness, with very similar lithology and structure in cross-section, strongly suggests that the material all came from one thin bed no more than 24 inches in thickness. This chert lens or lake deposit, with its fossil remains, must have originated under very specialized and unusual conditions of sedimentation, as no other similar occurrence is known in the widespread Purlawaugh sediments with which it is associated. Its palaeogeographical position was close to but not actually at the shoreline of Purlawaugh sedimentation which lay along steeply-rising hills of metamorphic basement rocks near Mudgee, 30 miles to the south, and near Gulgong, 20 miles to the south-west (Dulhunty, 1939, 1964; Dulhunty and Packham, 1962). The small fresh-water lake deposit probably accumulated over a relatively short period of time during a temporary cessation or reduction in rate of subsidence in an area of marginal lake environment. Under such circumstances it is difficult to imagine a small isolated lake existing for long. In fact, lack of layering or vertical variation in lithology of the chert suggests rapid deposition over a short period of time. It could represent as little as several seasons' deposit of silt in which the fish and plants were entombed. Alternatively, it may have accumulated over a number of years. Deposition probably proceeded at a rate of at least 0·1 inch per year as many of the almost complete fish skeletons occupying a depth of 0·05 to 0·075 inch in the chert would have disintegrated quickly if not buried. This rate of deposition, with a total thickness of the order of 24 inches, would represent a possible maximum of some 250 years for the life of the lake in which the Talbragar Fish Bed Chert accumulated.

Acknowledgements

In conclusion, the authors wish to acknowledge the assistance of the McMaster brothers of "Argyll", Uarbry, and the Scott brothers of "Cavanders Flat", Uarbry, in providing facilities which enabled field investigations to be carried out.

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Lower Devonian Conodonts from the Lick Hole Limestone, Southern New South Wales

P. G. Flood

Geology Department, University of New England, Armidale, N.S.W.[1]

Abstract—Fifteen species and subspecies of disjunct conodonts are recorded from a measured section of the Lick Hole Limestone. The conodonts, in particular *Polygnathus linguiformis dehiscens* Philip and Jackson, suggest a Lower Devonian (late Siegenian-early Emsian) age for the Lick Hole Limestone.

Introduction

The Lick Hole Limestone is exposed within the valley of the Yarrangobilly River, near Ravine, about 10 miles north-west of Kiandra. This area is part of a larger area mapped by Adamson (1954) and Moye *et al.* (1963), and it is included in the Australian 1 : 250,000 Geological Series, Sheet SI 55–15, Wagga Wagga (Adamson *et al.*, 1966). On these maps a Middle Devonian age is assigned to the Lick Hole Limestone.

The fauna of the limestone has been mentioned by several authors (Andrews, 1901 ; Dun, 1902 ; Harper, 1912 ; Benson, 1922 ; Adamson, *op. cit.* ; Moye *et al.*, *op. cit.*), but Sherrard's (1967) description of two species of Lower Devonian tentaculites—*Tentaculites chapmani* Sherrard and *Nowakia* aff. *acuria* (Richter)—was the first systematic study undertaken. The present paper records the occurrence and age significance of conodonts collected from a measured section of the Lick Hole Limestone, and in an article in preparation, I shall describe the brachiopods, which are the dominant faunal element of the formation.

Stratigraphy

In the Lob's Hole-Ravine area two distinct groups of sediments may be recognized : the Ravine Beds of Upper Silurian age, and the unconformably overlying Byron Range Group, partly at least of Lower Devonian age. The latter group consists of three conformable formations, in ascending order, Milk Shanty Formation (550 ft.), Lick Hole Limestone (1,600 ft.), and Round Top Formation (50 ft.). This succession, based partly on the work of Adamson (*op. cit.*), Moye *et al.* (*op. cit.*), and partly on original observation, is shown in Figure 1.

RAVINE BEDS

This group (Moye *et al.*, *op. cit.*) consists of greywacke, conglomerate, and siltstone. These sediments appear to be unfossiliferous, but limestone has been located in a drill hole at Ravine (Jacquet, 1918). Moye *et al.* (*op. cit.*) tentatively correlate it with the Silurian, Yarrangobilly Limestone, which crops out some ten miles north of Ravine.

BYRON RANGE GROUP

Unfossiliferous, hematite-stained siltstone, current-bedded sandstone, and conglomerate typify the lowest unit of the Byron Range Group (Moye *et al.*, *op. cit.*), known as the Milk Shanty Formation (Adamson, *op. cit.*). They are followed by richly fossiliferous, interbedded, bluish-grey mudstone, drab olive-grey, calcareous mudstone, and dark, fine-grained biogenic nodules and discontinuous nodular layers. The calcareous mudstone locally display current bedding, and sandy oolite bands occur in the upper part of the sequence. The uppermost 300 feet of sediment consists of unfossiliferous mudstone. This sequence has been referred to as the Lick Hole Limestone (Moye *et al.*, *op. cit.*). This in turn is succeeded by the Round Top Formation (Adamson, *op. cit.*), which includes interbedded red sandstone, maroon siltstone, and minor greenish-grey siltstone. Moye *et al.* (*op. cit.*, p. 20) record the presence of molluscs

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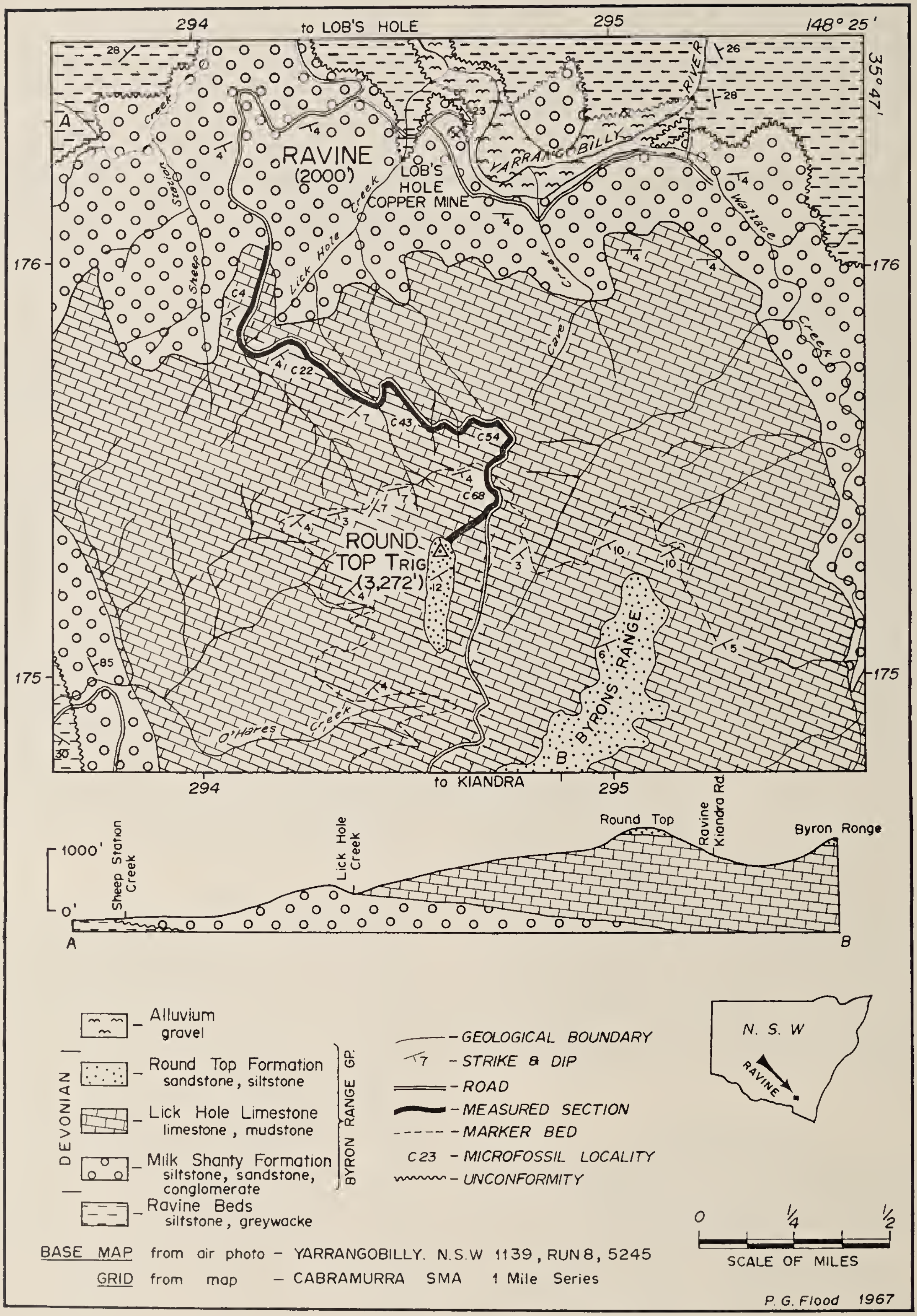

Fig. 1

Geological map, Ravine area.

in the " lowest quartzite beds ". An examination of these beds failed to reveal molluscs, but instead numerous inarticulate brachiopods (*Lingula* sp.) were collected.

The Conodont Fauna

Some 1,300 identifiable conodonts were recovered, using standard acetic acid techniques, from the insoluble residue of 200 kilogrammes of limestone, representing 42 samples collected throughout the measured section. Systematic descriptions are omitted because all the recovered species have been described previously. Some have been recorded from the Buchan Group (Philip, 1966), and some from the Murrumbidgee Group (Pedder, Jackson, and Philip, 1969).

The fauna includes the following forms :

Hibbardella perbona (Philip, 1966),
Hindeodella priscilla Stauffer, 1938,
Ligonodina salopia Rhodes, 1953,
Lonchodina n.sp. Philip, 1966,
Lonchodina sp. indet.
Neoprioniodus bicurvatus (Branson and Mehl, 1933),
Ozarkodina typica denckmanni Ziegler, 1956,
Ozarkodina typica australis Philip and Jackson, *in* Pedder *et al.*, 1969,
Plectospathodus alternatus Walliser, 1964,
Polygnathus linguiformis dehiscens Philip and Jackson, 1967,
Spathognathodus linearis (Philip, 1966),
Spathognathodus steinhornensis optimus Moskalenko, 1966,
Trichonodella inconstans Walliser, 1957,
Trichonodella symmetrica pinnula Philip, 1966.

Figure 2 shows that several long-ranging Lower Devonian conodonts persist through the entire sequence. The presence, however, of the index conodont of the *Polygnathus linguiformis dehiscens* conodont assemblage (Philip and Jackson, 1970) suggests, in terms of the existing knowledge of the sequence of Lower Devonian conodonts in eastern Australia, a late Siegenian-early Emsian age for the Lick Hole Limestone.

The Measured Section

The section is located at Ravine, south of the Yarrangobilly River, and follows, for approximately one and a half miles, the Ravine-Kiandra road. The section begins at G.R. 29421760 and ends at G.R. 29461753, and was measured with tape, abne and compass by A. E. H. Pedder and P. G. Flood in January, 1967.

Unit No.		Thickness in Feet	
		Unit	Total from Base
	Round Top Formation		
	Interbedded olive-grey siltstone and maroon sandstone ; contact with underlying formation is distinct but conformable	47	
	Lick Hole Limestone		
5	Mudstone, olive-grey, poorly bedded, poorly exposed, no fossils observed	300	1,600
4	Olive-grey mudstone and interbedded, dark, microcrystalline calcareous nodules ; rare occurrence of brachiopods	120	1,300
3	Massive, bluish-grey calcareous mudstone, and numerous biogenic nodules and nodular layers ; crowded with brachiopods, rarer bryozoan, and solitary rugosan ; upper part of the unit is ledge forming and provides an excellent marker bed	360	1,180
2	Olive-green mudstone, and thin biogenic nodular-limestone interbeds ; brachiopods and pelecypods present	522	820
1	Bluish-grey mudstone, and dark grey, calcareous siltstone ; few brachiopods present	298	298
	Milk Shanty Formation		
	Well-bedded, maroon siltstone, hematite-stained sandstone and conglomerate ; contact with overlying formation is distinct but conformable		

Acknowledgements

I am indebted to A. E. H. Pedder, J. H. Jackson and G. M. Philip for supplying a copy of their manuscript on the Lower Devonian Biostratigraphy in the Wee Jasper region of New South Wales in advance of publication. The present paper is published with the permission of the Director of the Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T.

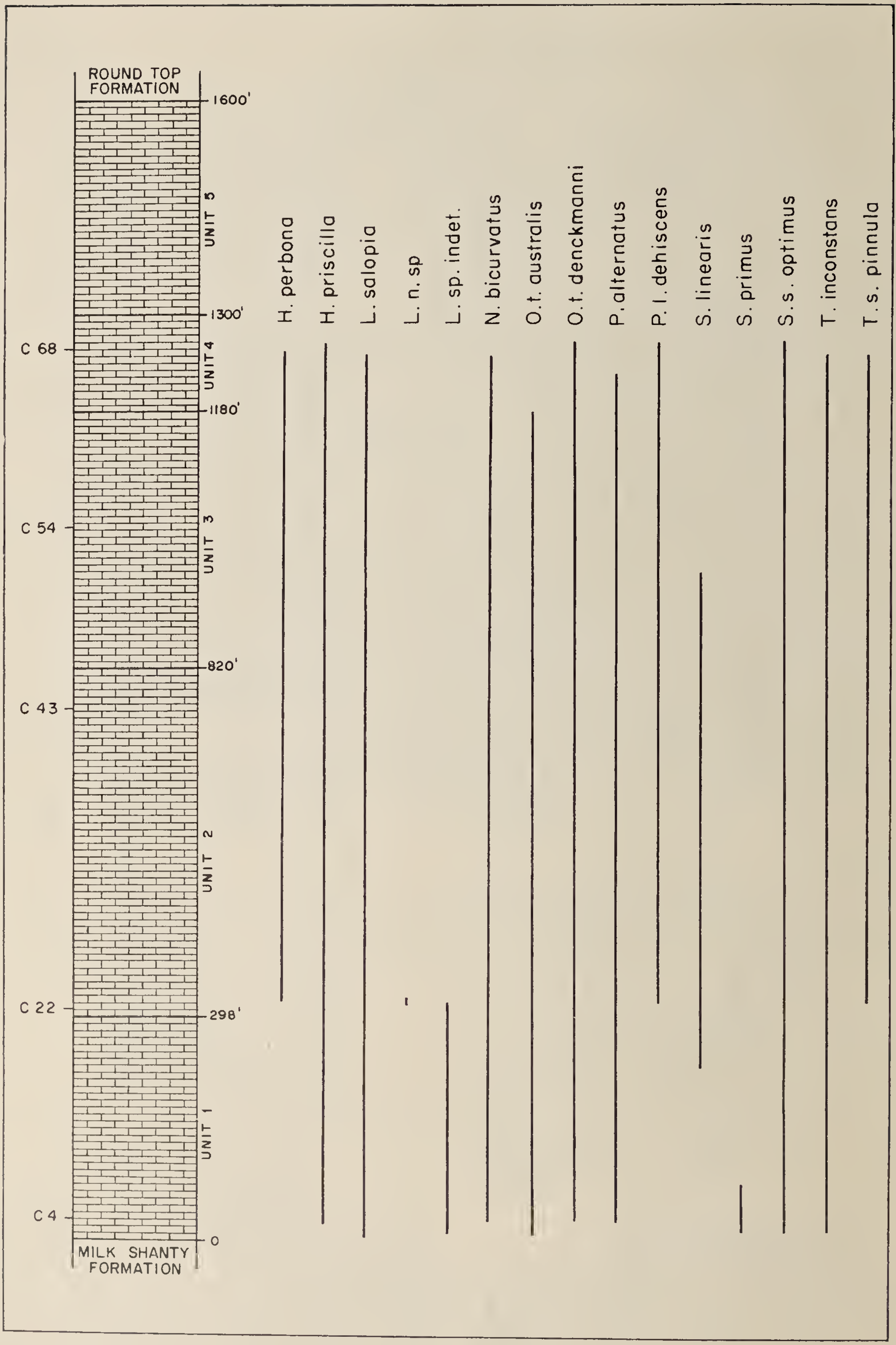

Fig. 2

Minimum teilzones of the conodont forms, mentioned in the text, within the measured section of the Lick Hole Limestone.


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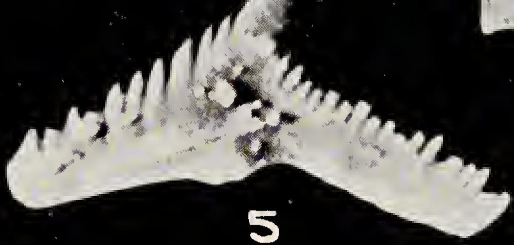
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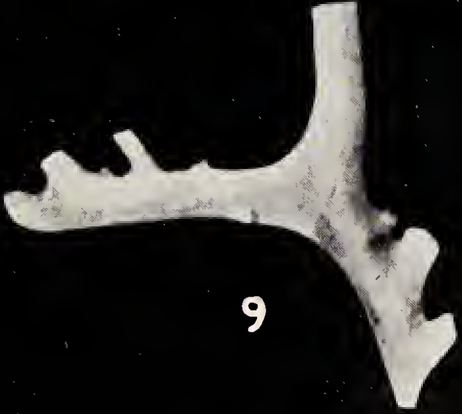
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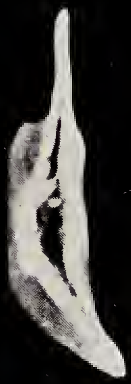
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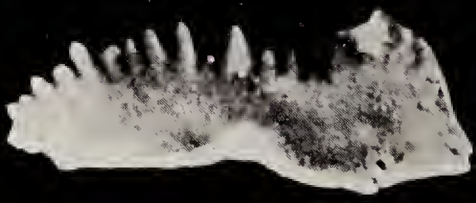
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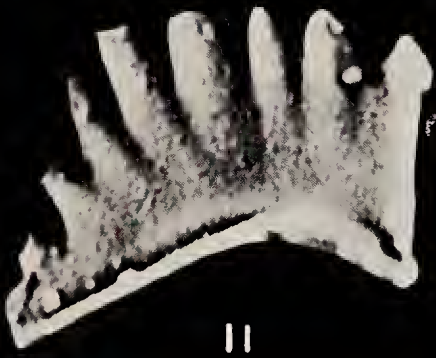
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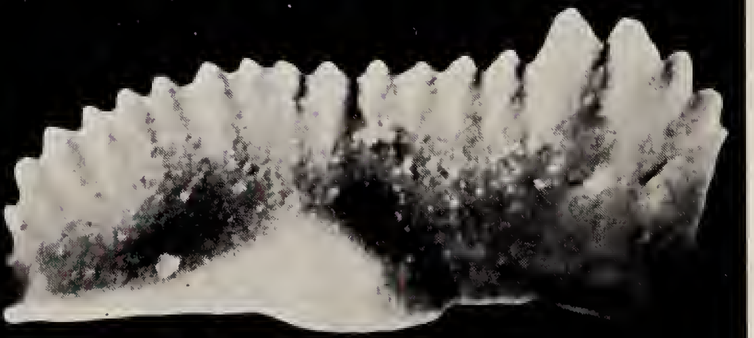
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Addendum

While this article was at press, G. Klapper (*J. Palaeont.* (1969), 43 (1), 1–27) published results of conodont studies from Royal Creek, Yukon, Canada. Several of the Royal Creek forms are identical to specimens from the Lick Hole Limestone. Of special importance is the occurrence of *Polygnathus lenzi* Klapper (=*Polygnathus linguiformis dehiscens* Philip and Jackson), to which he assigns an early Emsian age.

(Received 27 January 1969)

Explanation of Plates

All figures ×40 and specimens registered in the University of New England Palaeontological Collection.

Plate I

Fig. 1.—*Hibbardella perbona* (Philip). Posterior view of 10304/1, locality C22.
Fig. 2.—*Trichonodella symmetrica pinnula* Philip. Anterior view of 10304/11, locality C22.
Fig. 3.—*Neoprioniodus bicurvatus* (Branson and Mehl). Inner view of 10304/3, locality C22.
Fig. 4.—*Ozarkodina typica australis* Philip and Jackson. Lateral view of 10305/1, locality C24.
Figs. 5, 6.—*Ozarkodina typica denckmanni* Ziegler. Lateral views of 10307/1–2, locality C54.
Fig. 7.—*Plectospathodus alternatus* Walliser. Inner view of 10304/4, locality C22.
Fig. 8.—*Lonchodina* n.sp. Philip. Lateral view of 10304/2, locality C22.
Fig. 9.—*Ligonodina salopia* Rhodes. Inner view of 10303/2, locality C4.
Fig. 10.—*Lonchodina* sp. indet. Posterior view of 10306/2, locality C43.
Fig. 11.—*Trichonodella inconstans* Walliser. Posterior view of 10304/8, locality C22.

Plate II

Figs. 1–6—*Polygnathus linguiformis dehiscens* Philip and Jackson.
1–4. Oral views of 10307/5,11,6, locality C54, 10306/4, locality C43.
5, 6. Aboral views of 10307/10,9, locality C54.
Figs. 7–10.—*Spathognathodus steinhornensis optimus* Moskalenko.
7. Oral view of 10306/6, locality C43.
8. Aboral view of 10307/14, locality C54.
9, 10. Lateral views of 10306/7, locality C43, 10303/6, locality C4.
Fig. 11.—*Spathognathodus primus* (Branson and Mehl). Lateral view of 10302/1, locality C2.
Fig. 12.—*Spathognathodus linearis* (Philip). Lateral view of 10304/7, locality C22.

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Granitic Development and Emplacement in the Tumbarumba-Geehi District, N.S.W.

(1) The Foliated Granites

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Sydney, N.S.W., 2006

Abstract—In the Tumbarumba-Geehi district some of the granitic bodies that are in part foliated display a close association in mineralogy, chemistry and field relationships with the surrounding regionally metamorphosed psammopelitic sequence. These foliated rocks—the Cooma-type granites—are characterized by the presence of clusters of biotite, occasional cordierite and patchy zoning in the plagioclases. Chemically the rocks display low Ca contents and a high K : Na ratio, features that are evident in the associated metamorphics. There is a distinct similarity in the chemistry of biotites from the granites, their inclusions, and the high-grade metamorphics.

The following sequence of events is envisaged for the formation and emplacement of the Cooma-type granites : (*a*) high-grade metamorphism of a psammopelitic sequence, segregation of quartzo-feldspathic and biotite-rich sections, and some increase in Ca contents; (*b*) introduction of sodium, breakdown of micas and the formation of a partial melt, with development of alkali feldspars. Such reactions involve an increase in volume and thus a decrease in specific gravity of the granites with consequent migration and emplacement to higher levels in the crust.

Introduction

The granitic* rocks of the Tumbarumba-Geehi district, N.S.W. may be classified into several groups on the basis of their textural and mineralogical features and field association with regional metamorphic zones. The aim of this paper is to describe and consider the development of one of the groups—the Cooma-type granites (Vallance, 1967)—with particular reference to its relationship to the surrounding regional metamorphics. The other granitic rocks present (Khancoban, Mannus Creek and Dargals granites) post-date the regional metamorphism and will be discussed in a later paper. The distribution of rocks in the Tumbarumba-Geehi district has been noted elsewhere (Guy, 1969).

The Cooma-type granites of south-east Australia include the Cooma gneiss (Joplin, 1942), Albury gneiss (Joplin, 1947), Wantabadgery granite (Vallance, 1953), Mt. Wagra gneiss (Tattam, 1929) as well as the Corryong and Geehi granites of the Tumbarumba-Geehi district. The Corryong granite is part of a large batholith that extends from south-west of Corryong, Victoria to near Adelong, N.S.W. Portions of the mass were described by Edwards and Easton (1937) and later by Hall and Lloyd (1950), the latter authors applying the term Maragle Batholith. Vallance (1953) applied the name Green Hills granite to that section of the mass to the north of Tumbarumba. The Geehi granite forms part of a south-easterly extension of the Corryong granite but no investigation concerning the continuity of these bodies has been undertaken in connection with this study.

The Corryong and Geehi granites are medium grained, remarkably uniform rocks with a high biotite content and free from hornblende; massive in part but generally foliated. This foliation is delineated by a parallelism of bladed micas and elongated xenoliths. The foliation is steeply dipping and has a general trend north-south, and locally parallel to the contacts with the surrounding psammopelitic sequence of Ordovician rocks.

Mineralogy and Petrology

The normal granitic rocks vary from granits (s.s.) to granodiorite, with the bulk of the rocke being grey adamelites (Table 1). The grain size is even (1–2 mm.) though coarser types with alkali feldspars to 8–10 mm. occur and also some tendency for minerals to be present in clusters, especially biotite. Cell structures with-

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* Unless otherwise stated, the term "granitic", as used in this paper, applies to deep-seated bodies that may be acid-intermediate in composition.

in the quartz grains are evident and sometimes assume a typical polygonal arrangement (Plate 1a). The larger alkali feldspars enclose quartz and plagioclase, suggesting their development later than other phases. Alkali feldspars are optically monoclinic although some cross-hatch twinning occasionally occurs. The triclinicity, △, (Goldsmith and Laves, 1954) is in the range 0·25–0·40, and $2V\alpha$=80–90°. The K : Na ratio of the alkali feldspars may be estimated utilizing modal and chemical data (including plagioclase and biotite compositions), for specimen 21800 and for the biotite-granite from Vallance (1953, 1960). If assumptions are made as to the compositions of the micas and the accessory minerals, the K : Na ratio may also be estimated for specimens 21805, 21777. All such Or percentages fall in the range 62–68%. The plagioclases are more calcic than those noted by Vallance (1953) in the area north of Tumbarumba, where most contain 30–35% anorthite molecule. The average composition for plagioclases from the present area is An_{34-40}*, variation being from An_{55} (at core) to An_{20} (at margin). The calcic character of these plagioclases is of interest considering the relative low Ca contents of the rocks (Table 1). Most of the plagioclase grains are twinned, with up to four laws being present. A large number of plagioclases contain small areas, somewhat irregular in shape and distribution, that are at a slightly different optical orientation from the main portion of the crystal (Plate 1b). This "patchiness" displayed by the plagioclase is more evident in varieties where zoning rather than twinning is prominent. The outlines of these small areas is often partly controlled by twinning. Such small patches differ in optical orientation by only a few degrees from the host and do not obey any recognizable twin law. Most plagioclases have $2V\gamma$ from 70–85°, although sodic varieties have $2V\alpha$=85–88°. Biotite is present in clusters with blades being intergrown and occasionally twinned. Generally it is pleochroic red-brown, although some dark olive-brown biotites have been recorded. γ-ranges from 1·643 to 1·651. One red-brown biotite has been analysed from the present area (Guy, 1964) and its composition is summarized below (No. 1)—specimen 21800†, together with a biotite (No. 2) from the area to the north of Tumbarumba (Vallance, 1960).

TABLE 1

Chemical Analyses, Barth Mesonorms and Modes of Corryong and Geehi Granites

	1	2	3	4
SiO_2 ..	70·25	69·40	69·70	69·05
TiO_2 ..	0·41	0·49	1·15	0·29
Al_2O_3 ..	13·78	13·58	13·30	15·78
Fe_2O_3 ..	0·41	0·75	0·27	0·22
FeO ..	3·04	3·87	3·60	3·62
MnO ..	0·07	0·11	0·05	0·05
MgO ..	1·49	2·04	1·66	2·15
CaO ..	1·80	0·92	1·92	2·50
Na_2O ..	2·41	2·01	2·51	2·49
K_2O ..	4·86	5·14	4·25	3·85
P_2O_5 ..	0·16	0·04	0·15	n.d.
H_2O+ ..	1·13	1·64	0·94	0·28
H_2O- ..	0·07	0·04	0·09	0·13
Total	99·88	100·03	99·59	100·41
Q ..	32·96	35·10	34·49	32·54
Or ..	22·12	21·70	17·30	13·33
Ab ..	22·30	18·70	23·30	22·60
An ..	6·60	2·75	4·70	11·55
C ..	2·54	4·22	3·27	3·69
Bi ..	11·89	15·60	13·84	15·47
Ap ..	0·35	0·08	0·32	—
Ti ..	0·89	1·05	2·49	0·60
Mt ..	0·43	0·81	0·30	0·24
Quartz ..	30·0	39·6	39·7	31·4
Plagioclase	31·9	14·5	26·9	26·2
K-feldspar	17·6	23·8	13·2	24·0
Biotite ..	10·2	13·4	9·6	9·3
Muscovite	5·7	4·5	3·7	7·2
Cordierite	1·4	1·2	0·2	1·0
Inclusions(a)	3·2	2·1	5·4	0·5
Accessories(b)	0·1	0·7	1·3	0·5

(a) Included pelitic fragments (mainly muscovite, chlorite and quartz).
(b) Apatite, sillimanite, tourmaline, rutile.

1. Spec. No. 21842. Biotite adamellite. G.R.267.0–160.2* (Corryong granite).
2. Spec. No. 21847. Biotite adamellite. G.R.284.6–139.6 (Geehi granite).
3. Spec. No. 21800. Granodiorite. G.R.276.8–165.9 (Corryong granite).
4. Spec. No. 21777. Biotite adamellite. G.R.274.9–174.1 (Corryong granite).

Analyst: B. Guy.

* Snowy Mountains Authority grid reference (see Guy, 1969).

1. $(K_{0\cdot75}\ Na_{0\cdot05}\ Ca_{0\cdot04})\ (Al_{0\cdot36}\ Ti_{0\cdot13}\ Fe^{3+}_{0\cdot13}\ Fe^{2+}_{1\cdot19}\ Mg_{0\cdot98}\ Mn_{0\cdot01})\ (Si_{2\cdot74}\ Al_{1\cdot26})\ 0_{10}\ (OH)_2$
2. $(K_{0\cdot84}\ Na_{0\cdot08}\ Ca_{0\cdot03})\ (Al_{0\cdot45}\ Ti_{0\cdot18}\ Fe^{3+}_{0\cdot22}\ Fe^{2+}_{1\cdot06}\ Mg_{0\cdot83}\ Mn_{0\cdot01})\ (Si_{2\cdot71}\ Al_{1\cdot29})\ 0_{10}\ (OH)_2$.

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* Compositions of the plagioclases were determined from the extinction angle X'^(010) ⊥ [100] measured on a universal stage and referred to the low-temperature determinative curves of Bordet (1963).

† Further details of the analysed biotites will be published in a later communication.

Muscovite is significant as large blades in the Cooma-type granites but cross-cutting other constituents, and is associated with biotite which it may be replacing. The percentage of muscovite increases with increasing alkali feldspar content. About 2–3% of the granitic rocks is composed of cordierite or inclusions of pelitic material. The cordierite appears as anhedral grains (1–2 mm.) in part replaced by muscovite. It is homogeneous with $2V\alpha=80°$. Patches of sheet silicates, assuming ovoid shapes and 1–3 mm. in size, are ubiquitous in the granitic rocks. They are composed of chlorite, muscovite with some quartz, biotite and sillimanite. Texturally these micaceous aggregates appear as inclusions in the host granite. They may in part represent pseudomorphs after cordierite. Accessory minerals in the granitic rocks are opaque oxides, tourmaline, apatite, sillimanite, zircon, rutile, monazite, calcite and epidote. Marginal phases of the granites have high tourmaline and muscovite contents, with biotite being replaced by these two minerals.

Throughout these granites shear zones are numerous, varying from 5 cm. to a metre in width, though Vallance (1953) and Beavis (1961) describe crush bands several hundred metres wide in similar granitic rocks. Shearing effects produce some reduction in grain size with assemblages such as " quartz-feldspar-chlorite-muscovite " being produced.

Aplites, pegmatites and graphic granites form significant occurrences in the Cooma-type granites. Aplites occur as small veins occupying joints. Quartz, optically monoclinic alkali feldspar and oligoclase are the dominant phases, being in approximately equal quantities. Dark-green biotite, muscovite, tourmaline, apatite and opaque oxides are accessories. Tourmaline-rich bands characterize many of the aplitic veins. Pegmatites are mineralogically similar to the aplites, but oligoclase is subordinate. Tourmaline in the pegmatites has a basal parting (up to 0·5 mm. wide) filled with quartz and iron oxides.

Associated with the aplitic and pegmatitic phases are dark, fine grained dykes consisting essentially of chlorite and tourmaline with some quartz and opaques. These rocks are prevalent in the area south of Tumbarumba and are associated with shear bands in the granite and quartz-sulphide veins. Although the original composition has presumably been extensively modified, they may represent basic dykes that have been sheared and altered by hydrothermal activity.

Large inclusions (>5 cm.) are prominent throughout the Corryong and Geehi granites, being of psammitic to pelitic character and mineralogically and texturally similar to the high-grade regional metamorphics of the district (Guy, 1969). Some quartz nodules (5–10 cm. in size) are also common throughout the Cooma-type granites. Most inclusions differ from the country rocks in that plagioclase is significant in the former rock type as porphyroblasts of An_{35} composition. The plagioclase is euhedrally zoned with cores of An_{50}, and $2V\gamma=80–90°$; some " patchiness ", as described for plagioclases of the granitic rocks, is evident. Biotite is present throughout all the inclusions, and is frequently concentrated around the margins of the larger sandier types. Structural formulae for some biotites are noted below. Nos. 1 and 2 are red-brown types ($\gamma=1{\cdot}645$) common to most inclusions, while Nos. 3 and 4 are yellow-brown varieties ($\gamma=1{\cdot}625$) noted in some of the sandier rocks. No. 1 is from Vallance (1960) and the remainder from Guy (1964). Modal analyses of the host inclusions are noted in Table 2.

1. $(K_{0\cdot82}\ Na_{0\cdot12}\ Ca_{0\cdot03})\ (Al_{0\cdot37}\ Ti_{0\cdot17}\ Fe^{3+}_{0\cdot20}\ Fe^{2+}_{1\cdot11}\ Mn_{0\cdot04}\ Mg_{1\cdot04})\ (Si_{2\cdot65}\ Al_{1\cdot35})\ O_{10}\ (OH)_2$
2. (Spec. 21798) $(K_{0\cdot90}\ Na_{0\cdot12}\ Ca_{0\cdot02})\ (Al_{0\cdot44}\ Ti_{0\cdot12}\ Fe^{3+}_{0\cdot11}\ Fe^{2+}_{1\cdot10}\ Mn_{0\cdot01}\ Mg_{0\cdot97})\ (Si_{2\cdot67}\ Al_{1\cdot33})\ O_{10}\ (OH)_2$
3. (Spec. 21807) $(K_{0\cdot81}\ Na_{0\cdot16}\ Ca_{0\cdot00})\ (Al_{0\cdot30}\ Ti_{0\cdot05}\ Fe^{3+}_{0\cdot90}\ Fe^{2+}_{0\cdot62}\ Mn_{0\cdot00}\ Mg_{1\cdot77})\ (Si_{2\cdot89}\ Al_{1\cdot11})\ O_{10}\ (OH)_2$
4. (Spec. 21787) $(K_{0\cdot79}\ Na_{0\cdot08}\ Ca_{0\cdot03})\ (Al_{0\cdot32}\ Ti_{0\cdot05}\ Fe^{3+}_{0\cdot09}\ Fe^{2+}_{0\cdot82}\ Mn_{0\cdot01}\ Mg_{1\cdot59})\ (Si_{2\cdot80}\ Al_{1\cdot20})\ O_{10}\ (OH)_2$

The Mg-rich micas (Nos. 3 and 4) have only been observed or suspected in these inclusions, whereas they appear to be lacking in the granite and regional metamorphics. The lower grade metamorphics may prove to contain some exceptions (Guy, 1969, Table 1). The silica content is appreciably higher for these Mg-rich varieties.

Cordierite is abundant in the pelitic inclusions as ragged crystals with a distortion index, Δ, (Miyashiro, 1957) of $0{\cdot}19\pm0{\cdot}03$ and $\beta=1{\cdot}553\pm0{\cdot}003$, indicating (ca.) 25% Fe substitution for Mg. Sillimanite is present in the fibrolite form, although numerous needle-like crystals are associated with the matted fibrolite. Muscovites in the inclusions vary from large blades (2–3 mm. long), cross-cutting other minerals, to sericitic varieties which replace nearly all the phases except quartz. Chlorite, in part after cordierite, may be associated with the fine matted micas.

TABLE 2

Chemical Analyses, Barth Mesonorms and Modes for Inclusions in Cooma Type Granites

	1	2	3	4	5	6
SiO_2 ..	66·27	57·70	54·86	54·22	45·73	44·87
TiO_2 ..	0·88	1·80	1·18	1·78	0·13	2·50
Al_2O_3 ..	13·85	14·17	18·32	21·01	27·83	28·42
Fe_2O_3 ..	0·27	0·28	2·01	1·79	1·05	0·26
FeO ..	3·55	7·36	8·01	5·61	6·80	7·97
MnO ..	0·06	0·13	0·14	0·14	0·06	0·26
MgO ..	5·50	7·23	4·16	2·43	4·95	4·45
CaO ..	2·54	3·35	1·95	0·49	0·20	1·49
Na_2O ..	2·57	0·73	2·46	1·75	0·27	2·02
K_2O ..	3·01	4·51	5·22	7·41	8·17	3·71
P_2O_5 ..	0·01	0·12	—	0·31	n.d.	0·12
H_2O^+ ..	0·90	1·90	1·30	2·46	4·00	3·40
H_2O^- ..	0·18	0·23	0·22	0·36	0·40	0·23
F_2 ..	—	—	—	—	0·06	—
Less O for F_2 ..	—	—	—	—	0·03	—
Total	99·59	99·51	99·83	99·76	99·62	99·70
Q ..	33·05	29·61	16·46	15·04	12·14	16·80
Or ..	0·62	0·55	12·18	33·10	29·82	1·25
Ab ..	23·45	6·80	22·60	16·35	2·50	18·75
An ..	9·60	9·90	5·70	—	0·60	—
C ..	3·22	5·22	7·37	11·48	20·83	23·81
Bi ..	27·89	43·44	30·99	19·92	32·69	34·32
Ap ..	0·03	0·27	—	0·67	—	0·27
Ti ..	1·86	3·90	2·52	0·33	0·27	4·08
Mt ..	0·28	0·30	2·16	1·95	1·14	0·28
Rt ..	—	—	—	1·18	—	0·44
Quartz ..	34·9	28·5	22·2	*	*	0·2
Alkali feldspar	1·3	—	1·6	*	*	0·3
Plagioclase	32·8	22·3	24·4	*	*	15·7
Biotite ..	31·0	47·9	42·3	*	*	20·6
Muscovite	—	1·1	8·4	*	*	20·7
Cordierite	—	—	—	*	*	37·5
Sillimanite	—	—	(Present)	*	*	3·1
Accessories	—	0·1	1·0	*	*	2·0

1. Spec. No. 21807. Biotite-quartz-plagioclase rock. G.R. 278.5–175.4.
2. Spec. No. 21787. Biotite-rich psammopelite. G.R. 274.1–155.8.
3. Biotite-rich patch in granodiorite. Tenandra Trig. Vallance (1953).
4. Micaceous xenolith in granite, Mt. Wagra. Tattam (1929).
5. Pinitized cordierite inclusion, Kerungah Gap. Tattam (1929).
6. Spec. No. 21798. Cordierite-biotite-sillimanite rock. G.R. 277.2–165.2.

Analysts: 1, 2, 6—B. Guy. 3—T. G. Vallance. 4, 5—C. M. Tattam.
* Data not available.

Chemical Data

(i) Granitic Rocks. Four new analyses of granitic rocks from the Cooma-type granites are presented in Table 1. The granites are characterized by high Al_2O_3 contents, low CaO and a $K_2O : Na_2O$ ratio higher than unity. Chemical data have been summarized in Fig. 1.

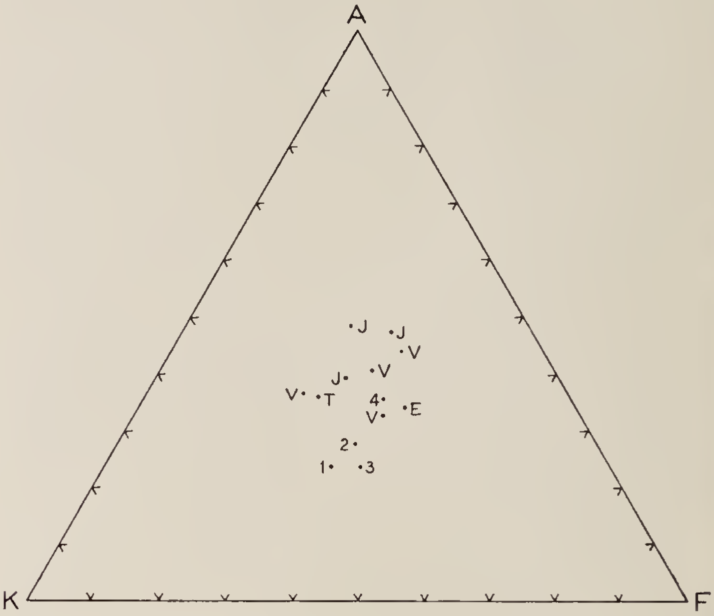

FIG. 1—AKF diagram for the Cooma-type granites. Analytical data from Table 1, this paper (Nos. 1, 2, 3, 4); Tattam, 1929 (T); Edwards and Easton, 1937 (E); Joplin, 1942 and 1947 (J); Vallance, 1953 (V).

Many of the rocks contain less than 80% normative AB+Or+Q and thus would not be classified by Tuttle and Bowen (1958) as granites* (s.s.).

(ii) Inclusions. Three new analyses are listed for inclusions from the Cooma-type granites in Table 2, together with analyses from Vallance (1953) and Tattam (1929). An examination of modes and the analytical data for the inclusions reveals a close correspondence indicating that the phases have compositions close to the ideal normative minerals calculated. Utilizing the biotite analysis for specimen 21798, together with the modal data, the Mg : Mg+Fe+Mn value for the cordierite of this specimen may be estimated at (ca.) 0·6. The associated biotite has a value of 0·44.

The Mg : Mg+Fe+Mn ratio averages 0·40 both for the Cooma-type granites in south-east Australia and the pelitic rocks in the associated Ordovician sequence, while the associated psammopelites and the psammites average 0·33. Inclusions of the latter rock type (Table 2) have an Mg : Mg+Fe+Mn ratio of 0·67.

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* Tuttle and Bowen utilized C.I.P.W. norms, whereas Barth mesonorms have been used in Table 1.

TABLE 3

Anions Associated with Cations in Metasediments, Inclusions and Granites*

(*a*) Psammites and Psammopelites

(?) Unmetamorphosed or Low-grade Zone	Biotite Zone	Knotted Schist Zone	High-grade Zone	Inclusions	Granites
186·55	182·17	188·06	174·46	169·53	170·04 170·94 170·95 172·57 173·45 173·76 173·85 174·75 175·36 175·41 175·54 175·78 179·89
—	185·04	—	178·01	167·80	
—	—	—	181·39	—	
Average : 186·55	183·61	188·06	177·95	168·67	
(*b*) Pelites					
162·13	175·18	172·39	167·13	163·96	
173·58	175·74	172·45	167·22	167·07	
173·67	177·13	172·77	167·67	167·86	
175·52	—	173·44	169·41	167·89	
178·65	—	174·80	170·19	—	
179·22	—	175·41	171·64	—	
185·14	—	181·81	—	172·08	
185·67	—	183·10	—	—	
Average : 177·95	176·02	174·65	169·29	166·70	173·92

* Cations summed to 100.00.

See Figs. 1 and 2 for references to analytical data on granites, and Guy (1969) for data on metasediments.

Anions associated with 100 cations in the Cooma-type granites, their inclusions and the Ordovician metasediments are listed in Table 3. The metasediments show a general trend of decrease in the number of associated anions from low grade through to the inclusions with an increase of (ca.) 4% from the inclusions to the granites.

Figures 1 and 2 summarize some of the chemical features of the metasediments, the inclusions and the Cooma-type granites.

Origin of the Granitic Rocks

The spatial distribution of the Cooma-type granites relative to the regional metamorphic zonal sequence and the high amount of included material in the granite suggest a close association between granite and surrounding country rock material. Mineralogically this is evident in that cordierite may be present in the granitic rocks and there is a similarity in the optical and chemical properties of the biotites in the metasediments and granite. The metasediments are characterized by a restricted chemical nature (Guy, 1969) being rich in alumina and potash, low in lime and soda, while the Cooma-type granites display a similar nature in that alumina and potash contents are high, with lime being low but slightly more significant than in the metasediments. Soda, however, is present in appreciable proportions in the granites. Vallance (1953) estimated the country rocks in the Wantabadgery area have an average composition of a psammopelite, with the ratio pelite :

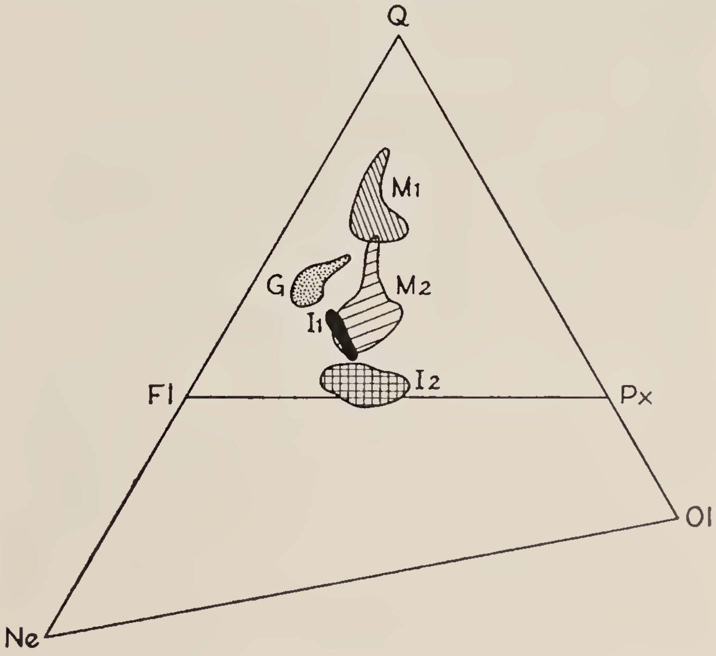

FIG. 2—Q-Fl-Px diagram showing the general distribution of Cooma-type granites (G), their inclusions (I_1, psammopelites ; I_2, pelites) and Ordovician metasediments (M_1, psammopelites ; M_2, pelites). See Guy (1969) for references to the analytical data of the metasediments.

psammopelite : psammites being 20 : 60 : 20. This approximation appears to be a satisfactory estimate of the relative proportions of such rocks in the Tumbarumba-Geehi district. Vallance observed that such an average " psammopelite " was chemically similar to the granite except for a deficiency in the Na and Ca in the former rock, and suggested that granites were derived largely from materials of the sedimentary pile.

Joplin (1962) has postulated the idea of an oligoclase magma being added to the " psammopelitic " sequence to produce the Cooma-type granites. It is doubtful if such a magma is really necessary to form such granites ; indeed Kolbe and Taylor (1966) have argued against this mainly on the basis of K : Rb ratios in these rocks. These latter authors, together with Pidgeon and Compston (1965), have suggested derivation of the Cooma-type granites entirely from the surrounding metasedimentary sequence. Joplin (1962) does not adhere to the idea of melting *in situ* alone because of the steep thermal gradients as indicated by the metamorphic zones surrounding the granite masses. Field relationships between granitic and metamorphic rocks in the Wantabadgery area led Vallance (1953) to suggest that the granites there probably developed at some lower level and were later emplaced at a higher level in the crust. Similar relations exist in the Tumbarumba-Geehi district.

Previous investigations of the Cooma-type granites have demonstrated that such rocks are derived primarily from metasediments similar to those exposed in Ordovician areas of south-east Australia. As yet there is little detailed information regarding the mineralogical processes involved in the transformation to such granites, or on the physical state of the metasediments during transformation. Before considering these aspects several important features of the Cooma-type granites should be emphasized. The granites are broadly homogeneous in that textural and mineralogical features are reasonably constant throughout the various bodies. However, on the scale of an outcrop (several square metres), such rocks are characteristically heterogeneous with numerous inclusions (>2 cms.) occupying up to 10–15% of an exposure. Smaller inclusions (<2 cms.), not always readily discernible macroscopically, may occupy 5% (see Table 1) of such granites. Clustering of mineral phases is particularly evident with the micas but also present in quartzo-feldspathic sections. Thus a granite analysis as quoted in the text and figures represents but an average of these features, while the bulk chemistry of, say, the Corryong granite cannot possibly be represented by " granite " analyses alone.

The predominance of included country rock material in the granites, the similarity in mineralogical features to both the metasediments and the granitic rocks, and the textural features outlined above suggest that the inclusions are at an intermediate stage in the transformation to granitic material rather than a " by-product " of granitic development. Most of the inclusions contain mainly quartz and biotite with minor plagioclase feldspar as well as cordierite, sillimanite, etc. The inclusions are mica-rich and from the analytical data (see Fig. 2) contain markedly lower quantities of silica than the metasediments. Thus transformation from metasediment to inclusion may involve a segregation into a quartz or quartzo-feldspathic section and a mica-rich section. The mica-rich sections are obvious on a microscopic to a macroscopic scale. The lighter coloured portions are not immediately apparent in the vicinity of biotite-rich areas. The quartzo-feldspathic components may have been able to diffuse into their surroundings or migrate some distance—perhaps to contribute to the aplitic, pegmatitic and graphic granite phases that are common throughout the Cooma-type granites. The predominance of quartz over feldspars in the metasediments could have resulted in the segregation of quartz-rich areas. Quartz nodules throughout the granite may be representatives of this segregation. The process of segregation is conceivably a continuation of the regional metamorphic processes with diffusion being a principal agent by which rearrangement of material takes place. Most of the inclusions contain small amounts of plagioclase. This plagioclase is somewhat similar to that observed in the granitic rocks and is reasonably calcic (cores of An_{50} have been recorded). The feldspars are discussed in more detail below (see p. 17). From an examination of Table 3, it is evident that the number of anions associated with 100 cations decreases with increasing grade of metamorphism. This effectively means that with increase in grade (until the stage of inclusions) there is a decrease in the overall volume of the rocks ($\sim$7%) and a corresponding increase in density.

Although there is a large variation in the degree of disintegration of the inclusions, transformation of inclusions to granite is very difficult to interpret. One of the most interesting features of the granitic rocks is that whereas bulk calcium contents are low (as are those of the original metasediments) calcic cores are not uncommon in the granite plagioclases. Such cores are unlikely to from unless temperature conditions were sufficiently elevated or calcium was locally concentrated relative to sodium. It is unlikely that P—T conditions in Tumbarumba-Geehi district were elevated enough for large scale melting to occur, and it is thus conceivable that in the early stages of transformation to granite there has been local concentration of calcium.

The rather patchy zoning of the plagioclases may reflect a later introduction of sodium into the system of the granitic rocks. Certainly Na_2O is deficient in the metasediments compared with the granites. Vance (1965) favours magmatic resorption due to the release of confining pressure associated with emplacement as a major cause of patchy zoning in plagioclase. This factor cannot be overlooked here although there are no criteria directly supporting such an explanation. Subhedral or euhedral crystals do not display any obvious embayments while many of the patchy areas terminate along twin boundaries (see Plate 1) that are essentially low energy boundaries and should not be a general limitation in resorption. It is noteworthy that the Cooma-type granites do not display the degree of oscillatory or sharp normal zoning that is evident in the Khancoban, Mannus Creek and Dargals granites (Guy, 1964). These later bodies are interpreted as having migrated rather further from their position of origin than the Cooma-type granites, and hence are more likely to contain mineralogical features compatible with a history of such emplacement.

It is considered that the features display by the plagioclases in the Cooma-type granites are a direct result of local concentration of calcium followed by an influx of sodium into the granitic rocks. Such an influx of sodium may have taken place by diffusion in the solid state, or through the introduction of melt or solution. Either process would be aided by an increase in temperature conditions. The physical state of the granitic rocks during the introduction of sodium may conceivably have been that of a partial melt. This aspect will be discussed in more detail below (p. 19).

The nature of the alkali feldspars is of interest in the granitic rocks. Marmo (1967) contends that potash feldspars of most synkinematic granites are highly triclinic microcline, although potash feldspars that form porphyroblasts not uncommonly have lower triclinicities. Such feldspars are younger than other constituents in these rocks. He suggests that where there has been reasonably rapid introduction of potassium with little time for Al-Si ordering in the developing feldspars, orthoclase may be formed, whereas if the introduction rate is slow, ordering results and microcline will develop. The optical properties of the alkali feldspars in the Cooma-type granites of the present area indicate that the alkali feldspars are not highly triclinic and form " porphyroblasts " and thus they may have formed in a manner envisaged by Marmo. However, according to the scheme of Laves and Viswanathan (1967), the feldspars with low $\triangle$ values and high 2V may consist of domains with a high degree of order, i.e. the alkali feldspar are submicroscopically twinned. Thus $\triangle$ values for this suite may not be as low as indicated. The reason for the paucity of twinning in such feldspars is difficult to interpret and growth may be similar to that suggested by Marmo, i.e. growth is rapid so that the phase grew essentially as a monoclinic phase and not as " microcline " The influence of post crystallization deformation cannot be neglected here. Microcline with higher obliquity than orthoclase should twin less readily, however, this does not appear to be the case for most natural occurrences. Possibly the optically monoclinic feldspars of these granites have a high triclinicity and do not display a great deal of obvious twinning due to a rapid fall in temperature conditions after their formation, and the lack of any major deformation.

The K : Na ratio of the alkali feldspars in the Cooma-type granites is somewhat lower than that observed in other granitic suites of the Tumbarumba-Geehi district. This may be related to high degree of unmixing in the latter rock types and perhaps the Cooma-type granite alkali feldspars have developed when there was a relatively greater availability of sodium.

Marmo (1967) considers that many of the synkinematic granites have experienced addition of K and to a minor degree Na. Chemical data from the present investigation is more suggestive of introduction of sodium, as potassium contents of the granitic rocks (considering the composition of the inclusions as well) does not appear to differ markedly from that of the metasediments. Textural evidence indicates that the alkali feldspars and muscovite have formed somewhat later than other constituents, however, it is considered that such potassium is derived locally from the disintegration of muscovite and biotite in the inclusions, perhaps associated with a rise in temperature conditions. Stability of micas until late in the transformation process may be responsible for survival (or perhaps production—see below) of cordierite in some of the granitic rocks.

It may be significant that the Mg : Mg+Fe+Mn ratio for the Cooma-type granites is slightly greater than that of an average psammopelitic metasediment (p. 8). This may imply that there has been a slight enrichment in Mg relative to Fe in the granitic rocks. The high value for this ratio in some of the analysed psammopelitic inclusions may be the result of such enrichment.

The transformation of inclusions to granitic material would require some addition of silica (see Fig. 2). This would be consistent with the expected reaction of micas (Si : O ratio ~1 : 3·3) transforming to feldspars (Si : O ratio ~1 : 2·7). Winkler (1967) suggests a reaction such as

> 2 biotite+6 sillimanite+9 quartz→2 K-feldspar component+3 cordierite+2 H_2O.

This reaction may in part be responsible for the paucity of quartz-rich or quartzo-feldspathic segregations immediately adjacent to mica segregations. The average bulk composition of the granite and biotite-rich inclusions would be markedly lower in SiO_2 than an average psammopelite. The transformation of inclusion to homogeneous granite would involve an increase in the number of anions associated with 100 cations (see Table 3) and hence an increase in volume or decrease in density. This may have influenced migration of granitic rocks to higher levels in the crust. The granites are in places surrounded by lower grade sections of the high grade zone or upper knotted schist zone rocks (Guy, 1969)—apart from where faulting has been operative. Such metasediments would have a similar specific gravity to that of the granites.

The bulk composition of the granitic rocks is such that few samples contain more than 80% Q+Or+Ab or fall in the low-temperature through of Tuttle and Bowen (1958). The normative ratio of Q : Or : Ab is approximately 45 : 30 : 25, although biotite clusters frequently have granular quartz associated with them, thus the Q content of portions of the granites capable of melting may be less than that indicated by the above ratio.

Von Platen (1965) has suggested that the Ab : An ratio is an important factor on the " minimum melting point " (Winkler, 1967) in the system Q–Ab–An–Or at $P_{H_2O}=2000$ bars. With increase in Ab : An ratio the "minimum melting temperature " decreases and is relocated towards the Ab corner, restricting the plagioclase field. A plot of some Cooma-type granites is noted in Fig. 3 with reference to this system. These analyses are presented on two Q–Ab–Or projections to illustrate the influence of Ab : An ratio on their crystallization history. Those rocks with low Ab : An ratio (<3·0) generally lie on the Ab side of the cotectic curve. Thus if such (or similar) rocks were melting plagioclase would be the last phase (neglecting biotite, etc.) to go into the melt. This may imply that any

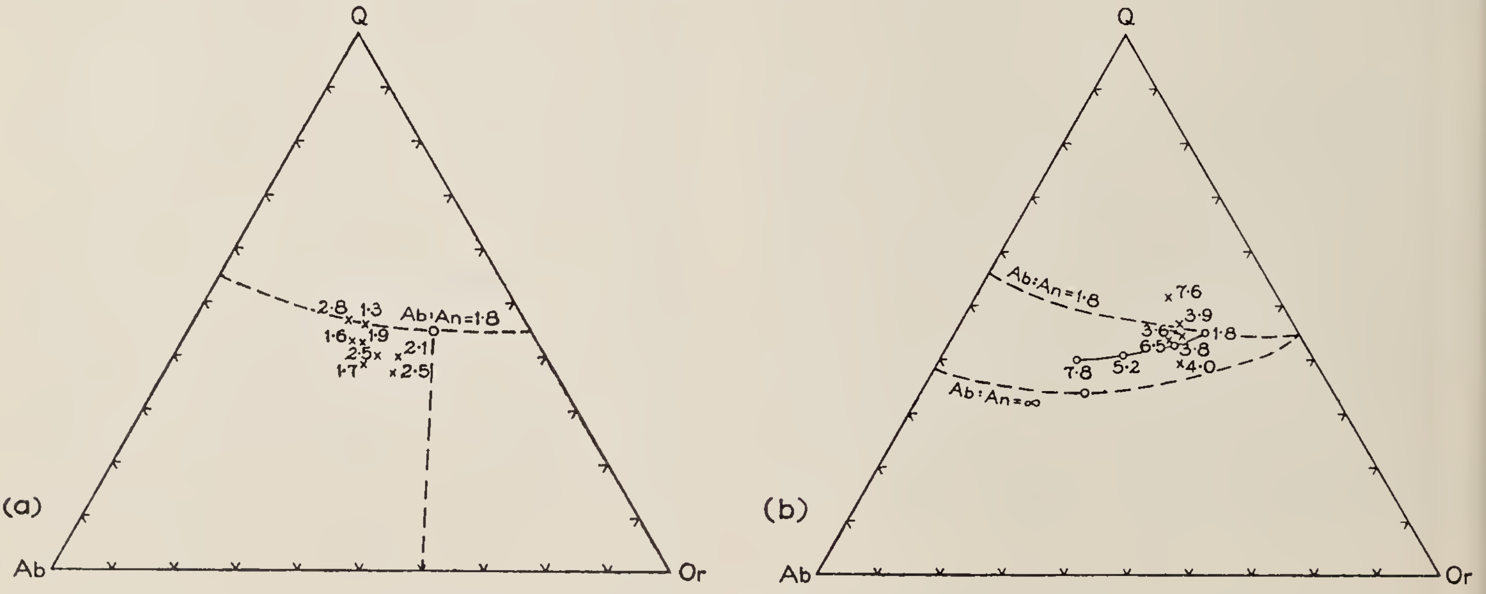

FIG. 3—Projections of sections through the system Q-Ab-An-Or-H_2O at P_{H_2O}= 2,000 bars. Points of " minimum melt " composition are indicated (○) and some cotectic curves for various Ab : An ratios. (After Von Platen, 1965.)

(*a*) Plot of Cooma-type granites (×) with Ab : An<3·0. The boundary between the plagioclase and K-feldspar fields (for Ab : An=1·8) is indicated.

(*b*) Plot of Cooma-type granites (×) with Ab : An>3·0. Figures against (×) symbols refer to the Ab : An ratio of the granites.

quartz-alkali feldspar-rich or quartz-rich segregations that may have developed in such granitic rocks through a segreation process, would be particularly susceptible to melt conditions.

If introduction of sodium followed some melting of rock types represented by Fig. 3a, there would be a marked change in the ratio of Ab : An (as the An contents are generally not large) as well as depressing the " minimum melting temperature ". The " minimum melt " and the cotectic line would be relocated towards the Ab corner. As such sodium introduction would not greatly change the amount of Ab relative to Or and Q, the plot of the granitic rocks on the diagram Q–Ab–Or would not be significantly altered.

If associated with sodium introduction, there was breakdown of micas (see p. 18) and perhaps some incorporation of quartz-rich segregations (*cf.* Fig. 2), the bulk composition of the granitic phases would be relocated away from the Ab corner. Thus the distribution of granitic rocks noted in Fig. 3b—i.e. those with high Ab : An ratio—may be explained by such a sequence of events. It is interesting that in the latter case those rocks with high Ab : An ratio, would lie on the Q side of the cotectic and thus quartz would be the last phase to melt. Thus fluctuation in temperature, pressure, breakdown of biotites, or introduction of Na would have a marked influence of the phase(s) in equilibrium with the melt. The patchy zoning of the plagioclases may be a direct result of such a crystallization history.

Some recent investigations by Weill and Kudo (1968) have thrown some doubt on the work of Von Platen. The former authors suggest that the Q–Or–Ab system does not have a unique melting point or a unique composition of initial melt. This does not detract from the suggestion by Winkler (1967) that for any Ab : An ratio there is still a minimum melting point for the system. Some doubt exists as to whether the minimum melting points determined by Von Platen is the absolute minimum in the system Q–Ab–An–Or for a fixed Ab : An ratio. Weill and Kudo's suggestion that there is a unique melting point for a given Ab : Or ratio may not be particularly significant for the Cooma-type granites considering that the development of such rocks is related to breakdown of the micas. If it is assumed that Von Platen's experimental study does suggest a trend for minimum melt composition with variation in Ab : An ratio, a feasible theory may be proposed for the development of the Cooma-type granites.

The sequence of events envisaged in the formation of these granites may be summarized as :

1. Very high grade metamorphism of a sequence of rocks with a compositional range close to that of a psammopelite. The metamorphism involves a decrease in volume with increase in grade. The principal phases would be quartz, micas (mainly biotite) and minor, but rather calcic plagioclase. Calcium and magnesium may have been locally concentrated at this stage. Some segregation of constituents may have taken place producing quartz-rich or quartzo-feldspathic-rich, and mica-rich sections. Diffusion would presumably have been the main process involved in migration of material. Melt is considered not to have been of much significance at this stage.

2. Introduction of sodium, possibly by local concentration from the metasediments, but more likely by diffusion from lower levels in the crust. Such diffusion of sodium would be favoured by elevated temperatures. Both controls (elevated temperature and Na introduction) would be conducive to the production of a partial melt and migration of the cotectic line of the system Q–Ab–An–Or–H_2O towards the Ab corner. Breakdown of micas, also compatible with increase in temperature would favour a change in the phase co-existing with the melt. Such conditions are considered to have been a significant factor in producing the patchy zoning in the plagioclase and the production of alkali feldspars in granitic rocks. The reactions involved in this transformation to granite may have resulted in an increase in volume (*cf.* Table 3) and a decrease in density. This may have been a factor in the migration of Cooma-type granites to higher levels in the crust. It is possible that these rocks have been annealed after emplacement with a significant modification of their textures. The cell structures noted in the quartz grains and some undulatory character of the feldspars may have developed through such a process as annealing.

Pidgeon and Compston (1965) have suggested an age of 415±12 m.y. for the Cooma granite and the surrounding high grade metamorphics at Cooma. More distant greenschist facies rocks are reports to have an age of 460±11 m.y. These authors indicate there is no evidence to suggest any metamorphism later than that developed in the high grade zone and propose that the Cooma granite is locally derived from rocks in the high grade zone. In the Khancoban area (Guy, 1969) there is evidence that the regional metamorphism is multiple in character and that this is discernible only in the higher grade metamorphics. Pidgeon and Compston have not discussed fully the significance of similar ages obtained for the Cooma granite and a section of the Murrumbidgee batholith.

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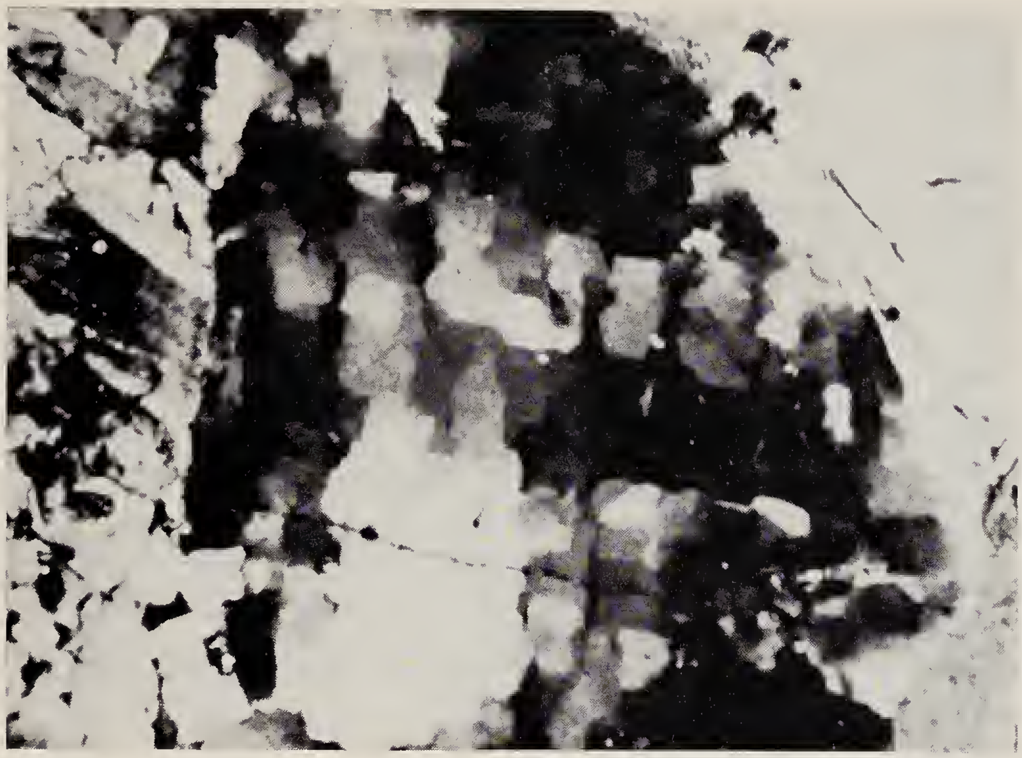

PLATE 1 (*a*)

Cell structure in a quartz grain from the Corryong Granite (spec. 21809). Note the polygonal arrangement of the small domains. Crossed nicols, × 120.

PLATE 1 (*b*)

Section of a plagioclase grain displaying patchy zoning, from the Corryong Granite (spec. 21842). This zoning is evident only near the extinction positions. Crossed nicols, × 45.

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The Nature and Occurrence of Heavy Minerals in Three Coastal Areas of New South Wales

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Abstract—A detailed mineralogical study has been undertaken in an attempt to determine the sources of heavy minerals in three areas of New South Wales. The areas studied are Twofold Bay and neighbouring South Coast districts between Pambula and Disaster Bay, Broken Bay near Sydney, and the Mid-North Coast between Port Macquarie and Grassy Head. The percentage variations of different minerals in both Pleistocene and Holocene sediments have been evaluated. Diagnostic heavy minerals have been traced in some barrier and dune sands, and it is believed that these were transported shorewards during marine transgressions accompanying interglacial periods, and reworked locally by longshore drifting. Most of the minerals in the unconsolidated deposits on the east Australian coast can be described as *polygenetic* because they have been derived from various sources, and their origin is very complex in relation to both time and place.

Introduction

(*a*) *The Nature of the Problem:*

The barriers[2] and dunes on the New South Wales coast are composed of sediments that were reworked during Pleistocene fluctuations of sea-level and during the post-glacial or Holocene marine transgression. Such deposits can therefore be described as *polygenetic* since they have been derived from various sources and their origin is very complex in relation to both time and place. The writer has analyzed Pleistocene and Holocene sediments in an attempt to determine the sources of the heavy minerals in three coastal areas of New South Wales. The areas, which differ geologically and physiographically, are Twofold Bay and neighbouring South Coast districts between Pambula and Disaster Bay (Figure 1), Broken Bay near Sydney (Figure 2), and the Mid-North Coast between Port Macquarie and Grassy Head (Figure 3).

The origin and distribution of heavy mineral beach sands in New South Wales and south-eastern Queensland have been mentioned briefly in technical reports by Gardner (1955), Whitworth (1956) and Connah (1962). Jones (1946) and Beasley (1948, 1950) have discussed the concentration of heavy minerals in beach deposits. Culey (1933, 1939) studied the heavy mineral assemblages of the Narrabeen and Hawkesbury Sandstones. However, no detailed investigations have been made to determine the relationship between heavy mineral concentration and longshore drifting, aeolian activity and the shoreward movement of material from the sea floor during marine transgressions.

(*b*) *The Physiography and Geology of the Areas:*

Dual barrier systems, composed entirely of quartzose sand and separated by swamps and lagoons, have been mapped on several sectors of the New South Wales coast. These have been termed Inner (Pleistocene) and Outer (Recent) Barriers by Langford-Smith and Thom (1969).[3]

The Holocene (Recent) barriers developed across the mouths of drowned river valleys to enclose estuarine lagoons partly or completely from the sea after 7000 B.P. (before the present), at a time when the rate of the post-glacial or Holocene rise of sea level slowed down appreciably (Hails, 1968). The barrier systems of the Central and South Coast of New South Wales are not as clearly represented by Pleistocene and Holocene components as those on the Mid-North Coast which border large fluvial-deltaic

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[2] The term *barrier* applies to littoral sand accumulations—either beaches, spits or islands—that stand permanently above high-tide level and enclose lagoons or shallow bays. Barriers are usually characterized by multiple beach ridges, but a few are comprised of a single ridge. A few beach ridge systems, for example, the Umina-Woy Woy system in Broken Bay, are not separated from a bedrock hinterland by large coastal lagoons.

[3] The terms Outer (Recent) Barrier and Inner (Pleistocene) Barrier will be used in the same context as originally defined by Langford-Smith and Thom (1969).

plains. This is because former broad protected bays of the North Coast, and an abundant supply of sand from large rivers, favoured the development of wide barriers, while the more rugged embayments and lack of large rivers on the Central and South Coast did not. The limited extent to which the estuarine lagoons on the South Coast have been filled by fluvial deposits also reflects the size, discharge and sediment yield characteristics of the river catchments (Bird, 1967).

Twofold Bay (Figure 1) and adjacent areas are composed of strongly folded and faulted Devonian strata, with Ordovician metamorphic rocks and Tertiary basalts (Brown, 1930, 1933 ; Steiner, 1966). The sedimentary rocks around Twofold Bay are of variable composition, and are associated with rhyolites, basalts and dolerites. Unconsolidated sands and gravels of varying thickness which directly overlie the Devonian rocks have been designated Tertiary (Hall, 1957).

Twofold Bay, one of the largest embayments on the South Coast, is actually a succession of smaller bays, with bayhead beaches, which are separated by headlands and small promontories. The Boyd Town barrier system is the largest of its kind inside the bay, and is situated between the Nullica River and Boyd Town Creek. It consists of a series of abandoned beach ridges with intervening swales and is backed by degraded sea cliffs. Eden barrier spit impounds Curalo Lake which occupies the drowned valleys of Bellbird Creek and adjacent coastal streams. Whale Beach barrier encloses the Towambah (Kiah) estuary and north of Twofold Bay, Pambula barrier spit partly encloses Merimbula Lake.

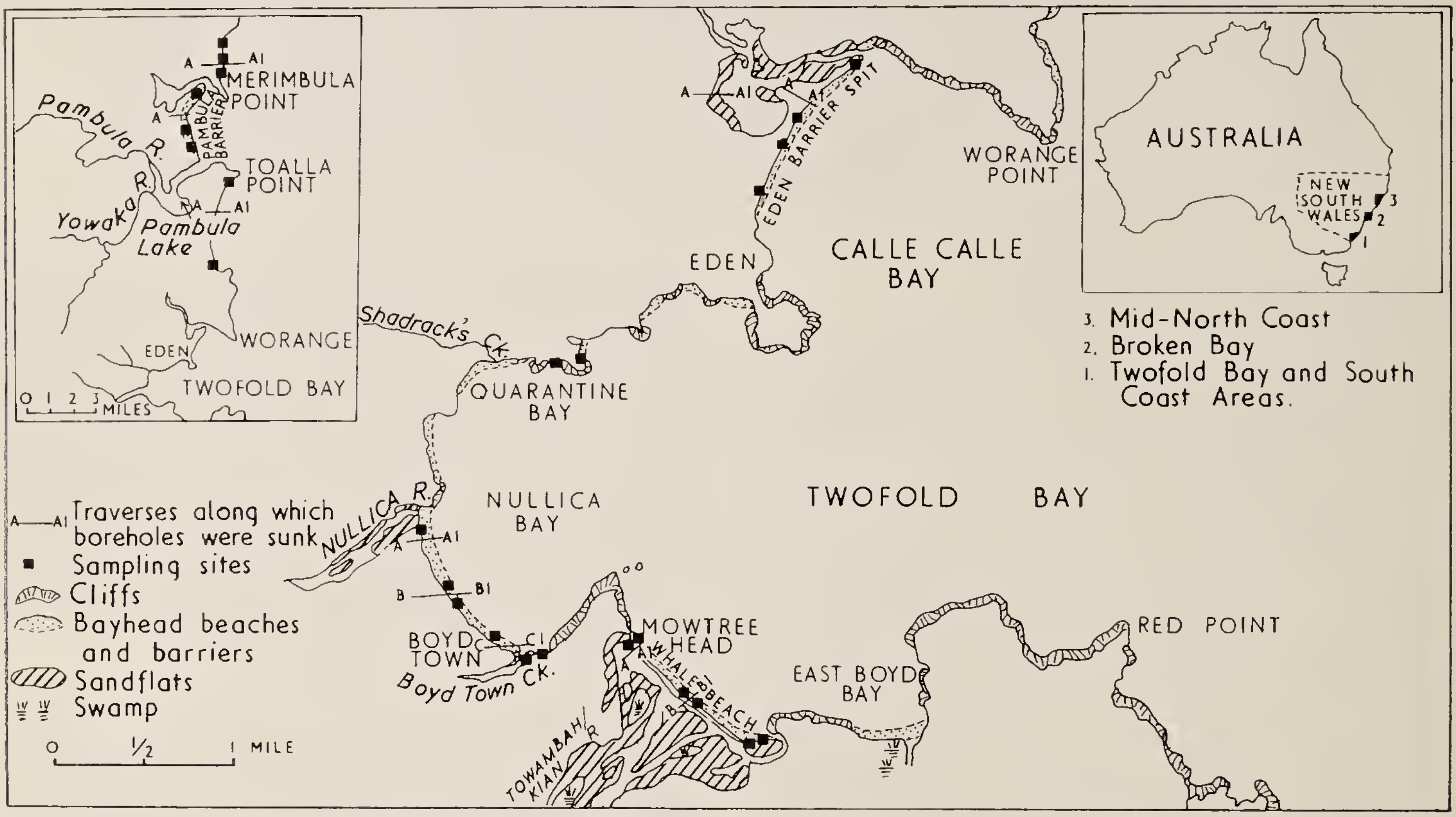


FIG. 1—Twofold Bay and adjacent South Coast areas. Inset map of Australia shows location of the three study areas in New South Wales.

Broken Bay (Figure 2) is part of the dendritic drowned valley of the Hawkesbury River, and is dominated by vertical cliffs cut in resistant, almost horizontally-bedded, Hawkesbury and Narrabeen sandstones of Triassic age. Lenticular layers of shale are interbedded with the sandstones which are characterized by major systems of vertical joints (David, ed. W. R. Browne, 1950). Tertiary dykes and sills have been reported in a few coastal sections. Patonga Beach is a sand barrier which almost completely encloses the mouth of Patonga Creek in Brisk Bay, whilst Pearl Beach barrier originally developed across the mouth of a small embayment.

The Umina-Woy Woy barrier is the largest depositional feature in Broken Bay. It consists of a series of abandoned beach ridges aligned parallel to the shoreline. There is some evidence to suggest that this barrier may be composed of Pleistocene as well as Holocene sediments (Hails, 1969), in contrast to Pearl Beach and Patonga Beach which are Holocene barriers.

The Mid-North Coast (Figure 3), is characterized by zeta-curved or arcuate bays which are flanked by resistant bedrock headlands. Some of the headlands are mantled with deeply podzolized Pleistocene cliff-top dunes that stand between 100 and 400 feet above present sea level.

According to Voisey (1934), the headlands are composed mainly of sandstones, tuffs, mudstones, claystones and shales with minor conglomerate bands. These deposits, termed the Kempsey Series, are believed to be of Permian age. The hinterland of the Mid-North Coast forms part of the New England Plateau which is composed predominantly of Palaeozoic rocks, and Tertiary basalts. The Macleay is the largest river on the Mid-North Coast, and its headwaters occupy valleys which have been incised into the New England Plateau. No deltas have been built seaward of the modern coast in northern New South Wales. Instead sedimentation and alluviation have taken place between an ancient bedrock coastline and the dual barrier systems, resulting in the construction of fluvial-deltaic plains.

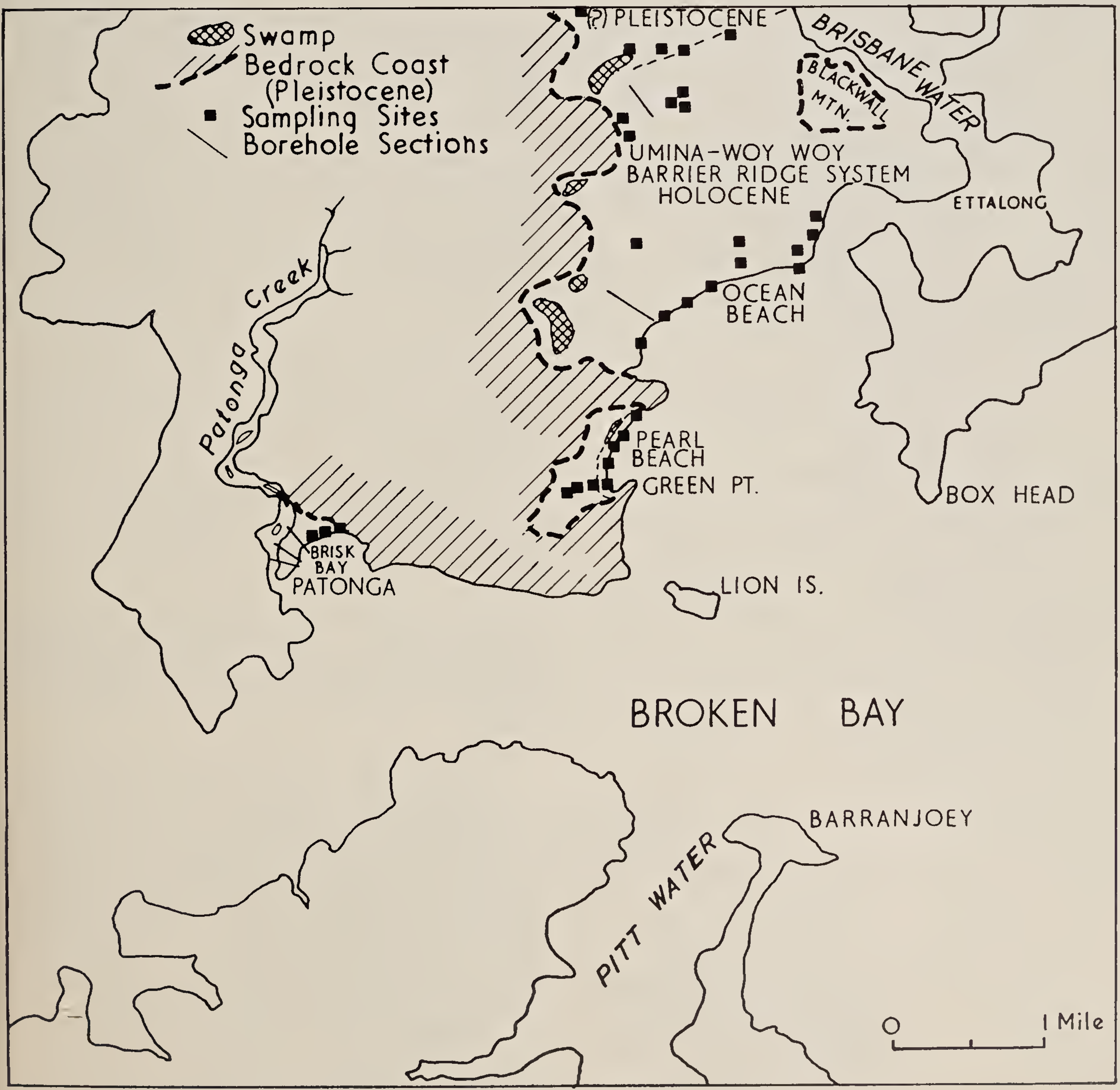


FIG. 2—Map to show the location of barriers in Broken Bay.

(*c*) *The Aims of the Study :*

The purpose of this study has been :

1. To trace the sources of the heavy minerals. Sources can be sub-divided into : indirect sources, such as material being reworked from immediately offshore, and direct sources, whereby minerals are derived from eroded adjacent cliffs and headlands.

2. To evaluate the percentage variation of the different minerals in Pleistocene and Holocene barrier and dune sands in order to determine whether there is any significant difference with age. An assessment has been made of the chemical stability of the heavy minerals and their resistance to abrasion. The percentage concentration of heavy minerals in barrier and dune sands has been examined in an attempt to assess the transporting effect of wind and wave action.

3. To compare the heavy minerals collected in the inland drainage basins of the Hastings and Macleay Rivers with those in coastal deposits to see if any diagnostic minerals have been transported alongshore. Also, to ascertain whether heavy minerals by-pass river, creek and lagoonal outlets, and are transported around headlands or promontories by littoral currents.

Because serpentine outcrops on the Mid-North Coast south of the Hastings River, the area between Port Macquarie and Grassy Head has been studied in detail (Figure 3). The writer considered that a few diagnostic minerals derived from serpentine rocks might be transported around Point Plomer, Big Hill, Delicate Nobby and other headlands flanking the arcuate bays.

4. To determine the roundness values of the heavy minerals in order to ascertain, if possible, the relationship between roundness and environments of deposition in the three physiographical areas.

Field and Laboratory Procedures

Barrier, dune (including cliff-top dune), fluvial and offshore neritic environments were sampled. Beach samples were collected just below the swash line of high water (HWM) and approximately at Bascom's (1951) " reference point " which is the part of the beach subjected to wave action at the mid-tide stage. Although mid-tide refers to a level half way between the previous high-tide and the succeeding low, the inter-tidal zone varies from its predicted position

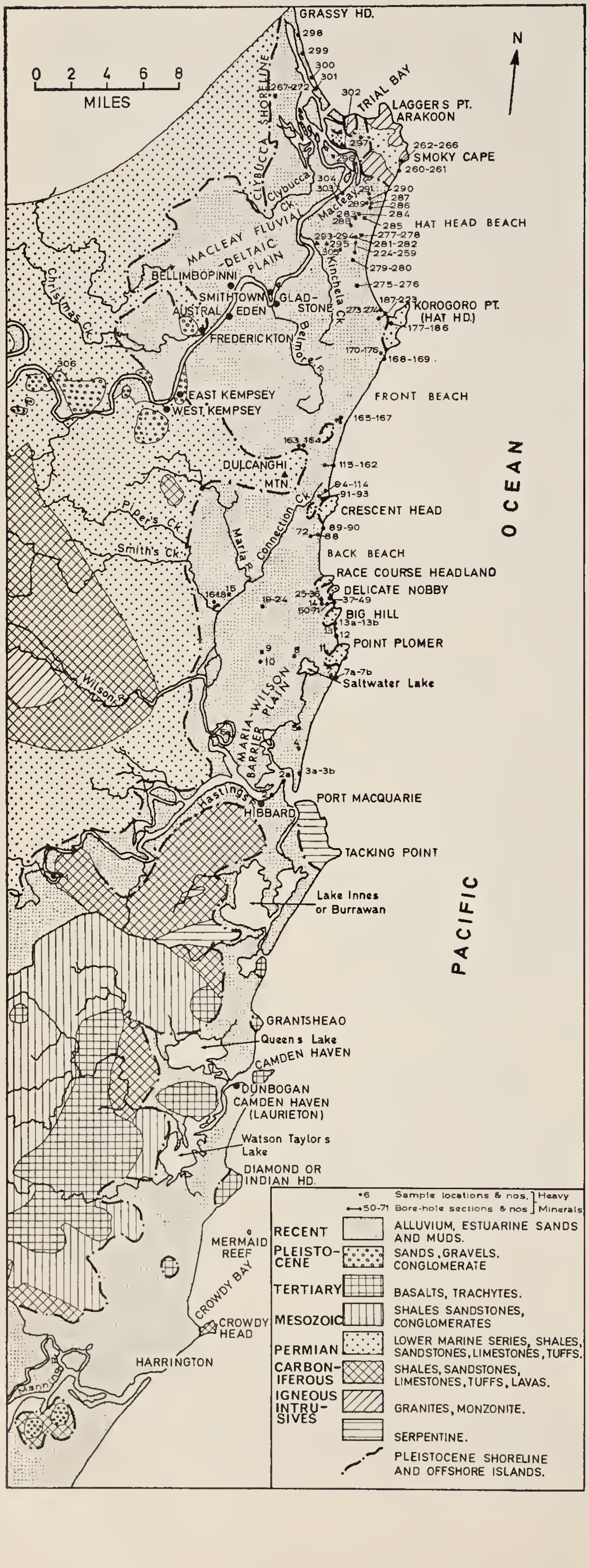


FIG. 3—Locality map of the Mid-North Coast showing location of heavy mineral samples. Geology based on the work of Voisey.

according to local conditions at the time of sampling. Barrier and dune samples were collected at one-foot intervals from boreholes sunk along surveyed transects across the barriers and deltaic plains. Lines of section were approximately perpendicular to the beach and extended from low water mark to a degraded coastline behind either the barriers or deltaic plains. No samples were collected below the water table because of the risk of contamination by material washed into the boreholes.

Samples collected from the swamps and deltaic plains which contained a high content of silt and clay were analyzed by the hydrometer method of Bouyoucos (1936).

All sand samples were oven dried and a 100 gm. sample split was sieved through a set of B.S.S. 8-inch sieves at the $\frac{1}{4}(\Phi)$ phi interval on a Ro-Tap machine for 15 minutes. The fractions retained on the sieves were weighed on a Mettler Precision Balance to 0·01 gm. and amounts smaller than 1 gm. were weighed to 0·001 gm. Tests showed that very few, if any, heavy minerals occurred in the −60 mesh (0·251 mm.) grade of sand. Therefore, only the −60+200 mesh (0·251–0·074 mm.) fractions were retained for heavy mineral analysis.

The light and heavy mineral fractions of a 5-gram sample split of each sample were separated in bromoform (S.G. 2·90) by using a centrifuge. The heavy residue was weighed and recorded as a weight per cent. A part of the heavy mineral residue, obtained with a microsplitter, was mounted in Canada balsam for microscopic examination and grain counts. In addition, microscope slides were made of the light-heavy, and rutile-zircon-ilmenite fractions of samples specially treated at Mineral Deposits Laboratory, Crescent Head, N.S.W. The percentage number of each mineral in an individual sample was determined by using a mechanical stage and by counting 300 grains. Dryden (1931) suggested that 300 counts is an optimum number, and also that the accuracy of the counts increases as the square root of the number of grains counted. The heavy mineral fractions of six samples collected from the Macleay and Hastings Rivers (Numbers 1, 2–2a, 3a–3b, and 306, Figures 3 and 8) were separated into magnetic and non-magnetic fractions by using a Model L-1 Frantz Isodynamic Separator.

The unmounted portion of the heavy residue of each sample was examined under a binocular microscope, and roundness analyses were conducted by following the method of Shepard and Young (1961). They modified the scale developed by Powers (1953) by introducing " pivotability ", whereby grains were viewed under a binocular microscope and compared visually with a scale of roundness (pivotability) which is divided into six categories. In order to prevent operator bias the samples were renumbered, so the writer was unaware of their location. 100 grains were counted in each sample.

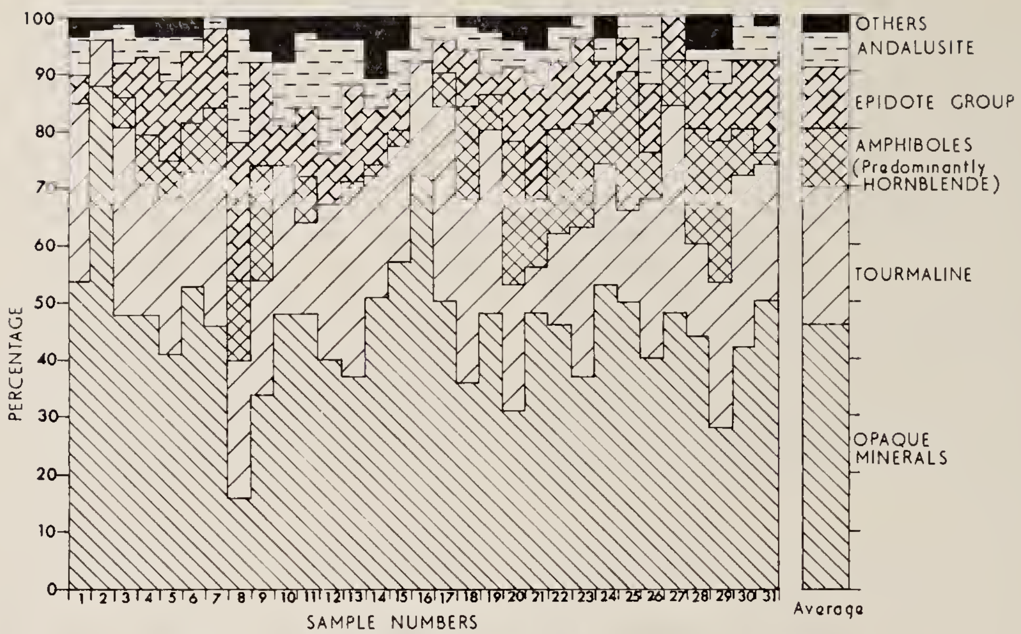
The accuracy of heavy mineral analyses, depending upon errors in both field sampling and laboratory studies, has been discussed by Dryden (1931), Krumbein and Rasmussen (1941), Manning (1953) and other workers. Rubey (1933) stated that large variations in the relative abundance of various minerals will be found in different grain sizes of the same sample. On the other hand, Van Andel (1955) and Poole (1958) concluded that only in special cases is it necessary to study various size fractions separately. In the light of more recent work by Carroll (1957) the writer considers that the method employed in this study has been valid and has not impaired the final results. Carroll (*op. cit.*) pointed out that procedural errors can probably safely be neglected from the mineralogical point of view when minerals have been subjected to previous sorting and sedimentation processes, even though it is recognized that certain minerals tend to occur in larger or smaller grain sizes than others.

Heavy Mineral Occurrences

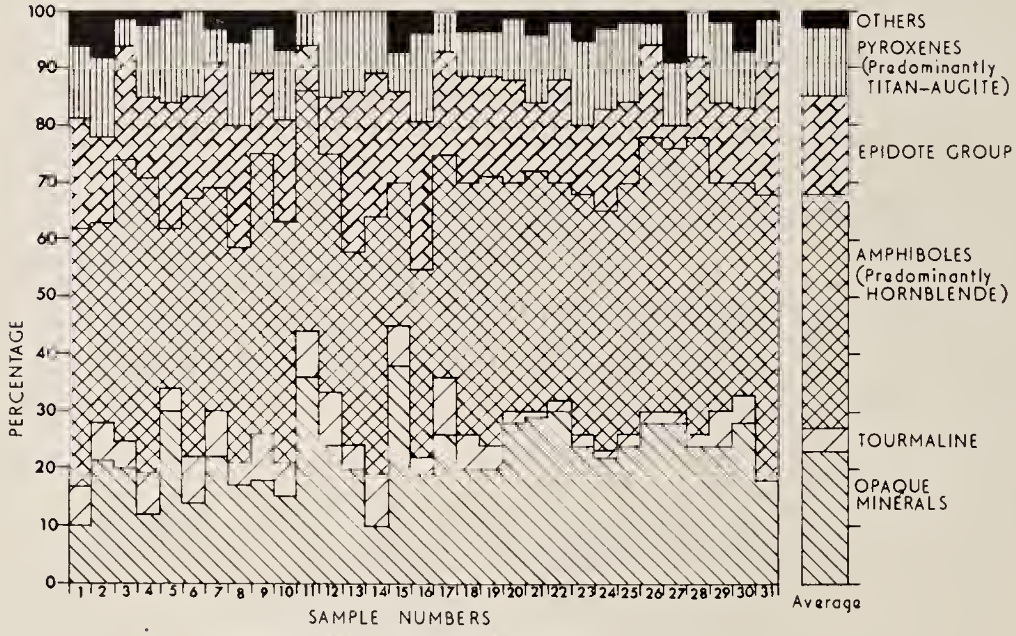
(*a*) *South Coast Samples:*

Tourmaline, amphiboles (chiefly hornblende), pyroxenes (chiefly titan-augite and diopsidic augite), members of the epidote group, and the opaques are the most common minerals in the South Coast beach and barrier samples. The opaque minerals and tourmaline constitute 70 and 80 per cent respectively of the heavy fraction in the Pambula and Eden barrier sands, whereas these minerals plus the amphiboles and epidote comprise 86 per cent of the total heavy mineral assemblage in the Boyd Town samples. In addition, andalusite, zircon, enstatite, topaz, rutile, sphene, garnet (colourless and pink), monazite and other minor constituents have been identified. With the exception of andalusite, the other minerals do not occur in sufficient quantities to be of importance. The variation in percentage of these minerals is shown in Figure 4, and listed in Tables 1 and 2. Table 1 compares the heavy mineral concentrates of barrier and dune sands in the three study areas.

PAMBULA BARRIER



TWOFOLD BAY — BOYD TOWN BEACH RIDGE SYSTEM



TWOFOLD BAY — EDEN BARRIER

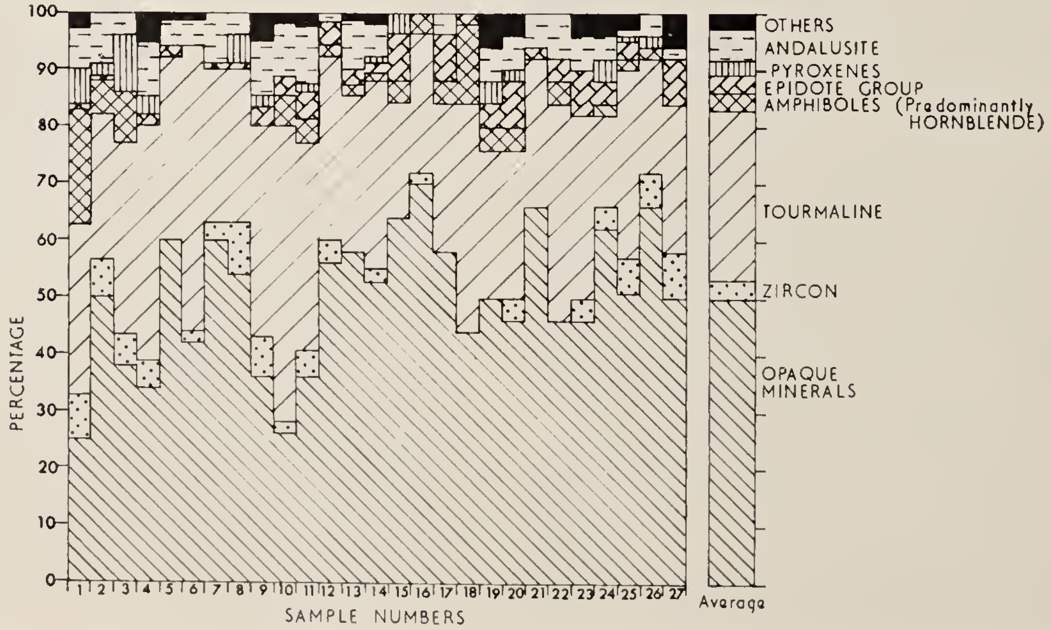


Fig. 4—The percentage occurrence (by number) of heavy minerals identified in South Coast barrier samples. The average composition is also shown. Sample numbers refer to sections and sampling sites shown in Fig. 1.

TABLE 1

Average Percentage Occurrence (by Number) of Heavy Minerals in Some Mid-North Coast, Broken Bay and South Coast Barrier and Dune Samples

Locality/ Environment	Mineral																
	Rutile	Zircon	Tourmaline	Monazite	Garnet	Apatite	Staurolite	Kyanite	Epidote Gp.	Amphiboles (chiefly Hornblende)	Andalusite	Topaz	Sphene	Pyroxenes (chiefly Augite)	Hypersthene	Enstatite	Picotite	Spinel
Mid-North Coast :																		
Delicate Nobby	21·23	16·29	50·60	0·21	2·08	0·02	1·25	0·08	1·93	0·27	4·08	0·19	0·02	0·21	0·27	0·95	0·32	—
Back Beach (inner barrier) . .	24·53	42·64	26·67	0·60	0·12	—	1·06	—	0·06	—	3·23	0·06	0·12	0·18	—	0·06	0·67	—
Killick Creek, nr. Crescent Head (inner barrier)	32·51	37·02	24·95	0·08	0·08	—	1·16	0·08	0·25	—	3·75	0·12	—	—	—	—	—	—
Front Beach (outer barrier) . .	15·77	17·41	53·73	0·40	0·90	0·04	1·50	0·21	1·64	1·18	5·00	—	0·37	0·37	0·41	1·03	0·04	—
Hat Head (outer barrier) . .	14·54	8·00	62·38	0·60	2·00	0·35	1·18	0·16	2·48	0·18	4·94	0·37	0·13	—	0·22	2·27	—	0·20
Hat Head (inner barrier) . .	9·72	32·40	52·69	—	0·06	0·11	1·08	—	0·28	—	3·60	0·06	—	—	—	—	—	—
Hat Head (cliff-top dunes) . .	17·90	35·70	42·10	—	—	0·40	0·90	—	0·40	—	2·40	0·20	—	—	—	—	—	—
Smoky Cape (cliff-top dunes) . .	14·20	40·40	44·20	—	—	—	—	—	—	—	1·20	—	—	—	—	—	—	—
Front Beach (transgressive dunes)	22·28	27·42	43·59	—	—	—	0·71	—	—	—	6·00	—	—	—	—	—	—	—
Clybucca shoreline	24·53	71·03	3·83	—	0·16	—	0·16	—	0·16	—	0·33	—	—	—	—	—	—	—
Maria - Wilson barrier plain . .	39·00	38·69	19·83	—	—	—	0·83	—	0·16	—	1·16	0·33	—	—	—	—	—	—
Broken Bay :																		
Umina-Woy Woy beach ridge system; Pleistocene (?) samples	36·95	26·85	24·71	1·80	0·09	—	—	—	1·83	3·68	3·68	0·02	—	0·32	0·07	—	—	—
Holocene samples	30·08	30·62	22·96	0·55	0·96	—	—	—	6·44	4·88	3·11	—	—	0·22	0·11	—	0·07	—
South Coast :																		
Boyd Town beach ridge system . .	0·09	0·51	6·35	—	0·49	0·03	—	—	21·87	54·00	1·29	0·35	0·22	14·19	—	0·61	—	—
Eden barrier spit	0·55	6·66	64·99	0·52	1·74	—	—	—	6·74	4·26	10·49	0·44	0·07	3·33	0·14	0·07	—	—
Pambula barrier spit	0·45	1·55	46·20	0·19	1·70	—	—	0·06	19·23	16·35	12·42	0·40	0·13	0·64	—	0·68	—	—

(*b*) *Broken Bay Samples :*

The most abundant heavy minerals for all samples are the opaques, rutile, zircon and tourmaline (Figure 5 ; Tables 1 and 3). Together, they generally constitute almost 90 per cent of the heavy minerals in the Broken Bay barrier and beach sands, and offshore sediments. Other minerals present in significant quantities include those of the amphibole (chiefly hornblende) and epidote groups, andalusite and monazite. Minor constituents in order of decreasing occurrence are garnet (colourless and pink varieties), pyroxenes (chiefly augite), hypersthene, topaz, picotite, staurolite, sphene, spinel, enstatite and apatite (Tables 1 and 4).

TABLE 2

Average Percentage Occurrence (by Number) of Heavy Minerals in South Coast Barrier Samples

(Percentage taken to nearest whole number)

Mineral	Eden Barrier Spit (Twofold Bay)	Boyd Town Barrier Beach Ridge System (Twofold Bay)	Pambula Barrier Spit
Opaques (magnetite, ilmenite, leucoxene, haematite, limonite) . .	50	23	46
Zircon	3	0*	0*
Tourmaline . .	30	5	24
Rutile	0*	0*	0*
Andalusite . .	5	0*	6
Amphiboles (chiefly hornblende) . .	3	41	10
Pyroxenes (chiefly titan-augite and augite) . .	3	11	0*
Epidote	3	17	11
Others	3	3	3

* Included in ' Others ' as percentage occurrence in samples is less than 3%.

(*c*) *Mid-North Coast Samples :*

The minerals identified in the Mid-North Coast samples can be divided into three distinct groups : opaque minerals, which include ilmenite, magnetite and leucoxene ; common detrital minerals, such as zircon, tourmaline and rutile, and those designated " others ", of which staurolite, andalusite, garnet, kyanite, epidote, picotite, hypersthene and spinel are considered to be the important diagnostic minerals. The first two groups together constitute more than 85 per cent of the heavy minerals present in the sedimentary environments that were sampled.

TABLE 3

Average Percentage Occurrence (by Number) of Heavy Minerals in Broken Bay Barrier Samples

Mineral	Umina (Ocean Beach)-Woy Woy Beach/Dune Ridge System		Pearl Beach Barrier Numbers	
	Holocene	Pleistocene (?)	1–7*	1–93*
Opaques (magnetite ilmenite, leucoxene, haematite, limonite)	36	44	31	21
Zircon . .	18	16	29	31
Tourmaline . .	15	12	6	6
Amphiboles . .	2·50	1·78	—	—
Epidote group	3·75	—	—	—
Rutile	20·50	22·25	33	40
Andalusite . .	2·25	2	—	1
Others . .	2	1·97	1	1

* See Figure 5.

TABLE 4

Percentage Occurrence of Minerals in Pearl Beach and Patonga Samples

(Percentage occurrence is not expressed by numbers per sample, but number of times the minerals have been found in the total number of samples analyzed. For example, Andalusite has been found in 38 of the 100 Pearl Beach barrier samples)

Mineral	Pearl Beach Barrier (100 samples)	Patonga Barrier Spit (217 samples)	Patonga Offshore (70 samples)
Monazite	31	18	27
Garnet	10	8	6
Apatite	—	1	—
Staurolite . .	2	<1	—
Epidote group . .	17	30	54
Amphiboles (chiefly Hornblende) . .	21	20	54
Andalusite . .	38	44	51
Topaz	—	4	7
Sphene	1	—	1
Pyroxenes (chiefly Augite) . .	2	9	11
Hypersthene . .	6	3	4
Enstatite . .	—	1	—
- - - - -	- - - - -	- - - - -	- - - - -
Picotite	6	2	1
Spinel	—	<1	—

Minerals are arranged with the least persistent mineral last. As picotite and spinel are not shown in the Order of Persistence Table (Table 5B), they have been placed below the dashed line.

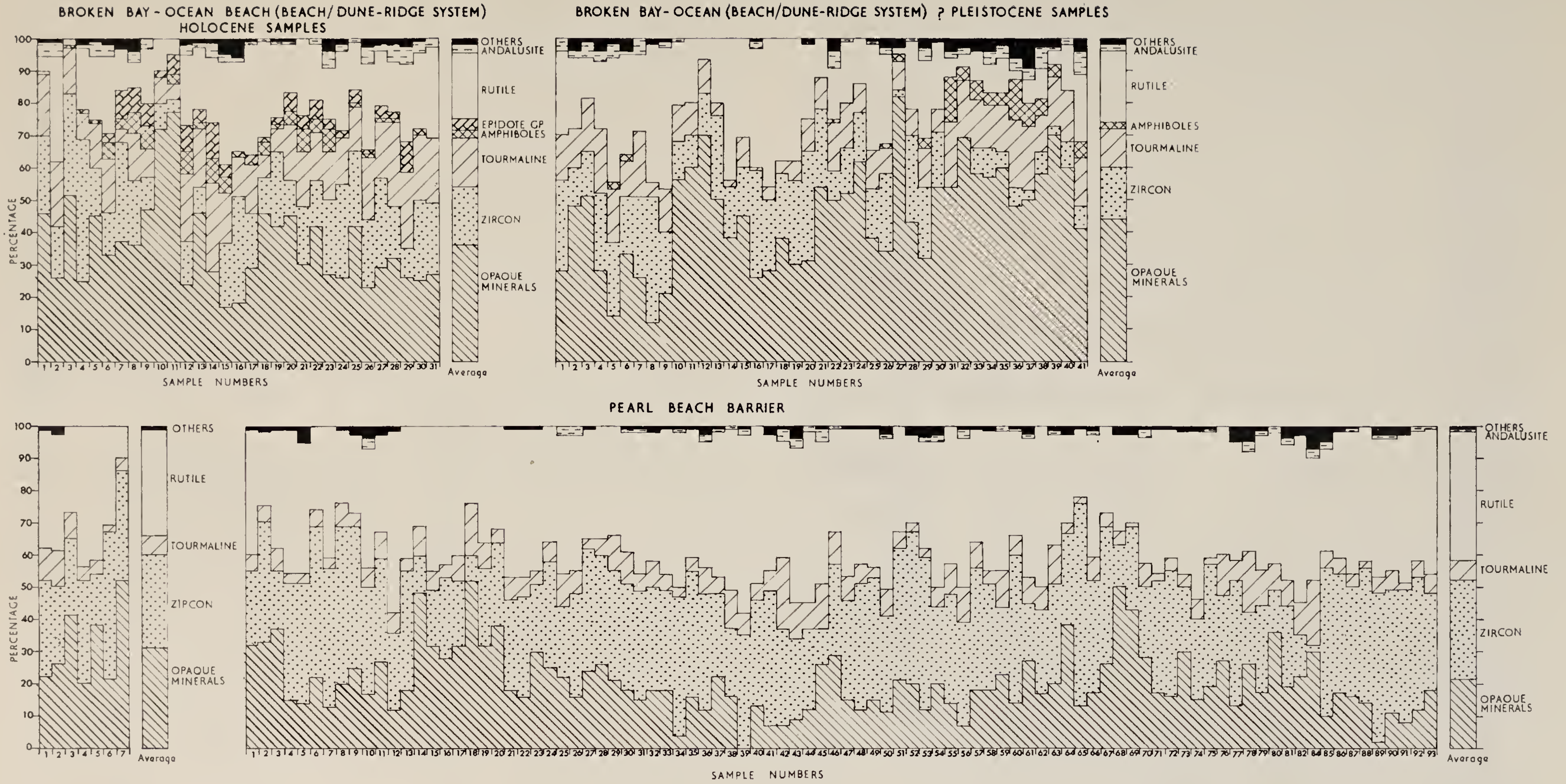


FIG. 5—The percentage occurrence (by number) of heavy minerals identified in Broken Bay barrier samples. Sample numbers refer to sections and sampling sites shown in Fig. 2.

Small quantities of monazite, apatite, amphiboles (hornblende), topaz, sphene and pyroxenes (chiefly augite) have been identified. The percentage occurrence (by number) of all these minerals is shown in Figures 6 and 7. The percentage range and mean of each mineral are plotted in Figure 7 which also shows the non-opaque heavy mineral composition of Pleistocene and Holocene barrier and dune samples. The variation in percentage of all the minerals, except the opaques, is listed in Table 1.

Discussion of the Results

(*a*) *South Coast Samples :*

The same minerals are common to practically all samples, but their percentage occurrence (by number) varies significantly in the Twofold Bay deposits. These variations can be partly explained by the different types of rock in the immediate vicinity of Twofold Bay. Shadrack's Creek and the Nullica River, which flow into Nullica Bay, drain catchments of unconsolidated Tertiary (?) deposits, Devonian rhyolites, dolerites and felsites, and Ordovician metamorphic rocks. In contrast, Bellbird Creek, which enters Curalo Lake (almost entirely isolated from Calle Calle Bay by Eden barrier spit), drains a catchment of predominantly sedimentary rocks—sandstones, siltsones, shales and quartzites. Therefore, it is not surprising that the analyses reveal significant differences in the percentage occurrence of epidote, titan-augite and the amphiboles in the barrier and beach sands of Nullica and Calle Calle Bays. For example, titan-augite is almost four times, epidote six times, and the amphiboles fourteen times more abundant in the Boyd Town barrier sands than in the Eden barrier samples (Table 2).

The percentage occurrence of hornblende is somewhat anomalous. Titan-augite and diopsidic augite, the most abundant of the pyroxenes identified, appear to have been derived locally. Probably, the former was derived from either the basalts or dolerites, in which it often replaces common augite, whilst the latter possibly originated in the rhyolites, such as the potash type at Eden. The comparatively small percentages of rutile, zircon and other minor

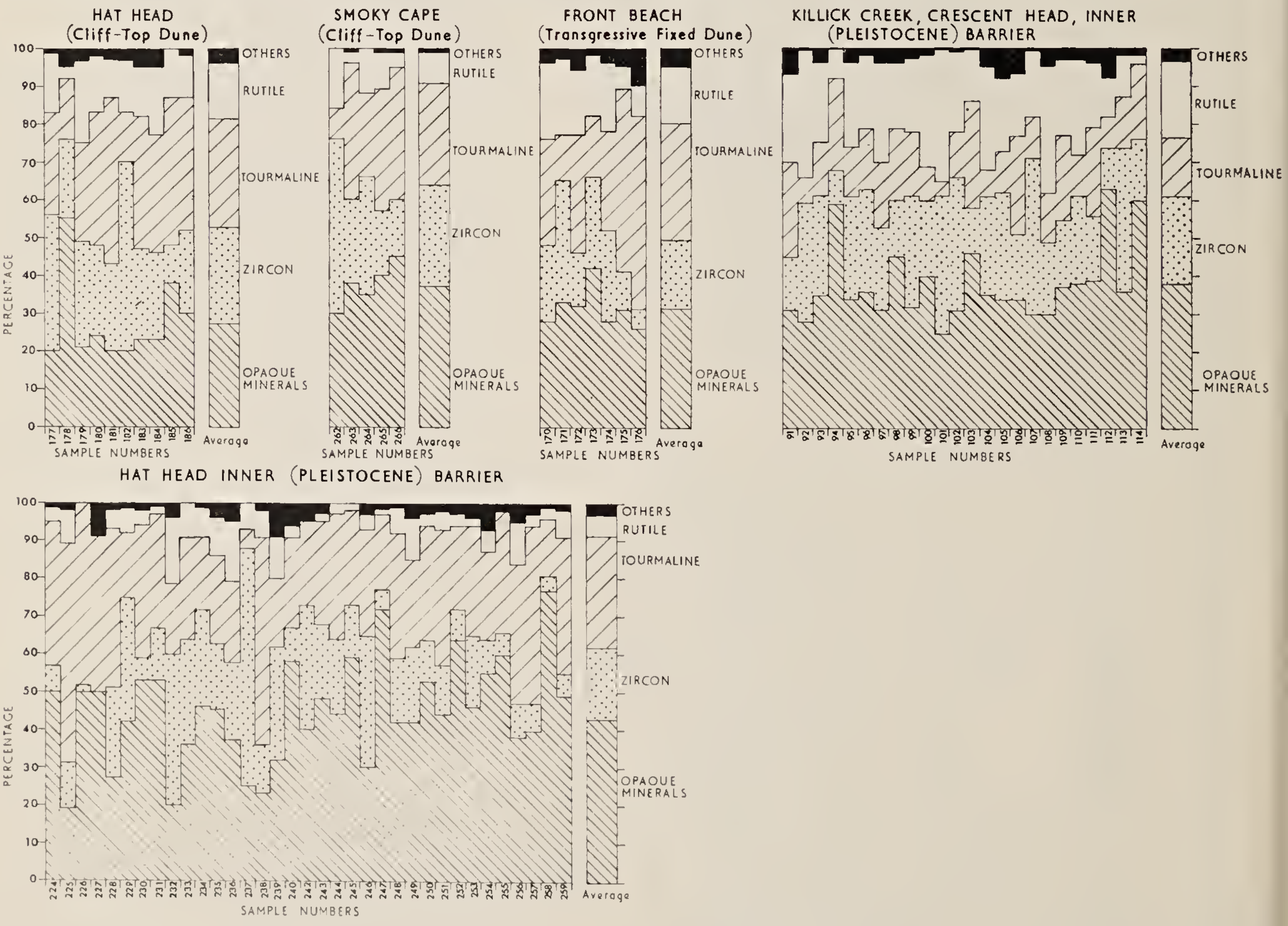
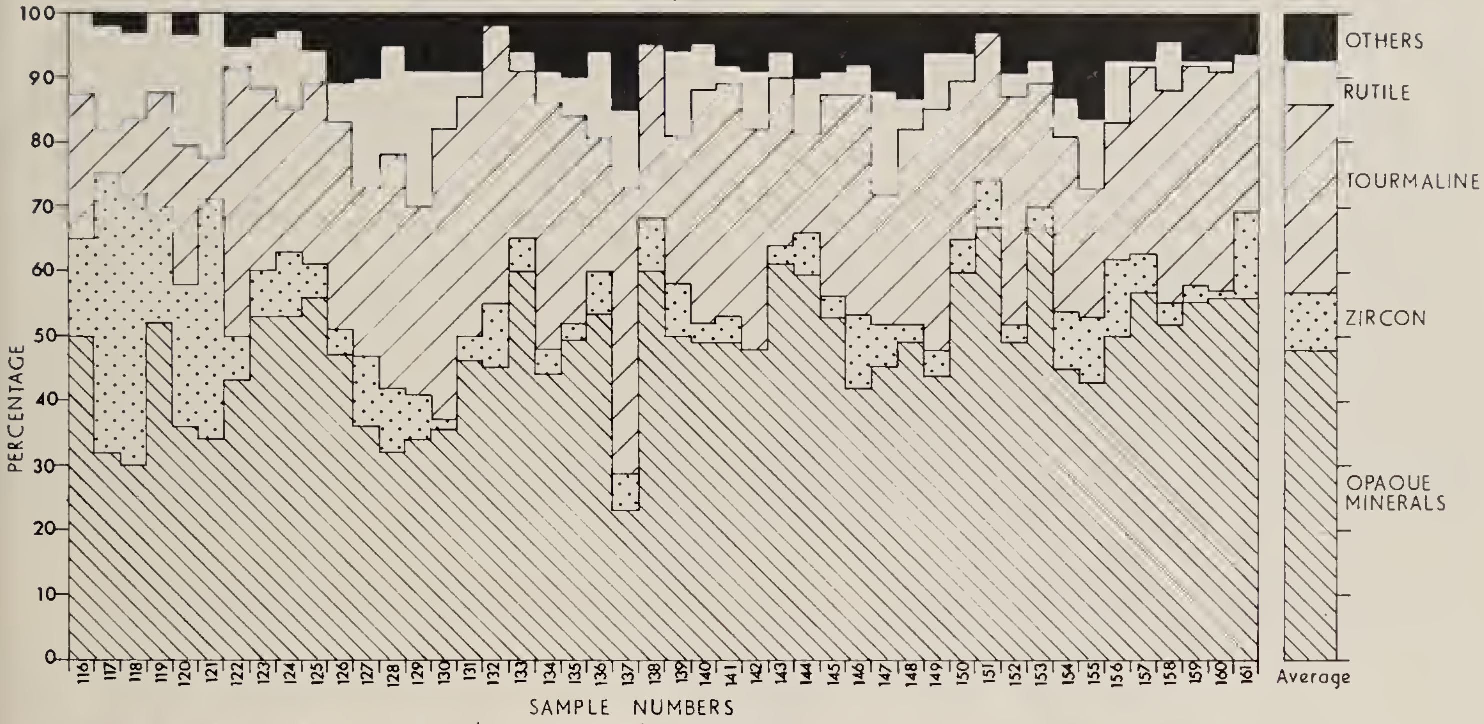


FIG. 6—The percentage occurrence (by number) of heavy minerals identified in Mid-North Coast barrier and dune samples.

(FIG. 6 — *continued.*)


FRONT BEACH (Crescent Head to Hungry Hill (Korogoro Point)).
OUTER (HOLOCENE) BARRIER.

HAT HEAD. OUTER (HOLOCENE) BARRIER.

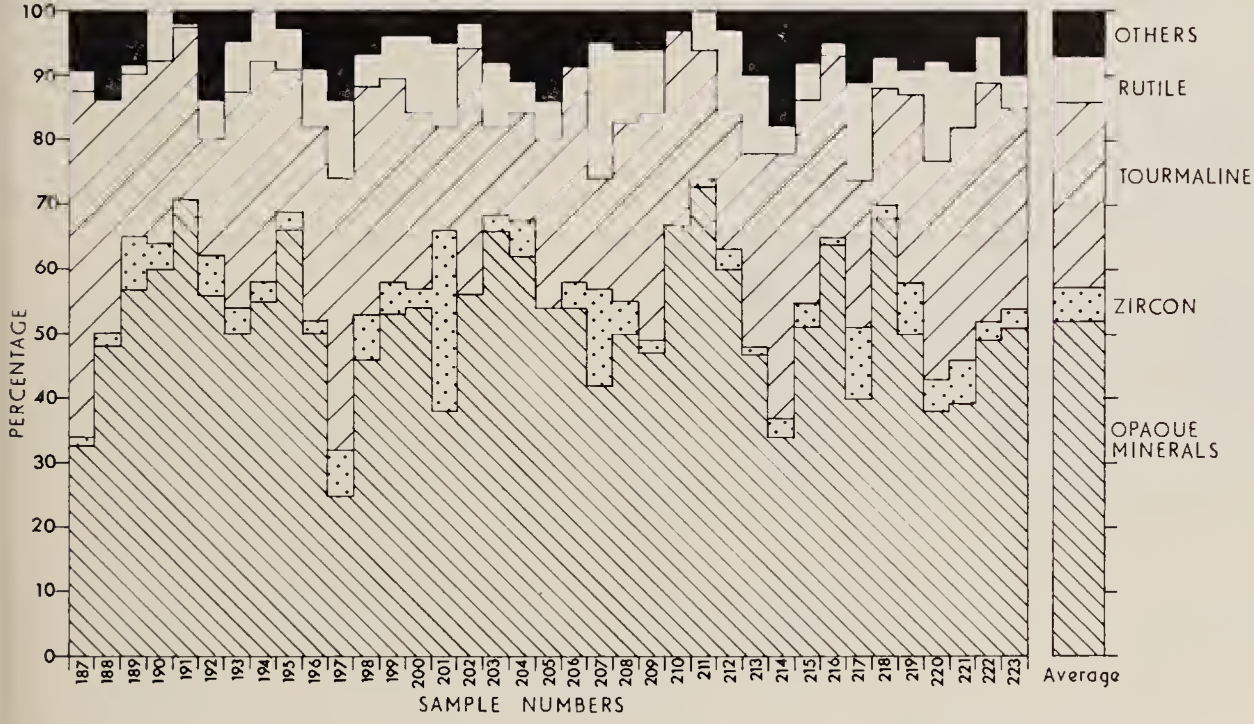


FIG. 6—The percentage occurrence (by number) of heavy minerals identified in Mid-North Coast barrier and dune samples.

constituents also seem to indicate the composition of the rocks being eroded in the Twofold Bay hinterland.

The variation in the percentage occurrence (by number) of the respective heavy minerals provides some evidence to discount the possibility that sediments, deposited within the smaller embayments of Twofold Bay, are transported around headlands. It is concluded, therefore, that the sediment yield, derived from the weathered rocks of the Twofold Bay hinterland and delivered to the nearshore zone by way of the rivers, is reworked and redeposited locally by wave action to nourish the barriers and bayhead beaches. This supply of sediment is supplemented, on a limited scale, by material derived from the erosion of adjacent headlands. Fine-grained material carried a short distance offshore, also appears to be transported shoreward subsequently without drifting around the headlands that separate the smaller embayments.

Additional evidence supporting the argument that sediments carried into Nullica Bay are not transported around neighbouring headlands can be found in the roundness values of the heavy minerals from the Boyd Town barrier system. Generally, these values are lower than those of the samples collected from Whale Beach barrier. It can be seen from Figure 9 that the heavy minerals from the Eden and Pambula barriers are particularly well rounded when compared with those from the Boyd Town barrier system. Most of the smaller bays inside Twofold Bay are low-energy wave environments compared with the exposed sectors of the far South Coast. Therefore, in the smaller embayments like Nullica Bay, it is unlikely that minerals would be altered appreciably by abrasion in the surf zone. But it would be presumptuous, considering some of the points made later about the roundness values of the Mid-North Coast minerals, to make conclusive statements about the Boyd Town samples. Fairly sub-angular grains, derived from the various catchments, might undergo minimal abrasion only before being deposited in the nearshore zone, because they are moved relatively short distances by the small coastal rivers.

Plates 1D–1F, which show some heavy mineral grains from the Boyd Town, Whale Beach and Pambula barriers, illustrate the marked contrast between the angular and sub-angular grains of the South Coast samples and the comparatively

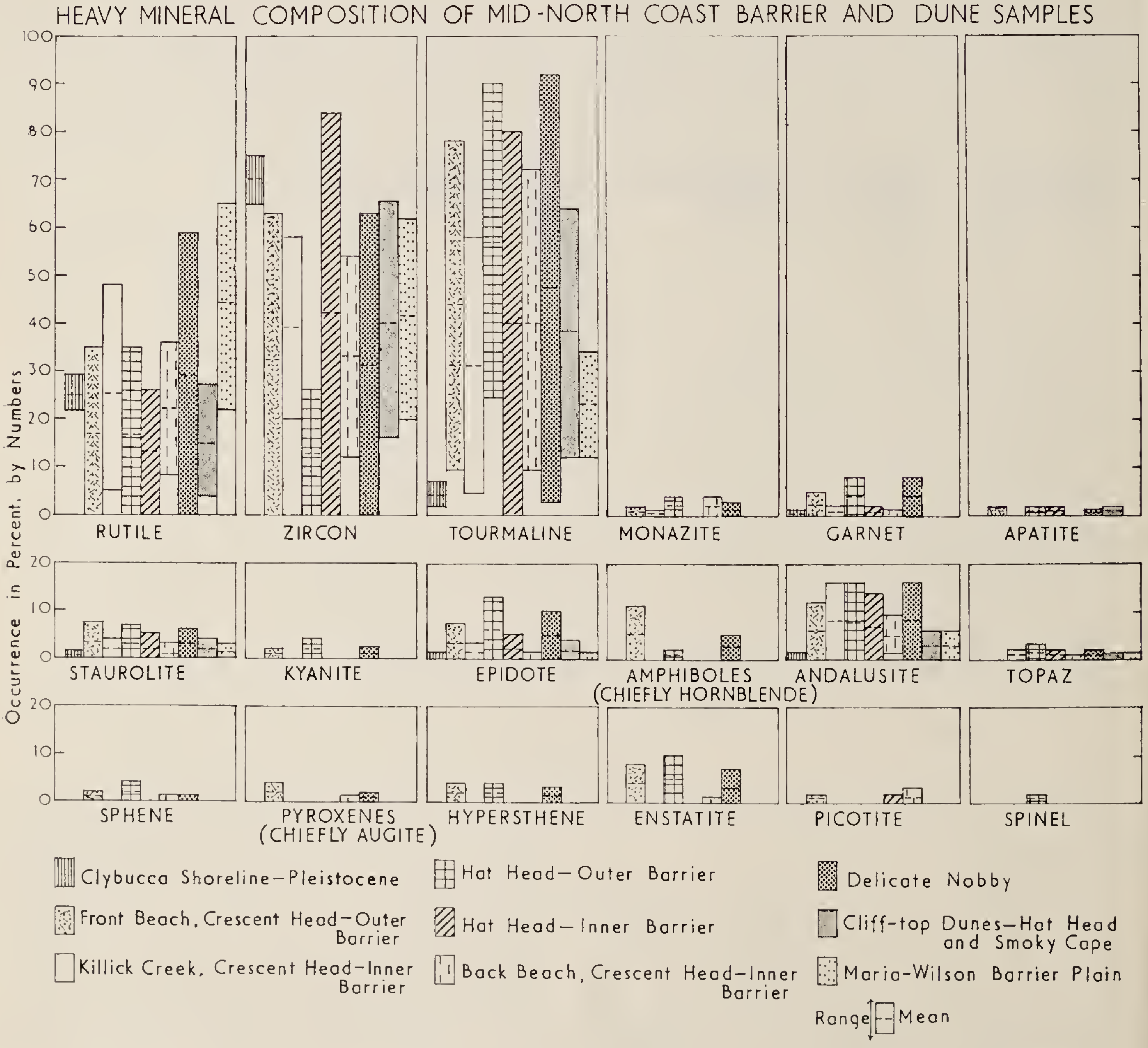


Fig. 7—Non-opaque heavy mineral composition of some barrier and dune samples collected on the Mid-North Coast.

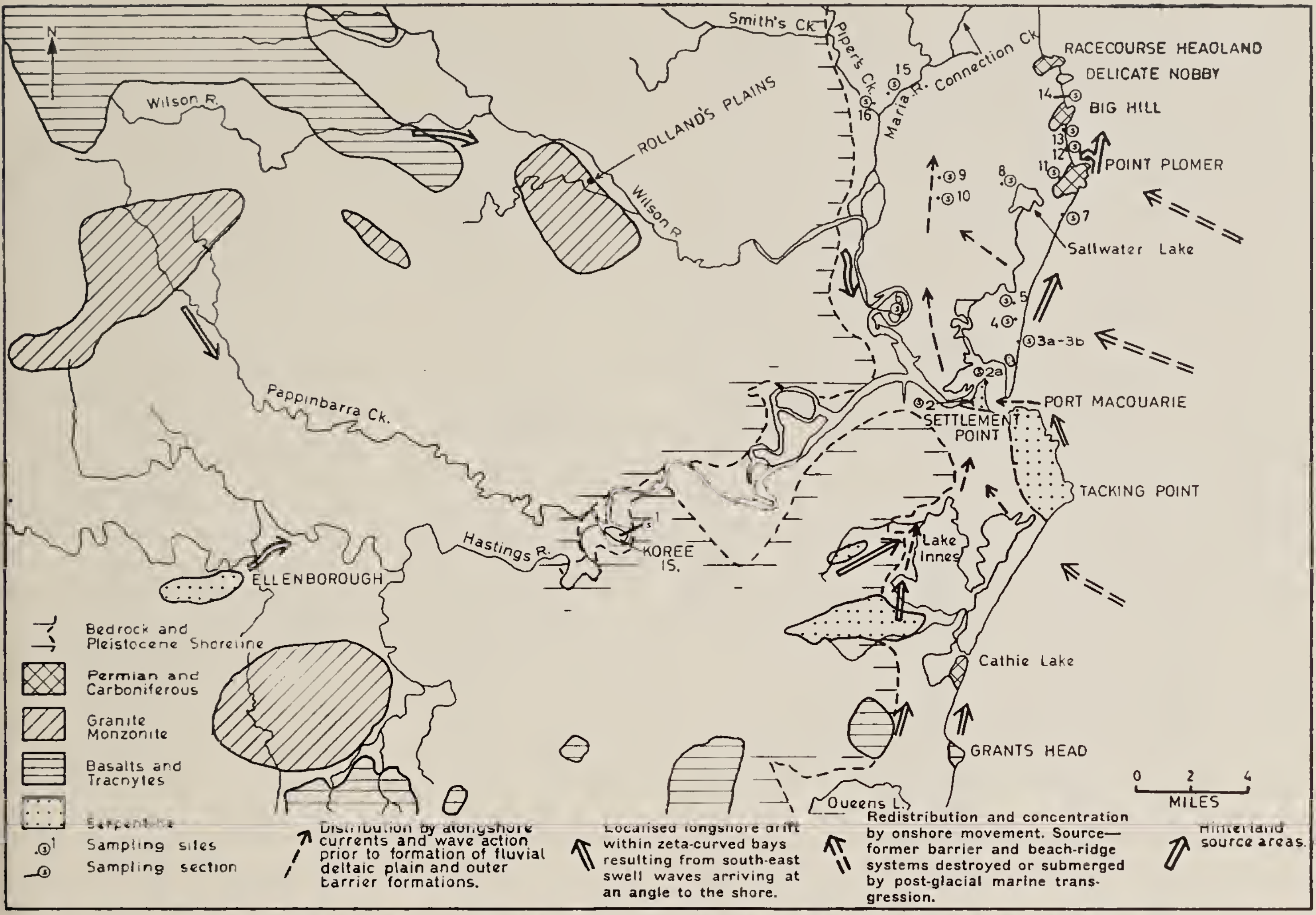


FIG. 8—Postulated sources of heavy minerals identified on the Mid-North Coast.

well rounded minerals collected from the other two study areas (Plates 1A–1C ; 1G–1I). Both Twofold Bay and Broken Bay are fairly well sheltered from wave action compared with the arcuate bays on the exposed Mid-North Coast, but even so, the Broken Bay minerals, except those of the Patonga barrier, are well rounded compared with the Boyd Town samples. The slightly lower values of the Patonga samples indicate that the material carried into Brisk Bay by Patonga Creek has travelled a relatively short distance from its source. In general, the roundness values reflect the polygenetic history of most of the Broken Bay minerals.

(*b*) *Broken Bay Samples :*

The analyses of Broken Bay samples provide some interesting information. Although hypersthene occurs in relatively few samples, its presence warrants some comment. Hypersthene is one of the least persistent minerals in the geologic column, and it is generally found in sediments derived from nearby hypersthene-bearing rocks, such as gabbros, norites, dolerites, basalts, andesites, and volcanic tuffs. According to David (ed. W. R. Browne, *op. cit.*), the Chocolate Shales of the Middle Narrabeen Series are usually regarded as redistributed fine basic tuff with a large admixture of purely clastic material. On the other hand, he states that the Hawkesbury Series is thought to be entirely free from volcanic material, though the Upper Wianamatta Stage is characterized by a large proportion of calcareous sandstone which is tuffaceous. Therefore, it seems that the hypersthene is being derived from such rocks in the Broken Bay hinterland since it has been identified in nearshore sediments collected by the writer from Brisk Bay. The mineral has been traced in four Holocene samples, but it is absent from the Umina-Woy Woy Pleistocene (?) barrier sands. The fact that hypersthene is not very resistant to abrasion is also supported by the results of Culey's (1933) mineralogical study of the Narrabeen Series ; only one hypersthene grain was identified in samples collected at the Entrance, Tuggerah.

The contention that volcanic material is being weathered in the vicinity of Broken Bay is also supported by the appearance of titan-augite in a few samples. The presence of picotite is not considered particularly significant because the

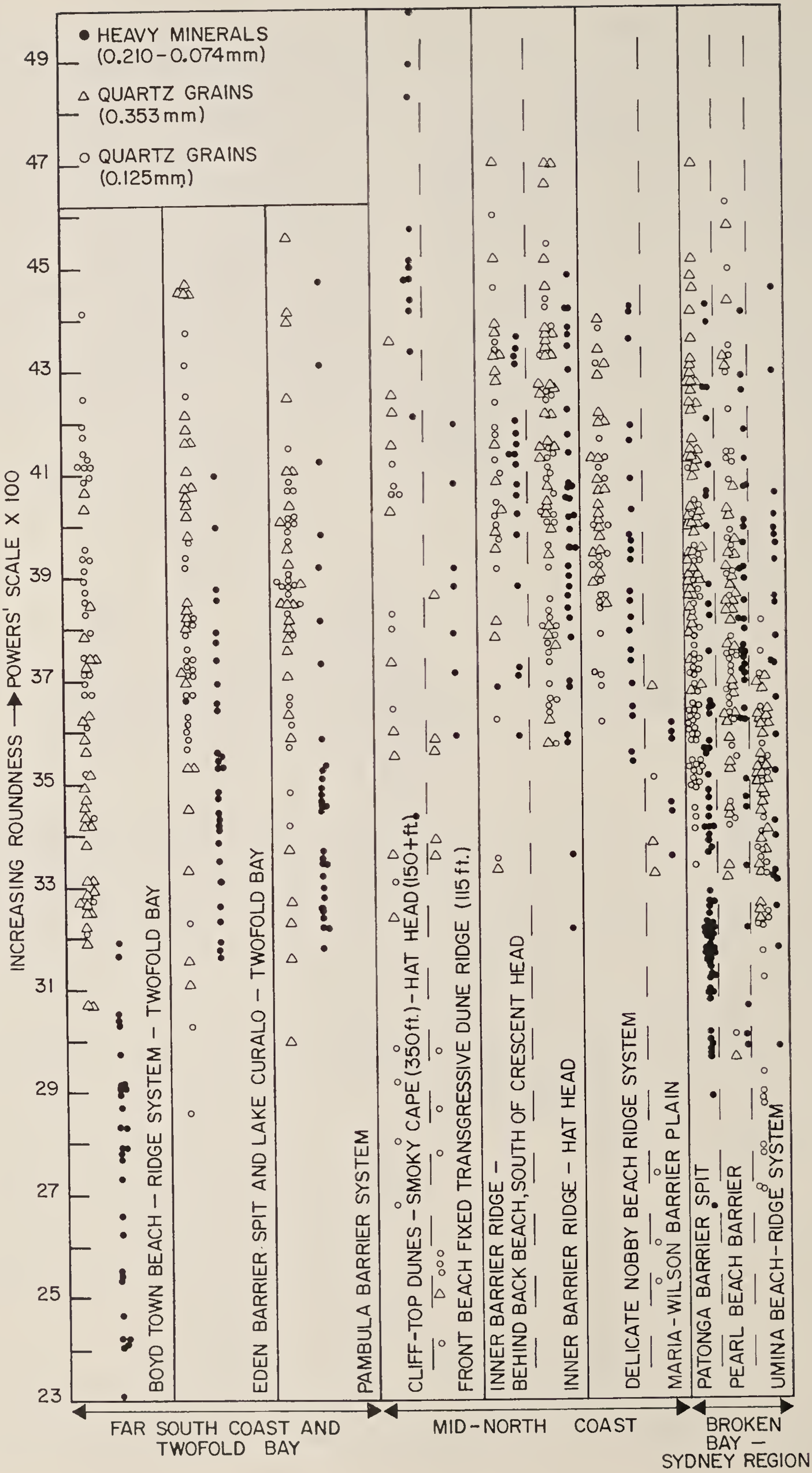


Fig. 9—Roundness values of quartz and heavy minerals, plotted on the Powers' scale.

mineral occurs in minor proportions in the various horizons of the Narrabeen Series. Staurolite is seldom found in Broken Bay samples, but garnet and andalusite are more common minerals. Unfortunately, the heavy mineral assemblage of the Pearl Beach and Patonga barriers does not provide clues on the movement of material around headlands, because it is identical with that of the Umina-Woy-Woy barrier system.

(*c*) *Mid-North Coast Samples :*

Distinctive constituents of the Mid-North Coast Pleistocene and Holocene barrier and dune sands are andalusite, staurolite, garnet, kyanite, zoisite and epidote. This heavy mineral suite suggests a medium-grade metamorphic source of which, however, there is no trace in the areas drained by the Mid-North Coast rivers. Although sillimanite-bearing metamorphic rocks occur in the Wongwibinda Complex (Binns, 1965), north-east of Armidale, sillimanite is absent from the coastal samples either because of its low chemical and mechanical stability, or because the tributaries of the Macleay River do not drain the Wongwibinda area. It is possible, therefore, firstly, that the observed metamorphic minerals were derived from a source which has been entirely removed by erosion. Secondly, they were eroded from cliffs and headlands, or delivered to the coast by rivers, outside the region thus necessitating the longshore movement of material around headlands and over considerable distances. Thirdly, the minerals were deposited as rivers extended their courses across the emerged continental shelf during Pleistocene low stands of sea level and were reworked and transported shoreward by wave action during subsequent marine transgressions. Fourthly, they were derived from a metamorphic source that was submerged during the post-glacial and earlier Pleistocene marine transgressions.

A similar heavy mineral assemblage to that of the coastal sands has been identified in bed load samples collected from the Hastings River, and Stockyard Creek which predominantly drains a serpentine rock area in the Macleay River catchment (Lindsay, 1963). However, the metamorphic minerals in the samples from Settlement Point on the Hastings River (Numbers 2–2a, in Figures 3 and 8) may have moved upstream from offshore because the river is tidal at this locality.

The presence of picotite in the river sands is also of some interest since as a detrital mineral it is of very restricted occurrence. Therefore it appears that the picotite identified in the Stockyard Creek samples, and those collected near Sherwood Bridge upstream from the tidal limit of the Macleay River at Aldavilla (Number 306, Figure 3), has been derived locally from the serpentine rock area. The occurrence of this mineral in the modern beach and Holocene barrier sands north of the Macleay River outlet in Trial Bay suggests that the heavy minerals reaching the coast are not transported southwards around headlands by longshore currents, but nearshore experiments, using radioactive or fluorescent tracer sand, are needed to verify this opinion. A northerly movement of material alongshore is also indicated by the occurrence of picotite in the Pleistocene and Holocene coastal sands north of Port Macquarie because the only other major serpentine rock areas on the Mid-North Coast are located south of the Hastings River (Figure 8).

Enstatite, hypersthene, kyanite, spinel, hornblende and augite are generally absent from the Inner Barrier and Pleistocene dune sands. Therefore, aeolian action seems the most plausible explanation to account for the unique presence of enstatite and augite in the Back Beach Pleistocene sands between Race Course Headland and Crescent Head. These minerals have been identified in samples collected within three feet of the surface of the barrier. The reason why they should be transported from the adjacent Outer Barrier on this section of the Mid-North Coast and not elsewhere is still a problem that has to be resolved.

The persistence of certain heavy minerals in the Mid-North Coast sediments appears to be determined by either their chemical or mechanical stability. For example, staurolite has an extremely low stability to weathering index compared with zircon and tourmaline and therefore its occurrence is attributed to its resistance to abrasion. Despite its relatively high position in the Order of Persistence Table (5B), biotite however appears to be an unstable mineral since it is absent from all the samples that have been analyzed, including the Holocene barrier sands and fluviatile sediments.

According to Baker (1962) though, differences in stability of any particular mineral undoubtedly exist in different areas according to variations in climate, topography and vegetation. Allen (1948), on the other hand, stated that the resistance of minerals to weathering depends upon the particular variety of the mineral in question. Dryden and Dryden (1946) in their study of the comparative rates of weathering of common heavy minerals *in situ* discovered that garnet is the least resistant to chemical alteration, even though most other workers list this mineral as highly stable.

It is generally accepted that the mechanical stability of minerals like tourmaline, rutile and zircon, for example, is controlled largely by their physical properties. Figure 9 shows that the heavy accumulates in the Mid-North Coast barrier and dune sands are composed of fairly well rounded minerals, and there is little difference between the values of Pleistocene and Holocene samples. This evidence partly supports the view put forward here that the minerals have been derived from ancient sediments and they have inherited their properties. Some minerals of course, can be derived locally and abraded in the surf zone before being redeposited as beach concentrates, but this seems unlikely on the Mid-North Coast because the mineralogical composition of the coastal sands differs from that of the adjacent bedrock headlands. Even so, the evidence does not entirely exclude the possibility that some minerals may have been derived from a source now submerged.

Contrary to the statements in some publications (Gardner, *op. cit.*; Beasley, *op. cit.*), the writer's analyses show that heavy minerals can be transported beyond the limit of high water mark. Although wave action is the initial cause of concentrating stable heavy minerals, the complementary effects of wind action seem to have been under-estimated (Hails, 1964). The mineral composition of Pleistocene and Holocene dune and barrier (and also modern beach) sands is basically similar, and the average weight per cent of heavy minerals in dune samples is 2·16 compared with 1·78 in barrier sands. Furthermore, the weight per cent of heavy minerals in the cliff-top dunes does not vary appreciably, irrespective of height above mean sea level and distance from immediate source areas. Specific gravity values of the different minerals in the dunes range from 2·98 to 5·18 and their hardness values (Mohs scale) range from 5 to 8 (Table 5A).

There appear to be two main reasons to account for the differences in the concentration of heavy minerals (by weight) in the Pleistocene and Holocene sands (Table 6). Firstly, there may have been low sediment yields from the river catchments in the past because of reduced erosion and slow weathering, or there were few heavy minerals offshore to be reworked and redeposited by wave action as the Pleistocene barriers were established. Also, nearshore processes may have controlled deposition only in certain areas. Secondly, ephemeral barriers existing off the present coast during periods of lower sea level, may have been partly eroded or destroyed before complete submergence during the late Holocene transgression. This process could have provided large supplies of sand for the construction of the Holocene Outer Barriers. However, temporary shorelines may not have existed immediately before the formation of the Inner Barrier. Undoubtedly, slight fluctuations in sea level and variations in local wave and wind regimes have controlled the concentration of heavy minerals since the major barriers were established (Hails, *op. cit.*).

Based on the accumulated evidence reported here, the writer has shown in Figure 8, the possible areas and sources from which some of the identified minerals have been derived. The closed arrows indicate the directions in which the minerals were transported to an embayed coast before the formation of the barriers and the deltaic plains. Dominant south-easterly swell waves, that arrived at an angle to the shore, undoubtedly moved some material northwards alongshore, and heavy minerals could have been

TABLE 5A

Specific Gravity and Hardness Values of Heavy Minerals Identified in Cliff-top Dunes

(Hardness values on Mohs scale)

Mineral	Specific Gravity	Hardness
Andalusite	3·16–3·20	7·5
Epidote	3·25–3·50	6–7
Ilmenite	4·50–5·00	5–6
Leucoxene	3·50–4·50	—
Magnetite	5·17–5·18	5·5–6·5
Piedmontite ..	3·45–3·50	6·5
Rutile	4·18–4·25	6·0–6·5
Staurolite	3·65–3·77	7·0–7·5
Topaz	3·51–3·61	8·0
Tourmaline ..	2·98–3·20	7·0–7·5
Zircon	4·20–4·86	7·5

TABLE 5B

Order of Persistence of Heavy Minerals in the Geologic Column

(Least persistent minerals are listed first. Minerals marked * occur in cliff-top dunes.) Table based on that of Pettijohn (1941). Read down columns

Olivine
Actinolite
Diopside
Hypersthene
Sillimanite
Augite
Zoisite* (epidote group)
Sphene

Topaz*
Andalusite*
Hornblende
Epidote*
Kyanite
Staurolite*
Magnetite*
Ilmenite*

Apatite
Biotite
Garnet
Monazite
Tourmaline*
Zircon*
Rutile
Anatase

TABLE 6

Range and Average Percentage Concentration by Weight of Heavy Minerals in Pleistocene and Holocene Sediments

Area/Location	Environment	Age	Heavy Mineral Concentration	
			Range	Average Percentage
Twofold Bay :				
Eden	Barrier spit	Holocene	0·1– 1·2	0·25
Boyd Town	Barrier beach ridges	Holocene	0·4–14·0	2·70
Whale Beach	Barrier spit	Holocene	0·2– 8·0	4·06
South Coast :				
Pambula	Barrier spit	Holocene	0·2– 4·6	0·96
Broken Bay :				
Pearl Beach	Barrier beach	Holocene	0·1–44·0	8·37
Umina-Woy Woy	Barrier beach ridges	Holocene	0·1–14·6	3·45
		(?) Pleistocene	0·6–22·0	2·74
Patonga Beach	Barrier spit	Holocene		
	(ridges)		0·1– 7·0	0·28
	(swales)		0·1– 3·0	0·23
	(foredune)		0·2– 1·8	0·49
	(random bores)		0·1–56·0	6·81
	Grand total		0·1–56·0	1·45
Patonga Offshore	Neritic	Holocene	0·1– 2·0	0·44
Mid-North Coast :				
Delicate Nobby	Barrier ridges	Holocene on Pleistocene	0·2–13·0	2·05
Back Beach	Inner barrier	Pleistocene	0·4– 6·6	2·30
Killick Creek	Inner barrier	Pleistocene	0·2–15·0	4·13
Front Beach	Outer barrier	Holocene	0·1– 7·6	1·14
Hat Head	Outer barrier	Holocene	0·2– 2·0	0·58
Hat Head	Inner barrier	Pleistocene	0·1– 5·2	0·76
Hat Head	Cliff-top dunes	Pleistocene	0·4– 2·4	1·50
Smoky Cape	Cliff-top dunes	Pleistocene	0·8– 7·8	3·56
Front Beach	Transgressive dunes	Pleistocene	0·2– 1·4	0·91
Clybucca shoreline	Beach ridges	Pleistocene	18–50·6	32·62

concentrated locally as waves were refracted around promontories, as indicated by the dashed arrows. However, the longshore movement of material was incidental to that moved onshore (open dashed arrows). The open arrows in Figure 8 show the most probable direction of longshore drift in the modern arcuate bays.

Summary and Conclusions

Locally derived titan-augite and diopsidic augite are the distinctive constituents of South Coast sediments. The occurrence of hypersthene in the Broken Bay barrier samples seems to indicate a volcanic rock source in the Patonga Creek catchment.

All the Mid-North Coast minerals are polygenetic because they have been derived from various sources, and have survived several phases of rock formation and weathering.

Andalusite, staurolite, garnet, kyanite and epidote are the most distinctive constituents of the Mid-North Coast sands and suggest a medium-grade metamorphic source of which there is no trace in the area drained by the Mid-North Coast rivers. It is therefore possible, firstly, that the minerals were derived from a source which has been entirely removed by erosion ; secondly, from other regions by being transported alongshore ; and thirdly, from offshore.

The picotite in the beach and barrier sands north of the Hastings and Macleay Rivers has been derived from the sepentine rocks in the Hastings River basin and from the small outcrops near Stockyard Creek.

The percentage occurrence (by number) of the common detrital minerals in the Pleistocene and Holocene barrier and dune sands does not vary appreciably. The most common detrital minerals on the Mid-North Coast and in Broken Bay are rutile, zircon, tourmaline and the opaques. Hornblende, the pyroxenes, and members of the epidote group are the most common minerals on the South Coast. Most minerals in the dunes on the Mid-North Coast were probably derived from neighbouring barrier and beach sands. The mineralogical composition of the cliff-top dunes reflects the strength and transporting power of wind.

The sub-angular minerals derived from the various catchments on the South Coast are not rounded appreciably by abrasion in the surf zone before being deposited as beach concentrates in the small embayments. Twofold Bay sediments are comparatively angular compared with those of the other two study areas. There is little difference between the roundness values of the Pleistocene and Holocene heavy minerals on the Mid-North Coast mainly because the minerals are polygenetic.

A possible sequence of events which led to the concentration of heavy minerals in the Holocene beach and dune deposits was the :

(i) formation and establishment of barriers a short distance from the coast ;

(ii) complete or partial destruction of those barriers during a rise in sea level ;

(iii) redeposition of heavy minerals along a newly established shoreline ;

(iv) modification of that shoreline by aeolian action and storm waves.

Finally, should coastal erosion cause foredune or beach ridge destruction, heavy minerals may become concentrated as the lighter quartz grains are removed. If erosion is followed immediately by a period of shoreline progradation, the minerals will be preserved as a concentrated deposit.

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Explanation of Plates

PLATES 1A-1C Heavy minerals in

A. Hat Head cliff-top dune samples. (× 58.)

B. Smoky Cape cliff-top dune samples. (× 36.)

C. Front Beach transgressive dune samples. (× 36.)

1. Piedmontite.
2. Zircon.
3. Rutile.
4. Tourmaline.
5. Leucoxene.
6. Magnetite.
7. Andalusite
8. Ilmenite.

PLATES 1D-1'I' Heavy minerals in

D. Boyd Town beach ridge system. (× 36.)

*A—Amphibole.
E—Epidote.
H—Hornblende.
T/Aug—Titan-augite.
P—Pyroxene.

E. Whale Beach barrier. (× 36.)

M—Magnetite.

F. Pambula barrier spit. (× 58.)

G. Number 3*a*–3*b*, Fig. 3, north of Port Macquarie.

An—Andalusite.
T—Tourmaline.

H. Patonga barrier spit, Broken Bay. (× 36.)

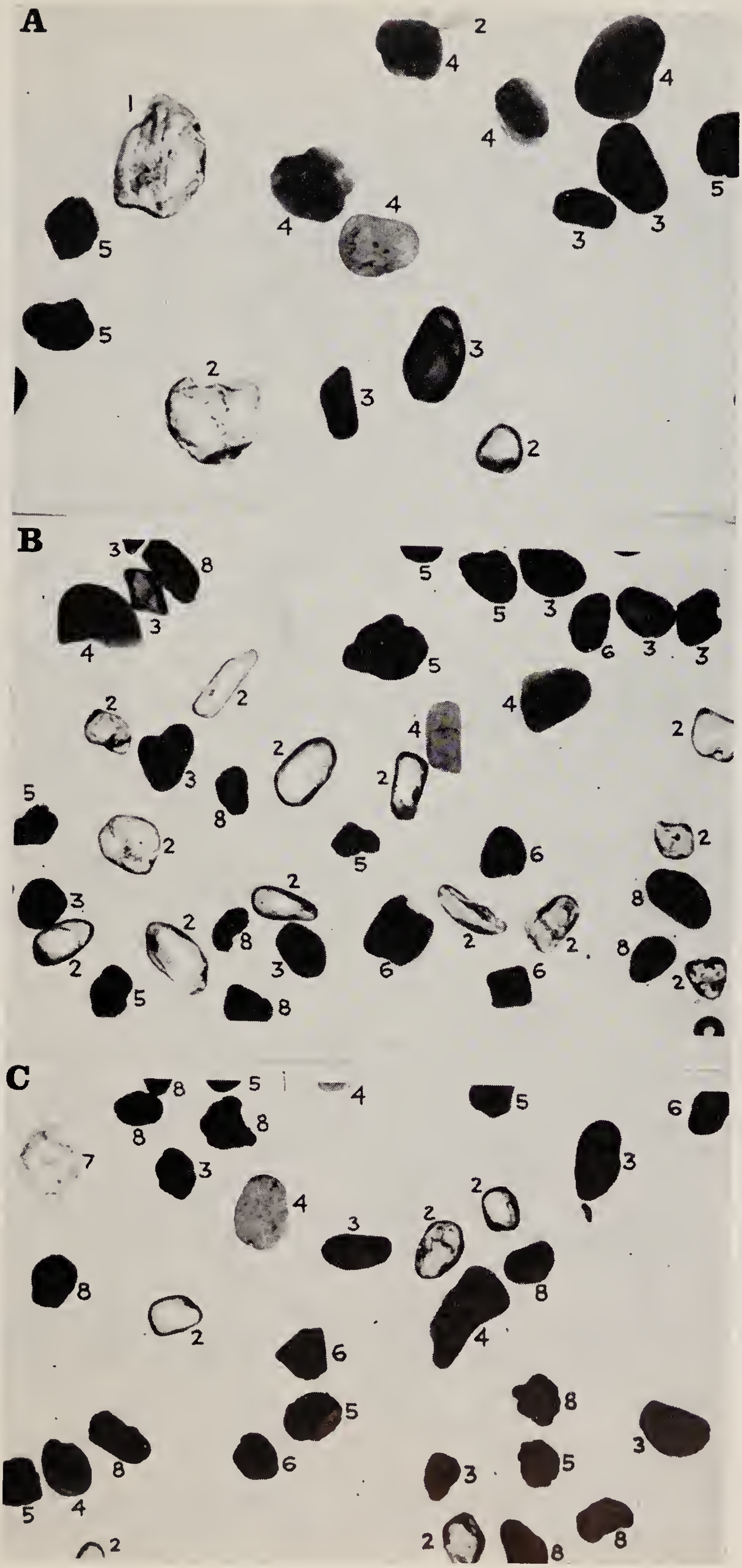
R—Rutile.
Z—Zircon.

'I'. Macleay River—Sherwood Bridge. (× 36.)

T—Topaz.

* Same symbols as for D'I' unless shown otherwise.

HAILS PLATE IA-IC




D
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P
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Stratigraphy and Structure of the Palaeozoic Sediments of the Lower Macleay Region, North-eastern New South Wales

John F. Lindsay *

Abstract—The Palaeozoic sedimentary rocks of the lower Macleay region have been divided into six stratigraphic units which are, in ascending order ; the Boonanghi Beds, the Majors Creek Formation, the Kullatine Formation, the Yessabah Limestone, the Warbro Formation and the Parrabel Beds.

The lowest exposed Carboniferous sedimentary rocks are turbidites ; these pass upwards into poorly-washed sandstones and mudstones, which are in turn overlain by a well-washed shallow-water sequence of sandstones, conglomerates, and mudstones. The oldest Permian rocks exposed are bioclastic limestones that pass upwards into interbedded mudstones and sandstones, some of which are laminated.

There are two distinct sets of faults, one intersecting and displacing the other, and a set of major folds carries some incongruent minor folds.

Introduction

This paper presents data on the stratigraphy and structure of Palaeozoic sedimentary rocks exposed in the lower Macleay region to the west of Kempsey, in northeastern New South Wales. The region is approximately 34 miles (54 km.) long and 21 miles (34 km.) wide and has an area of approximately 700 square miles (1800 km^2). It includes part of the coastal lowlands and part of the escarpment leading up to the New England Tablelands. The elevations range from 500 to 3,000 feet (150 to 900 m.).

Previous Investigations

Early maps show Devonian and Silurian rocks in the Kempsey district. De Koninck (1898) described fragmentary fossils that apparently came from the mudstones associated with the Yessabah Limestone, and considered them to be probably of Devonian age. Dun (1898) listed a collection of fossils from six miles (9·7 km.) west of Kempsey, probably from the vicinity of Gowings Mountain, and assessed their age as Permo-Carboniferous.

Woolnough (1911) gave the first account of the areal geology of the Macleay district, produced a sketch map, and described briefly the Yessabah Limestone at Moparrabah and Mount Sebastopol. He concluded that the limestone was Permo-Carboniferous in age and suggested a correlation with limestone at Pokolbin in the Hunter Valley. Woolnough correlated rocks underlying the limestone with the Lochinvar beds of the Hunter Valley.

A later reconnaissance sketch map by Carne and Jones (1919) showed all the known localities of the Yessabah Limestone. They also gave a brief description and some chemical analyses of the limestone. The geological map of the Commonwealth of Australia published in 1932 showed the district as consisting of " Lower Marine " rocks with Carboniferous to the south. The " Nambucca Phyllites " were shown to the north of the " Kempsey Area Fault ", and assigned to the Upper Silurian.

A more detailed regional map was published by Voisey (1934), who defined the Parrabel Anticline, made the first stratigraphic divisions of the sequence, and correlated the units with similar units elsewhere in eastern New South Wales and Queensland. Voisey (1936) described the results of detailed mapping of the structural complex in the vicinity of Yessabah, and he mentioned the district later in two papers on the Manning River region (Voisey, 1938, 1939*a*). In 1945 he correlated Carboniferous sequences throughout New South Wales and included some discussion of the lower Macleay region ; and in 1950 and 1958 he discussed the stratigraphic divisions of the sequence, and suggested correlations.

Campbell (1962) provided the first detailed age correlation for part of the Carboniferous sequence by describing two faunas from the Kullatine Formation.

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Stratigraphy

Most of the sedimentary rocks exposed in the lower Macleay region range in age from Lower Carboniferous to Lower Permian. Locally the hill tops are capped by river gravels of probable Pleistocene age.

The Palaeozoic sedimentary rocks of the lower Macleay region are at least 27,000 feet (8,200 m.) thick (Fig. 1). The Carboniferous sedimentary rocks range from turbidites at the base of the sequence to near-shore traction-current deposits at the top. The Permian sedimentary rocks are mainly interbedded sandstones and mudstones and have at their base a comparatively thin but very distinct crinoidal limestone.

Retaining Voisey's (1934, 1936, 1950, 1959) original nomenclature where possible, the author has divided the Permian and Carboniferous succession into six lithostratigraphic units (Fig. 2). In ascending order these are: the Boonanghi Beds, the Major Creek Formation, the Kullatine Formation, the Yessabah Limestone, the Warbo Formation and the Parrabel Beds. Other sedimentary rocks are discussed under " Undifferentiated Palaeozoic Sediments " and " High Level Gravels ".

Boonanghi Beds

The Boonanghi Beds were defined by Voisey (1934). The name is derived from the parish of Boonanghi. The unit comprises turbidites consisting mainly of regularly-graded lithic sandstone interbedded with laminated mudstone. Exposures of these sediments described by Voisey (1936, p. 186) along Dungay Creek are 1695 feet (519 m.) thick and are here defined as the type.

Lithology.—The unit consists mainly of interbedded sandstone and mudstone in a typical turbidite sequence, and contains infrequent beds of conglomerate with a discontinuous framework. Sandstone is more abundant toward the top of the unit, whereas laminated mudstone is the dominant rock type lower in the sequence. The sandstone is highly indurated, dark blue to blue green, relatively coarse-grained and poorly-sorted, and the grains are highly angular. Beds range from 1 inch to 20 feet (2·5 cm. to 6 m.) thick. Individual beds are graded and some contain angular chips of the underlying mudstone. The lower contacts of the beds are sharp and scour channels are common. Many beds have gradational upper contacts, whereas others have sharp upper contacts.

Mudstone forms approximately 87 percent of the lower part of the unit but only 10 percent of the upper part. Most of it is laminated, with alternating dark and light laminae between 0·25 and 4 inches (0·63 and 10 cm.) thick. The laminae are graded, cross-bedded, or structureless. The graded laminae are less than 0·05 inch (1·3 mm.) thick and are highly carbonaceous. The cross-bedded laminae are light-coloured and range from 0·2 to 0·5 inch (5 to 13 mm.) thick. They are generally weakly cross-bedded with the cross-beds lying at a low angle to the bedding plane. The structureless beds are light-coloured and much thicker than other beds (as much as 4 inches (10 cm.) thick). Worm trails occur in large numbers on the bedding planes and some are as much as 2 feet (60 cm.) long. Worm borings are present in some beds but are not as common as the trails. Soft-sediment distortion of bedding occurs in the mudstone at numerous localities and ranges in intensity from slight crenulations to complex overfolds and pull-apart structures.

Conglomerate with a discontinuous framework occurs at irregular intervals throughout the Boonanghi Beds but is more abundant in the basal portions. The beds are massive and range in thickness from 2 to 90 feet (0·5 to 27 m.); individual beds persist for as much as 5 miles (8 km.). At some localities a single unit consists of 3 or 4 individual beds of conglomerate. The upper and lower contacts are sharp and the base of many beds is a slight unconformity. The conglomerate consists of 5 to 30 per cent rounded phenoclasts as much as 8 feet (2·4 m.) in diameter and of a wide variety of lithologies. The phenoclasts are set in a fine-grained matrix of soft black mudstone or labile sandstone. The conglomerate at most localities contains slabs of laminated mudstone or armoured mudstone balls. The mudstone slabs reach 15 feet (4·6 m.) in length in some beds and are highly contorted.

Thickness.—Detailed measurements along Dungay Creek show the beds to be at least 5200 feet (1590 m.) thick.

Relation to Older Formations.—The base of the beds is not exposed in the area studied. The fact that the beds are subhorizontal and occur in the crest of an anticline suggests that the base of the beds probably is not exposed in adjacent areas.

Fauna and Age.—Voisey (1934, 1936) recorded the occurrence of *Loxonema* sp., *Rhipidomella* sp., and fragmentary fenestrate bryozoa, gastropods, and lamellibranchs. On the basis of

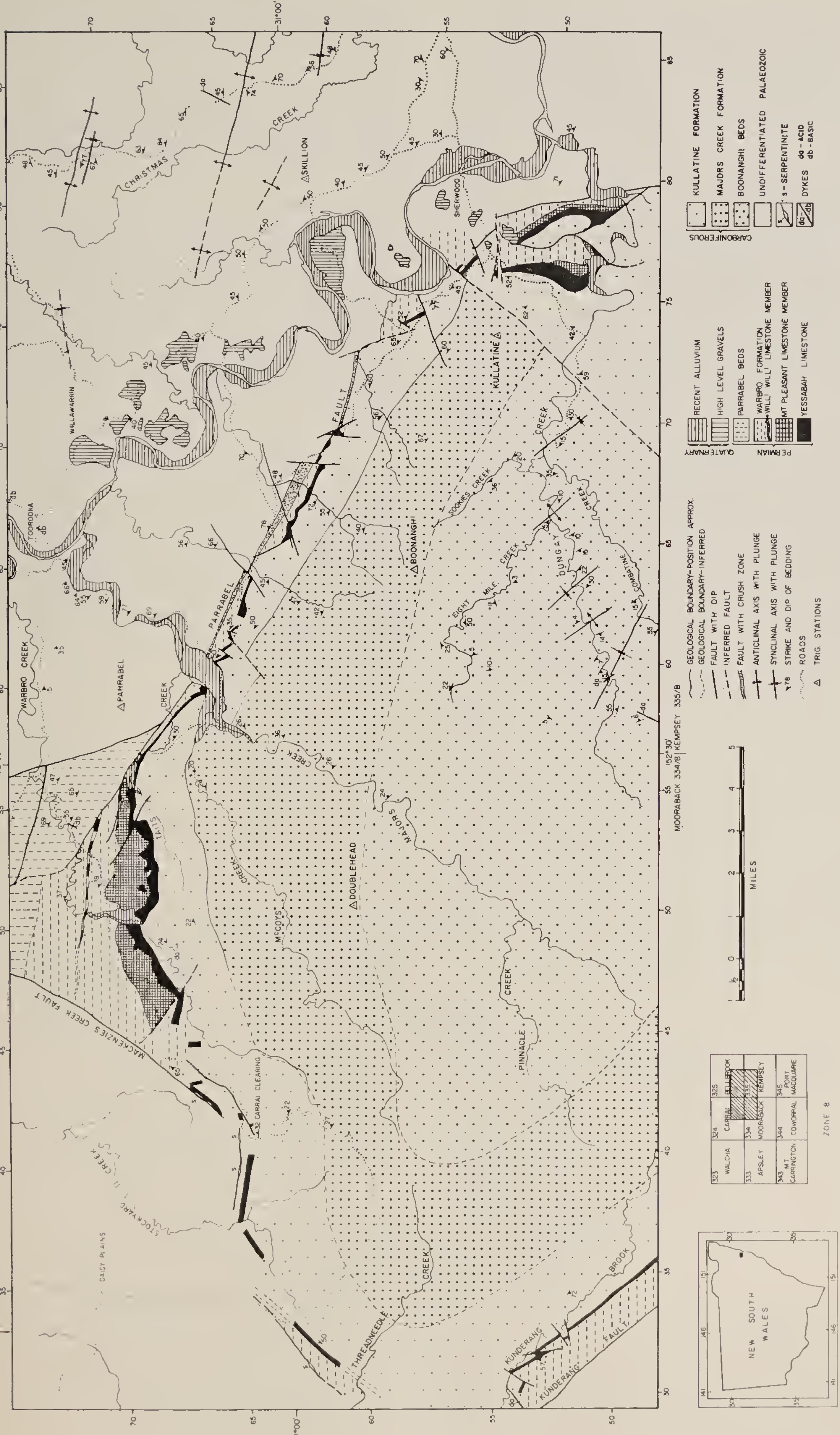

Fig. 1

Geological map of the Macleay district.

these fossils he correlated the Boonanghi Beds with " the Burindi Series of the Hunter Valley ". The fossil material was re-examined by the writer and it was found, as indicated by Voisey, that the fossils were too fragmentary to allow accurate determination of species.

Majors Creek Formation

The Majors Creek Formation is here defined as those sediments composed dominantly of massive labile sandstone and cherty mudstone that conformably overlie the Boonanghi Beds. The type section is defined as the section exposed along Majors Creek from 31° 01·5′ S, 152° 28·6′ E (Mooraback Military Map Sheet 334/8) to 30° 58·2′ S, 152° 31·7′ E (Bellbrook Military Map Sheet 325/8), which includes over 7,000 feet (2,100 m.) of sediments.

It appears that Voisey (1936, p. 187) included this formation in his Kullatine Series for he states " the lower beds of the Kullatine Series consists of sandstones, tuffs, sandy tuffs and breccias showing a great deal of variation in texture and composition, but possessing a general dark or light grey colour " and that they " must represent several thousands of feet of material ". The tuffs and sandstones referred to by Voisey appear to be the labile sandstone here included in the Majors Creek Formation.

Distribution.—The Majors Creek Formation is exposed in a broad belt following the form of the Parrabel Anticline. The belt is generally continuous and is only slightly disrupted by minor faults.

Lithology.—The formation is a traction current deposit of lithic sandstone and cherty mudstone.

The mudstone is black or dark blue, cherty, and has a rough conchoidal fracture. Most beds are massive and vary in thickness from 2 inches (5 cm.) to 3 feet (0·9 m.). A few beds are laminated ; some contain a little carbonaceous material.

The sandstone is blue or blue-green, fine-grained, and bedded in units from 2 to 12 feet (0·6 to 3·7 m.) thick, with an average thickness of about 4 feet (1·2 m.). The contacts of individual beds are sharp where the sandstone is inter-bedded with mudstone, but are confused by jointing where several sandstone units are bedded together. Some of the units are cross-bedded ; these units average 6 inches to 1 foot (15 to 30 cm.) thick.

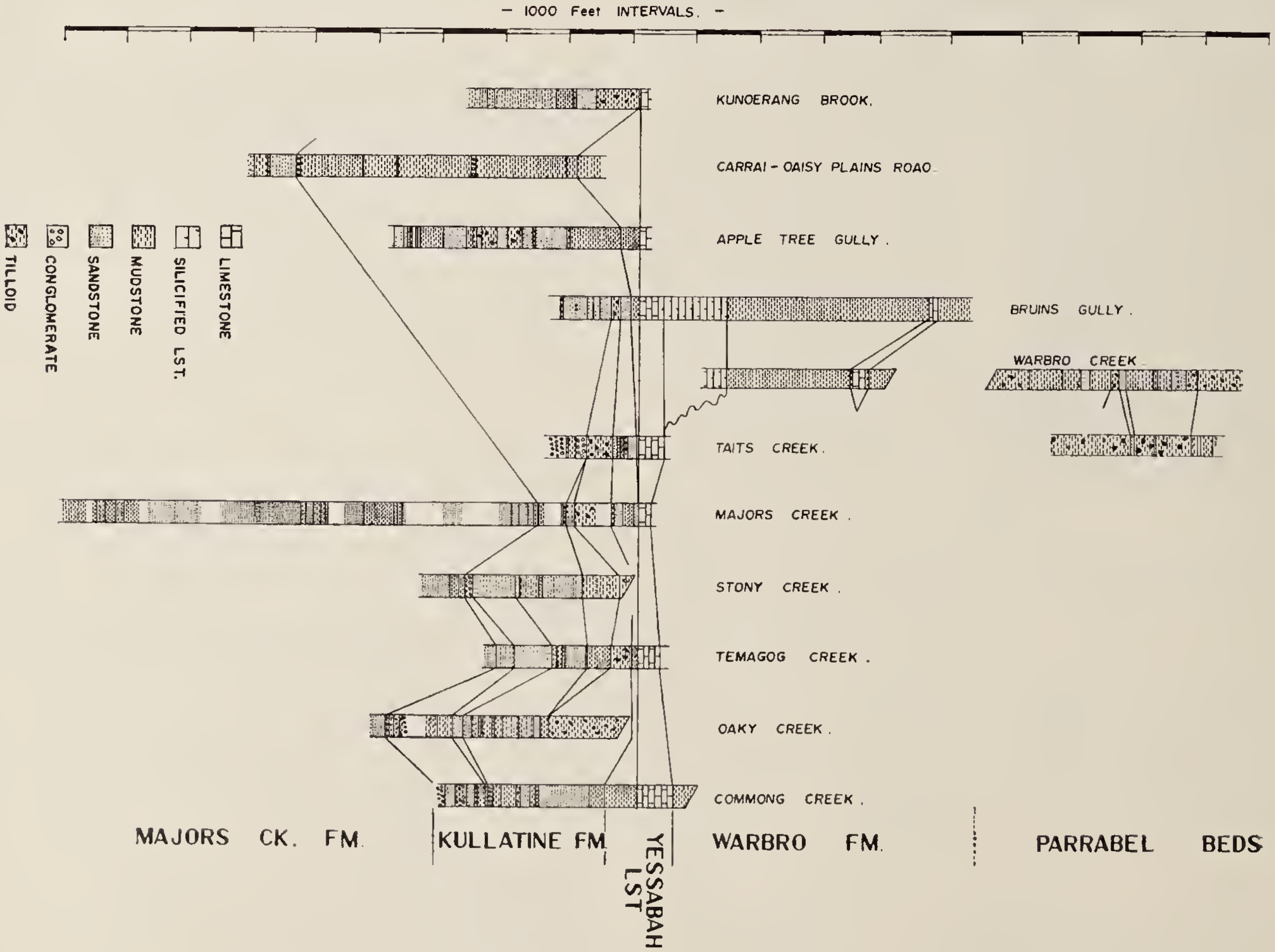

FIG. 2

Stratigraphic sections of the sedimentary rocks of the Macleay district.

Thickness.—In the type section the formation is 7,000 feet (2,000 m.) thick, but to the south it may be considerably thinner, as discussed below.

Relationship to Older Formations.—The contact between the Majors Creek Formation and the Boonanghi Beds appears conformable. The change in lithology resulted from a change from turbidity current transport to traction current transport. In the relatively inaccessible portion of the area to the south, the boundary between the two formations may transgress time planes and the Majors Creek Formation may disappear almost completely in the vicinity of Kunderang Brook. This change was apparently the result of a deepening of the basin to the south so that there the action of turbidity currents persisted to a much later time.

Fauna and Age.—Two fossil horizons have been found in the Majors Creek Formation. The lower horizon contains a branchiopod-bryozoa fauna, characterized by *Levipustula levis* Maxwell, which is similar to a fauna described by Campbell (1962) from the overlying Kullatine Formation. Species identified include: *Levipustula levis* Maxwell, *Spinuliplica spinulosa* Campbell, *Neospirifer pristinus* Maxwell, *Composita magnicarina* Campbell, *Fistulamina frondescens* Crockford, *Fenestella* spp., *Schizodus* sp. and *Peruvispira* sp. The presence of this horizon containing the *Levipustula* fauna 3,000 feet (915 m.) below the fauna described by Campbell from the Kullatine Formation poses several problems. Campbell compared his Kullatine fauna with similar faunas in other areas and concluded that it was Westphalian in age. However, lying stratigraphically between the two occurrences of the *Levipustula* fauna is another fauna containing the single species *Cravenoceras kullatinense* Campbell, which Campbell (1962) concluded to be Namurian in age. A detailed search revealed no structural complications and it can only be concluded that either one of the ages determined is incorrect or that the *Levipustula* fauna has a much greater age range than has been believed.

The second fauna contained in the Majors Creek Formation occurs close to the top of the unit and contains two small unidentified brachiopods and a small fenestrate bryozoan.

The formation is undoubtedly Middle to Upper Carboniferous in age, but is would be unwise to suggest any direct correlations with other formations until the faunal complications are resolved.

The Kullatine Formation

The name Kullatine Series was used by Voisey (1934) to include a sequence of coarse-grained rocks of freshwater origin with an Upper Carboniferous age. The name is derived from the parish of Kullatine where the rocks were first described by Voisey (1934). The Kullatine Formation is here redefined as the mudstone, sandstone, conglomerate, and diamictite conformably overlying the Majors Creek Formation and underlying the Yessabah Limestone. The section exposed along Temagog Creek from 31° 00·3′ S, 152° 36·5′ E to 30° 59·9′ S, 152° 36·5′ E (Kempsey Military Map Sheet 335/8) is here designated as the type section. The type section is 2,116 feet (645 m.) thick.

The Kullatine Formation as redefined is synonymous with the Taits Creek Formation and part of the Kullatine Series of Voisey (1958, p. 177, p. 179). In earlier papers Voisey referred the Taits Creek Formation to the Macleay Series (Voisey, 1934, p. 338–339; 1936, p. 187–189) and the Taits Creek Stage of the Macleay Series (Voisey, 1950, p. 66). Voisey based the division between the Taits Creek and the Kullatine Series on lithology and on lithogenesis indicated by fossil content. The presence of *Rhacopteris* in the Kullatine Series led him to believe that the unit was deposited under terrestrial conditions, whereas the Taits Creek Formation contains a marine fauna which led him to associate it with the Yessabah Limestone. Voisey (1950, p. 65) indicates that he found difficulty in separating the two units. The present author found that it was not possible to maintain the division between the two units on a purely lithologic basis, and for this reason the units have been redefined and the Taits Creek Formation and most of the Kullatine Series are here included in one formation—the Kullatine Formation.

Distribution.—The Kullatine Formation forms a relatively continuous unit arching broadly from Yessabah on Dungay Creek to Willi Willi. From Willi Willi it continues in a southwesterly direction to Kunderang Brook where it bends sharply to follow the creek. Over this distance the continuity of the formation is disrupted only slightly by minor faults.

Lithology.—The Kullatine Formation is a traction current deposit containing interbedded units deposited by subaqueous mass movement. Measurements of ten detailed sections of the formation show that sandstone and conglomerate make up the largest proportion of the sediments

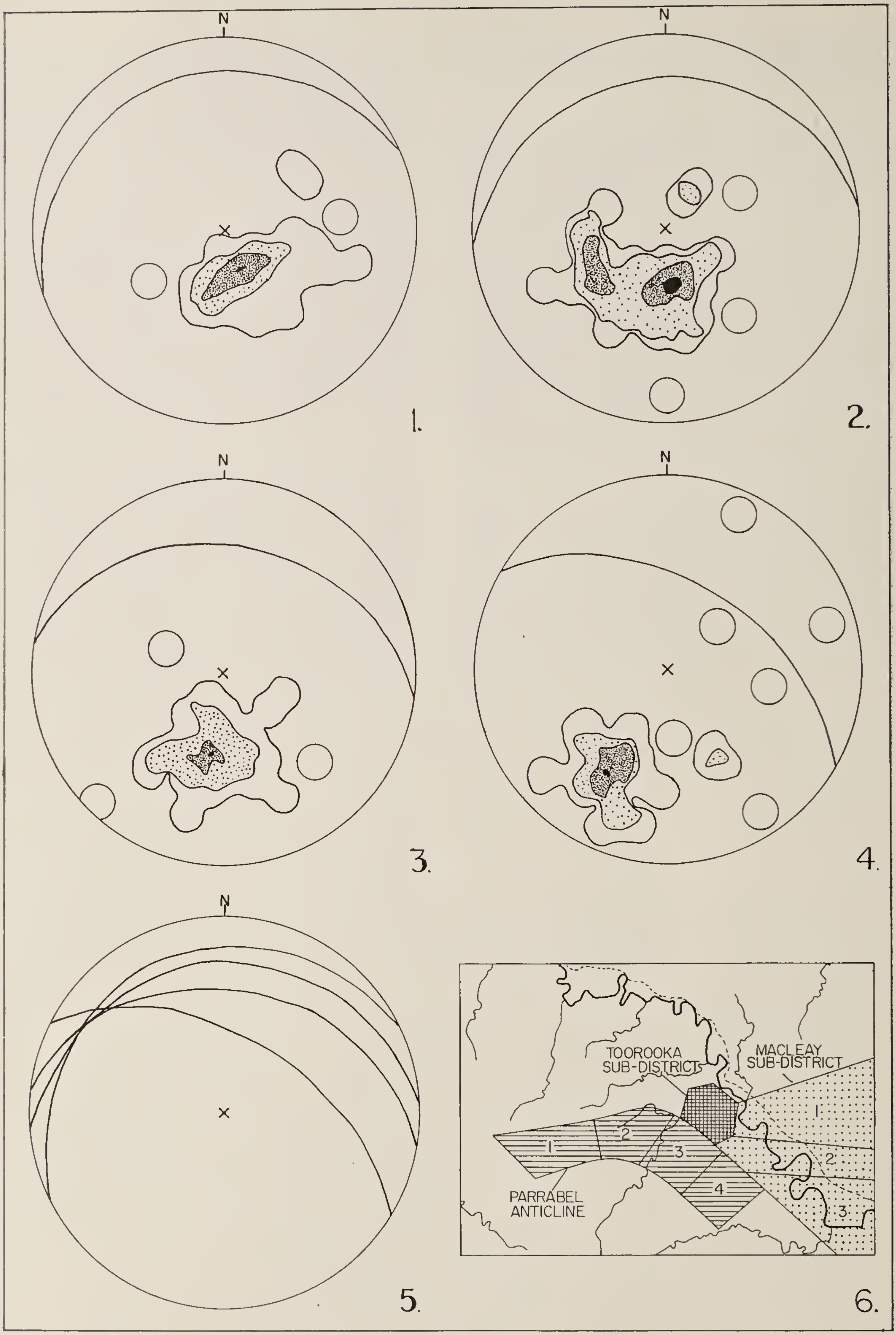

Fig. 3

S-pole diagrams of bedding plane attitudes for the Parrabel Anticline.

(*a*) Area (1) 52 readings, contours 0%, 10%, 20% and 30% per 1% area.
(*b*) Area (2) 34 readings, contours 0%, 5%, 10%, 20% and 25% per 1% area.
(*c*) Area (3) 42 readings, contours 0%, 10%, 20% and 25% per 1% area.
(*d*) Area (4) 34 readings, contours 0%, 10%, 15% and 20% per 1% area.
(*e*) Synoptic diagram showing intersection of mean bedding plane attitudes for all four areas.
(*f*) Map showing sub-districts and areas discussed in the structure of the lower Macleay region.

in the northern part of the area, whereas mudstone and finer sediments are dominant to the south. This, along with the occurrence of turbidites in the southern part of the area, suggests that the basin deepened considerably in a short distance to the south and that the sediment was being supplied from the north or north-west.

On the average, labile sandstone makes up 44 percent of the formation and is by far the most common rock type. Most of the sandstone is red or purple, but some beds near the base of the formation are blue-green. The sandstone occurs in well-bedded units 0·25 inch to 10 feet (6 mm. to 3 m.) thick. The contacts between the beds are sharp, although some beds exhibit loadcasts at their base. Sedimentary structures are not common, but graded beds are present in the turbidites to the south, and cross-bedding is present in some sandstone units in the northern sector. The sandstones at the base of the formation are coarse grained and well washed, but toward the top of the formation they are generally much finer and not as well washed.

Approximately 33 percent of the formation consists of grey or bright-purple mudstone, which is at most localities massively bedded in units up to 4 feet (1·2 m.) thick. The mudstones in the southern portion of the area are laminated and at some localities display large slump folds involving 10 to 20 feet (3 to 6 m.) of sediment. Apart from slump folds the only other common sedimentary features are sandstone dykes, which occur in the more massive beds of mudstone to the north.

About 6 percent of the formation consists of watersorted conglomerate, occurring as massive lenses over 300 feet (90 m.) thick and up to a mile (1·6 km.) in length, in the top 1,000 feet (300 m.) of the formation. Minor beds of conglomerate occur elsewhere in the formation but are generally less than 4 feet (1·2 m.) thick. The contacts between the conglomerate and the underlying sediments are sharp, although loadcasts occur locally where the underlying sediment is mudstone. The conglomerate is generally poorly sorted, ranging from medium-grained sand to boulders as much as 10 inches (25 cm.) in diameter. The coarse fraction is highly rounded.

The diamictites, which are considered to be mass-movement deposits (Lindsay, 1966) occur mainly in the upper 1,000 feet (300 m.) of the formation, although a few beds occur lower in the formation. These beds vary from 20 feet (6 m.) to over 200 feet (60 m.) in thickness. Laterally the beds are discontinuous and few extend for more than 200 yards (180 m.) along strike. They are very poorly sorted and range from silt to boulders 10 inches (25 cm.) in diameter. The coarse fragments are highly rounded. The fine fraction is fairly homogeneous in any one bed but varies in grain size from bed to bed. In some beds it is quite silty, in others sandy. Some of the beds contain large contorted masses of bedded sediment which were probably derived from the underlying beds while they were in a semi-consolidated state.

Thickness.—The formation ranges from 2,100 to 4,500 feet (640 to 1,370 m.) thick. The maximum thickness occurs in the vicinity of the Carrai clearing and the minimum at Majors Creek.

Relation to Older Formation.—The contact between the Kullatine Formation and the Majors Creek Formation in the northern part of the area has been mapped at the base of the lowest well-washed coarse-grained sandstone. Further south at Kunderang Brook the problem is not quite as simple, for the sediments are of deeper water origin and it may be difficult to separate the two formations. Changes in facies to be correlated with deepening of the basin to the south might prevent separation of the Carboniferous formations in this area. The contact between the Kullatine and Majors Creek formations is conformable at all localities examined. The change in lithology across the formational boundary in the northern portion of the area appears to be due to a shift in the strandline. The strandline shift resulted in the sandstones of the Kullatine Formation having a larger mean grain size and being well washed, in contrast to the fine-grained poorly-washed sandstones of the Majors Creek Formation.

Fauna and Age.—Campbell (1962) recorded three fossil horizons in the Kullatine Formation. A lower plant horizon is characterized by *Rhacopteris ovata* McCoy, a second is characterized by the small goniatite *Cravenoceras kullatinense* Campbell, and an upper horizon is characterized by the productid brachiopod *Levipustula levis* Maxwell.

Campbell considered the *Cravenoceras* fauna to be Namurian in age and the *Levipustula* fauna to be Westphalian. There are complications, for as mentioned earlier the *Levipustula* fauna occurs also in the Majors Creek Formation some 3,000 feet (1,020 m.) below the Kullatine occurrence.

Yessabah Limestone

The Yessabah Limestone was originally designated the Yessabah Stage by Voisey (1950) who subsequently changed the name of the unit to Yessabah Limestone (Voisey, 1958). The name comes from the village of Yessabah, near Kempsey. The formation consists of bioclastic limestone and calcareous mudstone conformably overlying the Kullatine Formation. As Voisey did not define a type section, it is defined here as the sediments exposed along Taits Creek from 30° 56·4′ S, 152° 29·9′ E to 30° 56·3′ S, 152° 30·0′ E (Carrai Military Map Sheet 324/8). The type section is 709 feet (216 m.) thick.

Distribution.—The formation occurs as a broad relatively continuous arch outlining the Parrabel Anticline. The continuity of the unit is disrupted slightly at numerous places by small normal faults. Blocks of the limestone are found at many localities in the crush zones of faults.

Lithology.—The formation comprises a basal calcareous mudstone overlain by bioclastic crinoidal limestone, the principal lithology, which is in turn overlain locally by silicified limestone of the Mount Pleasant Limestone Member.

The basal unit consists of soft bright-green calcareous mudstone that is locally highly fossiliferous. The unit is generally thin but in some places is 300 feet (102 m.) thick and forms as much as 30 percent of the formation. The mudstone is well-bedded and locally contains thin beds of crinoidal limestone. Where the beds are thin, crinkling or microfolding is commonly developed. The amount of deformation of fossils suggests that the mudstone suffered at least a 50 percent reduction in volume during compaction.

The bioclastic limestone occurs in massive beds about 10 feet (3 m.) thick. The limestone is pink or white at most localities and consists of well-sorted well-rounded bioclastic grains with an average maximum grain size of 4·9 mm., set in a microcrystalline matrix. A typical modal analysis is: crinoid fragment 43·3 percent, bryozoan fragments 25·9 percent, detrital quartz 0·3 percent, microcrystalline calcite 17·7 percent, sparry calcite 2·4 percent, rim cement 5·9 percent, and recrystallized calcite 4·5 percent (terminology after Stauffer, 1962, p. 360). Whereas the bioclastic fragments in most beds are dominantly crinoidal, the fragments in many beds are dominantly bryozoan. The limestone is 87 to 97 percent $CaCO_3$.

The Mount Pleasant Limestone Member is a silicified bioclastic limestone, in beds 3 to 6 feet (0·9 to 1·8 m.) thick, containing a few beds of calcareous mudstone and red chert. Unlike the main limestone unit, the silicified limestone consists mainly of interlocking fragments of the branching coral *Cladochonous* with subordinate amounts of crinoid, bryozoan, brachiopod and pelecypod fragments. The beds of calcareous mudstone are 2 to 6 inches (5 to 15 cm.) thick and at some localities contain well-preserved fossils. The beds of red chert are relatively uncommon and most occur near the top of the formation. The member varies in thickness from a feather edge to 1,000 feet (300 m.). The limestone grades laterally into cherty black laminated mudstone, which in turn grades into the Warbro Formation.

Thickness.—The formation varies in thickness from 20 feet (6 m.), where it crosses Stone Creek, to 1,500 feet (460 m.) at Willi Willi. The areas of greatest thickness, particularly at Willi Willi and Yessabah, are due to the presence of the Mount Pleasant Limestone Member. The main limestone unit changes thickness only gradually along strike, whereas the Mount Pleasant Limestone Member at Willi Willi increases in thickness from a feather edge to 1,000 feet (300 m.) in less than 2 miles (3·2 km.). The variation in thickness of the main crinoidal limestone appears to be due to variations in bottom topography at the time of deposition, with the greatest thickness of sediment accumulating in the hollows. The Mount Pleasant Member appears to be a series of reef-like bodies whose development depended on local environment conditions.

Relation to Older Formations.—The contact between the Yessabah Limestone and the Kullatine Formation is conformable. The base of the Yessabah Limestone is mapped at the base of the lowest calcareous sediment above the detrital sediments of the Kullatine Formation. The contact represents a distinct change in sedimentation from dominantly terriginous sediments in the Kullatine Formation to bioclastic sediments in the Yessabah Limestone. At most the calcareous mudstones contain only 10 percent of terriginous material.

Fauna and Age.—The Yessabah Limestone contains an abundant fauna of at least 33 species. Campbell (1962) concluded that the fauna was Sakmarian in age because it contains *Anidanthus springsurensis* (Booker), *Eurydesma cordatum* (Morris), and *Deltopecten mitchelli*

(Etheridge and Dun), all of which occur widely throughout eastern Australia in rocks considered to be Sakmarian.

The position of the Permian-Carboniferous boundary is not known but from the faunal evidence it must be close to the contact between the Kullatine Formation and the Yessabah Limestone.

Warbro Formation

The Warbro Formation was originally called the Warbro Stage by Voisey (1950) and later (Voisey, 1958) renamed the Warbro Formation. He derived the name either from the parish of Warbro or from Warbro Creek along which the beds are exposed. The formation consists of a sequence of interbedded lithic sandstones and mudstones with a thin crinoidal limestone which is here designated the Willi Willi Limestone Member. The formation conformably overlies the Yessabah Limestone. As a type section was not previously established for this formation, the section exposed along Warbro Creek from 30° 56·3′ S, 152° 26·4′ E to 30° 55·6′ S, 152° 26·5′ E (Carrai Military Map Sheet 324/8) is here designated the type. The type section is 3,380 feet (1,031 m.) thick.

Distribution.—The largest exposed area of the Warbro Formation is at Willi Willi where it occurs in a series of wedge-shaped blocks, bounded by the Parrabel and Mackenzies Creek faults and their associated splay faults. A smaller area, at Yessabah, is bounded by several small faults. Several minor exposures occur as narrow strips between the Yessabah Limestone and the Parrabel Fault.

Lithology.—The lithic sandstones and mudstones in the basal 500 feet (150 m.) of the formation are bedded in laminites I (Lombard, 1963). The bedding above the Willi Willi Limestone Member is more massive and the bedding planes less distinct. The beds of mudstone vary from 1 to 10 inches (2·5 to 25 cm.) in thickness near the base of the formation to over 8 feet (2·4 m.) in thickness above the limestone member. The fresh rock is black or grey and breaks readily to slivers. The mudstone is rarely exposed because it weathers readily to brown or yellow clayey soil. The lithic sandstone froms 20 to 25 percent of the formation and occurs in beds varying from a maximum thickness of 4 inches (10 cm.) in the laminites at the base of the formation to over 8 feet (2·4 m.) toward the top. The sandstone in the laminites has sharp contacts and individual beds are nearly constant in thickness along the strike. The sandstone in the lower part of the formation is pale grey; some higher in the formation is olive green.

The Willi Willi Limestone Member is a unit of massive bioclastic crinoidal limestone that varies from 50 to 200 feet (15 to 60 m.) in thickness and occurs approximately 3,000 feet (900 m.) above the base of the formation. Beds are outlined at some localities by stylolites, and bands of fossils every 2 to 3 inches (5 to 7·5 cm.). The limestone is dark grey or brown and locally contains angular fragments of green mudstone as much as 4 inches (10 cm.) in diameter. One sample of the limestone consists of about 55·3 percent crinoidal fragments, 3·3 percent bryozoan fragments, 1·8 percent brachiopod and pelecypod fragments, 0·8 percent terriginous material, 19·7 percent recrystallized calcite, 0·2 percent sparry calcite, and 18·9 percent microcrystalline calcite. Other samples are similar.

Thickness.—The formation is at least 3,500 feet (1,070 m.) thick; faults within the measured sections make knowledge of the total thickness uncertain.

Relation to Older Formations.—At most localities examined the Warbro Formation conformably overlies the Yessabah Limestone. However, at Yessabah and Willi Willi the lower portion of the Warbro Formation grades laterally into the Mount Pleasant Limestone Member, such that, at least in part, they are lateral equivalents.

Fauna and Age.—Identifiable fossils are rare in the Warbro Formation. The only genus identified is *Terrakea* (?) from the Willi Willi Limestone Member.

Parrabel Beds

The Parrabel Beds, as here defined, consist of a sequence of inter-bedded mudstones, lithic sandstones, and conglomerates, which appear to overlie the Warbro Formation. The top of the unit is faulted in all sections known. The name of the unit is derived from nearby Mount Parrabel. A typical section of these rocks is exposed along Warbro Creek from 30° 54·3′ S, 152° 29·8′ E to 30° 54·8′ S, 152° 29·1′ E (Carrai Military Map Sheet 324/8), where they are 1,583 feet (483 m.) thick. These rocks have not previously been described.

Distribution.—The Parrabel Beds are exposed in a series of fault blocks in the hills to the north and east of the Willi Willi area. The fault blocks are the product of the splay faults associated with the Mackenzies Creek and Parrabel faults.

Lithology.—Mudstone forms about 40 percent of the sequence. It is blue-green, hard, cherty or olive-green, soft, and calcareous. The hard cherty mudstones are at most localities strongly laminated and generally occur interbedded in thin units with sandstone beds of similar thickness. The softer olive-green mudstones are much more massive and at some localities are richly fossiliferous. The sandstones occur in beds from 1 inch to 5 feet (2·5 cm. to 1·5 m.) thick and form approximately 8 percent of the unit. The contacts of these beds are sharp and load casts occur on the base of some.

The conglomerate forms about 32 percent of the beds and occurs in massive units which range in thickness from 10 inches (25 cm.) to more than 200 feet (60 m.). The beds have sharp contacts and some individual units persist along strike for several miles. The conglomerate consists of approximately 90 percent matrix with 10 percent pebbles and cobbles forming a continuous framework. The pebbles and cobbles, which were derived mainly from sedimentary and plutonic rocks, average 1 to 2 inches (2·5 to 5 cm.) in diameter and some reach a maximum of 6 inches (15 cm.) in diameter. The matrix varies from black or green mudstone to blue-green lithic sandstone.

Thickness.—The upper and lower limits of the unit are not known with any certainty; the incomplete sections examined suggest a total thickness in excess of 4,000 feet (1,220 m.).

Relation to Older Formations.—At most localities the base of the unit is interrupted by faulting. To the north of Willi Willi, the Parrabel Beds and the Warbro Formation appear to be conformable.

Fauna and Age.—A fauna of branchiopods, pelecypods, and bryozoa occur at two horizons in the formation, but identification of species has not been made.

Undifferentiated Palaeozoic Rocks

Sediments northeast of the Parrabel Fault

Woolnough (1911) was the first to comment on these rocks when he made the following statement: " On the east, the Silurian rocks are bounded by a series of contorted and cleaved quartzites and slates which we may refer to as the Kempsey Slates ". Woolnough made no suggestions as to the age of the rocks except that by inference he did not include them with the strongly deformed undifferentiated Palaeozoic rocks (his Silurian rocks) to the north. Voisey (1934, 1936) referred to the same rocks as the Kempsey Series about which he said (Voisey, 1934, p. 340) " the Kempsey Series appears to follow the trend of the Parrabel Anticline from Willawarrin to Kempsey but has not been satisfactorily separated from the soft marine beds at the top of the Macleay Series (Lower Permian)—a fact which indicates a Permian age for part at least ". In 1950, Voisey reported a " marine Carboniferous shell Fauna " from a quarry beside the Kempsey-Telegraph Point road, and this coupled with the discovery of *Rhacopteris* beside the same road in rocks lithologically similar to the Kempsey Series led him to abandon his earlier ideas of a Permian age in favour of a Carboniferous age for the Kempsey Series.

Two distinct lithologies were recognized in the sediments to the northeast of the Parrabel Fault. The first lithologic type occurs in the area between the Parrabel Fault and the Macleay River. The sediments are well exposed along the lower reaches of Majors and Stony Creeks where at least 4,000 feet (1,220 m.) of section is exposed.

The unit consists of sandstone and mudstone interbedded in laminites, with occasional beds of polymictic conglomerate distributed at irregular intervals through the sequence. The mudstones occur in beds 2 to 4 inches (5 to 10 cm.) thick that are made of laminae 0·125 to 0·25 inch (3 to 6 mm.) thick. The individual laminae vary considerably in thickness and in some beds they lens out in an inch or less. Worm trails and worm borings occur in small numbers in some beds. Sandstone forms approximately 30 percent of the unit and occurs in beds 1 inch to 1 foot (2·5 to 30 cm.) thick. The upper contacts of most of the sandstone beds are gradational, and angular fragments of mudstone occur in this gradational zone. The lower contacts of most sandstones are sharp and show a variety of sole markings including flute casts, groove casts, bounce casts, and worm borings. Palaeocurrent studies based on these structures indicate that currents flowed to the southeast. Graded bedding is not common and reverse grading occurs almost as frequently as normal grading. The sandstones are well washed, well sorted, and consist of angular grains. The conglomerate forms less than 10 percent of the sequence. It is poorly sorted, well graded, and occurs in beds averaging 2 feet (60 cm.) thick. The conglomerate beds are notably thicker, coarser, and more numerous lower in the sequence. The lower contacts are sharp, the upper contacts gradational. The conglomerate consists of about 40 percent matrix and 60 percent pebbles and cobbles that have a maximum diameter of 3 inches (7·6 cm.) and form a discontinuous framework.

The second lithologic type occurs mainly on the northeastern side of the Macleay River where the sections along the Kempsey-Willawarrin road suggest the presence of at least 3,000 feet (900 m.) of rock.

Lithic sandstone forms about 40 percent of the unit and occurs in beds 1 inch to 4 feet (2·5 cm. to 1·2 m.) thick. The contacts of the beds are sharp. Worm borings, worm trails, and minor slump folds occur in the laminated sandstone. The massive beds are well jointed. The sandstone varies from dark to light grey depending on the carbon content. The mudstones occur in both massive and laminated beds from 0·5 inch (1·3 cm.) to over 3 feet (0·9 m.) thick. Sedimentary structures are common and include open-cast folds, low-angle cross-beds, boudins, scour and fill structures, and both worm borings and worm trails. Current structures suggest a source area to the north. The mudstone is black, grey, or dark green. The conglomerate, which has a discontinuous framework of angular to rounded pebbles, occurs in massive beds from 1 to 100 feet (0·3 to 30 m.) thick.

The sediments are structurally separated from the Parrabel Anticline by the Parrabel Fault complex and subsequently no evidence as to their age is available from superposition. They bear no lithologic similarities to any rocks of known Carboniferous age along the full length of the Manning-Macleay region. However, the sediments of both units contain an extremely high proportion of vitric volcanic fragments as do rocks of known Permian age. This suggests that the rocks were at least derived from the same source as the Permian rocks, and since there is an abrupt change in the composition of the volcanic fragments at or near the Permian-Carboniferous boundary it seems possible that they are Permian in age. The only fossils known definitely to come from the rocks northeast of the Parrabel Fault were found in a small aggregate quarry 16 miles (26 km.) to the north of Kempsey on the Pacific Highway (30° 56·2′ S, 152° 56·5′ E, Bellbrook Military Map Sheet 325/4). The fauna occurs in a fine-grained conglomerate and consists mainly of bryozoa.

Sedimentary Rocks northwest of Mackenzies Creek Fault

The sediments of the northwestern portion of the area consist of highly deformed mudstone, sandstone, and stretched pebble conglomerate. Remnant bedding is present but difficult to see at most localities. Some of these rocks, particularly the stretched pebble conglomerates, show marked similarities with the sediments of the Parrabel Beds. Comparison of the rocks in this area with rocks further north indicates that they have suffered considerably less deformation. The sediments further to the north bear no trace of bedding and show evidence of several periods of deformation.

Sedimentary Rocks southwest of Kunderang Fault

The undifferentiated Palaeozoic rocks in the southwestern corner of the area mapped are separated from the Parrabel Anticline by the Kunderang Fault. These rocks are well-bedded grey and white chert and red jasper that bear a marked similarity to the sediments of the Wooloomin Beds (Benson, 1912 ; Crook, 1961) farther west near Tamworth. Similar sediments were described by Voisey (1934, p. 335) from the Hastings district further south.

High Level Gravels

Deposits of alluvial gravel that cap the hills in the Macleay Valley are probably Pleistocene in age (Voisey, 1934) and possibly represent the remnants of one or more terraces. The gravels consist of well-rounded fragments of labile sandstone, black chert, cherty mudstone, red jasper, and white quartz ; locally the gravel consists entirely of rounded white quartz pebbles. The fragments are as much as 6 inches (15 cm.) in diameter and are set in a matrix of sandy material, or, in some cases, well-consolidated clay.

Structure

The lower Macleay region lies within the Eastern Belt of Folds and Thrusts (Voisey, 1959). Deposition of sediment was terminated early in the Permian (Voisey, 1939*b*) by the onset of an orogeny probably equivalent to the Hunter-Bowen Orogeny. The compound structural forms represented on the map appear to be the result of several superposed deformations which took place during this orogeny.

Folds

Most of the folds in the lower Macleay region are broad, open noncylindrical structures complicated to some extent by crossfolding. Where possible beta-axes have been determined for the folds. However, beta-axes do not necessarily have the same significance for broad open noncylindrical folds as they do for folds of tight cylindrical style, and since their significance is not completely understood they are consequently of value only in comparing adjacent areas and describing gross morphology.

For purposes of description the district has been divided into three sub-districts: the Parrabel Anticline, the Toorooka Sub-district, and the Macleay Sub-district (Fig. 4).

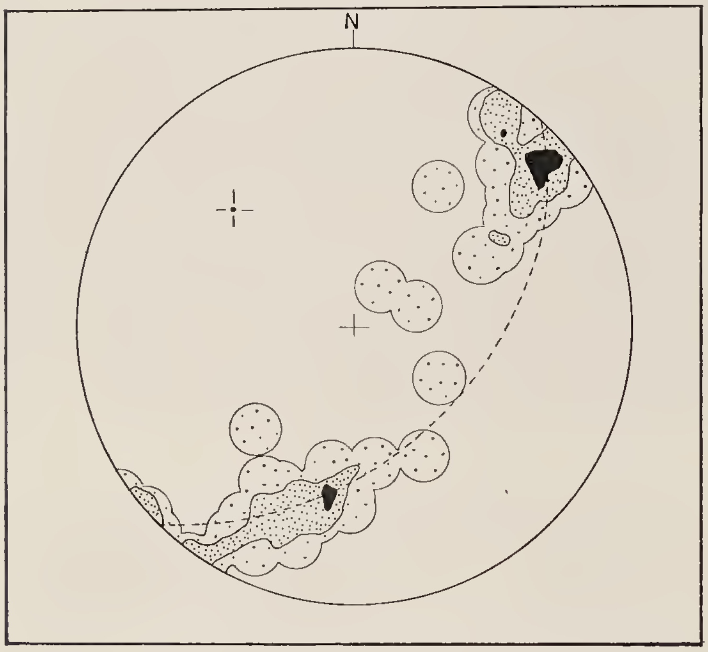

Fig. 4

S-pole diagram of bedding plane attitudes for the Toorooka sub-district. Contours 0%, 10% and 15% per 1% area, 35 readings.

Parrabel Anticline.—The Parrabel Anticline, a large non-cylincrical fold approximately 17 miles (27 km.) wide and at least 20 miles (32 km.) long, dominates the structure of the southwestern part of the district. The fold is bounded by the Kunderang, Mackenzies Creek, and the Parrabel Faults. The steeply dipping limbs and closure region of the fold have been divided into four smaller areas, within each of which the orientation of the bedding planes is statistically uniform. The mean bedding plane attitude has been determined for each area by plotting poles to bedding and a synoptic diagram constructed (Fig. 4) indicates that the beta-axis plunges at 18° to 316°.

The crestal region of the fold is very broad and in detail consists of a series of smaller folds with subparallel and subhorizontal axes. In contrast to the Parrabel Anticline the minor folds are cylindrical concentric structures. The axes of the minor folds parallel the beta-axis of the Parabel Anticline but plunge at only 5°. The axial planes of the minor folds appear to be almost vertical.

Toorooka Sub-district.—The Toorooka Sub-district is bounded in part by the Parrabel Fault and the Macleay Rivers. The sub-district consists of two blocks separated possibly by a fault. The opposing dips of the sediments suggest a faulted syncline, and for this reason bedding attitudes from both sides of the fault were plotted on the same diagram (Fig. 5). The assumption here is that if the fault was not involved in any rotational movement it should be possible to define the beta-axis of the syncline and compare it with that of the Parrabel Anticline. The plot indicates a beta-axis with a plunge of 38° in a direction of 314°. This is comparable in azimuth with the attitude of the beta-axis of the Parrabel Anticline, but of steeper plunge.

Macleay Sub-district.—The Macleay Sub-district includes most of the sediments mapped to the north of the Macleay River. Poor exposures in this area have resulted in a limited amount of data, obtained mostly from two road sections: Kempsey to Willawarrin and Kempsey to Taylors Arm. Using a method similar to that used to study the Parrabel Anticline, the area was divided into three sub-areas and a synoptic diagram constructed for the mean bedding plane attitudes (Fig. 6). This yields a beta-axis with a plunge of 9° in a direction of 284°, which is remarkably similar to the figures obtained for the Parrabel Anticline and Toorooka Subdistrict.

The beta-axes obtained from the Parrabel Anticline, Toorooka Sub-district and Macleay Sub-district suggest that they have the same deformational history. Bedding plane irregularities and limited data from incongruent minor folds suggest that the district might have been folded a second time, although the second folding was much less intense than the main folding.

Faults

The faults of the lower Macleay region are of two types, which appear to have resulted from separate deformations.

The first type characteristically extends for considerable distances and has steeply dipping fault planes, wide crush zones, and extensive splay patterns. The first type includes the Parrabel, Kunderang and Mackenzies Creek faults. The majority of these faults and their

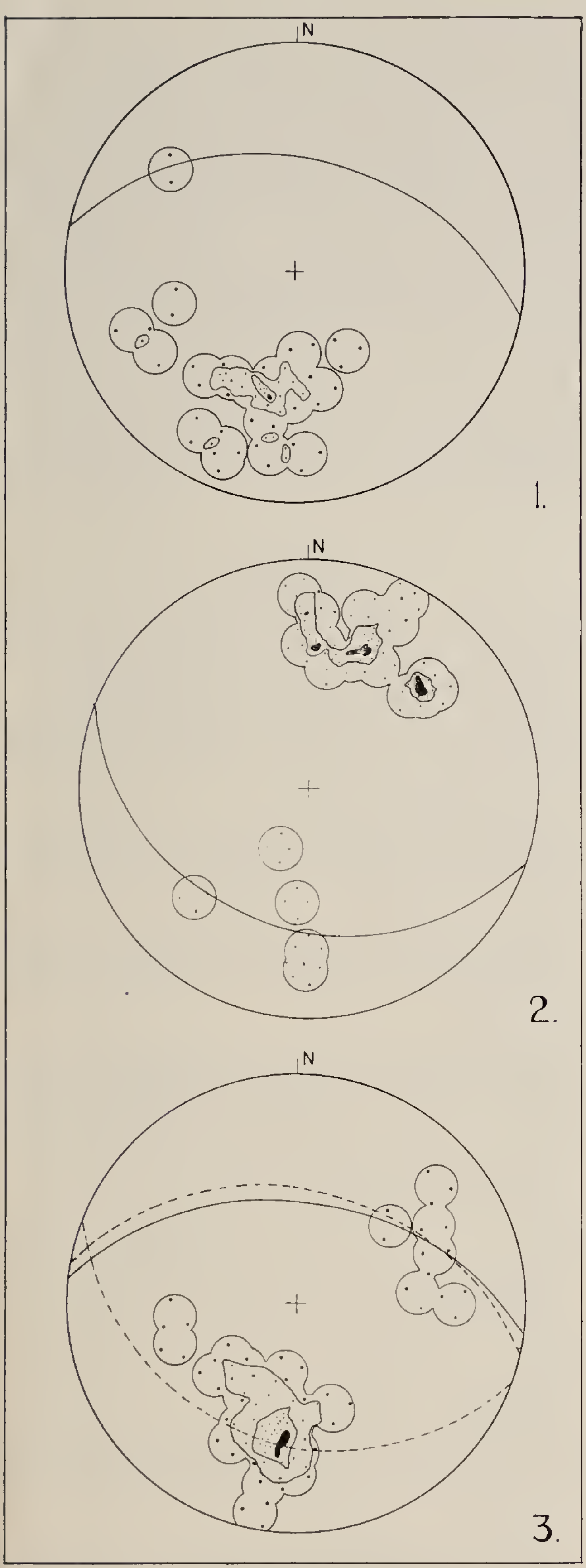

FIG. 5
S-pole diagrams of bedding plane attitudes and synoptic diagram for the Macleay sub-district.
(*a*) Area (1) 20 readings, contours 0%, 10%, 15% and 20% per 1% area.
(*b*) Area (2) 23 readings, contours 0%, 10% and 15% per 1% area.
(*c*) Area (3) 35 readings, contours 0%, 10%, 15% and 20% per 1% area, and also synoptic diagram showing intersection of mean bedding planes.

smaller splay faults trend in two main directions, 115° and 200°. There is no conclusive evidence to suggest the sense of movement on most of the faults. Stratigraphic relations across the faults suggest dip-slip displacements of the order of several thousands of feet on the Parrabel, Kunderang and Mackenzies Creek faults. Horses of Willi Willi Limestone in the crush zone of the Parrabel Fault indicate a strike separation of at least 6,000 feet (1,830 m.).

Faults of the second type intersect and displace the first type. They are shorter and all appear to be dip-slip faults of moderately steep dip, and they have narrow crush zones and displacements that seldom exceed 1,500 feet (460 m.). They strike in two prominent directions, 045° and 010°, and are prominent around the edge of the Parrabel Anticline where they displace the Yessabah Limestone. Few of these faults extend more than 2 miles (3·2 km.), whereas the Parrabel Fault (type one) extends for 26 miles (42 km.)

Correlation

Some earlier workers, particularly Woolnough (1911) and Voisey (1934, 1936, 1945, 1950, 1958), suggested correlations of rock units in the Manning-Macleay region with sequences outside the region. Problems of correlating the sequences come from two sources. First, too little is known of the stratigraphy of the region as a whole. Some formations, notably the Yessabah Limestone, are easily identified at widely spaced localities over the region, others have been recognized only locally. Consequently, many of the formational units established locally may prove inadequate as data from other parts of the region becomes available. Until the stratigraphy of the region is known more completely and the value of the present terminology tested on a local basis, correlations with sections outside the region have little meaning except in a broad sense. The second problem lies in the incomplete knowledge of the palaeontology of the sequence. For example, the only palaeontological evidence available for the lower Carboniferous age of the Boonanghi Beds comes from fragmentary fossils (Voisey, 1934, p. 336) that cannot be identified with any certainty. Further, the two faunas described by Campbell (1962) from the Kullatine Formation and thought to have a well-established age are confused by the occurrence of one of the faunas much in lower in the section in the Majors Creek Formation. The only fauna for which an age can be established readily is the *Eurydesma* fauna in the Yessabah Limestone, and this fauna has not been described in detail.

Consequently it is too early to attempt to correlate in any detail the sequence in the basin with sequences outside the basin.

Conclusions

The sediments of the Macleay district have been divided into six litho-stratigraphic units. Recognition of some of the units, particularly the Carboniferous units, might prove difficult farther south, for, as previously mentioned, the depositional basins appear to deepen considerably in this direction so that turbidites occur much higher in the sequence to the south than they do in the north. Further changes will be made as the palaeontology of the sequence becomes more completely known. These difficulties will be particularly important in any consideration of the stratigraphic position of the sediments to the northeast of the Parrabel Fault and in any consideration of correlations made outside the Manning-Macleay region.

Deposition of the sediments appears to have been terminated early in Permian time by an orogeny probably equivalent to the Hunter-Bowen Orogeny. The main axis of folding plunges at approximately 18° in a direction 316°, but the evidence is insufficient to define a second weaker axis. Two distinct sets of faults are known, one intersecting and displacing the other. The first fault type has steeply dipping fault planes with wide crush zones and extensive splay patterns. These faults extend for as much as 26 miles (42 km.). The second set of faults, which cuts the first, has fault planes with a moderately steep dip, narrow crush zones and small dip-slip displacements. Few of these faults extend for more than two miles (3·2 km.).

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Stratigraphy and Structure of the North-East Part of the Barrier Ranges, New South Wales

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Abstract—The succession of beds outcropping along the axis of the Caloola Syncline, between Sturt's Meadows and Nundooka is described. The lowermost strata are Upper Proterozoic beds of the top part of the Torrowangee Group and they consist of shales, dolomites and tillites overlain by shales and quartzites with a few dolomites. Detailed geological mapping has led to a subdivision of this part of the Torrowangee Group into several rock units, and has shown an unconformable relationship with overlying strata both of (?) Cambrian and of (?) Upper Devonian age.

A thick sequence of (?) Upper Devonian quartzose sandstones and associated sediments of a red-bed facies has also been mapped. These are apparently the marginal beds of the molasse phase of the Lachlan Geosyncline.

Small deposits of (?) Lower Tertiary sediments occur, and these are overlain by widespread remnants of silcrete, and younger deposits of ferricrete and kunkar. The eastern edge of the area is covered by substantial deposits of Quaternary age, mainly alluvial silt and clay.

Introduction

The area studied lies athwart the Silver City Highway some 60-70 miles north-east of Broken Hill between Nundooka and Sturt's Meadows homesteads and is about 300 square miles in extent. Geological mapping on a scale of 20 chains to one inch was carried out over the bulk of the area, with photo-interpretation to complete the coverage. The base map was compiled from aerial photographs, since no map is available on a scale of more than 1 : 250,000. This work formed the graduation theses of the authors, and was completed in January, 1967.

The area is at the eastern edge of the North Barrier Ranges. It consists of ridges and hills rising to 1043 feet above sea level at " Bluff " Trig Station, but with average relief of less than 500 feet. To the east of this high ground a flat plain extends some 25 miles to the Bynguano Range at Mootwingee. Most of the ridges are formed by more resistant strata and can be readily related to the geology of the area. Because these strata are folded in the Caloola Syncline they form distinctive curved outcrop patterns such as at the Bluff near Sturt's Meadows, with dip slopes often clearly distinguished.

Drainage is generally to the north-east and to the east from the higher ground of the ranges. Caloola Creek, Fowler's Gap Creek, Sandy Creek and Nundooka Creek are the most important drainage channels and carry water to Lake Bancannia 15 miles to the north-east of the area mapped. The streams flow only intermittently and are dry for most of the year. Most are heavily lined with gum trees, a probable indication of a higher water table along their courses.

The climate is semi-arid with a rather variable rainfall, but averages less than 8 inches per year. The distribution of rain is irregular and not confined to any particular season. The temperature ranges from over 100 degrees Fahrenheit in summer to less than 40 degrees Fahrenheit in winter, often with a substantial diurnal variation.

Previous Work

Sir Douglas Mawson (1912) named the " Torrowangee Series " and recognized its unconformity with the intensely metamorphosed " Willyama Series ". His work was followed in 1922 by that of E. C. Andrews who noted the " Torrowangee Series " and some Palaeozoic beds in the area north of the Broken Hill orebodies.

A substantial contribution was made by E. J. Kenny (1934) in which strata near Fowler's Gap are described and the regional geology of the West Darling District is discussed.

The major structural elements were named by King and Thompson (1953) and further work by Thompson is shortly to appear in the " Geology of N.S.W. " a publication of the Geological Society of Australia.

Geological maps on a scale of 1 : 250,000 are concurrently in preparation by the Geological Survey, N.S.W. Dept. of Mines. The Cobham Lake Sheet has been published and the Broken Hill Sheet is in preparation. Data from the present investigation is to be included in the Broken Hill geological map.

Structure

The Torrowangee Group north of Euriowie is folded into a series of anticlines and synclines as shown on the accompanying map (Fig. 3). King and Thompson (1953) give details of how these folds fit into the structural pattern of the Broken Hill District, and name the Caloola Syncline, Sturt's Meadows Anticline and Flood's Creek Syncline. Further folds and faults have been mapped by the Geological Survey, N.S.W. Dept. of Mines for the Broken Hill 1 : 250,000 Sheet. The area discussed in this paper lies along the Caloola Syncline and embraces part of the Sturt's Meadows Anticline. An unnamed anticline between the Caloola and the Flood's Creek Synclines has some influence on the Proterozoic beds in the north-west of the area.

The fold axes strike generally north-west, parallel to the unconformity with the Willyama Complex, but the strike becomes more northerly away from this feature. Several faults close to the strike of these fold axes were mapped by the authors and by the N.S.W. Geological Survey. One of these named the Nundooka Creek Fault occurs on the eastern edge of the rock exposure. The strike of this fault, like that of the fold axes, changes from north-westerly to northerly away from the area of the Willyama Complex. Similarly, the lines of the major unconformities, the Willyama-Torrowangee and the Proterozoic-Devonian lie in a north-westerly direction.

The Caloola Syncline is a south plunging fold outlined by quartzite marker horizons. The dips on its flanks reach 70 degrees but tend to lessen towards the fold axis. Faulting within the syncline is shown by offset of quartzite beds. These faults are of relatively small displacement in comparison with the Nundooka Creek Fault, and tend to strike symmetrically about the fold axis. They are probably related to the development of the syncline.

The Sturt's Meadows Anticline lies to the west of the Caloola Syncline. It plunges to the south with its axis parallel to that of the Caloola Syncline and is traced out clearly by beds of dolomite. To the north-west, beyond the area mapped, this anticline appears to be truncated by a major fault (G. Rose, pers. comm.). Dips recorded on the flanks of the fold are generally of smaller angle than on the Caloola Syncline.

A vertically dipping plane cleavage is developed in the Proterozoic folds. It is apparent in the shales of the sequence as a slaty cleavage, and in the quartzites and carbonate rock as a parallelism of crystalline material. The usually straight cleavage in the shale is distorted in places by chevron folds, due, perhaps, to local faulting. A set of joints occurs at right angles to this cleavage, due to tension in folding. Quartz veins fill these joints and also cut the quartzites, dolomites and shales in other more random directions.

Three dykes of altered andesite occur near the Sturt's Meadow's Anticline. The strike of these coincides with that of the tensional jointing described above.

In the core of the Caloola Syncline a slight angular unconformity separates the Torrowangee Group from beds of probable Cambrian age. These (?) Cambrian strata are gently folded into a syncline. Another marked angular unconformity separates the Proterozoic from Devonian strata.

The Nundooka Creek Fault is a normal fault with a steep dip to the east. It is downthrown to the east and immediately at the fault plane the beds of Devonian sandstone dip at a very steep angle. The amount of displacement is not known, owing to the lack of suitable stratigraphic markers, but it is clearly quite considerable. Its position is recognizable in the northern part of the area by truncation of beds, but in the centre near Fowler's Gap it can be detected only by dip and strike changes in the Devonian sandstone. However the physiographic expression of the fault line is clearly visible on aerial photographs and in the field.

Along a zone on each side of the actual fault the Devonian sandstones are heavily criss-crossed with veins of recrystallized quartz, which probably represent the initial stages of silica remobilization prior to quartz veining and is associated with the stresses produced by fault.

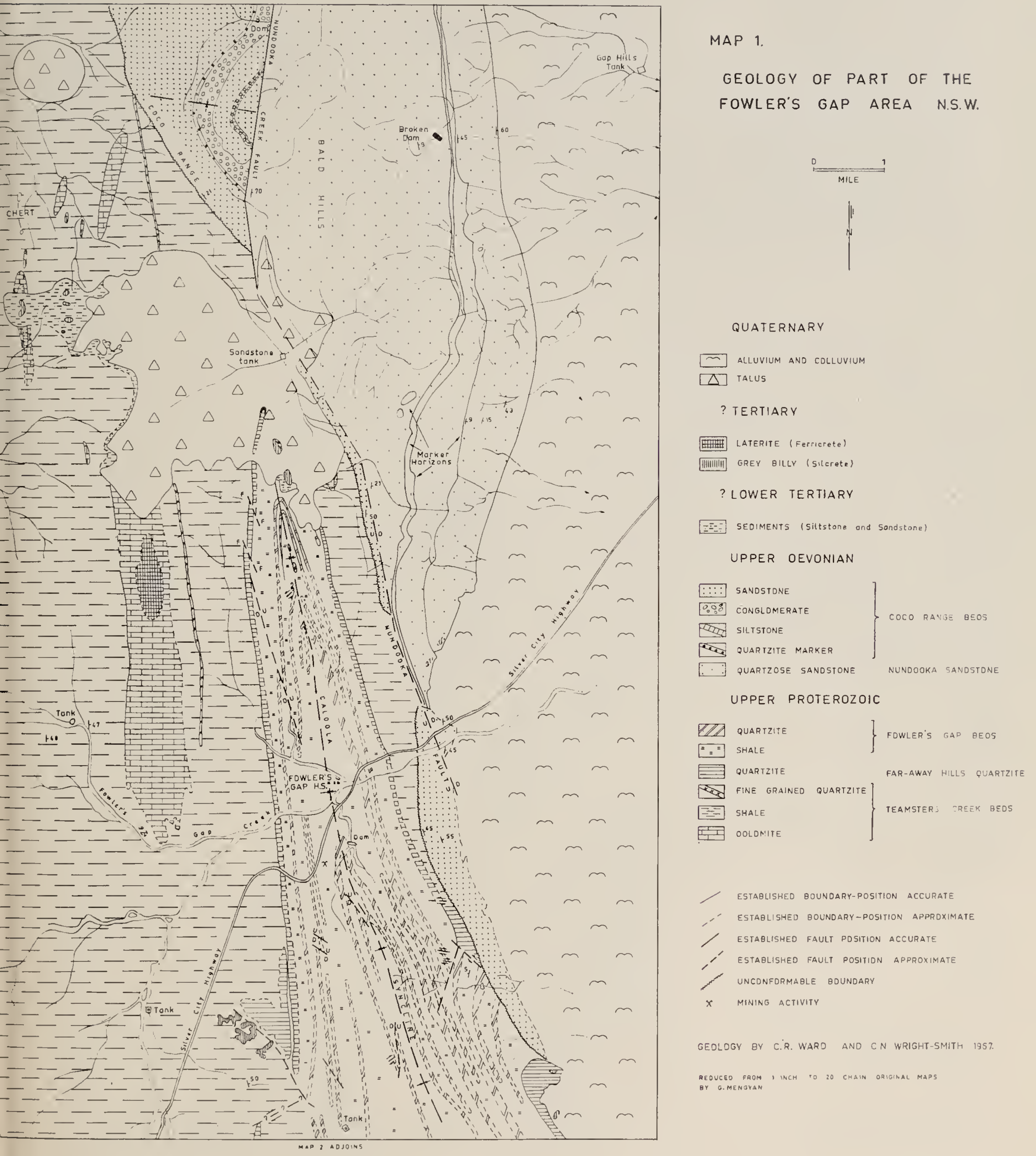

MAP 1.
GEOLOGY OF PART OF THE FOWLER'S GAP AREA N.S.W.
0 1
MILE
N
QUATERNARY
ALLUVIUM AND COLLUVIUM
TALUS
? TERTIARY
LATERITE (Ferricrete)
GREY BILLY (Silcrete)
? LOWER TERTIARY
SEDIMENTS (Siltstone and Sandstone)
UPPER DEVONIAN
SANDSTONE
CONGLOMERATE
SILTSTONE
QUARTZITE MARKER
COCO RANGE BEDS
QUARTZOSE SANDSTONE
NUNDOOKA SANDSTONE
UPPER PROTEROZOIC
QUARTZITE
SHALE
FOWLER'S GAP BEDS
QUARTZITE
FAR-AWAY HILLS QUARTZITE
FINE GRAINED QUARTZITE
SHALE
DOLOMITE
TEAMSTERS CREEK BEDS
ESTABLISHED BOUNDARY-POSITION ACCURATE
ESTABLISHED BOUNDARY-POSITION APPROXIMATE
ESTABLISHED FAULT POSITION ACCURATE
ESTABLISHED FAULT POSITION APPROXIMATE
UNCONFORMABLE BOUNDARY
MINING ACTIVITY
GEOLOGY BY C.R. WARD AND C.N. WRIGHT-SMITH 1957.
REDUCED FROM 1 INCH TO 20 CHAIN ORIGINAL MAPS BY G. MENGYAN
Dam
NUNDOOKA CREEK FAULT
COCO RANGE
Gap Hills Tank
Broken Dam
BALD HILLS
CHERT
Sandstone tank
Marker Horizons
NUNDOOKA
Silver City Highway
CALOOLA
Tank
FOWLER'S GAP HS.
Fowlers Gap Creek
FAULT
Dam
Tank
Silver City Highway
Tank
MAP 2 ADJOINS

FIG. 1

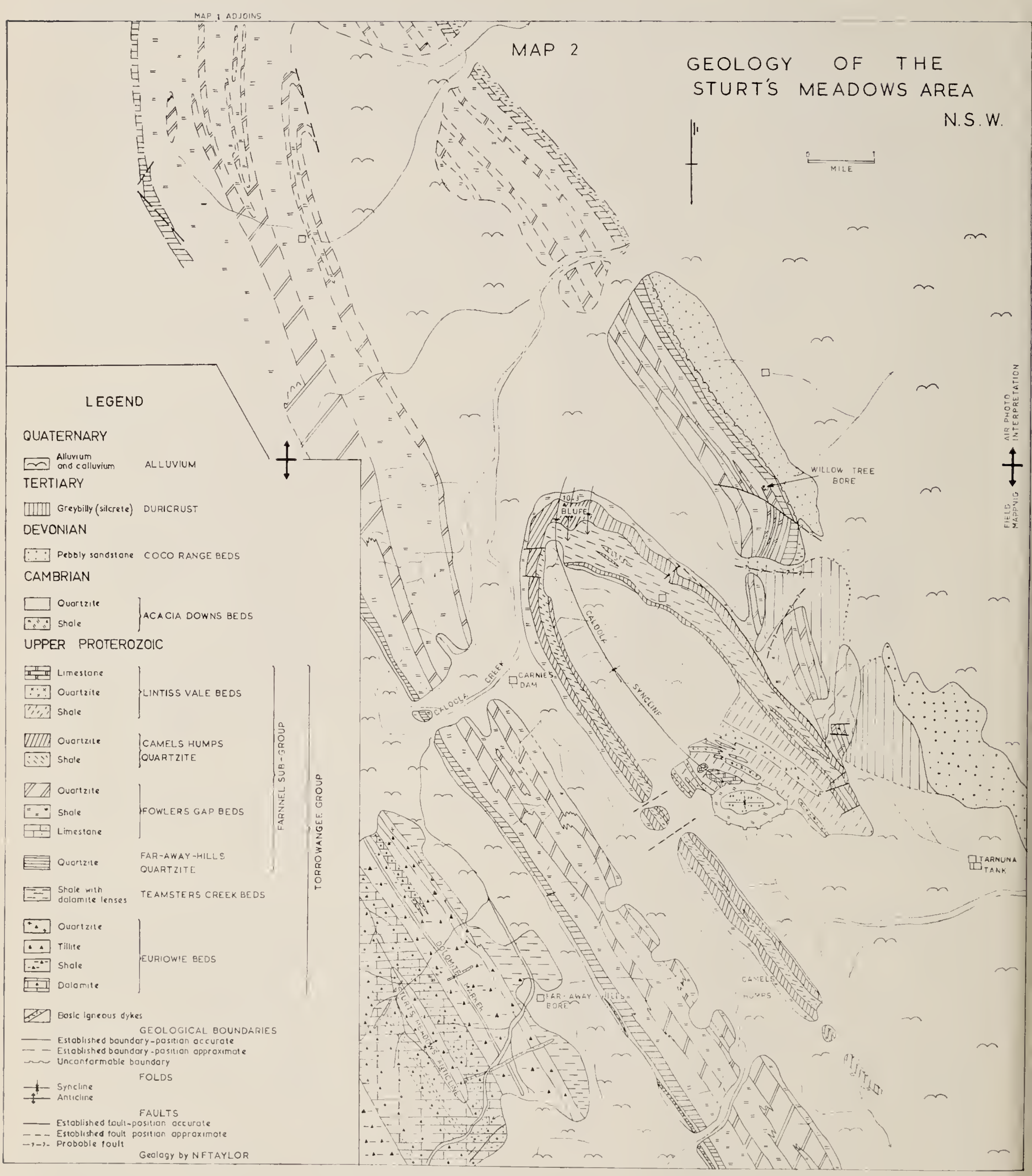

MAP 1 ADJOINS
MAP 2
GEOLOGY OF THE STURT'S MEADOWS AREA N.S.W.
0 MILE 1
AIR PHOTO INTERPRETATION
FIELD MAPPING
WILLOW TREE BORE
1043
BLUFF
CALOOLA SYNCLINE
CALOOLA CREEK
CARNIES DAM
TARNUNA TANK
CAMELS HUMPS
FAR-AWAY-HILLS BORE
DOLOMITE MARKER
STURTS MEADOWS ANTICLINE
LEGEND
QUATERNARY
Alluvium and colluvium
ALLUVIUM
TERTIARY
Greybilly (silcrete)
DURICRUST
DEVONIAN
Pebbly sandstone
COCO RANGE BEDS
CAMBRIAN
Quartzite
Shale
ACACIA DOWNS BEDS
UPPER PROTEROZOIC
Limestone
Quartzite
Shale
LINTISS VALE BEDS
Quartzite
Shale
CAMELS HUMPS QUARTZITE
Quartzite
Shale
Limestone
FOWLERS GAP BEDS
Quartzite
FAR-AWAY-HILLS QUARTZITE
Shale with dolomite lenses
TEAMSTERS CREEK BEDS
Quartzite
Tillite
Shale
Dolomite
EURIOWIE BEDS
FARNNEL SUB-GROUP
TORROWANGEE GROUP
Basic Igneous dykes
GEOLOGICAL BOUNDARIES
Established boundary-position accurate
Established boundary-position approximate
Unconformable boundary
FOLDS
Syncline
Anticline
FAULTS
Established fault-position accurate
Established fault position approximate
Probable fault
Geology by N F TAYLOR

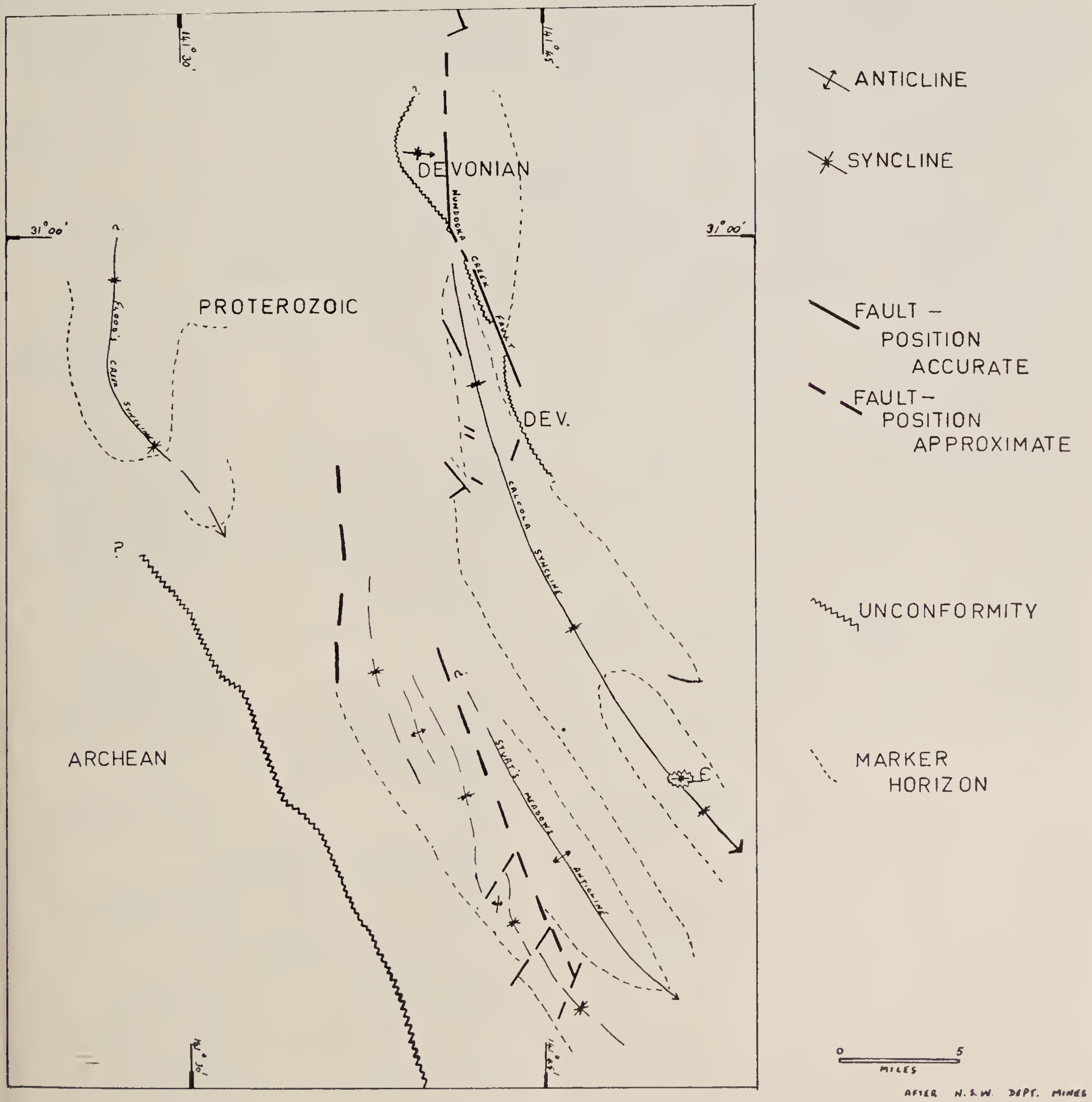
Fig. 2

Similar, but less intense veining also occurs along the axes of the gentle folds in these sandstones.

The Upper Devonian strata are folded into an easterly plunging syncline in the Coco Range, and a broad anticline east of Sandstone Tank. In the Coco Range the dip of the beds at the unconformity with the Proterozoic strata is 10 to 20 degrees to the north-east, and near Willow Tree Bore in the south it is also 20 degrees north-easterly. Dips of 45 to 60 degrees at the unconformity were noted, immediately east of Fowler's Gap, but these are probably due to the Nundooka Creek Fault.

East of the Nundooka Creek Fault the Devonian strata of the downthrown block show dips increasing from 9 degrees to 60 degrees easterly, until they are overlapped by Quaternary sediments.

Folding of the Proterozoic Strata to form the Caloola Syncline and Sturt's Meadows Anticline commenced before deposition of the (?) Cambrian strata of the Acacia Downs Beds. The generation of faults within the syncline mentioned above took place probably at the same time, but at least before the Upper Devonian beds were deposited. The Upper Devonian Coco Range Beds and Nundooka Sandstone were



AFTER N.S.W. DEPT. MINES

Fig. 3.—Structural elements.

deposited and folded prior to the formation of the Nundooka Creek Fault.

Since this faulting there have been slight changes in climate or elevation with silcrete and talus deposits having formed and being eroded under the present physiographic conditions.

Stratigraphy

The succession of strata discussed below in detail is based on the field work of the authors. Seven rock units are recognized and named by the authors, and two others are mapped which have been named by other workers.

Strata of the Upper Proterozoic Torrowangee Group are unconformably overlain by strata thought to be Lower Cambrian in age. Sandstones and some shales of (?) Upper Devonian age also overlie the Precambrian rocks with a strong angular unconformity, but nowhere within the area mapped are these strata in contact with the Cambrian beds.

Horizontal beds of sandstone and siltstone thought to be Lower Tertiary age are found in one small part of the area. Scattered residuals of duricrust in the form of silcrete and ferricrete also occur, and there are substantial deposits of Quaternary fluviatile, aeolian and colluvial sediments.

The assignment of ages to most of the rock units mapped is only on a tentative basis, because very few fossils were found in the entire sequence. The rock units are summarized in Table 1.

TABLE 1

Stratigraphy

Era	Epoch.	Group		Formation	Lithology	Thickness (feet)	Remarks
CAINZOIC	Quaternary			Alluvium	Silt and clay and some sand	300	Penetrated by bores
	Upper Tertiary ?			Duricrust	Silcrete and some ferricrete	10	See also Langford-Smith and Dury (1965) and Dury (1966)
	Lower Tertiary ?				Sandstone and siltstone	200	Age uncertain—similar sediments to the north
PALAEOZOIC	Upper Devonian ?			Nundooka sandstone	Quartzose sandstone and Orthoquartzite	3,500	Downthrown block of Nundooka Creek Fault Named by authors
				Coco Range Beds	Quartzose sandstone and orthoquartzite, pebbly sandstone, red and green shale	2,500	Upthrown block of Nundooka Creek Fault –Unconformably overlies Proterozoic Named by authors
	Lower Cambrian ?			Acacia Downs Beds	Quartzite and shale		Fossils reported but not found by authors unconformably overlies Proterozoic Named by B. Warris
PRECAMBRIAN	UPPER PROTEROZOIC	TORROWANGEE GROUP	FARNELL SUB-GROUP	Lintiss Vale Beds	Cleaved shale with quartzite and limestone	4,000	Named by authors
				Camels Humps Quartzite	Quartzite with shale	700	Marker horizon Named by authors
				Fowler's Gap Beds	Shale and quartzite with few limestone lenses	10,000 (approx.)	Named by authors
				Faraway Hills Quartzite	Quartzite	300	Marker horizon Named by authors
				Teamsters' Creek Beds	Shale with dolomite lenses	6,000 (approx.)	Named by authors
				Euriowie Beds	Shale, dolomite and tillite		Named by N.S.W. Dept. Mines for Broken Hill 1 : 250,000 Sheet. Rests conformably on remainder of Proterozoic sequence

Upper Proterozoic

TORROWANGEE GROUP

The Torrowangee " Series " of Mawson and succeeding workers has been revised as the Torrowangee Group for the Broken Hill 1 : 250,000 Geological map, by the N.S.W. Dept. of Mines. Its constituents formations include those named in this paper and several others cropping out beyond the present areas. A brief summary of the regional stratigraphic succession of the Torrowangee Group as shown on the Broken Hill 1 : 250,000 Geological Map is given below :—

Top	Cambrian and other strata.
Unconformity	
Farnell Sub-Group	Shale and quartzite with minor limestone lenses. See details below.
Teamsters' Creek Beds	Shale with dolomite lenses and tillite-like phases.
Euriowie Beds ..	Laminated tillite-like shale, dolomite and limestone, sandstone and conglomerate.
Yancowinna Beds	Conglomerate, sandstone numerous erratic pebbles and boulders of possible glacial origin ; some limestone.
Pintapah Quartzite	Quartzite, sandstone, pebbly quartzite.
Wilangee Volcanics	Basalt, epidotized basalt.
Unconformity	

WILLYAMA COMPLEX

Only the upper part of this sequence including the Farnell Sub-Group, the Teamsters' Creek Beds and part of the Euriowie Beds are found to crop out in the area mapped.

Details of these stratigraphic units are given below.

EURIOWIE BEDS

The Euriowie Beds are named by G. Rose for the Broken Hill 1 : 250,000 Geological Map. They crop out in the south-west corner of the area mapped in the present study, where they are exposed in the Sturt's Meadows Anticline.

The base of the unit is not seen in this area, but the top is clearly defined. It is taken as the top of the tillite marker horizon, including its laterally equivalent quartzite horizon as mapped on the flank of the anticline.

Dark grey-green shale is the lowest bed and is exposed on the crest of the fold. This is overlain by a sequence of grey-brown dolomite and grey-green shale. The shale often becomes dolomitic and grades into dolomite, especially in the lower part of the section. Dolomite beds are generally less than three feet thick, but they persist for quite some distance along strike and help delineate the structure. It is unfossiliferous with interlocking fine carbonate crystals and is probably recrystallized. These crystals show an apparent elongation which may either reflect bedding or a tectonic preferred alignment.

Shale becomes dominant again above this unit, but dolomite beds are still present. One horizon is particularly prominent. This is made up of ten closely spaced dolomite beds and can be traced as virtually a single unit 30 feet thick for over four miles along strike.

There is a layer of tillite at the top of the Euriowie Beds. This is about 300 feet thick on the eastern flank of the anticline, but on the western side, beyond the area mapped, it thickens to 1,500 feet and is much better exposed. It passes laterally into a quartzite further to the north. The tillite forms a dominant outcrop with many boulders scattered nearby. The rock assemblage displayed in these boulders is extremely heterogeneous with quartzite most abundant. Granite, gneiss, schist, basic igneous rock, shale, slate and limestone also present. The size of these fragments is also highly variable. Excluding those of the matrix, the fragments range from small pebbles and cobbles to boulders and several megaclasts with a maximum dimension of four to five feet. In sympathy with this size variation, the fragments range from sharply angular to sub-rounded and are from flat and platey to sub-spherical in shape.

The tillite is conformable with the rest of the Proterozoic sequence and often shows some degree of bedding. However, the thicker deposit on the western flank of the Sturt's Meadows Anticline is an unbedded mass of dispersed boulders. The boulders and pebbles are set in a matrix of angular sand grains and grey siliceous to blue-green argillaceous material.

Well bedded, thin layers of consolidated gravel, arkosic grit, coarse grained sandstone and quartzite occur throughout the tillite on the eastern limb of the anticline. Sometimes the gravels show several cycles of graded bedding.

The name " tillite " is applied to this rock type because of its appearance in the field. Although no striations were found on them, it is felt that the occurrence of such large boulders of diverse rock types, often separated by a high proportion of matrix is strongly indicative of glacial action. In view of the current importance attached to Precambrian glaciation on a world-wide basis (Nairn, 1964), further work on the origin of these beds may be justified.

The tillite becomes more shaley and the boulders more sporadic as it grades upwards into the Teamster's Creek Beds.

TEAMSTERS' CREEK BEDS

This unit is named by the authors after Teamsters' Creek, a water-course west of Fowler's Gap Tank. It conformably overlies the tillite horizon at the top of the Euriowie Beds, and is in turn overlain by the prominent Faraway Hills Quartzite.

It is exposed extensively along the western side of the area mapped and consists mainly of shales with limestone and dolomite lenses.

The boundary between the Teamsters' Creek Beds and the Euriowie Beds is exposed in the south-western corner of the area mapped. North and west of Fowler's Gap its area of outcrop becomes more extensive due to the presence of an anticline and possible faulting between the Caloola and Flood's Creek Syncline.

The shale is generally grey-green in colour, but in places becomes red-brown and buff. White calcareous phases are also encountered. A strong axial plane cleavage has been developed in the shale, and recrystallization has undoubtedly obscured much of the bedding. Microscopic and X-ray determination of the mineral assemblage indicates that metamorphism of the rock approached greenschist facies, thus the term " slate " should perhaps be applied. However shale is used in this text to maintain uniformity in definitions with other workers, especially those concerned with the Adelaide Geosyncline in South Australia. In some localities the strata are more intensely deformed, with phyllites of silky lustre due to the muscovite flakes and a dark green colour due to the presence of chlorite, often developed. This is especially noticeable near the Nundooka Creek Fault.

Throughout the Teamsters' Creek Beds, but especially in the north-west corner of the area, the shales become tillitoid. Boulders, pebbles and sand-size grains of quartz, quartzite and other rock fragments are set in a fine grained lepidoblastic micaceous matrix. The boulders range up to two feet across and generally appear more rounded than the grains. The fragments are poorly sorted but occasionally elongated boulders are aligned parallel indicating either bedding or rotation association with the development of slaty cleavage.

It is thought that the poor sorting and sporadic development of this coarse material in an otherwise fine grained shale is indicative of glacial action with possible ice-rafting, rather than fluviatile deposition of conglomerate. Beds of probable tillite occur lower down in the Torrowangee Group, especially at the top of the Euriowie Beds and in the Yancowinna Beds.

Dolomites and limestones occur as lenses throughout the sequence, and are often interbedded with white or grey-green shales. The dolomites are generally buff in colour and contain a high proportion (about 45%) of quartz. They are cut by numerous quartz veins and it is suggested that much of the silica in these dolomites is due to replacement of carbonates.

The limestones on the other hand are dark grey in colour and occur as only small lenses. They are largely free of quartz veins and contain almost no material other than carbonate.

Major lenses of dolomite are shown on the map. As well as these, there are minor occurrences of limestone and dolomite throughout the shales of the Teamsters' Creek Beds.

Two small outcrops of black, fine grained chert-like rock occur in the north-west of the area. These are comprised of quartz and muscovite, but their origin is uncertain. One of these lenses is very heavily veined with white quartz, giving a banded appearance.

A long prominent ridge of white, fine grained rock is mapped just west of Fowler's Gap. This is composed of recrystallized quartz less than 0·05 mm. in diameter with an interlocking fabric. It may represent a completely silicified bed of dolomite, although its shape is different from that of any other dolomite bed in the area, or it may be a deposit of silica (e.g. chert) which has been recrystallized. It does not appear to be intrusive as no contact effects are noted in the surrounding shale.

The Teamsters' Creek Beds are about 6,000 feet thick in the south-west of the area where both top and base are exposed. Structural complications to the north prevent any reliable estimate of thickness in the remainder of the area mapped.

FARNELL SUB-GROUP

Conformably overlying the Teamsters' Creek Beds is a sequence of quartzite beds and cleaved shale with subordinate limestone lenses. It is distinctly different from the underlying strata of the Teamsters' Creek and Euriowie Beds because no continuous beds of quartzite are found in the latter units.

The Sub-Group takes its name from the County of Farnell, Western Division in which the area lies. The unit is subdivided, as follows, into four formations, two of which are prominent marker horizons.

4,000 ft.	Lintiss Vale Beds	Shale with interbedded quartzite and dolomite.
900 ft.	Camels Humps Quartzite	Marker horizon — two quartzite beds separated by shales.
10,000 ft.	Fowler's Gap Beds.	Shale with numerous quartzite beds and subordinate limestone lenses.
300 ft.	Faraway Hills Quartzite	Marker horizon—single quartzite bed containing minor shale lenses.

The most complete section of the Farnell Sub-Group is exposed in the Caloola Syncline, as shown on the accompanying maps. Although some erosion may have occurred, the top is at present defined as the unconformable boundary with the overlying (?) Cambrian strata in the core of the syncline. The Broken Hill 1 : 250,000 Geological Map shows a further occurrence of these quartzites in the Flood's Creek Syncline near Mt. Westwood, north-west of the present area.

FARAWAY HILLS QUARTZITE

The lowest formation in the Farnell Sub-Group is a very prominent marker horizon consisting of a bed of medium grained quartzite 200 to 300 feet thick with occasional minor shale lenses up to 20 feet thick. It forms the highest of the ridges along both limbs of the Caloola Syncline and crops out east and west of the Fowler's Gap Homestead. King and Thompson (1954) show it as a marker horizon for the Caloola Syncline and refer to it as " Thirty Mile Ridge ".

The formation takes its name from the Faraway Hills Bore, in the southern part of the area, near its outcrop.

In thin section the quartzite is composed of 90% to 95% quartz, with some opaque iron oxides and traces of muscovite. The quartz shows some evidence of recrystallization and in places a cataclastic texture is present. The grain-size is up to 0·4 mm., but some of the brecciated fragments are as small as 0·01 mm. Recrystallization and brecciation have obliterated most of the characteristics of the original sedimentary rock. In some specimens a shearing effect is shown by parallelism of quartz crystals and increased brecciation. Both the sheared and the more massive types are clearly recognizable in hand specimens.

FOWLER'S GAP BEDS

Between the prominent marker beds of the Faraway Hills and the Camels Humps Quartzites is a sequence of interbedded quartzite and cleaved shale to which the name Fowler's Gap Beds is given. Fowler's Gap Station, from which the name is derived, lies in the centre of their outcrops on the Silver City Highway. The base and the top of the unit are defined by the top of the Faraway Hills Quartzite and the base of the Camels Humps Quartzite respectively.

The quartzites are similar in appearance to the Faraway Hills Quartzite described above, although about 5-10% of felspar (usually microcline), is present. The beds vary in thickness from six inches to six feet, but are very irregular and are often obscured by talus. They are often intimately interbedded with shale and the quartzite thickens, thins, splits and pinches out quite frequently. Areas shown on the map as quartzite usually include a considerable amount of shale, as lenses, or often as separate beds.

Shale makes up most of the rest of the unit. It is usually light grey-green in colour although buff and white types develop. At the top of the Fowler's Gap Beds just below the Camels Humps Quartzite at " Bluff " Trig Station the shale contains several thin bands, rich in goethite, haematite and calcite. It is thought that this represents " red-bed facies " development due to erosion of lateritic material in the source area. A similar horizon is reported by Thompson (1964) underlying the Pound Quartzite in South Australia.

Sedimentary structures suggestive of worm tracks are seen in the shale about two miles north-west of Willow Tree Bore. Smooth curved tracks about one eighth inch deep are associated with hemispherical pits of irregular shape and size.

Small lenses of limestone and dolomite occur throughout the shales. One of these, just west of the Fowler's Gap Homestead is seen to grade laterally through calcareous quartzite to quartzite.

Between Faraway Hills Bore and Camels Humps the Fowler's Gap Beds are about 10,000 feet thick. Their area of outcrop around Fowler's Gap Homestead is greater than would be expected due to a reduction of dip angle in the synclinal limbs. Hence the quartzite beds become separated in outcrop by a greater distance and so appear to be more numerous than further to the south.

CAMELS HUMPS QUARTZITE

This is a very prominent marker horizon tracing out the outline of the Caloola Syncline east of Sturt's Meadows. The formation lies conformably between the Fowler's Gap Beds and the Lintiss Vale Beds and is readily recognized by virtue of its prominent outcrop. The best development of quartzite is near the "Bluff" Trig Station where the steep slopes expose the full section. The name is taken from the locality "Camels' Humps", a ridge to the east of Faraway Hills Bore.

It is not a single mass of quartzite but consists of two major and one less prominent quartzite beds interbedded with shales. A typical section as exposed near the "Bluff", is as follows (thicknesses approximate).

Top :

100 feet.	Quartzite.
300 feet.	Shale.
250 feet.	Massive Quartzite.
150 feet.	Shale.
150 feet.	Massive Quartzite.

Base.

This gives a total thickness of some 900 feet. The lower two quartzites are shown as one unit on the map, and appear as a single ridge in the field. The top quartzite bed is included with the Camels' Humps Quartzite because of its lithological similarity to the main ridge-forming bed and its persistence compared to those of the Lintiss Vale Beds.

Some current markings are occasionally exposed on bedding planes of the massive quartzites and clay galls are found in the uppermost minor quartzite. These clay galls are markedly spherical, dark red inclusions in massive quartzite. They are about one to two inches in diameter and number about two or three to the square yard of exposed rock surface.

LINTISS VALE BEDS

Overlying the Camels' Humps Quartzite marker there is a sequence of shales with interbedded quartzites and a dolomite horizon at the top. These are the uppermost Proterozoic sediments in the Caloola Syncline and are unconformably overlain by strata believed to be Cambrian in age.

These are named by the authors the Lintiss Vale Beds after a property a few miles to the south. Although part of the section may have been eroded the formation is approximately 4,000 feet thick and is composed dominantly of shale with lenticular beds of quartzite in the upper half. Colluvial cover between their outcrop and the "Bluff" prevent a more complete study of these beds.

The top of the Lintiss Vale Beds has been taken at the unconformity with the Acacia Downs Beds. Immediately beneath these (?) Cambrian strata a thin dolomitic bed occurs. This horizon is only 40 feet thick and is made up as follows.

Top :

10 feet.	Flaggy Quartzite.
10 feet.	Dolomite.
10 feet.	Quartzite.
10 feet.	Dolomite.

Base.

The dolomites are similar to those of the Teamsters' Creek Beds and form a shallow dipping plateau beneath the (?) Cambrian strata. Some small scale slumping has been observed in these sediments.

The shales are buff-brown in colour, especially near the top of the sequence, as opposed to the more common grey-green colour typical of the rest of the Torrowangee Group in the area.

(?) Cambrian

ACACIA DOWNS BEDS

Resting with a slight angular unconformity on the Lintiss Vale Beds is a sequence 200 feet thick of light green-brown shale overlain by 150 feet thick grey quartzite. It is lithologically similar to the rocks of the Torrowangee Group beneath. The Cambrian age assigned to these rocks is based on the reported occurrence of fossilized worm tracks and arthropod trails by Messrs. Fitzpatrick and Johnson of Adelaide (M. F. Glaesner, pers. comm.), but no further specimens were found during the present study.

This formation has been named by B. Warris (unpublished) after the property "Acacia Downs" to the south. These sediments are only found in small areas at the centre of the Caloola Syncline, west of the Tarnuna Tank, with an extent of about a square mile.

Some cross bedding has been noted in the quartzite, which has both massive and flaggy phases. Sole markings, both tool and current types, are relatively abundant.

CORRELATION OF THE PROTEROZOIC

The Upper Proterozoic beds of the Torrowangee Group are separated from the type area succession in the Adelaide district by the Willyama Block, which acted as a positive tectonic element during Sturtian and Marinoan time (Sprigg, 1952), and from which much of the detritus was derived. The units in the area mapped can be correlated with the upper part of the sequence in the Adelaide Geosyncline by virtue of their environmental similarity, although they do not attain the great thickness of the type section. Table 2, gives a summary of the proposed correlation, using the rock unit names of Thompson *et al.* (1964) for the North Flinders Range.

In the Sturt's Meadows—Nundooka area, the most striking feature of the Torrowangee Group is the change from shales, dolomites and tillites of the Euriowie and Teamsters' Creek Beds to the persistent beds of quartzite in the Farnell Sub-Group. This is the same as in the Adelaide Geosyncline where the glacial character of the Umberatana Group gives way to the quartzites and shales of the Wilpena Group (Thompson *et al.*, 1964).

It is difficult to extend the stratigraphic correlation beyond this and attempt to correlate individual formations, largely because there is no continuous outcrop between the two areas. The Willyama Complex around Broken Hill is thought to have been a cratonic block during the late Precambrian, separating the Adelaide Geosyncline and the Torrowangee Group. Sprigg (1952) describes the derivation of the Sturtian glacials from this block, and it is quite likely to have persisted as a source area throughout the remainder of the Proterozoic. Thus the Willyama Block seems to have been in a position whence sediment was supplied to two depositional areas, at the same time. Any major climatic change or tectonic disturbance in this block would have affected the

TABLE 2

Stratigraphic Correlation of the Proterozoic Sequence

System	Series	Rock Units				
		NORTH FLINDERS RANGES (after Thompson *et al.* 1964)		STURT'S MEADOWS-NUNDOOKA (this paper)		
CAMBRIAN	LOWER CAMBRIAN		PARACHILNA FORMATION			ACACIA DOWNS FORMATION
		Local disconformity		Unconformity		
ADELAIDE SYSTEM	MARINOAN SERIES	WILPENA GROUP	POUND QUARTZITE	TORROWANGEE GROUP	FARNELL SUB-GROUP	LINTISS VALE BEDS CAMELS' HUMPS QUARTZITE
			WONOKA FORMATION BUNYEROO FORMATION			FOWLER'S GAP BEDS
			A.B.C. RANGE QUARTZITE			FARAWAY HILLS QUARTZITE
			BRACHINA FORMATION NUCCALEENA FORMATION			TEAMSTERS' CREEK BEDS
		UMBERATANA GROUP	YERALINA FORMATION			EURIOWIE FORMATION

type of sediment in each depositional area. A change of this type may well be responsible for the cessation of glacial activity and the commencement of deposition of quartzose sandstones which occurs in both the Adelaide Geosyncline and the area mapped. However deposition within each of the two areas was controlled by more local effects, and a sufficiently different sequence was developed in each to make exact correlation difficult.

It should also be noted that in the Adelaide Geosyncline there is an apparently conformable succession from the Proterozoic into the Cambrian, but at Sturt's Meadows there is a distinct angular unconformity between the Lintiss Vale Beds of the Proterozoic and the (?) Lower Cambrian Acacia Downs Beds. It is possible that the top of the Proterozoic sequence in the Caloola Syncline was removed by erosion prior to deposition of the Cambrian strata, and so the succession at present preserved there may not extend completely to the top of the Precambrian as it appears to do in the Adelaide Geosyncline.

Upper Devonian

Resting unconformably on a basement of Proterozoic shale at the eastern edge of the Barrier Range in the area mapped are beds dominantly of quartzose sandstone of probable Upper Devonian age. Previous published information has not recorded any fossils in these beds, but David (1950) regards them as Upper Devonian and probably equivalent to the " Lambian Stage " in eastern N.S.W. Dr. M. J. Rickard (pers. comm.) has recently found some fish plates c.f. *Bothriolepis* sp.) in the sandstones east of Fowler's Gap. These have an age of Middle to Upper Devonian and are probably indicative of fresh water conditions.

The Nundooka Creek Fault separates these beds into two blocks. The western, upthrown block has some lithological differences from the eastern block and the two units are given separate names. Since the fault separates these units along the entire length of their outcrop the full sequence cannot be seen anywhere, although they are probably stratigraphically conformable.

The units recognized are :

Coco Range Beds :—A sequence of quartzose sandstones and conglomerates with red and green-grey siltstones and claystones ; this unit immediately overlies the Torrowangee Group with a sharp angular unconformity.

Nundooka Sandstone :—A thick unit almost entirely of quartz sandstones brought down against the Coco Range Beds by the Nundooka Creek Fault.

It is clear that the Nundooka Sandstone overlies the Coco Range Beds but since the fault interrupts the exposure of the sequence no further stratigraphic relationships can be observed in this area, or even to the north, near Nundooka Homestead.

COCO RANGE BEDS

These rest with a marked unconformity on cleaved shale of the Upper Proterozoic Torrowangee Group. They are exposed along the eastern edge of the area but it is in the Coco Range to the north that the most complete sequence is to be seen. The unit is named by the authors after the Coco Range (Cobham Lake, N.S.W. 1 : 250,000 Military sheet grid ref. 469168), where the best development occurs.

At the base where it overlies the Proterozoic some red and green shaly units are exposed. These are in turn overlain by a thick sequence of conglomerates and sandstones. At least 2,500 feet of sediment is exposed in the Coco Range where the sequence is as follows :—(thicknesses approximate only)

Top :—Truncated by Nundooka Creek Fault.

600 feet.	Quartz sandstone.
3 feet.	Green-grey siltstone.
10 feet.	Pebbly sandstone and conglomerate.
300 feet.	Quartz sandstone.
600 feet.	Pebbly sandstone and conglomerate.
4 feet.	Orthoquartzite. (Marker horizon).
900 feet.	Quartz sandstone and orthoquartzite.

Unconformity

Base :—Proterozoic Torrowangee Group.

In lenticular patches above the unconformity exposures of argillaceous material are sometimes seen. A section measured east of Fowler's Gap Homestead at the base of the Coco Range Beds, is as follows :—

Top :—Quartzose sandstone.

2 feet.	Red and green claystone beds.
1 foot.	Red sandstone.
1 ft. 6 inches.	Coarse grit.
10 feet.	Red claystone.

Unconformity

Base :—Proterozoic shale.

Where these beds are not present sandstone rests directly on the Proterozoic. This Devonian sandstone often contains angular fragments of grey-green shale derived from the Torrowangee Group beneath.

The sandstones of the Coco Range Beds are medium grained, fairly well sorted and in places quite flaggy. They contain about 90% quartz and the rest consists of mica and rock fragments set in a matrix of white clay. Some iron oxide, probably authigenic, is also present. Many beds of orthoquartzite about four feet thick persist as distinct horizons both in the Coco Range and Nundooka sandstones. They are much harder than the sandstones described above, with a cemented nature due to secondary enlargement of quartz grains. This diagenetic precipitation of silica appears to have been confined to horizons of less clayey sandstone in the Devonian sequence.

Small hemispherical pits one eighth to one quarter inch in diameter are often seen in the Devonian sandstones. These are left by weathering out of spherical patches, rich in clay, within the sandstone. These clayey patches may be primary or diagenetic; not unlike concretions. Flattened blebs of grey shale also occur within the sandstone. Removal of the shale on exposure leaves polygonal hollows resembling fish plates, but these impressions do not have any regular shape or ornamentation.

The conglomerates contain rounded cobbles and pebbles of white vein quartz, up to four inches across, set in a sand and granule matrix. Although the proportion of pebbles varies, the bulk of the rock consists of pebbly sandstone rather than true conglomerate.

The upper limit of the Coco Range Beds is not clearly defined due to truncation by the Nundooka Creek Fault. However photogeological interpretation of the area to the north indicates that very little more of the sequence is likely to be exposed on the western side of the fault than seen in the area mapped.

Nundooka Sandstone

On the eastern side of the fault, a sequence of at least 3,500 feet of quartzose sandstone is exposed. This is called the Nundooka Sandstone after "Nundooka" Station to the north. The sandstone is very similar to that of the Coco Range Beds, but no conglomerate units were observed in the area mapped. Pebbly bands do occur in places and one very thin bed of green shale is exposed. Orthoquartzite beds similar to those described above occur with secondary enlargement of quartz. Three of these beds are persistent enough to trace as marker horizons over many miles.

The base of the units is obscured due to the Nundooka Creek Fault, and the top is covered by extensive deposits of alluvium to the east.

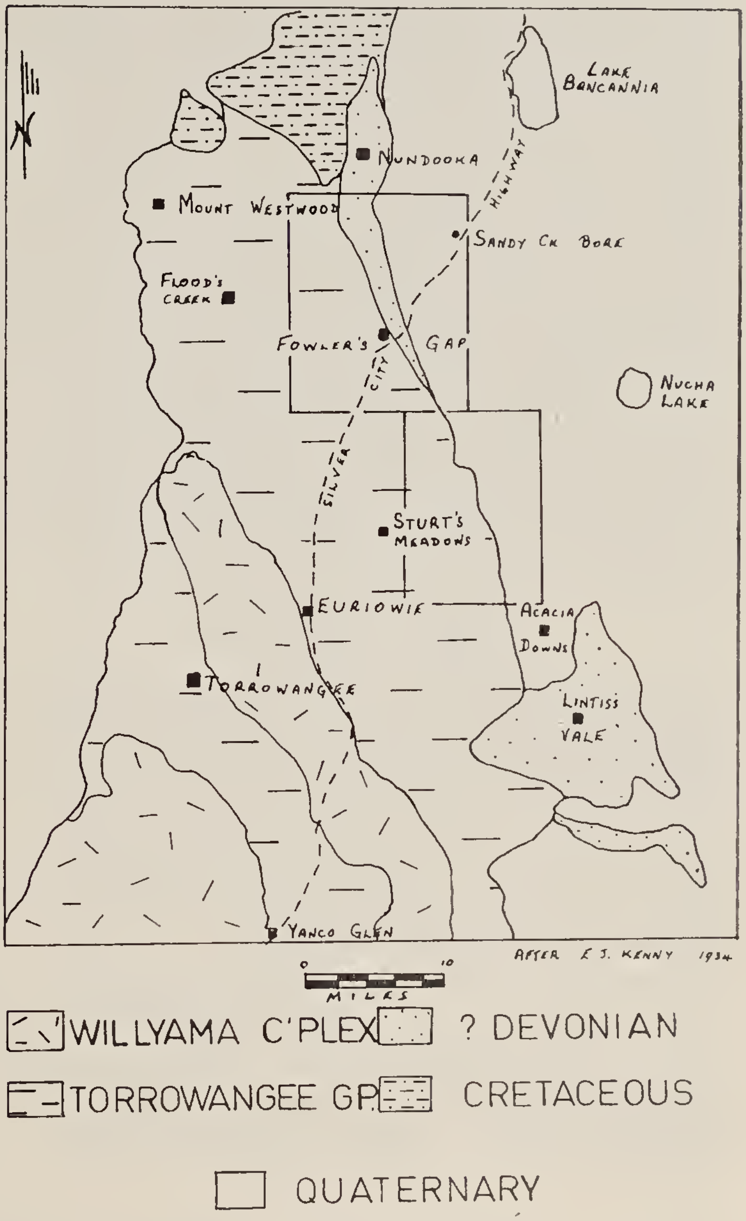


Fig. 4.—Regional geology

Depositional Environment of the Devonian

The association of quartzose sandstones with red and green siltstones and shales is considered (Pettijohn, 1957; Krumbein and Sloss, 1963) to be indicative of stable tectonic conditions. This is supported by the maturity of the sandstones and the presence of cross-bedding. The fish plates suggest a freshwater deposition (G. Rose, pers. comm.).

All writers (Voisey, 1959; Packham, 1960; Conolly, 1962) agree that, at the commencement of the Upper Devonian time the west of N.S.W.

was occupied by a miogeosyncline (Voisey, 1959) or molasse sedimentation conditions. This was a distinct environmental change from the engeosyncline or flysch of the earlier Palaeozoic. Conolly (1962) envisages a sea retreating eastwards throughout the Upper Devonian.

The Devonian sediments in the Coco Range Beds and the Nundooka Sandstone exposed to the north and east of Fowler's Gap probably represent the western limit of Upper Devonian sedimentation in the Lachlan Geosyncline. They rest unconformably on the quartzites and slates of the Proterozoic Torrowangee Group. The sandstones contain fragments of the underlying Torrowangee shale, suggesting that they were derived from the craton of the Broken Hill Block described by Packham (1960). However the lack of continuous outcrop between this area and the Mulga Downs Group (Conolly, 1962) at Cobar means that the stratigraphic position of these marginal sediments with respect to the remainder of the Upper Devonian sequence in N.S.W. is uncertain.

? LOWER TERTIARY

In the north-west of the area mapped several silcrete capped mesas occur. These consist of approximately 200 feet of sediment, the lower half being siltstone whilst the upper section is a sandstone or granule conglomerate. Further occurrences are substantially covered by colluvium around Sandstone Tank but isolated exposures are seen in creek beds.

Both the siltstone and the sandstone are very friable, although partially lithified. They are made up of quartz with a high proportion of muscovite flakes. The granule conglomerate is usually poorly sorted. A certain amount of calcareous cement is present.

The Lower Tertiary age assigned to these sediment is tentative only. They are older than the widespread " duricrust " or silcrete of western N.S.W. which is considered to be late Tertiary in age. (Kenny, 1934), and are believed to be younger than the Cretaceous sediments of the Great Artesian Basin (R. L. Brunker, pers. comm.).

? TERTIARY

The duricrust of western N.S.W. has been studied by several authors including Woolnough (1927), Langford-Smith and Dury (1965) and Dury (1966). In the area mapped there are several outcrops of silcrete left as residuals by the present pattern of erosion. This silcrete is typically grey in colour and contains grains of quartz set in a cement of microcrystalline silica. Some phases with less prominent quartz grains contain plant fossils of the *Cinnamonum* flora. Pebbles, mainly of locally derived quartzite, are occasionally to be found, cemented together by fine grained silica as part of a silcrete outcrop.

The silcrete rests on all the above mentioned rock types including Proterozoic shales and quartzites, Devonian sandstones and the (?) Tertiary sediments described above. The outcrop east of Fowler's Gap Tank has been noted by Langford-Smith and Dury (1965) and one south-east of Tarnuna Tank (beyond the area mapped) at Acacia Downs is recorded by Dury (1966). The other occurrences mapped have not previously been recorded.

Ferricreted aggregates of rock fragments are occasionally exposed. Red-brown iron oxide material also becomes quite prominent on bedrock, especially the Devonian sandstones, and the profile resembles that of a laterite. It is younger than the silcrete since fragments of " grey billy " are included in the iron cemented aggregates.

Calcareous material, or " kunkar " is sometimes seen cementing rock fragments in creek beds. It also forms a coating several millimetres thick in the base of the dry channel. This is a white, powdery deposit, often with a pinkish coloration, composed essentially of calcium carbonate. It is much younger than the silcrete or ferricrete and appears to be a precipitate from the present day stream water.

QUATERNARY

In the eastern part of the area and extending for some 20 miles to the Mootwingee district are flat plains of alluvium. A thickness of greater than 300 feet is indicated in some bores. It is made up dominantly of clay the colour of which ranges from black and red-brown to white, with occasional thin sandy units. On the surface is a thin veneer of drift sand and pebbles with underlying red-brown silt and clay. Near the hills on the western margin of the plains deposits of talus are common, containing coarse pebbles of the nearby bedrock including vein quartz, and silcrete fragments. The veneer of sand is commonly shifted by wind action and shows ripple marks often two to three inches high. Sand dunes are sometimes developed.

A large area of talus is seen around Sandstone Tank in the north of the area. This is derived from the quartzite bedrock of the nearby hills set in a silty and clayey matrix of weathered shale. This deposit is being eroded by the present stream pattern rather than being built up, suggesting a recent vertical uplift, tilting down to the east, or possibly a change in the stream pattern due to river capture.

Acknowledgements

The authors would like to express their gratitude to many members of staff of the University of N.S.W. both in Sydney and Broken Hill for assistance during the field mapping, especially Prof. L. J. Lawrence, who acted as supervisor, and Mr. R. L. Mercer, manager of the Fowler's Gap Research Station. Officers of the Geological Survey, N.S.W. Dept. of Mines, especially Messrs. G. Rose and R. Brunker, who also gave invaluable help, as did Dr. M. J. Rickard of the Australian National University. Prof. J. J. Frankel, Mr. J. H. Bryan and Mr. G. Rose kindly read the manuscript and offered much useful criticism.

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Where Are the Electrons ?*

R. D. Brown

When chemists come to interpret their observations in terms of the atomic molecular theory of matter one of the first questions to be settled is : where are the electrons ? This may arise at a relatively elementary level in balancing a redox equation or using the octet rule to derive a structural formula. At more sophisticated levels of valency theory the interpretation of virtually all chemical and physical properties of compounds depends heavily on a knowledge of how the electrons are distributed over a molecule.

This knowledge of the distribution of electrons being so basic to chemistry, it is instructive to consider how profound is this knowledge. There is much to suggest that chemists are fairly well informed on this matter. For example, many papers in the current literature contain confident pictures of electron distributions in molecules (as portrayed by drawing in covalent bonds, charges on atoms, etc.) and of electronic shifts accompanying chemical reactions. Basic textbooks describe ionic and covalent bonds, and more advanced texts discuss bonds in transition element compounds with synergic back donation of π-electrons strengthening the metal ligand σ-bond and simultaneously ameliorating its polarity. What is rarely pointed out is that all of these descriptions of electron distributions are based upon sets of rather sweeping assumptions, the validity of which is open to question. Indeed, when looked into closely it is surprising how little we know beyond reasonable doubt about where the electrons are in molecules. I propose to try to illustrate the current fight with ignorance and to do it at two levels. Firstly, I want to consider how much we know about the gross distribution of electrons when we merely try to assess the net charges that should be associated with each atom. Secondly, I want to consider to what extent we can distribute the atomic electron densities among the different atomic orbitals associated with each atomic nucleus. Thus at the first level I shall consider the overall distribution of electrons in formaldehyde and other molecules. At the second level I shall touch on questions such as : are the 3d orbitals of sulphur used to any appreciable extent to accommodate valence electrons in SF_6 ? Let us start with the problem of gross charges.

If we are interested in the charge distribution in formaldehyde, for example, a textbook is likely to indicate the electronic structure as shown in Fig. 1. We should first ask what this means. The only aspect of charge distribution that is observable in principle is the total electron density at various points in space, $|\psi^2|$; in practice only certain derived quantities that I shall mention later have been observed.

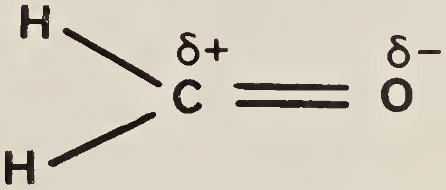

Fig. 1—Typical textbook representation of the charge distribution in formaldehyde.

Very accurate, theoretical information is available for some diatomic hydrides (Bader *et al.*, 1967), as shown in Fig. 2. To gain some impression of the changes that accompany bonding, it is useful to inspect the differences between these charge distributions and those for the separate uncharged atoms. Fig. 3 shows the difference maps. Fig. 4 shows an analysis into integrated charge transferred to bonding and to lone pair regions. We note that these data parallel our classical views that LiH is mainly ionic and that bonding becomes more and more covalent as we proceed across the periodic table. However, the appearance of the opposite ionic character, e.g. in HF, is hard to discern. One does not know just how this would reveal itself in the charge density contour maps—HF looks like the fluoride ion with a " pimple " representing the hydrogen.

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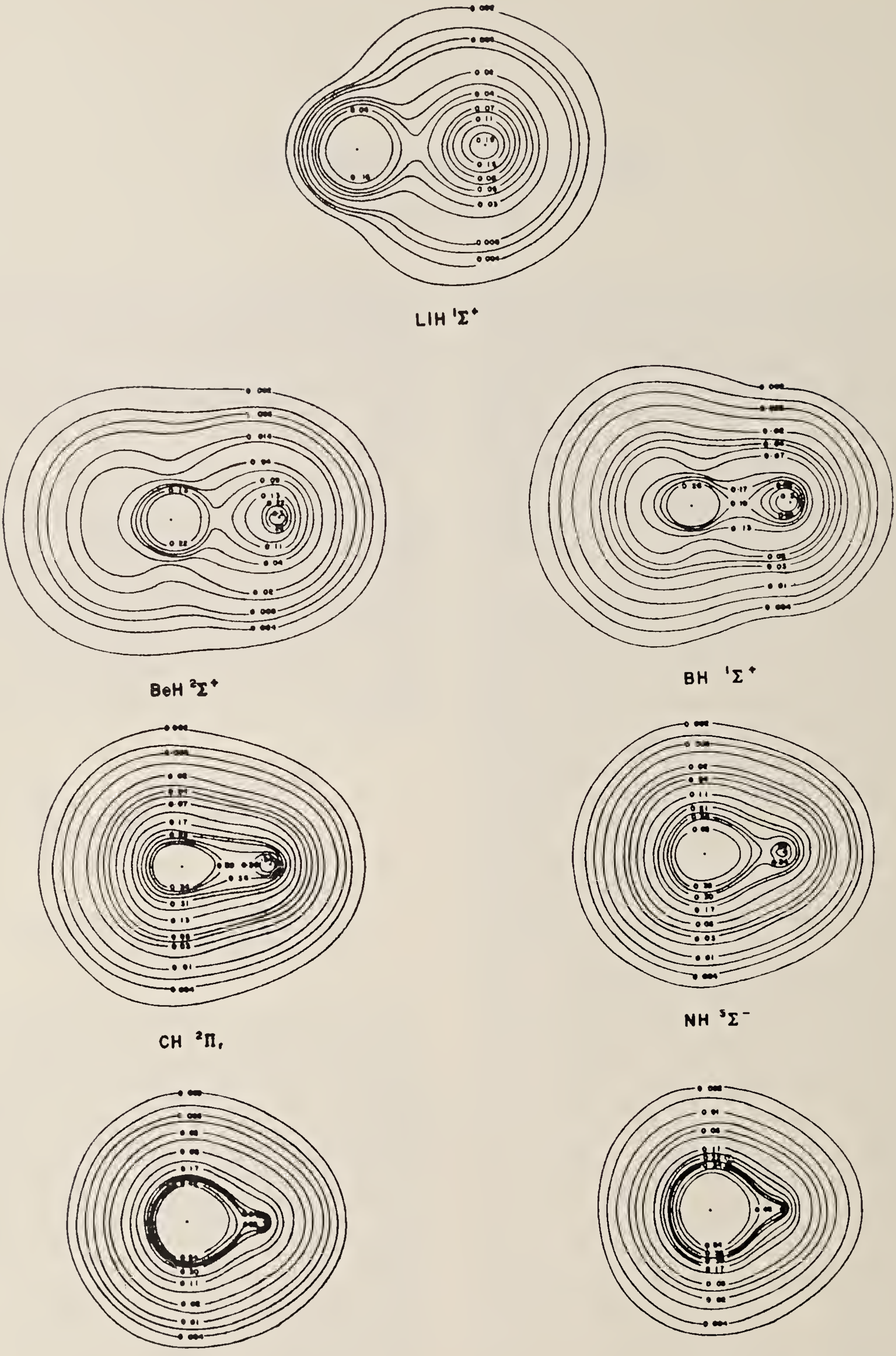
* Liversidge Lecture delivered before the Royal Society of New South Wales, July 17th, 1968.



LiH $^1\Sigma^+$

BeH $^2\Sigma^+$

BH $^1\Sigma^+$

CH $^2\Pi_r$

NH $^3\Sigma^-$

OH $^2\Pi_i$

HF $^1\Sigma^+$

Fig. 2—Total molecular charge density contours for the first-row diatomic hydrides (atomic units; H nucleus is on the right in each case). The innermost contours encircling the heavy nucleus have been omitted for the sake of clarity.

(Reproduced, with permission, from Bader *et al.*, 1967.)

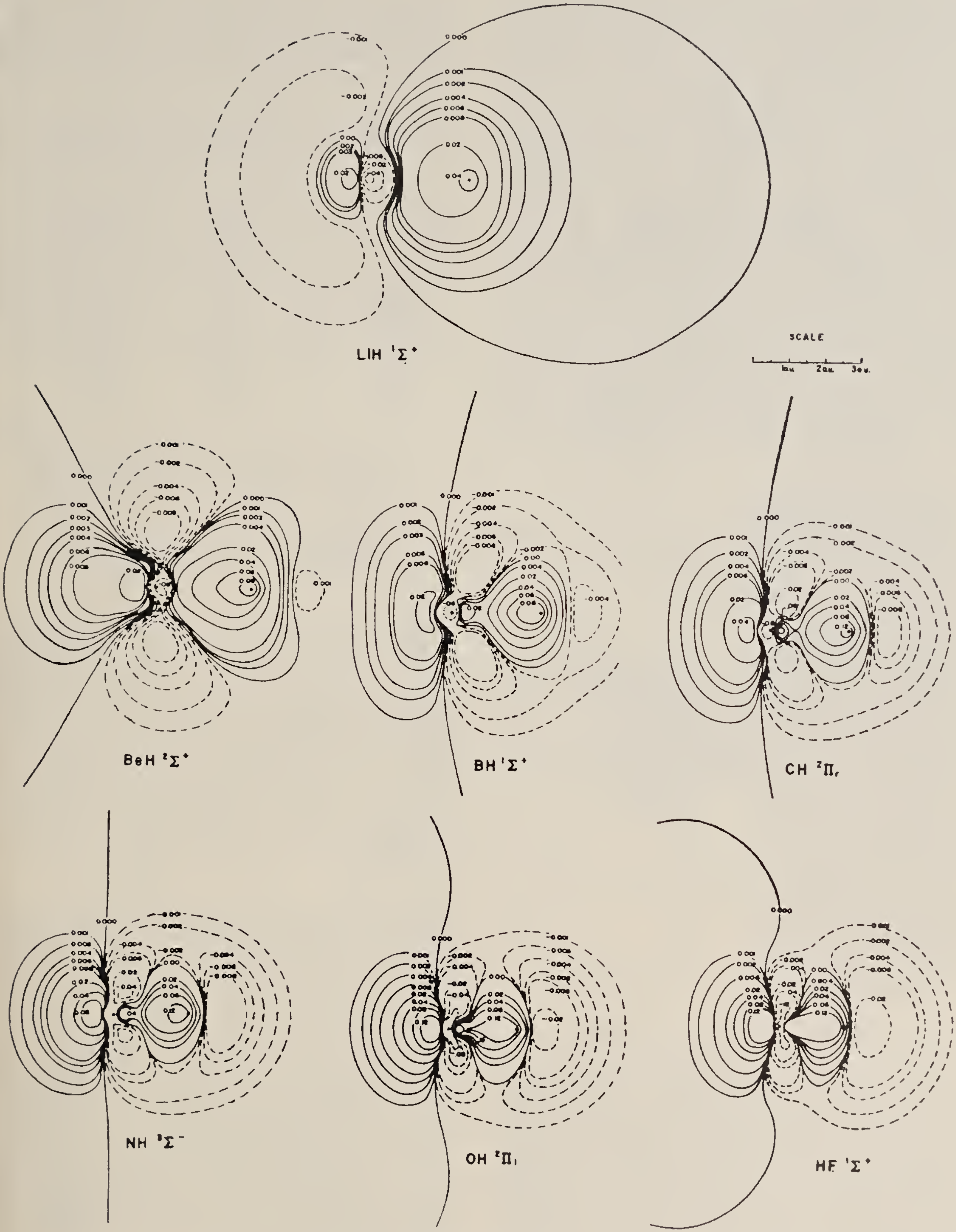


Fig. 3—Contour maps of the electron density difference (molecule—separate atoms) in atomic units for the first-row diatomic hydrides (H on right in each case).

(Reproduced, with permission, from Bader *et al.*, 1967.)

In order to associate different portions of the integrated charge density with different atoms, we must have some agreed scheme of partitioning. One could perhaps imagine surfaces dividing up all space into regions and associating each region with one of the atoms, but this presents difficulties in deciding where to place the partitions. However, instead it has proved more convenient to construct approximations of ψ using sets of functions associated with each of the atoms. We have become accustomed to call these functions atomic orbitals. It is straightforward to dissect the approximate $|\psi^2|$ algebraically in a way that yields occupation numbers for each of the atomic orbitals, and if we add up the occupation numbers for all of the orbitals on a particular nucleus we obtain the electron density for that atom. I do not want to go into details about this analysis, but rather to make two points.

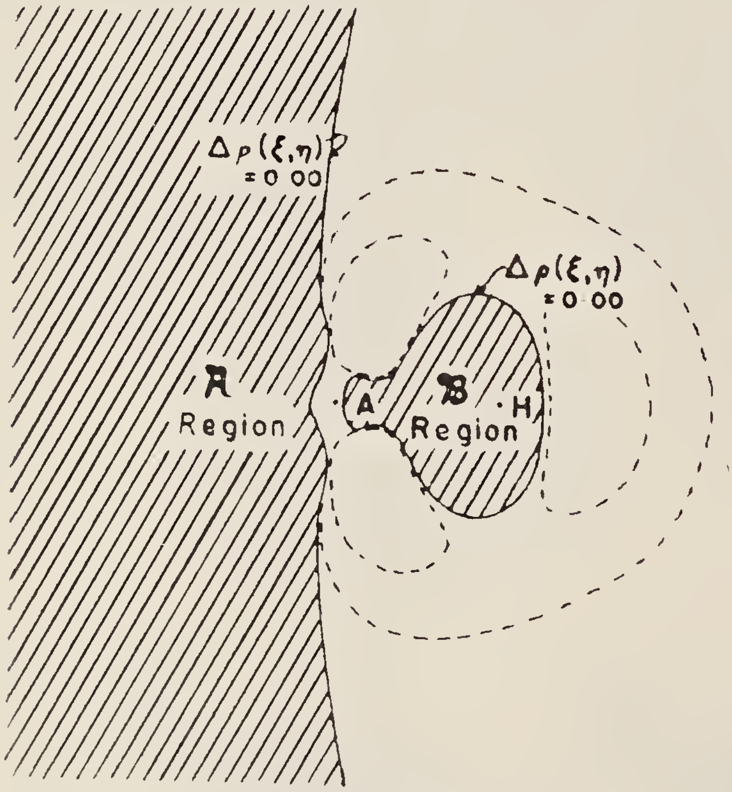


FIG. 4—Definitions of A and B regions.

Firstly, there is wide freedom in choosing the sets of atomic orbital functions used to represent ψ and it is even permissible to go to the extreme of using functions centred on only one of the atomic nuclei. In the latter case one might deduce that all the electrons are on one atom ! The lesson to be learned is that the conclusion that we draw about electron distributions will depend to some extent on the kind of atomic orbitals that we decide to use to build up the molecular eigenfunction. Secondly, if we use only a relatively simple set of atomic orbitals to obtain an approximate ψ the resultant analysis of electron distribution will be affected to some extent because we have not analysed the exact wave function.

*Total Charge Migration in Diatomic Hydrides as Determined by Density Difference Maps**

AH	Charge Increase in Region A	Charge Increase in Region B
LiH ..	0·01	0·55
BeH ..	0·11	0·35
BH ..	0·20	0·16
CH ..	0·20	0·16
NH ..	0·20	0·16
OH ..	0·22	0·19
HF ..	0·24	0·22

* These figures were obtained by numerical integration using a grid of 0·02 a.u. Regions A and B are defined in Figure above.

Reproduced from *J. Chem. Phys.*, 1967, **47**, 3381, Fig. 2 (6) and Table 11.

Let me now give you a survey of what some of the best available current wavefunctions for various small molecules have to say about charge distributions as analysed in terms of molecular orbitals, so that you can compare these with the popular mythology of textbooks. While I am doing this you may be asking how reliable are these wavefunctions, and later in this talk I shall point out some experimental data that can be used to test these wavefunctions.

First let us look at formaldehyde. The calculated electron distribution (Peters, 1963 ; Cook and McWeeny, 1968) is shown in Fig. 5. Notice that the qualitative tends to not agree with popular belief as represented in textbooks because the total carbon charge (—0·14) is more negative than the oxygen charge (—0·12). The overall polarity must be largely laid at the door of the positive net charges on the hydrogens, with an additional contribution from the atomic dipole of the oxygen. The carbonyl polarity is not that normally believed. It is possible that this is an artifact of the particular wavefunction used here, but several other recent approximate wavefunctions for formaldehyde display the same qualitative result.

As a second example (Veillard *et al.*, 1967), let us consider the prototype of the so-called dative bond $BH_3 \leftarrow NH_3$ (Fig. 6). From comparison with analogous calculations on BH_3 and on NH_3 separately, we see an interesting electron drift accompanying the association of the parts, quite different to that deduced by octet rule methods. In particular, the net charge on the boron is virtually unchanged by bond formation and a rather curious alternating drift of electrons, involving the hydrogens attached to boron, has occurred.

Somewhat similar distributions of electrons have been found in other saturated systems (Pople and Gordon, 1967). Thus when a fluorine substituent is introduced into a saturated hydrocarbon (Fig. 7) the immediate effect is to generate a net positive charge on the attached carbon, but the more distant influences seem to alternate in sign, not to fall monotonically! It is possible that a new set of rules for σ-electrons drifts will be called for in place of the beloved inductive shifts of organic chemistry.

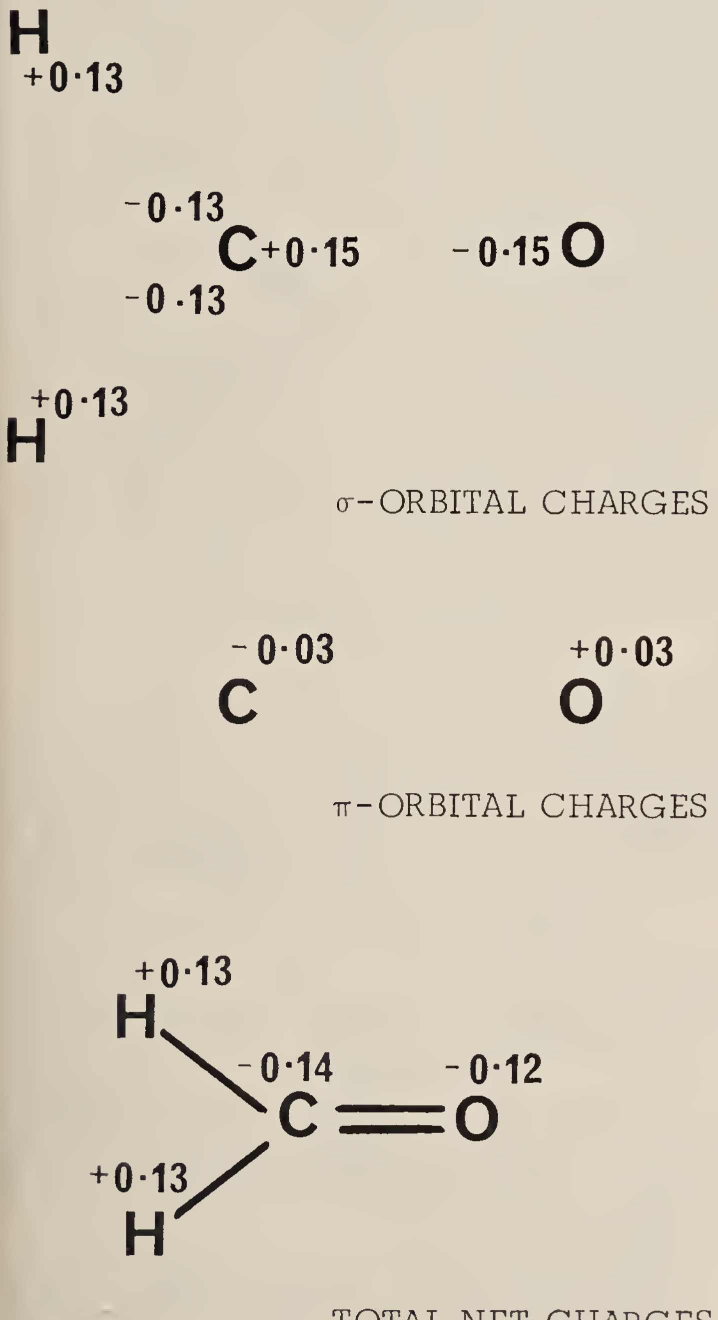


FIG. 5—Charge distribution in formaldehyde (Peters, 1963).

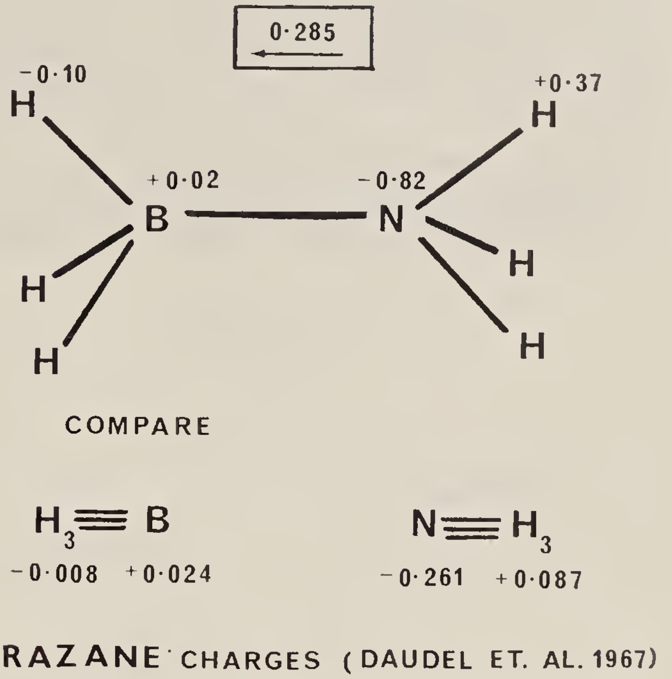
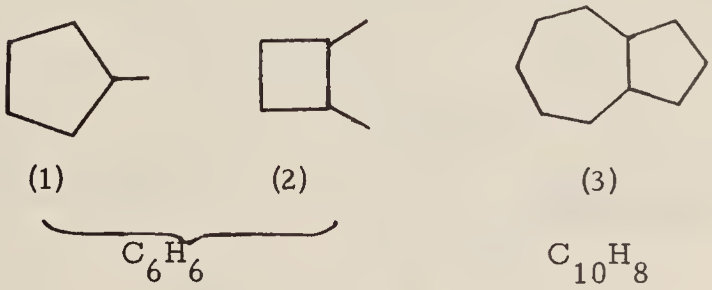


FIG. 6—Charge distribution in borazane (Daudel *et al.*, 1967).

Let me now turn to another example that has been of particular interest to us at Monash: that of non-alternant hydrocarbons. The interest centres largely around three conjugated cyclic hydrocarbons: fulvene (1), dimethylenecyclobutene (2) and azulene (3):



All three hydrocarbons have a substantial dipole moment—of the order of ten times the magnitude of analogous aromatic hydrocarbons. We ask to what should the polarity be attributed.

The initial proposal was that for conjugated hydrocarbons containing odd membered rings—so-called non-alternants—the distribution of π-electrons is non-uniform (Coulson and Rushbrooke, 1940), and this leads to the appreciable polarity. More recently it has been predicted (Brown and Burden, 1966), and then confirmed experimentally (Brown *et al.*, 1967), that dimethylenecyclobutene, though an alternant, should have an uneven distribution of π-electrons and so be polar. In attempting to account in more detail for the polarity, it has been suggested that the σ-electrons also contribute to the polarity, particularly because the hydrogen atoms are appreciably charged. Let us see now what the best available wave functions imply, first with dimethylenecyclobutene (Fig. 8).

Here the implication is that the polarity must be ascribed primarily to π-electrons, the total σ-electron effect being a minor contribution. The agreement of the calculated value with the observed dipole moment is impressive. However, let us next turn to fulvene (Fig. 9). Here the qualitative story is similar to that of dimethylenecyclobutene, but the agreement with the experimental dipole moment data is less satisfactory. Hitherto the value, deduced from measurements in solution on substituted fulvene, was 1·1D. We have been engaged in a precision measurement on fulvene vapour by microwave methods and now find that the dipole moment is 0·44D.

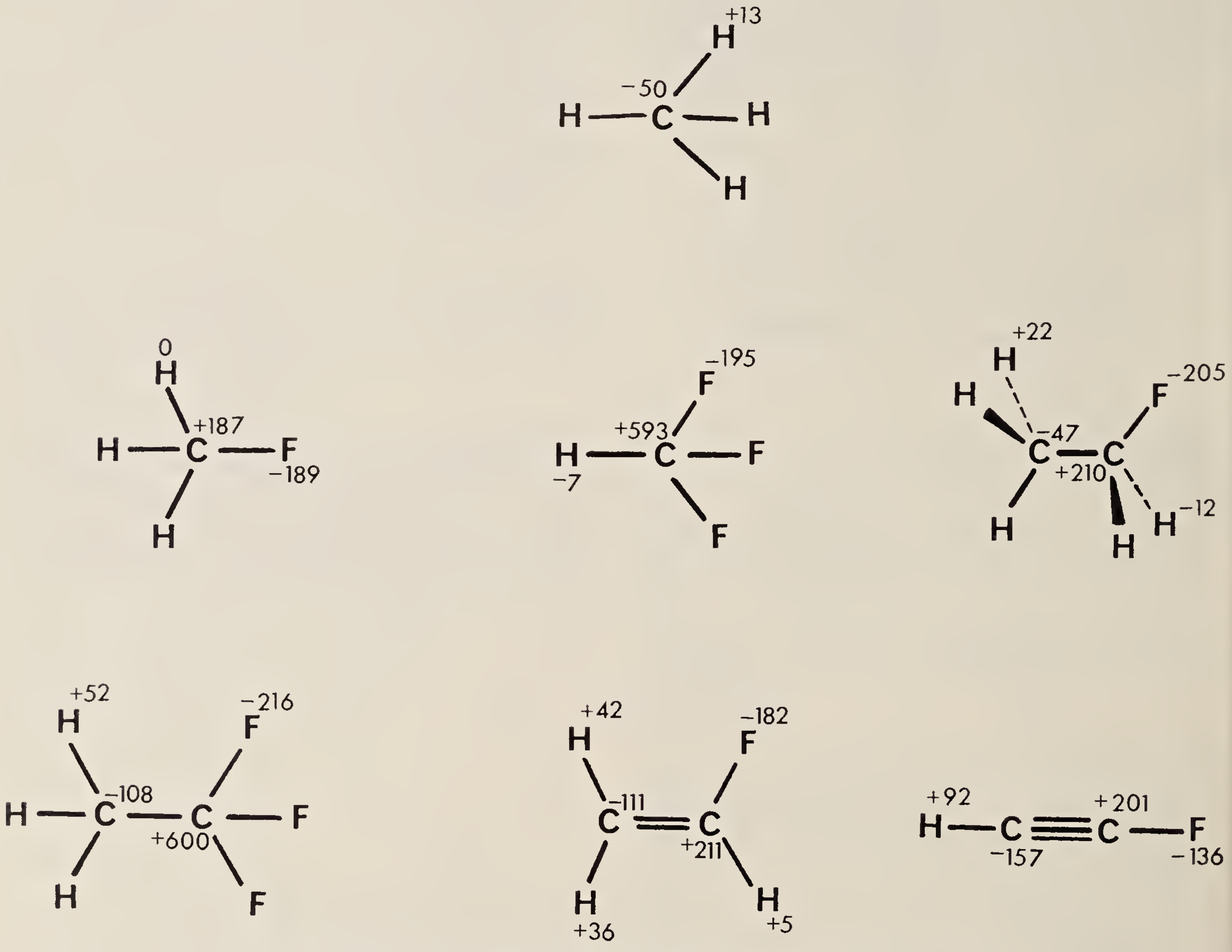


Fig. 7—Charge distribution in fluorocarbons (milliprotonic units).

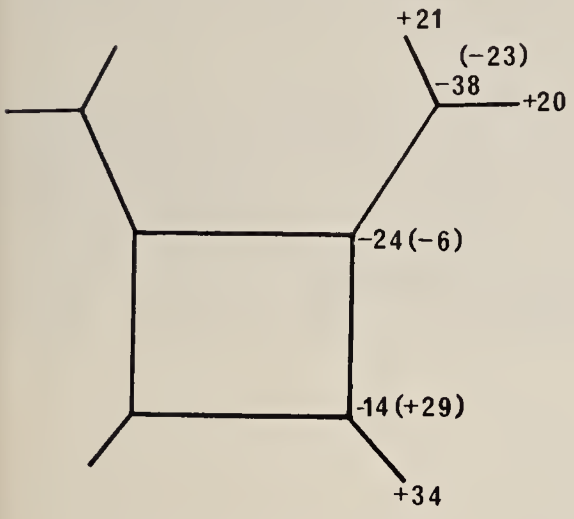
In the case of azulene, the story is still less satisfying. The theoretical computations again imply that the polarity stems essentially from a non-uniform π-electron distribution (Fig. 10) but the theoretical value of the moment is depressingly far from a recent precise experimental value for azulene vapour (Tobler *et al.*, 1965). Thus it is clear that the presently available electronic wavefunctions for molecules like azulene are not all that we would like; but perhaps the qualitative indication of the relative polarity contributions from σ- and π-electrons are sound.

Now let us move on to somewhat more complex systems involving larger atoms. First, a few words about SF_6, PF_5, etc. Textbooks will sometimes describe the bonding as involving sp^3d^2 or sp^3d hybrids on the central atom these hybrids being used to form somewhat polar covalent bonds with the fluorine ligands. Alternatively, a structure involving ionic-covalent resonance among the various ligand positions and only the s and p orbitals on the S (or P), has sometimes been advocated. On close analysis, it proves difficult to decide whether the d-orbitals of the central atom are involved in the bonding because of the variety of functional forms that can be written down as representing a d-orbital. However, if we agree that by orbitals we mean the various functions that are obtained by solving the H-atom problem so that

$$f_{3d}=N.\rho^2 e^{-\rho/3}.Y_{2m}(\theta,\varphi) \qquad (\rho=\zeta r/a)$$

(Y_{2m}: spherical harmonic of order 2)

then the best function that has so far been derived for these molecules (by Dr. Peel) implies (Table 1) that the 3d orbitals are insignificantly occupied in SF_6, PF_5, SF_4, CIF_5, etc.



DIMETHYLENE CYCLOBUTENE net charges (e/1000)
π net charges in parentheses

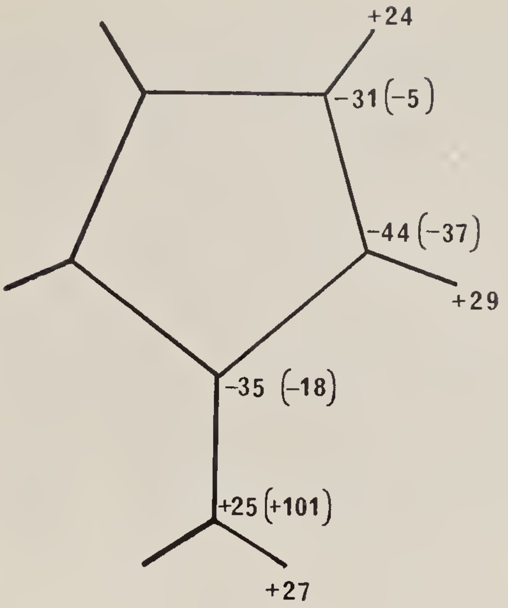
Dipole moment

σ densities	0.254 D	↑
σ hybridization	0.231	↓
π densities	0.607	↓
TOTAL	0.584 D	↓
experiment:	0.61$_8$ D	

FIG. 8—Dimethylenecyclobutene.

TABLE 1
Orbital Occupation Numbers

	PF_5	SF_4	CIF_3
3s ..	1·09	1·53	1·75
3p ..	2·15	2·67	3·80
3d ..	0·13	0·22	0·19



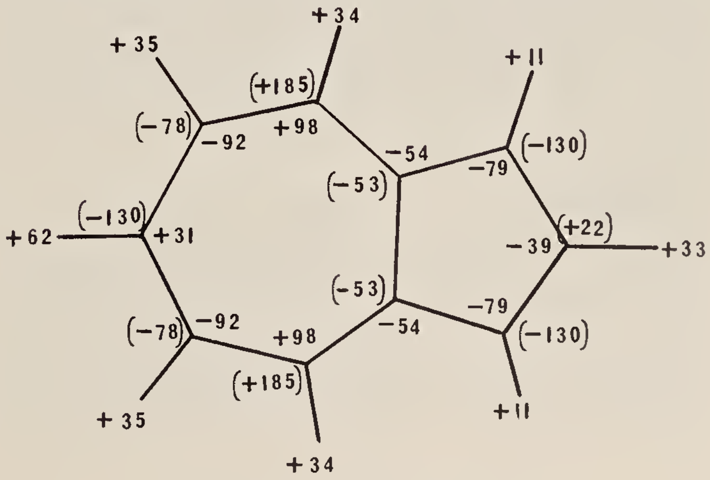
FULVENE net charges (e/1000)
π net charges in parentheses

Dipole Moment

σ densities	0.260 D	↑
σ hybridization	0.086	↓
π densities	1.061	↓
TOTAL	0.887 D	↓
experiment:	0.44 D	

FIG. 9—Fulvene.

Another example involving a transition element atom is the electronic structure of the permanganate ion. In recent years a number of investigations of the electronic structure of tetrahedral anions have been published. The



AZULENE NET CHARGES (e/1000)
π net charges in parentheses

Dipole Moment

σ density	0.809 D	→
σ hybridization	0.589	←
σ total	0.220	→
π density	3.446	←
TOTAL	3.226 D	←
experiment	0.79$_6$ D	

FIG. 10—Azulene.

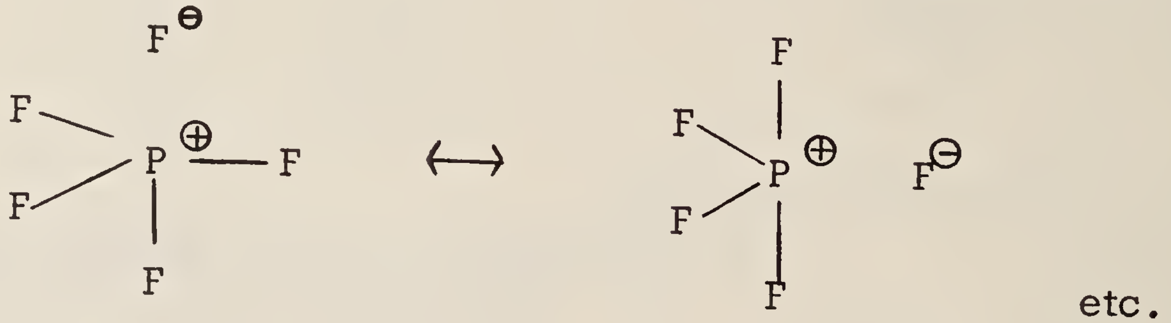
most elaborate of these (Table 2), obtained by Mr. James at Monash, implies that the 4s and 4p orbitals of Mn are but little occupied, the central atom using its 3d orbitals almost exclusively to accommodate valence electrons.

TABLE 2

Orbital Occupation Numbers

	MnO_4^-		CrO_4^{--}	
	MCZDO	CNDO	MCZDO	CNDO
3d	5·70	6·71	5·84	6·56
4s	0·08	0·10	0·04	0·10
4p	0·00	0·02	0·00	0·15

These calculations on systems containing larger atoms are necessarily rather less rigorous than those on smaller systems and it is possible that the picture could be changed somewhat by still more elaborate calculations. However, it seems unlikely that the qualitative description will be noticeably altered. The overall picture that we are left with is one rather different from the classical description in current textbooks.



Returning now to smaller systems, let us consider what kind of experimental tests can usefully be applied to molecular wavefunctions. Because of the widespread use of the variation theorem for computing wavefunctions, a habit of mind has grown of asking what kind of energy expectation value derives from the function ψ.

$$\langle E\rangle=\langle\psi\,|\,\hat{\mathscr{H}}\,|\,\psi\rangle/\langle\psi\,|\,\psi\rangle$$

The more negative $\langle E\rangle$ is the better function ψ is considered to be. However, the energy test depends critically on how well ψ accounts for electron correlation. If we are interested in electron distribution this correlation effect is less important and so functions that give only moderate values of $\langle E\rangle$ can sometimes give a good picture of the overall electron distribution in the molecule. It therefore seems better to apply different tests, namely the following:

$\langle r\rangle=\langle\psi\,|\,\hat{r}\,|\,\psi\rangle/\langle\psi\,|\,\psi\rangle$ derived from dipole moment.

$\langle r^2\rangle$—relative to molecular centre of gravity—derived from molecular g factor and susceptibility.

$\langle 1/r\rangle$—relative to a nucleus with $I\neq 0$—derived from spin rotation constant and chemical shift for a nucleus of non-zero spin.

Etc.

Most of these quantities are particularly taxing to determine experimentally, but values are starting to emerge for a few simple molecules as a result of the efforts of Flygare and his co-workers at Illinois. Values that he has just published for formaldehyde (Hüttner *et al.*, 1968) are shown in Tables 3 and 4. These

TABLE 3

Experimental Mean Values for Electrons in Formaldehyde

$\langle x^2\rangle$ ..	$3·2\pm0·3\times10^{-16}$ cm.^{2}
$\langle y^2\rangle$ ..	$5·2\pm0·3\times10^{-16}$ cm.^{2}
$\langle z^2\rangle$ ..	$11·4\pm0·3\times10^{-16}$ cm.^{2}

TABLE 4

Experimental Values (A.U.) of Various Electronic Properties of Formaldehyde

$q_{zz}(O)$	− 0·703
$q_{yy}(O)$	− 1·687
$r_0 \cos\theta$	19·495
x^2	11·3
y^2	18·7
z^2	40·8
z_O/r^3_O	1·261
z_C/r^3_C	1·262
$q_{\alpha\alpha}(D)$	− 1·446
$q_{\alpha\beta}(D)$	− 0·178
$q_{\beta\beta}(D)$	0·650
α_D/r^3_D	2·059
β_D/r^3_D	0·266
$1/r_H$	6·12

provide a very stringent test of electronic wavefunctions and so far even the best published wavefunctions for formaldehyde show deficiencies. However, further experimental work of this kind and further computational effort on wavefunctions must surely produce a steady increase in our knowledge of how the electrons are distributed in molecules.

Maybe if you are kind enough to invite me again to Sydney some years hence to talk on " Where Are the Electrons ? " I may be able to give you more confident answers such as textbooks now give. At present the honest answer is : " We do not know for sure but we have some suspicions ! "

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(Delivered on 17 July 1968)

Journal and Proceedings, Royal Society of New South Wales, Vol. 102, pp. 83–86, 1969

A Problem in Mine Ventilation

Presidential Address

by

A. Keane

1. The Problem

I am often asked, What does an Applied Mathematician do ? Perhaps there are as many answers to this question as there are applied mathematicians, but a review of a problem which was attacked by a number of us about ten years ago and which is currently being further investigated by an M.Sc. student at Wollongong will give some insight into applied mathematics in action.

Applied mathematics is concerned with deducing solutions of problems in the real world by using abstract mathematical techniques. The most important step involves the specification of a model simple enough to be treated mathematically yet containing sufficient detail to approximate reality. Herein lies the art of applied mathematics.

To illustrate the gradual development of sophistication, a problem on the ventilation of coal mines is examined, starting with the simplest model and progressing through a series of refinements. Ultimately, the complication of the model outstrips known techniques and the interest shifts from the original problem to the justification of the mathematical methods used in its solution.

A mine is ventilated by an exhaust fan which by drawing air out of the return airway causes fresh air to flow into the intake. The air entering the mine flows along the intake to the working face, where it is required to carry away gases and heat. However, most methods of mining either leave a broken porous goaf between the airways or a large number of thirlings or " cut throughs " which subsequently contain stoppings.

Our problem is to determine the effect of leakage through the goaf on the amount of air reaching the working face.

2. The Model

We assume there are two mine roadways, an intake and a return, of similar uniform construction and mathematically parallel. This ensures that the pressure drop will be the same in the intake and return. We will also assume that there is no pressure drop across the working face. Since only the pressure drop is important, it is valid to assume a pressure P_0 at the entrance to the intake, zero at the working face, and $-P_0$ at the fan. Our mine now looks as in Figure 1.

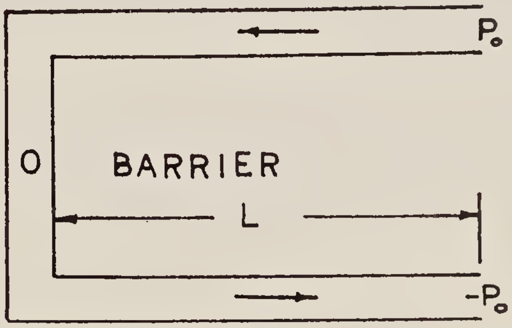

Fig. 1

As for the barrier, we assume at the moment that it is uniformly porous perpendicular to the airways but impervious in a direction parallel to the airways. Thus air will flow in a straight line through the barrier from the intake to the return.

The next specification required for our model is the relation between pressure drop and quantity of air flowing. From studies of fluid flow along pipes it is accepted that for streamlined motion $P=RQ$, while if the motion is fully turbulent $P=RQ^2$. In these relations P is the pressure drop, Q is the quantity of air flowing, and R is a measure of the resistance to flow. Let us assume that in the airways the air flow is fully turbulent, while flow through the goaf is streamlined.

Let R be the total resistance of the intake, so that r is the resistance per unit length and $R=rL$. If g is the conductance of the barrier per unit length of airway, then the total conductance of the barrier is $G=gL$. (Conductance is the inverse of resistance).

In this model we have not only neglected the irregularities of the mine but also the change of air density due to pressure and temperature. The effect of pressure changes is not very important, but temperature changes are large and could be important.

3. Simple Solution of the Model

Now we have a model and can begin to attempt a mathematical solution.

If the quantity of air entering the mine per second is Q_0 and the quantity reaching the face is Q_F, then Q_0-Q_F is lost through the goaf and $\frac{Q_0+Q_F}{2}$ is the average quantity flowing through the airways. Working with averages, the equation for flow in the airways is :

$$P_0=R\left(\frac{Q_0+Q_F}{2}\right)^2$$

and since the average pressure difference between the airways is P_0, the flow through the goaf is given by

$$(Q_0-Q_F)=GP_0.$$

If instead of turbulent flow in the airways we assumed streamlined flow so that

$$P_0=R\left(\frac{Q_0+Q_F}{2}\right)$$

then

$$P_0^2=\frac{R}{2G}(Q_0^2-Q_F^2)$$

and

$$Q_0/Q_F=1+RG.$$

4. A More Sophisticated Solution

The use of averages is not the approach of the applied mathematician. He will set up the equations in terms of the differential calculus, which gives

$$\frac{\mathrm{d}P}{\mathrm{d}l}=rQ^2$$

$$\frac{\mathrm{d}Q}{\mathrm{d}l}=2gP$$

for flow through minute lengths of airway and minute widths of barrier, remembering that the pressure difference between the airways is $2P$.

The solution of these equations gives relations between the pressure and quantity of air at any point of the airways (Peascod and Keane, 1955 ; Keane, 1956). Since $rL=R$ and $gL=G$, we find that

$$P^2=\tfrac{1}{3}\,\frac{R}{G}\,(Q^3-Q_F^3)$$

and

$$\frac{RG}{3}Q_F=\left\{F\left(\frac{1}{2},\frac{1}{6};\frac{7}{6};1\right)-k^{\frac{1}{2}}F\left(\frac{1}{2},\frac{1}{6};\frac{7}{6};k^3\right)\right\}^2$$

where

$$k=Q_F/Q_0,$$

and F is the hypergeometric function.

If the flow in the airways were assumed streamlined, then the equations would reduce to

$$\frac{\mathrm{d}P}{\mathrm{d}l}=rQ \quad \text{and} \quad \frac{\mathrm{d}Q}{\mathrm{d}l}=2gP,$$

which gives the solutions

$$P^2=\frac{R}{2G}(Q^2-Q_F^2)$$

and

$$Q_0=Q_F\cosh 2\sqrt{RG.}$$

These equations show that the use of averages in the previous section underestimates the leakage loss.

5. Improvements to the Model

We should now look closer at the assumptions of our model to see if it can be improved. The square law holds for fully turbulent flow, while the linear law holds for streamlined flow. In the airways it seems reasonable to assume that the flow lies somewhere between these two limits and a more realistic equation would be $P=RQ^n$ where $1\leqslant n\leqslant 2$ (Groden, 1956).

Measurements of pressure and air flow in a mine in the Newcastle district showed that the value of n should be 1·85. This practical study combined with improved computational techniques, formed the content of a Ph.D. thesis and was published in part by the Institute of Mining and Metallurgy (Rose, 1958).

It is usual practice in a mine to keep the intakes in good repair for the transport of men and materials and to let the returns fall into disrepair. This means that the resistances of the intake and return are not equal. If we still retain the assumption that the resistance of an airway is uniform, we can allow for the difference between the intake and return by using the average resistance of the airways (Low, 1956).

Up to this stage our model has assumed that the air leaking through the goaf travels in a direction at right angles to the airways. This in turn means that there is no pressure drop in the goaf in the direction of the airways—which is clearly wrong unless the goaf is impervious in this direction.

Referring to Figure 2, and assuming that flow of air is symmetrical about the x-axis, we can allow for some air motion in the direction of the airways by taking the pressure in the goaf to satisfy the equation

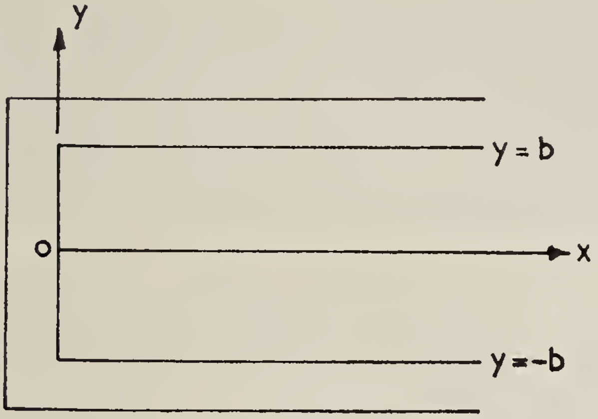

Fig. 2

$$\frac{\partial^2 p}{\partial y^2}+\lambda^2\frac{\partial^2 p}{\partial x^2}=0. \quad \ldots\ldots\ldots\ldots \quad (1)$$

If $\lambda=0$, we return to the previous model, while with $\lambda=1$ there is no preferable direction of motion. The value of λ depends on the particular method of mining.

The mathematical problem now is to solve the partial differential equation (1) subject to the boundary conditions

$$\begin{aligned} P&=(p)_{y=b} \\ \frac{\mathrm{d}Q}{\mathrm{d}x}&=\left(k\frac{\partial p}{\partial y}\right)_{y=b} \quad \ldots\ldots\ldots\ldots \quad (2) \\ \frac{\mathrm{d}P}{\mathrm{d}x}&=rQ^n. \end{aligned}$$

where $2b$ is the thickness of the goaf and $k=2bg$.

6. Solution for Streamlined Flow

When $n=1$ so that $\frac{\mathrm{d}P}{\mathrm{d}x}=rQ$ in the boundary conditions, corresponding to streamlined flow in the airways, there are known techniques for solving the partial differential equation.

Separation of variables leads to the solution as a sum of eigen solutions in the form

$$P(x,y)=\Sigma\frac{\sin\lambda y m_n}{\lambda m_n}A_n\sinh m_n x$$

where m_n are the roots of the equation

$$m\sin\lambda bm=\lambda rk\cos\lambda bm.$$

As an added boundary condition we will assume that no air leaks into the goaf between the mine entrances, so that

$$\frac{\partial p}{\partial y}=P_0/b$$

when $x=L$.

As a special case of the Dini expansion (Watson, 1944, p. 576), we can expand this boundary condition to determine the A_n, and thence the solutions

$$P=\frac{P_0}{b}\Sigma\frac{2rk}{b\lambda^2rk+\sin^2\lambda bm_n}\,\frac{\sin^2\lambda bm_n}{m_n^2}\,\frac{\sinh m_n x}{\sinh m_n L}$$

$$Q_0=\frac{P_0}{b}\Sigma\frac{2k}{b\lambda^2rk+\sin^2\lambda bm_n}\,\frac{\sin^2\lambda bm_n}{m_n}\coth m_n L$$

$$Q_F=\frac{P_0}{b}\Sigma\frac{2k}{b\lambda^2rk+\sin^2\lambda bm_n}\,\frac{\sin\lambda\, bm_n}{m_n}\operatorname{cosech} m_n L$$

7. A General Approximate Solution

For general values of n, a numerical approach will be required to obtain an accurate result. The errors introduced by numerical approximation can be reduced to a suitable level by comparison with the exact solution for $n=1$.

To proceed analytically, we have chosen to use operational techniques, but the approximations that have to be introduced require very careful study to establish their validity.

Writing equation (1) in operational form,

$$\frac{\partial^2 p}{\partial y^2}+\lambda^2D^2p=0,$$

where $D=\frac{\partial}{\partial x}\cdot$

Subject to the condition $p=0$, $y=0$, we obtain

$$p=\frac{\sin\lambda yD}{\lambda D}B(x)$$

or on applying the boundary conditions (2)

$$\begin{aligned} \frac{\mathrm{d}Q}{\mathrm{d}x}&=k\lambda D\cot\lambda bD.P \\ &=2g\lambda bD\cot\lambda bD.P. \end{aligned}$$

If we approximate the cotangent by the first two terms in its Laurent expansion, the resulting differential equation is

$$\frac{\mathrm{d}Q}{\mathrm{d}x}=2g\left(P-\frac{\lambda^2b^2}{3}\frac{\mathrm{d}^2P}{\mathrm{d}x^2}\right)$$

which can be solved simultaneously with the equation

$$\frac{\mathrm{d}P}{\mathrm{d}x}=rQ^n$$

to yield

$$P^2=\frac{1}{n+1}\frac{R}{G}(Q^{n+1}-Q_F{}^{n+1})+\tfrac{1}{3}\lambda^2b^2r^2(Q^{2n}-Q_F{}^{2n})$$

The range of validity of this approximate result must be checked by comparison with the numerical solution of the partial differential equation. The mathematical problem now has interest for its own sake independent of its applicability to the original ventilation problem.

8. Concluding Remarks

All this investigation was undertaken for a very practical reason. A particular mine on the South Coast was deficient in air at the working face, and methods of improving the ventilation were being considered.

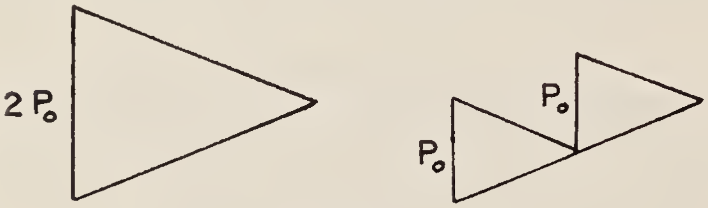

FIG. 3

Neglecting the leakage problem, it was only necessary to double the water gauge of the fan to double the quantity of air at the face, but when leakage was taken into account our theory showed that doubling of fan pressure would only increase the quantity by a few percent. Greater efficiency can be achieved by installing a second (or booster fan) underground. The simple diagrams in Figure 3 show that using an underground fan can maintain the pressure gradient, and hence air flow, while reducing the average pressure difference between intake and return, and thus reduce leakage.

When leakage is included, the correct positioning of the fan leads to minimizing costs, and this was the subject of a further series of papers (Peascod, 1955; Keane and Peascod, 1955, 1956*a*, 1956*b*; McKay, Low and Keane, 1957).

The state of repair of the returns and the high losses through the goaf in the mine we were studying forced the conclusion that the increase of face ventilation desired was impossible, and although costs would be high, the only solution was to sink a ventilating shaft which would eliminate the leakage problem.

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(Delivered on 2 April 1969)

Report of the Council for the Year ended 31st March, 1968

Presented at the Annual General Meeting of the Society held 3rd April, 1968, in accordance with Rule XXVIII(*a*).

At the end of the period under review the composition of the membership was 353 members, 18 associate members and 7 honorary members ; 14 new members were elected. Ten members resigned ; three names were removed from the list of members and one name from the list of associate members under Rule V(*b*). One associate member transferred to full membership.

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

Lord Florey, O.M., F.R.S. and an Honorary Member since 1949.

Mr. Edward W. Esdaile (elected 1908).

Dr. Edward Gordon Manchester (elected 1965).

Mr. Frank R. Morrison (elected 1922).

Dr. Patrick F. D. Murray (elected 1950).

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 the Council wish to express their sincere thanks and appreciation to the ten speakers who contributed to the success of these meetings, the average attendance being 54.

The Annual Social Function was held on 28th March at Science House, Sydney and was attended by 44 members and guests.

The Council has approved the following awards :

The *Clarke Medal* for 1968 to Professor H. G. Andrewartha, D.Sc., F.A.A., Department of Zoology, University of Adelaide.

The Society's Medal for 1967 to Mr. A. F. A. Harper, C.S.I.R.O., National Standards Laboratory, Sydney.

The *Edgeworth David Medal* conjointly to Dr. D. H. Green, Department of Geophysics and Geochemistry, Australian National University and Dr. W. J. Peacock, C.S.I.R.O., Division of Plant Industry, Canberra.

The *Archibald D. Ollé Prize* to Dr. J. R. Conolly, Department of Geology and Geophysics, University of Sydney.

The 34th Clarke Memorial Lecture was delivered by Professor S. W. Carey of the University of Tasmania, on 22nd June. The title of the lecture was " Tectonics of New Guinea ".

The Society has again received a grant from the Government of New South Wales, the amount being $1,500.00. The Government's continued interest in the work of the Society is much appreciated.

The Society's financial statement shows a deficit of $480.23.

The *New England Branch* of the Society held three meetings and the proceedings of the Branch follow.

The President represented the Society at the Commemoration of the Landing of Captain James Cook at Kurnell and attended the Garden Party at Government House.

The President attended the Annual Meeting of the Board of Visitors of the Sydney Observatory.

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

Four parts of the " *Journal and Proceedings* " have been published during the year.

Centenary Volume—Printing of this special publication is in progress.

During the year the Society received a protrait of S. L. Bensusan, Esq., painted by George Lambert, as a gift from the family of the late Mr. Bensusan who was the pioneer of the Silver Mining and Smelting Industry in Australia at Sunny Corner, New South Wales.

Council held 11 ordinary meetings and attendance was as follows : Assoc. Prof. A. H. Low 11 ; Dr. A. A. Day 7 ; Prof. R. J. W. Le Fevre 5 ; Mr. W. H. G. Poggendorff 6 ; Prof. A. H. Voisey 6 ; Mr. J. L. Griffith 10 ; Dr. A. Reichel 7 (absent-on-leave 3) ; Mr. H. F. Conaghan 9 ; Mr. R. A. Burg 6 ; Mr. J. C. Cameron 7 ; Mr. R. J. Griffin 4 ; Mr. T. E. Kitamura 10 ; Dr. D. B. Lindsay 0 ; Mr. J. W. G. Neuhaus 9 ; Mr. J. P. Pollard 8 ; Mr. M. J. Puttock 8 ; Mr. W. H. Robertson 10 ; Mrs. Krysko v. Tryst 10. During Dr. Reichel's absence, Mrs. Krysko has acted as Hon. Editorial Secretary.

The Library—Periodicals were received by exchange from 395 societies and institutions. In addition the amount of $124.83 was expended on the purchase of 11 periodicals. Repairs to the binding of some of the rarer sets of periodicals amounted to $168.00.

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

N.S.W. Govt. Depts.—Dept. of Agriculture, Geological Survey, Electricity Commission, Forestry Commission, Dental Hospital, State Fisheries, Dept. of Public Health, Railways Technical Library, State Office Block Library, M.W.S. & D. Board, W.C. & I. Commission.

Commonwealth Govt. Depts.—Aust. Atomic Energy Commission ; Bureau of Mineral Resources ; C.S.I.R.O. Depts. :—Library, Canberra ; Animal Physiology, Prospect ; Coal Research, Ryde ; Food Preservation, Ryde ; Kimberly Research Station, W.A. ; National Standards Laboratory, Sydney ; Textile Physics, Ryde ; Wild Life Research, Canberra.

Universities and Colleges—University of Adelaide, Waite Agricultural College, Broken Hill University College, Australian National University, University of Sydney, Macquarie University, University of Melbourne, Monash University, University of New England, University of New South Wales, University of Queensland, School of Public Health and Tropical Medicine, University of Tasmania, Townsville University College, University of Western Australia, Wollongong University College.

Companies—A.C.I. Ltd., Aust. Iron & Steel Co. Ltd., A.W.A. Ltd., B.H.P. Co. Ltd., Blue Metal & Gravel Co., Commonwealth Steel Co., C.S.R. Co. Ltd., Head Office ; Davis Gelatine Co., International Engineering, J. Lysaght Ltd., Mt. Isa Mines Ltd., Qantas, Standard Telephones & Cables, Unilever Ltd., Union Carbide Ltd.

Research Institutes—Animal Research Institute, Queensland ; B.H.P. Co. Ltd., Research Laboratories, Shortland ; Bread Research Institute ; C.S.R. Co. Ltd., Research Laboratory ; I.C.I. Research ; Institute of Dental Research ; Royal North Shore Hospital ; Government Chemical Laboratories, Perth ; Chemical Division, D.S.I.R., New Zealand.

Museums—Adelaide Museum ; Australian Museum ; Geological Museum and Library, Melbourne ; New Zealand Institute and Museum.

Miscellaneous—Encyclopedia Britannica ; Institution of Engineers, Aust., Dept. of Primary Industries, Brisbane.

J. L. Griffith.
Hon. Secretary.

3rd April, 1968.

The Honorary Treasurer's Report

The Society this year recorded a deficit of $480.23, as against $2,133.00 for the year 1966–67. Expenditure dropped by $1,018.00, and income showed an increase of $658.00. The drop in expenditure was mainly due to a decrease of $881.00 in the cost of the Journal and to the additional expenditure in 1966–67 of $402.00 on the centenary celebrations. The increase in surplus from the Science House Management Committee accounted for the increase in income.

The Science House Management Committee increased the rents of all tenants as from 1st June, 1967. As a result, the Society's rent for the year increased by $528.00 and its share of the Science House surplus by $661.00.

H. F. Conaghan,
Honorary Treasurer.

Abstract of Proceedings

5th April, 1967

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

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

Reginald William Hodgins, Konrad Heinrich Richard Moelle and Bevan Jon Warris were elected members of the Society.

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

The following awards of the Society were announced :

The Society's Medal for 1966 to Mr. H. A. J. Donegan, M.Sc.

The Clarke Medal for 1967 to Professor S. Smith-White, D.Sc.Agr., F.A.A.

The James Cook Medal for 1966 to Sir William Hudson, K.B.E., F.R.S.

The Edgeworth David Medal for 1966 to Dr. R. I. Tanner.

The Archibald D. Ollé Prize to Dr. R. A. Binns.

Notice of motion was given regarding proposed New Rules and By-Laws.

Office-bearers for 1967–68 were elected as follows :

President : A. H. Low, Ph.D.

Vice-Presidents : A. A. Day, Ph.D. (Cantab.), R. J. W. Le Fevre, D.Sc., F.R.S., F.A.A., W. H. G. Poggendorff, B.Sc.Agr., A. H. Voisey, D.Sc.

Hon. Secretaries : J. L. Griffith, B.A., M.Sc., A. Reichel, Ph.D., M.Sc.

Hon. Treasurer : H. F. Conaghan, M.Sc.

Members of Council : R. A. Burg, A.S.T.C., J. C. Cameron, M.Sc., B.Sc. (Edin.), D.I.C., R. J. Griffin, B.Sc., T. E. Kitamura, B.A., B.Sc.Agr., M. Krysko v. Tryst (Mrs.), B.Sc., Grad.Dip., D. B. Lindsay, B.Sc., M.A., D.Phil. (Oxon.), J. W. G. Neuhaus, M.Sc., J. P. Pollard, Dip.App.Chem. (Swinburne), M. J. Puttock, B.Sc.(Eng.), A.Inst.P., W. H. Robertson, B.Sc.

Messrs. Horley & Horley were re-elected Auditors to the Society for 1967–68.

The retiring President, Professor A. H. Voisey, delivered his Presidential Address, entitled " Geological Techniques ".

The following papers were read by title only :

" Petrology and Origin of the Cocoparra Group, Upper Devonian, New South Wales ", by J. R. Conolly.

" Autocondensation of Urea at 105–110° C.", by E. V. Lassak.

" Middle Devonian Conodonts from the Moore Creek Limestone, Northern New South Wales ", by G. M. Philip.

" Cyclic Sedimentation in the Carboniferous Continental Facies, New South Wales ", by J. H. Rattigan.

" A Note on Convex Contributions ", by J. L. Griffith.

At the conclusion of the Presidential Address the retiring President welcomed Dr. A. H. Low to the Presidential Chair.

3rd May, 1967

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

The President, Dr. A. H. Low, was in the chair. There were present 40 members and visitors.

Boyd Thomas Pratt, Lawrence Sherwin, Stanley Arthur South, Don Gregory Thompson and Philip Damien Tilley were elected members of the Society.

Motion. The Honorary Secretary moved that

> " The Society adopt the New Rules and By-Laws as circulated to members together with the addition of By-Law 5 (*g*).
>
> The ballot for the election of the Council shall take place at the Annual General Meeting. However, any member may make a postal vote if desired."

(This By-Law has been agreed to by Council but was inadvertently omitted from the typescript of the proposed By-Laws.)

A paper entitled " Cambro-Ordovician Sediments from the North-eastern Margin of the Frome Embayment (Mt. Arrowsmith, N.S.W.) ", by H. Wopfner, was read by title only.

Symposium. " The Problem of Transition from School to University Mathematics." The speakers were : Associate Professor W. B. Smith-White—" A Comparison of Schools and University Mathematics and of the Customary Methods in Teaching " ; Mr. J. L. Griffith—" Literary Content of Mathematics " ; Mr. M. G. Greening—" Some Attempts at Alleviating the Problem ".

7th June, 1967

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

The President, Associate Professor A. H. Low, was in the chair. There were present 36 members and visitors.

The motion regarding New Rules and By-Laws carried at the May General Monthly Meeting was confirmed. The motion read : " That the Society adopt the New Rules and By-Laws as circulated to members together with the addition of By-Law 5 (*g*). The ballot for the election of the Council shall take place at the Annual General Meeting. However, any member may make a postal vote if desired."

A paper entitled " Minor Planets Observed at Sydney Observatory During 1966 ", by W. H. Robertson, was read by title only.

An address entitled " Chromosomes and Evolution of the Australian Desert Flora " was delivered by Professor S. Smith-White, F.A.A., of the School of Biological Sciences, University of Sydney.

5th July, 1967

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

The President, Associate Professor A. H. Low, was in the chair. There were present 160 members and visitors.

The following papers were read by title only: "Abiogenesis Leading to Biopoesis", by K. Bahadur and I. Saxena; " Aquifer Water Resistivity—Salinity Relations ", by D. W. Emerson; " The Stratigraphy of the Putty-Upper Colo Area, Sydney Basin, N.S.W.", by M. C. Galloway; " Occultations Observed at Sydney Observatory During 1966 ", by K. P. Sims.

An address entitled " The Moon " was delivered by Mr. W. H. Robertson of Sydney Observatory.

2nd August, 1967

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

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

David Francis Branagan, Marcelle Gordon Ivy Pearce and Christopher John Lascelles Wilson were elected members of the Society.

An address entitled " Yacht Trials in Miniature " was delivered by Mr. R. F. Halliday, B.A., B.E., A.M.I.E.Aust., A.M.R.I.N.A., Senior Lecturer in Mechanical Engineering, in charge of the Hydrodynamics Laboratory at the University of Sydney.

6th September, 1967

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

The President, Associate Professor A. H. Low, was in the chair. There were present 11 members and visitors.

An address entitled " Programmed Instruction at the Tertiary Level " was delivered by Dr. D. V. Connor, Educational Research Unit, The University of New South Wales, Kensington.

4th October, 1967

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

The President, Associate Professor A. H. Low, was in the chair. There were present 20 members and visitors.

Carl Chiarella, Brian Keith Hall and Laurence Frederick Moore were elected members of the Society.

An address entitled " Urban Developments—Some Aspects of Environmental Engineering " was delivered by Professor N. Y. Kirov, Department of Fuel Technology, The University of New South Wales, Kensington.

1st November, 1967

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

The President, Associate Professor A. H. Low, was in the chair. There were present 54 members and visitors.

An address entitled " New Aspects of Solar Flares " was delivered by Mr. G. E. Moreton, C.S.I.R.O., Division of Physics, Sydney.

6th December, 1967

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

The President, Associate Professor A. H. Low, was in the chair. There were present 54 members and visitors.

A paper entitled " Precise Observations of Minor Planets at Sydney Observatory During 1965 and 1966 ", by W. H. Robertson, was read by title only.

An address entitled " Drugs—the Servants of Healers, the Masters of Abusers " was delivered by Dr. Stella Dalton of Parramatta Psychiatric Centre.

THE ROYAL SOCIETY OF NEW SOUTH WALES

BALANCE SHEET AS AT 29th FEBRUARY, 1968

LIABILITIES

1967 $		$	$
—	Accrued Expenses		38.00
92	Subscriptions Paid in Advance		45.75
141	Life Members' Subscriptions—Amount carried forward		128.10
	Trust Funds (detailed below)—		
4,270	Clarke Memorial	4,268.29	
2,426	Walter Burfitt Prize	2,527.61	
1,425	Liversidge Bequest	1,496.52	
581	Ollé Bequest	605.76	
			8,898.18
—	Centenary Volume—Amount held in Reserve		4,000.00
57,870	Accumulated Funds		57,287.31
7,520	Library Reserve Account		8,424.87
	Contingent Liability (in connection with Perpetual Lease)		
$74,325			$78,822.21

ASSETS

1967 $		$	$
1,765	Cash at Bank and in Hand		6,306.31
	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
518	Fixed Deposit—Long Service Leave Fund		541.06
	Debtors for Subscriptions	199.89	
	Less: Reserve for Bad Debts	199.89	
—			—
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
1,667	Furniture and Office Equipment—At Cost, *less* Depreciation		1,600.75
23	Pictures—At Cost, *less* Depreciation		21.66
2	Lantern—At Cost, *less* Depreciation		2.00
$74,325			$78,822.21

TRUST FUNDS

	Clarke Memorial $	Walter Burfitt Prize $	Liversidge Bequest $	Ollé Bequest $
Capital at 29th February, 1968	3,600.00	2,000.00	1,400.00	—
Revenue—				
Balance at 28th February, 1967 ..	670.32	426.43	25.04	581.26
Income for the Year	182.34	101.18	71.48	84.50
	852.66	527.61	96.52	665.76
Less : Expenditure	184.37	—	—	60.00
	$668.29	$527.61	$96.52	$605.76

ACCUMULATED FUNDS

	$	$
Balance at 28th February, 1967		57,870.28
Less :		
Increase in Reserve for Bad Debts ..	67.04	
Subscriptions Written Off	34.65	
Subscriptions Waived..	1.05	
Deficit for the Year	480.23	
		582.97
		$57,287.31

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 29th February, 1968, 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.
25th March, 1968.

(Signed) H F CONAGHAN,
Hon. Treasurer.
A. H. LOW,
President.

INCOME AND EXPENDITURE ACCOUNT

1st MARCH, 1967, TO 29th FEBRUARY, 1968

1967 $				$
35	Advertising			50.87
50	Annual Social			58.35
76	Audit			80.00
50	Branches of the Society			50.00
402	Centenary Celebrations			—
328	Cleaning			312.00
89	Depreciation			85.39
75	Electricity			72.34
10	Entertainment			17.70
75	Insurance			83.29
30	Legal Expenses			—
438	Library Purchases			295.31
450	Miscellaneous			448.78
318	Postages and Telegrams			298.92
	Printing—Journal—			
	Vol. 100, Parts 2–4	$2,796.61		
	Reprints	355.76		
	Postages	133.61		
			3,285.98	
	Less :			
	Sale of Reprints	725.28		
	Subscriptions to Journal	704.60		
	Sale of Back Numbers	34.50		
	Refund Postages	30.65		
			1,495.03	
2,671				1,790.95
24	Printing—General			188.59
2,454	Rent—Science House Management			2,982.75
15	Repairs			4.70
3,330	Salaries			3,094.18
87	Telephone			81.70
$11,007				$9,995.82

1967 $		$
1,949	Membership Subscriptions	1,972.65
13	Proportion of Life Members' Subscriptions	12.60
1,500	Government Subsidy	1,500.00
4,876	Science House Management—Share of Surplus	5,536.97
526	Interest on General Investments	489.67
10	Donations	3.70
2,133	Deficit for the Year	480.23
$11,007		$9,995.82

Section of Geology

Abstract of Proceedings, 1967

Four meetings were held during the year, the average attendance being about 13 members and visitors.

MARCH 17th (Annual Meeting) :

(1) Election of Office-bearers—Chairman : Mr. G. S. Gibbons ; Hon. Secretary : Mrs. M. Krysko von Tryst.

(2) Notes and Exhibits accompanied by short addresses.

(i) *Dr. H. G. Golding* delivered a short address titled " The Pseudophite Problem ". Pseudophite is an old term for compact chlorite rock of restricted occurrence associated with some serpentinites. It is excavated for ornamental stone and has been termed " precious serpentine ". European and N.S.W. occurrences were mentioned. Examples collected and studied by Dr. Golding from the Nundle and Coolac districts, N.S.W., were exhibited. The Coolac pseudophites formed by alumina metasomatism of serpentinites consisting of mixtures of chrysotile and lizardite. The metasomatism accompanied the release of alumina from chromite when the latter was oxidized during the general period of serpentinization of the Coolac-Goobarragandra ultramafic complex. During oxidation of the chromite the sequence Fe^{3+}, Fe^{2+}, Cr^{3+}, Mg^{2+}, Al^{3+} is one of increasing mobility of cations (increased tendency for total expulsion from the chromite system) from left to right, under the predominating conditions which operated. The Coolac pseudophites are accompanied by oxidized chromite. The apparent absence of chromite from one of the Nundle occurrences may indicate its removal by erosion or excavation. Alternatively some pseudophites form in other ways.

(ii) *Mr. L. Hamilton* exhibited a specimen of breccia from Minchinbury Quarry which contained a deformed and drawn-out argillaceous sandstone fragment. It was suggested that the sandstone had become plastic because of a weakening of its matrix. He then exhibited a photograph of an outcrop at Minchinbury showing deformed sediments at the margin of the breccia. These can be seen to be part of the wall rock formation. Mr. R. Helby has examined spores in coal from the deformed sediments and found them to represent a Triassic age. This confirms the proposition that the deformed sediments at the margin of the breccia are locally derived.

(iii) *Mr. G. S. Gibbons* exhibited a hollow joint block composed of goethite and found near Dubbo, N.S.W. Until cracked open it had appeared quite massive and impervious. The 20% shrinkage indicated by the cavity corresponds to that which would occur if a " clay ironstone " rock (composed essentially of siderite) were oxidized to limonite with removal of soluble products, followed by crystallization of the oxide, from the wall inwards, to form an impervious goethite shell.

(iv) *Dr. L. E. Koch* showed colour slides of outstanding exhibits of mineralogical and palaeontological objects made in the British Museum and other famous museums in Paris, Brussels, Vienna, Bonn and Florence.

MAY 19th : Address by Dr. I. M. Threadgold, "Taaffeite and Related Minerals Hoegbomite and Nigerite ".

Dr. I. M. Threadgold discussed the problems in determining the atomic structure of the minerals hoegbomite and taaffeite especially with respect to the variable size of the supercell. The discussion was illustrated with original single crystal X-ray patterns and diagrams. The possible stacking arrangements of oxygen patterns were illustrated with transparent overlays.

JULY 21st :

(1) *Mr. E. Lassak* exhibited limonitic stalactites from the roof of a cave in sandstone at Cataract Waterfall near Lawson. They show a lamellar internal structure which is preserved on leaching with dilute hydrochloric acid. The acid-insoluble matter is common opal.

(2) *Dr. H. G. Golding*, " Some Problems of the Coolac Chromitites." The chromitites in question occur as scattered lenses and pods within harzburgite and serpentinite along 30 miles of the Coolac Belt. Relict primary textures in the deformed chromitites are similar to those in Stillwater chromitites except that textural units are larger, euhedra are rare, and nodules are characteristic. Chromite compositions, however, differ notably from those of Stillwater chromites. The $Cr_2O_3 : Al_2O_3$ weight per cent. ratio of the Coolac chromites varies from 62 : 6 to 34 : 34 in different lenses and the cell size varies sympathetically. A bimodal frequency distribution of the chromitites, with respect to the Cr_2O_3 content of the chromite, with major and secondary maxima at 57% and 37% of Cr_2O_3, is indicated. The Cr-rich chromite is associated with olivine and the Al-rich chromite with diopside. The former occurs in chromitites throughout the Belt, but chromitites containing Al-rich chromite are interspersed with them in the north, where harzburgite abuts feldspathic and diopside-rich rocks.

The precipitation of chromite in magma domains of contrasted composition, and chromite segregation at two levels within an abyssal mafic complex, is suggested. The mafic magma may have been a partial melt from pyrolite, the refractory residuum of which corresponds to the harzburgite. During re-intrusion and re-emplacement of mafics and harzburgite to higher crustal levels, disrupted chromitite slabs sank into the harzburgitic mush prior to entrainment and upward rafting as autholiths within the mush. Mush re-emplacement doming might be invoked to account for the regional chromitite-country rock relations.

The address was illustrated with transparencies.

NOVEMBER 17th : Address by Dr. A. N. Carter, " Some Aspects of Cainozoic Geology of Europe and North America ".

Dr. Carter's lecture consisted of three parts :

(*a*) Problems of the base of the Tertiary in Europe.

(*b*) General remarks on other parts of the Tertiary sequence in Europe.

(*c*) Features of the marine Tertiary rocks of California which contrast with those of southern Australia.

The stratigraphy of the type area of the Danian Stage at Højerup and Fakse in Denmark were discussed, with illustrations of stratigraphical sections showing the disconformities which have confused the zonal evaluation of the Danian. The scene was then shifted to Maastricht in Holland, where the stratigraphical type section of the Maastrichtian Stage was illustrated, and also the equivalents of the Danian overlying the type Maastrichtian.

Illustrations of other type localities of Tertiary Stages, with brief discussions of each.

The strongly deformed marine Tertiary rocks of California were contrasted with the still-horizontal miogeosynclinal marine Tertiary sediments of southern Australia. Certain features were illustrated : folded sequences, unconformities, structural domes, oil fields and oil seeps.

Annual Report of the New England Branch of the Royal Society of New South Wales for 1967

Officers :

Chairman : R. L. Stanton.

Secretary-Treasurer : D. B. Lindsay.

Committee : J. H. Priestley, D. H. Fayle, R. H. Stokes, N. T. M. Yeates, J. V. Evans, N. H. Fletcher.

Branch Representative on Council : D. B. Lindsay.

Meetings were held as follows :

27th June : Professor R. L. F. Boyd, " British Space Research ".

19th September : Sir William Hudson, " Development of Natural Resources in Australia ".

11th October : Professor P. M. Sheppard, " Recent Evolution in Pests and Parasites ".

Financial Statement

	$
Balance at University of New England Branch C.B.C., Sydney, at June, 1967	258.28
Credit :	
Remittance from Royal Society of N.S.W., 1967	50.00
Interest to 30th June, 1967	5.04
Interest to 30th December, 1967 . .	5.15
	318.47
Debit :	
Expenses of Professor Boyd's Visit . .	18.49
Expenses of Sir William Hudson's Visit	57.90
Honorarium to Miss P. Clark for Secretarial Assistance	6.00
Balance, *April, 1968* . .	$236.08

D. B. LINDSAY,
Secretary-Treasurer.

Obituaries

1967-1968

Lord Howard Walter Florey, who died on 22nd February, 1968, was born in Adelaide on 24th September, 1898. He was educated at St. Peter's College and at the University of Adelaide, and later at Oxford and Cambridge. He was Rhodes Scholar for South Australia, 1921; Rockefeller Travelling Fellow in the United States, 1925; Huddersfield Lecturer in Special Pathology, Cambridge, from 1927; Joseph Hunter Professor of Pathology, University of Sheffield, 1931–35; Professor of Pathology and Head of the Pathology School, Oxford, 1935–62; and Provost of Queen's College, Oxford, from 1962.

Lord Florey received many scientific and academic honours, both British and foreign. He was Nuffield Visiting Professor to Australia and New Zealand, 1944; the first Australian President of the Royal Society, 1960–65; Nobel Prize Winner for Physiology and Medicine, 1945 (shared with E. Chain and A. Fleming). In 1941 he was elected a Fellow of the Royal Society, Knighted in 1944, and created a Life Peer in 1965.

Florey's best known work was on penicillin; its great therapeutic qualities remained unknown until experiments were conducted at Oxford by Florey and Chain.

During the Second World War he worked at Oxford with Keith Hancock, Mark Oliphant and Raymond Firth in formulating the concept of an Australian National University as a centre for post-graduate research. In 1944 he proposed the idea of the John Curtin School for Medical Research and was Chancellor of the University in 1965.

Lord Florey was elected an Honorary Member of the Society in 1949.

Edward William Esdaile, who died on 2nd October, 1967, was born in England on 26th November, 1882, and arrived in Australia in August, 1883, by sailing ship. He was educated at Fort Street School, and on leaving was apprenticed to the business of scientific and optical instrument makers which his father had established at 54 Hunter Street, Sydney, and he remained with the firm until his retirement in 1960.

Mr. Esdaile was a member of the British Astronomical Association, and took a great interest in designing and manufacturing telescopes and microscopes. He was well known at Sydney Observatory and later at the Belfield Amateur Astronomical Society.

He is survived by his widow and six of his seven children. Two of his sons now carry on the firm, which is situated at Glebe in larger premises.

Mr. Esdaile had been a member of the Society for many years, having been elected to membership in 1908.

Edward Gordon Haig Manchester was born on 2nd June, 1925, at Sydney, and was educated at The Hutchins School, Hobart, and Wesley, Melbourne. He graduated M.B., B.S., University of Sydney, in 1948.

Following graduation, Dr. Manchester was Junior Resident Medical Officer at Royal Prince Alfred Hospital, Sydney, until 1950, when he joined the R.A.A.M.C. He served as Medical Officer at B.C. of General Hospital, Japan, and in 1951 with the Field Ambulance Section, Korea. On his return to Australia he was O.C. 3 Camp Hospital.

In 1953 Dr. Manchester was Radiology Registrar, Royal Prince Alfred Hospital, Sydney, and in 1955 Assistant Radiologist, qualifying M.C.R.A. During 1956–58 he was an Assistant Radiologist in private practice, and was Honorary Radiologist at Crown Street, Western Suburbs and Sydney Hospitals. In 1959 he was Radiologist, Cerebral Surgery and Research Unit at Callan Park, and during 1960–62 was Director of Radiology, Launceston General Hospital, Tasmania.

Returning to Australia in 1963, Dr. Manchester was Medical Officer at the Australian Atomic Energy Commission, Lucas Heights, and from 1964 to the time of his death on 24th September, 1967, he was Assistant Director, Radiology Department, Sydney Hospital.

Dr. Manchester was elected to membership of the Society in 1965, and although his term of membership was a short one, he gave valuable assistance regarding assessments of the medical books in the library.

He is survived by Mrs. Rosemary Manchester and four small children.

Frank Richard Morrison, a member of the Society since 1922, died on 2nd October, 1967. He was a member of Council, 1942–1951, holding the position of Honorary Secretary, 1946 and 1947, and that of Vice-President, 1948, 1949 and 1951. Mr. Morrison was elected President in 1950 and in 1958 he was awarded the Society's Medal in recognition of his distinguished contributions to the science of chemistry and to services to the Society.

He received his scientific training at the Sydney Technical College, and joined the scientific staff of the Museum of Applied Arts and Sciences (then known as the Sydney Technological Museum) in 1916, entering the laboratory of H. G. Smith.

After his return from service abroad with the Australian Military Forces in the First World War, Mr. Morrison was joined in 1919 by Mr. A. R. Penfold, with whom he collaborated in their now famous researches on the chemistry of the Australian essential oil flora, continuing and expanding the labours of Baker and Smith. Thirty-four papers, either as sole author or with Penfold as co-author, were published in the Society's " Journal and Proceedings ". Probably the most significant contribution in this work was the " physiological form " concept, which demonstrated the frequency with which plant species may exist in chemically divergent forms, morphological constancy being preserved. The discovery of these chemically variable species has led to a great interest in this problem, and many chemists, geneticists and taxonomists are still working out its implications.

His Presidential Address, entitled " The Science Museum—Its Duties and Its Dues ", indicated his interest in science museum administration, and in 1952 he represented the museums of Australia as a UNESCO Fellow at the International Seminar on " The Role of Museums in Education ", held in New York.

He held the post of Director of the Museum of Applied Arts and Sciences from 1956 until his retirement in 1960.

He is survived by Mrs. Beryl Morrison and an only child, the Reverend Alexander Morrison.

Patrick Desmond Fitzgerald Murray was born at Dorchester, England, on 18th June, 1900, and died on 17th May, 1967. He was educated at St. Ignatius' College (Riverview) ; University of Sydney, graduating B.Sc. in 1922 ; University of Oxford, postgraduate B.Sc., 1924 ; University of Sydney, D.Sc., 1926 ; and was Demonstrator and Lecturer, 1926–29. Other appointments included Reader in Biology, St. Bartholomew's Hospital Medical School, University of London, 1939–49 ; Challis Professor of Zoology, University of Sydney, 1949–60 ; Reader in Zoology, University of New England, 1960–66 ; and Honorary Research Fellow, University of New England, 1966–67.

Dr. Murray received several honours, including John Coutts Scholarship, University Medal, Linnean Macleay Fellowship (University of Sydney) ; Rockefeller Fellowship (Universities of Freiburg and Cambridge) ; Royal Society Smithson Research Fellowship (Strangeways Laboratory) ; Hon.M.A. (Cantab.). In 1954 he was elected a Fellow of the Australian Academy of Science

His chief research interest was experimental embryology. His first publications (with J. S. Huxley) on this topic appeared in 1925. Much of his work dealt with the development of bone and cartilage.

Dr. Murray's deep understanding and his scholarly approach to problems in general biology are shown in the textbook *Biology*, published in 1950.

Dr. Murray was elected to membership of the Society in 1950, during which period of membership he gave valuable service to the Society, particularly as the representative of the New England Branch, serving on the Council of the Society.

Medallists, 1967-68

Citations

Clarke Medal for 1968

Professor H. G. Andrewartha

Professor H. G. Andrewartha, Professor of Zoology in the University of Adelaide, is a distinguished ecologist. His main contribution has been in developing a general theory of what determines the distribution and the abundance of animals. Much of his work has been done with three native Australian insects: the thrips, the Australian plague locust, and the Australian plague grasshopper. His studies of these insects have not only been of major importance from a theoretical point of view, but have also been important in any application of appropriate measures to reduce their deprecation as pests. Professor Andrewartha is the author of two books and many publications in these fields. He has also written numerous review articles on population biology.

In addition to this, Professor Andrewartha has made some distinguished contributions to the field of ecological physiology, notably his work on insect diapause and on the water relations of insects in dry places. He has, therefore, made a very nice tie-up between physiological studies and population studies based on Australian animals. He must be ranked as one of the outstanding living ecologists. His international reputation is high and his general advice and judgment on ecological issues are widely sought.

The Edgeworth David Medal for 1967

The Edgeworth David Medal for 1967 conjointly to Dr. D. H. Green, Department of Geophysics and Geochemistry, Australian National University, and Dr. W. J. Peacock, C.S.I.R.O., Division of Plant Industry, Canberra.

Dr. D. H. Green

David Headley Green gained the Master of Science degree from the University of Tasmania and the degree of Doctor of Philosophy from the University of Cambridge.

During the very short space of seven years, mostly since his appointment as a Research Fellow in the Research School of Physical Sciences at the Australian National University, he has produced a most impressive series of publications dealing with mineralogy, petrology and geochemistry. These form an outstanding contribution not only to the chemistry of basic and ultrabasic rocks and their magmas, but also to controlled speculation on the physics and chemistry of the mantle and crust and of the relation of these to one another and to orogeny.

The techniques of study used were the most modern. High temperature and pressure experiment and electron probe analysis were combined with a thorough, critical and thoughtful reading and interpretation of the literature. Most of the work was carried out in Australia, even though Dr. Green did take his higher degree at Cambridge.

Dr. W. J. Peacock

Dr. Peacock graduated B.Sc. with First-class Honours in Botany in 1957, before he had reached twenty years of age. During his work for his Ph.D., Dr. Peacock held first a C.S.I.R.O. graduate studentship and was then Macleay Fellow of the Linnean Society.

Early in 1963 Dr. Peacock was awarded a C.S.I.R.O. Overseas Post-doctoral Fellowship, and he used this to work in the University of Oregon with Professor E. Novitsky. After the expiry of the Fellowship he was appointed by the University of Oregon to a Visiting Associate Professorship, which he held for one year, but could have held longer. However, he chose to return to Australia and was given a position in C.S.I.R.O. Division of Plant Industry with the rank of Senior Research Scientist, although he was then only twenty-seven years of age. He remains in this position at the present time.

Dr. Peacock's contributions to biological science can be classified under three headings:

(1) Cytology and related studies of groups of Australian flora.

(2) Studies on the nature of crossing-over and on chromosome structure.

(3) Studies on Meotic Drive.

Dr. Peacock has achieved a world reputation in all three fields. He has been invited to international conferences as guest speaker (for example, Brazil, 1965) and he was responsible, whilst at Oak Ridge, for the initiation of an international conference on Genetic Recombination. This conference is to be held in Canberra in August, 1968. It may be said that in the field of study of genetic recombination he has helped put Australia on the world map.

The Society's Medal for 1967

Arthur Frederick Alan Harper, M.Sc., F.Inst.P., F.A.I.P.

Alan Harper, a Senior Principal Research Scientist in the Division of Physics, National Standards Laboratory, C.S.I.R.O., has been a member of the Society since 1936, served on Council 1955–63, 1966, and was elected President in 1959. He has always been a strong supporter of the Society, and he was a member of the special committee which recently completed the redrafting of the Society's Rules and By-Laws.

As a physicist, Mr. Harper's main interest has been in thermal phenomena, particularly in the field of temperature measurement and in the realization of temperature scales; he has published a number of papers on this subject. He has also made contributions in the fields of humidity, solid state and hypothermia, and has published papers thereon.

Mr. Harper was one of the architects of the Australian Institute of Physics, of which he is currently Vice-President. He is Secretary to the National Standards Commission and is also Technical Consultant to the Senate Select Committee on the Metric System of Weights and Measures. In the international sphere he is a member of the Advisory Committee on Thermometry of the Bureau International des Poids et Mesures and he is the Australian representative on the Organization International de Metrologie Legale.

Archibald D. Ollé Prize

John R. Conolly, B.Sc. (Syd.), Ph.D. (N.S.W.)

John R. Conolly, B.Sc. (Syd.), Ph.D. (N.S.W.) received this award for his paper entitled " Petrology and Origin of the Cocoparra Group, Upper Devonian, New South Wales ", published in Volume 100 of " Journal and Proceedings ". The background of extensive field and laboratory work involved, the standard and presentation, the positive approach to interpretive stratigraphy and sedimentology and its originality set this paper apart as a major contribution in the broad sense to our geological knowledge. This, together with other published papers, has established Dr. Conolly as the authority on most of the Upper Devonian rocks of New South Wales.

Members of the Society, April, 1969

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 (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).

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 (1949).

Firth, Raymond William, D.Litt., M.A., Ph.D., Professor of Anthropology, University of London, London School of Economics, Houghton Street, Aldwych, W.C.2, England (1952).

O'Connell, Rev. Daniel J., S.J., D.Sc., Ph.D., F.R.A.S., Director, The Vatican Observatory, Rome, Italy (1953).

Oliphant, Sir Marcus L., K.B.E., Ph.D., B.Sc., F.R.S., F.A.A., Professor of Particle Physics, Australian National University, Canberra, A.C.T. (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 (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 (1960).

*Albert, Adrien, D.Sc., F.A.A., Professor of Medical Chemistry, Australian National University, Canberra, A.C.T. (1938: P4).

Alexander, Albert Ernest, Ph.D., F.A.A., Professor of Chemistry, University of Sydney (1950).

Anderson, Geoffrey William, B.Sc., c/o P.O. Box 30, Chatswood (1948).

Andrews, Paul Burke, B.Sc., 50 Melbourne Road, East Lindfield (1948: P2).

Arnot, Richard Hugh Macdonald, B.A., B.Sc.Agr., 2/50 Park Road, Surrey Hills, Victoria (1963).

*Aston, Ronald Leslie, Ph.D., 39 Redmyre Road, Strathfield (1930; President 1948).

*Aurousseau, Marcel, M.C., B.Sc., 229 Woodland Street, Balgowlah (1919: P2).

Badham, Charles David, M.B., B.S., D.R.(Syd.), M.C.R.A., "New Lodge", 16 Ormonde Parade, Hurstville (1962).

Baker, Stanley Charles, Ph.D., Department of Physics, University of Newcastle (1934: P4).

Banfield, James Edmund, M.Sc., Ph.D.(Melb.), Department of Organic Chemistry, University of New England, Armidale (1963).

Banks, Maxwell Robert, B.Sc., Department of Geology, University of Tasmania, Hobart, Tas. (1951).

Basden, Kenneth Spencer, Ph.D., B.Sc., Department of Fuel, University of New South Wales, Kensington (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 (1950).

Beadle, Noel Charles William, D.Sc., Professor of Botany, University of New England, Armidale (1964).

Beale, James Edgar Osborne, Solicitor, 166 Keira Street, Wollongong (1968).

Beavis, Margaret, B.Sc., Dip.Ed., 3 Rosebank Avenue, Epping (1961).

Bell, Alfred Denys Mervyn, B.Sc.(Hons.), School of Applied Geology, University of New South Wales, Kensington (1960).

*Bentivoglio, Sydney Ernest, B.Sc.Agr., 41 Telegraph Road, Pymble (1926).

Binns, Raymond Albert, B.Sc.(Syd.), Ph.D.(Cantab.), Associate Professor of Geology, University of New England, Armidale (1964: P1).

*Bishop, Eldred George, 2/12 Muston Street, Mosman (1920).

Blanks, Fred Roy, B.Sc., 19 Innes Road, Greenwich (1948).

Blayden, Ian Douglas, B.Sc.(Hons.), 42 Eleebana Road, Eleebana (1966).

Blunt, Michael Hugh, M.R.C.V.S., Veterinary Surgeon, 185 Markham Street, Armidale (1961).

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 (1951: P1).

Booth, Robert Kerril, B.Sc., Dip.Ed.(Syd.), Science Teacher, 46 Jellicoe Street, Hurstville (1964).

Bradley, Edgar David, M.B., B.S.(Syd.), D.O., Ophthalmologist, 107 Faulkner Street, Armidale (1964).

Branagan, David Francis, M.Sc., Ph.D., Senior Lecturer, Department of Geology and Geophysics, University of Sydney (1967: P2).

Brennan, Edward, B.E.(Appl.Geology), P.O. Box 5, Mount Morgan, Queensland (1962).

Bridges, David Somerset, 19 Mount Pleasant Avenue, Normanhurst (1952).

*Briggs, George Henry, D.Sc., 13 Findlay Avenue, Roseville (1919: P1).

Brown, Desmond J., D.Sc., Ph.D., Department of Medical Chemistry, Australian National University, Canberra, A.C.T. (1942).

Brown, Kenneth John, A.S.T.C., A.R.A.C.I., 3 Karda Place, Gymea (1963).

Browne, Ida Alison, D.Sc., 363 Edgecliff Road, Edgecliff (1935: P12; President 1953).

*Browne, William Rowan, D.Sc., F.A.A., 363 Edgecliff Road, Edgecliff (1913 : P23 ; President 1932).

Bruce, Colin Frank, D.Sc., Physicist, 17 Redan Street, Mosman (1964).

Bryan, John Hamilton, B.Sc.(Hons.), Geologist, 9/90 Raglan Street, Mosman (1968).

Buckley, Lindsay Arthur, B.Sc., 131 Laurel Avenue, Chelmer, Queensland (1940).

Bullen, Keith Edward, Sc.D., F.R.S., F.A.A., Professor of Applied Mathematics, University of Sydney (1946 : P3).

Burg, Raymond Augustine, Senior Analyst, Department of Mines, N.S.W. ; p.r. 17 Titania Street, Randwick (1960).

Burns, Bruce Bertram, D.D.S., Dental Surgeon, Suite 607, T. & G. Building, Park Street, Sydney 1961).

Butland, Gilbert James, B.A., Ph.D., F.R.G.S., Professor of Geography, University of New England, Armidale (1961).

Cameron, John Craig, M.A., B.Sc.(Edin.), D.I.C., 15 Monterey Street, Kogarah (1957).

Campbell, Ian Gavan Stuart, B.Sc., c/o Barker College, Hornsby (1955).

*Carey, Samuel Warren, D.Sc., Professor of Geology, University of Tasmania, Hobart, Tas. (1938 : P2).

Cavill, George William Kenneth, Ph.D., D.Sc., Professor of Organic Chemistry, University of New South Wales, Kensington (1944).

*Chaffer, Edric Keith, 27 Warrane Road, Roseville (1954).

Chalmers, Robert Oliver, Australian Museum, College Street, Sydney (1933 : P1).

Chalmers, Maxwell Clark, B.Sc., 58 Spencer Street, Killara (1940).

Chiarella, Carl, M.Sc., 28 Curban Street, Balgowlah (1967).

Churchward, John Gordon, B.Sc.Agr., Ph.D., c/o The Australian Wheat Board, 528 Lonsdale Street, Melbourne (1935 : P2).

Clancy, Brian Edward, M.Sc., Australian Atomic Energy Commission, Lucas Heights (1957).

Coalstad, Stanton Ernest, B.Sc., Metallurgical Chemist, 16 Station Street, Marrickville (1961).

Cohen, Samuel Bernard, M.Sc., 46 Wolseley Road, Point Piper (1940).

Cole, Edward Ritchie, B.Sc., Associate Professor of Organic Chemistry, University of New South Wales, Kensington (1940 : P2).

Cole, Joyce Marie (Mrs.), B.Sc., 7 Wolsten Avenue, Turramurra (1940 : P1).

Collett, Gordon, B.Sc., 16 Day Road, Cheltenham (1940).

Conaghan, Hugh Francis, M.Sc., Chief Analyst, Department of Mines, N.S.W. ; p.r. 104 Lancaster Avenue, West Ryde (1960).

Conolly, John Robert, B.Sc.(Syd.), Ph.D.(N.S.W.), Department of Geology, University of Southern California, Columbia, S.C., U.S.A. (1963: P4).

Cook, Alan Cecil, M.A.(Cantab.), Wollongong University College ; p.r. Lot 19, Dallas Street, Mt. Ousley (1968 : P1).

Cook, Cyril Lloyd, Ph.D., c/o Propulsion Research Laboratories, Box 1424H, G.P.O., Adelaide, S.A. (1948).

Cortis-Jones, Beverley, M.Sc., 65 Peacock Street, Seaforth (1940).

Coss, Paul, B.Sc., 10 Lucia Avenue, St. Ives (1963).

Cox, Charles Dixon, B.Sc., 51 Darley Street, Forestville (1964).

Crawford, Edwin John, B.E., 7a Battle Boulevarde, Seaforth (1955).

Crawford, Ian Andrew, P.O. Box 635, Burnie, Tas. (1955).

*Cresswick, John Arthur, 101 Villiers Street, Rockdale (1921 : P1).

Croft, James Bernard, B.E., Ph.D., c/o Coffey & Hollingsworth, 12 Waterloo Road, North Ryde (1956).

Crook, Keith Alan Waterhouse, Ph.D., Geology Department, Australian National University, Canberra, A.C.T. (1954 : P9).

Cruikshank, Bruce Ian, B.Sc.(Hons.), 16 Arthur Street, Punchbowl (1965).

Davies, George Frederick, 57 Eastern Avenue, Kingsford (1952).

Davis, Gwenda Louise, B.Sc., Ph.D., Associate Professor, Department of Botany, University of New England, Armidale (1961).

Day, Alan Arthur, Ph.D., F.R.A.S., Department of Geology and Geophysics, University of Sydney (1952 : P1 ; President 1965).

Denton, Leslie A., Bunarba Road, Miranda (1955).

Divnich, George, Engineer Agronom.(Yugoslavia), Engineering Analyst, 90 Highclere Avenue, Punchbowl (1960).

Doherty, Gregory, B.Sc.(Hons.), Australian Atomic Energy Commission, Lucas Heights (1963).

*Donegan, Henry Arthur James, M.Sc., F.R.A.C.I., F.R.I.C., 18 Hillview Street, Sans Souci (1928 : P1 ; President 1960).

Drake, Lawrence Arthur, B.A.(Hons.), B.Sc., Director, Riverview College Observatory, Riverview (1962 : P1).

Drummond, Heather Rutherford, B.Sc., 2 Gerald Avenue, Roseville (1950).

Dulhunty, John Allan, D.Sc., Department of Geology and Geophysics, University of Sydney (1937 : P22 ; President 1947).

Eade, Ronald Arthur, Ph.D., School of Organic Chemistry, University of New South Wales, Kensington (1945).

Edgar, Joyce Enid (Mrs.), B.Sc., 12 Calvert Avenue, Killara (1951).

*Elkin, Adolphus Peter, C.M.G., Ph.D., Emeritus Professor, 15 Norwood Avenue, Lindfield (1934 : P4 ; President 1940).

Ellison, Dorothy Jean, M.Sc., 45 Victoria Street, Roseville (1949).

Emerson, Donald Westland, M.Sc., B.E.(Appl.Geol.), Department of Geology and Geophysics, University of Sydney (1966 : P1).

Emmerton, Henry James, B.Sc., 37 Wangoola Street, East Gordon (1940).

Engel, Brian Adolph, M.Sc., Geology Department, University of Newcastle (1961 : P1).

Evans, Phillip Richard, B.A.(Oxon.), Ph.D.(Bristol), Esso Palynology Laboratory, School of Applied Geology, University of New South Wales (1968).

Everett, Frederick A., B.Sc., Jannali Boys' High School, Jannali (1963).

Facer, Richard Andrew, B.Sc.(Hons.), Department of Geology, Wollongong University College, Wollongong (1965 : P1).

Fallon, Joseph James, Loch Maree Place, Vaucluse (1950).

Fayle, Rex Dennes Harris, Pharmaceutical Chemist, 141 Jeffrey Street, Armidale (1961).

Feather, Norman Thomas, B.A., M.A., Ph.D., Dip.Ed., Associate Professor of Psychology, University of New England Armidale (1966).
Fisher, Robert, B.Sc., 3 Sackville Street, Maroubra (1940).
Fleischmann, Arnold Walter, 5 Erang Street, Carss Park (1956 : P1).
Fletcher, Harold Oswald, M.Sc., 131 Milson Road, Cremorne (1933).
Fletcher, Neville Horner, B.Sc., M.A., Ph.D., Professor of Physics, University of New England, Armidale (1961).
Foldvary, Gabor Zoltan, B.Sc., 267 Beauchamp Road, Matraville (1965).
French, Oswald Raymond, 6 Herberton Avenue, Hunters Hill (1951).
Friend, James Alan, Ph.D., Professor of Chemistry, University of West Indies, St. Augustine, Trinidad, W.I. (1944 : P2).
Furst, Hellmut Friedrich, D.M.D.(Hamburg), 185 Elizabeth Street, Sydney (1945).

Galloway, Malcolm Charles, B.Sc., Geologist, 17 Johnson Street, Chatswood (1960 : P1).
Garretty, Michael Duhan, D.Sc., Box 763, G.P.O., Melbourne, Vic. (1935 : P2).
Gascoigne, Robert Mortimer, Ph.D., Department of Philosophy, University of New South Wales, Kensington (1939 : P4).
Gellert, Emery, Dr.phil.(Basle), 38 Toorak Avenue, Wollongong (1968).
Gibbons, George Studley, M.Sc., 75 Nicholson Street, St. Leonards (1966).
Gibson, Neville Allan, Ph.D., 103 Bland Street, Ashfield (1942 : P6).
Giles, Edward Thomas, M.Sc., Ph.D., D.I.C., F.R.E.S., Professor of Zoology, University of New England, Armidale (1961).
Gilks, Arthur Joseph, B.Sc., Lecturer in Mathematics, R.A.N. College, Jervis Bay (1968).
*Gill, Stuart Frederic, 45 Neville Street, Marrickville (1947).
Glasson, Kenneth Roderick, B.Sc., Ph.D., 70 Beecroft Road, Beecroft (1948 : P1).
Golding, Henry George, M.Sc., Ph.D., School of Applied Geology, University of New South Wales, Kensington (1953 : P4).
Goldstone, Charles Lillington, B.Sc.Agr.(N.Z.), School of Wool Technology, University of New South Wales, Kensington (1951).
Goodwin, Robert Henry, B.Sc., M.Sc., Geologist, 2/1 Musgrave Street, Mosman (1968).
Gordijew, Gurij, Engineer Hydro Geology (Inst. Hydro Meteorology in Moscow, 1936), 41 Abbotsford Road, Homebush (1962).
Gow, Neil Neville, B.Sc.(Hons.) (1966).
Grahame, Mervyn Ernest, B.A., Schoolteacher, 161 Parry Street, Hamilton (1959).
Grant, John Narcissus Guerrato, Dip.Eng., 37 Chalayer Street, Rose Bay (1961).
Gray, Charles Alexander Menzies, B.E., M.E., Professor of Engineering, Wollongong University College, Wollongong (1948 : P1).
Gray, Noel Macintosh, B.Sc., 1 Centenary Avenue, Hunters Hill (1952).
Griffin, Russell John, B.Sc. (1952).
Griffith, James Langford, B.A., M.Sc., Associate Professor of Mathematics, University of New South Wales, Kensington, (1952 : P16 ; President 1958).
Groden, Charles Mark, M.Sc., School of Mathematics, University of New South Wales, Kensington (1957 : P3).
Gutmann, Felix, Ph.D., 70a Victoria Road, West Pennant Hills (1946 : P1).
Gutsche, Herbert William, B.Sc., School of Earth Sciences, Macquarie University, North Ryde (1961).
Guy, Brian Bertram, B.Sc.(Syd.), Ph.D.(Syd.), Department of Geology and Geophysics, University of Sydney (1968 : P1).

Hackett, Ian Harry, B.Sc.(Chem.Eng.), Research Chemist, 24 Military Road, Merrylands (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, M.Sc., A.S.T.C., Chemistry Department, Wollongong University College, Wollongong (1968).
Hall, Norman Frederick Blake, M.Sc., 16a Wharf Road, Longueville (1934).
Hamilton, Lloyd, B.E., 64 Finlayson Street, Lane Cove (1965).
Hampton, Edward John William, 1 Hunter Street, Waratah (1949).
Hancock, Harry Sheffield, M.Sc., 16 Koora Avenue, Wahroonga (1955).
Hanlon, Frederick Noel, B.Sc., 31 Congewoi Road, Mosman (1940 : P14 ; President 1957).
Hardwick, Reginald Leslie, B.Sc., Visual Aids Officer, 183 Richmond Road, Kingswood (1968).
Harper, Arthur Frederick Alan, M.Sc., National Standards Laboratory, University Grounds, City Road, Chippendale (1936 : P1 ; President 1959).
Harris, Clive Melville, Ph.D., Associate Professor of Chemistry, University of New South Wales, Kensington (1948 : P6).
Harrison, Ernest John Jasper, B.Sc., N.S.W. Geological Survey, Department of Mines, Sydney (1946).
Haydon, Sydney Charles, M.A., Ph.D., F.Inst.P., Professor of Physics, University of New England, Armidale (1965).
*Hayes, Daphne (Mrs.), B.Sc., 412/108 Elizabeth Bay Road, Elizabeth Bay (1943).
Helby, Robin James, M.Sc., 344 Malton Road, North Epping (1966 : P1).
Henderson, Roger John, B.Sc.(Hons.), Lecturer in Exploration Geophysics, School of Earth Sciences, Macquarie University, North Ryde (1966).
Higgs, Alan Charles, c/o Colonial Sugar Refining Co. Ltd., Building Material Division, 1–7 Bent Street, Sydney (1945).
Hill, Dorothy, D.Sc., F.R.S., F.A.A., Professor of Geology and Mineralogy, University of Queensland, St. Lucia, Brisbane (1938 : P6).
Hill, Helen Campbell (Mrs.), 14 Miowera Road, North Turramurra (1951).
Hodgins, Reginald William, A.S.T.C., B.Sc., Engineering Analyst Department of Main Roads, N.S.W. ; p.r. 57 Home Street, Port Macquarie (1967).
*Hogarth, Julius William, B.Sc., 4 " Hillsmore ", 20 Joubert Street, Hunters Hill (1948 : P6).
Horne, Allan Richard, 149a Hawkesbury Road, North Springwood (1960).
Howe, Bernard Adrian, c/o Exploration Physics, 265 Old Canterbury Road, Dulwich Hill (1963).
Humphries, John William, B.Sc., Physicist, National Standards Laboratory, University Grounds, City Road, Chippendale (1959 : P1 ; President 1964).

*Hynes, Harold John, D.Sc.Agr., 7 Futuna Street, Hunters Hill (1923 : P3).

Iredale, Thomas, D.Sc., 8 Nulla Nulla Street, Turramurra (1943).

Jaeger, John Conrad, D.Sc., F.A.A., Geophysics Department, Australian National University, Canberra, A.C.T. (1942 : P1).
Jenkins, Thomas Benjamin Huw, Ph.D., Department of Geology and Geophysics, University of Sydney (1956).
Jones, James Rhys, 25 Boundary Road, Mortdale (1959).
Joplin, Germaine Anne, D.Sc., Geophysics Department, Australian National University, Canberra, A.C.T. (1935 : P10).

Keane, Austin, Ph.D., Professor of Mathematics, Wollongong University College, Wollongong (1955 : P4 ; President 1968).
Kemp, William Ronald Grant, B.Sc., Physicist, 16 Fig Tree Street, Lane Cove (1960).
Kimble, Jean Annie, B.Sc., 2/163 Homer Street, Earlwood (1943).
*Kirchner, William John, B.Sc., " Fairways ", Linkview Avenue, Blackheath (1920).
Kitamura, Torrence Edward, B.A., B.Sc.Agr., 18 Pullbrook Parade, Hornsby (1964).
Koch, Leo E., D.Phil.Habil., School of Applied Geology, University of New South Wales, Kensington (1948).
Korber, Peter Henry Wilibald, B.Sc., Analytical Chemist, 14/20 Warwick Avenue, Cammeray (1968).
Krysko v. Tryst, Maren (Mrs.), B.Sc., Grad.Dip., School of Applied Geology, University of New South Wales, Kensington (1959).

Lack, N. Edith (Mrs.), 471 Sailor's Bay Road, Northbridge (1968).
Lambeth, Arthur James, B.Sc., " Talanga ", Picton Road, Douglas Park, N.S.W. (1939 : P3).
Landecker, Kurt, D.Ing.(Berlin), Department of Physics, University of New England, Armidale (1961).
Lassak, Erich Vincent, M.Sc.(N.S.W.), B.Sc.(Hons.), A.S.T.C., Research Chemist, 167 Berowra Waters Road, Berowra (1964 : P1).
Lawrence, Laurence James, D.Sc., Ph.D., Associate Professor, School of Applied Geology, University of New South Wales, Kensington (1951 : P4).
Leaver, Gaynor Eiluned (Mrs.), B.Sc.(Wales), F.G.S.(Lond.), 30 Ingalara Avenue, Wahroonga (1961).
Le Fevre, Raymond James Wood, D.Sc., F.R.S., F.A.A., Professor and Head of the School of Chemistry, University of Sydney (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 (1936 : P3 ; President 1955).
*Lions, Francis, Ph.D., 44/630 Pacific Highway, Killara (1929 : P56 ; President 1946).
Lions, Jean Elizabeth (Mrs.), B.Sc., 44/630 Pacific Highway, Killara (1940).
Lloyd, James Charles, B.Sc., 1 Spurwood Road, Turramurra (1947).
Lockwood, William Hutton, B.Sc., Institute of Medical Research, Royal North Shore Hospital, St. Leonards (1940 : P1).
Lovering, John Francis, Ph.D., Professor of Geology, University of Melbourne, Parkville, Vic. (1951 : P4).
Low, Angus Henry, Ph.D., Associate Professor, Department of Applied Mathematics, University of New South Wales, Kensington (1950 : P4 ; President 1967).
Lowenthal, Gerhard, Ph.D., M.Sc., 17 Gnarbo Avenue, Carss Park (1959).
Lyons, Lawrence Ernest, Ph.D., Professor of Chemistry, University of Queensland, St. Lucia, Brisbane (1948 : P3).

Maccoll, Allan, M.Sc., Department of Chemistry, University College, Gower Street, London, W.C.1, England (1939 : P4).
McCarthy, Frederick David, Dip.Anthr., Principal, Australian Institute of Aboriginal Studies, Box 553, City P.O., Canberra, A.C.T. (1949 : P1 ; President 1956).
McClymont, Gordon Lee, B.V.Sc., Ph.D., Professor of Rural Science, University of New England, Armidale (1961).
McCoy, William Kevin, 86 Ave Da Republica, Macao, via Hong Kong (1943).
McCullagh, Morris Behan (1950).
McElroy, Clifford Turner, Ph.D., M.Sc., Director, Geological Survey of N.S.W., P.O. Box R 216, Royal Exchange, Sydney (1949 : P2).
McGlynn, John Albert, B.Sc.(Hons.), Analyst, Department of Mines, N.S.W., Sydney (1964).
McGregor, Gordon Howard, 4 Maple Avenue, Pennant Hills (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, Sydney (1943 : P12 ; President 1963).
McMahon, Barry Keys, B.Sc. (1961).
McMahon, Patrick Reginald, Ph.D., Professor of Wool Technology, University of New South Wales, Kensington (1947).
McNamara, Barbara Joyce (Mrs.), M.B., B.S., c/o Dr. B. Burfitt, Callan Park Hospital, Rozelle (1943).
MacKellar, Michael John Randal, B.Sc.Agr.(Syd.), B.A.(Hons.) (Oxon.), Agricultural Scientist, 1/47 Wolseley Road, Mosman (1968).
Magee, Charles Joseph, D.Sc.Agr., 57 Florida Road, Palm Beach (1947 : P2 ; President 1952).
Majstrenko, Petro, M.Sc.(Copenhagen), Lecturer in Mathematics, University of New England, Armidale (1966).
Males, Pamela Ann, 13 Gelding Street, Dulwich Hill (1951).
Manser, Warren, B.Sc.(Syd.), Department of Earth Sciences, University of Papua and New Guinea, Boroko, T.P.N.G. (1964).
Marsden, Joan Audrey, A.S.T.C.(Dip.App.Chem.), 203 West Street, Crows Nest (1955).
Marshall, Charles Edward, D.Sc., Professor of Geology and Geophysics, University of Sydney (1949 : P1).
Martin, Peter Marcus, M.Sc.Agr., Dip.Ed., Lecturer, Botany Department, University of Sydney (1968).
Meares, Harry John Devenish, 27 Milray Avenue, Wollstonecraft (1949).
*Mellor, David Paver, Professor of Inorganic Chemistry, University of New South Wales, Kensington (1929 : P25 ; President 1941).

Millership, William, M.Sc., 18 Courallie Avenue, Pymble (1940).
Minty, Edward James, M.Sc., B.Sc., Dip.Ed., 36 Castle Street, Castle Hill (1951 : P2).
Moelle, Konrad Heinrich Richard, Absolutorium (Innsbruck), Ph.D.(Innsbruck), Lecturer in Geology, University of Newcastle ; p.r. 2 Hillcrest Road, Merewether (1967).
Moore, Laurence Frederick, B.A.(N.E.), Teacher, 21 Cavendish Avenue, Blacktown (1967).
Morgan, James Albert, B.E.(Chem.)(N.S.W.), Engineer, 61 Sinclair Street, Wollstonecraft (1968).
Morris, Ronald James Huntbatch, M.Sc.(Melb.), Department of Physiology, University of New England, Armidale (1963).
Morrissey, Matthew John, M.B., B.S., 152 Marsden Street, Parramatta (1941).
Mort, Francis George Arnot, 29 Preston Avenue, Fivedock (1934).
Mosher, Kenneth George, B.Sc., 9 Yirgella Avenue, Killara (1948).
Moss, Francis John, M.B., B.S., Department of Biochemistry, University of New South Wales, Kensington (1955).
Moye, Daniel George, B.Sc., 36 Sylvander Street, North Balwyn, Vic. (1944).
*Murphy, Robert Kenneth, Dr.Ing.Chem., 68 Pindari Avenue, North Mosman (1915).
Murray, Jascha Ann (Mrs.), M.Sc., Strangeways Research Laboratory, Wort's Causeway, Cambridge, England (1961).

Nashar, Beryl, Ph.D., Professor of Geology, University of Newcastle ; p.r. 15 Princeton Avenue, Adamstown Heights (1946 : P2).
*Naylor, George Francis King, Ph.D., Department of Psychology and Philosophy, University of Queensland, St. Lucia, Brisbane (1930 : P7).
*Neuhaus, John William George, M.Sc., 32 Bolton Street, Guildford (1943).
*Newman, Ivor Vickery, Ph.D., School of Biology, Macquarie University, North Ryde (1932).
Noakes, Lyndon Charles, B.A., Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T. (1945 : P1).
*Noble, Robert Jackson, Ph.D., 32a Middle Harbour Road, Lindfield (1920 : P4 ; President 1934).
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'Farrell, Antony Frederick Louis, A.R.C.Sc., B.Sc., Professor of Zoology, University of New England, Armidale (1961).
O'Halloran, Peter Joseph, B.Sc., Dip.Ed., M.Sc., In charge of Mathematics Department, R.A.N. College, Jervis Bay (1968).
Old, Adrian Noel, B.A., B.Sc.Agr., Senior Chemist, N.S.W. Department of Agriculture ; p.r. 13 Fallon Street, Rydalmere (1947).
Oxenford, Reginald Augustus, B.Sc., 10 Greaves Street, Grafton (1950).

Packham, Gordon Howard, Ph.D., Department of Geology and Geophysics, University of Sydney (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 (1967).
*Penfold, Arthur Ramon, Flat 516, Baroda Hall, 6a Birtley Place, Elizabeth Bay (1920 : P82 ; President 1935).
Perry, Hubert Roy, B.Sc., 74 Woodbine Street, Bowral (1948).
Petersen, George Arthur, B.Sc., B.E., 55 Roseville Avenue, Roseville (1966).
Philip, Graeme Maxwell, M.Sc.(Melb.), Ph.D. (Cantab.), F.G.S., Professor of Geology, University of New England, Armidale (1964 : P1).
Phillips, Marie Elizabeth, Ph.D., 16 Lawley Place, Deakin, A.C.T. (1938).
Phipps, Charles Verling Gayer, Ph.D., Department of Geology and Geophysics, University of Sydney (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 (1965).
Pinwill, Norman, B.A., The Scots College, Victoria Road, Bellevue Hill (1946).
Plummer, Brian Alfred George, M.A., F.R.G.S., Department of Geography, University of New England, Armidale (1961).
Poggendorff, Walter Hans George, B.Sc.Agr., 85 Beaconsfield Road, Chatswood (1949).
Pollard, John Percival, M.Sc.(N.S.W.), Dip.App.Chem.(Swinburne), Mathematician with the Australian Atomic Energy Commission ; p.r. 25 Nabiac Avenue, Gymea (1963).
Pratt, Boyd Thomas, B.Sc.(Hons.)(N.S.W.), 11 Harbourne Road, Kingsford (1967).
Priddle, Raymond Arthur, B.E., 34 Cleveland Street, Wahroonga (1956).
Priestley, John Henry, M.B., B.S., B.Sc., Medical Practitioner, 137 Dangar Street, Armidale (1961).
Prokhovnik, Simon Jacques, M.A., B.Sc., School of Mathematics, University of New South Wales, Kensington (1956 : P3).
*Proud, John Seymour, B.E., Finlay Road, Turramurra (1945).
Puttock, Maurice James, B.Sc.(Eng.), A.Inst.P., Principal Research Officer, C.S.I.R.O., Sydney ; p.r. 2 Montreal Avenue, Killara (1960).

*Quodling, Florrie Mabel, Ph.D., B.Sc., 145 Midson Road, Epping (1935 : P5).

Rade, Janis, M.Sc., Consulting Geologist, Box 5440C, G.P.O., Melbourne (1953 : P6).
Ramm, Eric John, Experimental Officer, Australian Atomic Energy Commission, Lucas Heights (1959).
Rattigan, John Herbert, Ph.D., M.Sc. (1966 : P2).
*Rayner, Jack Maxwell, O.B.E., B.Sc., 5 Tennyson Crescent, Forrest, Canberra, A.C.T. (1931 : P1).
Read, Harold Walter, B.Sc., 1/29 Spinks Road, Corrimal (1962 : P1).
Reichel, Alex, Ph.D., M.Sc., Department of Applied Mathematics, University of Sydney (1957 : P4).
Rice, Thomas Denis, B.Sc., 24 Alliott Street, Campbelltown (1964).
Rigby, John Francis, B.Sc.(Melb.) (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 (1961).
Ritchie, Arthur Sinclair, M.Sc., Associate Professor of Geology, University of Newcastle (1947 : P2).
Ritchie, Ernest, D.Sc., F.A.A., Chemistry Department, University of Sydney (1939 : P19).

Robbins, Elizabeth Marie (Mrs.), M.Sc., Waterloo Road, North Ryde (1939 : P3).

Roberts, Herbert Gordon, B.Sc., c/o Anaconda Aust., Inc., 34 Hunter Street, Sydney (1957).

Roberts, John, Ph.D., Bureau of Mineral Resources, Geology and Geophysics, Box 378, Canberra City, A.C.T. (1961 : P3).

Robertson, William Humphrey, B.Sc., c/o Sydney Observatory, Sydney (1949 : P28).

Robinson, David Hugh, A.S.T.C., Chemist, 12 Robert Road, West Pennant Hills (1951).

Roper, Geoffrey Harold, M.Sc., Ph.D., Associate Professor, School of Chemical Engineering, University of New South Wales (1966).

Rosenbaum, Sidney, 5 Eton Road, Lindfield (1940).

Rosenthal-Schneider, Ilse, Ph.D., 48 Cambridge Avenue, Vaucluse (1948).

Ross, Victoria (Mrs.), M.Sc., B.Sc.(Hons.), " Merroo ", Mill Road, Kurrajong (1960).

Rountree, Phyllis Margaret, D.Sc., Royal Prince Alfred Hospital, Sydney (1945).

Royle, Harold George, M.B., B.S.(Syd.), 161 Rusden Street, Armidale (1961).

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 (1920).

Scholer, Harry Albert Theodore, M.Eng., Civil Engineer, c/o Harbours and Rivers Branch, Public Works Department, N.S.W., Phillip Street, Sydney (1960).

Scott, John Alan Belmore, B.Sc.(Qld.), 193 Forest Road, Kirrawee (1964).

See, Graeme Thomas, B.Sc., School of Nuclear Chemistry, University of New South Wales, Kensington (1949).

Selby, Edmond Jacob, P.O. Box 121, North Ryde (1933).

*Sharp, Kenneth Raeburn, B.Sc., Engineering Geology Branch, Snowy Mountains Authority, North Cooma (1948).

Shaw, Stirling Edward, B.Sc.(Hons.), Ph.D., F.G.A.A., School of Earth Sciences, Macquarie University, North Ryde (1966).

Sherrard, Kathleen Margaret (Mrs.), M.Sc., 43 Robertson Road, Centennial Park (1936 : P6).

Sherwin, Lawrence, B.Sc.(Hons.)(Syd.), 186 Sylvania Road, Miranda (1967).

Simmons, Lewis Michael, Ph.D., The Scots College, Victoria Road, Bellevue Hill (1945 : P3).

Sims, Kenneth Patrick, B.Sc., 25 Fitzpatrick Avenue East, French's Forest (1950 : P14).

Slade, George Hermon, B.Sc., W. Hermon Slade & Co. Pty. Ltd., Mandemar Avenue, Homebush (1933).

Slade, Milton John, B.Sc., Dip.Ed.(Syd.), M.Sc.(N.E.), 162 Donnelly Street, Armidale (1952).

Smith, Ann Ruth (Mrs.), B.Sc., Box 134, P.O., Queenstown, Tas. (1959).

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Smith-White, William Broderick, M.A., Associate Professor of Mathematics, University of Sydney (1947 : P4 ; President 1962).

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Wilkinson, John Frederick George, M.Sc.(Qld.), Ph.D.(Cantab.), Associate Professor of Geology, University of New England, Armidale (1961 : P1).
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Wilson, Christopher John Lascelles, B.Sc., Department of Geophysics and Geochemistry, Australian National University (1967 : P1).
Winch, Denis Edwin, Ph.D., M.Sc., Senior Lecturer in Applied Mathematics, University of Sydney (1968).
Wood, Clive Charles, Ph.D., B.Sc. (1954).
Wood, Harley Weston, D.Sc., M.Sc., Government Astronomer, Sydney Observatory, Sydney (1936 : P16 ; President 1949).
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Griffith, Elsie A. (Mrs.), 9 Kanoona Street, Caringbah (1956).
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Willey, Helen Ann (Mrs.), B.Sc., Department of Geology, University of New England, Armidale (1965).

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VOLUME 102 1969 PART 2

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Journal and Proceedings, Royal Society of New South Wales, Vol. 102, pp. 109–117, 1969

Precise Observations of Minor Planets at Sydney Observatory during 1967 and 1968

W. H. Robertson

The programme of precise observations of selected minor planets which was begun in 1955 is being continued and the results for 1967 and 1968 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 placed in front of the lens, giving first order spectra which are 2·3 magnitudes fainter than the central image and displaced 0·32 mm. from it in an east-west direction. The spectra were measured for the planet and the central image for the stars.

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 $0^{s}{\cdot}033 \sec\delta$ in right ascension and 0″·34 in declination. This corresponds to probable errors for the mean of the two results from one plate of $0^{s}{\cdot}014 \sec\delta$ and 0″·14. The result for 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 $0^{s}{\cdot}012 \sec\delta$ in right ascension and 0″·13 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).

The plates are now measured in a Grubb Parsons coordinate measuring machine in which the bisection is performed photoelectrically by scanning the image of the star under observation over a pair of slits by means of a rotating plate. The correctness of bisection is determined by the equality of two pulses on the screen of a cathode ray oscilloscope. The measuring system consists of two diffraction gratings at right angles which are read by Moiré fringe counting directly to 1 micron.

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, 28) and the Cape Catalogue (Vols. 17, 18). The plates were measured by Miss R. Bull, Miss D. Hare, Miss J. Phillips, Miss D. Robinson, Mrs. B. Stolk 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	″	
		4 Vesta 1967 U.T.									
813	Mar.	16·77236	15	55	40·268	−10	50	30·68	+0·032	−3·41	S
814	Mar.	16·77236	15	55	40·308	−10	50	31·59			
815	Mar.	20·75394	15	57	47·692	−10	46	20·68	+0·007	−3·42	W

TABLE I—*continued*

No.			R.A. (1950·0)			Dec. (1950·0)			Parallax Factors		
			h	m	s	°	′	″	s	″	
		4 Vesta—*continued*									
816	Mar.	20·75394	15	57	47·666	−10	46	20·22			
817	April	04·72026	16	01	29·428	−10	20	27·34	+0·019	−3·48	S
818	April	04·72026	16	01	29·431	−10	20	26·78			
819	April	12·69775	16	00	28·420	−10	01	52·22	+0·019	−3·52	W
820	April	12·69775	16	00	28·386	−10	01	52·26			
821	April	17·67720	15	58	46·247	−09	49	31·20	+0·001	−3·55	R
822	April	17·67720	15	58	46·172	−09	49	31·12			
823	April	27·64716	15	53	04·689	−09	25	18·39	+0·005	−3·60	S
824	April	27·64716	15	53	04·640	−09	25	18·58			
825	May	03·62672	15	48	24·139	−09	12	27·36	+0·003	−3·63	W
826	May	03·62672	15	48	24·129	−09	12	27·48			
827	May	09·60249	15	43	01·578	−09	02	02·67	−0·010	−3·66	R
828	May	09·60249	15	43	01·588	−09	02	03·08			
829	May	17·56909	15	35	14·718	−08	53	43·32	−0·029	−3·68	S
830	May	17·56909	15	35	14·683	−08	53	43·44			
831	May	25·55138	15	27	25·232	−08	53	31·38	0·000	−3·68	W
832	May	25·55138	15	27	25·232	−08	53	30·68			
833	May	29·53707	15	23	43·366	−08	56	50·56	−0·002	−3·67	R
834	May	29·53707	15	23	43·384	−08	56	50·24			
835	June	30·43365	15	07	38·738	−10	50	05·96	−0·018	−3·40	R
836	June	30·43365	15	07	38·662	−10	50	06·09			
837	July	06·42500	15	08	03·849	−11	26	09·82	+0·006	−3·32	R
838	July	06·42500	15	08	03·812	−11	26	10·01			
839	July	11·40830	15	09	15·885	−11	58	47·28	−0·007	−3·24	W
840	July	11·40830	15	09	15·862	−11	58	47·36			
841	July	19·38907	15	12	43·696	−12	55	02·42	−0·006	−3·11	R
842	July	19·38907	15	12	43·672	−12	55	02·60			
843	Aug.	03·36922	15	23	49·678	−14	49	19·02	+0·037	−2·84	W
844	Aug.	03·36922	15	23	49·668	−14	49	18·06			
845	Aug.	15·34577	15	36	28·520	−16	24	10·62	+0·039	−2·61	R
846	Aug.	15·34577	15	36	28·516	−16	24	10·72			
		18 Melpomene 1967 U.T.									
847	May	31·76593	20	56	17·080	−07	28	24·96	+0·010	−3·89	R
848	May	31·76593	20	56	17·114	−07	28	24·96			
849	July	10·66408	21	00	19·386	−07	42	29·28	+0·024	−3·86	R
850	July	10·66408	21	00	19·411	−07	42	29·44			
851	Aug.	01·58142	20	44	39·610	−10	34	13·76	−0·012	−3·46	R
852	Aug.	01·58142	20	44	39·574	−10	34	12·86			
853	Aug.	08·57269	20	38	24·886	−11	48	50·94	+0·034	−3·29	S
854	Aug.	08·57269	20	38	24·866	−11	48	49·72			
855	Aug.	15·52971	20	32	26·101	−13	07	09·31	−0·028	−3·10	R
856	Aug.	15·52971	20	32	26·135	−13	07	09·55			
857	Aug.	25·50736	20	25	16·723	−14	58	48·40	+0·003	−2·83	S
858	Aug.	25·50736	20	25	16·769	−14	58	48·43			
859	Aug.	28·48958	20	23	37·721	−15	30	44·12	−0·024	−2·75	S
860	Aug.	28·48958	20	23	37·769	−15	30	44·32			
861	Sept.	08·46650	20	20	05·668	−17	17	35·71	+0·006	−2·49	S
862	Sept.	08·46650	20	20	05·616	−17	17	35·89			
863	Sept.	21·42672	20	21	45·480	−18	55	09·45	−0·011	−2·25	R
864	Sept.	21·42672	20	21	45·520	−18	55	09·74			
865	Sept.	28·41552	20	25	18·230	−19	33	11·10	+0·006	−2·15	R
866	Sept.	28·41552	20	25	18·249	−19	33	11·82			
867	Sept.	29·41976	20	25	57·608	−19	37	47·22	+0·028	−2·15	S
868	Sept.	29·41976	20	25	57·572	−19	37	47·54			
		1 Ceres 1968 U.T.									
869	Feb.	28·75243	14	31	03·590	−01	21	59·06	+0·015	−4·69	S
870	Feb.	28·75243	14	31	03·630	−01	21	59·32			
871	April	01·65434	14	21	36·150	+00	25	19·00	+0·010	−4·92	R
872	April	01·65434	14	21	36·178	+00	25	18·65			
873	April	10·63441	14	14	45·566	+00	56	05·28	+0·039	−4·98	S
874	April	10·63441	14	14	45·546	+00	56	04·98			

TABLE I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		1 Ceres—*continued*									
875	April	22·58229	14	04	20·476	+01	26	08·64	+0·001	−5·05	W
876	April	22·58229	14	04	20·444	+01	26	07·84			
877	April	30·54669	13	57	19·100	+01	35	40·89	−0·026	−5·06	R
878	April	30·54669	13	57	19·103	+01	35	40·55			
879	May	24·48286	13	41	03·136	+01	00	41·82	+0·014	−4·99	S
880	May	24·48286	13	41	03·124	+01	00	41·74			
881	May	31·46697	13	38	31·076	+00	32	50·24	+0·029	−4·93	S
882	May	31·46697	13	38	31·110	+00	32	50·40			
883	June	03·44900	13	37	47·660	+00	18	47·11	+0·001	−4·90	R
884	June	03·44900	13	37	47·646	+00	18	47·36			
885	June	20·40197	13	37	42·156	−01	21	42·88	−0·001	−4·69	W
886	June	20·40197	13	37	42·212	−01	21	43·03			
887	June	24·39981	13	38	38·193	−01	49	41·62	+0·024	−4·53	S
888	June	24·39981	13	38	38·222	−01	49	41·48			
889	July	01·37167	13	41	04·662	−02	41	35·46	−0·009	−4·51	R
890	July	01·37167	13	41	04·622	−02	41	35·09			
891	July	08·35776	13	44	29·280	−03	36	55·11	0·000	−4·39	R
892	July	08·35776	13	44	29·328	−03	36	55·48			
893	July	16·33720	13	49	27·336	−04	43	16·01	−0·008	−4·24	W
894	July	16·33720	13	49	27·333	−04	43	16·26			
		3 Juno 1968 U.T.									
895	April	01·67492	14	46	21·558	−03	22	07·30	+0·021	−4·43	R
896	April	01·67492	14	46	21·606	−03	22	05·96			
897	April	22·59865	14	31	39·937	−00	56	30·40	−0·006	−4·74	W
898	April	22·59865	14	31	39·982	−00	56	30·38			
899	April	30·57250	14	25	16·874	−00	07	56·56	−0·006	−4·85	R
900	April	30·57250	14	25	16·892	−00	07	56·42			
901	June	03·46734	14	03	32·527	+01	39	26·77	+0·002	−5·07	R
902	June	03·46734	14	03	32·532	+01	39	27·49			
		6 Hebe 1968 U.T.									
903	April	22·79511	18	52	44·690	−07	10	14·88	+0·042	−3·93	W
904	April	22·79511	18	52	44·722	−07	10	14·86			
905	April	30·75499	18	56	05·899	−06	38	30·05	−0·022	−4·00	R
906	April	30·75499	18	56	05·939	−06	38	30·05			
907	May	06·75326	18	57	36·864	−06	16	32·01	+0·020	−4·05	S
908	May	06·75326	18	57	36·890	−06	16	32·13			
909	May	28·70402	18	55	03·886	−05	23	34·28	+0·059	−4·17	R
910	May	28·70402	18	55	03·882	−05	23	34·14			
911	May	30·67177	18	54	11·525	−05	21	51·59	−0·022	−4·17	R
912	May	30·67177	18	54	11·493	−05	21	51·86			
913	June	03·66882	18	52	06·194	−05	20	22·48	+0·008	−4·18	S
914	June	03·66882	18	52	06·220	−05	20	21·87			
915	June	19·61214	18	40	06·456	−05	44	10·23	−0·007	−4·12	R
916	June	19·61214	18	40	06·432	−05	44	09·98			
917	June	24·60790	18	35	25·628	−06	02	14·58	+0·032	−4·08	W
918	June	24·60790	18	35	25·643	−06	02	14·22			
919	July	03·57483	18	26	32·540	−06	47	28·81	+0·025	−3·98	S
920	July	03·57483	18	26	32·493	−06	47	28·79			
921	July	15·53367	18	15	02·013	−08	10	16·98	+0·024	−3·79	W
922	July	15·53367	18	15	02·052	−08	10	16·55			
923	July	24·51005	18	07	43·206	−09	25	10·08	+0·042	−3·62	R
924	July	24·51005	18	07	43·242	−09	25	11·00			
925	July	29·48561	18	04	27·434	−10	09	49·46	+0·014	−3·51	S
926	July	29·48561	18	04	27·418	−10	09	49·38			
927	Aug.	09·44627	17	59	45·464	−11	52	05·05	−0·003	−3·27	R
928	Aug.	09·44627	17	59	45·510	−11	52	05·38			
929	Aug.	22·41169	17	59	03·630	−13	53	09·25	+0·001	−2·98	R
930	Aug.	22·41169	17	59	03·624	−13	53	09·92			
931	Aug.	30·41567	18	01	19·662	−15	04	47·07	+0·078	−2·83	S
932	Aug.	30·41567	18	01	19·682	−15	04	47·15			
933	Sept.	11·36921	18	08	20·700	−16	43	49·58	+0·020	−2·56	R
934	Sept.	11·36921	18	08	20·764	−16	43	48·64			

TABLE I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		7 Iris 1968 U.T.									
935	April	22·68299	16	21	25·774	−24	41	20·10	+0·021	−1·67	W
936	April	22·68299	16	21	25·750	−24	41	20·00			
937	April	30·64938	16	15	50·691	−24	22	56·66	−0·006	−1·42	R
938	April	30·64938	16	15	50·686	−24	22	57·08			
939	May	20·59368	15	57	09·901	−23	11	42·30	+0·034	−1·60	W
940	May	20·59368	15	57	09·840	−23	11	42·30			
941	May	30·54969	15	47	02·630	−22	26	03·06	+0·002	−1·71	R
942	May	30·54969	15	47	02·550	−22	26	03·14			
943	June	03·53929	15	43	10·086	−22	06	59·80	+0·012	−1·76	S
944	June	03·53929	15	43	10·092	−22	06	59·50			
945	June	20·48362	15	29	29·900	−20	49	29·07	+0·013	−1·96	R
946	June	20·48362	15	29	29·870	−20	49	28·72			
947	June	24·47870	15	27	09·196	−20	33	28·14	+0·038	−1·99	S
948	June	24·47870	15	27	09·203	−20	33	28·02			
949	July	12·41190	15	21	38·552	−19	39	51·58	−0·008	−2·12	R
950	July	12·41190	15	21	38·486	−19	39	51·12			
951	July	16·41015	15	21	32·744	−19	32	27·20	+0·023	−2·14	W
952	July	16·41015	15	21	32·778	−19	32	27·34			
953	July	24·39569	15	22	32·964	−19	22	43·12	+0·022	−2·16	S
954	July	24·39569	15	22	32·989	−19	22	42·79			
955	Aug.	01·37326	15	25	04·420	−19	19	26·46	+0·037	−2·18	W
956	Aug.	01·37326	15	25	04·360	−19	19	25·82			
		39 Laetitia 1968 U.T.									
957	April	30·77887	19	24	37·960	−10	17	42·44	−0·009	−3·67	R
958	April	30·77887	19	24	37·983	−10	17	42·57			
959	May	09·77129	19	27	47·631	−09	45	35·50	+0·037	−3·57	S
960	May	09·77129	19	27	47·684	−09	45	35·00			
961	May	29·69810	19	28	03·710	−08	54	32·11	−0·021	−3·69	R
962	May	29·69810	19	28	03·672	−08	54	32·14			
963	June	19·63763	19	18	13·594	−08	48	18·38	−0·010	−3·70	R
964	June	19·63763	19	18	13·586	−08	48	18·74			
965	June	24·63458	19	14	36·540	−08	55	44·95	+0·031	−3·69	W
966	June	24·63458	19	14	36·539	−08	55	44·72			
967	July	03·59619	19	07	21·450	−09	17	59·82	+0·004	−3·63	S
968	July	03·59619	19	07	21·430	−09	17	59·79			
969	July	15·55860	18	57	09·041	−10	03	49·23	+0·010	−3·53	W
970	July	15·55860	18	57	09·075	−10	03	49·55			
971	July	24·52893	18	50	00·116	−10	47	50·10	+0·010	−3·42	R
972	July	24·52893	18	50	00·082	−10	47	50·82			
973	Aug.	02·48202	18	44	02·635	−11	37	19·26	−0·056	−3·31	R
974	Aug.	02·48202	18	44	02·688	−11	37	19·28			
975	Aug.	22·43637	18	37	18·004	−13	34	18·30	−0·004	−3·03	R
976	Aug.	22·43637	18	37	18·030	−13	34	18·27			
977	Aug.	30·43493	18	37	33·342	−14	19	37·74	+0·060	−2·93	S
978	Aug.	30·43493	18	37	33·250	−14	19	37·92			
979	Sept.	11·39343	18	41	08·698	−15	21	58·04	+0·024	−2·77	R
980	Sept.	11·39343	18	41	08·552	−15	21	58·78			
981	Sept.	16·37527	18	43	42·656	−15	45	26·22	+0·004	−2·71	R
982	Sept.	16·37527	18	43	42·586	−15	45	26·12			
		433 Eros 1968 U.T.									
983	April	01·52752	11	09	20·781	−38	50	58·35	+0·038	+0·80	R
984	April	01·52752	11	09	20·746	−38	50	57·66			
985	April	08·49974	11	06	11·779	−37	19	27·00	+0·012	+0·64	S
986	April	08·49974	11	06	11·710	−37	19	28·00			
987	April	22·47356	11	09	34·680	−33	39	02·45	+0·048	0·00	S
988	April	22·47356	11	09	34·610	−33	39	03·00			
989	April	23·46723	11	10	15·082	−33	22	58·68	+0·032	−0·04	R
990	April	23·46723	11	10	15·004	−33	22	59·95			

TABLE I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		433 Eros—*continued*									
991	May	03·44830	11	19	38·694	−30	48	10·60	+0·038	−0·44	S
992	May	03·44830	11	19	38·739	−30	48	10·18			
993	May	06·43002	11	23	16·052	−30	05	31·94	−0·007	−0·57	R
994	May	06·43002	11	23	16·000	−30	05	31·84			

TABLE II

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
813	5521	0·362834	28·785	36·92	830	5441	0·426363	16·851	08·77
	5563	0·357603	39·437	15·08		5454	0·303059	14·412	57·07
	5543	0·279563	28·978	41·35		5488	0·270578	02·275	28·33
814	5517	0·448661	54·714	33·32	831	5395	0·387552	56·650	31·38
	5547	0·321478	12·152	50·02		5411	0·180678	33·916	00·88
	5582	0·229860	25·925	59·53		5426	0·431770	35·181	04·54
815	5543	0·345773	28·978	41·35	832	5394	0·331762	46·967	19·02
	5593	0·233701	27·260	11·38		5399	0·277458	28·039	46·99
	5547	0·420526	12·152	50·02		5433	0·390780	03·093	01·98
816	5534	0·524226	23·194	39·06	833	5371	0·318654	11·986	52·78
	5563	0·249798	39·437	15·08		5394	0·338596	46·976	19·02
	5582	0·225976	25·925	59·53		5403	0·342749	56·994	31·16
817	5556	0·268040	50·653	41·64	834	5362	0·356620	34·219	45·70
	5615	0·229170	18·482	01·12		5399	0·240794	28·039	46·99
	5569	0·502790	18·984	09·92		5409	0·402586	15·282	03·11
818	5541	0·257780	28·232	09·69	835	5285	0·269911	29·781	04·37
	5568	0·347107	17·527	10·36		5315	0·215570	31·498	17·83
	5597	0·395113	03·052	56·30		5312	0·514519	37·015	59·47
819	5556	0·235034	50·653	41·64	836	5281	0·404270	22·834	14·23
	5541	0·246591	28·232	09·69		5331	0·251602	40·154	44·65
	5585	0·518375	28·923	29·10		5306	0·344128	58·775	11·40
820	5549	0·297354	31·973	32·69	837	5295	0·335904	56·201	06·20
	5597	0·280777	03·052	56·30		5313	0·405987	38·041	03·82
	5568	0·421869	17·527	10·36		5320	0·258110	56·328	00·22
821	5556	0·342070	50·653	41·64	838	5292	0·404903	22·652	35·25
	5595	0·340074	52·024	39·59		5315	0·332500	58·797	11·37
	5541	0·317856	28·232	09·69		5326	0·262597	02·518	38·70
822	5534	0·300426	23·194	39·06	839	5302	0·220162	08·480	12·54
	5585	0·361675	28·923	29·10		5312	0·378813	37·015	59·46
	5561	0·337899	33·334	40·24		5326	0·401025	02·518	38·71
823	5529	0·301096	23·300	42·23	840	5292	0·267828	22·653	35·25
	5540	0·448970	00·007	07·72		5310	0·347030	28·441	57·38
	5541	0·249934	28·232	09·69		5331	0·385142	40·154	44·65
824	5522	0·333278	34·949	51·66	841	5321	0·345928	06·706	05·27
	5556	0·429128	50·653	41·64		5326	0·338082	02·518	38·70
	5534	0·237594	23·195	39·06		5356	0·315990	23·778	40·80
825	5504	0·261232	38·540	30·64	842	5320	0·273410	56·327	00·23
	5524	0·404840	11·046	33·86		5325	0·294460	01·044	12·77
	5529	0·333928	23·300	42·23		5349	0·432130	39·406	34·23
826	5499	0·379692	50·902	27·11	843	5646	0·402986	14·162	25·53
	5536	0·246502	37·839	01·17		5677	0·219381	50·024	44·57
	5517	0·373806	54·714	33·33		5680	0·377633	29·436	49·74
827	5488	0·468630	02·275	28·33	844	5381	0·379346	18·082	00·39
	5503	0·208141	33·516	55·65		5670	0·385071	17·542	25·66
	5507	0·323229	55·260	37·83		5685	0·235583	08·963	35·40
828	5491	0·485070	48·225	32·32	845	5713	0·252844	07·044	23·47
	5494	0·151433	05·102	59·65		5733	0·414797	10·381	31·34
	5505	0·363497	37·942	49·09		5746	0·332359	24·680	22·77
829	5444	0·525642	08·378	25·95	846	5719	0·343150	22·690	40·17
	5468	0·231108	48·883	26·14		5723	0·375746	55·591	07·44
	5475	0·243250	18·301	54·94		5753	0·281104	06·748	43·57

Table II—*continued*

No.	Star	Depend.	R.A.	Dec.
847	7505	0·337836	26·657	31·88
	7514	0·210432	11·612	35·72
	7540	0·451732	54·978	34·18
848	7504	0·332402	08·694	58·12
	7530	0·186468	25·597	04·01
	7536	0·481130	00·857	27·20
849	7539	0·221648	13·152	58·63
	7544	0·523231	31·064	32·33
	7551	0·255121	45·067	53·27
850	7527	0·303636	46·753	15·56
	7550	0·245096	28·683	48·49
	7554	0·351267	15·041	57·81
851	7355	0·435764	54·173	49·92
	7356	0·273850	56·374	44·43
	7374	0·290386	28·550	35·70
852	7342	0·272108	53·572	32·64
	7362	0·431200	25·791	02·22
	7372	0·296692	04·694	50·05
853	7295	0·220344	32·830	44·74
	7321	0·513860	58·369	04·80
	7328	0·265796	32·697	22·00
854	7310	0·473984	44·220	57·11
	7322	0·231504	01·836	27·66
	7330	0·294512	37·628	56·61
855	7268	0·292908	26·320	52·26
	7269	0·373613	32·635	06·57
	7292	0·333478	18·461	52·12
856	7256	0·381122	45·165	39·88
	7277	0·308756	34·210	16·39
	7303	0·310122	35·924	21·19
857	7696	0·379695	16·288	01·67
	7705	0·395216	41·953	03·40
	7709	0·225089	14·429	38·10
858	7689	0·544647	29·369	18·67
	7703	0·198112	29·478	22·94
	7722	0·257241	54·223	14·34
859	7668	0·284275	22·996	07·05
	7696	0·481317	16·288	01·68
	7708	0·234408	14·424	46·64
860	7672	0·338857	15·469	51·80
	7688	0·329132	26·238	24·48
	7709	0·332012	14·429	38·10
861	7641	0·351958	16·780	19·09
	7664	0·336796	43·239	54·72
	7692	0·311246	40·909	31·14
862	8716	0·343064	01·528	53·73
	7660	0·393358	52·990	22·83
	7700	0·263578	35·012	59·31
863	8720	0·265192	13·266	36·21
	8751	0·273096	11·425	48·61
	8762	0·461713	31·869	53·96
864	8723	0·277731	39·910	06·48
	8750	0·287292	07·534	37·99
	8761	0·434977	29·446	59·34
865	8761	0·445130	29·447	59·34
	8796	0·382459	54·740	02·78
	8766	0·172411	12·374	01·21
866	8759	0·353126	02·768	04·79
	8800	0·342912	28·247	05·56
	8770	0·303962	21·908	49·88
867	8761	0·316142	29·447	59·35
	8799	0·418963	08·472	47·65
	8776	0·264895	27·195	41·00
868	8751	0·251302	11·426	48·61
	8787	0·404961	51·639	31·38
	8794	0·343737	39·394	19·72
869	3755	0·372320	20·898	29·62
	3759	0·280362	11·099	17·89
	3767	0·347318	51·903	06·54
870	3751	0·459731	40·585	36·58
	3762	0·219900	05·911	49·11
	3772	0·320369	38·229	04·14
871	3720	0·229014	55·491	39·18
	3735	0·477335	11·979	49·89
	4954	0·293651	30·039	37·73
872	3717	0·338688	53·245	56·34
	3739	0·302758	28·980	01·82
	4958	0·358554	28·238	01·66
873	4910	0·313044	16·764	11·05
	4919	0·420399	35·928	02·85
	4931	0·266557	55·508	39·35
874	4902	0·377086	08·638	39·99
	4926	0·270494	01·571	27·73
	3717	0·352419	53·245	56·34
875	4871	0·321511	33·444	08·23
	4873	0·464002	44·467	45·41
	4881	0·214487	48·872	37·70
876	4861	0·244082	17·506	56·91
	4875	0·481652	11·086	43·69
	4884	0·274266	19·668	45·52
877	4822	0·291314	15·515	50·66
	4839	0·310046	42·165	13·03
	4847	0·398640	12·506	55·97
878	4820	0·292875	47·527	31·88
	4846	0·372263	05·098	32·59
	4849	0·334862	18·838	47·73
879	3617	0·242315	47·941	46·90
	4782	0·284572	47·218	35·58
	4790	0·473113	54·161	44·64
880	4768	0·433148	33·491	45·73
	4787	0·175497	31·232	36·03
	3637	0·391355	22·041	13·70
881	3607	0·326654	25·511	22·13
	4769	0·285174	01·344	30·20
	4790	0·388172	54·161	44·64
882	3612	0·314368	56·554	57·35
	4768	0·333407	33·491	45·73
	4789	0·352225	33·922	51·45
883	3612	0·381416	56·554	57·35
	3632	0·256947	45·955	29·81
	4768	0·361637	33·491	45·73
884	3618	0·434692	50·406	48·48
	3634	0·186853	54·125	44·16
	4769	0·378455	01·343	30·20
885	3610	0·282714	09·629	22·05
	3624	0·336633	38·275	07·31
	3627	0·380652	23·434	24·12
886	3614	0·380901	18·545	08·33
	3618	0·249447	50·405	48·48
	3628	0·369652	25·672	19·26
887	3609	0·343210	59·668	42·59
	3627	0·455987	23·434	24·12
	4927	0·200803	35·146	53·40
888	3614	0·393083	18·545	08·33
	3626	0·349484	19·458	00·73
	3628	0·257434	25·672	19·26
889	3624	0·356954	38·276	07·31
	4919	0·395897	04·107	25·81
	4945	0·247148	03·728	30·59
890	4913	0·215240	07·537	36·44
	4941	0·201653	20·151	45·33
	3626	0·583106	19·458	00·73

Table II—*continued*

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
891	4925	0·266509	09·688	57·91	913	6333	0·363812	51·638	38·25
	4935	0·288141	11·556	00·77		6403	0·353674	32·303	26·86
	4946	0·445350	04·273	22·60		6453	0·282515	15·660	42·86
892	4919	0·306863	04·107	25·81	914	6366	0·585622	20·991	32·13
	4943	0·378822	49·920	36·11		6370	0·251318	44·497	55·17
	4947	0·314315	12·656	49·31		6400	0·163060	21·984	02·32
893	4948	0·279699	18·252	30·74	915	6261	0·384989	26·309	14·21
	4956	0·398107	45·238	49·74		6278	0·217461	44·185	32·15
	4973	0·322194	03·495	25·50		6320	0·397550	53·837	00·52
894	4943	0·432322	49·921	36·13	916	6253	0·371178	23·053	29·11
	4969	0·285041	06·444	46·62		6299	0·311820	37·277	30·64
	4970	0·282637	19·653	53·38		6313	0·317002	59·547	19·12
895	5211	0·300332	06·324	36·29	917	6217	0·384338	39·516	12·71
	5213	0·324327	35·988	32·73		6273	0·218476	55·972	18·64
	5230	0·375341	40·986	50·53		6264	0·397186	06·818	00·10
896	5205	0·221190	59·773	25·43	918	6231	0·230728	11·979	54·39
	5218	0·419780	32·130	41·96		6236	0·473518	30·373	51·57
	5224	0·359030	50·458	00·92		6263	0·295754	51·515	18·16
897	3758	0·273497	08·709	27·26	919	6186	0·273048	30·577	01·37
	3761	0·513562	33·804	49·02		6200	0·284996	25·891	01·87
	3767	0·212941	51·903	06·55		6209	0·441956	07·748	05·17
898	3756	0·266327	37·660	59·12	920	6187	0·384220	32·379	17·68
	3757	0·432826	28·128	09·09		6206	0·393322	08·605	18·84
	3775	0·300847	31·029	28·54		6217	0·222458	39·516	12·71
899	3734	0·336538	01·966	28·99	921	6126	0·279652	40·419	24·61
	3740	0·246404	03·233	42·75		6135	0·262563	27·412	16·02
	3756	0·417058	37·660	59·12		6155	0·457785	25·137	19·98
900	3737	0·295508	42·500	52·04	922	6124	0·373234	35·570	41·03
	3744	0·540264	12·626	57·40		6148	0·303088	59·212	20·20
	3758	0·164228	08·709	27·27		6156	0·323678	06·458	12·66
901	4857	0·321392	37·938	24·74	923	6088	0·473122	26·021	58·50
	4868	0·404718	22·895	18·49		6126	0·257674	40·419	24·60
	4883	0·273890	11·664	58·84		6208	0·269204	13·355	32·60
902	4853	0·228687	42·849	52·10	924	6102	0·242710	51·778	38·12
	4876	0·442408	20·848	27·61		6108	0·260480	56·790	17·42
	4877	0·328904	07·236	41·62		6114	0·496810	02·068	34·48
903	6405	0·326368	32·226	50·85	925	6088	0·176276	26·021	58·50
	6455	0·282994	22·904	51·74		6102	0·422769	51·777	38·12
	6472	0·390638	57·837	06·01		6172	0·400955	51·810	27·85
904	6414	0·281922	20·916	26·17	926	6145	0·352331	38·436	48·86
	6449	0·498119	02·087	40·78		6181	0·280126	46·693	55·40
	6473	0·219959	09·694	10·81		6112	0·367543	18·347	56·99
905	6463	0·297229	07·642	25·42	927	6118	0·412670	52·495	14·49
	6475	0·414072	26·756	46·47		6152	0·218869	53·908	16·42
	6516	0·288699	03·769	10·29		6167	0·368461	25·446	30·90
906	6449	0·236260	02·087	40·78	928	6135	0·163875	42·702	05·99
	6493	0·317849	56·934	31·66		6147	0·226630	52·668	56·87
	6494	0·445891	06·997	37·70		6148	0·609495	59·717	39·91
907	6475	0·349096	26·756	46·47	929	6125	0·304764	57·596	19·53
	6516	0·377050	03·769	10·28		6163	0·324036	11·920	51·70
	6425	0·273854	23·107	35·45		6477	0·371200	10·054	57·16
908	6484	0·351540	20·030	08·51	930	6475	0·362887	44·908	52·07
	6518	0·399175	14·976	16·46		6513	0·255351	04·795	11·21
	6412	0·249286	48·162	08·29		6140	0·381762	14·526	47·53
909	6375	0·267324	52·260	29·41	931	6490	0·347451	58·080	54·54
	6403	0·373412	32·303	26·86		6492	0·238102	06·944	30·32
	6493	0·359263	56·934	31·66		6532	0·414448	34·460	44·61
910	6379	0·457412	42·008	20·85	932	6474	0·300732	39·416	54·03
	6429	0·264680	44·907	55·74		6512	0·281830	04·116	01·92
	6475	0·277909	26·756	46·47		6527	0·417438	11·101	38·35
911	6366	0·406682	20·991	32·13	933	6550	0·213884	11·244	47·12
	6403	0·340448	32·303	26·86		6562	0·284246	12·187	58·70
	6493	0·252870	56·935	31·66		6597	0·501870	54·600	23·01
912	6373	0·271165	46·975	47·59	934	6529	0·226692	18·867	49·76
	6375	0·290456	52·260	29·41		6588	0·411246	19·512	22·20
	6419	0·438379	13·184	43·41		6595	0·362062	45·472	15·09

Table II—*continued*

No.	Star	Depend.	R.A.	Dec.
935	11451	0·397613	18·789	47·29
	11460	0·380764	00·255	59·65
	11490	0·221623	57·438	37·37
936	11449	0·244110	53·934	22·96
	11469	0·235264	56·553	27·57
	11471	0·520626	22·819	07·97
937	11415	0·432909	30·453	54·13
	11430	0·224483	34·071	07·47
	11433	0·342608	03·706	46·80
938	11400	0·321692	51·608	57·27
	11437	0·277014	10·307	02·88
	11440	0·401294	19·594	45·70
939	11237	0·313002	37·228	53·33
	11247	0·416973	45·307	29·65
	11272	0·270025	35·396	30·16
940	11243	0·549268	25·700	33·34
	11246	0·311978	39·348	14·87
	11292	0·138754	12·679	55·71
941	11149	0·232179	04·573	23·93
	11167	0·384622	28·121	31·25
	6538	0·383199	11·991	58·26
942	11115	0·445430	14·296	04·63
	11194	0·227503	16·637	19·07
	6564	0·327067	37·035	19·15
943	6495	0·244812	14·677	25·56
	6528	0·521091	25·844	47·87
	11115	0·234097	14·296	04·63
944	6506	0·512158	24·629	15·26
	6526	0·243542	59·691	53·88
	11139	0·244300	01·665	41·29
945	6398	0·205401	28·585	12·58
	6403	0·309974	28·115	33·42
	6432	0·484625	04·702	31·60
946	6393	0·339866	32·403	08·67
	6451	0·278260	15·417	10·40
	6415	0·381874	32·558	47·17
947	6386	0·261658	12·804	01·84
	6398	0·325960	28·586	12·57
	6415	0·412382	32·557	47·17
948	6391	0·323702	24·909	18·99
	6422	0·318282	10·848	58·89
	6396	0·358016	01·764	11·79
949	6340	0·182730	35·145	31·95
	6371	0·397562	48·236	49·65
	6381	0·419708	41·822	27·02
950	6351	0·305714	44·144	18·44
	6360	0·366555	08·871	01·21
	6396	0·327731	01·765	11·79
951	6351	0·274644	41·144	18·44
	6360	0·363085	08·871	01·21
	6389	0·362271	04·589	12·39
952	6340	0·171942	35·145	31·95
	6371	0·489181	48·236	49·65
	6381	0·338877	41·822	27·02
953	6363	0·309362	49·164	36·86
	6371	0·369218	48·236	49·65
	6389	0·321420	04·589	12·39
954	6361	0·472806	19·284	37·21
	6380	0·281997	15·784	52·11
	9396	0·245197	01·765	11·79
955	6370	0·370790	37·507	15·42
	6387	0·269874	41·850	51·23
	6410	0·359337	54·643	27·42
956	6363	0·259726	49·164	36·86
	6395	0·323772	51·688	02·98
	6400	0·416502	06·623	51·19
957	6735	0·324965	48·564	20·77
	6783	0·340877	07·982	56·80
	6829	0·334158	56·256	47·18
958	6769	0·296208	09·385	34·60
	6813	0·317583	03·018	05·07
	6760	0·386209	18·881	41·96
959	6797	0·247491	50·727	18·94
	6848	0·317173	34·562	22·73
	6786	0·435336	10·218	30·61
960	6760	0·314000	18·881	41·96
	6798	0·399181	07·692	46·63
	6839	0·286820	39·351	04·58
961	6763	0·227899	28·888	55·52
	6784	0·314836	53·001	29·53
	6801	0·457265	28·259	30·43
962	6760	0·257816	18·881	41·96
	6772	0·325087	46·705	57·21
	6808	0·417096	45·513	20·83
963	6678	0·373236	34·178	20·23
	6693	0·324260	58·142	54·47
	6719	0·302504	32·847	27·79
964	6667	0·243414	15·118	53·26
	6687	0·388576	18·974	31·15
	6722	0·368010	09·096	54·75
965	6648	0·260750	03·059	16·11
	6657	0·365332	42·857	46·06
	6678	0·373918	34·178	20·23
966	6647	0·424937	53·811	43·47
	6661	0·303704	34·403	39·28
	6688	0·271360	19·750	07·57
967	6577	0·468976	27·413	59·04
	6600	0·227732	15·005	36·84
	6616	0·303292	37·838	20·72
968	6563	0·372683	55·105	57·96
	6630	0·220408	43·109	09·13
	6650	0·406909	41·290	32·24
969	6529	0·218512	50·422	01·17
	6544	0·335624	40·807	59·52
	6510	0·445863	38·058	43·94
970	6525	0·230792	14·573	48·56
	6585	0·202910	52·499	33·52
	6492	0·566297	00·175	27·99
971	6458	0·386291	28·956	01·82
	6505	0·209090	41·981	18·21
	6512	0·404619	29·195	55·88
972	6477	0·215078	17·958	35·83
	6478	0·343428	21·451	39·58
	6509	0·441494	06·539	02·59
973	6414	0·240288	44·694	16·19
	6445	0·328216	56·803	07·67
	6447	0·431496	11·764	15·09
974	6419	0·370083	37·833	44·67
	6434	0·346008	08·018	45·67
	6477	0·283909	17·958	35·83
975	6370	0·376868	10·463	40·58
	6424	0·254714	18·159	04·49
	6872	0·368418	03·767	13·32
976	6828	0·263428	42·361	30·22
	6915	0·218818	49·752	22·77
	6400	0·517753	48·181	04·07
977	6851	0·342576	32·765	34·24
	6900	0·299008	30·348	53·66
	6402	0·358417	57·927	52·34
978	6861	0·439100	03·129	20·03
	6862	0·207960	11·092	04·82
	6897	0·352940	13·994	27·58

TABLE II—*continued*

No.	Star	Depend.	R.A.	Dec.
979	6878	0·419632	38·779	03·89
	6900	0·319516	30·348	53·66
	6936	0·260852	55·802	02·59
980	6865	0·427652	50·016	10·05
	6923	0·287646	58·717	14·61
	6926	0·284702	45·677	24·11
981	6901	0·372775	31·795	45·72
	6932	0·301345	14·628	32·71
	6936	0·325880	55·802	02·59
982	6878	0·353606	38·780	03·89
	6923	0·279205	58·717	14·61
	6957	0·367189	23·103	16·03
983	5192	0·246012	20·04	10·8
	5236	0·420334	20·19	43·2
	5241	0·333654	04·14	10·9
984	5209	0·358582	31·11	20·2
	5229	0·310074	26·75	52·9
	5242	0·331344	13·11	20·5
985	5177	0·422606	30·63	32·0
	5210	0·261198	42·55	59·1
	5220	0·316196	30·13	07·0
986	5182	0·321712	56·67	40·4
	5195	0·329581	30·19	11·0
	5225	0·348706	55·44	28·4
987	5486	0·501998	57·08	15·9
	5506	0·166920	32·43	48·3
	5530	0·331082	03·81	08·8
988	5465	0·224590	03·55	16·8
	5516	0·475334	29·10	03·8
	5518	0·300075	46·51	13·5
989	5486	0·346580	57·08	15·9
	5518	0·300992	46·51	13·5
	5530	0·352428	03·81	08·8
990	5494	0·389483	38·96	12·0
	5496	0·263760	46·75	30·5
	5537	0·346757	09·59	26·7
991	5563	0·294274	42·564	15·78
	5622	0·408712	11·397	56·37
	5624	0·297014	24·386	23·61
992	5566	0·340738	51·203	36·99
	5598	0·304058	23·574	28·25
	5641	0·355204	30·850	04·44
993	5615	0·310369	32·697	11·42
	5680	0·337116	03·234	13·28
	7517	0·352515	02·620	03·51
994	5622	0·306539	11·397	56·37
	5641	0·243516	30·850	04·44
	7534	0·449945	32·455	33·97

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Occultations Observed at Sydney Observatory during 1967-68

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 *Mount Stromlo Observatory Bulletins A* was applied to the 1967 observations to convert them to universal time (UT2). For 1968 the corrections to the observed times in UTC were derived from *Bureau International De L'Heure Circulaire D.* In 1967 a correction of +0·01028h (=37 seconds) was applied to the time in UT2 to convert it to ephemeris time with which *The Astronomical Ephemeris for 1967* was entered to obtain the position and parallax of the Moon. In 1968 this correction was +0·01056h (=38 seconds). The apparent places of the stars of the 1967–68 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, 1967). The observers were W. H. Robertson (R), K. P. Sims (S) and H. W. Wood (W). Except for occultations 497, 498 and 525 which were reappearances at the dark and bright limbs, 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 are those of the *Catalog* of 3539 *Zodiacal Stars for Equinox* 1950·0 (Robertson, 1940).

References

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SIMS, K. P., 1967. *J. Proc. Roy. Soc. N.S.W.*, **100**, 189. Sydney Observatory Papers No. 56.

TABLE I

Serial No.	Z.C. No.	Mag.	Date	U.T.2	UT2–UTC	Observer
493	0598	5·7	1967 Mar. 17	9 20 49·34	+0·03	R
494	1416	7·2	1967 Apr. 19	12 39 53·06	+0·03	R
495	1647	6·7	1967 Apr. 21	9 31 41·55	+0·03	S
496	2025	6·8	1967 Apr. 24	10 50 07·86	+0·03	R
497	2480	5·3	1967 Apr. 27	14 34 37·23	+0·03	S
498	2479	5·3	1967 Apr. 27	14 34 42·03	+0·03	S
499	1733	5·2	1967 May 19	13 21 10·43	+0·04	W
500	1544	5·7	1967 July 11	7 55 53·83	+0·04	W
501	2424	6·9	1967 July 18	8 37 50·63	+0·04	R
502	2427	7·1	1967 July 18	9 53 03·67	+0·04	R
503	1134	5·0	1968 Apr. 6	9 01 56·53	+0·02	W
504	1137	5·1	1968 Apr. 6	9 22 04·62	+0·02	W
505	1139	8·0	1968 Apr. 6	9 54 33·69	+0·02	W
506	1740	7·6	1968 June 5	10 04 42·58	+0·02	R
507	1746	7·1	1968 June 5	12 59 27·27	+0·02	S
508	1865	7·2	1968 June 6	13 16 16·57	+0·02	S

TABLE I—*Continued*

Serial No.	Z.C. No.	Mag.	Date	U.T.2	UT2–UTC	Observer
509	1966	8·1	1968 June 7	8 15 31·83	+0·02	R
510	1596	7·0	1968 July 1	7 46 58·92	+0·03	R
511	1603	7·1	1968 July 1	10 09 26·62	+0·03	R
512	1824	7·8	1968 July 3	12 51 13·28	+0·03	S
513	1911	7·1	1968 July 31	11 32 36·37	+0·03	R
514	2031	8·7	1968 Aug. 1	12 26 18·67	+0·03	S
515	2153	8·4	1968 Aug. 2	12 02 32·34	+0·03	R
516	2289	8·1	1968 Aug. 3	8 26 52·74	+0·03	W
517	2299	6·4	1968 Aug. 3	11 02 19·10	+0·03	W
518	2449	7·5	1968 Aug. 4	8 18 19·20	+0·03	W
519	2470	6·1	1968 Aug. 4	13 43 09·24	+0·03	W
520	2617	4·7	1968 Aug. 5	7 58 55·13	+0·03	W
521	2644	6·3	1968 Aug. 5	12 35 48·96	+0·03	W
522	2257	6·7	1968 Aug. 30	11 02 43·83	+0·02	S
523	2366	1·2	1968 Sept. 27	8 30 48·73	+0·01	S
524	2373	6·2	1968 Sept. 27	9 36 23·26	+0·01	S
525	2366	1·2	1968 Sept. 27	9 36 51·19	+0·01	S
526	2536	7·4	1968 Sept. 28	11 05 20·10	+0·01	W
527	3180	8·2	1968 Oct. 2	12 48 38·33	+0·01	R
528	2489	8·5	1968 Oct. 25	10 10 37·83	+0·02	S
529	3391	6·8	1968 Oct. 31	9 48 09·79	+0·02	W
530	3389	7·6	1968 Oct. 31	9 52 36·95	+0·02	W
531	3388	5·6	1968 Oct. 31	10 03 41·93	+0·02	W
532	3394	7·4	1968 Oct. 31	10 56 44·22	+0·02	W
533	2583	5·8	1968 Nov. 22	9 22 26·76	+0·02	S
534	3240	6·6	1968 Nov. 26	12 40 07·23	+0·02	R

TABLE II

Serial No.	Lunation No.	p	q	p^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of	
										$\Delta\alpha$	$\Delta\delta$
493	547	+64	+77	41	+49	59	−0·5	−0·3	−0·4	+5·6	+0·91
494	548	+67	−74	45	−50	55	0·0	0·0	0·0	+5·3	−0·93
495	548	+80	−60	64	−48	36	+0·6	+0·5	−0·4	+6·7	−0·89
496	548	+90	+43	81	+39	19	−1·1	−1·0	−0·5	+14·7	0·00
497	548	−70	−71	49	+50	51	+0·8	−0·6	−0·6	−10·7	−0·60
498	548	−71	−71	50	+50	50	−0·2	+0·1	+0·1	−10·8	−0·59
499	549	+74	−67	55	−50	45	−0·3	−0·2	+0·2	+5·1	−0·94
500	551	+77	−63	60	−49	40	+0·5	+0·4	−0·3	+6·4	−0·90
501	551	+98	−18	97	−18	3	+0·1	+0·1	0·0	+12·6	−0·36
502	551	+94	−34	88	−32	12	−0·3	−0·3	+0·1	+11·6	−0·51
503	560	+89	+46	79	+41	21	−1·4	−1·2	−0·6	+12·5	+0·33
504	560	+98	−20	96	−20	4	−0·5	−0·5	+0·1	+12·4	−0·34
505	560	+100	+ 2	100	+2	0	+1·4	+1·4	0·0	+13·1	−0·14
506	562	+87	−49	76	−43	24	+0·5	+0·4	−0·2	+8·1	−0·84
507	562	+74	−68	54	−50	46	+1·5	+1·1	−1·0	+4·9	−0·95
508	562	+96	−28	92	−27	8	−2·0	−1·9	+0·6	+10·7	−0·70
509	562	+59	−81	35	−48	65	+0·8	+0·5	−0·6	+2·7	−0·98
510	563	+97	+25	94	+24	6	−0·7	−0·7	−0·2	+14·4	−0·22
511	563	+97	−23	95	−22	5	−1·5	−1·5	+0·3	+11·2	−0·65
512	563	+84	+54	71	+45	29	+0·6	+0·5	+0·3	+15·0	+0·08
513	564	+47	+88	22	+41	78	−0·1	0·0	−0·1	+12·1	+0·58
514	564	+97	+25	94	+24	6	+0·9	+0·9	+0·2	+14·3	−0·17
515	564	+81	+59	65	+48	35	−0·9	−0·7	−0·5	+13·5	+0·28
516	564	+76	+65	58	+49	42	−0·8	−0·6	−0·5	+12·3	+0·43
517	564	+100	+6	100	+6	0	+0·1	+0·1	0·0	+13·4	−0·19
518	564	+86	+51	74	+44	26	−0·3	−0·3	−0·2	+12·4	+0·38
519	564	+52	−85	27	−44	73	+1·0	+0·5	−0·8	+5·5	−0·91

TABLE II—*continued*

Serial No.	Lunation No.	p	q	q^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of	
										$\Delta\alpha$	$\Delta\delta$
520	564	+45	−89	20	−40	80	+0·7	+0·3	−0·6	+5·8	−0·90
521	564	+97	+26	93	+25	7	−0·4	−0·4	−0·1	+13·2	+0·03
522	565	+90	+43	81	+39	19	−0·6	−0·5	−0·3	+13·5	+0·16
523	566	+93	−37	86	−34	14	−0·3	−0·3	+0·1	+11·2	−0·55
524	566	+81	−58	66	−47	34	+2·0	+1·6	−1·2	+9·2	−0·73
525	566	−86	−52	73	+44	27	−0·1	+0·1	+0·1	−12·6	−0·34
526	566	+72	−70	51	−50	49	+0·6	+0·4	−0·4	+8·9	−0·74
527	566	+100	−8	99	−8	1	0·0	0·0	0·0	+13·6	+0·31
528	567	+98	−19	96	−19	4	+0·1	+0·1	0·0	+12·8	−0·28
529	567	+99	−16	97	−16	3	−0·2	−0·2	0·0	+14·1	+0·32
530	567	+73	+68	53	+50	47	−0·2	−0·1	−0·1	+4·9	+0·94
531	567	+45	+89	20	+40	80	−0·2	−0·1	−0·2	−0·1	+1·00
532	567	+94	−33	89	−31	11	−0·7	−0·7	+0·2	+14·7	+0·14
533	568	+99	−12	99	−12	1	+0·1	+0·1	0·0	+13·1	−0·14
534	568	+40	−92	16	−37	84	+2·4	+1·0	−2·2	+10·9	−0·66

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A Note on a Kinematical Derivation of Lorentz Transformations

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1. There is a close analogy between the assumptions of Milne's Kinematical Relativity (Milne, 1948) and the k-calculus with the help of which Bondi (1964) derives Lorentz transformations. In both accounts a rigid measuring rod is replaced by measurements of distance carried out by means of light signals. This is particularly appropriate when " distant " events are being observed since a " measuring rod " can, at best, be transported only to the nearest celestial bodies.

Kinematics based on signalling techniques will be called " Radar Physics ". The purpose of this note is to analyse the axioms needed to derive the velocity formula of Special Relativity from which the Lorentz transformations can be easily obtained. All observers (and all observable events) of Radar Physics are assumed to be equipped with a signal-sending device, a mirror capable of reflecting signals instantaneously, and with a clock. It is also necessary to assume that an observer can measure local velocities ; that is, that he can determine relative to himself, the speed of any signal he may send or receive. Likewise, he must be able to measure (again relative to himself) the speed of any observer who passes close to himself (coincides instantaneously at a given point in space).

Two observers, O and O′, situated at different points in space, can easily determine whether they are at rest relative to each other, or not. In fact, let t_0 and t_1 be the times of emission of consecutive signals as recorded by O, and let t_1 and t_2 respectively be the times when he receives these signals back, after their reflection by O′. If

$$t_1 - t_0 = t_2 - t_1, \qquad \ldots\ldots\ldots \quad (1)$$

O′ is said to be at rest relative to O, even if the velocity (according to O) of the reflected signal should differ from that of the emitted one. We must assume, however, that there is no fluctuation in the direction of their relative motion, if any. By repeating the above experiment several times in succession, O can also discover whether O′ is in a state of uniform motion relative to himself.

To simplify the analysis, let us assume that an observer always sends and receives signals with the same speed c. He cannot have any knowledge of what happens to the signal in transit. Hence he is constrained to define distances as if the transit speed of his signals were the same as measured locally. The relativistic principle of constancy of the velocity of light becomes then a purely local concept.

2. Let O and O′ coincide initially in space. At that instant they can synchronize their clocks to read

$$t_0 = t'_0 = 0.$$

Let us suppose also that O finds O′ moving with a speed

$$v = cV, \text{ say,}$$

so that V is dimensionless. Furthermore, let O and O′ observe a distant event E which remains, for the sake of simplicity, in their mutual line of sight (so that O, O′ and E are collinear in a flat space-time).

If a signal sent by O at $t_0 = 0$ is reflected by E at t_A (on E's clock ; t_A is not O-observable), and received by O again at t_1, the distance x_A of E as calculated by O, is

$$x_A = ct_A = c(t_1 - t_A). \quad \ldots\ldots\ldots \quad (2)$$

Hence

$$t_A = \tfrac{1}{2}t_1, \quad x_A = \frac{c}{2}t_1.$$

O then repeats the experiment with initial and final time readings t_1 and t_2 respectively, to get, say

$$x_B = \frac{c}{2}(t_2 - t_1), \quad t_B = \tfrac{1}{2}(t_2 + t_1). \quad \ldots\ldots \quad (3)$$

In this case, O would conclude that in the course of the observations E moved from A to B with an average speed

$$u=\frac{x_B-x_A}{t_B-t_A}=c\left(1-2\frac{t_1}{t_2}\right). \quad \ldots\ldots (4)$$

In a similar way O′ obtains for the "uniform speed" of E relative to himself

$$u'=c\left(1-2\frac{t'_1}{t'_2}\right). \quad \ldots\ldots\ldots (5)$$

Let

$$k=\frac{t_2}{t_1}, \quad k'=\frac{t'_2}{t'_1}. \quad \ldots\ldots\ldots (6)$$

A transformation law between u' and u (that is, the addition formula for velocities) corresponds, therefore, to a relation between k and k'.

3. Let us suppose that this transformation is of the form

$$k'=f(V)k+g(V), \ \ldots\ldots\ldots (7)$$

where f and g are at most bilinear functions of V, for all conceivable cases of uniform relative motion of O, O′ and E. When O and O′ read, on their respective clocks,

$$t_1=t_2, \quad t'_1=t'_2,$$

the event E coincides with them initially. Hence

$$f(V)+g(V)=1, \text{ for all } V. \quad \ldots . (8)$$

If O and O′ travel together so that their clock readings remain the same, we have

$$f(0)=1 \ \text{(that is, } g(0)=0\text{)}. \quad .. (9)$$

Next, suppose that O′ travels with the signal so that he is unable to communicate with O except by reversing his velocity with the consequences familiar from the discussion of the "clock paradox" of Special Relativity. In other words, we have $k'=1$ when $V=1$, or

$$f(1)=0 \ \text{(or } g(1)=1\text{)}. \quad \ldots . (10)$$

Finally, let O′ regard himself at rest, so that the relative velocity of O and O′ is reversed (hitherto we have been viewing the situation as it appears to O). We obtain

$$k=f(-V)k'+g(-V).$$

By comparison with (7), we have

$$g(-V)=-\frac{g(V)}{f(V)}$$

and

$$f(-V)f(V)=1. \quad \ldots\ldots\ldots\ldots (11)$$

The conditions (8)–(11) are sufficient to determine f and g uniquely. Indeed

$$f(V)=\frac{1-V}{1+V} \quad \text{and} \quad g(V)=\frac{2V}{1+V}. \quad .. (12)$$

or

$$1-\frac{2}{k'}=\frac{1-\frac{2}{k}-V}{1-V\left(1-\frac{2}{k}\right)}. \quad \ldots . (13)$$

4. By equations (4), (5) and (6), (13) becomes Einstein's formula for the addition of velocities:

$$u'=\frac{u-v}{1-\frac{uv}{c^2}}. \quad \ldots\ldots\ldots (14)$$

Special Lorentz transformations follow in the usual way providing we assume equivalence of the observers O and O′. For example, it is sufficient to require that O's clock should go faster than that of O′ if the former regards himself as being at rest and conversely. It is clear that the clocks of O and of O′ must register differently in any case.

It is harder to interpret the assumption involved in writing down (7). There seems to be no *a priori* reason for not having

$$\frac{1}{k'}=\frac{f(V)}{k}+g(V), \quad \ldots\ldots (15)$$

instead. Of course, if the transformation between k and k' is linear, that between $\frac{1}{k}$ and $\frac{1}{k'}$ is bilinear and conversely. In the latter case, an additional condition (for example, that $k=0$, implies $k'=0$)is necessary if (14) is to result. It follows that the choice made here (equation (7)) is to be preferred on the grounds of simplicity.

SUMMARY

A set of axioms is proposed for the derivation of Lorentz transformations in Bondi's "Radar Physics".

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Lorentz Transformations and Invariance of Maxwell's Equations

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It is well known that one of the fundamental assertions of the Theory of Special Relativity is the invariance of Maxwell's equations under Lorentz transformations in a flat space time continuum. The converse of this result is that if Maxwell's equations are invariant under a certain general class of linear transformation then the latter belong necessarily to the representations of the Lorentz group. Validity of the converse is less frequently realized. We shall prove it in this note.

Let us write Maxwell's equations in the standard, four-dimensional notation:

$$f_{\mu\nu,\nu}=S_{\mu}, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$f_{\mu\nu}=\varphi_{\nu,\mu}-\varphi_{\mu,\nu}, \quad \ldots\ldots\ldots \quad (2)$$

where Greek indices go from 1 to 4, comma denotes partial differentiation with respect to the coordinates x_{μ}, and the summation convention over repeated indices is used. φ_{μ} is the four-vector potential and S_{μ} the four-current density vector, and we restrict ourselves to a flat, pseudoeuclidean space time so that no distinction between covariant and contravariant vectors needs to be considered *a priori*. Indeed it is convenient to work in a linear vector space Σ to which x_{μ}, S_{μ}, etc., belong and in which the field tensor $f_{\mu\nu}$ represents an ordinary bilinear mapping.

The equations (1) and (2) are assumed to be invariant under a group of linear endomorphisms of Σ:

$$x'=Ax, \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

which induce on any vector $v\varepsilon\Sigma$ an identical transformation

$$v'=Av. \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

We shall say that the endomorphisms A form the Lorentz group if

$$AA^{T}=A^{T}A=I, \quad \ldots\ldots\ldots\ldots \quad (5)$$

the identity transformation, and A^{T} is the adjoint (or transpose) of A.

We assume that Σ admits an inner product, so that, for any $v\varepsilon\Sigma$, also $f\cdot v\varepsilon\Sigma$. The requirement of invariance implies that

$$(f\cdot v)'=f'\cdot v'. \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

(6) is an additional assumption in the proof. However, it says little more than that f is a tensor field. It is sufficient to consider only the first set of Maxwell's equations (eq. (1)). The second set (eq. (2)) then serves to define the structure of the electromagnetic field. From equations (4) and (6), we have

$$f'\cdot v'=f'\cdot Av=(f'A)\cdot v=Af\cdot v,$$

so that

$$f'=AfA^{-1}. \quad \ldots\ldots\ldots\ldots \quad (7)$$

We can write equation (1) in the form

$$f\chi=s \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where χ is the differential divergence operator. Then χ belongs to the dual space of Σ (e.g., Raikov, 1965) and therefore transforms according to the law

$$\chi=A^{T}\chi'. \quad \ldots\ldots\ldots\ldots\ldots \quad (9)$$

Since we have similarly to (6)

$$(f\chi)'=f'\chi', \quad \ldots\ldots\ldots\ldots\ldots \quad (10)$$

the last two equations give

$$f'\chi'=Af\chi'=AfA^{T}\chi,$$

or

$$f'=AfA^{T}. \quad \ldots\ldots\ldots\ldots\ldots \quad (11)$$

But the transformation (3) of the coordinates induces a unique transformation law of the field tensor. Hence, comparing (7) and (11), we have

$$A^{-1}=A^{T}, \quad \ldots\ldots\ldots\ldots \quad (12)$$

which is equivalent to the definition (5) of a Lorentz transformation.

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The First Commonwealth Statistician: Sir George Knibbs*

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The Constitution of the Commonwealth of Australia empowered the national government to engage in census-taking and statistical compilation and publication, and a *Census and Statistics Act* was passed in 1905, authorizing the creation of the Commonwealth Bureau of Census and Statistics. In the following year its work began under the direction of George Handley Knibbs.

(1) BIOGRAPHICAL NOTES

Knibbs was born in Sydney on 13th June, 1858, the son of John Handley Knibbs. He was educated as a surveyor and joined the General Survey Department of New South Wales in 1877, resigning in 1879 to take up private practice; in 1889–90 he joined the teaching staff of the University of Sydney's Engineering School as an independent lecturer in geodesy, astronomy and hydraulics, an appointment nominally held till 1905, when he was appointed Director-General of Technical Education for New South Wales and also Acting Professor of Physics at Sydney University. He joined the Royal Society of New South Wales in 1881 and was Honorary Secretary and Editor of its *Journal and Proceedings* for a total of nine years, and President in 1898–99. To 1906 he made 14 contributions to the Journal, mostly of a technical nature and arising from his work.[1]

He was also variously President of the Institution of Surveyors,[2] Sydney, of the New South Wales Branch of the British Astronomical Society,[3] and of the Society for Child Study. In 1902 he represented the University of Sydney on the board composing regulations for administering Cecil Rhodes' bequest providing scholarships to Oxford, and in 1902–03 travelled through Europe as a member of a commission on education.[4] He visited Europe from April to December, 1909, representing Australia at the International Congress on Life Insurance (Vienna), on the special committee revising the nomenclature of diseases (Paris), at an International Congress on the Scientific Testing of Materials (Copenhagen), at the International Institute of Statistics (Paris), and at the Geodetical Congress in London.

While Commonwealth Statistician, Knibbs sat on the board reporting on possibilities of the Canberra site and on the Royal Commission investigating the problems of trade and industry in war; he was a consulting member of the 1915 Committee on Munitions in War and sat on other wartime committees, and was chairman of the Royal Commission which in 1918–19 considered the taxation of Crown leaseholds. In 1919 he represented Australia at the London conference on double income tax and war profits, in 1920 attended the British Empire Statistician's Conference in London (chairing the Census Committee), and in 1921 was elected vice-president of the International Eugenics Congress, New York.

During his lifetime he received various honours, of which he was perhaps inordinately proud. He was created C.M.G. in 1911 and Knight Bachelor in 1923, was variously an Honorary Fellow of the Royal Statistical Society, a Fellow of the Royal Astronomical Society, an Honorary Member of the American Statistical Association and of the Statistical Societies of Paris and of Hungary, and a member of the International Institute of Statistics, the British Science Guild and the International Association for Testing Materials. In 1921 he presided over the Social and Statistical Section of the Conference of the Australasian Association for the Advancement of Science, and in 1923 was its General President.[5]

In 1921 Knibbs had left the Bureau to become Director of the newly constituted Commonwealth Institute of Science and Industry, resigning in 1926 and living in retirement till his death on 30th March, 1929.

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* The bibliographical details for this note were drawn from the catalogue of the National Library of Australia and from the catalogue (incomplete) and shelves of the Library of the Commonwealth Bureau of Census and Statistics. Many references were traced through later citations.

(2) KNIBBS AS STATISTICIAN

Knibbs considered his duties to extend far beyond the boundaries of statistical collection and processing in fields dictated by others. He saw himself as " assisting the administrative statesman with his counsel and advice ",[6] and it was to this end that he published such works as his report on social insurance, where he elaborated an organic theory of the state and justified public health measures on the grounds of national development rather than humanitarianism.[7]

His major interest was in vital statistics, and it was here that he won his international reputation. Here too he became involved in theory, embracing at least in the later part of his life a doctrine he labelled " The New Malthusianism ". He considered that at current growth rates the world would reach human capacity in two and a half centuries. Although he advocated increased population for Australia as necessary for self-preservation, he warned against indiscriminate immigration, thus reflecting contemporary government policy as well as social thinking.[8]

Knibbs was a mathematician and statistician rather than an economist,[9] although he was concerned with studying such phenomena as unemployment and fluctuations in the purchasing power of money. His emphasis within statistics was on social problems and improvement of the human condition. In his data collection he was always hampered by lack of co-operation from his hoped-for respondents, for his expectations of others were high. His suggestions for a detailed nosological classification[10] would have placed considerable strain on the medical profession, despite its undoubted worth, and his cost of living enquiries[11] were too onerous for most housewives to respond. Knibbs was a keen advocate of international statistical co-operation, and in particular of an international statistical institute as an offshoot of the League of Nations, but he had to be satisfied with a less grandiose Imperial statistical bureau.[12]

(3) KNIBBS AND THE EARLY WORK OF THE COMMONWEALTH BUREAU OF CENSUS AND STATISTICS

(i) *Unification of Statistical Collection*

Uniform statistical requirements for the Australian colonies were originally set by the British Government, but after the granting of responsible government divergences arose. In most States individual departments prepared their own statistics for a central collating department, and six pre-Federation conferences of State Statisticians failed to achieve uniformity in the methods, subjects and timing of statistical enquiries. Even in census-taking uniformity had proved impossible, although as the methods of individual colonies were based on United Kingdom practices they were similar. A conference of statisticians in Hobart in 1890, and another in Sydney in 1900, improved uniformity and effectiveness, but even so the presentation of the 1901 Census results was not uniform, and incomplete tabulation of results, and differences in the interpretation of terms meant Commonwealth totals were difficult to obtain in some cases.

The prime task of the newly established Bureau was therefore the achievement of uniformity, and a conference of State Statisticians and a New Zealand representative was held under Knibbs' presidency in 1906. The Commonwealth Statistician presented 150 forms ensuring comparability of State returns. Among the specific points he wished discussed were : the fixing of the areas to which various statistical aggregates should apply, as at that time territorial divisions for different purposes seemed unrelated and he felt it desirable to resolve the question before the 1911 census ; the best method of estimating the quantity and value of production, and the means of obtaining statistics concerning primary and secondary production, all industries and finance ; the attainment of greater precision in vital and social statistics and in estimates of the fluctuating populations of States ; the accurate recording of interstate trade and the adoption of a uniform listing of items in Trade and Customs returns,[13] and the necessity for uniformity of the order of supply of information to the Commonwealth office and a suggested list of precedence.

It was resolved by the conference that the extent of compilation by State bureaux, and where the conference had adopted set forms, the method and date of compilation should be the same ; that except for data collected in confidence the information in each bureau should be immediately available to other State bureaux and to the Commonwealth Statistician ; that rapid population movement in Australia necessitated a quinquennial rather than decennial enumeration of population ; that a monthly record of trade between States was necessary ; that production statistics should not disclose data for individual concerns, or, more generally, that secrecy was necessary to retain public confidence ; that the Commonwealth Statistician should prepare instructions for uniform compilation and interpretation of data, and that he should decide all questions of mathematical method ; and that publications of Commonwealth and States should be uniform in size and ordering of data.

(ii) *The Issue of the Official Year Book of the Commonwealth of Australia*

The issue of a *Year Book* was not new to Australia. Victoria's series began in 1873 when H. H. Hayter became Government Statist. New South Wales had its *Statistical Register* and Coghlan's annual *The Wealth and Progress of New South Wales* and *The Seven Colonies of Australasia.*

The first Commonwealth *Year Book,* published in 1908, contained statistics for the Federal period 1901–07, with corrected statistics for 1788–1900, such that the *Year Book* could become the authoritative source for Australian statistics. The statistics dealt with population and its characteristics, pastoral and agricultural production, forests, fisheries, and mines, manufacturing industries, domestic and foreign commerce, transport, communications, government and private finance, public instruction, justice, charity, local government, industrial matters and defence. The subject matter was to be viewed from three angles : the progress of Australia as a whole, its statistical comparisons with other countries, and the development of the States.

It was intended that each issue should contain not only statistics but articles dealing with special subjects of continuing interest such as the discovery, colonization and federation of Australia ; its geography, geology, flora, fauna and climate ; and land tenure and settlement. Most articles were to appear only once, though they might possibly be summarized in later issues. Use was to be made of maps, graphs and other diagrammatic representation.

The *Year Books* appear to have been well received by the public. Melbourne's *Argus* described the *Year Book* as " a monument to Knibbs' energy, clear-sightedness, and enthusiasm "[14] while *The Times* in a leading article, says of it : " The most wonderful book of its kind in the world . . . the creation of a genius . . . the Commonwealth Statistician, and there is no other publication in the Empire to compare with it ".[15] As Knibbs' *Year Book* was but a development of Coghlan's compilation for New South Wales, such personal praise was perhaps a little misplaced.

(iii) *The First Commonwealth Census*

That Knibbs was personally interested in demographic and social statistics is evident from his later papers for the Royal Society of N.S.W.,[16] his works on nosology,[17] the Bureau's publications during his term,[18] and his works on the problem of world population.[19] He was concerned with the collection of comprehensive and useful data and with its mathematical analysis. His most important demographic collection was the first Commonwealth census, a major effort in organization.

The third part of the *Census and Statistics Act* 1905 dealt specifically with the taking of the census, providing for a census in 1911 and in every tenth year thereafter. State supervisors were appointed, this being in all cases but one the State Statistician (Western Australia had the Chief State Electoral Officer). Each State was divided into census districts, in charge of enumerators who supervised individual collectors. The census date was selected as 3rd April, to coincide with the United Kingdom and other parts of the Empire, but this proved unsuited to local conditions as wet weather in Queensland delayed collection considerably.

Particulars to be specified in the schedule were laid down by the Act, mostly following existing State practices : name, sex, date of birth (or age last birthday only where actual date was unknown, for this resulted in a tendency for ages to be rounded to numbers ending in 0 or 5), condition as to, and date of existing marriage, relation to head of the household, sickness or infirmity (blindness or deaf-mutism), religion (optional query), education (whether able to read and write English or able to read only, illiterate, or receiving education), birthplace, length of residence in Australia if born abroad, and nationality. Profession or occupation was queried and the occupation of employer, or his industry, was investigated to help in classification. Eight main classes were distinguished in tabulation, including professional, domestic, commercial, transport and communication. These were eventually classified into 654 occupational groups. The grade of occupation was asked (e.g., employee). The occupation to be stated was that usually followed ; if the respondent had been unemployed for more than one week the period was to be stated. The questions concerning period of unemployment and employer's industry were innovations. This information was to be furnished in respect of each person in each dwelling on the night in question. Also to be specified were the material of the outer walls of the dwelling and the number of its rooms including kitchen and excluding bathroom. Under the Census Regulations the additional questions concerned—for persons—race, number of children (living or dead, from existing and/or previous marriage), date of arrival in Australia if born elsewhere (as a check on the length of residence query) ; for dwellings—the nature of the building (private home, hotel, etc.), whether the occupier was owner, tenant or rent purchaser, and the weekly rent payable or rental value per week.

Previously one schedule per dwelling had been used, with each personal query heading a vertical column and space for particulars of 20 persons provided horizontally. In this census each person was required to fill in, or to have filled in for him by the householder or the collector, a personal card. The householder was in addition required to fill in a card showing particulars of the dwelling and the numbers of personal cards enclosed, with names and sexes shown. The advantages of the personal cards were seen as numerous ; firstly, they would ease the task of dealing with returns ; secondly, the increased individual privacy allowed to persons such as residents of boarding houses was expected to call forth more accurate answers ; the work of the householder would be lightened ; and the risk of confusion on the householder's schedule was lessened. Collectors required to fill in locality details and check individual cards were less enthusiastic about their adoption, but Knibbs was always prepared to ask for more detailed information and time-consuming collection than respondents wished to give, as his own C.B.C.S. papers on vitality statistics show clearly. The householder's cards, besides giving information on dwellings and providing a check on personal cards, gave a summary of members of the household which could be used for a quick population count. Collectors kept compilation books in which they summarized population results, these summaries being checked by enumerators and passed quickly to the Commonwealth Statistician. State populations were required by the Commonwealth Electoral Office, and also by the Commonwealth Treasury for the allocation of *per capita* subsidies under the *Commonwealth Surplus Revenue Act,* 1910.

Although Knibbs on his visit overseas in 1909 had seen the organization and equipment of other bureaux and recent developments in scientific methods in census and statistics, he used neither tabulating nor sorting machines in the 1911 census as he felt the relatively small population and relatively simple combinations did not warrant them, but he introduced electrically-operated adding machines and some calculating machines. The card system, used in enumeration, was further employed in tabulation. Particulars of married couples were written on to conjugal cards before the household envelopes were destroyed and male and female cards separated. Answers were in some cases translated into a numeral code. The temporary tabulating staff was selected after an elementary examination by the Commonwealth Public Service Commissioner. Like collecting staff, they were bound by Declarations of Secrecy.

Results appeared in 17 *Census Bulletins*, with final results appearing in a full *Report*[20] ; this included a review of census development from about 4000 B.C., of modern methods of census-taking and some modern censuses, and of the history of census-taking in Australia. The objects of the census were outlined as falling into four groups : demographic (population and its distribution in space, sex, age, conjugal condition, birth, marriage and death rates, and life tables) ; socio-economic (families, dwellings, education, religion, occupation, infirm/dependent, emolument, scope and continuity of employment) ; ethnographic (race, nationality and immigration) ; and statistical and administrative. The objects of the census, historical notes, organization of the census and instructions for complying with requirements were previously covered by Knibbs in a pamphlet[21] issued prior to census day and distributed for public guidance, in many cases to school children who were the most literate members of the families concerned. Also discussed in the *Report* were the various methods of enumeration, e.g., population *de jure* or *de facto* (the canvasser and householder methods, respectively) and the scope of the census, e.g., whether the request for a few particulars only resulted in a greater accuracy of the replies. A detailed account of the preliminary work of the census was given to help with the organization of future censuses.

Also included with the *Statistician's Report* (Vol. 1 of the census) is the post-censal adjustment of population estimates for the intercensal period 1901–11. The use of intercensal records of natural increase and net immigration resulted in an overstatement,[22] the main cause of the discrepancy apparently being unrecorded departures (e.g. late bookings on board ship). Also, the census recorded all persons on ships between Australian ports, whereas overseas migration figures referred only to passengers. The difficulties in intercensal estimates of State populations and the need for at least a minor census quinquennially were discussed.

Detailed tables of census results for various classifications were given in Vols. II and III; most gave separate results for males, females and total population. The combination of figures for males and females was considered inappropriate to life tables, and for the occupational classification the cost of publication of data by sex was not justified by the results offered. Volume I reported on the detailed tables and their significance.

Appendix A to the *Statistician's Report* was Knibbs' " Mathematical Theory of Population ". Knibbs said his purpose in preparing this monograph had been twofold : to create mathematical techniques of analysis of vital statistics, and to interpret material from the 1911 census. He suggested that the formulae developed might be of value to other investigations making use of statistical methods. He pointed out that although fluctuations in numbers and constituents of population, and its varying characteristics, might appear to be subject to complex and dissimilar forces that rendered them unsuited to mathematical analysis, in fact this type of analysis tended to make their trend more definite and reveal their significance. For this purpose changes had to be assumed to occur continuously by infinitesimal amounts. Concepts were developed and expressed in formulae for population in the aggregate, its age and sex distribution, masculinity, natality, nuptiality, fertility, mortality and migration.

(iv) *The Organization of the Labour and Industrial Branch of C.B.C.S.*

This branch was formed to investigate subjects such as trade unionism, wages and hours of labour, strikes and lockouts, the unemployed, prices, fluctuations in the exchange value of goods and the cost of living, apprenticeship and industrial education, the employment of women and children, production costs and the regulation and restriction of output. The first reports were published after much research into the techniques adopted by other countries.[23]

Knibbs began in 1912 the compilation of the first Australian indexes of retail, wholesale and overseas trade prices. Earlier overseas discussions had dealt with matters which were largely sterile from the point of view of historical interpretation, and concerned the use of different formulae to measure concepts which were only vaguely defined. This may account for the previous lack of interest in Australia, for the approach to abstract concepts from a mathematical point of view would have held little appeal for Coghlan, the able New South Wales Statistician, who might have been expected to have kept abreast with these developments. He was primarily interested in statistical data as an aid in interpreting economic tendencies, and certainly made a great deal of use of prices in analysis, but largely of prices of individual items designed to illustrate general tendencies. With a relatively narrow range of products available in the nineteenth century, the course of price changes could perhaps be more easily charted by reference to a few such commodities. These individual price series at least in the wholesale price area—or indexes of a few closely related commodities taken together—are back in fashion as analytical tools in preference to general wholesale price indexes.

Knibbs found an exhaustive examination of price movements had been necessitated by the influence of variations in the cost of commodities on the decisions of industrial tribunals and wages boards. The investigation demonstrated the need for rigorous techniques, and as a mathematician he was drawn to the intricacies of price index formulae. Much of his work on the theory of price index numbers turned out to have ephemeral interest only, but it did lead to the production of the first Australian price indexes on a clearly defined formula. His strong and articulate advocacy[24] of this, the fixed weights aggregative index formula, was a factor in its wide acceptance overseas for practical purposes. Not only were Knibbs' theoretical discussions of index number formulae of a high order, his empirical work was considerably more sophisticated than that of most of his overseas colleagues. Most practical data collection up to this stage, and particularly in the nineteenth century, had been with wholesale prices, but Knibbs' collection and measurement of purchasing power of retail prices—for food, clothing and house-rent, was in itself a progressive step. He was interested in differences in prices between places as well as between times. His first effort in overseas trade price indexes was a combined import and export price index which did not prove particularly useful and later in his term of office the publication of a separate export price index was begun, but no separate import price series appeared.

(v) *The War Census and Wealth Estimates*[25]

The war census was authorized by the *Commonwealth War Census Act* of 1915, and taken from 6th to 15th September, the onus of obtaining cards from post offices being on respondents.

Two schedules were issued, the first to be filled in by all males aged 18 and under 60, this being a personal card designed to obtain details of names, addresses, ages, marital status and dependants, occupations, health, military training, nationality and firearms held. To all respondents between 18 and 45 who were not enemy subjects were sent recruiting appeals. The second schedule was a wealth and income card, " to be filled in by all persons aged 18 or upwards possessed of property, or holding property on trust, or in receipt of income, and by other persons, companies, corporations, associations corporate or unincorporate, institutions, or other bodies specified in any proclamation under the War Census Act ". It asked names, addresses, motor vehicles possessed, a series of questions on income from various sources and a further series on real and personal property. War loan appeals and prospectuses were issued to those shown to possess £1,000 or more. Considerable tabulation of results was undertaken, by occupations of males and of females, average net income, the aggregate net assets of males and of females in each State, the average net assets per return, and classes of assets.

Knibbs used the war census records to prepare an incomplete estimate of the private wealth of Australia in 1915. His total was £1,643m. An inventory-method estimate gave £1,620m., which, when allowance was made for items such as locally held government securities included in the wealth census was increased to £1,760m. He suggested that a combination of wealth census and inventory methods would give the most satisfactory results, rejecting probate-return methods, as the outcome of his devolution estimates based on probate returns and an average rate of devolution (the outcome of an involved argument) was unsatisfactory. He also discussed the relationship between wealth and income, obtained a frequency relationship for both males and females, and graphed their wealth-income surfaces.

A quinquennial inventory estimate of wealth was suggested by Knibbs, supplemented by a decennial census of wealth. Inventory estimates were continued by Wickens, who provided parallel estimates of human capital.

(vi) *Other*

Apart from these four major projects with which Knibbs was certainly associated, the Bureau during his term produced a wealth of statistics covering demography and social statistics, transport and communication, finance, production, overseas trade, customs and excise.[26] Special reports were prepared on topical subjects such as social insurance and superannuation.[27]

(4) CONCLUSION

With ability and confidence evident in all his work, Knibbs won for the new office of Commonwealth Statistician considerable prestige, confounding those who had criticized his appointment. Certainly he had been a surprising choice in the light of his inexperience in the field, although it appears that the obvious candidate, T. A. Coghlan, who had proved an able State Statist for New South Wales for two decades, had declined a Federal offer in 1904.[28]

Knibbs' early training in pure rather than social science, like Coghlan's career as a civil engineer, fitted him mathematically for his new post ; but his preoccupation with mathematical excellence, while undoubtedly producing results of major significance, remained untempered by the degree of human interest and perception which endowed Coghlan's work with much of its character.

Was Knibbs' transfer from the post of Commonwealth Statistician a demotion, although naturally none of the Prime Minister's remarks in announcing the appointment hint at this ? It is possible that his failure to concern himself with current economic questions coupled with self-assurance and didacticism bordering on pomposity may have rendered him unpopular with both his colleagues and political masters. On the other hand, his personality may have belied his written expression of it, for one obituary[29] refers to his " charm of manner and his unvarying kindness of heart " and says that " unlike many whose lives are associated with advanced mathematics, he remained intensely human in his outlook on life ". Certainly his interests were extraordinarily wide—he even turned his talents to verse[30]—and his descriptive works are still well worth perusal for the detailed portraits they draw of his times.

Notes

[1] " A System of Accurate Measurement by Means of Long Steel Ribands ", *Journal and Proceedings of the Royal Society of New South Wales*, 1885, Vol. XIX ; " The Theory of Repetition of Angular Measures with Theodolites ", 1890, Vol. XXIV ; " The History, Theory and Determination of the Viscosity of Water by the Efflux Method ", 1895, Vol. XXIX ; " Note on Recent Determinations of the Viscosity of Water by the Efflux Method " and " The Rigorous Theory of the Determination of the Meridian Line by the Altaximuth Solar Observations ", 1896, Vol. XXX ; " The Theory of the Reflecting Extensometer of Professor Martens " and " On the Steady Flow of Water in Uniform Pipes

and Channels ", 1897, Vol. XXXI ; the President's Anniversary Address appeared in 1899, Vol. XXXIII, with two further articles ; " Observations on the Determination of Drought-intensity " and " Some Applications of and Developments of the Prismoidal Formula " in the same issue ; " On the Relation, in Determining the Volumes of Solids, Whose Parallel Transverse Sections are n^{ic} Functions of Their Position on the Axis, Between the Number, Position and Coefficients of the Sections and the (Positive) Indices of the Functions " and " The Sun's Motion in Space ; Part I, History and Bibliography ", 1900, Vol. XXXIV ; " The Theory of City Design ", " On the Principle of Continuity in the Generation of Geometrical Figures in Pure and Pseudo-homaloidal Space of n-Dimensions ", and " Some Theorems Concerning Geometrical Figures in Space of n-Dimensions Whose $(n-1)$ Dimensional Generatrices are n^{ic} Functions of Their Position on an Axis, Straight, Curved or Tortuous ", 1901, Vol. XXXV ; " The Hydraulic Aspect of the Artesian Problem ", 1903, Vol. XXXVI.

[2] Prize essay on *The Nature and Public Utility of Trigonometrical, General and Cadastral Survey*, published by the Institution of Surveyors, N.S.W., Inc., 1891.

[3] *The Place of Astronomy in a Liberal Education*, Presidential Address to the Annual Meeting of the British Astronomical Association, N.S.W. Branch, printed by S. E. Lees, Sydney, 1898.

[4] *Commission on Primary, Secondary, Technical and Other Branches of Education* (Commissioners Knibbs and Turner), Government Printer, Sydney, 1904–05.

[5] *Science and its Service to Man*, Presidential Address to the Australasian Association for the Advancement of Science at the New Zealand meeting, January, 1923. (Report of the Sixteenth Meeting, W. A. G. Skinner, New Zealand Government Printer.) This was a popular exposition of some scientific wonders, e.g. in astronomy and electronics.

[6] G. H. Knibbs, " The Problems of Statistics ", Report of the Twelfth Meeting of the Australasian Association for the Advancement of Science, held at Brisbane, 1909, p. 509.

[7] G. H. Knibbs, *Social Insurance*, J. Kemp, Government Printer, Melbourne, September, 1910. His " organic theory of the State " is outlined in Crawford Goodwin's *Economic Enquiry in Australia*.

[8] Shortly before his death he published *The Shadow of the World's Future* or *The Earth's Population Possibilities and the Consequences of the Present Rate of Increase of the Earth's Inhabitants*. Ernest Benn, London, 1928.

[9] Knibbs' successor, Charles Wickens, described him thus in an obituary. *Economic Record*, November, 1929.

[10] " The Classification of Disease and Causes of Death, from the Standpoint of the Statistician ", an address by Knibbs to the Victorian Branch of the British Medical Association which was subsequently printed in the *Intercolonial Medical Journal of Australasia* for 20th June, 1907 (reprint by Stillwell and Co.). " Proposals of the International Statistical Institute regarding the Statistics of Tuberculosis ", reprinted from the *Transactions of the Eighth Session of the Australasian Medical Congress*. This was a translation of a paper presented by Dr. Jacques Bertillon to the 1907 Congress of the International Institute of Statistics. Also relevant here is " The Nomenclature of Diseases and Causes of Death ", a translation by Knibbs in 1907 ; a second edition, " Nomenclature of Diseases (Statistics of Morbidity-Statistics of Death) agreed upon by the International Commission charged with the Decennial Revision of the International Nosological Nomenclature (Bertillon Nomenclature) in its Second Session, 1909 ", including a Preface by Knibbs, was printed by W. A. Gullick, Government Printer, Sydney, 1910. " On the Statistical Opportunities of the Medical Profession " and " The Tuberculosis Duration Frequency Curves and the Number of Existing Cases Ultimately Fatal " were reprinted from the *Transactions of the Eighth Session of the Australasian Medical Congress* held at Melbourne in October, 1908. (J. Kemp, Government Printer, Melbourne.) " The International Nosological Classification and Accurate Certification of Causes of Death ", " The Secular Progress of Pulmonary Tuberculosis and Cancer in Australia for the past thirty years, their Annual fluctuation, and their frequency according to age ", " The Improvement in Infantile Mortality : its annual fluctuations and frequency according to age in Australia " and " The Secular and Annual Fluctuations of Deaths from Several Diseases in Australia ; scarlet fever, measles, whooping-cough, diphtheria and croup, typhoid, diarrhoea and enteritis and dysentery, and the frequency of death according to age of this last " were reprinted from the Journal of the Australasian Medical Congress, Sydney, September, 1911. (W. A. Gullick, Government Printer, Sydney, 1913.)

[11] C.B.C.S. *Inquiry into the Cost of Living in Australia*, McCarron, Bird and Co., Melbourne, December, 1911, and in *Labour Report* No. 4, " Expenditure on Living in the Commonwealth, November 1913 ".

[12] G. H. Knibbs, " The Organisation of Imperial Statistics ", *Journal of the Royal Statistical Society*, 1920, pp. 201–14, and " Statistics in Regard to World and Empire Development ", Report of the Fifteenth Meeting of the Australasian Association for the Advancement of Science held in Melbourne, 1921, pp. 181–204.

[13] E.g., a suggested listing of categories of Trade and Customs. At the urgent request of the Department of Trade and Customs the 1906 figures were published alphabetically, but for 1907 the new list was adopted.

[14] *Argus*, 1st April, 1929.

[15] *Ibid.*, cited as " several years ago ".

[16] " On the Influence of Infantile Mortality on Birthrate ", and " Note on the Influence of Infantile Mortality on Birthrate ", in 1908, Vol. XLII ; and *Abstract of Proceedings*, 1910, respectively. These were both reprinted as C.B.C.S. *Professional Papers*. " Studies in Statistical Representation : on the nature and computation of the curve $y-Ax^{m}e^{nxp}$ ", *Abstract of Proceedings*, 1910 ; " Statistical Applications of the Fourier Series, illustrated by the analysis of the rates of marriage, temperature, suicide, etc ", *Journal and Proceedings*, 1911 ; and (with F. W. Barford), " Curves, their Logarithmic Homologues, and anti-Logarithmic Generatrices ; as applied to Statistical Data ", 1914, Vol. XLVIII. These three studies were reprinted as C.B.C.S. *Professional Papers*. " Suicide in Australia : a statistical analysis of the facts ", 1911, Vol. XLV. Reprinted as a C.B.C.S. *Professional Paper*. " Multiple Births, Their Characteristics and Laws Mathematically Considered ", 1925, Vol. LIX. " The Human Sex-ratio and the Reduction of Masculinity through Large Families ", 1925, Vol. LIX. " Note on the Occurrence of Triplets Among Multiple Births ", 1926, Vol. LX. " Protegenesis

and Ex-nuptial Natality in Australia ", 1927, Vol. LXI. " Rigorous Analysis of the Phenomena of Multiple Births ", 1927, Vol. LXI. " Proof of the Laws of Twin Births ", 1927, Vol. LXI.

[17] See footnote 10.

[18] The Bureau's *Population and Vital Statistics Bulletin* (which from 1921 became *Demography Bulletin*) commenced publication in 1907. Bulletin No. 1 was *Determination of the Population of Australia for each quarter from 31st December, 1900 to 31st December, 1906*, comprising a review of census methods, the methods of estimating population, and the results of each census of the several States of Australia ; together with a complete tabular statement of the recorded fluctuations of the population of the several States since the inauguration of the Commonwealth. Bulletin No. 2 presented a *Summary of Commonwealth Demography for the years 1901–1906*, this being continued till 1910 on an annual basis ; and annual bulletins (beginning with Bulletin No. 8 for 1907) of *Vital Statistics of the Commonwealth* similarly continued till 1910, after which the two were amalgamated in *Commonwealth Demography*, which appeared annually till 1918. Bulletin No. 3, *Vital Statistics of the Commonwealth for the quarter ended 31st March, 1907*, began a quarterly series which continued till 1911, after which it was incorporated in the *Monthly* (later *Quarterly*) *Summary of Australian Statistics*. A *Social Statistics Bulletin*—statistics as to Education, Hospitals and Charities, and Law and Crime—was published from 1907 to 1915.

[19] See footnote 8 also. " The Problems of Population, Food Supply and Migration ", in *Scientia*, Vol. XXVI (December, 1919).

[20] *Census of the Commonwealth of Australia taken for the night between 2nd and 3rd April, 1911. Vol. I* contained the *Statistician's Report*, including appendices. Appendix A was entitled *The Mathematical Theory of Population, of its Character and Fluctuations and of the Factors which influence them, being an Examination of the general scheme of Statistical Representation, with deductions of necessary formulae ; the whole being applied to the data of the Australian Census of 1911, and to the elucidation of Australian population statistics generally*, and was also prepared by Knibbs. *Vol. II* contained parts 1–8 of the detailed tables (1. Ages, 2. Birthplaces, 3. Residence, 4. Education, 5. Schooling, 6. Religions, 7. Infirmities, 8. Aliens) and *Vol. III* parts 9–14 (9. Conjugal Condition, 10. Families, 11. Life Tables, 12. Occupations, 13. Dwellings, 14. Summary).

[21] *The First Commonwealth Census*, 3rd April, 1911 : Notes (J. Kemp, Government Printer, Melbourne). " The Evolution and Significance of the Census " appeared in the *Addresses and Proceedings*, 1910, of the Imperial Federation League of Australia.

[22] The 31st March, 1901, census figures for Australian population were 1,977,928 M., 1,795,873 F., giving a total of 3,733,801 ; corresponding figures for 3rd April, 1911, were 2,313,035 M., 2,141,970 F., total 4,455,005. This total was adjusted back to 31st March, 1911 ; comparison with the intercensal estimates showed an overstatement of 70,265.

[23] *Report* No. 1 (1912) concerned " Prices, Price Index and Cost of Living in Australia ". The next *Report* dealing with this subject was No. 4, *Expenditure on Living in the Commonwealth, November 1913 ; Price Indexes, their Nature and Limitations etc.* ; other *Reports* during Knibbs' term were No. 2, *Trade Unionism, Unemployment, Wages, Prices, and Cost of Living in Australia, 1891 to 1912* ; No. 3, *Manufacturing Industries in the Commonwealth, 1912* ; and Nos. 5–9, *Prices, Purchasing Power of Money, Wages, Trade Unions, Unemployment and General Industrial Conditions*. The quarterly Labour *Bulletin* appeared from March, 1913, till June, 1917, after which it was incorporated in the *Quarterly Summary of Australian Statistics*.

[24] *Labour Report* No. 1 had two appendices which bore Knibbs' name and contained most of the mathematical material : " Theory of Determining Price-indexes, Shewing Variations in the Exchange-value of Gold, or in the Cost of Living " (Appendix VIII) and " On the Establishment of a Basis for International Comparisons of the Exchange-value of Gold, and Variations in the Cost of Living " (Appendix IX). Appendix I gave a comprehensive bibliography of previous work on the subject. Knibbs' views were further developed in an article published by the American Statistical Association, " The Nature of an Unequivocal Price-index and Quantity-index ", which appeared in two parts in March and June, 1924. A less technical account appeared in " Price Indexes and Purchasing Power of Money ", a paper contributed to the Interstate Conference of Employers' Federations held in Melbourne in September, 1917, and issued by the Central Council of Employers in Australia, Melbourne, McCarron, Bird and Co., while his final word in the *Labour Reports* appeared in No. 9 (1918), *Price-indexes, Their Nature and Limitations, the Technique of Computing Them, and Their Application in Ascertaining Power of Money*, which had previously been published separately.

[25] The War Census of 1915 was reported in *The Private Wealth of Australia and its Growth as ascertained by various methods, together with a Report of the War Census of 1915*, published in 1918, McCarron, Bird and Co., Melbourne. Knibbs also contributed " The Private Wealth of Australia and its Growth " to M. Atkinson (ed.) *Australia : Economic and Political Studies, 1920*.

[26] In addition to publications mentioned in earlier footnotes, an annual *Transport and Communication Bulletin* was issued, the first covering the period 1901 to 1906, the second 1901 to 1908, the third 1901 to 1909, and so on. An annual *Finance Bulletin* also appeared, the first covering 1901 to 1907, 1916–17 to 1918–19 appeared in one volume, and future issues were to be biennial. The *Production Bulletin* was also annual, covering 1901–06, 1901–08, 1907–09, and so on.

The Commonwealth's Trade and Customs Returns were at first prepared by the New South Wales Government Statistician for the Minister for Customs ; in 1907 the Bureau of Census and Statistics published *Trade and Customs and Excise Revenue of the Commonwealth of Australia for the year 1906*. It continued to appear annually—with a change of financial year basis from 1914–15—and eventually became the *Oversea Trade Bulletin*. *Shipping and Overseas Migration of the Commonwealth of Australia* was issued by the Bureau for the period 1906 to 1915–16, when it was discontinued. It replaced the Department of Trade and Customs *Annual Statement of Navigation and Shipping*. A monthly bulletin of trade, shipping and overseas migration statistics appeared from January, 1907 ; from January, 1912, this became the *Monthly Summary of Australian Statistics* ; after September, 1917, this became the *Quarterly Summary of Australian Statistics* which has already been mentioned above as incorporating other published statistics.

The Bureau's major publication of a comprehensive nature has always been the *Official Year Book*, but a smaller publication, with description and statistics, was *The Australian Commonwealth : its resources and production*, which appeared annually from 1908 to 1915. *A Pocket Compendium of Commonwealth Official Statistics* was issued in 1913, 1914, 1916, and annually from 1918. (In 1916, it was published as a *Commonwealth Statistical Digest.*)

In addition, Knibbs edited " Miscellaneous Notes on Australia, its People and their Activities " in the Federal Handbook prepared in connection with the eighty-fourth meeting of the British Association for the Advancement of Science, held in Australia in August, 1914.

[27] Four special reports were prepared by Knibbs under Ministerial direction : *The Desirability of Improved Statistics of Government Railways in Australia* (February, 1909) ; *Social Insurance* (September, 1910, J. Kemp, Government Printer, Melbourne) ; *Superannuation* (October, 1910, J. Kemp, Government Printer, Melbourne) ; and *Local Government in Australia* (July, 1919, A. J. Mullet, Government Printer, Melbourne). He also compiled *Australian Life Tables, 1901–1910* (McCarron, Bird and Co., Melbourne, 1914), tables based on mortality experience of the Commonwealth of Australia, 1901–1910. *Australian Joint Life Tables, 1901–1910* were published in 1917.

[28] See E. C. Fry's 1965 A.N.Z.A.A.S. address, *T. A. Coghlan as an Historian*, and Joan M. Cordell, " T. A. Coghlan, Government Statist of New South Wales, 1886–1905 ", thesis submitted to the Department of Statistics, University of Sydney, 1960.

[29] *Melbourne Argus*, 1st April, 1929.

[30] *Voices of the North : and Echoes of Hellas*, Alston Rivers Ltd., London, 1913. Scandinavian and Greek sagas respectively.

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Triassic Stratigraphy—Blue Mountains, New South Wales

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ABSTRACT—Geological mapping in the Blue Mountains revealed previously unknown Narrabeen Group sediments in Glenbrook Creek and a modification of the previously recognized western boundary of the Hawkesbury Sandstone. Examination of the Hawkesbury Sandstone-Narrabeen Group stratigraphic boundary indicates that the Burralow Formation (upper Narrabeen) thins and undergoes a facies change in a westward direction. At the westernmost extent of the Hawkesbury Sandstone, between Hazelbrook and Lawson on the Great Western Highway, the Burralow Formation, although probably still present, cannot be distinguished from the Grose Sandstone.

Within the massive Grose Sandstone there are two extensive continuous reddish-brown claystone horizons which are used for subdivision and marker horizons.

Introduction

The Triassic Narrabeen Group exposed in the Blue Mountains of New South Wales (Figure 1) is a sequence of more than 1,000 feet of quartz lithic to quartzose sandstone, claystone and shale. The Narrabeen Group lies with apparent conformity on top of coal-bearing sediments of Permian age and is in turn overlain by the Triassic Hawkesbury Sandstone. There is no evidence of a major break in sedimentation throughout the sequence.

The purpose of this study was to examine the stratigraphy of the Narrabeen Group and to determine criteria for establishing the position of the Narrabeen Group-Hawkesbury Sandstone boundary.

Stratigraphy

Although the sandstones of the Blue Mountains appear to be flat-lying in individual outcrops, they possess a regional dip to the east. A slight change in dip accompanies the change from the Hawkesbury Sandstone to the Narrabeen Group. East of the Woodford Main Ridge the dip is $1\frac{1}{2}°$, while west of the ridge it is slightly steeper at between 2° and $2\frac{1}{2}°$. The Woodford Main Ridge represents the most westerly ridge made up completely of Hawkesbury Sandstone.

The Triassic Narrabeen Group in the Blue Mountains of New South Wales has been subdivided into three formations by Crook (1956). Within these formations Goldbery (1966) recognized various members. The stratigraphic position and subdivisions of the formations are shown in Table 1.†

Caley Formation

The Caley Formation (Crook, 1956) is the basal unit of the Narrabeen Group in the Blue Mountains. It immediately overlies with apparent conformity the uppermost coal seam of the Illawarra Coal Measures, the Katoomba Seam, while the top of the unit is determined by the presence of the prominent, massive sandstones of the overlying Grose Sandstone.

Crook (1956) measured a provisional partial section of the Caley Formation, one mile east of Mount Caley in the Grose River Valley. Goldbery (1966) subdivided the Caley Formation into five members, and at Beauchamp Falls, near Blackheath, measured a full section which he proposed as the type section for the formation.

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† A complete geological map too large for publication may be examined at the School of Applied Geology, University of New South Wales (Goodwin, 1968).

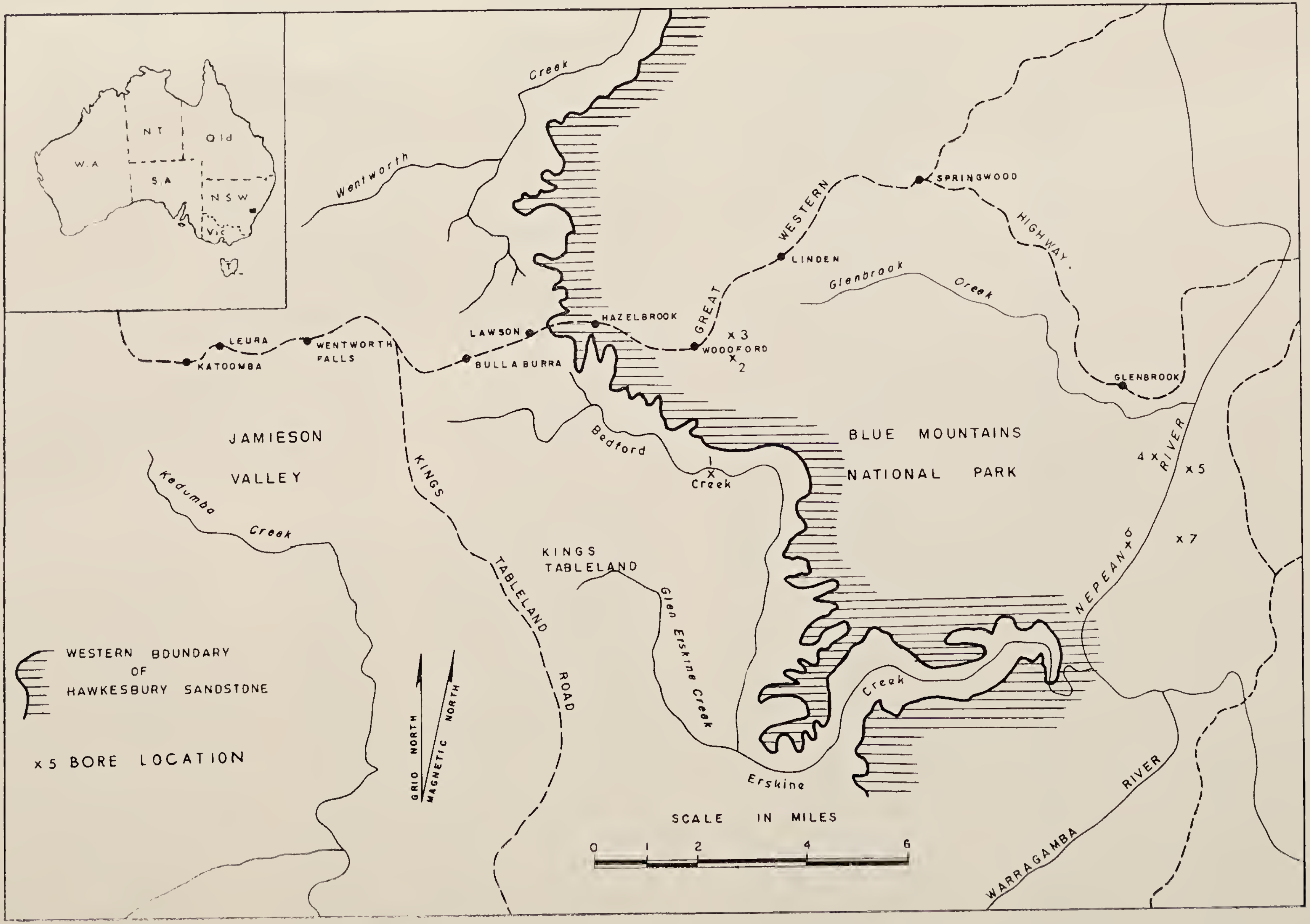

Fig. 1.—The study area showing the Hawkesbury-Sandstone–Narrabeen Group boundary and borehole localities: (1) Bedford Creek, (2) Woodford No. 1, (3) Woodford No. 2, (4) Euroke, (5) Mulgoa, (6) Breakfast Creek, (7) A.O.G. Mulgoa No. 2.

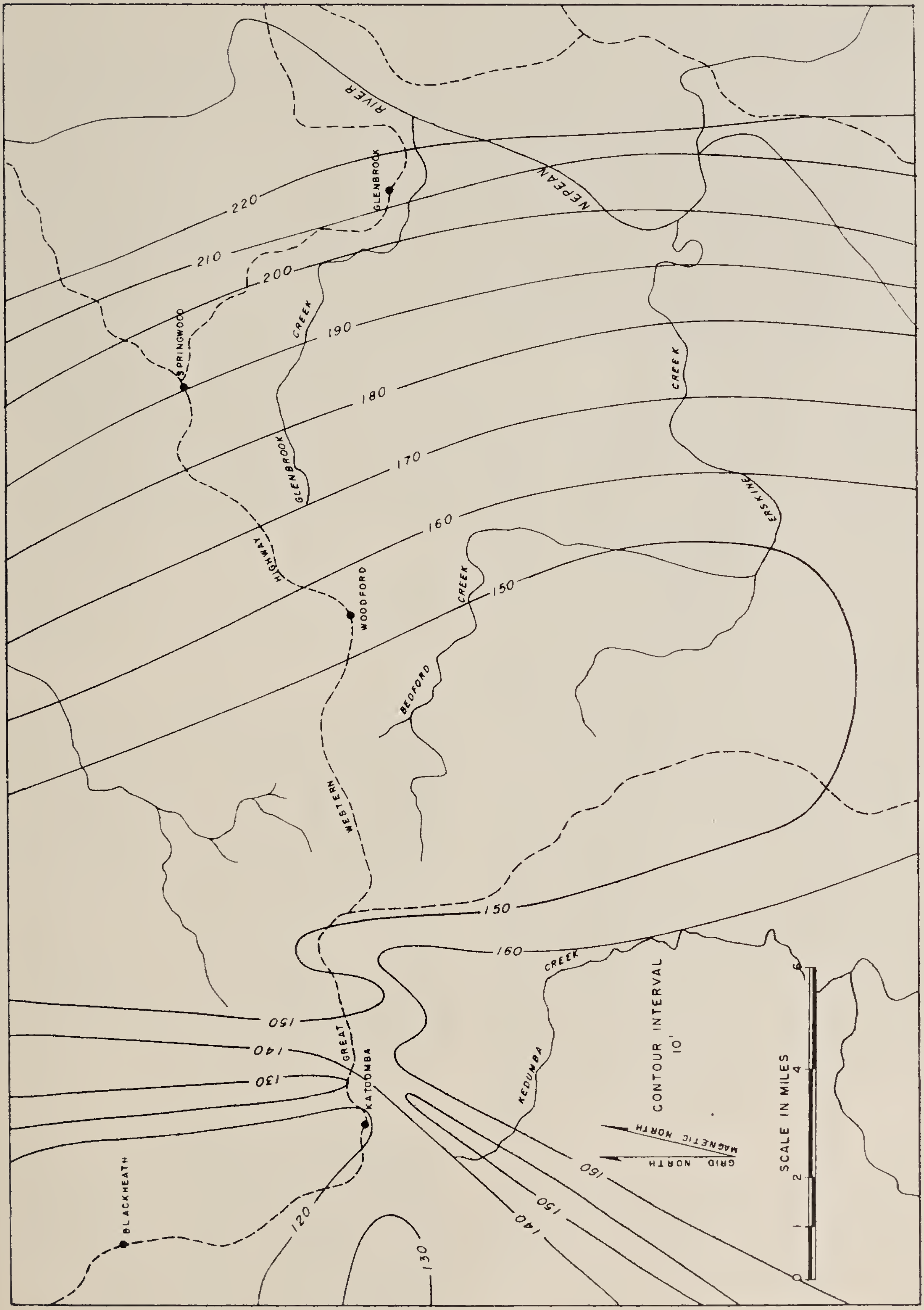

FIG. 2.—Isopach map of the Caley Formation.

Table 1

Stratigraphy of the Blue Mountains

System	Group	Formation	Member
TRIASSIC	Wianamatta Group	Ashfield Shale Mittagong Formation	
	Hawkesbury Sandstone		
	Narrabeen Group	Burralow Formation	
		Grose Sandstone	Banks Wall Sandstone
			Mount York Claystone
			Burra-Moko Head Sandstone
		Caley Formation	Hartley Vale Claystone
			Govett's Leap Sandstone
			Victoria Pass Claystone
			Clwydd Sandstone
			Beauchamp Falls Shale
PERMIAN	Illawarra Coal Measures		

The Caley Formation crops out at the base of the cliffs from Narrow Neck Peninsula to McMahon's Point, and in parts of Erskine Creek. The formation thickens to the east and south (Figure 2). At Katoomba it is 120 feet thick, whereas in the Bedford Creek Bore (Figure 1) it measures 162 feet. In the Kurrajong Heights No. 1 Bore located to the north and east of the study area the unit has a thickness of 250 feet.

In the Blue Mountains the Caley Formation has been subdivided into the five members of Goldbery (1966). However, in the Erskine Creek area, the middle member, the Victoria Pass Claystone is absent. The Caley Formation is distinguished from the Grose Sandstone by the presence of greater quantities of shale and claystone and by a slightly higher lithic content of the sandstones.

Within the Caley Formation the thickness of individual members is quite variable, however the overall thickness of the formation changes only gradually. The lithology of the Caley Formation is discussed with reference to the individual members.

Beauchamp Falls Shale Member

In all sections examined the Beauchamp Falls Shale forms the basal member of the Caley Formation. It is overlain by the Clwydd Sandstone and underlain by the Katoomba Seam, the uppermost unit of the Illawarra Coal Measures. It consists of interbedded carbonaceous shales, siltstones, claystones and fine-grained sandstones, a lithology which is distinctive in outcrop and easily identifiable even where the Katoomba Seam is absent.

A fluctuating depositional environment has produced marked variations in the thickness of this unit. In the Bedford Creek Bore it measures 31 feet 4 inches, at Wentworth Falls 17 feet, at the Valley of the Waters 28 feet, at Leura Falls 5 feet 8 inches, and at the Giant Stairway, Katoomba, 12 feet 9 inches.

Clwydd Sandstone Member

The predominant lithology of the Clwydd Sandstone is a coarse-grained quartz lithic sandstone. Occasionally this member contains fine-grained sandstones and lenticular claystones. Red and green subangular jasper pebbles up to $\frac{1}{4}$ inch in diameter are not uncommon in the coarse fraction.

The thickness of the member is variable. At Golden Stairway on Narrow Neck Peninsula, it is 17 feet, in the Bedford Creek Bore 26 feet 4 inches, while in Erskine Creek, where the

Victoria Pass Claystone is absent, it attains a maximum thickness of 130 feet.

VICTORIA PASS CLAYSTONE MEMBER

The Victoria Pass Claystone is the middle unit of the Caley Formation. It is recognizable by the hard dense grey claystone of which it is made up and the tendency of the unit to be eroded, forming a notch in the cliff face. The absence of the Victoria Pass Claystone in Erskine Creek makes the distinction between the Clwydd Sandstone and the Govett's Leap Sandstone tenuous.

The thickness of the Victoria Pass Claystone is variable. In the Bedford Creek Bore it is 17 feet 1 inch thick and is comprised of fine grey shale with some silty bands. Along the cliffs from Wentworth Falls to Katoomba, a distance of four miles, variations in thickness are quite apparent. At Wentworth Falls the thickness is 7 feet 1 inch, at Valley of the Waters 24 feet, at Leura Falls 9 feet, and at the Giant Stairway, Katoomba, 4 feet 6 inches.

With the exception of the Bedford Creek Bore, there is little variation in lithology throughout the study area. It is composed of a medium to dark grey, hard, dense claystone.

GOVETT'S LEAP SANDSTONE MEMBER

The Govett's Leap Sandstone is a fine- to coarse-grained quartz lithic sandstone. It contains a clay-rich matrix that tends to render the rock quite friable. In the Bedford Creek Bore the basal 4 feet 7 inches of the Govett's Leap Sandstone is a fine, light greenish grey conglomerate. This is the only occurrence of conglomerate in the Caley Formation within the study area.

The thickness of the Govett's Leap Sandstone is variable. In the Bedford Creek Bore it is 57 feet 8½ inches, while at Leura Falls it is 83 feet, and at the Golden Stairs on Narrow Neck Peninsula only 33 feet 6 inches.

HARTLEY VALE CLAYSTONE MEMBER

The Hartley Vale Claystone is the uppermost unit of the Caley Formation. It is distinctive as a fine-grained unit that usually forms a notch on the cliff face due to erosion and marks the base of the cliff, forming Grose Sandstone. The less resistant nature of this unit and the tendency of the overlying Grose Sandstone to fracture along vertical joint planes is presumably the reason for the formation of the great precipices for which the Blue Mountains are famous. If the Hartley Vale Claystone were more resistant to erosion than the Grose Sandstone, the development of talus slopes, similar to those associated with the Burralow Formation, would be expected.

The lithology of the Hartley Vale Claystone ranges from fine-grained sandstone to claystone and shale. The average thickness of the unit is 8 feet and variations are relatively small. With the exception of the Valley of the Waters, the unit is easily recognizable throughout the area studied. At the Valley of the Waters the lower portion of the Grose Sandstone contains numerous claystone bands and the precise position of the boundary between this unit and the underlying Caley Formation is uncertain.

Grose Sandstone

The Grose Sandstone, the middle formation of the Narrabeen Group, was named by Crook (1956) after the outcrops in the Grose River Valley. Here the massive sandstone attains thicknesses of 700 feet and forms majestic cliffs. The Grose Sandstone also forms the cliffs of the Jamieson and Megalong Valleys.

The Grose Sandstone crops out on the surface of the Blue Mountains Plateau from Lawson to Katoomba and in many of the river valleys in the study area. It has been subdivided into three members by Goldbery (1966).

Grose Sandstone :
  Banks Wall Sandstone Member.
  Mount York Claystone Member.
  Burra-Moko Head Sandstone Member.

The presence of the Mount York Claystone Member was confirmed by the author, who also found another continuous claystone horizon, usually distinctive by its reddish brown coloration, below the Mount York Claystone. This lower claystone is very useful as a marker horizon and can be used for mapping purposes. In order to prevent the nomenclature from becoming chaotic, this lower red brown claystone has not been given member status but herein is referred to as the " Unnamed Claystone Marker Bed ".

UNNAMED CLAYSTONE MARKER BED*

The " Unnamed Claystone Marker Bed " is a lower reddish brown claystone which crops out an average of 150 feet above the base of the Grose Sandstone. Generally it occurs between 130 and 170 feet above the base of the Grose

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* At the time of writing the nomenclature of the Blue Mountains is in a state of revision (see " Geology of the Western Blue Mountains ", N.S.W. Geol. Survey Bull. 20). Until finalized, the informal name of Katoomba Claystone is proposed for this unit.

Sandstone, whereas the Mount York Claystone is located 340–400 feet above that level. Along the cliff faces these two horizons are easily recognized by (1) their red coloration, (2) their weathering to form an erosional notch, and (3) by a line of trees commonly growing upon them. The reddish brown coloration is in places intermittent, although persistent, and represents the only reddish-brown claystones in the Narrabeen Group of the study area.

The " Unnamed Claystone Marker Bed " is continuous and may be traced along the cliffs from Narrow Neck Peninsula (Plate I) to McMahon's Point, a distance of almost 20 miles. It is evident in the Bedford Creek Bore, where the base is 127 feet above that of the Grose Sandstone and the thickness is 8 feet 6 inches. The contacts with the sandstones above and below are sharp and straight, virtually no brecciation or gradation being observed. In some stratigraphic sections, such as at the Giant Stairway, Katoomba, the claystone is split into several bands. The claystone bed normally forms an erosional notch on the cliff face (Plate II), while the colour varies from reddish brown to mottled, white and light grey.

The existence of this horizon was not noted by Goldbery (1966) in the Grose Valley. He does refer to a reddish-brown claystone, 5 feet 6 inches thick, in his Govett's Leap Stratigraphic Section, but states that it is lenticular " when observed on the nearby cliff face ".

The continuity and relatively constant thickness make the " Unnamed Claystone Marker Bed " useful for correlation and mapping. It is felt that re-examination of adjacent areas such as the Grose Valley and Burragorang Valley will show the presence of this horizon.

BURRA–MOKO HEAD SANDSTONE MEMBER

The lower member of the Grose Sandstone, the Burra-Moko Head Sandstone, has a maximum thickness in the study area of 670 feet at the Bedford Creek Bore. The unit thickens in a north-easterly direction (Figure 3) across the mapped area. The anomalous thickness centred on the Bedford Creek Bore location is a localized depositional high. The Mount York Claystone does not occur in the bore. A reddish brown claystone outcrops 80 feet above the level of the top of the bore and can be traced upstream several miles, where it can be correlated with the Mount York Claystone in several stratigraphic sections measured as a part of this study.

The lithology is medium- to coarse-grained quartz lithic sandstone. Quartzose sandstone is rare in this member. Lenticular claystones and shales are common and range up to 3 feet in thickness. The sandstones are often cross-stratified. The bedding is usually massive and the matrix is rich in clay minerals which tend to render the sandstone friable. Quartz pebbles up to 1 inch are common. Ironstone concretions are prevalent, however they are not as abundant as in the Banks Wall Sandstone Member.

Goldbery (1966) postulated a rapid thinning of this member in the Katoomba-Blackheath area ; however, this characteristic has not been substantiated by the present study. It would appear that Goldbery correlated the " Unnamed Claystone Marker Bed " at Kanimbla Valley, Megalong Valley, Narrow Neck Peninsula, Scenic Hill and Victoria Pass, with the Mount York Claystone along the western edge of the area covered by his study.

MOUNT YORK CLAYSTONE MEMBER

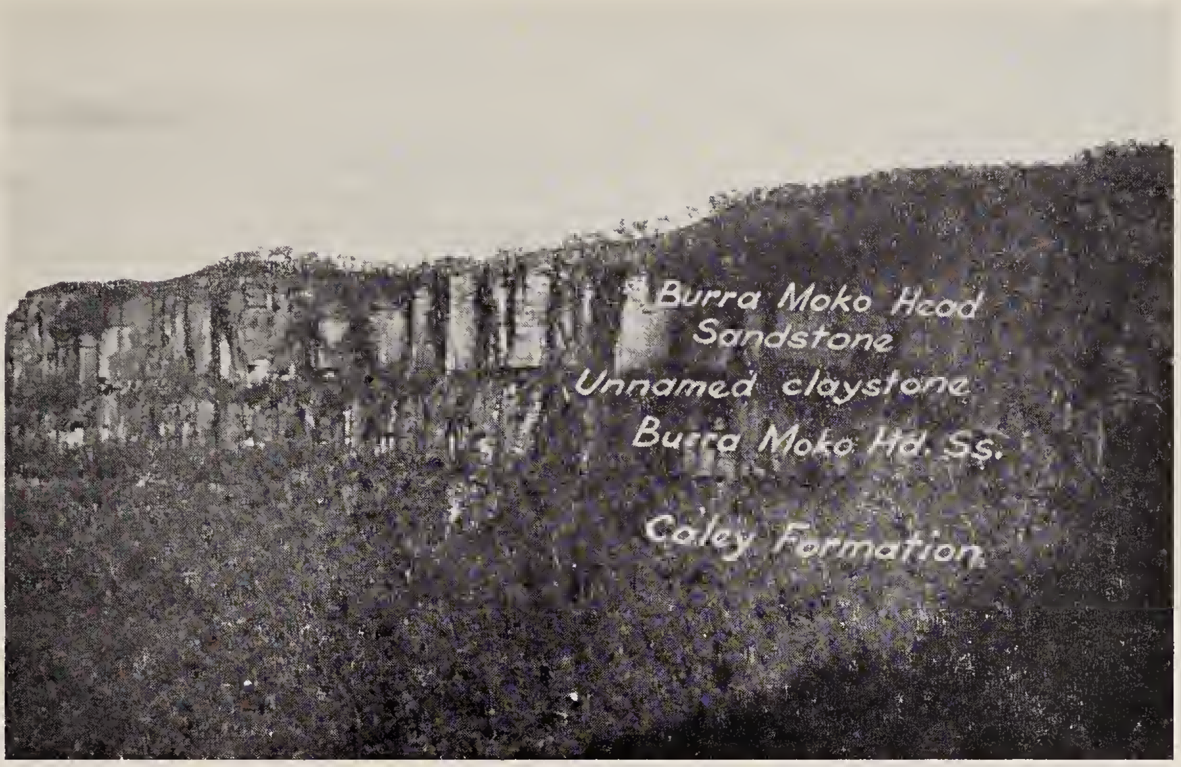
The Mount York Claystone is a reddish brown claystone which occurs as a single bed or two closely spaced beds with a thin sandstone bed separating them. It occurs between 340 and 400 feet above the base of the Grose Sandstone and crops out continuously in the western Blue Mountains.

The claystone ranges from reddish brown, mottled or white to light grey, although it is unusual for the claystone to persist more than 100 yards without some red coloration being present. Along the Kedumba Walls the Mount York Claystone outcrops close to the top of the cliffs and occasionally, because of irregularities in the height of the cliffs, outcrops on the surface of the plateau.

BANKS WALL SANDSTONE MEMBER

The Banks Wall Sandstone is the uppermost member of the Grose Sandstone in the Blue Mountains. Because of the absence of the Burralow Formation west of Hazelbrook, it is not possible to assign a definite thickness to this unit although it is in the order of 350 feet. At Euroka Trig, which was the only place where a full section was measurable, the thickness is 325 feet ; however, it is not known if this value is typical. Goldbery (1966) reports a maximum thickness of 370 feet in the Upper Grose Valley.

The Banks Wall Sandstone crops out along the surface of the plateau from Lawson to Katoomba and comprises the surface outcrop of the plateau as far south as Lake Burragorang. It also crops out further east in the major river valleys, the most notable being Erskine Creek.



Unnamed claystone marker bed on Narrow Neck Peninsula.

Unnamed claystone marker bed, Wentworth Falls. Note erosional notch.

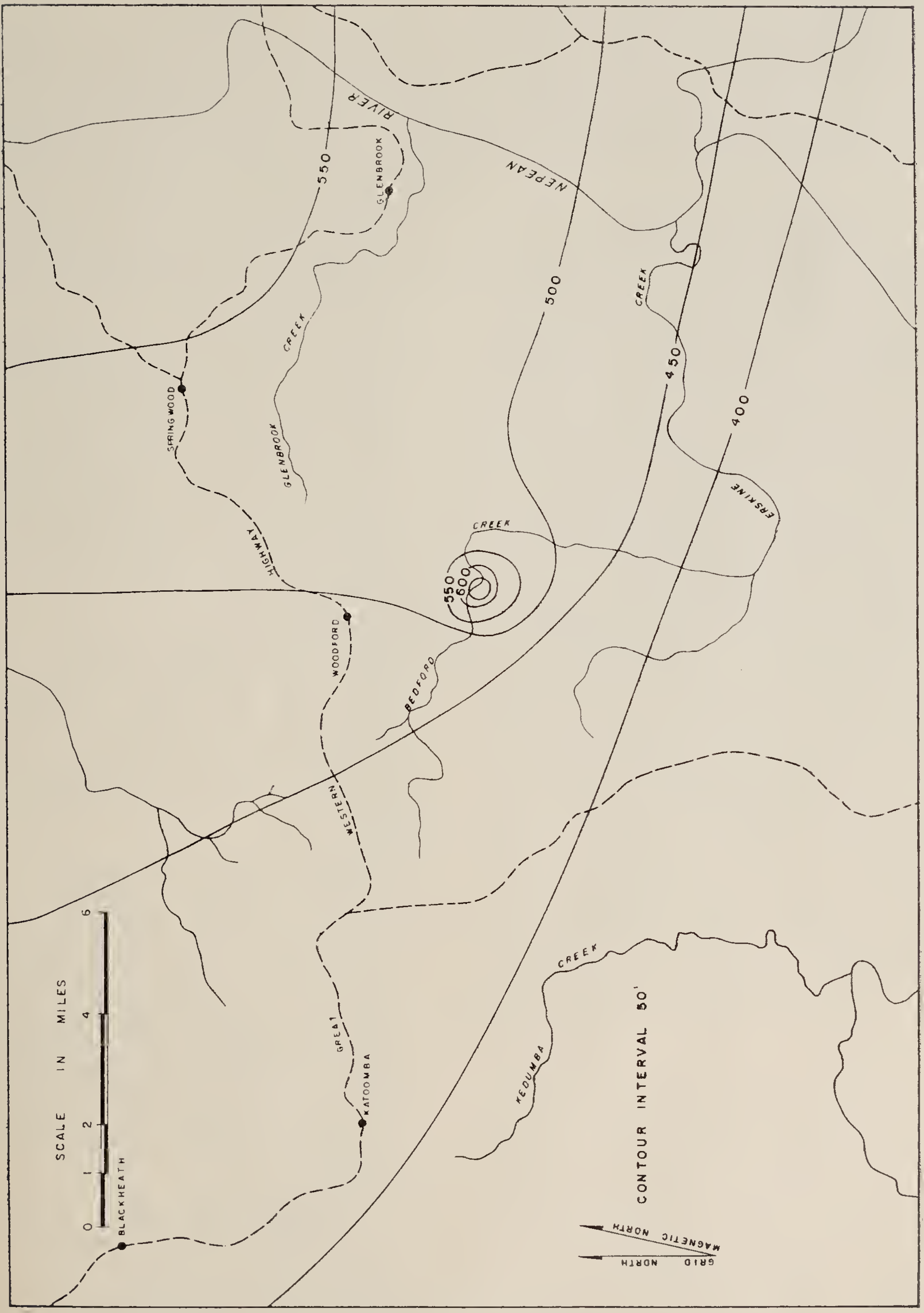


Fig. 3.—Isopach map of Burra-Moko Head sandstone.

The sand is quartzose with a small percentage of lithic fragments. The percentage of lithic material in the sandstone increases towards the base. Cross-stratification is common, as are ironstone bands, which are usually oriented sub-parallel or at random to the bedding planes. Lenticular claystones occur throughout the sandstone and increase in abundance toward the base.

Burralow Formation

The Burralow Formation is the uppermost unit of the Narrabeen Group. The Burralow Formation is overlain by the Hawkesbury Sandstone and underlain by the Grose Sandstone.

The lithology of the Burralow Formation consists of fine-grained micaceous sandstones, claystones and shales. Full sections of the formation are rare and outcrops are generally poor due to the occurrence of talus slopes. The formation has a high percentage of sandstone ; however, due to the nature of outcrop, it was not possible to distinguish the Tabarag Sandstone Member described by Crook (1956).

The extent of outcrop (Figure 4) closely approximates that of the overlying Hawkesbury Sandstone (Figure 6) and the variations in thickness are proportionate. In the Mulgoa No. 2 bore on the eastern edge of the study area the thickness is 400 feet, while in the Kurrajong Heights No. 1 bore to the north and east of the study area a thickness of 540 feet was recorded.

From the eastern boundary of the Blue Mountains, the Lapstone Monocline, the Burralow Formation increases in grain size and sand content in a westward direction. At the western edge of outcrop near Hazelbrook, the Burralow Formation is indistinguishable from the Grose Sandstone. This change in facies (Figure 5) makes recognition of the Burralow Formation difficult towards the western edge of outcrop and where definite recognition was impossible the strata have been mapped as Grose Sandstone.

The micaceous character of the sandstones is persistent throughout the entire area of outcrop. On the eastern part of the study area the formation is composed of numerous claystone shale and siltstone bands, alternating with fine- to medium-grained micaceous quartz-rich sandstones with only a few lithic fragments. Toward the west the argillaceous bands become less frequent and the sand becomes medium- to coarse-grained and sub-lithic in character. Cross stratification is rare in the Burralow Formation and reddish-brown claystones are completely absent.

Narrabeen Group-Hawkesbury Sandstone Boundary

A number of criteria for the recognition of a Narrabeen Group-Hawkesbury Sandstone boundary have been proposed by Standard (1961, 1964), Galloway (1965, 1967) and Goldbery (1966). The main field criteria used during this study to distinguish the Hawkesbury Sandstone from the Narrabeen Group (Figure 1) were :

(1) The lithological change in character of the sandstones from a quartzose nature in the Hawkesbury Sandstone to a sub-lithic and then to a quartz-lithic nature within the Narrabeen Group.

(2) The occurrence of a coarse quartz conglomerate at the base of the Hawkesbury Sandstone. In the eastern portion of the study area the occurrence of this conglomerate horizon is quite consistent.

The pebbles, ranging up to 2 inches in diameter, consist of quartz and are cemented by silica. The thickness of the conglomerate is variable, the maximum thickness recorded being 10 feet 6 inches at Linden Tank.

(3) The increasing frequency and size of the quartz pebbles in the Hawkesbury Sandstone as the conglomerate horizon and the base of the Hawkesbury Sandstone is approached. This observation may be useful for the examination of a large stratigraphic interval as no true marker beds exist within the Hawkesbury Sandstone.

(4) The fine-grained micaceous nature of the sandstones and the regularity of the interbedded shales and claystones of the top of the Burralow Formation over the eastern portion of the study area. The lateral lithofacies change in a westward direction to a medium-grained sand makes the differentiation between the Burralow Formation and the Hawkesbury Sandstone difficult. On the western margin of outcrop of the Hawkesbury Sandstone the only possible distinction is the slightly more lithic character of the Narrabeen Sandstones.

(5) The increase in clay content, as matrix, of the Narrabeen sandstones. This change is relatively abrupt and distinctive in the eastern portion of the area ; however, approaching the westward limit of outcrop of the Hawkesbury Sandstone the clay content of the Hawkesbury Sandstone increases and this characteristic is no longer useful for distinction.

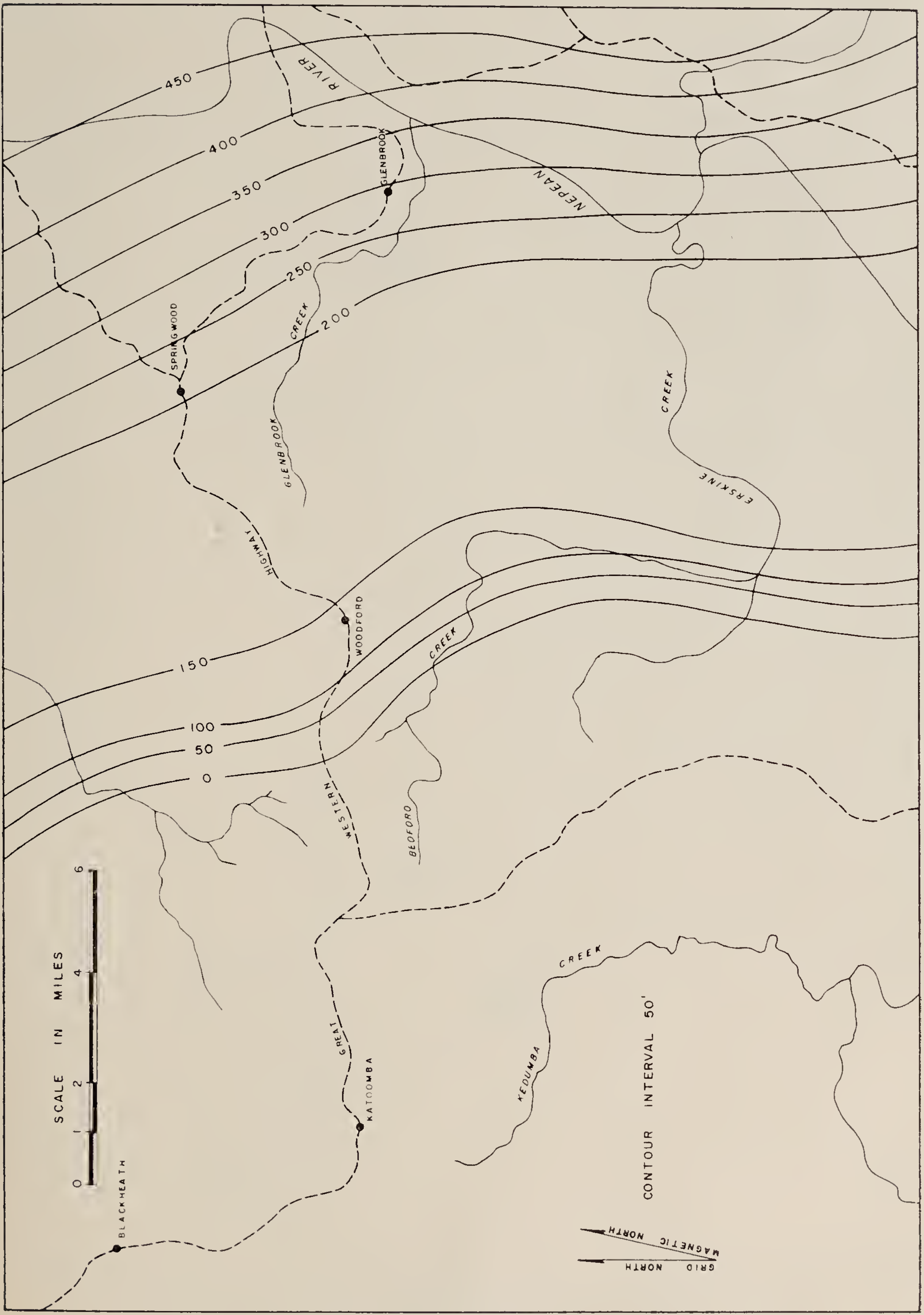


Fig. 4.—Isopach map of Burralow Formation.

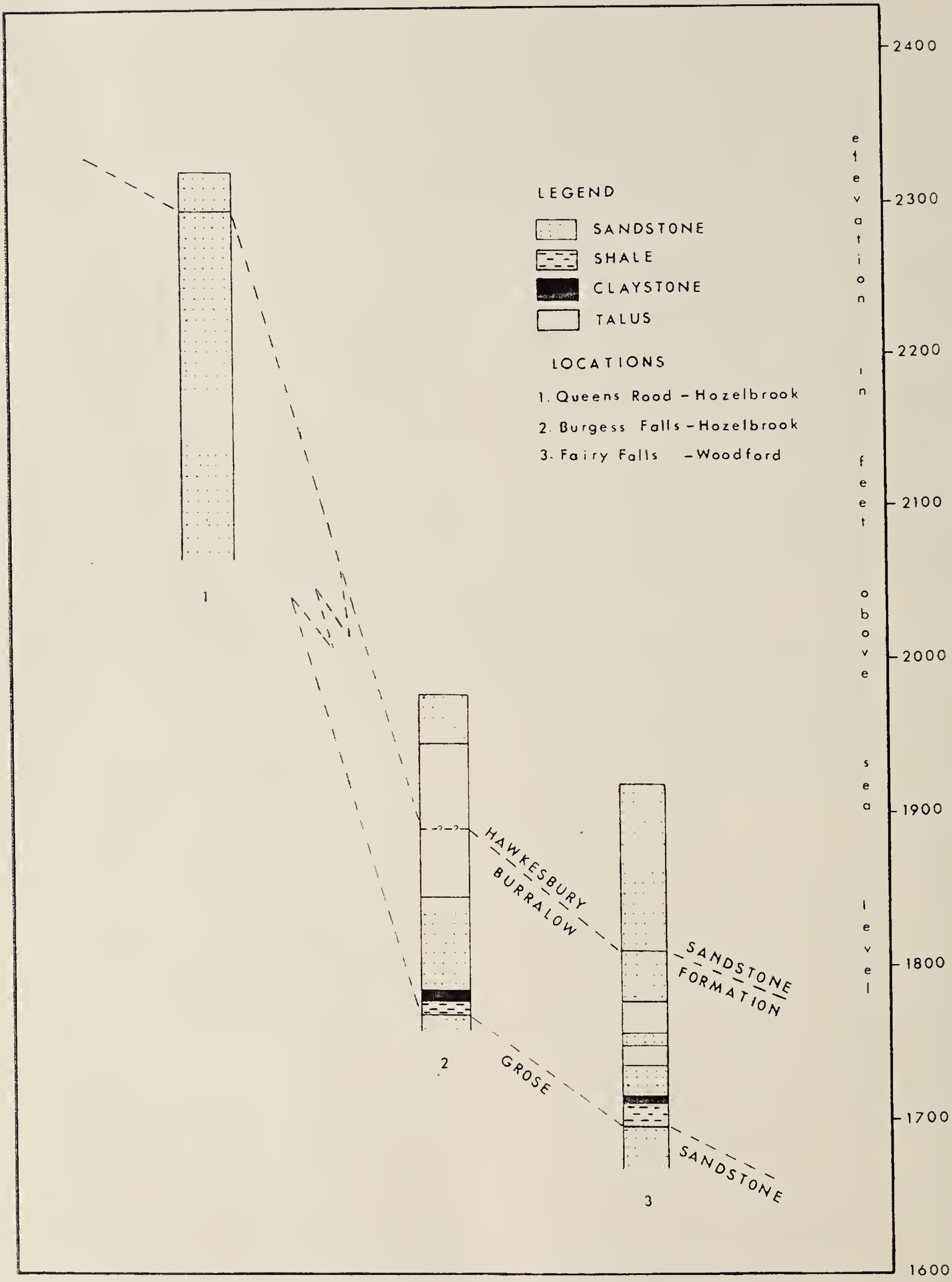


FIG. 5.—Stratigraphic cross-section Woodford to Hazelbrook.

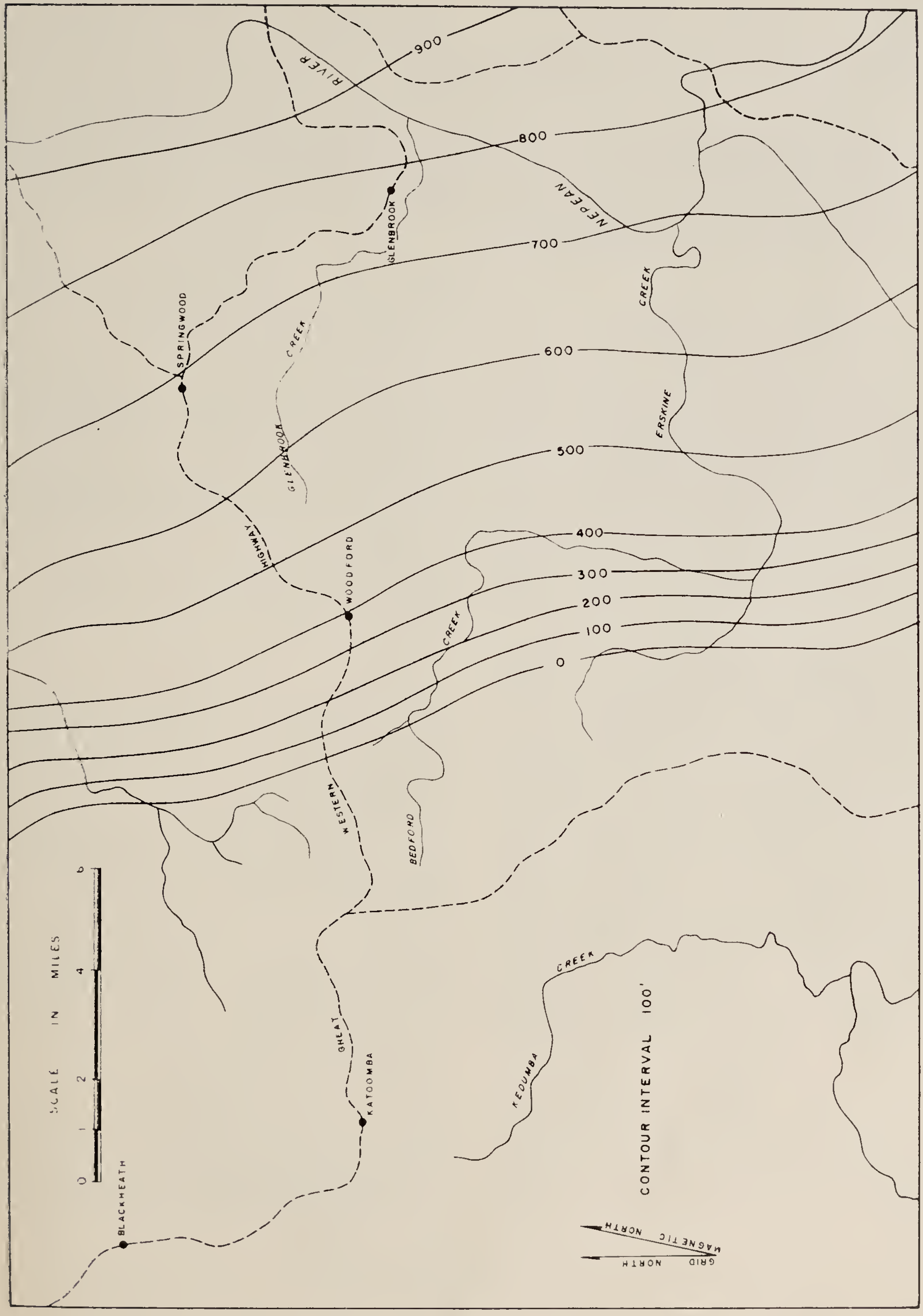


Fig. 6.—Isopach map of Hawkesbury Sandstone.

In the eastern portion of the area under consideration the recognition of the boundary is not difficult. The Burralow Formation is quite distinctive and can be easily recognized in conjunction with a quartz conglomerate horizon at the base of the Hawkesbury Sand-Sandstone. As the western extent of the Hawkesbury Sandstone (Figure 2), just east of Lawson on the Great Western Highway, is approached, the lateral lithofacies change of the Burralow Formation and the disappearance of the conglomerate horizon makes the distinction tenuous.

Hawkesbury Sandstone

Within the study area the Hawkesbury Sandstone attains a maximum thickness of 760 feet in the Mulgoa No. 2 Bore. The Hawkesbury Sandstone is overlain by the Wianamatta Group and underlain by the Burralow Formation of the Narrabeen Group.

With the exception of a few isolated outliers of shales of the Mittagong Formation and the Ashfield Shale (Wianamatta Group), the Hawkesbury Sandstone outcrops at the surface of the plateau from the Lapstone Monocline as far west as Hazelbrook. The Hawkesbury Sandstone thickens rapidly near the western edge of outcrop (Figure 6) and continues to thicken gradually in an easterly direction.

A typical hand specimen of Hawkesbury Sandstone is a white to light brown, medium to coarse-grained sandstone. The sandstone is usually poorly sorted and often iron-stained, although concentrations of iron in the form of bands is uncommon. The matrix of the sandstone is made up of clay minerals, mainly kaolinite, and where iron-staining is absent the sandstone is quite friable. Commonly the sandstone is highly cross-stratified, although thick sequences occur where this is not apparent. Quartz pebbles up to 2 inches diameter commonly occur, particularly toward the base of the sandstone. Lenticular clays and shales, although not common, range in thickness up to 11 feet. Only one occurrence of a siltstone was noted in the Hawkesbury Sandstone, this being in a road cutting on the Great Western Highway west of Linden.

Acknowledgements

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Granitic Development and Emplacement in the Tumbarumba-Geehi District, N.S.W.

(ii) The Massive Granites

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ABSTRACT—The massive granites of the Tumbarumba-Geehi district may be classified into three groups—the Khancoban, Mannus Creek and Dargals granites—on the basis of spatial distribution. The emplacement of Khancoban and Mannus Creek granites post-dates the regional metamorphism of the district although mineralogically and chemically such rocks bear some similarity to the foliated Cooma-type granites that are considered to have been produced in the regional metamorphic processes (Guy, 1969*b*). Chemically such massive granites have high CaO and Na_2O contents and are considered to have developed either at the same time as the foliated granites or by a regeneration of such granitic material.

The Dargals granites are leucocratic with more than 80% normative Q+Or+Ab. It is considered they have migrated far from their position of origin, but may have been produced during the cycle of development of the other massive bodies.

Introduction

Associated with the Ordovician metasediments of the Tumbarumba-Geehi district, N.S.W. (Guy, 1969*a*) are several groups of granitic* bodies. These granites are essentially either foliated or massive, the former—the Cooma-type granites (Guy, 1969*b*)—being associated with the regional metamorphics, while the massive granites post-date the metamorphism, superimposing contact influences on the country rocks. This paper is concerned with the development and emplacement of the massive bodies. These may be subdivided into three groups (viz. the Khancoban granite, the Mannus Creek granite and the Dargals granite) on the basis of spatial distribution (Guy, 1969*a*).

Khancoban Granite

The Khancoban granite is a poorly exposed mass outcropping over some 100 square kilometres. Associated with it is a small body (¼ sq. km.) at Mt. Youngal (G.R. 278.9–134.5)† near Geehi. Contacts with the metasediments are sharp and nearly vertical, while the mass transgresses regional metamorphic zones (Guy, 1969*a*) with a relatively narrow contact aureole developed. Within the body, acid to basic dyke rocks are common, especially in the northern section, as well as north-east trending shear bands being prominent—presumably due to the influence of the Yellow Bog-Khancoban thrust (Cleary *et al.*, 1964). The granite is medium- to coarse-grained with no apparent change in grain size marginally. Although generally massive, a weak but definite north-south foliation is evident, particularly in exposures along the Swampy Plains River. Compared with the Cooma-type granites, there is a notable paucity of aplitic and pegmatitic phases in the mass. Inclusions are limited throughout the body, however, along sections of the Swampy Plains River, clusters of pelitic to psammitic xenoliths have been observed.

MINERALOGY AND PETROLOGY

Most of the granitic phases in the body are strictly granodiorites, being coarse-grained and more leucocratic than the Cooma-type granites, although biotite is often as high as 12%. The general grain size is 3–5 mm., with alkali feldspars in places to 15 mm. The larger alkali feldspars are optically monoclinic with Δ values generally in range 0·20–0·35, although there is notable variation throughout the body. $2V_x$=75–80°. These feldspars, frequently poikilitic enclosing plagioclase and biotite, have fine perthite lamellae developed. From the

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* The term " granite " as used in this paper includes all acid plutonic rocks unless otherwise stated.

† Snowy Mountains Authority grid reference.

one analysis of the Khancoban granite available (spec. 21817) the bulk composition of the alkali feldspar is estimated at Or_{85-90}, assuming minor amounts of sodium in the micas present. The plagioclases have a bulk composition of An_{35}* with normal zoning from An_{45} to An_{20}. In some sections of the body the average composition of the plagioclases is as low as An_{20}. The plagioclases frequently display an accumulophyric effect (see Plate 1 (*a*)) which is more evident in marginal sections of the body. Such plagioclase clusters are composed of some 20 to 50 small laths, all having approximately the same orientation. The plagioclase also displays " patchy " zoning (*cf.* Guy, 1969*b*) with some areas of the feldspar at slightly different optical orientation to the host. Biotite forms subhedral crystals with Z=dark brown to dark olive-brown and $\gamma=1{\cdot}645$, $2V_x=3\text{–}7°$. Alteration of this mineral to chlorite and epidote is common. Muscovite is subordinate and where present is in large ragged blades cross-cutting grain boundaries of other phases. Opaque oxides and apatite are accessories.

The small granodiorite body at Mt. Youngal is somewhat similar texturally to the main Khancoban granite. Hornblende is common with X=pale brown-yellow, Y=dark olive-green and Z=sea-green. $2V_x=50\text{–}55°$ and $Z\wedge c=25°$. Biotite with $\gamma=1{\cdot}650$ and Z=dark yellow-brown or green-brown is also a prominent phase. Plagioclase is somewhat more calcic (average An_{47}) than in the Khancoban granite. Chlorite and epidote are developed at the expense of the mafic minerals.

Inclusions within the Khancoban granite have granoblastic textures with some orientation of micas. Grain sizes average 0·5 mm., with subhedral porphyroblasts of plagioclase to 2–3 mm. The plagioclase (An_{37}) has weak diffuse zoning. Biotite occurs as small flakes with Z=olive-green and $\gamma=1{\cdot}640$. The structural formula of an analysed sample (spec. 21815) is

$$(K_{0\cdot93}\ Na_{0\cdot15}\ Ca_{0\cdot05})(Al_{0\cdot20}\ Ti_{0\cdot08}\ Fe^{3+}_{2\cdot07}\ Fe^{2+}_{1\cdot19}\ Mn_{0\cdot01}\ Mg_{0\cdot98})(Si_{2\cdot74}\ Al_{1\cdot26})O_{10}\ (OH)_2.$$

The pronounced green colour of the biotites is in contrast with those biotites in the granitic phases and those in the inclusions of the Cooma-type granites (Guy, 1969*b*). An analysis of the host rock of the biotite is noted in Table 1 (No. 3).

TABLE 1

Chemical Analyses, Barth Mesonorms and Modes of Rocks from the Khancoban Granite

Oxide	1	2	3
SiO_2 . .	73·26	70·20	69·82
TiO_2 . .	0·24	0·26	0·90
Al_2O_3 . .	12·79	15·83	13·13
Fe_2O_3 . .	0·47	3·04	0·71
FeO . .	1·90		3·59
MnO . .	0·08	0·08	0·08
MgO . .	0·62	0·75	1·49
CaO . .	2·28	2·87	3·84
Na_2O . .	3·77	2·97	3·31
K_2O . .	4·23	3·57	1·88
P_2O_5 . .	0·03	—	0·07
H_2O^+ . .	0·46	—	0·81
H_2O^- . .	0·06	—	0·13
Total	100·19	99·57	99·76
Q . .	28·64	31·40	34·37
Or . .	23·17	15·75	3·50
Ab . .	34·25	27·15	30·60
An . .	5·55	13·60	15·87
C	—	2·37	—
Bi . .	3·39	9·20	12·72
Act . .	—	—	0·08
Di . .	3·92	—	—
Ap . .	0·05	—	0·16
Ti	0·51	0·51	1·95
Mt . .	0·49	—	0·76
Quartz . .	36·0	35–40	41·1
K-feldspar	21·0	30–35	—
Plagioclase	34·7	20	38·1
Biotite . .	8·3	7	17·3
Muscovite	—	2	0·8
Chlorite . .	—	—	0·4
Epidote . .	—	1	2·3

1. Spec. 21817, granodiorite, G.R. 281.8–146.0 (3 km. south-east of Khancoban). Anal. B. Guy.
2. Spec. Kh-1, adamellite, Kolbe and Taylor (1966).
3. Spec. 21815, psammopelitic inclusion, G.R. 279.2–139.8 (11 km. south of Khancoban). Anal. B. Guy.

CHEMICAL DATA

Only one new analysis is available for the Khancoban granite, and this is presented in Table 1 together with an analysis of an inclusion from the body, and another analysis of the Khancoban granite from Kolbe and Taylor (1966). The granite analyses indicate higher CaO contents than for the Cooma-type granites (Guy, 1969*b*) and Na : K ratios slightly greater than unity. No amphibole has been recorded in the main phase of the Khancoban granite, but normative diopside occurs. The chemical data are summarized in Figs. 1 and 2 (*a*).

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* Compositions of the plagioclase were determined from the extinction angle $X\wedge(010)\perp[100]$ measured on a universal stage and referred to the low-temperature determinative curves of Bordet (1963).

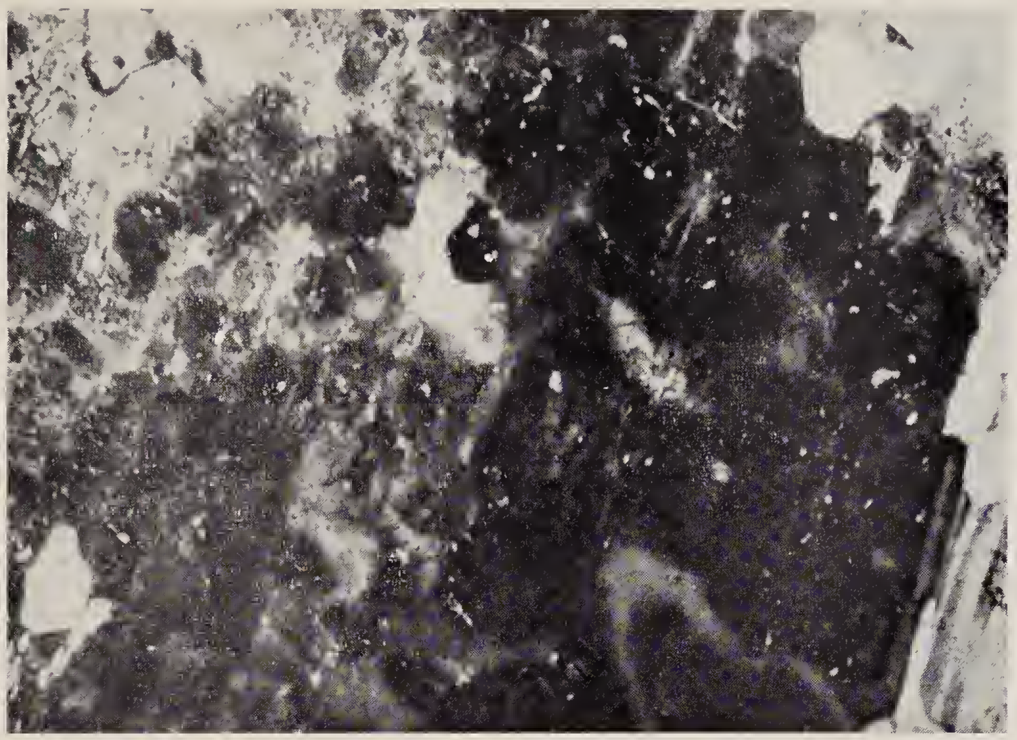

PLATE I (*a*)
Section of a plagioclase from Khancoban granite (spec. 21817). The plagioclase consists of numerous small crystals all of which display some zoning. Crystal near extinction position. (×45.)

PLATE I (*b*)
Section of zoned plagioclase from Munderoo granodiorite (spec. 21840). Note development of patchy zoning. (×45.)

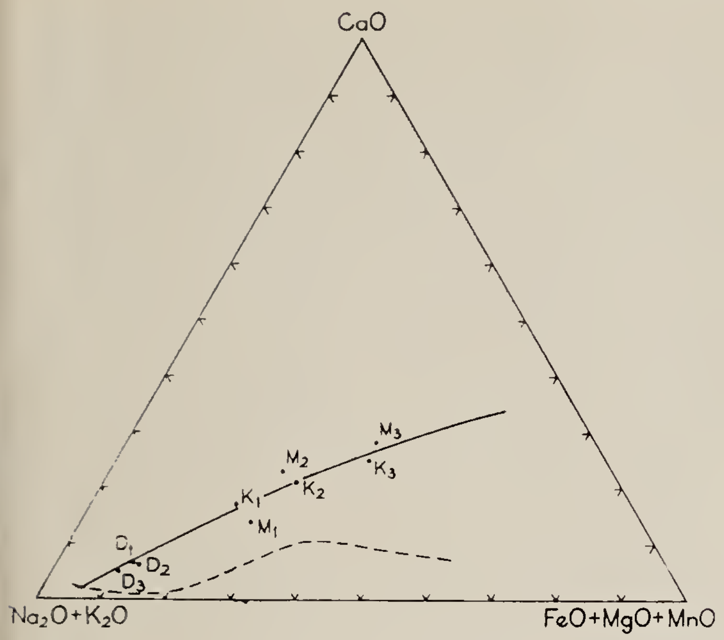

FIG. 1—Plot of Khancoban (K), Mannus Creek (M) and Dargals (D) granites on a $CaO-Na_2O+K_2O-FeO+MgO+MnO$ diagram. Dashed line indicates variation displayed by Cooma-type granites and solid line the variation for Bathurst granites. Murrumbidgee-type granites generally lie between these two curves. (*After* Vallance, 1967.)

It is interesting to compare the analysis of the inclusion with those of the Cooma-type granites since all the inclusions may be derived from rocks similar to the surrounding meta-sediments (Guy, 1969*a*). The Na : K ratio is high (2·67) while the Fe : Mg+Fe ratio is also high (0·56).

Mannus Creek Granite

In the vicinity of Mannus Creek, a small (*ca.* 64 sq. km.) granite complex occurs surrounded by a contact aureole 1·6 km. wide. This complex constitutes the Mannus Creek granite which varies in composition from leucocratic adamellites to hornblende-rich granodiorites. To the west of the area mapped this mass intrudes the Corryong granite. Three major units within the Mannus Creek granite have been recognized (Fig. 3), viz. the Bogandyera granite, the Munderoo granodiorite and the Prison Farm granodiorite. The Bogandyera granite is typically fine- to medium-grained, in places porphyritic in quartz and feldspar. It is usually a granite (*sensu stricto*) or an adamellite. The Munderoo granodiorite is medium-grained with biotite the only mafic phase and is a heterogeneous unit having gradational boundaries with the other units. The attitude of the granite-sediment contact is variable but generally steep, with some shallowly dipping contacts to the north of G.R. 270–170 suggesting the mass exposed may be near the roof of the complex.

All the granitic rocks in this suite are massive and devoid of any directional structures. Apart from some hornblende-rich inclusions in marginal phases of the Prison Farm granodiorite xenoliths are not common, while aplitic and pegmatitic rocks are restricted.

MINERALOGY AND PETROLOGY

The Bogandyera granite has an average grain size of 0·6 mm. with numerous small subhedral phenocrysts mainly of quartz and alkali feldspar. Marginal phases are markedly finer grained. The Munderoo granodiorite has a grain size of 2–3 mm. with occasional phenocrysts of alkali

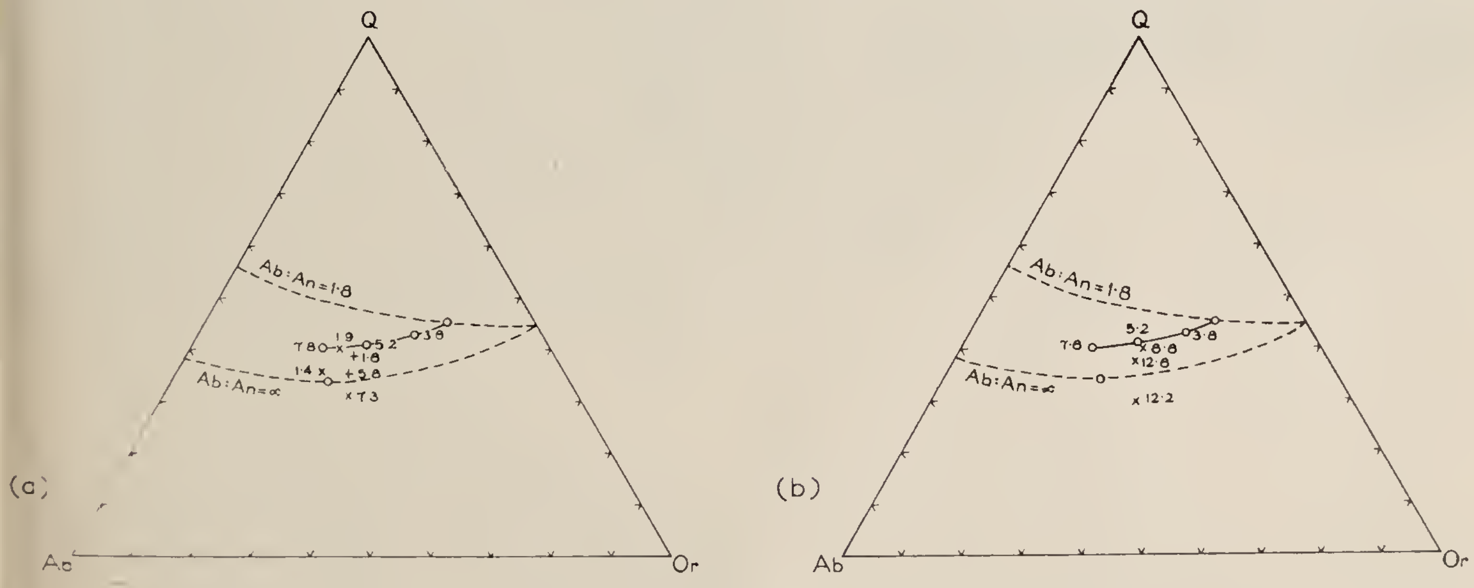

FIG. 2—Projection of $Q-Or-Ab-An$ system at $P_{H_2O}=2,000$ bars, indicating cotectic curves for Ab : An ratios of 1·8 and ∞ and the maximum melting points (o) for various Ab : An ratios. (*After* Von Platen, 1965.)
(*a*) Khancoban (+) and Mannus Creek (×) granites, with Ab : An ratios indicated.
(*b*) Dargals (×) granites with Ab : An ratio indicated.

TABLE 2

Chemical Analyses, Barth Mesonorms and Modes of the Mannus Creek Granites

Oxide	1	2	3
SiO_2 ..	71·68	70·60	65·49
TiO_2 ..	0·47	0·30	0·59
Al_2O_3 ..	13·06	14·75	14·69
Fe_2O_3 ..	0·70	0·59	1·37
FeO ..	2·51	2·13	4·13
MnO ..	0·10	0·12	0·13
MgO ..	0·85	0·82	1·92
CaO ..	1·99	2·95	4·79
Na_2O ..	3·92	3·21	3·07
K_2O ..	4·59	3·28	2·79
P_2O_5 ..	0·09	0·10	0·10
H_2O^+ ..	0·39	0·73	0·87
H_2O^- ..	0·05	0·07	0·04
Total	100·40	99·65	99·98
Q ..	24·58	31·87	24·83
Or ..	25·05	15·28	10·07
Ab ..	35·45	29·50	28·25
An ..	4·52	13·25	18·48
C	—	1·31	—
Bi ..	3·68	7·31	10·85
Act ..	4·80	—	4·58
Ap ..	0·19	0·21	0·21
Ti.. ..	0·99	0·66	1·26
Mt ..	0·73	0·63	1·47
Quartz ..	27·2	34·6	25·7
K-feldspar	40·0	14·0	2·5
Plagioclase	20·8	38·5	46·8
Biotite ..	6·8	10·8	14·6
Hornblende	4·8	—	10·0
Accessories	0·3	2·2	0·5

1. Spec. 21831, Bogandyera adamellite, G.R. 271.1–167.4 (10 km. north-west of Tooma). Anal. B. Guy.
2. Spec. 21814, Munderoo granodiorite. G.R. 269.0–175.9 (1 km. east of Mannus). Anal. B. Guy.
3. Spec. 21836, Prison Farm granodiorite. G.R. 271.3–173.1 (8 km. south-west of Tumbarumba). Anal. B. Guy.

feldspar and quartz attaining 5–7 mm., while the Prison Farm granodiorite is even-grained (1–2 mm.). Quartz phenocrysts of the Bogandyera granite are ragged and appear somewhat resorbed. The alkali feldspars are generally optically triclinic with Δ values $>0{\cdot}50$. The bulk composition of the feldspars, as estimated from modal and chemical data, and assuming compositions for the micas, is estimated to be in the range Or_{55} to Or_{75}. This is exclusive of the Prison Farm granodiorite; it contains only minor quantities of this feldspar. Fine string perthite lamellae may be present in these rocks. Plagioclases are subhedral with normal euhedral zoning. Granitic members of the complex have plagioclases from An_{35} to An_{20}, while in granodioritic phases the plagioclases have cores of An_{45} and occasionally An_{65} (*cf.* Snelling, 1960, p. 194). As noted in the Khancoban granite, some plagioclases display an accumulophyric effect, with patchy zoning also developed (Plate 1 (*b*)). Biotite is present as ragged grains with Z=dark olive-brown (nearly opaque) and $\gamma=1{\cdot}650$. This mica is often associated with, and sometimes replaces, hornblende. Hornblende is euhedral to subhedral but in the Bogandyera granite occurs as small ragged grains exhibiting a glomerophyric texture. All hornblendes have X=light brown, Y=medium brown-green, and Z=blue-green, with zoning from a brown core to green margin, $Z{}^\wedge c=23$–$25°$, and $2V_x=65°$. Chlorite, epidote and muscovite appear as alteration products, while apatite and zircon are accessories.

Inclusions within this granitic complex are generally restricted to the Prison Farm granodiorite, and consist of quartz, optically monoclinic alkali feldspar, plagioclase (average An_{35}), biotite and hornblende. Most of the phases are similar optically to those observed in the host rocks.

CHEMICAL DATA

Analyses of granitic rocks from this complex are presented in Table 2. Chemical data are summarized in Figs. 1 and 2 (*a*). The group as a whole displays lower SiO_2 and Al_2O_3 contents than the Cooma-type granites but are similar to the Khancoban granite. CaO, N_2O and the Na : K ratio are higher than for the Cooma-type granites. The Munderoo granodiorite shows some chemical similarity to the Cooma-type granites (but compare Fig. 1). It may be significant that mineralogically and texturally (*e.g.* grain size, clustering of micas) the Munderoo and Cooma bodies are not dissimilar. Further field work to the west of the area noted in Fig. 3 may establish significant information regarding the relationship of the Munderoo granodiorite to the Cooma-type granites.

Dargals Granite

The Dargals granite outcrops over some 230 sq. km. and is generally a rather deeply weathered medium-coarse-grained leucocratic granite. Along its western margin, near the Tooma River, a fine-grained variety predominated, in which mafic minerals constitute several percent of the rock. In such cases

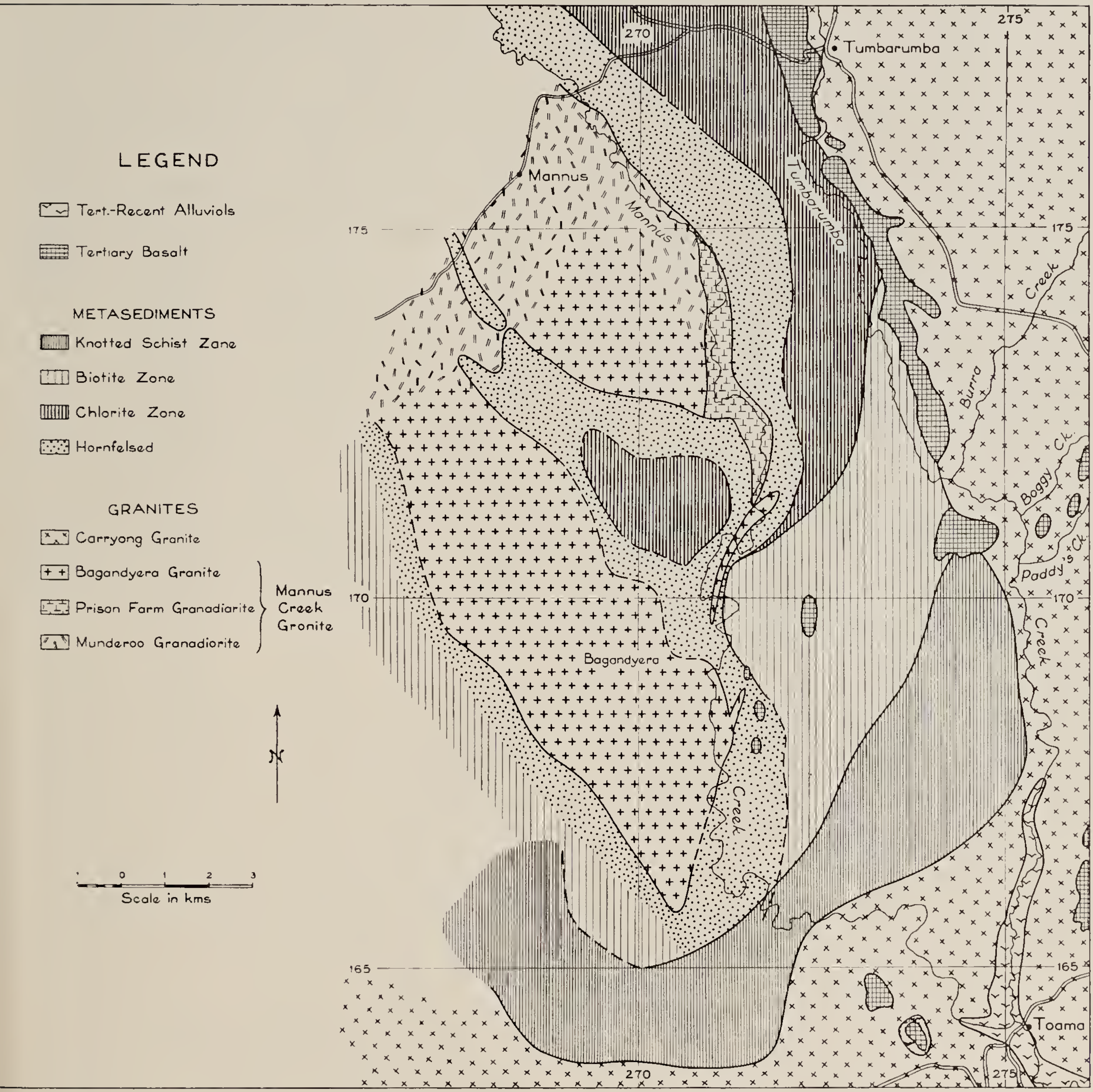

FIG. 3—Distribution of Mannus Creek granites, south of Tumbarumba, referred to S.M.A. grid.

outcrops are more pronounced and a distinctive flora (conifers) is present. In the vicinity of the Big Dargal (G.R. 284.0–155.8) the granite is coarse-grained with megacrysts of subhedral alkali feldspars and occasionally quartz. The Dargals granite is massive throughout and well jointed. Aplitic veins are common, pegmatites less so. Included country rock material is virtually absent, while a prominent exogenous contact zone is developed. Towards the north-east this mass intrudes another granite similar to the Khancoban granite (see Guy, 1969*a*, Fig. 2), however, no detailed examination of this area has been made. The Pine Mountain granite and the Mt. Mittamatite granite (Edwards and Easton, 1937) some 25 km. to the west of the Dargals granite are remarkably similar mineralogically and chemically to the Dargals granite. Small masses at the Granite Knob (G.R. 286.0–114.0) and at Biggera (G.R. 271.0–144.0) may belong to this group.

MINERALOGY AND PETROLOGY

The medium-grained phases of the granite have an average grain size 2–3 mm., while finer sections average 1·0 mm. Perthitic alkali feldspars are common as subhedral megacrysts up to 5 mm. Δ values average 0·25 for small grains and 0·40 for larger grains, the latter with $2V_x = 70°$. Assuming that the micas contain no sodium and that the alkali feldspars contain about 4% An, the composition of these feldspars may be estimated as Or_{80}, from modal and chemical data. Biotite is ragged with numerous small crystals occurring near the ends of, and having the same optical orientation as the larger laths. For these micas Z=dark olive-brown and $\gamma = 1{\cdot}657$. In the porphyritic granite clots of biotite occur (up to 5–6 mm.). These clots are commonly constituted of two varieties, one with Z=dark red-brown and with pleochroic haloes around zircon crystals inclusions, the other with Z=mid-green. The latter biotite appears to replace the red-brown biotite. Accessory minerals in the granite include opaque oxides, apatite, zircon and fluorite.

CHEMICAL DATA

Two rocks from the main Dargals granite have been analysed. The data are presented in Table 3 with an analysis from Kolbe and Taylor (1966). This group of rocks is characterized by high SiO_2 and low total iron, MgO and CaO reflecting the paucity of mafic constituents. Total alkalis are high while the Na : K ratio is near unity. These granites have a high oxidation ratio compared with other granitic suites in the Tumbarumba-Geehi district. Chemical data are summarized in Figs. 1 and 2 (*b*).

TABLE 3

Chemical Analyses, Barth Mesonorms and Modes of the Dargals Granite

Oxide	1	2	3
SiO_2	77·02	76·74	75·37
TiO_2	0·10	0·01	0·06
Al_2O_3	12·02	12·53	13·8
Fe_2O_3	0·61	0·33	0·87
FeO	0·61	0·92	
MnO	0·06	0·07	0·06
MgO	0·23	0·18	0·086
CaO	0·65	0·65	0·50
Na_2O	3·63	3·35	3·65
K_2O	4·79	4·79	4·71
P_2O_5	0·01	0·03	—
H_2O^+	0·41	0·48	—
H_2O^-	0·09	0·10	—
Total	100·23	100·18	99·11
Q	34·30	35·40	33·27
Or	27·70	27·22	26·83
Ab	33·00	30·55	33·05
An	2·40	3·15	2·30
C	—	0·71	2·14
Bi	1·68	2·56	2·27
Ap	0·14	0·05	—
Ti	0·15	0·03	0·15
Mt	0·64	0·34	—
Quartz	39·2	36·0	45
K-feldspar	30·4	40·2	15
Plagioclase	27·7	19·7	35–40
Biotite	2·4	4·0	2
Accessories	0·2	0·1	1

1. Spec. 21821, adamellite. G.R. 283.5–152.5 (9 km. north-east of Khancoban). Anal. B. Guy.
2. Spec. 21827, granite. G.R. 280.0–158.9 (12 km. south-east of Tooma). Anal. B. Guy.
3. Spec. Ja–1, leucogranite. Kolbe and Taylor (1966).

Discussion on the Origin of the Granitic Rocks

It is not uncommon to find an association of granite types in south-east Australia and it has been claimed by Browne (in David, 1950) that such rocks may be classified into one of the following groups: (i) Ordovician (gneissic granites associated with regional metamorphics), (ii) Silurian (foliated granites with little metamorphic influence), and (iii) post-Silurian (massive granites). Joplin (1962) has postulated that granitic rocks cannot be assigned to definite orogenic periods on the characteristics suggested by Browne. She claims that the granitic rocks of south-east Australia may be classified according to their position in the Tasman geosyncline which influenced eastern Australia during the Palaeozoic (see Packham, 1960). Joplin correlates granitic type with time, place and tectonic development in relation to the orthogeosyncline, and also to " intensity of movement during emplacement " (*cf.* Read's 1955 " granite series "). Vallance (1967) has also recognized granitic groups in south-east Australia and refers to such as " Cooma-type ", " Murrumbidgee type " and " Bathurst type ". He has pointed out that each group of granites displays markedly different chemical characteristics, and this may be illustrated when analytical data are plotted on a " $CaO-Na_2O+K_2O-FeO+MgO+MnO$ (wt. %) " diagram. Vallance suggests that the relatively high CaO contents of the Murrumbidgee and Bathurst type granites may be related to a varying and locally increasing (perhaps through vulcanism) basaltic component of the crust during geological time. This explanation would not be applicable to the various granitic types of the Tumbarumba-Geehi area as all such bodies are at present localized in a non-volcanic Ordovician terrain. However, it is possible that the massive granites have originated at greater depths than the Cooma-type granites, possibly in sections of the crust adjacent to basaltic rock types.

Several salient points may be emphasized concerning the relationship of the massive granites in the Tumbarumba-Geehi area. The Khancoban and the Mannus Creek granites bear some similarity to the Cooma-type granites, while the Dargals granite and the Pine Mountain granite (Edwards and Easton, 1937) are petrographically and chemically distinct. Discussion on this latter group is deferred (see p. 156). The Khancoban granite displays a weak but discernible secondary foliation yet clearly is not directly connected with the regional metamorphism, superimposing some contact influence on the country rock. This granite, then, probably post-dates the foliated Cooma-type granites, but may have been emplaced while the regional stress field was still active. The petrographic similarity of the Mannus Creek, Khancoban and Cooma-type granites is evident in that the plagioclases have calcic cores and patchy zoning. Chemically these massive granites differ from the Cooma-type granites in that the former have higher CaO and Na_2O contents. Total iron and magnesium contents do not differ markedly (*cf.* Snelling, 1960 ; Vallance, 1953).

The possibility that the massive granites have developed either as a continuation of the regional processes involved in the formation of the Cooma-type granites or a later regeneration of " Cooma-type material " must be examined. Some light may be shed on the problem by the investigations of Von Platen (1965) on the system Q—Or—Ab—An at $P_{H_2O}=2000$ bars. Although recent studies by Weill and Kudo (1968) have placed some serious doubt on the validity of the minimum melting points in this system, as determined by Von Platen, the latter author's result may indicate satisfactorily the trend of a minimum melting point with variation in Ab : An ratio. In an explanation of the development of the Cooma-type granites, it was suggested (Guy, 1969*b*) that such rocks formed by (*a*) accumulation of CaO in high-grade metasediments together with a segregation into quartzo-feldspathic and mica-rich sections, and (*b*) accumulation of Na_2O coupled with a breakdown of micas resulting in the formation of alkali feldspars. It was suggested that not all Cooma-type granites had undergone to the the same degree the processes outlined. Those granites which had undergone both (*a*) and (*b*) processes lay in a field on the " Q-side " of the cotectic in the system Q—Or—Ab—An, while those in which there had been limited breakdown of micas lay on the " plagioclase side " of the cotectic. It may be noted that the distribution of the massive granites is well into the plagioclase field. Thus if the Khancoban and Mannus Creek granites represent highly mobilized metasediments or regenerated Cooma-type granites, then it is unlikely that such rocks would have undergone stages (*a*) and (*b*) outlined above for the Cooma-type granite development, as fluid or " host-rock " phases would tend to be in the " Q-field ". However, such massive granites have higher CaO and Na_2O contents than the foliated granites, hence a possible sequence of events for the formation of the former granites could be (1) accumulation of CaO and segregation into quartzo-feldspathic and mica-rich sections, (2) mobilization of less refractory portions, (3) accumulation of Na_2O in this less refractory section. Of course such segregation in step (1) would not be complete. Kolbe and Taylor (1966) have suggested that the foliated and massive granodioritic rocks from south-east Australia have arisen through (?) complete melting of sedimentary rocks of " Ordovician clay-rich psammopelites with more normal geosynclinal greywackes and shales ".

Although present studies (Guy, 1969*a*) suggest that " normal greywackes and shales " are not common in the sequence—most rocks having relatively high $K_2O : Na_2O$ ratio and high alumina contents—the geochemical data presented by Kolbe and Taylor is compatible with the proposed process of granitic development.

The Khancoban and Mannus Creek granites bear some mineralogical similarity to the Murrumbidgee granites, although chemically some may be similar to Bathurst granite types (see Fig. 2). Other investigators have suggested a somewhat similar origin of other Murrumbidgee type granites from south-east Australia. For instance, Vallance (1953) indicates that the massive to foliated Ellerslie and Wondalga granites may have arisen partly through " a certain ' rejuvenation ' of the earlier granitic material ". Snelling (1960) has concluded that some of the acid phases of the Murrumbidgee batholith represent the primary magma type with which there had been contamination to produce the " contaminated granites " of the Murrumbidgee batholith.

The process of development of the Khancoban granite implies that mica-rich phases may develop as a by-product of granitic formation. This may also have undergone a process of sodium enrichment and some of the inclusions in the Khancoban granite (Table 1, No. 3) may be chemically similar to such a by-product. Some of the abundant dyke rocks (Joplin, 1958) of dioritic composition occurring throughout the Snowy Mountain region of N.S.W. also may be a result of such granitic development.

The Dargals and Pine Mountain granites are examples of the " leucogranites " of Kolbe and Taylor (1966) that contain significantly more than 80% Q+Or+Ab. The two analyses (Table 3 (1 and 2)) of the Dargals granite plot near the cotectic line for a specified Ab : An ratio in the system Q—Or—Ab—An (Von Platen, 1965). It is possible that such rocks have been largely fluid at some stage during their development and hence may have migrated far from their position of origin. There is no evidence to suggest any substantial modification of their composition through assimilation of other rock types. Such massive leucogranites may have developed through mobilization of the low temperature melting fraction of the other (and older) granitic suites examined.

Acknowledgements

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Journal and Proceedings, Royal Society of New South Wales, Vol. 102, pp. 157–158, 1969

A Solar Charge and the Perihelion Motion of Mercury

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Abstract—The effect of a possible net solar charge on the perihelion motion of Mercury is examined by using non-relativistic mechanics and by using the Reissner-Nordström metric of general relativity.

(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. It is thus of interest to discuss the possible effect of a solar charge on the motion of the perihelion of Mercury.

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 and is considered in Section (2) of this note.

If the sun has a net charge of sufficient magnitude, space-time about it will be represented in general relativity by the Reissner-Nordström metric rather than by the Schwarzschild metric normally used: space-time is modified by the charge, which thus exerts a gravitational effect in addition to purely electromagnetic effects. Perihelion motion in this case is considered in Section (3).

(2) The Non-relativistic Effect

Suppose that the sun is a sphere with a net electrostatic charge Q e.s.u. distributed symmetrically about its centre, and that Mercury can be regarded as an uncharged conducting sphere; the charge on the sun induces a dipole in Mercury. Since the distance r from the sun to Mercury is much greater than both the radius of the sun and the radius a of Mercury, the force on the planet becomes

$$F(r)=-\frac{GM_1M_2}{r^2}-\frac{2f^2a^3Q^2}{r^5}\cdot \quad \ldots\ldots(1)$$

Here G is the gravitational constant, while M_1 and M_2 are the masses of the sun and of Mercury. The factor f, where $0\leqslant f\leqslant 1$, allows for partial screening of the solar charge by plasma clouds (Bailey, 1965).

The advance δ of the perihelion in radians per revolution is (Gerjuoy, 1956)

$$\delta=-\pi\left(2+\frac{r}{F}\,\frac{\mathrm{d}F}{\mathrm{d}r}\right), \quad \ldots\ldots\ldots\ldots (2)$$

r being taken to be approximately constant. If

$$2\frac{f^2Q^2}{GM_1M_2}\left(\frac{a}{r}\right)^3\leqslant 1, \quad \ldots\ldots\ldots\ldots (3)$$

equations (1) and (2) give

$$\delta\doteqdot 6\pi\frac{f^2Q^2}{GM_1M_2}\left(\frac{a}{r}\right)^3. \quad \ldots\ldots\ldots\ldots (4)$$

Substituting numerical values, (3) becomes $f^2Q^2\leqslant 20\times 10^{64}$ and (4) gives an advance of $f^2Q^2\times 40\cdot 3\times 10^{-58}$ seconds of arc per century. With $f=1$, this would agree with the observed residual of 43″ if $Q=\pm 1\cdot 0\times 10^{29}$ (Gerjuoy, 1956). The value $-Q=2\cdot 2\times 10^{28}$ e.s.u. (Bailey, 1960*c*) gives, with $f=1$, an advance of 2·0 seconds of arc per century; this may be compared with the effect of the solar oblateness determined by Dicke and Goldenberg (1967), namely 3·4 seconds of arc per century, but has been found by regarding Mercury as a perfect conductor and by neglecting screening.

(3) The Effect in General Relativity

Under conditions of spherical symmetry, the space-time metric can be written, using spherical polar co-ordinates (r, θ, φ),

$$ds^2 = A(r)dt^2 - B(r)dr^2 - r^2(d\theta^2 + \sin^2\theta d\varphi^2) \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

where ds is the space-time interval and t is the time co-ordinate. For a spherically symmetric body of mass M and charge Q, (5) becomes the Reissner-Nordström metric in which (Jeffery, 1921)

$$A = B^{-1} = 1 - \frac{2m}{r} + \frac{GQ^2}{c^4r^2} \quad \ldots\ldots \quad (6)$$

where $m = GM/c^2$. When $Q=0$, A and B reduce to the forms appropriate to the Schwarzschild metric.

Suppose that A and B in (5) can be expressed in the forms (Anderson, 1967)

$$A = 1 - \frac{2m}{r} + \alpha_2\left(\frac{2m}{r}\right)^2 + \ldots \quad \ldots \quad (7a)$$

and

$$B = 1 + \beta_1\left(\frac{2m}{r}\right) + \beta_2\left(\frac{2m}{r}\right)^2 + \ldots \quad (7b)$$

where the coefficient of $1/r$ in ($7a$) has been chosen to give the Newtonian law of gravitation in the appropriate limit. The advance of perihelion of a planet is then given by (Anderson, 1967)

$$\delta \doteq \delta_0 \frac{1}{3}(2 + \beta_1 - 2\alpha_2). \quad \ldots\ldots\ldots\ldots \quad (8)$$

For the Schwarzschild metric, the α's vanish and the β's are all unity; then $\delta = \delta_0$. The factor multiplying δ_0 in (8) depends on the central body only. For the Reissner-Nordström metric $\alpha_2 = Q^2/4GM^2$ and $\beta_1 = 1$, so that

$$\delta \doteq \delta_0(1 - Q^2/6GM^2).$$

Hence, for the sun, $\delta \doteq \delta_0(1 - 6{\cdot}43 \times 10^{-61}Q^2)$. For example, if $Q = \pm 1{\cdot}2 \times 10^{29}$ e.s.u., δ is reduced by 1% from δ_0.

(4) Discussion

The values for $-Q$ deduced by Bailey were around 10^{28} e.s.u. From the above it would seem that such a charge would probably not have a significant effect on the perihelion motion of Mercury. Thus there is probably no inconsistency between Bailey's theories and the successful explanation of Mercury's motion by general relativity.

Acknowledgement

I thank the referee for correcting the numerical coefficient in (3).

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The Distribution of Eupatorium adenophorum Spreng. on the Far North Coast of New South Wales

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ABSTRACT—*Eupatorium adenophorum* Spreng., crofton weed, has remained a major problem in certain areas on the far north coast of New South Wales in spite of a long continued eradication programme. In some areas the weed had been effectively controlled using mechanical and chemical methods. An analysis of the occurrence of crofton weed with respect to a number of environmental factors revealed that rainfall, tree cover and steepness of land each appeared to influence distribution. It was estimated that there was a 76% chance of the occurrence of a significant infestation in areas which had steep land, no tree cover and an annual rainfall in excess of 70 inches. Inaccessibility of steep land with respect to the normal control measures was considered to be the main factor limiting the progress of crofton weed eradication in the area.

Introduction

Eupatorium adenophorum Spreng., crofton weed, an erect perennial herb, is a native of Mexico. It was first recorded in Australia in 1920 under the name of *E. glandulosum* H.B.K. non Michx. (Blakeley, 1920). The correct identity of the plant was not established until 1938 (Everist, 1967, personal communication). Although eaten by sheep and goats, the plant is unpalatable to cattle, and it spread considerably in the northern coastal dairying areas of New South Wales between 1940 and 1955.

Crofton weed was declared a noxious plant on the far north coast of New South Wales under the Local Government Act in 1943. In spite of an eradication programme by the regional weed control authority, the plant has persisted in a large portion of the area, and in 1967 covered 8·4% of the Richmond-Tweed region in significant density (Auld, 1969*a*). In view of this a detailed survey was designed to define the distribution of crofton weed with respect to a number of environmental factors.

Methods

The region (Figure 1) was sampled by a series of belt transects each 5,000 yards wide. The first of these was positioned arbitrarily in an east-west direction, extending from the coastline to the Richmond Range at the western extremity of the region. Similar transects were then placed parallel to this at intervals of 10,000 yards. Each transect was subdivided into 1,000 by 1,000 yard quadrats, each of which

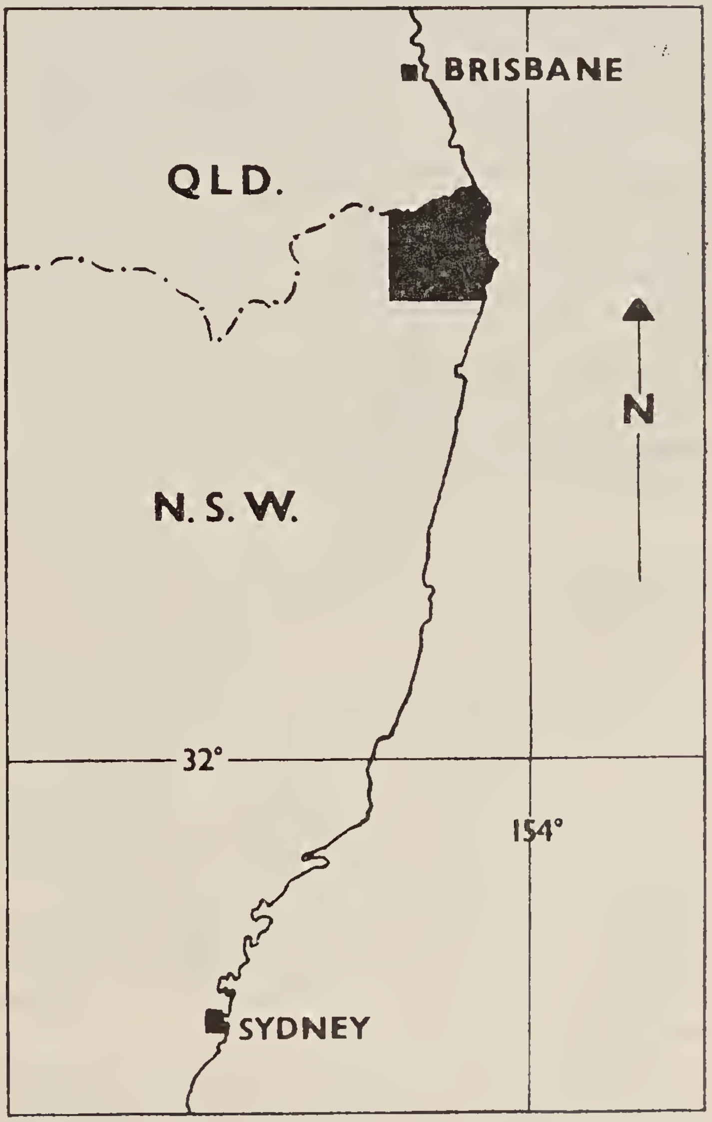

FIGURE 1.—The shaded area indicates the Richmond-Tweed region on the far north coast of New South Wales, where this work was conducted. Scale: 1 inch to 100 miles.

was examined. An infestation of crofton weed was regarded as significant if the total area covered by the perpendicular projection of the aerial parts of the plants exceed 1% of the quadrat area.

The following information was recorded for each quadrat: presence of crofton weed, steepness of land, aspect, tree cover, and average annual rainfall. Each of these factors was divided into a number of classes (Table 1).

The total number of quadrats in each class with or without significant stands of crofton weed was computed. Calculations were also made of the percentage of each class with significant infestations and of the total amount of crofton weed in each class.

TABLE 1

Observed Incidence of Crofton Weed

Main Factor	Class	Percentage	
		(i) Class Infested*	(ii) Total Crofton Weed Present
Steepness ..	<20°	7	18
	⩾20°	21	82
Aspect	North	15	22
	South	18	32
	East	16	25
	West	13	21
Tree cover ..	Dense	2	1
	Some	11	14
	Nil	21	84
Average rainfall	<50″	6	11
	50–60″	2	5
	61–70″	21	20
	>70″	49	65

* Expected percentage of class infested: 16.

The expected incidence of crofton weed in each class was estimated on the basis of a random distribution (i.e., equal density over the whole region) of the plant. The influence of each factor on distribution was examined for significance by a chi-square test, comparing observed with expected values in each class. A significant effect of a factor on distribution was taken to be indicated by a probability value of less than 0·05, using the data for all classes within that factor.

It has been noted that crofton weed favours frost-free hillside localities such as abandoned banana plantations (Richmond-Tweed Development Committee, 1966), and that the plant is susceptible to frost (Auld, 1969*b*) and usually absent from flat land (Auld, 1969*a*). For these reasons the flat areas of the region were not considered in this survey.

Results

The percentage of each class infested with crofton weed and the percentage of the total amount of crofton weed which occurred in each class is presented in Table 1.

With the exception of aspect, the influence of each factor on distribution was statistically significant ($P<0{\cdot}05$).

The number of infested quadrats with given slope, degree of tree cover and average annual rainfall was determined by summation (Table 2).

TABLE 2

Effect of Interaction of Steepness, Tree Cover and Rainfall on Distribution

Class Combination			Number of Quadrats with Crofton Weed Present	
Steepness	Tree Cover	Rainfall	Observed	Expected
<20°	Dense	<50″	0	1
		50–60″	1	3
		61–70″	0	0
		>70″	0	1
	Some	<50″	0	7
		50–60″	0	5
		61–70″	0	3
		>70″	5	1
	Nil	<50″	7	23
		50–60″	0	14
		61–70″	9	15
		>70″	16	10
⩾20°	Dense	<50″	0	5
		50–60″	0	22
		61–70″	0	1
		>70″	2	7
	Some	<50″	8	11
		50–60″	1	8
		61–70″	2	2
		>70″	14	4
	Nil	<50″	9	14
		50–60″	7	12
		61–70″	30	19
		>70″	98	20

In the sample taken 10% of the region had the following "environment": (i) nil tree cover, (ii) land equal to or greater than 20° in slope, and (iii) an average annual rainfall exceeding 70 inches per annum. The probability of the occurrence of a significant infestation in this environment was 76%, and indeed 47% of all crofton weed in the area surveyed occurred in such an environment. By including an additional 7% of the region with similar slope and cover, but with a rainfall of from 61 to 70 inches per annum, the occurrence of some 61% of all crofton weed infestations is accounted for.

Discussion

The preference of crofton weed for areas of nil tree cover may well be associated with the fact that its seeds require light for germination (Auld, 1969*b*), while the small size of the seedlings would presumably limit their initial competitive ability under forest conditions.

The observation that this species occurs chiefly in high rainfall areas confirms earlier observations in Hawaii (Ripperton and Hosaka, 1942).

The influence of slope on distribution was marked (Table 2). It is considered that slope has been the major physical factor limiting the progress of crofton weed control in the Richmond-Tweed region because areas where slope is equal to or greater than 20° cannot normally be negotiated by wheel tractors, which renders impractical control by normal mechanical treatments or by high volume herbicide application.

These physical problems render the cost of reclaiming such areas relatively high. In some cases greater returns may be forthcoming from more intensive development of the flatter portions of properties.

The use of crawler tractors rather than wheel tractors is useful in many cases on steep land. However, areas too steep or too rocky to be dealt with in this way still pose a problem. The aerial application of herbicides is not practical because of the danger of drift on to neighbouring horticultural crops, and the results of the attempted biological control of crofton weed have not been very encouraging (Auld, 1969*c*). These areas of rugged terrain, particularly where infestations are scattered, may prove amenable to the use of powder forms of herbicides applied from horseback.

Acknowledgements

I wish to thank the Weed Inspectors of the Far North Coast County Council for assistance with the field work, and personnel of the Biometrical Branch of the New South Wales Department of Agriculture for the analysis of the data.

I also wish to thank Mr. P. Martin, Lecturer in Botany at the University of Sydney, for his advice and criticism.

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Chemicals in Food*

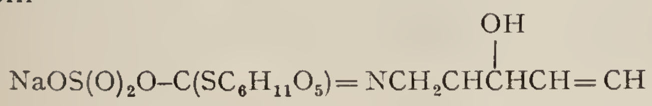
J. W. G. NEUHAUS

All food consists of mixtures of chemicals. These are principally proteins, carbohydrates and fats, with minor proportions of phospholipids, sterols, vitamins, minerals and alkaloids, among others. This address is not concerned with the major chemical complexes of food, but rather with the minor components, whether naturally present or deliberately or accidentally added.

Our food embraces many plants and animals which contain chemicals with known toxic properties as natural components. Generally, man has learned to avoid dangerous exposure to these components in his food, but under special circumstances, such as unusual concentration, for example, accidents occur. Acute toxicity, which is frequently recognized and the source subsequently identified, is much rarer than chronic toxicity. The latter only becomes evident after long exposures, and is almost never related to the causative agent.

Natural Compounds in Food

An example of compounds which occur naturally in food and cause chronic toxicity are the goitrogens. It was not until 1928 that the relation between diet and goitre had been established, but it was 1949 before a goitrogen was isolated from Brassicae, an important family of food plants including such vegetables as cabbage, kale and turnips. The compound isolated was l-5-vinyl-2-thiooxazolidone, which owes its activity to its ability to stimulate the secretion thyrotrophin by the pituitary gland. l-5-vinyl-2-thiooxazolidone does not occur free in Brassica seeds but is produced probably from



$$NaOS(O)_2O\text{–}C(SC_6H_{11}O_5){=}NCH_2CH\overset{\displaystyle OH}{\overset{|}{C}}HCH{=}CH$$

by enzymatic hydrolysis. Because the compound contained sulphur, investigations have been carried out into the effect of sulphate concentration in the soil on the production of this goitrogen. It was found that high sulphate greatly increased goitrogen production. This compound is not the only goitrogen found in the cabbage family: Langer *et al.* (1962) suggested that the thiocyanate content of cabbage would contribute to its goitrogenicity. However, a daily intake of about 22 lb. of kale or cauliflower would be required to furnish enough thiocyanate to produce a goitrogenic concentration in the blood. Fortunately, much of the activity of these compounds is destroyed by cooking.

Among other substances in food which have some goitrogenic activity attributed to them are non-iodine halides, calcium, arsenic, cobalt, ergothionine, cyanoglycosides and polysulphides. In the case of the non-iodine halides the evidence is slight. In some areas, notably in England, Punjab, South Africa and Soviet Asia, where fluoride occurs naturally in water, the presence of endemic goitre seems to be co-extensive with the fluoride. However, in similar circumstances in Israel, where the iodine intake is adequate, the incidence of goitre is low.

Chemicals with estrogenic activity occur in some foods. Two substances of this type have been identified in soya beans: these are 4′,5,7-trihydroxyisoflavone (genestein) and 4′,7-dihydroxyisoflavone (daidzein). These compounds are weak estrogens. Many plants have shown some estrogenic activity; some of these are carrots, wheat, rice, oats, barley, apples, cherries, plums, and parsley. Because the estrogenic activity of plants is very weak, it is almost impossible to consume sufficient material to invoke an estrogenic response.

Of the toxic chemicals found in food, the cyanogenetic glycosides are one of the most dangerous groups. These compounds, widely distributed in the plant kingdom, yield, on hydrolysis, hydrocyanic acid. Amygdalin, which occurs in the seeds of bitter almond, is perhaps the best known of the cyanogenetic

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* Presidential Address delivered before the Royal Society of New South Wales on 1st April, 1970.

glycosides. This compound, on hydrolysis, yields hydrocyanic acid, gentiobiose and benzaldehyde.

The Lima bean, a legume used extensively for food, contains a cyanogenetic glycoside, phaseolunatin, which on hydrolysis yields glucose, acetone and hydrocyanic acid (HCN). It appears that the hydrolysis takes place only if the beans are crushed before cooking. Viehoever (1940) found that the HCN liberated from crushed beans varied from 0·01 0·3%. Serious outbreaks of poisoning from cooked Lima beans have been reported from various parts of the world (Rathenasinkam, 1947 ; Dunbar, 1920). Experiments with cooked Lima beans raises the possibility that the human body may contain enzymes capable of releasing significant quantities of HCN from cyanogenetic glycosides (the lethal dose of HCN is about 100 mg.).

The occurrence of alkaloids in the plant kingdom is fairly common, and well over 4,000 different alkaloids are known. The humble potato contains an alkaloid, solanine, mainly in the tissue immediately below the skin. The concentration is very high in the green tissue developed prior to shooting. Tea and coffee contain the alkaloid caffeine, and infusions of these plants may contain several per cent. of this alkaloid. The stimulating effect of tea and coffee is due to caffeine, which is said to facilitate mental and muscular effort and to diminish drowsiness ; caffeine also has a marked diuretic effect.

A large number of amino compounds, many with high physiological activity, occur naturally in food. Included amongst these are the highly potent amines histamine, tyramine, tryptamine, and 5-hydroxytryptamine (serotonin). Bananas, plantains (sugar bananas), pawpaw and pineapple contain serotonin in concentrations up to 10 mg. per 100 g. of fresh fruit. Even the tomato contains about 0·4 mg. serotonin per 100 g. Aged cheese is a source of physiological amines, e.g. one specimen of Camembert contained 200 mg. tyramine per 100 g. The primary route of detoxification of primary amines is the oxidation to the corresponding carboxylic acid through the agency of the enzyme monoamine oxidase. As might be expected, accidents have been reported when patients were treated with monoamine oxidase-inhibiting drugs. One such accident occurred when a group of patients, receiving the tranquillizer " Parnate " (tranylcyramine), ate some matured cheese. This gave rise to hypertensive crises which were fatal in some cases. The serotonin intake of certain African peoples who use plantains as a major item of diet may reach 200 mg. per day. The high incidence of cardiovascular disease amongst these peoples may be related to the high intake of serotonin.

One of the most important groups of anti-enzymes contained in food is the cholinesterase inhibitors. The cholinesterases occupy a unique position in the animal kingdom, for they are involved in nerve impulse conduction and thus are vital to the well-being of animals. Some edible plants which yield cholinesterase inhibitors are, for example, broccoli, cabbage, pepper, Valencia orange, pumpkin, squash, carrot, strawberry, apple and potatoes. In the case of the potato it appears that the alkaloid solanine may be the cholinesterase inhibitor.

There are many other substances in food which have toxic effects ; for example, there is a complicated antagonism between unsaturated fatty acids and carotene.

The foregoing examples should serve to illustrate that food is not necessarily safe.

Natural Additives in Food

FUNGI

Bacterial or fungal infections can give rise to toxin in food. For example, *Clostridium welshii*, a spore-forming anaerobic organism, is often the causative organism in food poisoning. A common source of poisoning is chicken salad which has been stored at room temperature for some time before serving. Among the compounds which are formed in food by micro-organisms are a group of substances which can cause fibrous growths. Some of the most important of these compounds are the aflatoxins.

The effect of these substances was first noticed in England when about 100,000 turkey poults died in 1960 from what was then known as " turkey X disease ". The disease was soon traced to peanut meal. Subsequently, in 1961, it was found that the infection was caused by a strain of *Aspergillus flavus*, and the toxic substance was named " aflatoxin ". The aflatoxins cause serious liver toxic reactions, producing fibrosis and cirrhosis in young Rhesus monkeys. These compounds cause a high incidence of carcinomas in the livers of rats at levels of 1–6 μg. per day. The purified aflatoxins are carcinogenic in the livers of rainbow trout at a level of about 0·08 p.p.m.

METALS

Practically every element in the periodic table can occur either naturally or accidentally in food. Some metals, like iron and cobalt, are essential for the well-being of animals. Some, such as arsenic and barium, have no known useful function in the diet and are harmful at quite low concentrations. No method is known to avoid metallic contamination of food if the metal occurs in the soil where the crops are grown or where the animals graze. The traces concerned are usually so small that no harmful effects arise from their consumption and it is possible that harmful effects may arise in their absence. Of the trace metals essential for life, copper is an interesting example. Formerly, much of the food processing equipment was fabricated from copper; today stainless steel is the principal metal used. Some years ago there was a spate of complaints of "off" odours and flavours in bottled milk delivered to homes. This problem was traced to the copper content of the milk. Copper, which normally occurs in milk at about 0·15–0·2 part per million, had increased to several parts per million. Investigation revealed that the excess copper was coming from pasteurizers in the milk factory. This milk, on standing in sunlight, very rapidly developed "off" flavours and odours due to the copper greatly accelerating the normal staling processes in the milk fat. These effects are usually masked by bactriological changes producing, amongst other things, lactic acid. Copper is essential for animals because it is involved in haemoglobin formation. Many plants and animals used for food contain traces of copper such that the daily intake is about 2 mg. This is more than sufficient for metobical requirements.

Lead is one of the harmful metals which occurs in traces in practically all foods. These traces are derived from the soil in which the plant grows. Research indicates that some lead may be derived from lead tetraethyl used in motor spirit. As early as 1930, fears were being expressed about the effects of leaded petrol, and the government laboratory of the Departmental Committee on "Ethyl Petrol" found that the average amount of lead inhaled from the air of towns in Great Britain was 0·077 mg. per day. Lead is also a frequent accidental contaminant of food, sometimes from unsuspected sources such as old paint on ceilings slowly chalking or from leadlighted panels in kitchen cabinets.

Substances Deliberately Added to Food

These substances are often referred to as food chemicals, and are often very much safer than chemicals naturally present. Chemical compounds are added to food to achieve one or more of the following aims: to improve the keeping quality, the nutritional properties and the appearance or to improve tastes, and thus consumer acceptability of the food. The substances used fall into three main categories:

(*a*) Complex chemical substances such as proteins extracted from other foods, e.g. casein added in sausages.

(*b*) Naturally-occurring simple substances such as salt, acetic acid and ascorbic acid.

(*c*) Synthesized substances not found in nature, such as antioxidants, emulsifiers, preservatives and colours.

At the Delaney enquiry in 1954 it was stated that there were 704 different chemicals being used in food in the U.S.A. Now the number of chemicals given approval for such use by the Food and Drug Administration of the U.S.A. is about 10,000. Such is American law now, that any new substance proposed as a food additive must not only be safe, but must be proved to be safe, usually by protracted animal feeding experiments. The testing programme of food additives has resulted in some substances being removed from the permitted list on evidence which is so slender that it is almost impossible to find the reason. Fortunately, sodium chloride is one of the substances on the "gras" (*generally regarded as safe*) list, for if it were to be tested under the conditions required, it would fail miserably and be banned in the U.S.A.

Preservatives have been in use from very early times. The process of "salting" or "smoking" fish was perhaps the first preserving process using chemicals. "Smoking", a once popular process, added formaldehyde amongst other things to the meat. Modern preservatives include disodium acetate, which is used to preserve bread (anti-mould), where up to 6 oz. is used per 100 lb. of flour. Benzoic acid, which occurs naturally in cranberries, is used extensively in soft drinks. Benzoic acid has been used in ice to keep fish fresh. It prevents trimethylamine being detected without interfering with bacterial spoilage. This highlights one of the hazards of using chemical preservatives. It is most important that the preservative does not permit the growth of abnormal flora such as pathogens while obscuring spoilage changes.

Other acid preservatives include sorbic acid used to prevent mould growth in baked goods. Sulphur dioxide has been used for a long time as a preservative, especially in beverages, dried fruits and meats. The action of sulphur dioxide is not clearly understood, but it may inhibit sulphur-containing enzymes. Sulphur dioxide also acts as an anti-oxidant, for it can be used to protect ascorbic acid during the drying of fruit. Unfortunately, sulphur dioxide destroys thiamine in the food treated with it. Mapson *et al.* (1961) reported a 30% destruction of thiamine in sulphite-treated chipped potatoes, and Mallette *et al.* (1946) reported almost complete destruction of the thiamine in cabbage blanched in sulphite solutions, while riboflavin and niacin were unaffected. Another preservative is hydrogen peroxide, which is used to prevent staling of cream. The advantage of this preservative is that the by-products are oxygen and water. Further, excess peroxide can be destroyed by catalase, which can eb inactivated by heat and therefore does not affect further processing.

Fatty foods are susceptible to oxidative changes in the fat molecule with the production of rancid flavours and odours. The autoxidation of fats involves the formation of a free radicle. This process can be catalysed by traces of metals such as copper, 0·05 p.p.m. of which was found to double the rate of oxidation. Once a free radicle is formed, the reaction becomes self-perpetuating, with the regeneration of the free radicle and the production of a peroxide molecule :

$$R^{\cdot}+O_2 = RO_2^{\cdot} \text{ (peroxy radicle)}$$
$$RO_2^{\cdot}+RH = ROOH \text{ (peroxide)}+R^{\cdot}.$$

To slow the rate of autoxidation, compounds like butylated hydroxy anisole and propyl, octyl or dodecyl gallate are used. These compounds can exchange the free radicle with the fat molecule, but because of steric hindrance the free radicle so produced is unable to propagate further free radicle formation. The chain is then terminated by dimerization :

$$R^{\cdot}+AH \text{ (anti-oxidant)} = RH+A^{\cdot}$$
$$A^{\cdot}+A^{\cdot} = AA$$
$$\text{or } A^{\cdot}+R^{\cdot} = AR \text{ (inactive).}$$

It is obvious that these processes " use up " the anti-oxidant.

Compounds like glycerolmonostearate and sorbitan or polyoxyethylene fatty esters are used as emulsifying agents. These compounds improve volume and uniformity of flour confectionery. In bread they help to produce a loaf with a softer crumb and somewhat slower staling rate.

The texture of ice-cream and other frozen desserts is dependent, in part, on the size of the ice crystals in the product. The size of ice crystals can be controlled to some extent by the addition of some form of stabilizer. Substances typically used include agar-agar, gelatin, gums and alginates.

A group of chemical compounds commonly used in food are the dyes, the " Coal Tar Colours ", so called in an allusion to the early methods of production. There are about 46 separate dyes produced specifically for use in food. Of this number only six are common to 40 or more countries—three reds, two yellows and one unsatisfactory blue. It is almost certain that the permitted lists of each country have been drawn up with the same object in mind ; that is, to protect the ultimate consumer. Unfortunately, a satisfactory list of universally acceptable colours does not exist. The New South Wales list has 23 shades : eight reds, one orange, six yellows, one green, two blues, one violet, three browns, and one black. Some of these dyes contain an azo group and are, according to one school of thought, suspect. The most studied azo dye is 4-dimethylamino-azobenzene, known as butter yellow or methyl yellow. This dye was formerly used extensively in some countries as a food colour. The dye has been shown to be carcinogenic to rats, but strangely enough only when the diet was nutritionally deficient, particularly in riboflavin, which participates in the metabolism to harmless derivatives. There is no firm evidence that any of the food colours have caused any adverse reactions in man.

The chemicals in food which have received the greatest publicity are the residues of pesticides used to control weeds, insects, fungi or plant growth. The use of large quantities of pesticide is usually justified by the need to produce more food. Of the pesticides, D.D.T. has received most attention. Many publications have appeared pointing out the dangers of the accumulation of chlorinated pesticide residues. Some have pointed to the decrease in fertility of some species of sea birds, others have drawn attention to the presence of D.D.T. in the fat of the Weddle seal. With all the spate of literature it is almost impossible to tell whether the reduction in fertility of some sea birds is due to D.D.T. or to some other as yet unidentified cause, or if, indeed, a reduction in fertility has occurred at all. The danger is that chlorinated pesticides may be blamed and the true cause ignored, especially when efforts are being made by some pressure groups to have D.D.T. banned.

The residue position is so emotionally charged that it will be very many years before a truly objective perspective can be obtained; until this time the true position will remain obscure.

The problem with chlorinated pesticides appears to be related to their very long life and the fact that they are fat-soluble. Endrin and dieldrin, in relatively large doses, such as arise from accidental ingestion of toxic quantities, produce epileptic-type spasms and are feared for this reason.

The organic phosphorous insecticides are, generally speaking, much more toxic than the chlorinated compounds because they are cholinesterase inhibitors. The life of these phosphorous compounds is very much shorter, being measured in weeks or days rather than years, which is the rule for the chlorinated compounds. Because of their short life, they present relatively little problems of chronic toxicity. Nevertheless, a major hazard can develop from the use of these compounds. The recommended usage includes a withholding time after application, but the withholding time is almost impossible to police, partly because market and weather conditions may dictate an earlier harvest than was anticipated.

Pesticides are not the only chemicals used in agriculture which cause concern. Some German work has indicated that the humble spinach can be deadly to babies when grown in soils with a high available nitrogen content. The nitrate content of many leaf vegetables is dependent on the available nitrogen in the soil. After harvest and cooking, some of the nitrate may be converted to nitrite. Nitrite is a dangerous substance because it causes slowly reversible changes in the haemoglobin of the blood, thus reducing the oxygen capacity of the blood, which may result in cyanosis and death in severe cases.

With all the problems associated with food, we must eat to live and must consume about 400 g. of food each day. Naturally, each one of us can no longer produce all his own food, and must depend more and more on processed food. Perhaps in time all food will be safe to eat. This I know: the testing of new additives is so rigorous that the danger from this source is much less than that from " natural " food.

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The Occurrence and Significance of Triassic Coal in the Volcanic Necks near Sydney

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ABSTRACT—The breccia pipes near Sydney contain numerous inclusions of coal. Spores have been macerated from some of this material, the microflora obtained being no older than Hawkesbury Sandstone equivalent. The coal both in the breccia pipes and in the peripheral contorted zones is of bituminous rank, which is evidence that it has not been heated above quite modest temperatures.

Introduction

Although David (1896) suggested that the coal in the Euroka Farm breccia pipe was probably derived from the " Hawkesbury Sandstone ", coal fragments in other similar breccia pipes near Sydney have generally been assumed to be of Permian age. New evidence indicates that coal in at least several of these breccia pipes is of Triassic age and is now at a lower position than the strata from which it was derived.

The volcanic necks under discussion are situated in an area extending to about 25 miles north, 43 miles east, and 30 miles south-east of Sydney. Localities are given in the table as Army Grid references for the Sydney Four-Mile Topographic Sheet. Further details on the localities are given by Adamson (1966). Wilshire (1961) has described some of the volcanic necks as layered diatremes. They generally occur as vertical pipes with circular to irregular elongated outcrops ranging in area from a few acres to more than 40 acres. The breccias consist predominantly of altered basaltic fragments, commonly amygdaloidal, set in a matrix of clay and carbonate minerals and scattered quartz grains. They also contain a wide variety of other igneous and sedimentary rock fragments, including coal.

Peripheral Zones in the Pipes

At some localities contorted beds of sedimentary rocks have been exposed between the breccia and the non-deformed country rocks. Coal occurs sporadically in such peripheral zones at Minchinbury quarry and Erskine Park quarry. At an exposure in Minchinbury quarry the contact between the contorted sediments and the wall rock is marked by a small fault. Here the contorted sediments are less deformed and are clearly part of the country rock. The sedimentary beds in the peripheral zones are generally centroclinal.

The coal in the peripheral zones attains a maximum thickness of about one foot. It is a moderately bright humic coal and contains a high proportion of exinite, especially in the form of leaf cuticle. This abundance of leaf cuticle is not typical of the Permian coals of the Sydney basin, but is much more characteristic of some Triassic coals—such as the Ipswich coals of south-eastern Queensland (Cook and Taylor, 1963). The maximum reflectance of the vitrinite in the contorted sediments lies within the range 0·87–0·97%. These low reflectance figures suggest maximum temperatures probably of less than 100° C. Deformation in the contorted sediments has resulted in fragmentation of the coal, with rotation of the fragments and their subsequent bonding by " pressure welding ". The optical anisotropy of these fragments, however, is related to the original direction of bedding, indicating that the fragments were not plastic during deformation. This also indicates that the coal was subject to a maximum temperature well below 350° C., at which the vitrinite would become appreciably plastic (Brown, Taylor and Waters, 1965). It also suggests that this coal may have been of sub-bituminous or bituminous rank at the time of deformation.

An abundant, well-preserved, microflora has been extracted from the coal in the contorted sediments. It consists of *Alisporites* spp., *Aratrisporites* spp., *Cadargasporites senectus*, *Converrucosisporites cameroni*, *Dictyophyllidites mortoni*, *Cycadopites nitidus*, *Kraeuselisporites differens*, *Lycopodiumsporites* sp., *Microreticulatisporites* sp., *Neoraistrickia taylori*, *Nevesisporites limatulus*, *Polypodiisporites ipsviciensis*, *Punctatisporites* spp., *Punctatosporites walkomi* and *Verrucosisporites* spp. In particular, the presence of *Cadargasporites senectus* in association with *Kraeuselisporites differens* and *Nevesisporites limatulus* indicates that the microflora is no older than the equivalent of the Minchinbury Sandstone, i.e., it is of M.–U. Triassic age.

Localities of Pipes and Reflectances of Coal Specimens

	Pipe	Locality		Maximum Reflectance of Vitrinite at λ of 527 nm.
		Army Grid Reference	Adamson's (1966) Reference	
Fragments in Breccias	Hornsby Quarry	409,837	4	0·98–1·26
	Minchinbury Quarry	383,824	5	0·84–0·92
	Erskine Park Quarry	379,822	6	0·85–1·09
	Richardson's Farm	382,821	31	0·80–0·86
	Norton's Basin	361,817	35	0·76–1·04
	Davidson's Quarry	383,835	7	0·81–0·96
	Bulls Hill	389,818	32	0·92–0·97
	Patonga	428,859	—	0·73–1·78*
	Fitzpatrick's First Quarry	391,824	28	0·93–0·98
	Gilligans Road	405,840	21	0·66–0·91
	Campbelltown	377,786	36	1·80–1·90†
	Bloodwood Road	407,852	14	0·78–0·94
Peripheral Zones	Minchinbury Quarry	383,824	5	0·76–0·96
	Erskine Park Quarry	379,822	31	0·82–1·04

* The material of higher reflectance shows textural evidence of heat alteration, presumably by the basaltic intrusion which occurs in the pipe.

† A single specimen from vicinity of intrusion which appears to have caused abnormal reflectance.

Coal Fragments in the Breccias

Every breccia pipe in the Sydney region so far examined by the writers contains sparsely and unevenly distributed coal fragments. Although the coal fragments in the breccias are now of approximately the same rank as the coal in the peripheral zone (i.e., high volatile bituminous), most of these fragments appear to represent former single pieces of wood. The coalified wood fragments are generally elongated and range in length from about one millimetre to some tens of centimetres. They are commonly surrounded by rims up to several millimetres thick of calcite containing euhedral prismatic crystals of quartz. The presence of the rims suggests that the fragments of woody coal have shrunk, usually to between one-half and three-quarters of their former volume. Also, the even thickness of the rims around fragments of banded coal suggests that they have shrunk uniformly to some 80–90% of their former volume.

A well-preserved microflora has been extracted from two coal specimens from the Hornsby breccia. It consists of *Alisporites* spp., *Aratrisporites* spp., *Cycadopites nitidus*, *Duplexisporites gyratus*, *Granulatisporites minor*, *Kraeuselisporites pallidus*, *Neoraistrickia taylori*, *Osmundacidites* spp., *Pilasporites plurigenus*, *Polypodiisporites ipsviciensis*, *Punctatisporites* spp., *Punctatosporites walkomi*, *Verrucosisporites* sp., and *Vitreisporites pallidus*. The microflora is dominated by *Kraeuselisporites pallidus* and *Pilasporites plurigenus* and represents a particularly specialized assemblage reminiscent of some of the microfloras extracted from Ipswich coals of Triassic age. The presence of *Duplexisporites gyratus* indicates that the microflora is certainly no older than middle Hawkesbury Sandstone equivalent.

A well-preserved microflora also has been extracted from coal in the Patonga breccia. It consists of *Acenthotriletes* sp., *Alisporites* spp., *Cycadopites nitidus*, *Cycadopites* sp., *Dictyophyllidites mortoni*, *Kraeuselisporites differens*, *Monosulcites* sp., *Neoraistrickia taylori*, *Osmundacidites* spp., *Pilasporites plurigenus*, *Polypodiisporites ipsviciensis*, *Punctatisporites* spp., *Vitreisporites* sp., and *Circulisporites parvus*. The microflora is dominated by *Alisporites* spp. and *Neoraistrickia taylori*. The acritarch *Circulisporites parvus* is also particularly common. Overall, the assemblage is similar to the microfloras described previously, the presence of *Cycadopites nitidus* indicating that it is no older than Hawkesbury Sandstone equivalent.

The coal fragments from which spores have been extracted are petrologically very similar to the coal in the peripheral contorted zones at the margins of the Erskine Park and Minchinbury pipes.

A comparison of coaly material from the various breccia pipes and the peripheral zones is given in the table. The reflectances of woody and banded coals fall within the same range, although woody coal is in general isotropic and banded coal is anisotropic.

The table shows that the maximum reflectances of vitrinite from coal in the peripheral zones mostly lie within the same range as those from the breccias. All of the values are significantly lower than those for Permian coal in the northern part of the Southern Coalfield, N.S.W., where the maximum reflectance values so far recorded lie between 1·35% and 1·51%.

Discussion

The rank of the coaly material at the time of its incorporation in the breccia poses something of a problem. The properties of fragments of banded coal in the contorted sediments and, probably, in the breccia also, point to the coal having been at or close to the bituminous coal stage of rank. However, this would appear to conflict with available stratigraphic evidence, which suggests that an insufficient thickness of sediments could have overlain a Wianamatta-age coal at the time the breccia was formed.

All microfloras recovered from the coal to date indicate a specific Triassic age for the breccia formation. This is consistent with the observation that volcanic detritus is the dominant component of Wianamatta Group sediments above the Ashfield Shale, suggesting contemporaneous volcanic activity. There is also some evidence that at least one of the volcanoes (Richardson's Farm) has been buried by Wianamatta sediments.

None of the coal shows evidence of profound thermal alteration, which, had it occurred, would have been indicated under the microscope by changes in the optical and structural properties of the vitrinite and exinite minerals. In the same way spores are excellently preserved after maceration. The banded coal fragments have undergone very little deformation while in the breccia, and the only effects attributable to their incorporation are shrinkage, as indicated by rims, and a possible slight increase in rank. Some of the woody fragments of coal in the breccia have deformed plastically, apparently prior to a fairly uniform shrinkage. These effects of shrinkage and rank are probably the result of slight increases in temperature. The low temperature indicated is consistent with the hypothesis that cooling may have occurred as a result of adiabatic expansion. This is also suggested by the glassy nature of the basaltic fragments (though much of this is now altered) and by the occurrence of tiny vesicles in the same material.

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The Coolac-Goobarragandra Ultramafic Belt, N.S.W.

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Abstract—The Coolac-Goobarragandra ultramafic belt, in the south-east of New South Wales, delineates a steeply inclined sheet of peridotite and serpentinite 56 km. long and up to 2 km. thick, which occupies a tectonic zone between western Lower Palaeozoic beds and the Siluro-Devonian Burrinjuck granite mass on the east.

Petrogenetically critical components of the principal rock association of the belt include predominant cataclastic harzburgite which encloses autolithic Cr-rich and Al-rich chromitite pods, and gabbro-derived garnet-vesuvianite rodingite veins and rootless dykes which penetrate both the harzburgite and the chromitites. A magmatic gabbro-wehrlite complex of doubtful status occurs in the north.

The whole association is tentatively interpreted as a mush- and tectonically-re-emplaced and partly re-intruded abyssal complex in which a quasi-stratiform configuration of harzburgitic mush and basic magma components at depth was to some extent reproduced but also telescoped at a shallow crustal level.

1. Introduction

Ultramafic rocks in south-eastern New South Wales were referred to briefly by Carne (1892), Card (1896), Jaquet (1896), Raggatt (1925, 1936), Benson (1926), Brown (1929), David (1950), Adamson (1957), Joplin (1962) and Golding (1961–1967). The rocks occur at intervals within a broad linear zone trending south-south-east from Girilambone, near Nyngan; through Fifield, Arramagong and the Coolac-Gundagai district to Tumut Pond, near Kiandra (Rayner, 1961); over a distance exceeding 300 miles (Figures 1 and 2). The terms Gundagai Serpentine Belt (Rayner, 1961), Lachlan Serpentinite Belt (Fraser, 1967) and Girilambone-Kiandra Belt (Golding and Bayliss, 1968) have been proposed for the whole zone.

The Coolac-Goobarragandra ultramafic belt is the largest of the exposed subsidiary units within the Girilambone-Kiandra Zone, and its size and accessibility recommend it as a type unit in studies of the whole zone.

Field observations in the period 1961–1965, the examination of some 1,200 thin sections (including those of Veeraburus (1963) and Fraser (1967)) and unpublished studies of the chromitites (Golding, 1966) have contributed to the writer's conception of the belt.

This paper summarizes the available data on the setting and petrography of the belt, draws attention to problematic features requiring

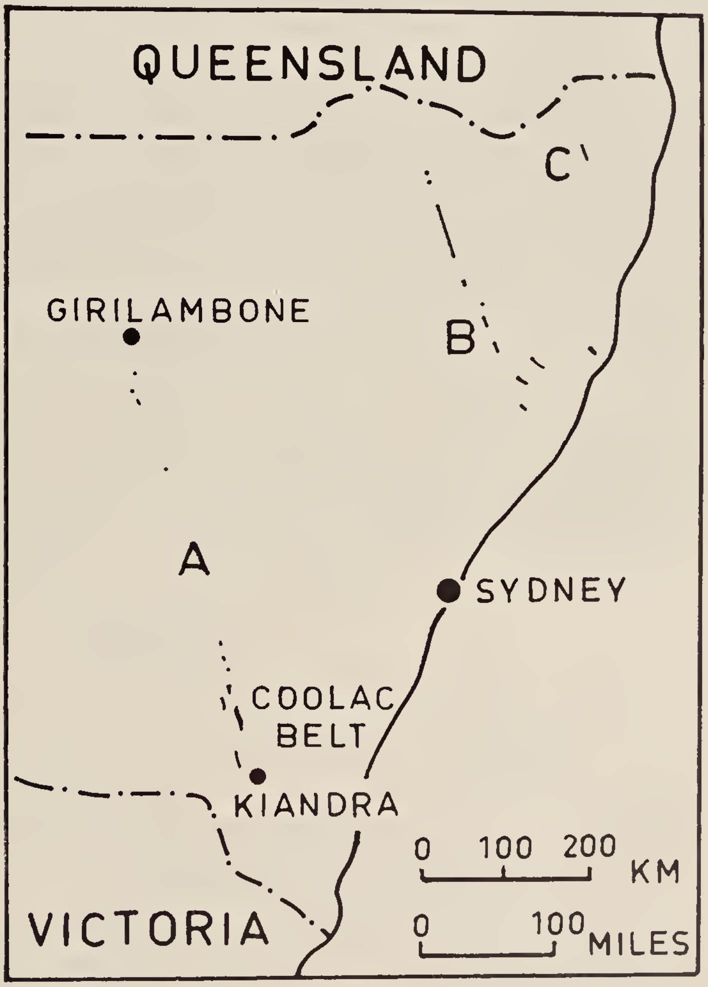

Figure 1.—Sketch map of eastern New South Wales showing the principal ultramafic belts. (A) The Girilambone-Kiandra Belt enclosing the Coolac subsidiary Belt. (B) The Great Serpentine Belt of New South Wales. (C) The Baryulgil Belt.

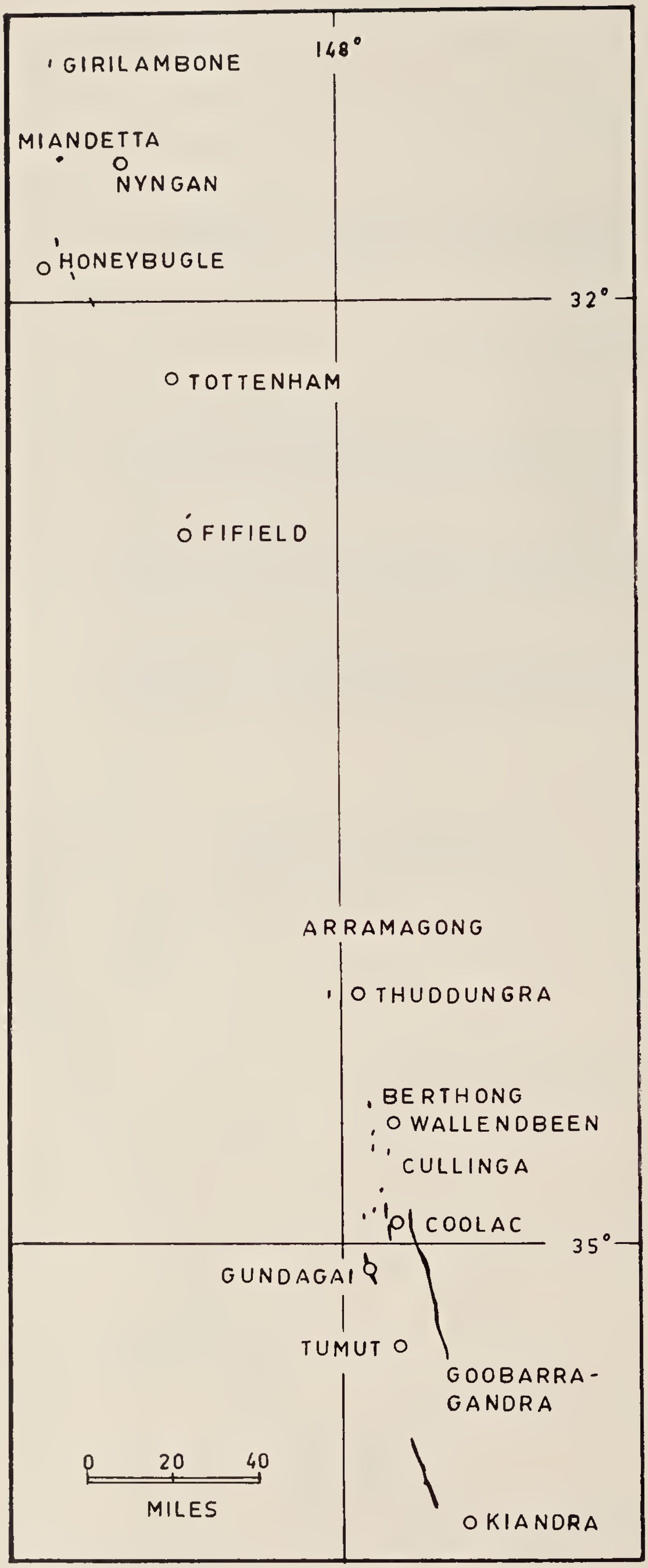

FIGURE 2.—Reported occurrences of ultramafic rocks in the Girilambone-Kiandra Belt.

more intensive study, and outlines a sequence of events to account for aspects of the observed rock association.

In the following account the terms Coolac belt or belt refer to the Coolac-Goobarragandra subsidiary unit, which is more closely defined hereunder.

2. Location and Physiography

The Coolac belt includes two steeply dipping, almost contiguous ultramafic lenses of unknown depth which are separated by a few hundred yards and which, end to end, outcrop almost continuously for 35 miles (56 km.) along the strike. The principal or northern lens is 27 miles long and attains a maximum thickness and outcropping width of about 2,200 yards (2 km.). The southern lens is composite and includes at least two narrow, sub-parallel serpentinite sheets separated by low-grade metamorphic rocks having a maximum overall width of about 600 yards.

The belt trends south-south-east from the Hume Highway, five miles north-east of Coolac and 240 miles by road west of Sydney ; crosses the Murrumbidgee River at Gobarralong ; passes some eight miles east of Tumut ; and terminates one mile south of the Goobarragandra River, on Patten's Ridge (Figure 3). Outcrops of ultramafic rock beyond these limits (Golding, 1966 ; Boots, 1968) are not considered hereunder.

The region traversed by the belt is broadly divisible into three meridional physiographic zones which reflect lithologic and structural discontinuities. The eastern zone consists largely of a dissected plateau about 3,000 feet A.S.L. and is underlain by the Burrinjuck granite mass. The central physiographic zone is also a zone of major tectonism which encloses all the ultramafic rocks with the possible exception of certain wehrlites in the extreme north. This zone largely coincides with the ridges and scarps of the Mooney Mooney and Honeysuckle Ranges indicated, with subdivisions, in Figure 3.

The western zone descends to 800 feet A.S.L. at the Tumut River west of the ultramafic belt, and is underlain by Lower Palaeozoic, probably Silurian, sedimentary, volcanic and low-grade metamorphic rocks, folded about sub-meridional axes, locally intruded by porphyrites and, in the south, by the Bogong granite of probable Devonian age (Adamson, 1957 ; Veeraburus, 1963 ; Golding, 1966 ; Fraser, 1967 ; Boots, 1968).

3. Broad Lithologies and Structure

In the Honeysuckle Range both serpentinization and shearing increase westward so as to roughly demarcate an eastern sector predominantly of blocky, partly serpentinized hazrburgitic peridotite from a western sector of sheared serpentinite. This east-to-west division persists into the southern half of the Mooney

Mooney Range, but further north gabbroic rocks take the place of serpentinite on the west and are associated with wehrlite and harzburgite (Figure 4) in the North Mooney complex. The narrow southern lens is lithologically similar to the western sector of the Honeysuckle Range.

The ultramafic rocks are separated from the western beds by a marginal zone 10 to 100 yards wide of pseudo-concordancy, within which fault septa of serpentinite and western beds alternate. Cleavage in the western beds, lithologic-structural planes in the marginal zone, fractures in the serpentinite, major joints in the harzburgite and foliation in the eastern granite all trend with the strike of the belt and are sub-vertical. Faulted contacts of serpentinite with eastern granite and with western beds, along Bombowlee Creek Road and Tumorrama Road respectively, dip east at 65° to 80°.

The eastern flanking rocks consist partly of granodiorite and the terms granite and granitic are therefore used broadly hereunder. Granitic rocks are massive and leucocratic at North Mooney Ridge and Mt. Lightning, strongly foliated and biotite-rich along Mundongo Scarp, and variably foliated elsewhere. The intensity of the foliation decreases away from the contact. Granitic rocks of the same mass 10 and 20 miles east of the belt were respectively dated as Siluro-Devonian and Middle to Upper Devonian by Evernden and Richards (1962). Alkali olivine basalts, dolerites and limburgites of probable Tertiary age cap the granite at the eastern contact of the harzburgite on the Red Hill Plateau (Veeraburus, 1963). At Patten's Ridge a wedge of amphibole schists, epidosites and amphibolite separates the serpentinite from the eastern granite.

4. The Eastern Contact

The eastern contact is marked by a zone of brecciated granite up to several yards wide abutting peridotite in the Honeysuckle Range; and by a selvage of laminated granite mylonite, some inches wide, abutting sheared serpentinite along Mundongo Scarp. Apophyses and thermal effects indicating liquid magmatic intrusion of either rock into the other; schlieren of either rock within the other; and fragments of ultramafic rock in the marginal granite breccia are all absent. Large enclosures of the eastern granite in marginal harzburgite, however, occur on both banks of the Murrumbidgee River and are either wedges stoped from the granite by ascending harzburgitic material, or locally infaulted slices. These features establish the overall tectonic character of the eastern contact but suggest that marginal granite brecciation pre-dated the existence of the harzburgite at the observed contact.

Although slices of peridotite, away from the contact, are flanked by selvages of sheared serpentinite between which they may have ascended tectonically, much peridotite and serpentinite at the contact itself is massive and lacks slickensides and megascopic brecciation. Thin sections, however, reveal post-serpentine microbrecciation which is superimposed on the normal pre-serpentine microcataclasis (Section 6). These features are compatible with the introduction of the harzburgite as a crystal mush into a pre-existing fracture and the subsequent ascent, minimal at the eastern contact but increasing westward, of slices of solid harzburgite.

Post-tectonic fluids localized by the fault promoted the formation of magnesite, chlorite, opal and chalcedony in marginal peridotite from place to place; and induced sporadic metasomatism of the granite breccia to resistant prehnite- and zoisite-rich rocks which stand in relief along the contact.

5. The Western Marginal Zone

From north to south in the Mooney Mooney Range ultramafic rocks are successively flanked on the west by gabbros; by intertonguing serpentinite and basic volcanics; and by alternating septa of volcanics, rodingite, albitite, cherts and serpentinites. At Mt. Lightning some marginal basic volcanics enclose angular fragments of serpentinite; others consist of unaltered spilitic variolite (Golding, 1966). Shales abut serpentinite in the Adjungbilly Valley and separate prominent sheets of sheared serpentinite along the Tumorroma Road. Andesitic rocks intertongue with serpentinite along Keef's Scarp and persist to the southern extremity of the belt.

The development of the western marginal zone presumably involved (i) the ascent of harzburgitic · mush into wet sediments and volcanics; (ii) the concomitant coherence and serpentinization of the mush; and (iii) the piecemeal ascent of serpentinite, and perhaps of lenticles of country rock, by slip on fracture planes. The recurrence of such movements is possible, perhaps when compression coincided either with hydrothermal episodes or with heating and dehydration of serpentinite (Raleigh, 1967).

The tectonic zone has been regarded as an overthrust (Browne, 1929) and as a possible strike-slip fault (Lambert and White, 1955;

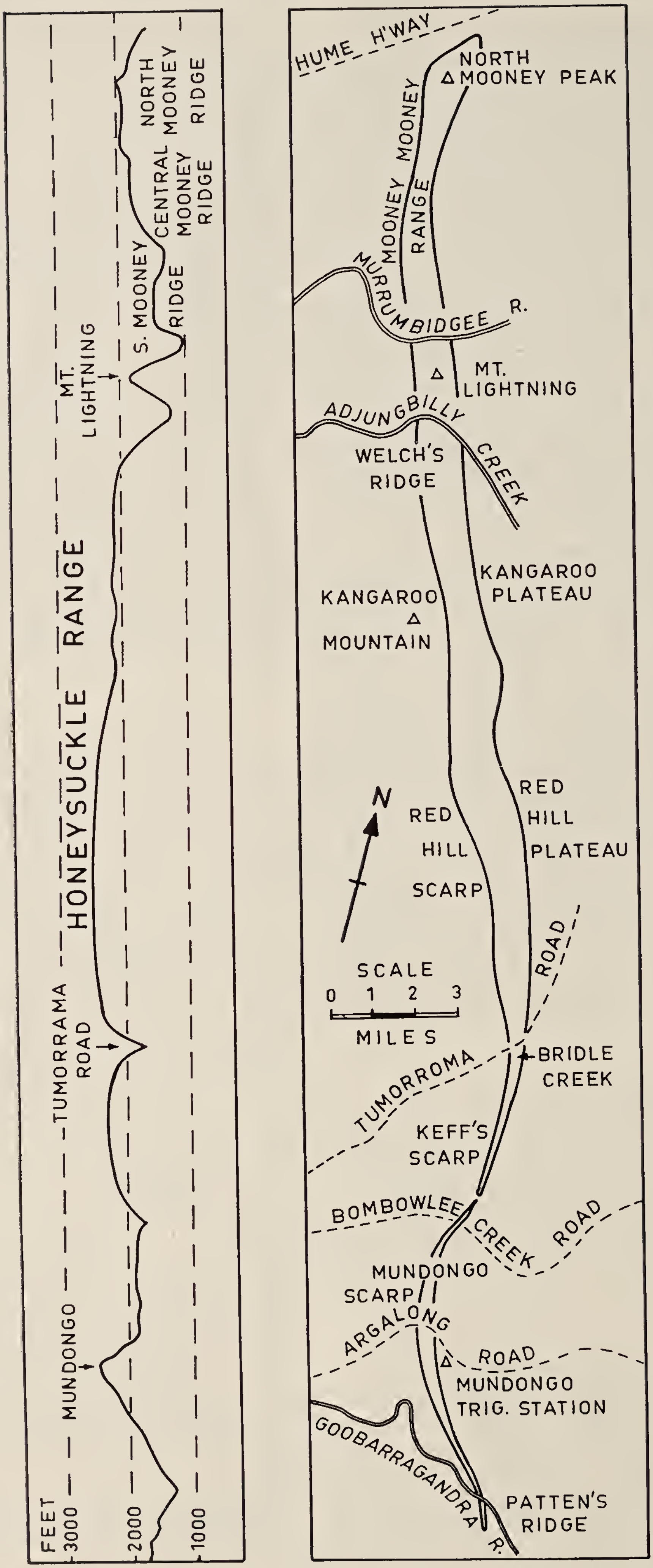

FIGURE 3.—The Coolac-Goobarragandra ultramafic belt—physiographic features. Meridional section (left) and plan (right).

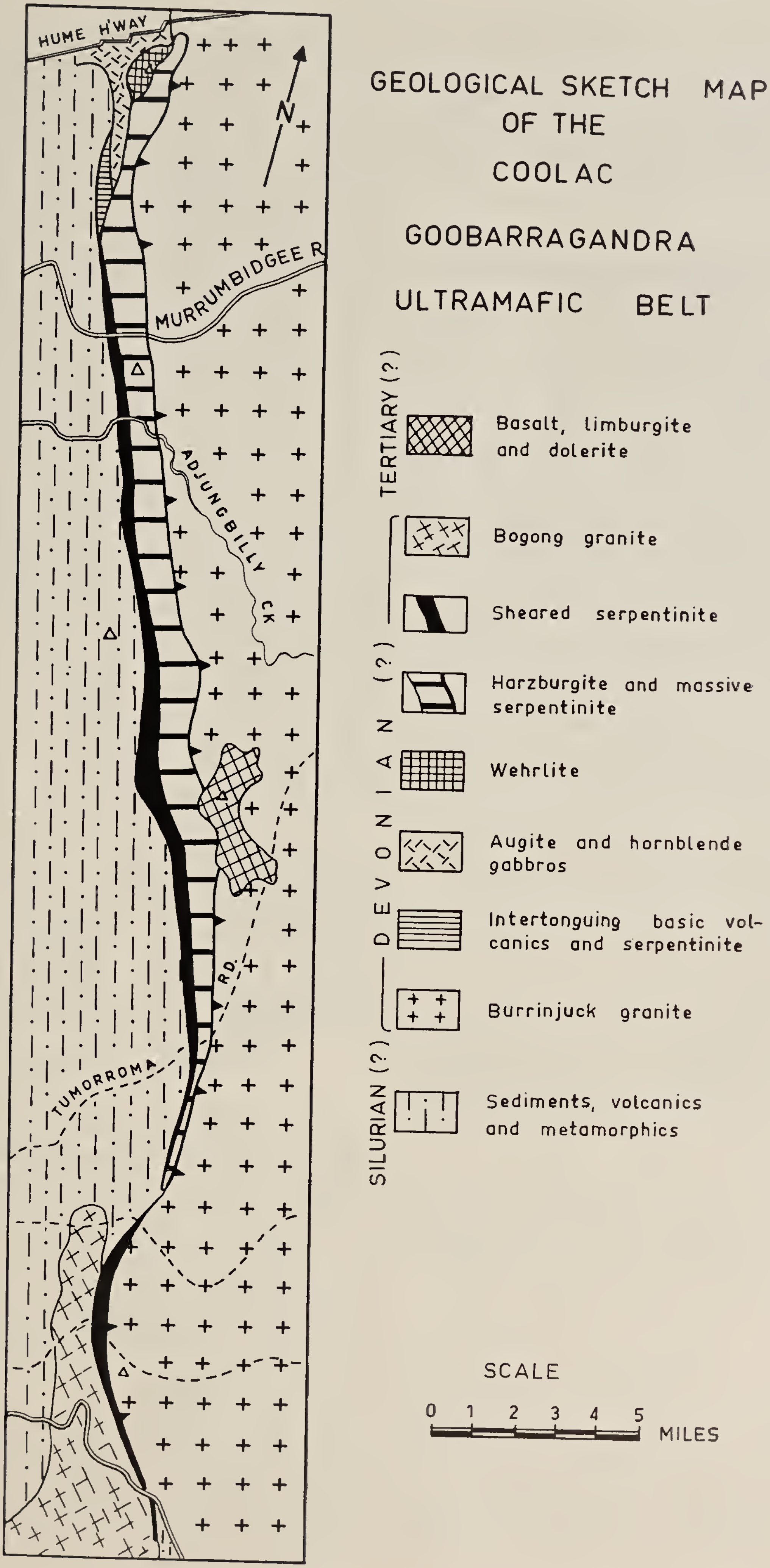
GEOLOGICAL SKETCH MAP
OF THE
COOLAC
GOOBARRAGANDRA
ULTRAMAFIC BELT
HUME H'WAY
N
MURRUMBIDGEE R
ADJUNGBILLY CK
RD.
TUMORROMA
TERTIARY (?)
Basalt, limburgite and dolerite
DEVONIAN (?)
Bogong granite
Sheared serpentinite
Harzburgite and massive serpentinite
Wehrlite
Augite and hornblende gabbros
Intertonguing basic volcanics and serpentinite
Burrinjuck granite
SILURIAN (?)
Sediments, volcanics and metamorphics
SCALE
0 1 2 3 4 5
MILES

Figure 4.

Rod, 1966). Because it may delineate a major relict lateral crustal discontinuity, and a fracture which extended to the mantle (Ringwood, 1964), its evolution is regarded as the principal geologic problem of the belt. The contents of the zone present a more or less independent series of problems.

6. The Honeysuckle Range Harzburgite

In terms of reconstructed (anhydrous) minerals, the harzburgite contains 60–95% (usually ≃80%) of olivine, 2–40% (usually ≃15%) of enstatite, up to 5% (usually ≃1%) of diopside, and about 1% of chromite. Commonly, about half the olivine and enstatite are serpentinized; local transitions of harzburgite to bastite serpentinite are frequent; and occasional lenses of dunitic serpentinite devoid of pyroxene and bastite occur around chromite deposits and elsewhere in the eastern sector. In most outcrops the rock is massive, but a few reveal alternating enstatite-rich and dunitic layers, 1–2 cm. thick, traceable over a few feet.

Megascopically, the harzburgite and derived serpentinite show orthopyroxenes, 5 mm. wide, within a groundmass which varies from medium grey and finely granular in rocks with densities of 3·0 g. cm.^{3}, which contain up to 6% of combined water; to black and aphanitic in rocks with densities of 2·7–2·4 g. cm.^{3} which contain 9–11% of combined water (Table 1).

Thin sections of harzburgite reveal rare clusters of olivine grains with allotriomorphic granular fabric and grains up to 2 mm. wide showing deformation lamellae. Usually disoriented olivine sub-grains, 0·1 mm. wide, are cemented and replaced by unfractured bluish-grey serpentine enclosing sporadic magnetite granules. The olivine, about $Fa_7 (2V_Z = 86 \pm 3°)$ was fragmented before or during serpentinization.

The enstatite near En_{90} $(2V_Z = 84 \pm 3°)$ encloses lamellae of clinopyroxene, and is ragged, warped and marginally replaced by recrystallized (?) olivine. The diopside and chromite grains are angular.

The pervasive cataclasis of the harzburgite might be attributed to slumping or compressive deformation of a cumulate derived from mafic magma more or less at the observed site (Challis, 1965; Challis and Lauder, 1966). Other features of the Coolac rocks (Section 9), however, favour the ascent of the harzburgite in a largely crystalline condition from a substantially deeper level.

Apart from possible upthrusting of masses or slices of solid rock; proposed mechanisms for the emplacement of alpine-type peridotite which emphasize the role of solid components range from (1) emplacement of a crystallo-magmatic suspension (Smolin, 1964); and (2) of a stiff, semi-solid crystal mush rendered mobile by crushing, local melting and recrystallization, and capable (at times) of magmatic flow (Thayer, 1963*a*, 1964); to (3) emplacement of a near-solid crystal mush deforming plastically during the removal by filter-pressing of associated liquid (Raleigh, 1965); and (4) emplacement of a completely crystalline mass deforming at low to moderate temperatures by recrystallization and crushing (Ragan, 1963, 1967); or (5) deforming at higher temperatures by recrystallization alone (Green, 1964, 1967).

The Honeysuckle Range harzburgite was probably emplaced in a heterogeneous manner involving several of these mechanisms which changed with increasing coherence of the mush during the emplacement period.

The harzburgite presumably originated either as a gravity differentiate of a mafic magma or as a refractory residue formed by the partial fusion of pyrolite (Ringwood, 1964; Ringwood and Green, 1966) and the incomplete segregation of the fused and residual fractions. By either origin the material would have been largely crystalline, but associated with subordinate liquid, at its inception. The re-emplacement of this crystal mush within the tectonic zone during appropriate stresses to high crustal levels is visualized. Further aspects of the re-emplacement are suggested by the enclosures of other rocks within the harzburgite (Section 9).

7. The North Mooney Complex

This complex occupies two to three square miles, mainly west of North Mooney Ridge, and is characterized by wehrlitic, gabbroic and harzburgitic rock types the mutual relations of which are obscure. The third type is probably an extension of the Honeysuckle Range harzburgite, but apart from some inclusions within serpentinite (Section 10) more than 20 miles to the south the other types appear to be absent elsewhere in the belt.

(*a*) *The Wehrlites*

These rocks contain from 50% to more than 90% (and ≃80%) of diopside and thus grade into clinopyroxenite. Orthopyroxene and feldspar are absent. Olivine, the second constituent, is usually represented by felted antigorite. Fine-grained (1 mm.) and coarser

(5–10 mm.) and massive and foliated types occur. The rocks are tougher than the harzburgite. Fractured surfaces of pyroxene-rich types are greyish-green.

Some wehrlite outcrops are separated by antigorite serpentinite presumably derived from dunite. This relation may represent (i) dykes of wehrlite in dunite or *vice versa*, (ii) associated tectonic slices of the two rocks, or (iii) wehrlite-dunite layering of settled, magmatic flowage or metamorphic types. Settled layering, however, is suggested by changes in the pyroxene-olivine ratio and in the grain-size of the pyroxene, in different specimens from the area ; and by the micro-textures.

Thin sections reveal colourless twinned diopside near $Ca_{41}Mg_{57}Fe_2$ ($2V_z=55°$, $N\beta=1{\cdot}672$), occasionally with marginal secondary amphibole. The crystals are variably fractured, but never granulated, and mush re-emplacement involving crushing is ruled out. The texture varies with the pyroxene-olivine ratio. Pyroxene-rich wehrlite reveals either allotriomorphic granular diopside with small interspaces containing antigorite, or shows frameworks of subhedral grains making point contacts. In pyroxene-poor wehrlite single diopside grains and small grain clusters appear to float in antigorite.

Two varieties of basic pegmatite occur within the wehrlite. These are firstly segregations a few feet thick of green clinopyroxene several centimetres wide, separated by cream-coloured saccharoidal zoisite, and secondly smaller patches of coarse hornblende associated with white saussurite which are localized along fissures near the junction with gabbros (Sub-section (*c*) below).

(*b*) *Marginal and Local Peridotite Variants*

Near the contact with granite in the extreme north the wehrlite contains a little garnet and turbid material, and occasionally veinlets of garnet, chlorite and serpentine replace olivine and diopside. Elsewhere in the mass rocks containing more antigorite than diopside, enstatite and antigorite, and enstatite and turbid material occur. Near the junction of wehrlite and harzburgite occasional veins of clinopyroxenite 1–2 cm. wide penetrate harzburgite. Rocks with distinctive magmatic textures also occur. In one variant green spinel separates clinopyroxene crystals enclosing resorbed olivine grains. In another, resorbed olivine is enclosed within ortho- and clinopyroxene, which abut pale brown amphibole.

(*c*) *Gabbroic Rocks*

Of these rocks some contain variably uralitized augite, others additionally contain a brown-green hornblende, and a third group contains hornblende to the exclusion of augite and uralite. Other constituents include saussuritized plagioclase, chlorite, leucoxenized opaques, zoisite veinlets and, rarely, traces of garnet. The hornblende gabbros predominate in the north of the gabbro area (Figure 4), and possibly separate the wehrlite from the augite gabbros. Most outcrops of gabbroic rocks reveal uneven and coarse-grained apophyses intruding country rock volcanics. Such gabbros apparently crystallized in place from volatile magma, and some apophyses may represent country rocks remobilized by volatiles. In places hornblende gabbro (or diorite) intrudes volcanics which contain angular blocks and fragments of (?) similar gabbro (or diorite).

The status of the North Mooney complex is problematic. Gabbro-wehrlite associations elsewhere occur in belts of serpentinized harzburgite (Taliaferro, 1943 ; Rynearson and Wells, 1944), in some stratiform and pseudostratiform complexes (Irvine and Smith, 1967 ; Rothstein, 1957 ; Smith, 1958), and in the Ural-Alaskan type of zoned complex (Ruckmick and Noble, 1959 ; Taylor and Noble, 1960 ; Taylor, 1967).

Whether the wehrlite and gabbro are normal associates of the Honeysuckle Range harzburgite which have been largely removed by erosion, or whether the complex is fundamentally of a localized type, remains to be determined.

8. The Serpentinites

X-ray and differential thermal analysis using the respective criteria of Whittaker and Zussman (1956) and Faust and Fahey (1962) indicate that the bastite serpentinites of the Honeysuckle Range consist predominantly of associated lizardite and chrysotile. Increasing westward serpentinization of this type within the harzburgite is compatible with an influx of water into the peridotitic material from the western beds (Section 5). An increase in ferric at the expense of ferrous iron, and a decrease of lime accompanying increasing hydration of these rocks seems likely (Table 1). The bastite serpentinites are green or black, and the dunite serpentinites often brown or grey with purple haematitic streaks, suggesting the field term serpentine pseudobreccia. Thin sections reveal a mesh texture in most of these rocks, with brown turbid patches in the pseudobreccias. Sulphide and awaruite particles are conspicuous in some types (Golding, 1963, 1966).

Antigorite serpentinite predominates on North Mooney Ridge, and is accompanied by antigorite-talc and talc-magnesite rocks on Central Mooney Ridge. These rocks derived from dunite, harzburgite and pre-existing bastite serpentinite, the final modifications of which may have been promoted by one or other of the gabbroic intrusions or late magmatic fluids associated with them. In the Bombowlee Creek-Mundongo area antigorite serpentinites are associated with chlorite-, talc-, magnesite- and amphibole-bearing serpentinites (Fraser, 1967), the formation of which was influenced, at least partly, by the intrusion of the Bogong granite.

TABLE 1

Chemical Analyses of Serpentinized Harzburgites and Serpentinites[1]

	1	2	3	4	5	6
SiO_2	41.79	40.88	40.24	39.82	39.92	39.71
Al_2O_3	2.28	1.30	1.96	1.12	0.04	0.34
Fe_2O_3	1.40	2.18	4.80	5.27	7.53	8.51
FeO	6.25	5.77	3.35	2.80	2.15	0.84
MgO	39.52	41.49	36.88	38.78	38.52	36.67
CaO	2.35	1.51	2.29	0.54	0.18	Nil
Na_2O	0.05	0.10	—	0.04	0.03	0.01
K_2O	0.04	0.06	—	0.02	0.02	tr.
H_2O+	5.45	5.66	8.75	10.72	10.84	11.15
H_2O-	0.03	0.32	0.23	0.08	0.04	1.90
CO_2	0.09	Nil	0.11	0.22	0.32	Nil
TiO_2	0.05	0.02	—	0.03	0.03	0.02
P_2O_5	tr.	tr.	0.02	0.03	0.02	tr.
F	—	—	Nil	0.13	0.14	—
Cr_2O_3	0.38	0.35	0.45	—	—	0.55
MnO	0.11	0.15	0.92	0.11	0.06	0.06
NiO	0.17	0.25	0.22	—	—	0.46
Li_2O	—	—	Nil	0.01	0.01	—
Free C	0.10	Nil	Nil	0.07	0.12	Nil
Totals*	100.06	100.04	100.22	99.73	99.91	100.22
S.G.	3.03	3.00	2.67	2.45	2.54	2.34

* Corrected for loss $O=F_2=0.06$ in analyses 4 and 5.

[1] Arranged in order of increasing water content from left to right. Samples 1–4 from the eastern, and samples 5 and 6 from the western sector.

Sample 1 : Grey, fine-grained, partly serpentinized harzburgite. Mt. Lightning.

Sample 2 : Grey fine-grained, partly serpentinized harzburgite. Mt. Lightning.

Sample 3 : Grey to black, fine-grained to aphanitic, massive bastite serpentinite containing about 25% of unaltered olivine and pyroxene. Adjungbilly Valley.

Sample 4 : Black, aphanitic, massive bastite serpentinite containing small amounts of unaltered olivine and pyroxene. Tumorroma Road.

Sample 5 : Sheared serpentinite containing traces of unaltered olivine and pyroxenes. Tumorroma Road.

Sample 6 : Massive, grey serpentine pseudobreccia with purple streaks, completely serpentinized and somewhat porous. Adjungbilly Creek.

Analysts : Samples 1, 2 and 6 : J. H. Pyle (N.S.W. Mines Dept.) ; Sample 3 : R. Fisher (Sydney) ; Samples 4 and 5 : A. Ithikasem (Thai Geol. Survey).

Sources : Samples 1, 2 and 6 : Golding (1966) ; Samples 3, 4 and 5 : Veeraburus (1963).

Lizardite-rich pods of black serpentine up to a few centimetres wide, separated by slickensided platy chrysotile, predominate within the sheared serpentinites of the western sector. Additional local variants of serpentinite have been described by Golding (1966) and by Golding and Bayliss (1968*b*).

9. Enclosures in the Harzburgite

Enclosures account for about five volume per cent. of the harzburgite. These are (*a*) the garnet-vesuvianite (Group 1) rodingites, and the " sub-rodingites ", (*b*) the Haystack Creek metasomites (including the Group 2 rodingites), (*c*) the acid feldspathic rocks, and (*d*) the chromitite pods. Groups (*a*) and (*c*) (above) account for about 60% and 30% of the enclosures respectively. The apparent structural relations of the enclosures to the harzburgite are indicated in Table 2.

(*a*) *The Garnet-Vesuvianite Rodingites*

These rodingites are pale coloured rocks with a " flinty " or finely sucrose to coarsely gabbroic megascopic appearance. They contain variable amounts of garnet (N=1·700–1·735) belonging to the grossular-hydrogrossular series, vesuvianite, chlorite and relict non-cataclastic diopside, all of which are colourless in thin section. Amphiboles and serpentine minerals are rare accessories. The occurrence of garnet in wehrlite and gabbro (Section 7) is excluded from consideration here.

These rocks form tabular bodies up to 50 ft. long and 3 ft. wide, but usually much smaller, which occupy sub-vertical, usually meridional spaces in massive harzburgite and serpentinite. They are most abundant along North and Central Mooney Ridges and at Mt. Lightning. Some masses are homogeneous, but streaky and patchy mineral segregations occur in others. Marginal slickensides and brecciation are absent or rare. The rocks are similar to those elsewhere regarded as metasomatized basic dykes (Arshinov and Merenkov, 1930 ; Miles, 1950 ; Bloxham, 1954 ; Baker, 1958), but dissimilar to the rodingitized tectonic inclusions within sheared serpentinite (Schlocker, 1960 ; Vuagnat, 1965 ; Coleman, 1966).

Fig. 1.—Chromite-rodingite breccia from the Vulcan South Mine, North Mooney Ridge.

Fig. 2.—Rodingite veins (white) transecting and offsetting schlieren-banded (spotted and streaky) chromitite (chromite with serpentine minerals) and massive chrome ore (black) from the Mooney Trig Mine, North Mooney Ridge.

Although lime released during serpentinization possibly contributed to metasomatism, the presence of unaltered diopside in some wall rocks, and the availability of lime in the precursor rocks and magmas themselves, suggest the latter as the major sources of the added lime in the Group 1 rodingites.

Many Group 1 rodingite bodies appear to be rootless dykes which represent pockets of residual gabbroic magma, and some, at least, either consolidated and were metasomatized at the observed sites or have been transplanted, together with their wall rocks in larger, fault-bounded, composite blocks from pre-existing sites.

Group 1 rodingite dykes and veins frequently transect chromite deposits, particularly in the north of the belt. The intrusive *in-situ* character of the precursor magma with respect to the chromite host is unambiguous, and rodingite-chromite breccia (Plate 1, Fig. 1) indicates that the chromite was competent when the precursor magma was injected.

The rarity of dykes of harzburgite (or serpentinite) in chromitite, and the absence of harzburgite-chromite breccia and of rodingite-harzburgite breccia contrast with the rodingite-chromite associations. These relations reflect marked differences between the physical states of the harzburgite and rodingite precursor materials and between the competency of the chromitite and harzburgite hosts of rodingite.

TABLE 2

Enclosure Types Within the Harzburgite

Structural exotics (mechanically transported)	Exogenous	Infaulted wedges of eastern granite (*c*),* Murrumbidgee and Red Hill. ? Fault-displaced segments of marginal granite micro-breccia (*c*), Keef's Scarp.
Mush-transported exotics, autoliths, and roof pendants	Exogenous (xenoliths)	Composite feldspathic body (*c*), Tumorroma Road.
	Endogenous (autoliths)	Chromitites (*d*). ? Wehrlite roof pendants east of Mooney Peak.
Liquid magmatic intrusions and rootless dykes essentially at the site of consolidation	Exogenous	Non-cataclastic granite-aplite dykes (*c*), Patten's Ridge. ?Variolite apophyses and derived metasomites (*b*) at Mt. Lightning.
	Endogenous (co-magmatic)	Garnet-vesuvianite-chlorite rodingites (*a*). " Sub-rodingites " (*a*). ? Wehrlite dykes and apophyses east of Mooney Peak. Cataclastic acid feldspathic enclosures (*c*).

* (*a*)–(*d*) as in introduction to Section 9.

The occurrence of a rodingite vein sharply transecting and offsetting magmatic flow layers (Sub-section 9 (*d*)) in chromitite (Plate 1, Fig. 2) and the previously noted inter-relationships jointly indicate that chromitite was the earliest and the rodingite precursor the latest rock to consolidate.

While a two-stage origin involving precipitation of gabbroic minerals, followed by rodingitization, is visualized for many Group 1 rodingites, some may be direct precipitates from a more aqueous fluid (Anirudda, 1967), and narrow veinlets of monomineralic chlorite, garnet and vesuvianite in some of the chromitites may be related to such a fluid. The variable hydration of the precursor fluid is also suggested by tabular bodies of brown hornblende-prehnite rock and by others containing fibrous (? tremolitic or lamellae-bearing) clinopyroxene and zoisite. These bodies, here termed " sub-rodingites ", were encountered only at Bridle Creek and Mt. Lightning, but may have been overlooked elsewhere since their grey colour differs only slightly from that of the harzburgite host.

Although Group 1 rodingites are abundant near the augite gabbro in the Mooney Mooney Range, they are also abundant at Mt. Lightning, where gabbro is lacking. The rodingites and augite gabbros may have derived from the same initial source (inter-cumulus liquid or partial melt), but if so their history diverged. The uralitization and ensuing saussuritization (see Ehlers, 1953 ; Harpum, 1954) of the augite gabbro did not result in Group 1 rodingite minerals except on a microscopic scale. Conversely, Group 1 rodingites contain little or no amphibole or zoisite. The alteration of basic rocks in the Coolac belt thus followed three trends : the uralitic-saussuritic, the Group 1 rodingitic, and the Group 2 rodingitic (subsection 9 (*b*)). When the mush liquid did not precipitate as gabbroic Group 1 precursor material, it may have split into pyroxenitic or amphibole-rich (" sub-rodingitic ") and feldspathic (Sub-section 9 (*c*)) fractions. The consolidation of the Group 1 rodingitic precursor, " sub-rodingitic " and feldspathic bodies was probably the final event in the bulk coherence of the harzburgitic mass.

(*b*) *The Haystack Creek Metasomites*

Although prehnite- and zoisite-bearing rocks appear in diverse settings (Section 4 ; Section 7, Sub-section (*a*)) in the belt, the occurrences at Haystack Creek, Mt. Lightning, are the most distinctive. Haystack Creek (Golding, 1966) marks the eastern junction of a mass of variolite about 300 yd. long and 50 yd. wide within the eastern sector. The least altered variolite is megascopically similar to that in the western marginal zone (Section 5), 700 yd. distant, but thin sections show it to be prehnitized.

One group of rocks in the creek includes a series of greenish-grey metasomites derived from basic rocks of doubtful status, in which colourless amphibole is the sole constituent in some outcrops but is associated with antigorite ; with prehnite ; and with diopside, chlorite, prehnite, clinozoisite and sphene in adjacent outcrops.

Another group of rocks includes pale coloured, fine-grained metasomites which vary from homogeneous to gneissic in structure, and include several with relict variolitic texture. Most of these rocks formed at junctions of peridotite or serpentinite either with variolite or with acid feldspathic rocks. Some outcrops reveal up to six metasomatic zonal segregations with vertical junctions. These rocks (the Group 2 rodingites) contain variable amounts of prehnite, zoisite, garnet, chlorite and sphene. They differ from the Group 1 rodingites as follows : diopside and vesuvianite are absent, calcite is present in some, the chlorite is greenish, and prehnite and zoisite are characteristic and occur in substantially monomineralic rocks. The garnet, however, is similar.

The metasomatism at Haystack Creek is of the lateral or contact type and may have been promoted by the water which induced serpentinization in the associated rocks, or by fluids of other affiliations.

(*c*) *The Acid Feldspathic Rocks*

These are streaky grey and white, cherty and fine-grained rocks occurring in small masses similar in size and shape to that of the Group 1 rodingites. They are strongly micro-cataclastic and exhibit micro-faulted and impacted feldspars with bent twin lamellae, intensely sutured quartz and abundant mylonite. Single samples are not representative of a given mass.

Specimens from Keef's Scarp contain microperthite, oligoclase, quartz, leached biotite, rosettes of pale amphibole and zoisite. Plagioclasite with zoned andesine to oligoclase, muscovite, chlorite, sphene, quartz and zoisite ; and albitite with striated and checker-board albite, chlorite, sphene, leucoxene and (?) stilpnomelane occur in different masses along Haystack Creek. From a single mass on Red Hill plateau each of eight specimens revealed different assemblages : microcline-, plagioclase-, albite-, chlorite- and carbonate-rich, as well as hornblende-, garnet- and pyroxene-bearing types being represented.

Similar enclosures in ultramafic rocks elsewhere have been regarded as foreign intrusions (Benson, 1913 ; Watson, 1953) or hydrothermal bodies (Francis, 1955), as co-magmatic differentiates of the ultrabasic magma (Arshinov and Merenkov, 1930 ; Suzuki, 1953), as co-magmatic and metasomatic members of the " alpine mafic magma stem " (Thayer, 1963*b*, 1967), as metasomatic complements of rodingite (Green, 1958), as metasomatized gabbro (Olsen, 1961), as reconstituted sediments (Baker, 1958), and as metasomatized sediments and volcanic rocks (Coleman, 1966 ; Leonardos and Fyfe, 1967).

Diorites containing zoned plagioclase may be differentiates of the gabbroic precursor magma of Group 1 rodingite. Some other types appear to be metasomatic modifications of this diorite or of gabbro. The reciprocal rodingitization of gabbro at one point and its acid feldspathization at another seems possible. The cataclasis suggests movement of largely crystalline material during emplacement and metasomatism.

Some enclosures may represent fault-displaced segments of marginal granite micro-breccia ; and a composite feldspathic body within harzburgite along the Tumorroma Road is probably a xenolith derived from the Burrinjuck granite. Aplite dykes associated with the Bogong granite contain micrographic intergrowths of quartz and microperthite and are non-cataclastic.

(*d*) *The Chromite Segregations*

Lenses (pods) of massive and disseminated chromite (chromite deposits, chrome ores, chromitites) up to 200 ft. long and a few feet wide, but usually much smaller, are unevenly distributed within the harzburgite, and over a length of 5 km. along Welch's Ridge they appear to be absent. Textures indicate their development in three principal stages : (i) an abyssal or cumulate stage, (ii) a re-emplacement, desegregation or deformational stage when flow-layering and lineation were superimposed on cumulate textures (Golding, 1966, 1967*b*), and (iii) a stage of metasomatic modification (Golding and Bayliss, 1968*a*).

The principal silicates in the ores are olivine, diopside, serpentine minerals and chlorites. These form the matrix of chromite fragments in flow-layered ore, but fill intercumulus spaces, or occupy fractures and breccia spaces in massive ore. The distinction of primary silicates and their derivatives from subsequently introduced rodingitic and other material, and from material fortuitously intermixed with, or juxtaposed against, chromite during re-emplacement and tectonism, is thus dependent on the recognition of primary textures which are preserved in small relict portions of ore.

The sizes of the chromite and olivine grains in undeformed Coolac ores are significantly larger than those in the stratiform (Bushveld and Stillwater) chromitites (Jackson, 1961, 1963) and point to differences in the duration, depth or other conditions of crystallization.

Characteristic compositional features of the primary (unaltered) chromite are (i) the low content (usually <5%) of Fe_2O_3, and (ii) the large variation in Cr_2O_3 and Al_2O_3 (Table 3). Chemical analyses of chromite concentrates from 29 deposits and further data based on a linear relation between the $Cr_2O_3 : Al_2O_3$ ratio and the cell dimensions (Golding, 1966) indicate that Cr_2O_3 varies from 62 to 34 and Al_2O_3 from 6 to 34 weight per cents. There is also a bimodal frequency distribution of the deposits with respect to the $Cr_2O_3 : Al_2O_3$ ratio, with major and secondary maxima at about 57% and 37% Cr_2O_3 (and 10% and 30% Al_2O_3) respectively. Of the seven largest deposits, five contain Cr-rich and two contain Al-rich chromite.

The Cr-rich chromite is usually associated with mesh texture serpentine derived from olivine in deposits throughout the belt. At Mt. Lightning and at North and Central Mooney Ridges and near the Tumorroma Road, however, these deposits are interspersed with others containing Al-rich chromite associated with diopside or with derived chlorite containing minute garnets. The Cr-rich chromite accumulated, and probably precipitated with olivine, and the Al-rich chromite apparently accumulated and may have precipitated with diopside. The greater frequency of resorbed chromite in the Cr-rich, but of relict primary textures in the Al-rich, chromite suggests that the former had a longer history.

Table 3

Chemical Analyses of Cleaned Chromite from Segregations in the Honeysuckle Range Harzburgite

	1	2	3	4
Cr_2O_3	31.3	35.8	59.1	59.9
Al_2O_3 ..	33.6	30.1	10.0	5.8
Fe_2O_3 ..	4.9	2.2	4.9	17.1
FeO	8.2	11.2	12.8	
MgO	17.4	17.1	12.4	14.5
MnO	0.2	0.1	0.2	0.2
TiO_2 ..	0.1	0.1	0.1	0.2
SiO_2	0.7	1.8	0.3	1.0
H_2O	1.0	—	0.1	1.4
Etc.	0.2	0.1	0.2	—
Total ..	97.6	98.5	100.1	100.1
a_0 Å ±0.005 ..	8.213	8.217	8.312	8.317

1. Chromite with a little chlorite impurity. Vulcan North Mine. North Mooney Ridge.
2. Chromite with chlorite and traces of relict diopside. Quilter's South Mine, Mt. Lightning.
3. Chromite with a little serpentine impurity. Mt. Miller Mine, Tumorroma Road.
4. Chromite with a small amount of chlorite, serpentine, grossularite and opal. Kangaroo East Mine, Honeysuckle Range.

Analysts : Nos. 1 and 3 : Mines Dept., N.S.W. ; Nos. 2 and 4 : B.H.P. Co. Ltd., Newcastle, with a separate determination of FeO (analysis 2) by R. Fisher, Sydney.

The two chemically and mineralogically contrasting ore types presumably derived penecontemporaneously from contrasting magmas or magma domains, or at different periods from different magmas or from a magma the chemical and/or physical character of which changed with time. The close proximity at several localities and within identical harzburgite of the two chromitite types suggests that at least one type originated in a different environment from that in which the harzburgitic minerals precipitated, if such minerals are in fact magmatic precipitates (and not refractory residues). It is concluded that some chromite pods at least have a " primary exotic " relation to their containing rocks.

The ore pods may represent fragments of former layers, but their stream-lined shapes (Golding, 1966) and scattered distribution suggest that after isolation the pods were entrained within and re-emplaced with the harzburgitic mush, as proposed by Thayer (1960, 1964), for podiform chromite deposits generally. To some extent, therefore, all the pods have a " secondary exotic " (autolithic or xenolithic) relation to their present host rocks.

The occurrence elsewhere of Cr-rich chromite deposits in feldspar-free peridotite masses and of Al-rich chromite deposits in ultramafic complexes containing feldspathic members was noted by Thayer (1946). The Cr-rich Coolac chromites are similar to those of the Pacific Coast Province (Thayer, 1946). The Al-rich Coolac chromites are similar to those in East Oregon (Thayer, 1946), in Camaguey, Cuba (Flint *et al.*, 1948), in the Philippines (Stoll, 1958) and in the Kempirsay pluton in the south of the Uralian geosyncline (Pavlov and Chuprynina, 1967), all of which are associated with gabbro, troctolite or anorthosite and several of which contain anorthite in the chrome ores. The absence of feldspar or its alteration products in the Al-rich Coolac ores may indicate their formation at greater pressures than those which operated elsewhere (Turner and Verhoogen, 1960, pp. 130–31 ; Kushiro and Yoder, 1964 ; Irvine, 1967).

If the usual sequence from lower peridotitic to higher feldspathic members in stratiform and pseudostratiform peridotite-gabbro complexes is applicable to the precursor complex of the Coolac rock association, Cr-rich chromitites originated at lower levels, and the Al-rich chromitites at higher levels (nearer the feldspathic material). The regional distribution of the Coolac chromitites also points to a relation between the Al-rich type and the more calcic and aluminous members (rodingites, gabbros and wehrlites) of the Coolac rock association.

10. Enclosures in the Serpentinite

These enclosures increase westward and include (i) fragmented representatives of the types which occur in the harzburgite, tectonic inclusions of country rock (Section 5) and their metasomatic derivatives, (ii) sulphide deposits, (iii) isolated masses of quartzo-feldspathic and cordierite - spinel - anthophyllite hornfelses (Golding, 1966), and (iv) certain metagabbroic and wehrlitic enclosures referred to below.

A mass of heterogeneous metagabbro about 300 ft. long and 50 ft. wide lies within schistose serpentinite of the western sector along the Tumorroma Road. Some portions are pyroxene- and other portions amphibole-bearing ; fabrics are partly granoblastic and partly igneous and metasomatic (Golding, 1966). Another metagabbro enclosure and also one of wehrlite similar to that in the North Mooney complex occur within serpentinite two miles to the north of the Tumorroma Road (Veeraburus, 1963). These occurrences suggest the former existence in this area of intrusions similar to those in the north of the belt. The serpentinite has moved around these enclosures, the earlier history of which is problematic.

11. Speculations on the Genesis of the Ultramafic Association

Assuming the origin of the harzburgite either as a cumulate or as a refractory residue (Section 6), a stage existed when harzburgitic mush formed the lower component and liquid mafic magma the upper component of a bipartite, abyssal mush and magma complex. Its depth of formation (Green, Green and Ringwood, 1967), duration at one or successive depths, and the independent history of the components would have influenced the derived rock association.

With a protracted duration, the formation of transitional cumulate mushes of dunitic, wehrlitic or troctolitic character might be envisaged and may be exemplified at the Bay of Islands, Newfoundland (Smith, 1958). If the harzburgite is a cumulate, Cr-rich chromite may have accumulated with it and Al-rich chromite may have accumulated with higher level transitional mushes. If the harzburgite is a refractory residue, and provided no chromite segregations derived as such from pyrolite, Cr-rich chromite may have accumulated at the interface of harzburgitic and transitional mushes, and Al-rich chromite at the higher level interface of transitional mush and magma.

The subsequent history of an abyssal complex of the second type intersected by the tectonic zone, or its precursor, might be visualized, in outline, as follows : The mafic magma advanced ahead of the transitional mush and the latter, remobilized on ascending to lower pressure levels, in turn preceded the more sluggish harzburgitic mush. Disrupted Cr-rich chromite segregations, released from the lower interface, were captured by and entrained within but tended to lag behind, the frontal edge of the harzburgitic mush. Al-rich chromite masses released from the higher interface entered the mush later. A second-order vertical zonation of chromite autoliths thus developed within the rising front of the mush. A near-frontal mush zone enclosing Al-rich and the smaller and less compacted Cr-rich autoliths preceded a zone enclosing the larger and denser Cr-rich autoliths which, in turn, preceded barren harzburgitic mush.

Of the earlier expressed mafic and transitional magmas, a portion reached the surface through sporadic volcanic feeders and other portions consolidated in sub-volcanic reservoirs. Accompanying further tectonism, the harzburgitic material continued its ascent and pierced the roots of the earlier intrusions and down-folded portions of the earliest extrusions.

Assuming mush re-emplacement doming, or block or slice tectonic uplift of the central part of the belt (between the Adjungbilly Valley and the Tumorroma Road), erosion could account for the observed rock and ore distribution. Thus, near-frontal harzburgite enclosing mixed chromite autoliths, abundant Group 1 rodingites and related enclosures (near the roof of the harzburgite), together with volcanics, gabbro and wehrlite representing the earlier mobilized magmas, are exposed in the north; but elsewhere have been eroded so as to uncover deeper levels of harzburgite enclosing Cr-rich chromite autoliths, and, in the centre of the dome (Welch's Ridge-Kangaroo Plateau), the still deeper zone of barren harzburgite.

The peridotite-gabbro association of the Coolac belt, according to this interpretation, is a mush- and partly tectonically-re-emplaced and also partly re-intruded abyssal complex in which a quasi-stratiform configuration of mush and magma components at depth was to some extent reproduced but also telescoped at shallower levels.

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Radio-Carbon Datings of Ancestral River Sediments on the Riverine Plain of South-eastern Australia and Their Interpretation

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ABSTRACT—This paper deals with the configuration of Quaternary sediments of the Riverine Plain. The origin of fluviatile sediments and their relationship to the present river system is discussed. It is shown that the Older Alluvium of the Plain is relatable to a series of prior streams which are still traceable as a relict distributory stream system. The Younger Alluvium is deposited by ancestral rivers which form a tributary pattern. The ancestral river system displays evidence of three separate phases of stream activity. Radio-carbon datings of wood samples from sediments representative of the three phases are presented. Results substantiate the earlier published relative chronology. A palaeo-climatic interpretation of the presented carbon dates, and those published previously, is put forward.

The purpose of this paper is to present new datings of three reliable carbon samples obtained from ancestral river sediments and to correlate these with earlier published dates. With relatively few dates available at this stage, inferences drawn from the limited data should still be regarded as contributions towards an eventual understanding of the region's geochronology.

Surface sediments of the Riverine Plain consist of two geological subdivisions: the Older and Younger Alluvium. Sediments deposited by prior streams (Butler, 1950) are the Older Alluvium, while Younger Alluvium consists of the ancestral river (Coonambidgal) sediments. The datings presented in this paper are from the Younger Alluvium.

The near-perfect preservation of prior streams on the present Older Alluvium surface in some locations was first taken as evidence for a very youthful age. However, subsequent studies showed that they are of considerable antiquity, and regional stratigraphic studies confirm this.

Carbon samples occurring conformably in current bedded sands and gravels of stratigraphically the most recent prior stream beds, gave C14 age determinations of greater than 36,000 years (Pels, 1964*a*). This determination of age represented the limit of the dating equipment, so that it is not known how much older the sediments are.

On the other hand, Langford-Smith (1963) published dates of wood samples obtained from shallow depths in prior streams which indicated a much younger age. He attributed these dates to possible reactivation of prior stream beds during floods or root growth not related to the time of deposition.

Regional surveys (Pels, 1964*b*, 1966) have shown that the ancestral river system quite definitely post-dates the period of prior stream activity. This can be demonstrated generally over the Plain in N.S.W. and is substantiated by soils studies (Butler, 1958).

The two papers (Pels, *loc. cit.*) dealt with the surface configuration of the ancestral river system and subsurface geological aspects respectively. Both stressed the geochronological importance of movement along the Cadell Fault which enabled ready determination of three separate phases of river activity. It was shown that there is a non-diverted phase (Coonambidgal I) and two diverted phases (Coonambidgal II and III) and that each phase consisted of a degradational and aggradational sub-phase.

Carbon Datings

Datings of samples collected during the regional survey, which formed the basis of the two earlier papers, have now become available. Results of these datings substantiate the earlier postulations.

The radio-carbon datings were carried out by the Department of Nuclear and Radiation Chemistry of the University of New South Wales on samples obtained from sediments representing the three aggradational sub-phases, as follows.

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COONAMBIDGAL I

This depositional system has a width of one mile and is clearly delineated on the Cadell Tilt Block near Womboota. It is a filled-in river unaffected by further river activity because of movement along the Cadell Fault. It represents both a downcutting and infilling phase. A carbon sample was obtained from the centre of this system at a depth of 6′ 6″. It formed a layer of carbon conformably interbedded with thin layers of gravel. The site's location is:

Portion 16, Parish of Wombоota, County of Cadell, N.S.W.
Geographic co-ordinates: 35° 54′ S.; 144° 41′ E.
Sample No.: 67/12 N.S.W. 31.
Age: Exceeding 28,600 years, i.e. beyond the limit of the equipment.

COONAMBIDGAL II

It is known from stratigraphical evidence and the drastic diversion pattern of the ancestral river system near Mathoura (see Fig. 1) that this system again represents a downcutting phase with subsequent infilling. The fill is now represented by the higher older terrace along the Edward River at Deniliquin. The carbon sample, obtained from a borehole in this terrace, was a fragment of a knotted tree branch and definitely an aerial part. It was obtained from a depth of 40′ in State Forest No. 397, Parish of South Deniliquin, County of Townsend, N.S.W.

Geographic co-ordinates: 35° 32′ S.; 144° 58′ E.
Sample No.: 67/14 N.S.W. 32.
Age: 24,050±835 years.

COONAMBIDGAL III

There is a further distinct system of younger alluvium which can be traced adjacent to the Bullatale Creek between Tocumwal and Deniliquin. Near the latter town it becomes superimposed on the Coonambidgal II sediments associated with the Edward River. It now forms the lower terrace adjacent to the Edward River near Deniliquin (for details, see Pels, 1966, p. 34).

A deep trench was excavated across the lower terrace during construction of the Lawson siphon. This siphon, which was constructed to take irrigation supplies across the lower flood-plain (terrace) of the river, is restricted to this terrace and an elevated canal was constructed on the higher Coonambidgal II sediments.

The carbon sample was a block of wood cut out of a log encountered at a depth of 15′ during excavation. Its location is described as State Forest No. 397, Parish of South Deniliquin, County of Townsend, N.S.W.

Geographic co-ordinates: 35° 34′ S.; 145° 01′ E.
Sample No.: 67/13 N.S.W. 33.
Age: 9,800±200 years.

The three datings indicate a definite chronological sequence. If the position of the Coonambidgal I sample within the sediments (6′ 6″ from the surface) were taken as an indication, it could be inferred that the age of greater than 28,600 years applies to the final stages of the infilling phase of Coonambidgal I.

The second date of 24,050 years would apply to the early stage of the infilling phase of Coonambidgal II (40′ from the surface) and the age of 9,800 years would also represent an early stage of infilling of Coonambidgal III. It is likely that the total phase of infilling occupied a considerable period of time.

This point is important when further correlations are attempted with other carbon datings from the region. From stratigraphical evidence the sequence of ancestral river activity of the Goulburn and Murray systems is visualized as shown in Fig. 1.

Bowler (1967) has published a date for ancestral river sediments associated with the Goulburn River near Shepparton showing an age of 30,600±1,300 years (N298).

It is known that the three phases are superimposed at this location, and the dated sediments would therefore represent Coonambidgal I. The sample from Wombоota (>28,600) could be of similar age, and this lends weight to the mapping of Coonambidgal I as shown in Fig. 1.

At the same location near Shepparton, younger sediments were dated as 26,200 and 24,500 years, and these dates again do not conflict with that determined for the Coonambidgal II near Deniliquin (24,050±835 years).

As can be seen from Fig. 1, the three phases are superimposed in some locations, but in others become laterally separated. Because of this, it was possible to establish (Bowler, 1967; Pels, 1966) that source-bordering sand dunes are common on the leeward side of Coonambidgal II ancestral rivers.

From this and other evidence, Bowler dated Coonambidgal II sediments at three further locations (samples N301, ANU29 and N296) (Bowler, 1967), which showed dates of 16,600±400, 13,500±700 and 13,400±340 years respectively.

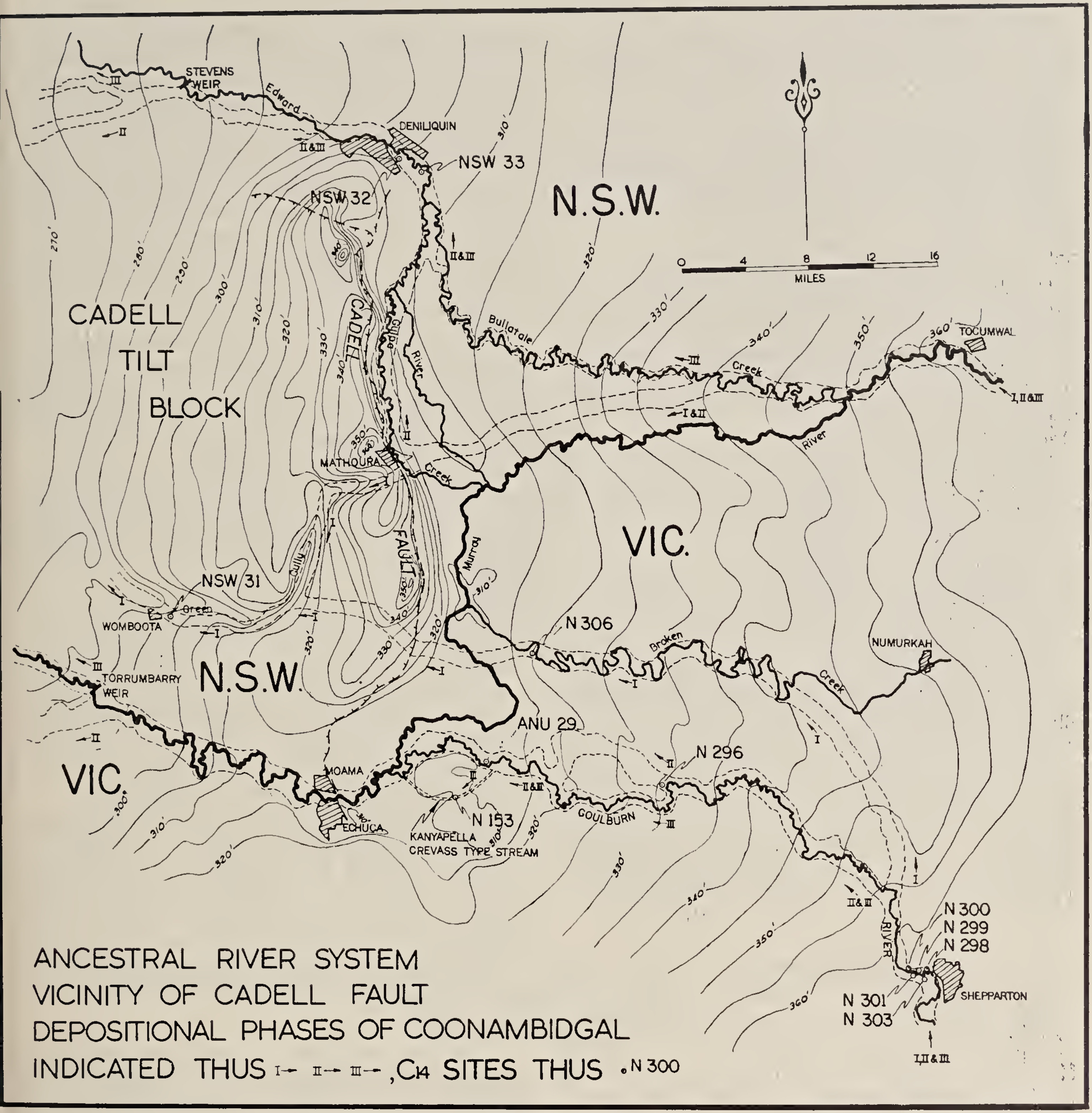

FIGURE 1.

The known dates of Coonambidgal II sediments therefore range from 26,200 to 13,400 years.

A further series of dates quoted by Bowler and ranging from 8,320±160 to 4,200±130 years appear to represent Coonambidgal III sediments of the Goulburn ancestral river system.

Bowler and Harford (1966) described sample N153 as having been derived from the Kanyapella prior stream. The present author suggests that this is a crevass-type stream which can be traced as leaving the final deposition of the third phase ancestral Goulburn (Coonambidgal III) and returning on to it as a continuous trace.

Except for the source-bordering sand dunes, deposition during the aggrading phases was generally restricted to the old river channel (valley fills in meandering valleys), but there are isolated instances where crevass-type traces lead from, and return to, the aggraded ancestral river. Such stream traces also occur along the Billabong ancestral river (Pels, 1964*b*).

The age of the crevass-type Kanyapella stream sediments is 4,200 years (N153) and represents the final sedimentation of this phase. The combined dates therefore indicate that Coonambidgal III sedimentation took place between 9,800 and 4,200 years ago.

It should also be mentioned that in an extensive older alluvial environment the meandering valley walls may, in some locations, no longer be discernible, and this has given rise to confusion in the nomenclature used in papers on the Riverine Plain's geomorphology. One instance of this is the naming of the " Tallygaroopna prior stream " in the Goulburn Valley by Bowler. This is clearly a deserted ancestral river and is again described as such in a later paper by the same author (Bowler, 1967).

The only dating which does not fit in with the discussion so far and the sequence depicted in Fig. 1 is Bowler's N306 age determination, which, from the locations description, should represent Coonambidgal I (see Fig. 1). In view of the dates obtained from Womboota and Shepparton the age indicated by this sample, 20,900±500 years, is not acceptable as it is now known that this phase was diverted prior to at least 26,000 years B.P., as indicated by the age of sample N299 from Coonambidgal II sediments near Shepparton and by sample NSW32 from phase II sediments near Deniliquin. The younger date of sample N306 could be accounted for by root growth at that time.

Interpretation

The correlation of carbon datings with events which created the present configuration of alluvial sediments can only be tentative. However, sufficient information is now available to warrant an attempt to draw up a geochronology and to draw from it palaeoclimatological inferences.

This information includes, apart from the C14 datings,

(i) the clear diversion pattern of ancestral rivers around the Cadell Fault,
(ii) the readily recognizable surface expression of these former river systems,
(iii) the widely separated independent courses of the river in some locations and superimposition in others.

In earlier papers it has been stated that downcutting of a river channel is thought to occur under relatively pluvial conditions and infilling under more arid conditions. This is the majority of opinion in the world literature on climatically-induced terrace levels of misfit rivers. Recent work by Schumm (1966) gave similar conclusions from morphological studies of ancestral river and present-day river channels of the Murrumbidgee River. Whitehouse (1940) discussed the common occurrence of three terraces along the major rivers in Queensland. Taylor and England (1929) described three terrace levels with differing soil development along the lower Murray River near Renmark.

By applying the same reasoning to these investigations, it has been inferred that the three aggrading phases took place under more arid conditions and that the last phase concluded approximately 4,000 years ago.

The present river represents a further downcutting phase. It is to be noted that the three phases were of decreasing intensity, as shown by the dimensions of the respective ancestral rivers.

Figure 2 shows, in diagrammatic form, how the sequence of events is visualized.

Before any carbon datings were carried out, there was evidence to suggest that a recurring process of degradation and aggradation occurred. Carbon datings have now supplied corroborating evidence and have given some indication of the time spans involved in these sequences.

Present results are at variance with conclusions by Bowler (1967), who states : " These two drainage systems (Coonambidgal I and II) are seen rather as part of one single phase of high discharge during glacial times. The notion that tectonic interruption occurred just at the conclusion of one pluvial-arid cycle and before the beginning of another, is not yet substantiated."

It is reiterated that a fully aggraded river channel (Green Gully) was tectonically uplifted and that the subsequently newly created diverted ancestral river now also forms a deeply incised and subsequently filled channel, thus indicating that consecutive pluvial-arid phases were responsible.

Recurring climatic fluctuations can be traced further back into the geological history of the Plain.

Sections bored through prior streams (Pels, 1964*a*) commonly show a distinct vertical break from sand and gravel at the bottom of the stream bed to heavy clay. This abrupt break, together with characteristic shapes of incised channels, indicates that prior stream phases also commenced with downcutting which was followed by aggradation. However, unlike ancestral rivers this aggradation was not restricted to the incised channels but eventually extended beyond the channel banks by lateral overtopping, giving rise to widespread lateral distribution of stream bed, levee and floodplain sediments so typical of prior streams.

limited drainage at that time from the region. It appears to have been a large inland area of sediment accumulation.

The extensive nature of the prior stream systems and the large quantities of sediments involved indicates that large-scale erosion in the highlands and deposition on the Plain were parallel processes.

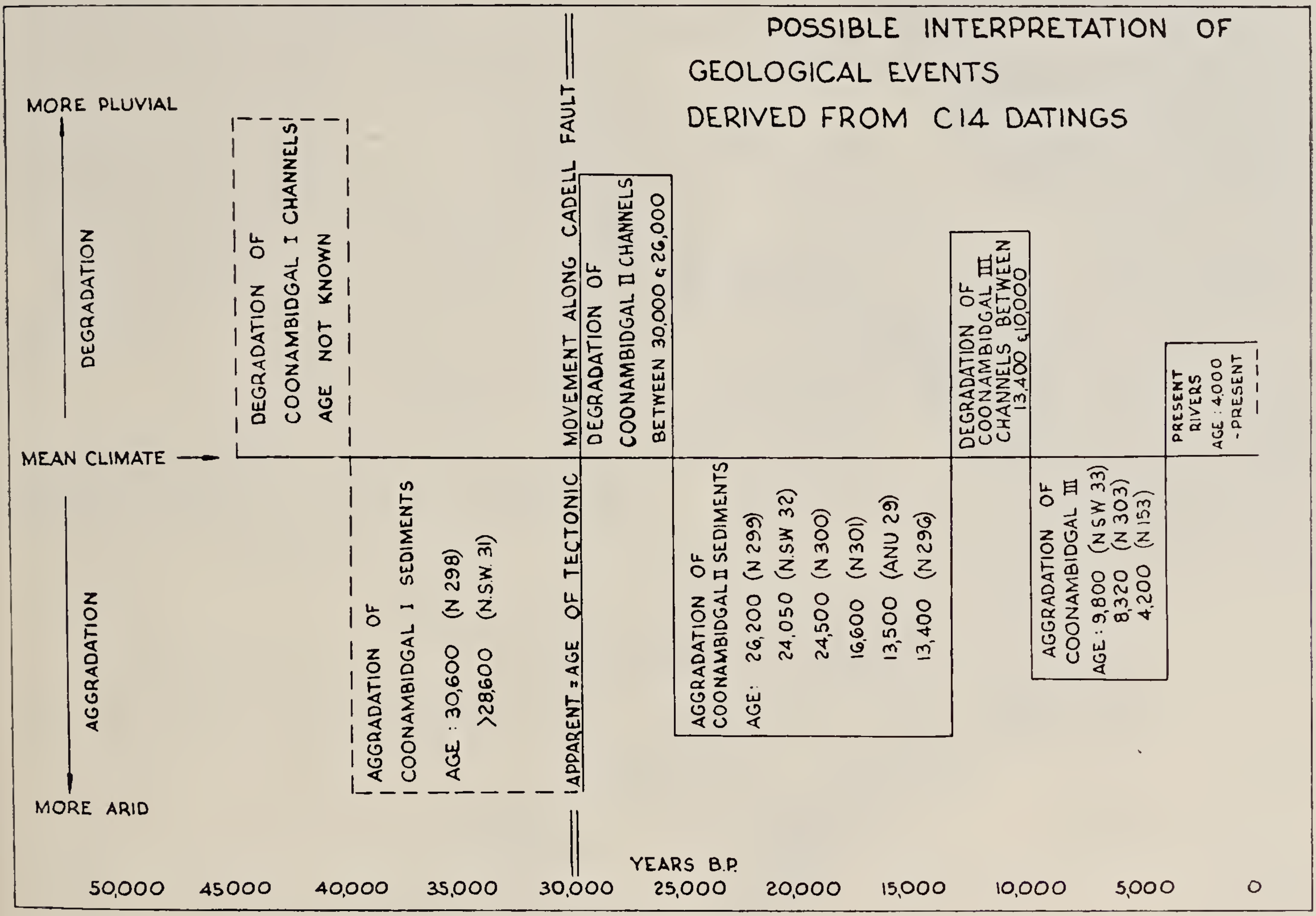

FIGURE 2.

The pattern of prior streams over the plain is not visualized as having been actively depositing simultaneously, and several phases of deposition and diversions to lower lying areas are probably responsible for the present distributary pattern of prior stream traces (see Fig. 3).

The definite change from prior streams to ancestral rivers warrants further consideration. It represents a major change in the drainage system of the region.

The distributary pattern of prior streams over the Plain and its dissipating nature towards the west suggests that there was very

This is in contrast with evidence shown by ancestral rivers. From the general occurrence of terraces along the entire river, it is clear that the process of degradation (and later aggradation) was synchronous along the entire river course. Terraces are common along the Murray River in the upper reaches and also in South Australia. Where they are absent in the central sector, they have been accounted for as deserted floodplains.

Furthermore, the prior streams form a distributary pattern, while ancestral rivers form a tributary system (Fig. 3).

Such an overall change in the behaviour of rivers and streams suggests a drastic change in

FIGURE 3.—The Riverine Plain in New South Wales.
(Drawn by W. Mumford, A.N.U.)

the drainage system of the Plain and there is evidence to substantiate such a postulation. The western fringe of the Riverine Plain consists predominantly of heavy-textured fluviatile sediments, indicating semi-lacustrine conditions of deposition and evaporite accumulation. It contains numerous lake and lunette relicts and Mallee outliers. Prior stream patterns generally dissipate before reaching this zone.

Surface water penetrated the lower lying areas of the Mallee, and chains of lakes are known to have occurred where the present Murray course is now located. There are remains of lunettes adjacent to the river, and preserved lakes occur in its vicinity. The great chain of lakes at the end of Willandra Creek, which branches off the Lachlan River near Hillston, forms a similar set of landscape conditions.

The absence of older alluvial (prior stream) sediments along the Murray River west of Wakool Junction suggests that this is a " post-prior stream " course which now drains the area.

The creation of this drainage channel from the region would account for the change-over from a distributory-prior stream system to a tributary ancestral river system, and would explain the present rivers of transit being unrelated to the Plain's surface sediments. It further explains the increasing salt status of the Riverine Plain's soils towards the west and the occurrence of an otherwise anomalous vast area of alluvial deposition along, what is now, the middle reach of the Murray River system.

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Note on Coals Containing Marcasite Plant Petrifactions, Yarrunga Creek, Sydney Basin, New South Wales

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Abstract—Coals of low bituminous rank, resembling in type a coal from the Clyde River Coal Measures, contain numerous plant petrifactions of marcasite with minor pyrite. The iron sulphides were emplaced early in the history of the coal and are associated with vitrinite-rich layers. They have replaced plant tissue rather than filled up voids in the peat. Massive marcasite is thought to represent complete replacement, whereas the material with relict plant structure may represent an intermediate stage.

Introduction

The coal measures at Yarrunga Creek were discovered in 1967 by geologists of the Metropolitan Water, Sewerage and Drainage Board during site investigations along the Kangaroo River (Gray, 1969). The location of the occurrence is shown in Figure 1, and the stratigraphic column in Table 1. The characteristics of the coals are of interest, as this occurrence forms one of the most extensive developments of coal measures near the base of the Shoalhaven Group. The coals have unusually large amounts of iron sulphides which contain plant petrifactions.

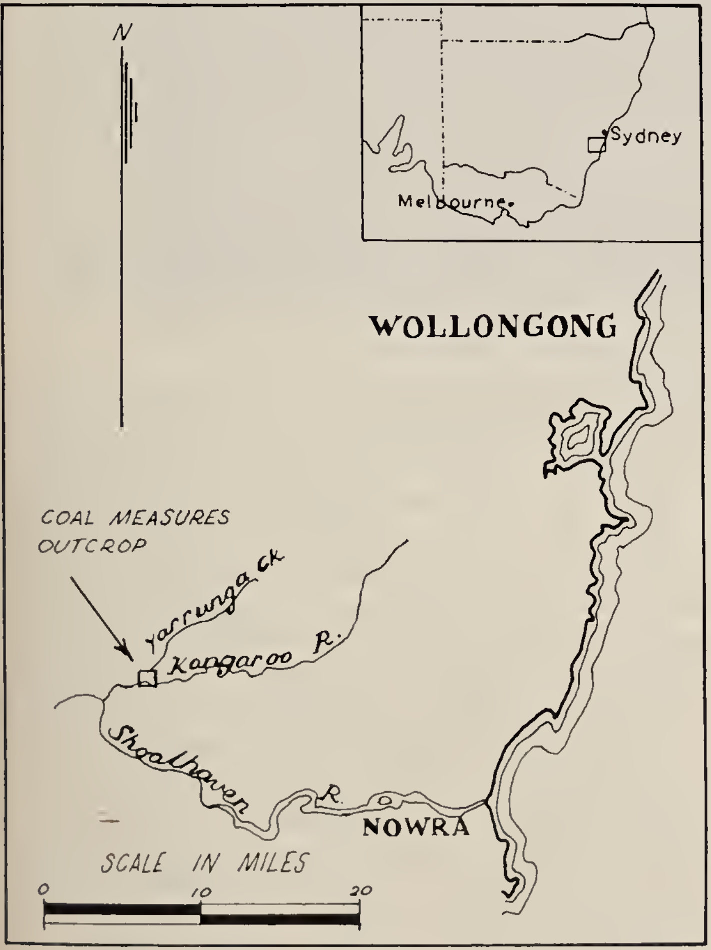

Figure 1.—Locality map.

Table 1

		Thickness (Feet)
Permian	Conjola Formation—sandstone	200+
	Coal measures—sandstone shale with coal seams	0–50
	Sandstone and conglomerate . .	200+
Basement	Older Palaeozoic Rocks	

Table 2

Petrographic Composition and Sulphur Content of Coal Seams

	Site A			Site B
	Bore 1 Seam A	Bore 4 Seam A	Bore 1 Seam B	Bore 3
Thickness . .	3′ 9″	5′ 6″	1′ 5″	2′ 7″
Petrographic analysis :				
Vitrinite . .	56	34	39	56
Exinite . .	2	3	1	6
Micrinite . .	19	24	15	12
Semifusinite	15	24	19	19
Fusinite . .	2	2	2	2
Mineral matter	6	13	24	5
Total . .	100	100	100	100
Sulphur content (approx.)	4%	8%	4%	2%*

* On floats at 1·60 specific gravity.

Petrography of Coals

The coals are generally similar in appearance to the Clyde River Coal Measures coal described by Cook and Read (1968). In hand-specimen they are mainly dull, or finely laminated, dull and bright, but contain a few bright lenses over 2 mm. in thickness.

The maceral analyses (Table 2) show that considerable variations in petrographic composition occur. Much of the vitrinite occurs in intermediate microlithotypes rather than as vitrite. Exinite is present as microspores, resin bodies and leaf cuticles. The mineral matter is mainly clay, quartz, marcasite and pyrite.

Reflectance measurements on vitrinite samples from two bores gave an average mean value of 0·85%, which is equivalent to a carbon content of 83–84% (d.m.m.f.). The rank is therefore similar to that found for the Clyde River Coal Measures coal by Cook and Read (1968). It is also similar to the rank of coals in the Illawarra Coal Measures in the extreme south-west of the South Western Coalfield (Cook and Wilson, 1969). Unfortunately as yet there are no rank data available for both the Illawarra Coal Measures and the base of the Shoalhaven Group at the one locality.

Marcasite and Pyrite

Abundant lenses and nodules, up to 3 cm. long and 0·5 cm. thick, of iron sulphides are present. Chemical analysis of a hand-picked sample of sulphide gave Fe 36·2%, S 40·9%, ignition loss 22·0%, with minor traces of Si, Ni, Co, Al, Cr, Mn and Mg. Assuming the ignition loss corresponds to coal, the sulphur-to-iron ratio is 1·97.

The iron sulphides occur chiefly in the brighter coal lenses and are associated with vitrinite. Some lenticular chalcedony plant petrifactions were also noted near sulphide lenses. The iron sulphides are an intimate mixture of marcasite and pyrite with the marcasite being the dominant phase. The marcasite and pyrite occur as plant petrifactions, showing transitions from well-preserved uncrushed cell structure (Plate I) to crushed and disordered cell structure. There are also transitions to massive replacements lacking evidence of plant structure (Plate II). The petrifactions are similar to those figured on cards 45–48 in *Bildkartei der Erzmikroskopie* (1961). This type of petrifaction has not been recorded previously from coals in the Sydney Basin. The relationship of the sulphide lenses to the surrounding and included coal provides some evidence as to the mode of emplacement.

The boundaries between the vitrinite and the sulphide lenses are discordant, with marked compaction structures being present in the surrounding coal. However, the plant structures visible at the edges of the sulphide masses indicate that the plant structures in them were originally continuous with those of the surrounding vitrinite.

The plant cell structures in the marcasite are rendered visible by the presence of remnants of organic material preserved as vitrinite. These vitrinite fragments are typically in the range of 0·5 to 5 microns and represent partially replaced secondary walls and middle lamellae. Pit structures are still preserved in some examples, and it appears that in general the middle lamellae are more extensively replaced than the secondary cell walls. The cell lumens are usually completely replaced by marcasite, but in some lumens (Plate III) embayed remnants of vitrinite are present. A different, though possibly related phenomenon, is the presence in some cell lumens of material which is optically homogeneous but which has a lower reflectivity and polishing hardness than the surrounding marcasite (Plate III). It is thought that this represents incomplete replacement of plant material with the particle size of the organic material being too small to be resolved optically.

The marcasite and pyrite grain boundaries commonly show some control by the plant cell structure (Plate I). Individual cell lumens generally consist of a small number of crystals, while many lumens consist of a single crystal. However, some crystals cover a number of cell lumens. In the massive structureless marcasite, grain boundaries give no indication of previously existing cell structure, although surrounding or included cell structure strongly suggests that it was originally present.

The uncrushed nature of much of the plant structure indicates that mineralization must have occurred relatively early in the development of the coal. The presence of embayed vitrinite in some cells and a possible marcasite-vitrinite mixture in others makes it probable that the marcasite in the cell lumens generally replaced organic material rather than filled up voids in the plant tissue. It appears that the precipitation of the sulphide phase was controlled by a favourable chemical environment rather than by space considerations. Indirect confirmation of this is to be found in the absence of marcasite from cell lumens in semifusinite. The cell lumens of the semifusinite would probably have been empty or only incompletely filled by clay and quartz at the time of the

Plate I.—Plant cells preserved as marcasite petrifactions. Reflected light, oil immersion, crossed nicols. ×230.

PLATE II.—Massive marcasite with minor pyrite. Cell structure is present on the right-hand margin of the field of view. Reflected light, oil immersion, crossed nicols. × 230.

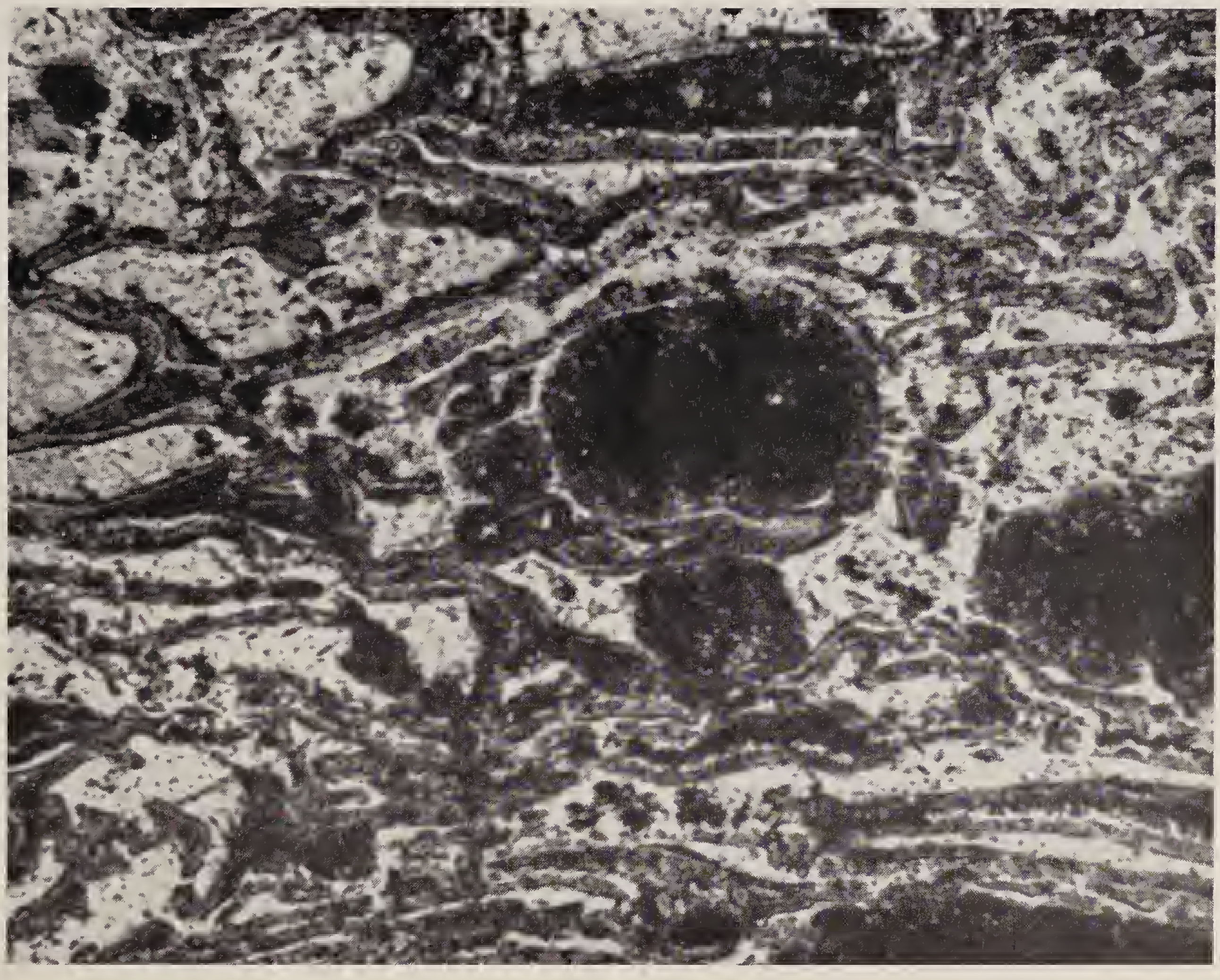

Plate III.—Vitrinite (black) occurring as partially replaced cell walls and cell lumens. The marcasite (white) has a lower reflectance and polishing hardness than that shown in other figures and may represent a marcasite-vitrinite mixture at a submicroscopic scale. Reflected plane polarized light. ×630.

formation of the marcasite. The relation of the massive sulphide to the sulphide-containing relict cell structures indicates that the structured phase represents an intermediate stage with the massive phase resulting from complete replacement of the plant material.

Acknowledgements

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Meson Field Potential in Fundamental Theory

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Abstract—It is shown that Yukawa's potential of a meson field can be generated within Eddington's Fundamental Theory.

In this note we shall discuss a method of deriving a formula for the meson field potential in Fundamental Theory of Eddington (1946). Eddington himself maintained that the formula must be given by a Gaussian distribution

$$\exp\left(-A(r-r_0^2)\right), \quad A>0. \quad \ldots. \quad (1)$$

To correct his mistake, Kilmister and Tupper (1962) considered the expectation value ψ of the potential per unit charge with a Gaussian distribution function. Defining a non-Coulombian potential ψ_1 by

$$\psi_1=\frac{1}{r}-\bar{\psi}(r), \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

they found a remarkable approximation

$$\psi_1\approx\frac{1}{r}\exp\left(-1{\cdot}17r/25\right). \quad \ldots\ldots \quad (3)$$

The error was $<0{\cdot}004$ for $0<r<1{\cdot}5/\sqrt{A}$.

The formula (3) is, of course, of the form of a Yukawa potential. It seems, however, that there is little connection between the above result and the argument of Fundamental Theory. In the latter, a meson is a decaying object associated with the transition from an unrestricted energy state (presumably, of an atomic nucleus) to a stable, symmetric configuration (Klotz, 1969). This can be regarded as a scattering experiment in which the scattering agent is a spherically symmetric, impenetrable region of the ordinary three-dimensional space and radius r_0. It is essential for the scattering centre to be represented as if it had no field of its own, since the stabilization process of Fundamental Theory has no location in the physical space-time. The "impinging" particle is then equally likely to be anywhere within $r>r_0$, but it cannot penetrate into the region $r<r_0$.

Let us consider now the conditional probability P_c of an event $u>x+dx$, whenever $u>x$. If the frequency function of u is f,

$$P_c=\frac{\text{Probability }(u>x+dx)}{\text{Probability }(u>x)}=1-\frac{f(x)dx}{\int_x^\infty f(z)dz} \quad \ldots\ldots\ldots\ldots \quad (4)$$

Suppose now that no additional information is to be derived from $u>x+dx$ as long as $u>x$. Then

$$(1-P_c)\text{ is proportional to }dx. \quad \ldots \quad (5)$$

Hence we can write

$$f(x)=\alpha\int_x^\infty f(z)dz \quad \ldots\ldots\ldots\ldots \quad (6)$$

where α is a constant. For continuous and differentiable f, therefore,

$$f(x)=f_0\exp(-\alpha x).$$

Since f is a distribution,

$$\int_0^\infty f dx=1=f_0/\alpha.$$

Therefore

$$f(x)=\alpha\exp(-\alpha x). \quad \ldots\ldots\ldots \quad (7)$$

If we associate the above probability distribution with a charge (electrical or mesonic as the case may be), the potential must be a function of the form

$$q(x)/x \quad \ldots\ldots\ldots\ldots \quad (8)$$

Hence, when q has the frequency distribution (7) we obtain a Yukawa potential

$$\frac{q_0\exp(-r/r_0)}{r}. \quad \ldots\ldots\ldots \quad (9)$$

This shows that it is possible to set up probabilistic hypotheses within Fundamental Theory, which conform to the known facts relating to the meson fields. Eddington's Gaussian distribution now relates only to the connection between cosmology and quantum scale physics.

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The Energy Storage of a Prescribed Impedance*

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Abstract—The problem of inferring the total average energy storage of a passive linear electrical impedance from its observed or specified terminal behaviour alone is discussed. Only in a few special cases is the energy storage (for sinusoidal external excitation) uniquely determinable.

A general expression for the energy storage is derived which involves, in addition to terminal properties, properties of a set of functions describing the separate dissipative processes. This expression is used to find a new minimum energy storage for a lumped-element network which all realizations of the impedance must equal or exceed. There exists a minimum energy synthesis storing minimum energy at all frequencies, which corresponds to minimum phase shift Darlington synthesis of the impedance. This minimum energy storage synthesis can be realized provided gyrators can be employed.

I. Introduction

When a linear passive network is excited sinusoidally there is generally a storage of electromagnetic energy by the reactive elements. Assuming the terminal behaviour is known, the question may be asked : to what extent is the physical energy storage of the network determined by the terminal behaviour ? Alternatively : what can be inferred about the energy storage of a network from measurements of its terminal behaviour alone ? To be specific, we consider the impedance $Z_0(p)$ of a hypothetical linear, passive one-port to be given for all $p=i\omega$, and examine the possible corresponding energy storage from excitation by a r.m.s. current I_0.

If $Z_0(p)$ is a pure reactance, it is well known (Bode, 1945, sec. 9.4 ; Maa, 1943 ; Montgomery *et al.*, 1948 ; Pannenborg, 1952) that the energy storage for a given sinusoidal excitation is uniquely determined. Also, if $Z_0(p)$ is known to result from a reciprocal network containing only two kinds of elements the energy storage is also easily shown to be unique (Section III). However, it can be seen that in the general case the energy if not fixed by $Z_0(p)$ alone. Suppose we have a particular network realization of $Z_0(p)$ which is assumed not to be a pure reactance. Then any resistance in this realization which is dissipating power may be replaced by an all-pass network terminated in a resistance, or some other combination of reactive and resistive elements which behaves terminally as a resistance (e.g. Cauer, 1958, p. 53), without changing the terminal behaviour $Z_0(p)$ of the network as a whole. (If distributed circuits are introduced each resistance may be replaced by a loss-free transmission line of arbitrary length terminated by its characteristic impedance). Although $Z_0(p)$ is unchanged by this transformation, the energy storage is changed (increased) by the introduction of additional reactive elements.

Thus it becomes clear that the energy storage of a system described by the general impedance $Z_0(p)$ depends upon aspects of the internal structure of the network, in striking contrast to the purely reactive case. In other words the energy depends upon the particular realization of $Z_0(p)$, and terminally equivalent networks are not necessarily equivalent as far as energy storage is concerned.

By the above procedure it is possible to increase the energy storage associated with a specified dissipative impedance $Z_0(p)$. This suggests the existence of either a minimum possible energy storage at a particular frequency or a minimum energy realization over all frequencies. Both of these conjectures are shown to be true. For systems containing no non-reciprocal elements (as typified by gyrators) a simple lower bound exists for the energy (see Section III) at any frequency $p=i\omega$.

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* Work performed under the auspices of the United States Atomic Energy Commission.
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However, if non-reciprocal (i.e. gyrator-like) behaviour is exhibited by the network this minimum energy expression is not applicable (Smith, 1967), and a lower energy may sometimes be possible. In Section VII the minimum possible energy is found and it is shown that a minimum energy realization by Darlington synthesis is always possible provided gyrators are employed. The natural requirement for gyrators to obtain the minimum energy network is somewhat curious but it is demonstrated that in general they are essential.

In Sections II and III some elementary observations on equivalent circuits and particular results for special cases are noted. In Section IV general expressions are obtained for the energy storage which involve internal functions associated with the energy dissipation. For the special case of a reciprocal network for which $Z_0(p)$ is specified as a function of the magnitudes of the individual resistances, Vratsanos' theorem may be employed to deduce the energy uniquely (Section V).

The energy storage of networks with one resistor is treated in Section VI. This case, although special in itself, occupies a central role in showing the existence of a minimum energy and a minimum energy storing network (Sections VII and VIII). In Section IX a very simple example is discussed at length to illustrate points in the main body of the paper. The discussion is oriented towards lumped-element systems because this is where synthesis methods are available, but much of it is not necessarily restricted to this case only. Energy storage is interpreted to mean the total average physical energy storage resulting from the excitation. In a complex system this may not be entirely electromagnetic energy ; for example T and V might both contain a mechanical energy component in a dispersive system (Smith, 1967). The microscopic distinction (Tonning, 1960) between purely electromagnetic and other forms of energy is not made here.

II. Some Remarks on Equivalent Circuits

The term equivalent circuit is well entrenched in the literature with the meaning of equivalent terminal behaviour or equivalent with regard to exterior behaviour. We have seen in I that equivalent circuits in this sense need not have the same energy storage. Objections to the use of the term " equivalent " to apply to the terminal behaviour alone have been made before and Gross and Braga (1961) have suggested the use of " pseudo-equivalent " to emphasize the terminal equivalence only. The use of the term " internally equivalent " is suggested to imply not only equivalence in the usual sense but also that internally equivalent networks have the same average magnetic (kinetic) and electric (potential) energy storages T, V and power dissipation P for similar excitation. The need for the specification of both T and V rather than the total energy $(T+V)$ arises because of further complications with non-reciprocal (gyrator containing) networks. It is easily shown (Balabanian, 1958, sec. 1.6, 1.7) for reciprocal networks that

$$I_0^* I_0 Z_0(i\omega) = 2i\omega(T-V)+P \quad \dots\dots\dots\dots \quad (1)$$

where I_0 is the r.m.s. excitation current of Z_0 at $p=i\omega$. Thus

$$T-V = I_0^* I_0 X_0(i\omega)/2\omega \quad \dots\dots\dots\dots \quad (2)$$

so that for a specified impedance T and V are both fixed when the total energy $W=T+V$ is known. Thus reciprocal equivalent networks having the same total energy are internally equivalent.

However, since Eq. (2) is inapplicable to gyrator-containing networks (Smith, 1967), the same total energy does not imply the same T and V for a given impedance.

The term equivalent network was also used by Cauer (1958, Chap. 10) in describing a transformation which formed a set of networks having the same terminal behaviour. We shall show that Cauer's equivalent networks are also internally equivalent.

Suppose the n mesh equations of a reciprocal network are

$$\mathbf{ZI}=\mathbf{V} \quad \dots\dots\dots\dots \quad (3)$$

$$\mathbf{V}=\begin{pmatrix} V \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad \dots\dots\dots\dots \quad (4)$$

where V is the voltage source exciting the network in the first mesh only and $\mathbf{I}$ is the mesh current vector. $\mathbf{Z}$ has the form

$$\mathbf{Z}=p\mathbf{L}+\mathbf{R}+\mathbf{D}/p \quad \dots\dots\dots\dots \quad (5)$$

where $\mathbf{L}$, $\mathbf{R}$, $\mathbf{D}$ are constant real symmetric matrices. The Cauer transformation transforms the mesh currents $\mathbf{I}$ to $\mathbf{I}'$ through the non-singular, real, constant, transformation $\mathbf{T}$

$$\mathbf{I}=\mathbf{T}\mathbf{I}'. \tag{6}$$

If $\mathbf{T}$ is required to have the first element of the first row equal to 1 and all other elements in the first row zero, Cauer shows that an n mesh network having the mesh impedance matrix

$$\mathbf{Z}'=\mathbf{T}^T\mathbf{Z}\mathbf{T} \tag{7}$$

will be an equivalent network.

For $p=i\omega$ it is easily seen that the energy of the original network is given by

$$\begin{aligned} 2W=2(T+V)&=\mathbf{I}\dagger(\partial\mathbf{Z}/\partial p)_{p=i\omega}\mathbf{I} && (8)\\ &=\mathbf{I}'\dagger\mathbf{T}^T(\partial\mathbf{Z}/\partial p)_{p=i\omega}\mathbf{T}\mathbf{I}' \text{ (from (6) and } T \text{ real)} && (9)\\ &=\mathbf{I}'\dagger[\partial/\partial p(\mathbf{T}^T\mathbf{Z}\mathbf{T})]_{p=i\omega}\mathbf{I}' \text{ (} T \text{ constant)} && (10)\\ &=\mathbf{I}'\dagger(\partial\mathbf{Z}'/\partial p)\mathbf{I}' \text{ (from (7))} && (11)\\ &=2(T'+V')=2W' && (12) \end{aligned}$$

where $W'=T'+V'$ is the total energy of the equivalent network for the same excitation. Since we are considering only reciprocal networks, this implies that the Cauer equivalent networks are internally equivalent.

III. Energy Storage in Simple Cases

Two elementary cases where the energy storage is unique are reviewed. Another special case will be discussed in Section V after general expressions for energy storage are derived.

(*a*) *Loss-free Networks*

For loss-free networks, i.e. $Z_0(p)$ a reactance function, the energy storage is given uniquely by (Bode, 1945, sec. 9.4; Maa, 1943; Montgomery *et al.*, 1948).

$$W=T+V=\tfrac{1}{2}I_0^*I_0(\partial Z_0/\partial p)_{p=i\omega}. \tag{13}$$

Bode remarks that Eq. (13) implies that the total volt ampere rating of the elements in a reactance network is independent of the manner of synthesis. Thus from (13) and (1) the following proposition applies for reciprocal networks. All equivalent reciprocal reactance networks are internally equivalent. For non-reciprocal networks Eq. (13) for the total energy still applies (Tonning, 1960 ; Smith, 1965 ; Carlin, 1967), so that equivalent reactance networks store the same total energy. However, because Eq. (1) no longer applies this does not imply equality of the magnetic and electric energies separately.

(*b*) *RL and RC Circuits and a Simple Bound for Reciprocal Networks*

If the network is known to be reciprocal, Eq. (1) applies. Further, if it is also known to be either an RL or RC network, V or T respectively is zero and Eq. (1) gives

$$|T+V|=|T-V|=I_0^*I_0|X_0|/2\omega. \tag{14}$$

Notice that it is not sufficient for $Z_0(p)$ to be of a form for RL or RC synthesis to be possible (e.g. Balabanian, 1958, sec. 2.3, 2.4). The network itself must actually be an RL or RC synthesis of $Z_0(p)$. When this is the case, Eq. (14) shows that the energy storage is again independent of the details of the network synthesizing $Z_0(p)$. For example, the two Cauer canonical forms and the two Foster forms (Balabanian, 1958) will all store the same energy, and this will be the same as for any other two-element kind synthesis.

Thus the problem of energy storage for two-element kind reciprocal networks or for loss-free non-reciprocal networks is easily solved uniquely. For reciprocal RLC networks Eq. (1) may still be used to give a bound on the energy at any particular frequency

$$|T+V|\geq|T-V|=I_0I_0^*|X_0|/2\omega. \tag{15}$$

For RL and RC networks this bound is attained at all frequencies. This bound is not applicable to non-reciprocal networks, and it will be shown in Sections VII and VIII that the absolute minimum energy storage may well be less than that given by (15).

IV. General Expressions for the Energy Storage

It will be shown that the average energy storage may be written in terms of the reactive behaviour of the impedance, and a set of causal frequency-dependent functions describing the several dissipative processes. The energy storage expression may be obtained conveniently in two ways: (i) by writing out circuit equations so as to treat the network as a reactive n-port, the energy storage of which is known (Maa, 1943), together with the resistors causing the dissipation; (ii) by considering energy conservation for a terminal excitation $\exp(i\omega+\sigma)t$ with $\sigma\rightarrow 0$.

The first type of argument has been used by Kishi and Nakazawa (1963) in their paper relating group delay and energy storage. The second method, an adaptation of the methods of Cauer (1958, Chap. 4) for proving the positive real character of impedance functions has been used by Tonning (1960) and Carlin (1967) to find the energy storage of reactances. This method has the virtue of being independent of the nature of the system and is not restricted to lumped-element or reciprocal systems.

Suppose the impedance $Z_0(p)$ is excited by a current which has the instantaneous value

$$\mathscr{I}_0=\mathrm{Re}\,\{\sqrt{2}I_0\exp pt\} \quad \ldots\ldots\ldots\ldots \quad (16)$$

with

$$p=i\omega+\sigma, \qquad \sigma>0 \quad \ldots\ldots\ldots\ldots \quad (17)$$

The instantaneous voltage across the impedance is then

$$\mathscr{V}_0=\mathrm{Re}\,(\sqrt{2}Z_0(p)I_0\exp(pt)). \quad \ldots\ldots\ldots\ldots \quad (18)$$

Since the only sources of energy dissipation in the impedance are the resistances, we can write the following instantaneous energy conservation equation

(Power supplied by the excitation) = (Power used to increase energy storage in the impedance)
+ (Power dissipated in the resistors). .... (19)

The impedance is supposed to be in the quiescent state (zero energy storage) at $t=-\infty$. To find the energy stored at time t_0 for this excitation, we must integrate Eq. (19) from $t=-\infty$ to $t=t_0$.

(total energy supplied by the excitation) = (energy stored by the network)
+ (energy dissipated by the network) .. (20)

We now introduce the functions $f_k(p)$,

$$f_k(p)=I_k(p)/I_0 \quad \ldots\ldots\ldots\ldots \quad (21)$$

where $I_k(p)$ is the complex current in the k^{th} resistor R_k for the excitation (16). I.e.

$$\begin{aligned}\mathscr{I}_k&=\mathrm{Re}\,\{\sqrt{2}I_k(p)\exp pt\} \quad \ldots\ldots\ldots\ldots \quad (22)\\ &=\mathrm{Re}\,\{\sqrt{2}f_k(p)I_0\exp pt\}\end{aligned}$$

is the instantaneous current flowing in the k^{th} resistor. Notice that the current $\mathscr{I}_k$ is causally derived from the excitation current, so $f_k(p)$ is a transfer function analytic in the right half of the p plane. This analyticity extends on to the imaginary p axis since the dissipation in each resistor must remain finite for finite I_0. $f_k(p)$ is also a real function of p.

If $\mathscr{W}(t_0)$ is the energy storage at time $t=t_0$, Eqs. (19) and (20) become

$$\mathscr{V}_0\mathscr{I}_0=\mathrm{d}\mathscr{W}/\mathrm{d}t+\sum_k \mathscr{I}_k^2R_k \quad \ldots\ldots\ldots\ldots \quad (23)$$

$$\int_{-\infty}^{t_0}\mathscr{V}_0\mathscr{I}_0\mathrm{d}t=\mathscr{W}(t_0)+\sum_k R_k\int_{-\infty}^{t_0}\mathscr{I}_k^2\mathrm{d}t \quad \ldots\ldots\ldots\ldots \quad (24)$$

i.e.,

$$\begin{aligned}2\int_{-\infty}^{t_0}&\mathrm{Re}\,\{Z_0(p)I_0\exp(pt)\}\,\mathrm{Re}\,\{I_0\exp(pt)\}\mathrm{d}t\\ &=\mathscr{W}(t_0)+2\sum_k R_k\int_{-\infty}^{t_0}[\mathrm{Re}\,\{f_k(p)I_0\exp(pt)\}]^2\mathrm{d}t \quad .. \quad (25)\end{aligned}$$

i.e.

$$\begin{aligned}\int_{-\infty}^{t_0} & \mathrm{e}^{2\sigma t}\,\mathrm{Re}\,\{Z_0(p)I_0^2\mathrm{e}^{2i\omega t}+I_0I_0^*Z(p)\}\mathrm{d}t \\ &=\mathscr{W}(t_0)+\sum_k R_k\int_{-\infty}^{t_0}\mathrm{e}^{2\sigma t}\,\mathrm{Re}\,\{[f_k(p)I_0]^2\mathrm{e}^{2i\omega t} \\ &\qquad +f_k(p)f_k^*(p)I_0I_0^*\}\mathrm{d}t.\end{aligned} \tag{26}$$

Performing the integration and dropping the subscript on t_0, we obtain

$$\begin{aligned}&\mathrm{e}^{2\sigma t}\,\mathrm{Re}\,\{Z_0(p)I_0^2\mathrm{e}^{2i\omega t}/2(\sigma+i\omega)+Z(p)I_0I_0^*/2\sigma\} \\ &\quad=\mathscr{W}(t)+\sum_k R_k\mathrm{e}^{2\sigma t}\,\mathrm{Re}\,\{(f_k(p)I_0)^2\mathrm{e}^{2i\omega t}/2(\sigma+i\omega)+f_k(p)f_k^*(p)I_0I_0^*/2\sigma\}.\end{aligned} \tag{27}$$

The energy corresponding to sinusoidal excitation $p=i\omega$ is obtained from Eq. (27) by considering its limiting form as $\sigma\rightarrow+0$. The average energy is then obtained by averaging over a full cycle $2\pi/\omega$. The terms requiring special consideration are those having 2σ as denominator. Write

$$Z_0(p)=R_0(p)+iX_0(p). \tag{28}$$

Then for small σ, $Z_0(p)$, being analytic, may be expanded as a Taylor series about $p=i\omega$ provided $p=i\omega$ is not a pole of $Z_0(p)$.

Then

$$R_0(i\omega+\sigma)=R_0(i\omega)+(\partial R_0/\partial\sigma)_{p=i\omega}\,\sigma \qquad \text{to first order in } \sigma. \tag{29}$$

Further, $f_k(p)$ is also analytic, so

$$f_k(p)f_k^*(p)=f_k(i\omega)f_k^*(i\omega)+\sigma\frac{\partial}{\partial\sigma}(f_kf_k^*)_{p=i\omega} \qquad \text{to first order in } \sigma. \tag{30}$$

Furthermore, in the steady harmonic state the total dissipation $I_0I_0^*R_0(i\omega)$ is equal to the sum of the powers dissipated in the individual resistances R_k. I.e.

$$I_0I_0^*R_0(i\omega)=\sum_k R_kf_k(i\omega)f_k^*(i\omega)I_0I_0^*. \tag{31}$$

After substituting (29), (30), (31) in (27), the limit $\sigma\rightarrow0$ may be taken to give

$$\begin{aligned}&\mathrm{Re}\,\{Z_0(i\omega)I_0^2\mathrm{e}^{2i\omega t}/2i\omega\}+\tfrac{1}{2}I_0I_0^*(\partial R_0/\partial\sigma)_{p=i\omega} \\ &\quad=\mathscr{W}(t)+\sum_k R_k[\mathrm{Re}\,\{(f_k(i\omega)I_0)^2\mathrm{e}^{2i\omega t}/2i\omega\}+\tfrac{1}{2}\partial/\partial\sigma(f_kf_k^*)_{p=i\omega}I_0I_0^*].\end{aligned} \tag{32}$$

Thus

$$\mathscr{W}(t)=\tfrac{1}{2}I_0I_0^*(\partial R_0/\partial\sigma)_{p=i\omega}-\tfrac{1}{2}I_0I_0^*\sum_k R_k\partial/\partial\sigma(f_kf_k^*)_{p=i\omega}+\mathrm{Re}\,\{I_0^2(Z_0(i\omega)-\sum_k R_kf_k^2(i\omega))\mathrm{e}^{2i\omega t}/2i\omega)\}. \tag{33}$$

The average energy storage $\overline{\mathscr{W}(t)}=W=T+V$ is found by averaging over a cycle $2\pi/\omega$ giving

$$W=\tfrac{1}{2}I_0I_0^*(\partial R_0/\partial\sigma)_{p=i\omega}-\tfrac{1}{2}I_0I_0^*\sum_k R_k\partial/\partial\sigma(f_kf_k^*)_{p=i\omega}. \tag{34}$$

Since the impedance $Z_0(p)$ is analytic, the Cauchy-Riemann equations may be used to write

$$(\partial R_0/\partial\sigma)_{p=i\omega}=(\partial X_0/\partial\omega)_{p=i\omega}. \tag{35}$$

Also

$$\partial/\partial\sigma(f_kf_k^*)_{p=i\omega}=2(\mathrm{Re}\,f_k)\partial/\partial\sigma(\mathrm{Re}\,f_k)+2(\mathrm{Im}\,f_k)\partial/\partial\sigma(\mathrm{Im}f_k). \tag{36}$$

But $f_k(p)$ is also analytic, so using the Cauchy-Riemann equations

$$\partial/\partial\sigma(f_kf_k^*)_{p=i\omega}=[2(\mathrm{Re}\,f_k)\partial/\partial\omega(\mathrm{Im}\,f_k)-2(\mathrm{Im}\,f_k)\partial/\partial\omega(\mathrm{Re}\,f_k)]_{p=i\omega} \tag{37}$$

$$=2[(\mathrm{Re}\,f_k(-p))\,\mathrm{Im}\,(\partial f_k(p)/\partial\omega)+(\mathrm{Im}\,f_k(-p))\,\mathrm{Re}\,(\partial f_k(p)/\partial\omega)]_{p=i\omega}. \tag{38}$$

Since $f_k(p)$ is a real function of p.

$$=2\,\mathrm{Im}\,(f_k(-p)\partial f_k(p)/\partial\omega)_{p=i\omega} \tag{39}$$

$$=2\,\mathrm{Re}\,(f_k(-p)f_k'(p))_{p=i\omega}. \tag{40}$$

Substitution of (35) and (40) into (34) gives

$$W=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*\sum_k R_k \operatorname{Re}\,(f_k(-p)f_k'(p))_{p=i\omega}. \qquad (41)$$

The dissipation is more conveniently described by the real causal functions

$$F_k(p)=R_k^{\frac{1}{2}}f_k(p) \qquad (42)$$

so that (31) becomes

$$R_0(i\omega)=\sum_k F_k(i\omega)F_k^*(i\omega)=\sum_k F_k(-i\omega)F_k(i\omega) \qquad (43)$$

and the total average energy expression is

$$W=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*\sum_k \operatorname{Re}\,(F_k(-p)F_k'(p))_{p=i\omega}. \qquad (44)$$

This equation may also be obtained from Goubau's version of Eq. (34) (Goubau, 1961) by a similar manipulation.

For loss-free systems the F_k, if any, are all identically zero, and Eq. (13) is recovered. Equations (44) and (43) also show, however, that if the resistive component of an impedance vanishes at some frequency (as for a minimum resistance impedance) the energy storage at that frequency is given uniquely by Eq. (13). Otherwise the energy storage depends upon the properties of the functions $F_k(p)$ describing the dissipation processes.

Similarly, by considering the one-port as an admittance

$$Y_0(p)=G_0(p)+iB_0(p) \qquad (45)$$

$$W=\tfrac{1}{2}V_0V_0^*\partial B_0/\partial\omega-V_0V_0^*\sum_k \operatorname{Re}\,(\Psi_k(-p)\Psi_k'(p))_{p=i\omega} \qquad (46)$$

where V_0 is the complex r.m.s. excitation voltage and

$$\Psi_k(p)=R_k^{-\frac{1}{2}}V_k(p)/V_0 \qquad (47)$$

are real causal transfer functions describing the dissipation. Clearly, the Ψ_k and F_k are related by

$$\Psi_k(p)=Y_0(p)F_k(p). \qquad (48)$$

Equations (44) and (46) are algebraically equivalent at all frequencies $p=i\omega$ except for poles or zeros of $Z_0(p)$, where the differentiations and substitutions are invalidated.

Finally, a scattering matrix version of (44) and (46) also exists which does not have the singular frequencies on the $p=i\omega$ axis. Let $S_0(p)$ be the scattering matrix (one-dimensional) of the impedance $Z_0(p)$. Further, let $S_{0k}(p)$ be elements of the scattering matrix **S** of the network as a whole where the o-port constitutes the given port $Z_0(p)$ and the k^{th}-port is terminated in the k^{th} resistor R_k. The **S** matrix is normalized to the resistances R_k terminating the ports. Two properties of **S** are important here. (i) Since **S** describes a loss-free system it is unitary. (ii) The elements of **S** are real analytic functions of p for $\operatorname{Re} p>0$ (causal behaviour). A similar energy conservation argument to that used for deriving (44) gives

$$W=-a_0a_0^*\operatorname{Im}\{S_0(-i\omega)\partial S_0(i\omega)/\partial\omega\}-a_0a_0^*\operatorname{Re}\{\sum_k S_{0k}(-i\omega)S_{0k}'(i\omega)\} \qquad (49)$$

where $a_0a_0^*$ is power incident on the one-port. In obtaining (49), the unitarity of **S** occupies an equivalent place to (31) or (43) in obtaining the impedance form (44). The scattering matrix form (49) for the energy storage is essentially the same as that derived rather differently and under more restricted conditions by Kishi and Nakazawa (1963). Notice that the present derivations of Eqs. (44), (46) and (49) are not restricted to circuits containing only reciprocal elements. Neither are they intrinsically restricted to lumped-element circuits since only general analytical properties of the immittance functions are used. However, for a continuum of dissipative processes the summations over the k resistors must be replaced by integrations over the volumes in which dissipation occurs.

The expressions (44), (46) and (49) for the energy storage, as expected, all involve some aspects of the internal structure of the one-port. The derivation has been a complementary one in which attention has been concentrated not on the mechanisms of energy storage, but on the mechanisms by which energy is not stored (i.e., dissipated). The results thus involve properties of the way in which energy is dissipated in the network as typified by the functions $F_k(p)$. Apart from general transfer functions conditions and the overall loss condition (43), these functions are arbitrary and depend upon the exact realization of the one-port.

The three forms (44), (46) and (49) all have the same content except for the inappropriateness of (44) or (46) at poles or zeros respectively of $Z_0(p)$. Equation (49) is the most general in this sense since the scattering matrix formulation avoids these problems. However, in other ways the impedance or admittance forms are more closely related to conventional language and synthesis techniques for one-ports. Thus Eq. (44) will be regarded as the basic expression for further development, although with some modifications similar arguments could be based on (46) or (49).

One fact that is immediately apparent from (44) and (13) is that if $Z_0(p)$ is not a minimum reactance impedance (i.e., it has simple poles on the $p=i\omega$ axis) the energy storage is the same as that of two impedances excited by the same current, one impedance being the minimum reactance part of $Z_0(p)$ and the other a pure reactance corresponding to the non-minimum reactance part of $Z_0(p)$. The f_k and hence the F_k of the resulting minimum reactance impedance are the same as for the original $Z_0(p)$. Thus at our convenience we need consider only minimum reactance impedances, the energy storage for a non-minimum reactance impedance being obtained by the addition described above.

V. Application of the Vratsanos Theorem

Although the separate dissipation transfer functions F_k are not usually known, if $Z_0(p)$ is known as a function of the magnitudes of the separate resistors R_k in the network, Vratsanos' theorem (Vratsanos, 1957) may be used to determine the energy storage uniquely. This approach is limited further to reciprocal networks only, since Vratsanos' theorem is valid only for reciprocal networks.

Suppose $Z_0(p)$ is given as the functional form $Z_0(p,R_k)$, where the R_k are the actual magnitudes of all of the resistors in the network. Then Vratsanos' theorem states that

$$I_k^2/I_0^2=\partial Z_0/\partial R_k \qquad (50)$$

i.e.

$$f_k^2=\partial Z_0/\partial R_k \quad \text{from (21)} \qquad (51)$$

or

$$F_k^2=R_k\partial Z_0/\partial R_k \quad \text{from (42)} \qquad (52)$$

i.e.

$$F_k^2=(\partial Z_0/\partial \ln R_k) \qquad (53)$$

or if we introduce the sensitivity S_k of Z_0 with respect to R_k, i.e.

$$S_k=\frac{\partial \ln Z_0}{\partial \ln R_k}=\frac{R_k}{Z_0}\frac{\partial Z_0}{\partial R_k} \qquad (54)$$

$$F_k^2=Z_0S_k. \qquad (55)$$

Thus the F_k^2 may be determined from (52) or (53) and used to evaluate $\sum_k \mathrm{Re}\,(F_k(-i\omega)F_k'(i\omega))$ for substitution into Eq. (44) for the energy storage. I.e.

$$F_k(-i\omega)F_k'(i\omega)=\tfrac{1}{2}[(\partial Z_0(-i\omega)/\partial R_k)/(\partial Z_0(i\omega)/\partial R_k)]^{\frac{1}{2}}\partial^2 Z_0(i\omega)/\partial i\omega\partial \ln R_k. \qquad (56)$$

In principle only the dependence of $R_0(i\omega)$ on the R_k is essential. From (53)

$$\mathrm{Re}\,(F_k(i\omega))^2=\partial R_0(i\omega)/\partial \ln R_k \qquad (57)$$

and since $F_k(p)$ and hence $(F_k(p))^2$ is analytic and finite for $\mathrm{Re}\,(p)\geq 0$, the conjugate $\mathrm{Im}\,(F_k(i\omega))^2$ may be found from the Gewertz or Bode procedure (Balabanian, 1958, sec. 3.6) for rational functions, or by a Hilbert transform (Bode, 1945, Chap. XIV). Notice also that

$$\begin{aligned} R_0(i\omega)&=\sum_k F_k(-i\omega)F_k(i\omega)\\ &=\sum_k |\,\partial Z_0(i\omega)/\partial \ln R_k\,|. \end{aligned} \qquad (58)$$

VI. Energy Storage in Networks with One Resistance

A network containing a single resistance is the simplest case of a network which can represent a general impedance Z_0. Darlington synthesis (Balabanian, 1958) shows that any lumped-element impedance can be obtained from such a network. Apart from being a simple special case, this type of network occupies a central position in demonstrating that a minimum energy storage exists and that a minimum energy synthesis is possible.

Since the system contains only one resistance, the dissipation is described by a single $F_k(p)=F(p)$ and Eq. (43) is simply

$$R_0(i\omega)=F(-i\omega)F(i\omega)=F^*(i\omega)F(i\omega) \quad \dots\dots\dots\dots\dots\dots \quad (59)$$

and the energy storage (Eq. (44)) is

$$W=T+V=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*\,\mathrm{Re}\,\{F(-i\omega)F'(i\omega)\} \quad \dots\dots\dots\dots \quad (60)$$

$$=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*R_0\,\mathrm{Re}\,\{F'(i\omega)/F(i\omega)\} \text{ using (59).} \quad \dots\dots\dots \quad (61)$$

For a lumped element network $F(p)$ can always be written as a product of a unique minimum phase shift function $F_{\min}(p)$, having no zeros in $\mathrm{Re}\,p>0$ and satisfying Eq. (59), together with a non-minimum phase shift factor, i.e.

$$F(p)=F_{\min}(p)\prod_k\{(p-p_k)/(p+p_k)\}^{M_k} \quad \dots\dots\dots\dots\dots\dots\dots \quad (62)$$

where M_k is the multiplicity of the zero of $F(p)$ at $p=p_k$ and

$$\mathrm{Re}\,p_k>0. \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (63)$$

Substitution of Eq. (62) in (61) gives

$$W=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*R_0\,\mathrm{Re}\,\{F'_{\min}(i\omega)/F_{\min}(i\omega)\}+I_0I_0^*R_0\sum_k M_k\left\{\frac{p_k}{p_k^2+\omega^2}+\frac{p_k^*}{p_k^{*2}+\omega^2}\right\} \quad \dots \quad (64)$$

$$=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*\,\mathrm{Re}\,\{F_{\min}(-i\omega)F'_{\min}(i\omega)\}+2I_0I_0^*R_0\sum_k M_kp_k/(p_k^2+\omega^2) \quad \dots\dots\dots \quad (65)$$

since complex values of p_k occur in conjugate pairs. But

$$\frac{p_k}{p_k^2+\omega^2}+\frac{p_k^*}{p_k^{*2}+\omega^2}=\frac{(p_k+p_k^*)(\omega^2+p_kp_k^*)}{(p_k^*p_k-\omega^2)^2+\omega^2(p_k+p_k^*)^2}>0$$

$$\text{since } \mathrm{Re}\,p_k>0, \quad \dots\dots\dots \quad (66)$$

thus the contribution from non-minimum phase shift factors to the energy storage, namely

$$2I_0I_0^*R_0\sum_k M_kp_k/(p_k^2+\omega^2), \quad \dots\dots\dots\dots\dots\dots\dots\dots \quad (67)$$

is always positive. Physically, surplus non-minimum phase shift factors increase the group time delay for the transfer of energy to the energy dissipating resistance and so increase the energy storage (Kishi and Nakazawa, 1963).

Consequently,

$$W\geq\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*R_0\,\mathrm{Re}\,\{F'_{\min}(i\omega)/F_{\min}(i\omega)\} \quad \dots\dots\dots\dots \quad (68)$$

equality applying when $F(p)$ has no zeros in $\mathrm{Re}\,p>0$.

For the subsequent development, or for the situation in which R_0 is known only from measurements of Z_0 rather than analytically, another form of (68) may be obtained. At the same time this form indicates how the specialization to lumped-element networks might be relaxed.

From Eq. (59) and the fact that $F(p)$ is a real function of p

$$-\tfrac{1}{2}(\partial R_0/\partial\omega)/R_0=\mathrm{Im}\,\{F'(i\omega)/F(i\omega)\}. \quad \dots\dots\dots\dots\dots\dots \quad (69)$$

The contribution to the energy in Eq. (61), which involves the dissipation function $F(p)$, is proportional to $\mathrm{Re}\,\{F'(i\omega)/F(i\omega)\}$. Thus we require the real part of the function $G(i\omega)=F'(i\omega)/F(i\omega)$ whose imaginary part is known in terms of R_0 from (69). For $\mathrm{Re}\,p\geq0$, $F(p)$ is a real analytic function. Consequently so is

$$G(p)=F'(p)/F(p) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (70)$$

except when $F(p)=0$. Moreover, if $F(p)$ has a zero of order M_k at $p=p_k$, $G(p)$ has a simple pole of residue M_k. Thus $G(p)$ is analytic in $\operatorname{Re} p \geq 0$ except for simple poles of residue M_k at zeros of $F(p)$. These poles can occur in complex conjugate pairs anywhere in $\operatorname{Re} p > 0$ as a result of non-minimum phase shift factors in $F(p)$, or on the $p=i\omega$ axis if $R_0(i\omega)$ vanishes.

Contour integration may now be used to relate the real and imaginary parts of $G(i\omega)$. The presence of poles of $G(p)$ in $\operatorname{Re} p \geq 0$ necessitates a slightly different treatment from the usual one (Bode, 1945, Chap. XIV). We suppose $G(p)$ regular at infinity with

$$\lim_{\omega \to \pm\infty} G(i\omega) = G_\infty. \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (71)$$

Since $G(p)$ is a real function of p, G_∞ is real.

Consider the contour integral

$$\int_\Gamma \frac{G(p)-G_\infty}{p-i\omega} \mathrm{d}p,$$

where Γ is basically a large semi-circular contour extending $-i\rho$ to $i\rho$ along the imaginary p axis and closed by an arc of radius ρ in the half-plane $\operatorname{Re} p > 0$. The contour is indented into $\operatorname{Re} p > 0$ by small semi-circles of radius ε at $p=i\omega$ and at any zeros, $p=i\omega_n$, of $F(p)$ on the imaginary p axis.

Then by Cauchy's theorem

$$\int_\Gamma \frac{G(p)-G_\infty}{p-i\omega} \mathrm{d}p = -2\pi i \{\text{sum of residues of } (G(p)-G_\infty)/(p-i\omega) \text{ inside } \Gamma\}. \quad \ldots\ldots \quad (72)$$

As $\rho \to \infty$ the contribution from the large semi-circle vanishes, and as $\varepsilon \to 0$ the small semi-circles contribute according to the residues s_n of $(G(p)-G_\infty)/(p-i\omega)$ at the points $p=i\omega_n$ and at $p=i\omega$. Equation (72) then becomes

$$\mathscr{P}\int_{-\infty}^{\infty} \frac{G(i\xi)-G_\infty}{\xi-\omega} \mathrm{d}\xi + i\pi\{G(i\omega)-G_\infty\} + \pi i \sum_n s_n(\omega) = -2\pi i \sum_k r_k(\omega) \quad \ldots\ldots\ldots\ldots \quad (73)$$

where $\mathscr{P}$ denotes the Cauchy principal value and $r_k(\omega)$ are residues of $G(p)/(p-i\omega)$ at poles of $G(p)$ in $\operatorname{Re} p > 0$. The imaginary part of Eq. (73) gives

$$\operatorname{Re} G(i\omega) = G_\infty - \frac{1}{\pi}\mathscr{P}\int_{-\infty}^{\infty} \frac{\operatorname{Im} G(i\xi)}{\xi-\omega} \mathrm{d}\xi - 2\sum_k \operatorname{Re} r_k(\omega) \quad \ldots\ldots\ldots\ldots\ldots \quad (74)$$

After using (69) and evaluating the residues, this becomes

$$\operatorname{Re}\{F'(i\omega)/F(i\omega)\} = G_\infty + \frac{1}{2\pi}\mathscr{P}\int_{-\infty}^{\infty} \frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\xi)(\xi-\omega)} \mathrm{d}\xi - 2\sum_k \frac{M_k p_k}{p_k^2+\omega^2}. \quad \ldots \quad (75)$$

Thus from (61)

$$W = \tfrac{1}{2} I_0 I_0^* \partial X_0/\partial\omega - I_0 I_0^* R_0 \left\{ G_\infty + \frac{1}{2\pi}\mathscr{P}\int_{-\infty}^{\infty} \frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\xi)(\xi-\omega)} \mathrm{d}\xi - 2\sum_k \frac{M_k p_k}{p_k^2+\omega^2} \right\}. \quad \ldots \quad (76)$$

For a finite lumped-element system G_∞ vanishes and (76) reduces to (65) with

$$\operatorname{Re}\{F_{\min}(-i\omega) F'_{\min}(i\omega)\} = \frac{R_0}{2\pi}\mathscr{P}\int_{-\infty}^{\infty} \frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\xi)(\xi-\omega)} \mathrm{d}\xi. \quad \ldots\ldots\ldots\ldots\ldots \quad (77)$$

In distributed systems for which G_∞ need not vanish, the term in G_∞ has a simple physical interpretation. $(-G_\infty)$ is the time delay as $\omega \to \pm\infty$ and arises from a surplus exponential factor representing a constant time delay. Consequently G_∞ is always non-positive.

We conclude that

$$W \geq \tfrac{1}{2} I_0 I_0^* \partial X_0/\partial\omega - I_0 I_0^* R_0 \frac{1}{2\pi}\mathscr{P}\int_{-\infty}^{\infty} \frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\xi)(\xi-\omega)} \mathrm{d}\xi \quad \ldots\ldots\ldots \quad (78)$$

or

$$W \geq \tfrac{1}{2} I_0 I_0^* \partial X_0/\partial\omega - I_0 I_0^* \operatorname{Re}\{F_{\min}(-i\omega) F'_{\min}(i\omega)\} \quad \ldots\ldots\ldots\ldots \quad (79)$$

equality holding when $F \equiv F_{\min}$, the dissipation function having no non-minimum phase factors of any kind. Thus to a prescribed one-resistor network there corresponds a minimum energy storage uniquely determined by (78) from the given impedance function.

If the network is a lumped-element network and R_0 is a known rational function, Eq. (79) can be used directly using standard algebraic methods for finding $F_{\min}$ rather than by evaluating the Hilbert transform in Eq. (78). Otherwise, in principle the Hilbert transform can be evaluated numerically from terminal measurements of R_0, but care is necessary in dealing with the principal value near singularities. Alternative forms for writing the transform (Bode, 1945 ; Morse and Feshbach, 1953) are then useful. For example

$$\begin{aligned}\frac{1}{\pi}\mathscr{P}\int_{-\infty}^{\infty}\frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\xi)(\xi-\omega)}\mathrm{d}\xi &= \frac{1}{\pi}\mathscr{P}\int_{-\infty}^{\infty}\frac{\{\partial \ln R_0(i\xi)/\partial\xi - [\partial \ln R_0(i\xi)/\partial\xi]_{\xi=\omega}\}}{\xi-\omega}\mathrm{d}\xi \\ &= \frac{1}{\pi}\mathscr{P}\int_{-\infty}^{\infty}\frac{\partial/\partial\xi(\ln [R_0(i\xi)/R_0(i\omega)])}{\xi-\omega}\mathrm{d}\xi. \qquad (80)\end{aligned}$$

The Hilbert transform form (78) for the minimum energy storage also occupies a central position in the subsequent theoretical development.

The above analysis, though not restricted to lumped-element networks, is limited to cases for which the assumption that $\lim_{\omega\to\pm\infty} G(i\omega)$ exists, is justified. The ordinary criteria for physical realizability do not exclude, for example, the possibility of an unbounded infinite set of zeros of R_0 and hence of $F(p)$ on the $p=i\omega$ axis. In such a case $\lim_{\omega\to\pm\infty} G(i\omega)$ does not exist. There is of course no difficulty with lumped-element systems and any distributed systems considered for extension of the results are assumed to be free of such complications.

VII. The Minimum Energy Storage of a General Network

In the previous section it was shown that for one-resistor networks there is a minimum energy storage, and an expression was derived for this minimum energy in terms of the terminal properties of the network as described by $Z_0(p)$. We now show that any network having the prescribed terminal behaviour irrespective of the number of resistors must store at least as much energy as this minimum for any particular $p=i\omega$.

A general network will contain N resistances R_k, the dissipation in each being described by the N functions F_k. The functions F_k are unknown in detail apart from the condition (43) on the total dissipation, i.e.

$$R_0(i\omega) = \sum_{k=1}^{N} | F_k(i\omega) |^2. \qquad (81)$$

Each $F_k(p)$ is a real causal function without poles for Re $(p) \geq 0$, so that $F_k(p)$ is determined by $| F_k(i\omega) |^2$ over the whole $p=i\omega$ axis except for non-minimum phase shift all-pass factors. Now suppose we write

$$R_0^{(k)}(i\omega) = | F_k(i\omega) |^2 \qquad (82)$$

so that $R_0^{(k)}$ is the contribution to the total terminal resistance R_0 from dissipation in the k^{th} resistor of the network. Since $R_0^{(k)}(i\omega)$ is always non-negative, there is associated with $R_0^{(k)}$ a minimum reactance impedance

$$Z_0^{(k)}(i\omega) = R_0^{(k)}(i\omega) + iX_0^{(k)}(i\omega). \qquad (83)$$

There is also a minimum reactance impedance $Z_0^{(\min)}$ associated with the total resistance R_0, and

$$\begin{aligned} Z_0^{(\min)} &= \sum_{k=1}^{N} Z_0^{(k)} \qquad (84) \\ &= \sum_{k=1}^{N} (R_0^{(k)} + iX_0^{(k)}). \qquad (85)\end{aligned}$$

The prescribed impedance $Z_0(p)$ can differ from $Z_0^{(\min)}$ only by its non-minimum reactance component, i.e.

$$Z_0(i\omega)=iX(i\omega)+\sum_{k=1}^{N} Z_0^{(k)}(i\omega) \qquad \dots\dots\dots\dots\dots\dots\dots\dots \quad (86)$$

where $iX(i\omega)$ is the non-minimum reactance function, if any, associated with Z_0. It has been seen in Section IV that the non-minimum reactance component of Z_0 presents no difficulties regarding energy storage, so we assume for simplicity in the current discussion that it has been subtracted out. That is, all of the impedances Z_0, $Z_0^{(k)}$ are minimum reactance. From (44) the energy storage is

$$W=\sum_{k=1}^{N}\left\{\tfrac{1}{2}I_0I_0^*\partial X_0^{(k)}/\partial\omega-I_0I_0^*\,\mathrm{Re}\,[F_k(-p)F_k'(p)]_{p=i\omega}\right\}. \qquad \dots\dots \quad (87)$$

Thus from (60) the energy storage of the multi-resistor network realization is the same as the energy storage of N one-resistor networks having reactances $X_0^{(k)}$ and dissipation transfer functions F_k. We have already examined one-resistor networks in detail in the previous section. There is a minimum-energy storage $W_{\min}^{(k)}$ given by equation (78) for each of these networks. Thus

$$W\geq\sum_{k=1}^{N} W_{\min}^{(k)} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (88)$$

the equality sign holding if every $F_k(p)$ has no zeros for $\mathrm{Re}\,p>0$. The magnitude of the sum in (87) will depend upon how the dissipation is distributed between the N resistors. We now consider another representation of Z_0 in which all dissipation takes place in a single resistor. From (78) the energy storage of this network exceeds

$$W_{\min}^{(0)}=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*R_0\frac{1}{2\pi}\mathscr{P}\int_{-\infty}^{\infty}\frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\xi)(\xi-\omega)}\mathrm{d}\xi \qquad \dots\dots\dots\dots \quad (89)$$

unless $F(p)$ is minimum phase shift and equality applies. We now show that

$$\sum_{k=1}^{N} W_{\min}^{(k)}\geq W_{\min}^{(0)} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (90)$$

so that from (88) the energy storage of any network realizing $Z_0(p)$ satisfies

$$W\geq\sum_{k=1}^{N} W_{\min}^{(k)}\geq W_{\min}^{(0)} \qquad \dots\dots\dots\dots\dots\dots \quad (91)$$

Because

$$X_0(i\omega)=\sum_{k=1}^{N} X_0^{(k)}(i\omega) \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (92)$$

it is only necessary to show that

$$R_0(i\omega)\mathscr{P}\int_{-\infty}^{\infty}\frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\xi)(\xi-\omega)}\mathrm{d}\xi\geq\sum_{k=1}^{N} R_0^{(k)}(i\omega)\mathscr{P}\int_{-\infty}^{\infty}\frac{\partial R_0^{(k)}(i\xi)/\partial\xi}{R_0^{(k)}(i\xi)(\xi-\omega)}\mathrm{d}\xi \qquad \dots\dots \quad (93)$$

where

$$R_0^{(k)}(i\omega)\geq 0 \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (94)$$

and

$$R_0(i\omega)=\sum_{k=1}^{N} R_0^{(k)}(i\omega). \qquad \dots\dots\dots\dots\dots\dots\dots\dots \quad (95)$$

Set

$$\eta_k(\omega)=R_0^{(k)}(i\omega)/R_0(i\omega). \qquad \dots\dots\dots\dots\dots\dots \quad (96)$$

Then η_k denotes the fraction of the total power that is dissipated in the k^{th} resistor. I.e.

$$0\leq\eta_k(\omega)\leq 1. \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (97)$$

The η_k are not defined by (96) when $R_0=0$, which from (94), (95) implies $R_0^{(k)}=0$. η_k may be defined as a limit in the vicinity of $R_0=0$, but this is not necessary since the principal value reckoning of the integrals avoids such points. It is assumed, of course, that $\eta_k(\omega)\neq 0$, but $\eta_k(\omega)$ can still have zeros when $R_0^{(k)}(i\omega)=0$ with $R_0(i\omega)\neq 0$. Because η_k is positive and indefinitely differentiable, its power expansion about a zero has an even power as the first non-vanishing term. This behaviour will be useful in dealing with the principal values of the integrals in (93) at $\eta_k=0$. Now consider

$$\mathscr{P}\sum_{k=1}^{N}\eta_k(\omega)\int_{-\infty}^{\infty}\left\{\frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\xi)(\xi-\omega)}-\frac{\partial R_0^{(k)}(i\xi)/\partial\xi}{R_0^{(k)}(i\xi)(\xi-\omega)}\right\}\mathrm{d}\xi \quad \ldots\ldots \quad (98)$$

$$=-\mathscr{P}\int_{-\infty}^{\infty}\sum_k\eta_k(\omega)(\partial\ln\eta_k(\xi)/\partial\xi)\frac{\mathrm{d}\xi}{\xi-\omega} \quad \ldots\ldots \quad (99)$$

$$=-\mathscr{P}\int_{-\infty}^{\infty}[\partial\sum_k\{\eta_k(\omega)\ln[\eta_k(\xi)/\eta_k(\omega)]\}/\partial\xi]\frac{\mathrm{d}\xi}{\xi-\omega} \quad \ldots\ldots \quad (100)$$

$$=\mathscr{P}\left\{\left[\frac{-\sum_k\eta_k(\omega)\ln\{\eta_k(\xi)/\eta_k(\omega)\}}{\xi-\omega}\right]_{-\infty}^{\infty}-\int_{-\infty}^{\infty}\frac{\sum_k\eta_k(\omega)(\ln\eta_k(\xi)-\ln\eta_k(\omega))}{(\xi-\omega)^2}\mathrm{d}\xi\right\}$$

from integrating by parts .. (101)

$$=-\mathscr{P}\int_{-\infty}^{\infty}\frac{\sum_k(\eta_k(\omega)\ln\eta_k(\xi)-\eta_k(\omega)\ln\eta_k(\omega))\mathrm{d}\xi}{(\xi-\omega)^2} \quad \ldots\ldots \quad (102)$$

≥ 0 since the integrand in (102) is always ≤ 0 (see Appendix) .... (103)

The boundary terms from the integration by parts in (101) vanish because of the behaviour of η_k near zeros, and because of the factor $1/\eta_k(\omega)$ in the logarithm at $\xi=\omega$. The equality sign in (103) only holds when the integrand in (102) is identically zero, which requires (see Appendix)

$$\eta_k(\xi)\equiv\eta_k(\omega)=\text{constant}. \quad \ldots\ldots \quad (104)$$

Equation (103) is equivalent to (93), so we have shown that (90) is generally true, the equality sign applying when the $\eta_k(\omega)$ are constants.

Thus, finally from (89), (90) and (91) it has been shown that for any specified minimum reactance impedance there exists a minimum energy storage $W_{\min}^{(0)}$, i.e.

$$W\geqq W_{\min}^{(0)} \quad \ldots\ldots \quad (105)$$

with

$$W_{\min}^{(0)}=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*R_0\left(\frac{1}{2\pi}\right)\mathscr{P}\int_{-\infty}^{\infty}\frac{\partial R_0(i\xi)/\partial\xi}{R_0(i\omega)(\xi-\omega)}\mathrm{d}\xi \quad \ldots\ldots \quad (106)$$

$$=\tfrac{1}{2}I_0I_0^*\partial X_0/\partial\omega-I_0I_0^*\operatorname{Re}\{F_{\min}(-i\omega)F'_{\min}(i\omega)\} \quad \ldots\ldots \quad (107)$$

where $F_{\min}(i\omega)$ is the minimum-phase shift function satisfying

$$F(-i\omega)F(i\omega)=R_0(i\omega).$$

Further, this minimum energy storage corresponds at all frequencies $p=i\omega$ to the energy storage of a minimum phase-shift Darlington synthesis of the impedance. Any non-minimum reactance component of the impedance $Z_0(p)$ can now be replaced in (106), (107) making them valid for a general impedance.

VIII. Realization of the Minimum Energy Storage

On general mathematical grounds the minimum energy storage was shown to correspond to that of a network with one-resistor in which the transfer function $F(p)$ is minimum phase shift (i.e., a minimum phase shift Darlington synthesis of $Z_0(p)$). It is well known that in conventional Darlington synthesis using reciprocal networks (Balabanian, 1958) minimum phase shift synthesis is not always possible, extra non-minimum phase shift factors in $F(p)$ being required to effect a synthesis. However, Hazony (1961) has shown that by using gyrators it is possible to carry out Darlington synthesis without surplus factors, so that minimum phase shift Darlington synthesis is possible. Thus the minimum energy storage for a lumped-element network corresponds to a realizable network. Thus the problem of a minimum energy synthesis of an impedance $Z_0(p)$ is at once both posed and solved. Minimum energy synthesis will normally require non-reciprocal elements. It will certainly require non-reciprocal elements if for some $p=i\omega$

$$I_0 I_0^* \mid X_0/2\omega \mid > W_{\min}^{(0)} \quad \ldots\ldots \quad (108)$$

since from (15) $I_0 I_0^* \mid X_0/2\omega \mid$ is the lower bound on the energy storage of a reciprocal network. This occurs in the simple example to be considered in the next section.

IX. A Simple Example

A simple example will illustrate a number of points without the complexities of elaborate realizations. Take $Z_0(p)=1+1/(p+1)$, and suppose a unit excitation current. By following the introductory steps to classical impedance synthesis the realization of Fig. 1 (a) is obtained. However, $Z_0(p)$ corresponds to an RC network function (Balabanian, 1958), so we know that the minimum energy storage for reciprocal networks is (Eq. (14))

$$W=\mid X_0 \mid /2\omega=\tfrac{1}{2}/(1+\omega^2) \quad \ldots\ldots \quad (109)$$

corresponding to Fig. 1 (a). Figure 1 (b) is an alternative synthesis with the same energy storage

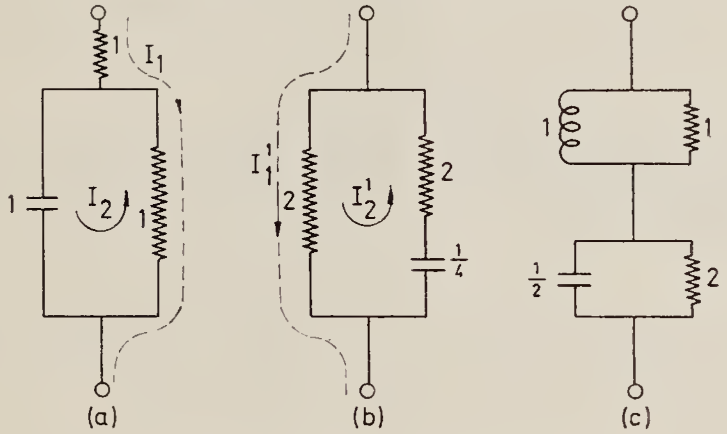

FIG. 1—Realizations of $Z_0(p)=1+1/(1+p)$.

Choosing mesh currents I_1 and I_2 in Fig. 1 (a) and I_1' and I_2' in Fig. 1 (b) gives mesh impedance matrices

$$\mathbf{Z} = \begin{pmatrix} 2, & -1 \\ -1, & 1+1/p \end{pmatrix} \quad \ldots\ldots \quad (110)$$

$$\mathbf{Z}' = \begin{pmatrix} 2, & 2 \\ 2, & 4+4/p \end{pmatrix} \quad \ldots\ldots \quad (111)$$

The two networks store the same energy and we see they are connected by a Cauer equivalence transformation (7) with

$$\mathbf{T} = \begin{pmatrix} 1 & 0 \\ 0 & -2 \end{pmatrix} \quad \ldots\ldots \quad (112)$$

A simple example of a reciprocal network realization storing more energy than the minimum for reciprocal network is shown in Fig. 1 (c). This network is degenerate in the sense that the structure indicates two poles of $Z_0(p)$, but the choice of component values leads to only one in $Z_0(p)$. Such superfluous pole or zero behaviour is a characteristic of non-minimum energy reciprocal networks. This particular network stores three times the energy of the networks of Fig. 1 (a), 1 (b).

$\overline{Z_0(p)}$ may also be realized by a reciprocal non-minimum phase shift Darlington synthesis (Fig. 2 (a)), for which

$$F(p)=(\sqrt{2}-p)/(1+p). \quad \ldots\ldots \quad (113)$$

It cannot be realized by a minimum phase shift synthesis using reciprocal elements alone. The energy storage of this realization is found from Eq. (60) to be

$$W=\tfrac{1}{2}(3+2\sqrt{2})/(1+\omega^2) \qquad (114)$$

$$=(3+2\sqrt{2})\,|X_0/2\omega| \qquad (115)$$

which is $(3+2\sqrt{2})$ times that of the minimum-energy storing reciprocal networks. It must of course exceed the minimum for reciprocal networks because there is magnetic as well as electric energy storage.

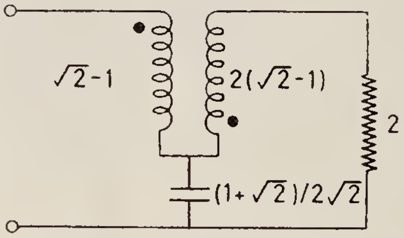

FIG. 2—Darlington reciprocal network synthesis of $Z_0(p)=1+1/(1+p)$.

We now consider what is the minimum possible energy storage for any realization of $Z_0(p)$. This may be evaluated either by (106) or more conveniently by (107). The minimum phase shift $F(p)$ for this impedance is

$$F_{\min}(p)=(\sqrt{2}+p)/(1+p). \qquad (116)$$

The non-minimum phase shift function (113) differs from this by the all pass factor $(\sqrt{2}-p)/(\sqrt{2}+p)$. The minimum possible energy storage is then

$$T+V=\tfrac{1}{2}(3-2\sqrt{2})/(1+\omega^2)=(3-2\sqrt{2})\,|X_0/2\omega|. \qquad (117)$$

Thus the minimum energy is only $(3-2\sqrt{2})\approx 0{\cdot}17$ of the minimum reciprocal network energy storage. We note also that (115) exceeds (117) by

$$2\sqrt{2}/(1+\omega^2)=2R_0.\{\sqrt{2}/(\omega^2+2)\}. \qquad (118)$$

This excess is the non-minimum phase shift contribution (Eq. (65)) from the zero of $F(p)$ at $p=\sqrt{2}$. All that remains is to show how to achieve a synthesis with this minimum energy. Hazony (1961) has considered examples of non-reciprocal Darlington synthesis without surplus factors. His methods give the syntheses shown in Fig. 3 (*a*), (*b*).

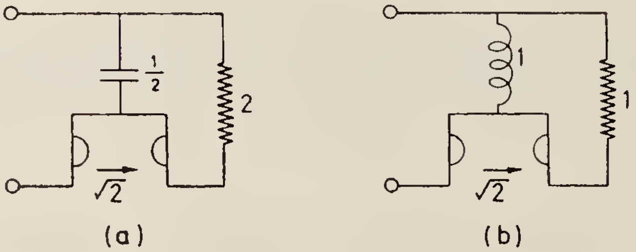

FIG. 3—Non-reciprocal Darlington syntheses of $Z_0(p)=1+1/(1+p)$.

These syntheses are independent of the sign of the gyrator coupling. One sign, as in Fig. 3 with Carlin's convention (Carlin, 1955), gives minimum phase shift networks corresponding to the $F(p)$ of Eq. (116), while the other gives $F(p)$ corresponding to (113). Notice also that both networks in Fig. 3 (with appropriate gyrator coupling signs) store the same energy and represent the same impedance, but in one it is entirely electric and in the other it is entirely magnetic. (This behaviour is peculiar to non-reciprocal networks (Smith, 1967).)

To illustrate the use of Vratsanos' theorem in evaluating the energy storage by this impedance, we must suppose $Z_0(p)$ is given as a function of the magnitudes of all resistors in the network and that the network is composed of reciprocal elements. For example, take the case where there are two resistors and

$$Z_0(p,R_k)=\frac{pR_1}{R_1+p}+\frac{2}{p+1/R_2}\ . \qquad\ldots\ldots\ldots\ldots\ldots\ldots(119)$$

Then

$$Z_0(p,R_k)=1+1/(1+p) \text{ when } R_1=1 \text{ and } R_2=1.$$

From (52)

$$F_1^2(p)=R_1(\partial Z_0/\partial R_1)_{R_1,R_2=1}=p^2/(1+p)^2 \qquad\ldots\ldots\ldots\ldots\ (120)$$

and

$$F_2^2(p)=2/(1+p)^2. \qquad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (121)$$

The energy storage can then be evaluated to obtain

$$T+V=\frac{3}{2}/(1+\omega^2) \qquad\ldots\ldots\ldots\ldots\ldots\ldots\ (122)$$

which is the same as for the network of Fig. 1 (*c*).

X. Summary and Discussion

The average energy storage of a sinusoidally excited, general linear, passive network has been seen to be not determined by terminal behaviour alone. That is, equivalent circuits in the usual terminology do not store the same energy for the same excitation. However, the class of networks related by Cauer's equivalence transformation do.

The energy storage is uniquely determined by the terminal behaviour whenever the system dissipates no energy, is an RL or RC network, or when the dependence of the terminal behaviour on the individual dissipative processes is known.

For reciprocal element networks a simple lower bound exists for the energy storage at each frequency. This bound is attained at all frequencies by RL or RC networks.

A general expression for the energy storage has been found and used to show that for any linear, passive network there is a minimum possible energy storage corresponding to a prescribed impedance. Further, this bound is attainable at all frequencies as a minimum energy synthesis. The minimum energy synthesis is a minimum phase-shift Darlington synthesis, and normally non-reciprocal elements (gyrators) are required for its realization.

Only sinusoidal excitation of the impedance has been considered in detail. If we consider excitation represented by a Fourier integral, Parseval's formula can be used to find the time integral of the instantaneous stored energy since the storage in every element is a quadratic function of the voltage or current. The time integral of the energy storage is the integral over all frequencies of the energy storage associated with the individual Fourier components of the excitation. Consequently the network storing minimum energy (in the sense of an integration over time) is the minimum energy synthesis of the impedance. Instantaneous energy storage as a function of time would need to be approached by energy conservation arguments analogous to Section IV, but involving the time-domain behaviour of the dissipation functions.

The methods used in the development are not intrinsically restricted to lumped-element systems, so that with perhaps some qualifications the results should extend to distributed systems with non-rational $Z_0(p)$. Also, the results are not restricted to electrical impedances, for example, the same arguments apply for an acoustic impedance. An extension to multi-port systems may also be possible. That non-reciprocal elements may sometimes be necessary for the general case to attain the minimum energy can be expected intuitively from relationships between group time-delay and energy storage (Kishi and Nakazawa, 1963). Carlin (1967) considers time-delays in a matched loss-free two-port and shows that negative group time delays are possible, but only in non-reciprocal systems.

There are still some further questions of interest. Is there a synthesis of a general RLC network which attains the reciprocal network minimum energy bound $\frac{1}{2}I_0I_0^*\left|\frac{X_0}{\omega}\right|$ at all frequencies?

This is easily shown to be impossible in general, by the counter example of a unit inductor in series with a parallel combination of a unit resistor and unit capacitor. $Z_0=(p^2+p+1)/(p+1)$. This network is a minimum energy network, and for unit current stores a non-zero amount of energy at $\omega=0$. But $\frac{1}{2}|X_0/\omega|=0$ at $\omega=0$, which is less than the minimum possible energy. Thus the bound $\frac{1}{2}I_0I_0^*\left|\frac{X_0}{\omega}\right|$ for reciprocal networks is not a close one and the absolute minimum can exceed it. Perhaps there is a better bound for the energy storage in reciprocal networks. If so, is it attainable at all frequencies by some realization ? That is, is there a minimum energy reciprocal element synthesis in the same way as there is an overall minimum energy synthesis ? Classical methods of synthesis have stressed the number or types of elements required for synthesis. We could ask whether Brune synthesis, for example, occupies a special place in the energy storage hierarchy.

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XII. Appendix

The following inequality is proved :

If $$f=\sum_{i=1}^{N}(p_i\ln q_i-p_i\ln p_i) \quad .. \quad \text{(A1)}$$

with $$\sum_{i=1}^{N}p_i=1,\quad p_i>0 \quad ...... \quad \text{(A2)}$$

and $$\sum_{i=1}^{N}q_i=1,\quad q_i>0 \quad ...... \quad \text{(A3)}$$

then $$f\leq 0 \quad .... \quad \text{(A4)}$$

the equality sign implying
$$p_i=q_i,\ i=1,\ N \quad ...... \quad \text{(A5)}$$

Write f as
$$f=\sum_{i=1}^{N}p_i\left(\ln\frac{q_i}{p_i}+1-\frac{q_i}{p_i}\right) \quad .. \quad \text{(A6)}$$

which is equivalent to (A1) by virtu of (A2) and (A3).

Now $\ln x+1-x<0$ for all $x>0$ except $x=1$ when $\ln x+1-x=0$. Consequently, from (A6) $f<0$ unless all $p_i=q_i$, in which case $f=0$.

(The author is indebted to an unknown American referee for suggesting this simplified proof.)

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