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Precise Observations of Minor Planets at Sydney Observatory During 1973 and 1974

T. L. MORGAN AND W. H. ROBERTSON

ABSTRACT. Positions of 1 Ceres, 3 Juno, 11 Parthenope, 18 Melpomene, 39 Laetitia, 40 Harmonia and 185 Eunike obtained with the 23 cm camera are given.

The programme of precise observations of selected minor planets which was begun in 1955 is being continued and the results for 1973 and 1974 are given here. The methods of observation and reduction were described in the first paper (Robertson 1958). All the plates were taken with the 23 cm camera (scale 116" to the millimetre). Four exposures were made on each plate except those for 185 Eunike for which there were two.

In Table 1 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 $0^s.035 \sec \delta$ in right ascension and 0".43 in declination. This corresponds to probable errors for the mean of the two results from one plate of $0^s.015 \sec \delta$ and 0".19. The result from the first two exposures was compared with that from the last two by adding the movement computed from the ephemeris. The means of the differences were $0^s.008 \sec \delta$ in right ascension and 0".12 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 2. No correction has been applied for aberration, light time or parallax, but the factors give the parallax correction when divided by the distance. The observers at the telescope were W.H. Robertson (R), K.P. Sims (S) and Harley Wood (W).

In accordance with the recommendation of Commission 20 of the International Astronomical Union, Table 2 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, 19, 20, 21, 22). The plates were measured by Mrs A. Brown, Miss J. Fitt and Mrs J. Saunders who have also assisted with the reductions.

REFERENCES

Robertson, W.H., 1958. Precise observations of minor planets at Sydney Observatory during 1955 and 1956. *J. Proc. R. Soc. N.S.W.*, *92*, 18-23. *Sydney Observatory Papers No 33.*

TABLE 1

POSITIONS OF MINOR PLANETS

No.	Time of Observation	R.A. (1950.0) h m s	Dec. (1950.0) ° ' "	Parallax Factors s	Parallax Factors "	
	1 CERES 1973 U.T.					
1193	Mar. 27.77284	17 04 26.338	-17 29 58.74	-0.018	-2.44	R
1194	Mar. 27.77284	17 04 26.357	-17 29 59.30			
1195	Apr. 02.77436	17 06 21.721	-17 38 28.37	+0.036	-2.43	S
1196	Apr. 02.77436	17 06 21.672	-17 38 29.05			
1197	Apr. 25.69104	17 04 56.334	-18 10 23.56	-0.027	-2.35	R
1198	Apr. 25.69104	17 04 56.324	-18 10 23.88			
1199	May 02.68872	17 01 41.186	-18 20 44.14	+0.034	-2.32	S
1200	May 02.68872	17 01 41.229	-18 20 44.30			
1201	May 21.61890	16 47 27.119	-18 50 37.44	+0.008	-2.25	R
1202	May 21.61890	16 47 27.136	-18 50 37.62			
1203	May 28.59680	16 40 53.995	-19 02 08.78	+0.013	-2.22	S
1204	May 28.59680	16 40 54.006	-19 02 09.02			
1205	Jul. 02.46782	16 11 55.798	-20 07 43.78	-0.031	-2.06	R
1206	Jul. 02.46782	16 11 55.816	-20 07 44.14			

TABLE 1 - continued

No.	Time of Observation	R.A. (1950.0)	Dec. (1950.0)	Parallax Factors		
		h m s	° ' "	s	"	
	1 CERES continued 1973 U.T.					
1207	Jul. 20.43634	16 06 27.996	-20 54 00.52	+0.039	-2.45	S
1208	Jul. 20.43634	16 06 28.026	-20 54 00.10			
1209	Aug. 02.39225	16 07 40.187	-21 34 25.26	-0.014	-1.84	R
1210	Aug. 02.39225	16 07 40.153	-21 34 25.02			
1211	Aug. 09.37080	16 10 01.222	-21 58 21.22	-0.004	-1.78	R
1212	Aug. 09.37080	16 10 01.219	-21 58 20.35			
	3 JUNO 1973 U.T.					
1213	Apr. 25.71489	17 26 24.640	-06 38 02.40	+0.002	-4.00	R
1214	Apr. 25.71489	17 26 24.624	-06 38 02.52			
1215	May 02.70444	17 23 49.480	-06 04 24.94	+0.034	-4.07	S
1216	May 02.70444	17 23 49.488	-06 04 24.82			
1217	May 28.61739	17 06 46.854	-04 23 12.32	+0.021	-4.30	S
1218	May 28.61739	17 06 46.864	-04 23 12.10			
1219	Jul. 02.48972	16 38 53.960	-04 03 21.32	-0.019	-4.34	S
1220	Jul. 02.48972	16 38 53.986	-04 03 20.97			
1221	Jul. 20.45301	16 30 18.669	-04 52 08.12	+0.038	-4.23	S
1222	Jul. 20.45301	16 30 18.692	-04 52 07.35			
1223	Aug. 02.42321	16 28 09.027	-05 45 25.86	+0.060	-4.12	R
1224	Aug. 02.42321	16 28 08.996	-05 45 25.32			
	11 PARTHENOPE 1973 U.T.					
1225	Apr. 02.75791	16 43 30.196	-16 03 36.02	+0.033	-2.64	S
1226	Apr. 02.75791	16 43 30.146	-16 03 35.97			
1227	Apr. 25.67044	16 42 43.304	-15 22 33.68	-0.044	-2.76	R
1228	Apr. 25.67044	16 42 43.323	-15 22 34.06			
1229	May 02.67197	16 39 21.030	-15 07 21.59	+0.029	-2.80	S
1230	May 02.67197	16 39 21.036	-15 07 21.72			
1231	May 21.59682	16 24 22.753	-14 28 12.60	-0.009	-2.89	R
1232	May 21.59682	16 24 22.656	-14 28 12.74			
1233	May 28.57868	16 17 35.748	-14 16 59.65	+0.007	-2.91	S
1234	May 28.57868	16 17 35.710	-14 16 59.43			
1235	Jul. 02.44972	15 51 02.668	-14 24 37.78	-0.041	-2.90	R
1236	Jul. 02.44972	15 51 02.609	-14 24 38.04			
1237	Jul. 20.41879	15 49 35.974	-15 18 38.98	+0.021	-2.76	S
1238	Jul. 20.41879	15 49 35.982	-15 18 39.26			
1239	Aug. 02.36656	15 54 31.208	-16 14 24.16	-0.044	-2.64	R
1240	Aug. 02.36656	15 54 31.328	-16 14 23.56			
	39 LAETITIA 1973 U.T.					
1241	Sep. 18.50621	22 05 39.910	-12 28 28.90	-0.008	-3.19	R
1242	Sep. 18.50621	22 05 39.896	-12 28 28.42			
1243	Sep. 26.47501	22 02 21.362	-13 22 59.02	-0.031	-3.07	R
1244	Sep. 26.47501	22 02 21.311	-13 22 59.74			
	40 HARMONIA 1973 U.T.					
1245	Sep. 18.52402	22 12 24.105	-18 30 02.16	+0.033	-2.32	R
1246	Sep. 18.52402	22 12 24.078	-18 30 02.22			
1247	Sep. 26.49845	22 07 52.914	-18 45 04.01	+0.031	-2.29	S
1248	Sep. 26.49845	22 07 52.956	-18 45 04.34			

TABLE 1 - continued

No.	Time of Observation	R.A. (1950.0) h m s	Dec. (1950.0) o ' "	Parallax Factors s	Parallax Factors "	
	185 EUNIKE 1973 U.T.					
1249	Feb. 05.62505	09 54 09.985	+06 25 36.40	+0.026	-5.65	W
1250	Feb. 05.62505	09 54 10.056	+06 25 37.00			
1251	Mar. 01.53997	09 35 27.426	+10 53 47.24	+0.005	-6.16	R
1252	Mar. 01.53997	09 35 27.402	+10 53 47.37			
	1 CERES 1974 U.T.					
1253	Jun. 26.79021	23 21 15.055	-16 47 14.70	-0.003	-2.57	R
1254	Jun. 26.79021	23 21 15.111	-16 47 13.56			
1255	Jul. 27.71629	23 24 05.956	-19 05 01.92	+0.024	-2.24	W
1256	Jul. 27.71629	23 24 05.978	-19 05 03.47			
1257	Aug. 15.65466	23 15 20.604	-21 14 05.00	+0.035	-1.91	W
1258	Aug. 15.65466	23 15 20.564	-21 14 05.38			
1259	Aug. 29.61179	23 04 52.550	-22 46 03.08	+0.021	-1.69	W
1260	Aug. 29.61179	23 04 52.552	-22 46 03.30			
1261	Oct. 09.47970	22 35 28.204	-24 23 30.23	+0.022	-1.44	S
1262	Oct. 09.47970	22 35 28.242	-24 23 30.07			
1263	Oct. 14.46801	22 33 43.470	-24 13 21.76	+0.033	-1.47	S
1264	Oct. 14.46801	22 33 43.402	-24 13 21.76			
1265	Oct. 23.44214	22 32 03.885	-23 44 35.75	+0.032	-1.55	S
1266	Oct. 23.44214	22 32 03.864	-23 44 35.76			
1267	Nov. 05.39181	22 33 00.188	-22 42 53.48	-0.019	-1.69	R
1268	Nov. 05.39181	22 33 00.212	-22 42 53.19			
	3 JUNO 1974 U.T.					
1269	Jun. 19.78734	22 53 53.860	+00 56 22.26	-0.013	-5.01	W
1270	Jun. 19.78734	22 53 53.822	+00 56 22.49			
1271	Jun. 26.76832	22 58 27.224	+01 18 11.94	-0.022	-5.05	R
1272	Jun. 26.76832	22 58 27.236	+01 18 12.58			
1273	Jul. 27.69919	23 07 12.696	+01 14 00.22	+0.007	-5.05	W
1274	Jul. 27.69919	23 07 12.777	+01 14 00.44			
1275	Aug. 15.63912	23 01 47.670	-00 35 52.91	-0.007	-4.81	W
1276	Aug. 15.63912	23 01 47.672	-00 35 52.70			
1277	Aug. 29.59221	22 53 10.816	-02 50 22.60	-0.015	-4.52	W
1278	Aug. 29.59221	22 53 10.779	-02 50 22.66			
1279	Oct. 09.46786	22 28 44.830	-10 16 24.12	-0.002	-3.51	S
1280	Oct. 09.46786	22 28 44.810	-10 16 23.52			
1281	Oct. 14.45473	22 28 02.716	-10 54 23.50	+0.001	-3.42	S
1282	Oct. 14.45473	22 28 02.720	-10 54 21.44			
1283	Oct. 23.42382	22 28 39.983	-11 47 16.15	-0.020	-3.29	S
1284	Oct. 23.42382	22 28 40.023	-11 47 17.74			
1285	Nov. 05.40424	22 33 49.054	-12 28 32.24	+0.019	-3.20	R
1286	Nov. 05.40424	22 33 48.986	-12 28 33.22			
	18 MELPOMENE 1974 U.T.					
1287	May 29.77824	21 20 49.220	-06 58 14.32	-0.019	-3.96	S
1288	May 29.77824	21 20 49.215	-06 58 14.00			
1289	Jun. 19.74784	21 35 21.042	-05 59 57.72	+0.033	-4.10	W
1290	Jun. 19.74784	21 35 21.037	-05 59 57.40			
1291	Jun. 26.72112	21 37 51.454	-05 58 12.34	+0.004	-4.10	R
1292	Jun. 26.72112	21 37 51.512	-05 58 12.22			
1293	Jul. 23.64162	21 34 38.194	-07 49 12.58	-0.007	-3.85	W
1294	Jul. 23.64162	21 34 38.174	-07 49 13.12			
1295	Sep. 03.50303	21 04 38.361	-15 42 40.69	-0.017	-2.73	R
1296	Sep. 03.50303	21 04 38.332	-15 42 40.82			
1297	Sep. 11.48158	21 01 25.998	-17 06 06.80	-0.009	-2.52	S
1298	Sep. 11.48158	21 01 25.932	-17 06 06.52			
1299	Sep. 16.47384	21 00 31.740	-17 51 13.30	+0.012	-2.41	S
1300	Sep. 16.47384	21 00 31.828	-17 51 12.93			

TABLE 1 - continued

No.	Time of Observation	R.A. (1950.0) h m s	Dec. (1950.0) ° ' "	Parallax Factors s	Parallax Factors "	
	18 MELPOMENE continued 1974 U.T.					
1301	Oct. 09.42953	21 08 30.012	-19 56 12.14	+0.054	-2.12	S
1302	Oct. 09.42953	21 08 30.080	-19 56 12.63			
1303	Oct. 15.40969	21 13 40.434	-20 06 25.14	+0.031	-2.09	R
1304	Oct. 15.40969	21 13 40.512	-20 06 25.00			
1305	Oct. 18.40010	21 16 41.535	-20 08 11.30	+0.020	-2.08	S
1306	Oct. 18.40010	21 16 41.497	-20 08 10.81			
1307	Oct. 23.40192	21 22 19.771	-20 06 19.00	+0.058	-2.10	S
1308	Oct. 23.40192	21 22 19.683	-20 06 18.04			

TABLE 2

REFERENCE STAR POSITIONS AND DEPENDENCES

No.	Star	Depend.	R.A.	Dec.
1193	6095	0.212888	21.677	03.87
	6122	0.470255	05.900	26.39
	6127	0.316857	31.858	01.67
1194	6098	0.469066	35.299	22.75
	6130	0.325191	12.427	34.80
	6141	0.205743	08.365	24.97
1195	6112	0.337464	21.473	42.14
	6127	0.287192	31.858	01.67
	6154	0.375344	42.170	40.33
1196	6096	0.296730	31.951	12.38
	6141	0.339664	08.365	24.97
	6147	0.363606	37.794	05.28
1197	6966	0.296665	32.001	12.65
	7006	0.410101	22.852	51.74
	6120	0.293234	59.073	27.25
1198	6098	0.265214	35.300	22.76
	6136	0.431639	05.807	10.74
	6987	0.303147	48.313	26.78
1199	6080	0.428792	19.534	26.16
	6987	0.255334	48.313	26.78
	6989	0.315874	05.810	25.36
1200	6949	0.351492	07.456	15.31
	6988	0.298102	48.882	36.71
	6098	0.350406	35.300	22.76
1201	6855	0.384326	36.493	52.86
	6867	0.355731	52.516	28.52
	6890	0.259942	58.359	57.55
1202	6848	0.315053	50.706	15.02
	6869	0.495556	13.700	36.83
	6902	0.189392	22.113	41.90
1203	6816	0.259506	32.531	40.12
	6833	0.557220	09.851	55.98
	6848	0.183274	50.706	15.02
1204	6821	0.482801	02.356	36.31
	6835	0.251143	28.276	34.49
	6844	0.266056	44.290	57.76
1205	6685	0.402191	58.932	56.41
	6736	0.220889	41.148	48.72
	6727	0.376920	56.906	34.02
1206	6682	0.387824	43.151	23.39
	6742	0.355180	58.738	44.91
	6711	0.256996	19.111	36.80
1207	6638	0.273124	31.495	14.04
	6684	0.324940	51.538	56.41
	6686	0.401935	01.804	11.03
1208	6662	0.383003	48.054	45.65
	6676	0.392790	39.137	06.82
	6692	0.224206	58.926	36.17
1209	6654	0.375180	52.421	12.32
	6692	0.349945	58.926	36.17
	6708	0.274875	10.641	11.22
1210	11337	0.281174	30.697	31.06
	6669	0.304936	39.109	34.29
	6705	0.413890	37.702	31.93
1211	6684	0.505250	51.536	56.40
	6695	0.220995	10.485	24.77
	11417	0.273754	42.355	21.18
1212	11337	0.283648	30.696	31.06
	11419	0.347160	50.122	32.62
	6692	0.369192	58.925	36.17
1213	5915	0.406059	30.006	27.80
	5917	0.277274	11.878	11.62
	5936	0.316667	55.028	57.60
1214	5912	0.351208	16.305	35.15
	5941	0.340335	10.174	25.74
	5875	0.308457	43.508	37.64
1215	5899	0.271232	53.238	34.82
	5929	0.364240	52.189	48.33
	5873	0.364527	27.014	36.96
1216	5898	0.230472	12.034	21.52
	5926	0.237570	16.142	25.11
	5875	0.531958	43.508	37.64
1217	5817	0.404758	25.433	26.19
	5835	0.369186	10.881	18.64
	5840	0.226056	39.264	47.52
1218	5821	0.238368	48.490	27.58
	5827	0.417823	42.933	53.24
	5838	0.343809	08.250	50.05
1219	5711	0.421518	43.960	39.41
	5731	0.401273	16.650	38.88
	5740	0.177209	26.686	22.46
1220	5712	0.294634	18.507	34.41
	5720	0.371312	16.684	17.86
	5738	0.334054	45.547	57.24

TABLE 2 - continued

No.	Star	Depend.	R.A.	Dec.
1221	5674	0.256087	08.998	10.40
	5687	0.392949	36.117	32.38
	5705	0.350964	08.460	36.72
1222	5679	0.497478	04.237	38.73
	5691	0.336880	55.227	25.09
	5715	0.165642	48.224	36.56
1223	5697	0.286171	24.636	00.38
	5679	0.320696	04.237	38.73
	5694	0.393133	39.655	52.93
1224	5664	0.262819	10.433	57.09
	5676	0.354851	57.376	17.43
	5699	0.382330	40.875	40.12
1225	6011	0.270543	05.134	54.36
	6014	0.511970	12.385	38.18
	6034	0.217487	12.361	28.23
1226	6004	0.347078	57.273	07.10
	6025	0.341808	23.780	23.96
	6029	0.311114	29.484	10.58
1227	6011	0.540823	05.133	54.36
	6013	0.123246	36.764	28.99
	6025	0.335932	23.780	23.96
1228	6004	0.254106	57.273	07.10
	6006	0.359634	33.705	41.06
	6034	0.386260	12.361	28.23
1229	5994	0.342739	40.805	34.76
	6003	0.241860	44.177	36.08
	6011	0.415401	05.133	54.36
1230	5993	0.414271	14.582	00.53
	5997	0.336764	59.600	33.04
	6022	0.248965	40.654	17.10
1231	5931	0.305555	31.907	00.29
	5950	0.387361	35.042	07.64
	5699	0.307084	25.624	32.54
1232	5682	0.327608	31.636	32.30
	5934	0.365249	37.744	17.84
	5964	0.307143	40.157	40.73
1233	5913	0.246367	35.774	30.14
	5933	0.252744	30.807	12.21
	5654	0.500890	05.717	51.53
1234	5911	0.284414	22.996	09.22
	5931	0.317582	31.909	00.29
	5657	0.398003	32.642	43.12
1235	5776	0.172080	42.917	02.99
	5819	0.366651	08.255	16.52
	5514	0.461269	28.624	42.48
1236	5796	0.473315	20.739	17.02
	5807	0.258468	51.991	05.85
	5523	0.268217	16.869	37.77
1237	5782	0.384250	06.887	11.15
	5794	0.356808	09.827	13.03
	5818	0.258942	53.302	13.16
1238	5777	0.338468	45.008	10.17
	5802	0.423202	14.325	57.33
	5804	0.238330	08.995	52.74
1239	5814	0.405016	29.637	15.39
	5818	0.384499	53.301	13.16
	5838	0.210485	39.148	56.05
1240	5803	0.378850	20.677	03.37
	5830	0.420119	28.881	22.45
	5842	0.201030	31.348	18.25
1241	7804	0.266903	05.061	29.00
	7830	0.280650	02.841	38.77
	7838	0.452447	05.930	17.74
1242	7814	0.345617	07.955	23.13
	7821	0.369068	36.601	41.66
	7833	0.285315	35.471	49.20
1243	8249	0.332852	27.176	55.67
	7804	0.263141	05.062	29.01
	7830	0.404007	02.842	38.76
1244	7795	0.257650	43.016	38.50
	7814	0.400221	07.955	23.13
	8275	0.342129	46.441	53.97
1245	9444	0.515235	58.564	10.20
	9451	0.147781	50.903	37.08
	9468	0.336984	49.267	44.01
1246	9436	0.364321	34.260	31.44
	9454	0.264214	07.143	46.64
	9471	0.371465	22.485	57.21
1247	9415	0.327888	36.241	45.82
	9417	0.281534	14.273	28.22
	9444	0.390578	58.564	10.20
1248	9406	0.269010	09.622	28.73
	9424	0.370749	11.631	05.38
	9454	0.360241	07.143	46.64
1249	5280	0.430951	56.359	16.09
	5316	0.291076	42.779	27.75
	5334	0.277973	06.363	03.38
1250	5291	0.429691	00.777	21.05
	5297	0.291204	59.989	26.41
	5333	0.279105	41.842	39.05
1251	3808	0.378975	40.531	28.85
	3822	0.233278	21.092	31.01
	3826	0.387747	39.697	55.74
1252	3802	0.286645	53.685	52.10
	3814	0.284182	15.956	16.79
	3828	0.429173	17.718	14.30
1253	9788	0.313737	44.815	25.93
	8649	0.543151	10.408	39.42
	8672	0.143111	00.766	18.44
1254	8637	0.380159	14.919	55.80
	8643	0.246570	12.618	10.32
	8662	0.373272	58.585	15.07
1255	9784	0.425062	18.715	44.86
	9838	0.306217	20.053	23.89
	9839	0.268721	24.696	59.41
1256	9805	0.418566	57.417	58.95
	9811	0.254179	34.874	15.27
	9837	0.327254	00.796	28.84
1257	9757	0.310700	32.806	44.62
	9796	0.332744	28.666	23.95
	15613	0.356556	00.456	54.14
1258	9746	0.305624	01.384	15.13
	9789	0.378347	56.267	11.82
	15642	0.316030	11.099	25.30
1259	15524	0.340410	13.121	40.43
	15554	0.418554	37.546	40.61
	15565	0.241036	18.631	34.77
1260	15517	0.333363	30.834	15.34
	15551	0.441954	16.901	57.20
	15582	0.224684	03.325	27.32
1261	15294	0.279101	23.639	41.80
	15310	0.282748	14.140	36.39
	15324	0.438151	56.341	43.68
1262	15282	0.309146	25.488	18.14
	15323	0.416170	48.484	23.80
	15329	0.274682	00.362	44.49
1263	15283	0.392727	24.771	05.75
	15295	0.300885	28.494	38.42
	15324	0.306388	56.341	43.68
1264	15280	0.404514	05.486	28.30
	15307	0.356510	53.749	25.34
	15321	0.238974	26.582	10.37

TABLE 2 - continued

No.	Star	Depend.	R.A.	Dec.
1265	15268	0.328349	59.951	36.54
	15277	0.297924	19.780	32.23
	15318	0.373728	06.967	36.05
1266	15266	0.378462	48.257	19.29
	15294	0.347844	23.639	41.80
	15307	0.273694	53.751	25.34
1267	15277	0.268155	19.781	32.24
	15297	0.319630	31.487	12.81
	15303	0.412215	20.394	59.15
1268	15272	0.213814	20.850	14.74
	15285	0.413152	10.979	24.43
	15317	0.373034	59.271	02.85
1269	5736	0.149379	19.422	40.16
	5746	0.331651	19.050	21.15
	5747	0.518970	22.224	31.65
1270	5733	0.301944	08.166	46.60
	5738	0.244954	40.518	54.43
	5757	0.453102	16.206	05.32
1271	5746	0.232700	19.050	21.15
	5777	0.351639	06.320	01.41
	7936	0.415660	40.796	16.48
1272	5745	0.348666	08.582	01.78
	5772	0.243914	24.437	17.05
	7953	0.407420	22.530	13.32
1273	7968	0.174508	54.148	34.08
	7999	0.446021	59.218	43.52
	5787	0.379470	16.908	23.95
1274	7983	0.339607	44.446	33.85
	8007	0.313930	45.592	16.89
	5786	0.346462	20.917	35.95
1275	5767	0.314566	55.762	04.16
	5773	0.365230	28.907	38.83
	5782	0.320204	59.012	59.85
1276	5762	0.377377	28.380	43.01
	5772	0.327787	24.438	17.04
	5783	0.294836	11.759	00.78
1277	7910	0.220930	48.050	01.38
	7915	0.300648	28.008	08.84
	7944	0.478422	54.555	14.67
1278	7919	0.511816	57.848	18.78
	7928	0.225830	08.353	40.21
	7942	0.262354	40.595	21.86
1279	7935	0.301184	24.288	30.47
	7949	0.394284	14.393	57.98
	8049	0.304532	42.791	49.33
1280	7941	0.476938	04.768	02.21
	7956	0.258261	47.918	51.83
	8047	0.264801	43.254	16.31
1281	7938	0.322768	40.248	08.83
	7943	0.404698	07.309	43.72
	7959	0.272534	02.658	45.90
1282	7935	0.351224	24.288	30.47
	7945	0.233548	24.182	36.86
	7956	0.415228	47.918	51.84
1283	7932	0.393526	13.078	39.89
	7956	0.402248	47.918	51.83
	7660	0.204226	09.319	45.78
1284	7925	0.279866	01.694	23.61
	7950	0.495554	27.307	48.33
	7973	0.224580	40.687	14.64
1285	7960	0.284943	09.318	45.78
	7980	0.432594	27.437	26.74
	7985	0.282464	31.425	42.04
1286	7969	0.354875	27.648	52.39
	7972	0.460471	33.956	52.72
	7990	0.184654	03.313	11.79
1287	7668	0.339304	52.321	24.31
	7672	0.329588	16.451	04.76
	7701	0.331108	21.535	48.08
1288	7674	0.275699	42.284	38.44
	7679	0.450783	30.017	31.19
	7691	0.273518	28.380	21.99
1289	7753	0.464338	11.992	13.36
	7766	0.271505	04.103	13.92
	7790	0.264156	25.540	07.03
1290	7754	0.378044	13.221	29.56
	7768	0.425004	13.068	29.83
	7792	0.196951	43.169	06.37
1291	7754	0.270002	13.221	29.56
	7800	0.279225	48.594	34.48
	7584	0.450773	48.225	25.28
1292	7753	0.407000	11.992	13.36
	7798	0.342236	41.421	47.33
	7802	0.250764	33.940	26.31
1293	7752	0.364122	49.431	38.65
	7758	0.235508	07.520	21.66
	7777	0.400370	35.082	27.69
1294	7750	0.291859	05.033	08.77
	7764	0.456279	01.159	33.12
	7779	0.251862	53.939	20.10
1295	7942	0.312754	47.339	36.94
	7950	0.431473	22.478	29.41
	7974	0.255773	21.546	26.11
1296	7934	0.114825	33.651	42.49
	7938	0.481098	11.409	39.70
	7980	0.404077	27.339	54.68
1297	7916	0.411218	42.477	06.01
	7933	0.253192	33.420	55.27
	7954	0.335589	40.415	06.07
1298	7935	0.299471	34.288	25.23
	7965	0.350328	54.650	09.34
	9003	0.350201	49.678	41.79
1299	7916	0.221620	42.477	06.01
	9028	0.588468	14.535	09.18
	7945	0.189912	32.133	07.02
1300	7902	0.369084	49.716	42.45
	7954	0.346345	40.415	06.07
	9029	0.284570	15.557	05.77
1301	9065	0.395552	20.537	46.52
	9078	0.300307	33.362	43.86
	9112	0.304141	30.100	00.57
1302	9070	0.380328	00.658	49.37
	9075	0.344818	43.320	59.23
	9115	0.274854	10.372	28.17
1303	9103	0.319440	07.067	47.55
	9112	0.441780	30.100	00.57
	9136	0.238780	03.667	43.85
1304	9090	0.304704	23.564	32.65
	9092	0.247018	56.160	41.68
	9142	0.448277	24.709	35.34
1305	9134	0.230340	49.679	12.05
	9136	0.555843	03.667	43.85
	9157	0.213817	15.564	47.01
1306	9115	0.306368	10.372	28.16
	9130	0.297437	29.125	43.83
	9159	0.396194	31.932	59.18
1307	9164	0.388656	19.441	09.50
	9171	0.399226	11.840	21.40
	9189	0.212118	24.922	47.30
1308	9157	0.378604	15.564	47.01
	9177	0.290950	19.179	58.04
	9192	0.330446	57.762	55.75

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The Geology of the Licking Hole Creek Area, near Walli, Central Western New South Wales

IAN G. PERCIVAL

ABSTRACT. In the Licking Hole Creek area, of central N.S.W., the Early-Middle? Ordovician Walli Andesite is overlain unconformably? by 363 m of Cliefden Caves Limestone. The latter, of probable Gisbornian-Eastonian age, includes a bedded Lower Member (consisting of big shell unit, and overlying thinly-bedded unit), a massive Middle Member, and an Upper Member (comprising the 'Island' unit, and overlying grey unit). Much of the limestone sequence is inferred to have been deposited in a shallow-water environment, at or somewhat below wave base. The conformably overlying Malongulli Formation contains graptolites of the *Dicranograptus hians* Zone at the base, and an assemblage of the *Pleurograptus linearis* Zone at the top. The Angullong Tuff (of Bolindian age) succeeds conformably, and is in turn overlain unconformably by Late Devonian clastics. The Ordovician succession is faulted, along the Columbine Mountain Fault, against the Early Silurian Millambri Formation. The latter is disconformably overlain by the late Llandovery Liscombe Pools Limestone. Intrusives mapped in the area include the Licking Hole Creek Diorite, and a quartz-porphyry neck. Another major fault, the Wonga Fault, extends obliquely across the area, merging with the Columbine Mountain Fault to the south-west.

INTRODUCTION

This paper presents the results of a study of the geology of an area of about 16 km^2 in the vicinity of Licking Hole Creek, near Walli, N.S.W. (Fig. 2). The area, adjoining that described by Ryall (1965), is situated on the east flank of the north-south trending tectonic unit known as the Molong High (Packham, 1969). The earliest investigations of a geological nature in the district were those of Wilkinson (1892) and Carne and Jones (1919). Stevens (1950; 1952; 1954; 1956) mapped and defined the main Palaeozoic formations, and Smith (1969) has investigated regional low-grade metamorphism of the volcanogenic rocks.

Studies of Ordovician faunas from the Licking Hole Creek area include descriptions of stromatoporoids (Webby, 1969), trilobites (Webby, 1971a), rugose corals (Webby, 1971b; 1972), tabulate corals (Webby and Semeniuk, 1971), nautiloids (Glenister, 1952) and graptolites (Sherrard, 1954; revised by Moors, 1970). Ross (1961) described a Silurian heliolitid from limestone in the western part of the area.

In the present study, particular emphasis is placed on the Ordovician and Silurian sedimentary sequence (Fig. 1) which occupies the majority of outcrop. The nomenclature of Pettijohn (1957) is employed for sedimentary rocks exclusive of the carbonate facies, which are classified on the basis of depositional texture as proposed by Dunham (1962).

Grid references (GR) throughout the text refer to Fig. 2, and are taken from the Canowindra 1:63,360 Military Sheet.

WALLI ANDESITE

The stratigraphically lowest formation in the area (Fig. 1) is the Walli Andesite, which Stevens (1952) considered to be conformably overlain by

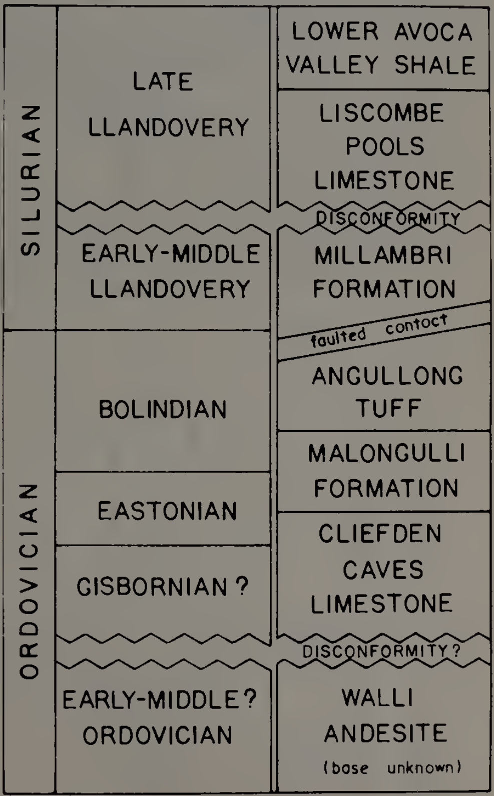
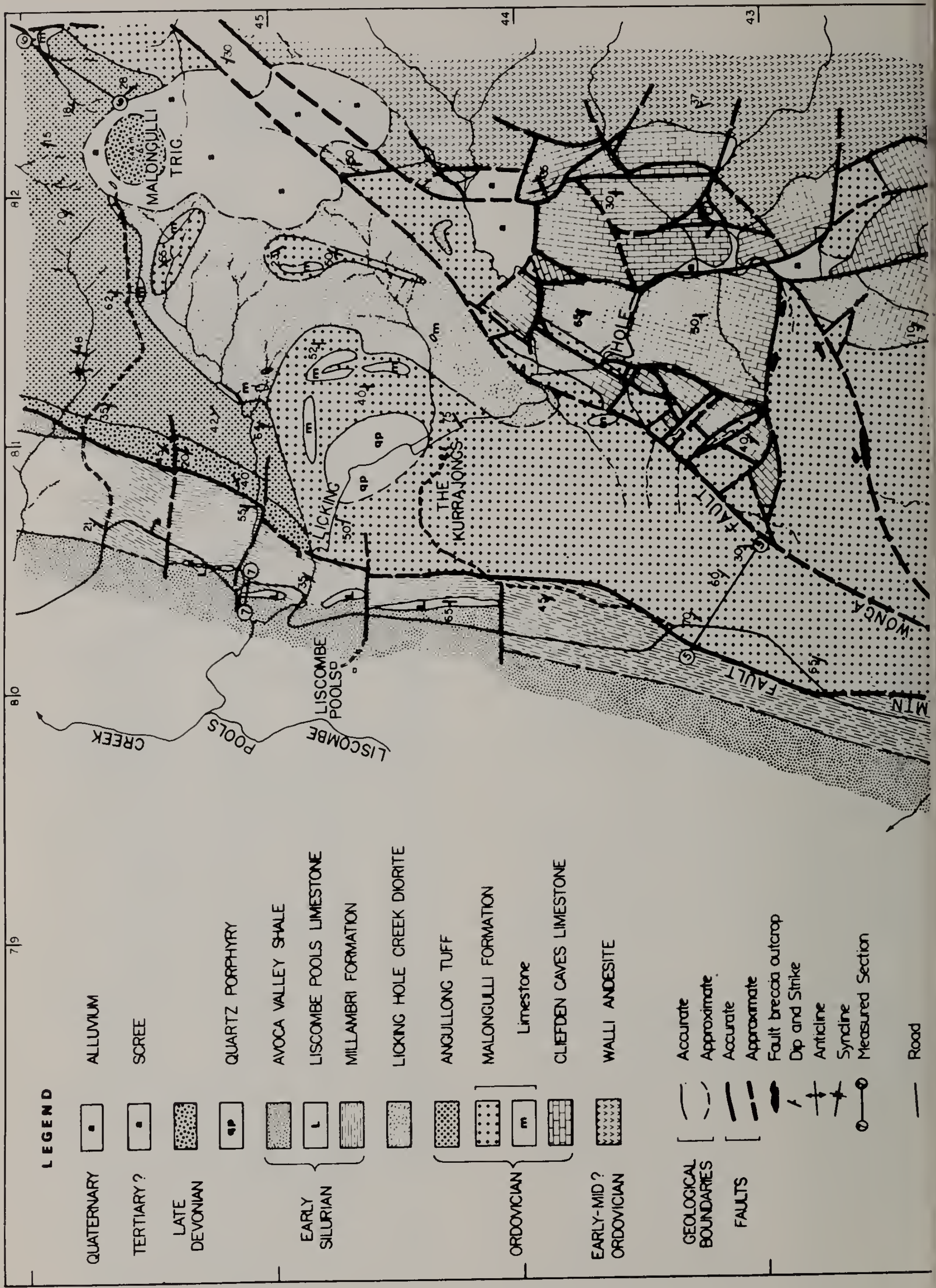


Fig. 1. Generalised stratigraphy, Licking Hole Creek area


LEGEND
QUATERNARY
ALLUVIUM
TERTIARY ?
SCREE
LATE DEVONIAN
QUARTZ PORPHYRY
EARLY SILURIAN
AVOCA VALLEY SHALE
LISCOMBE POOLS LIMESTONE
MILLAMBRI FORMATION
LICKING HOLE CREEK DIORITE
ORDOVICIAN
ANGULLONG TUFF
MALONGULLI FORMATION
Limestone
CLIEFDEN CAVES LIMESTONE
EARLY-MID ? ORDOVICIAN
WALLI ANDESITE
GEOLOGICAL BOUNDARIES
Accurate
Approximate
FAULTS
Accurate
Approximate
Fault breccia outcrop
Dip and Strike
Anticline
Syncline
Measured Section
Road
MALONGULLI TRIG.
LICKING HOLE FAULT
THE KURRAJONGS
LISCOMBE POOLS
LISCOMBE POOLS CREEK
WONGA MTN FAULT
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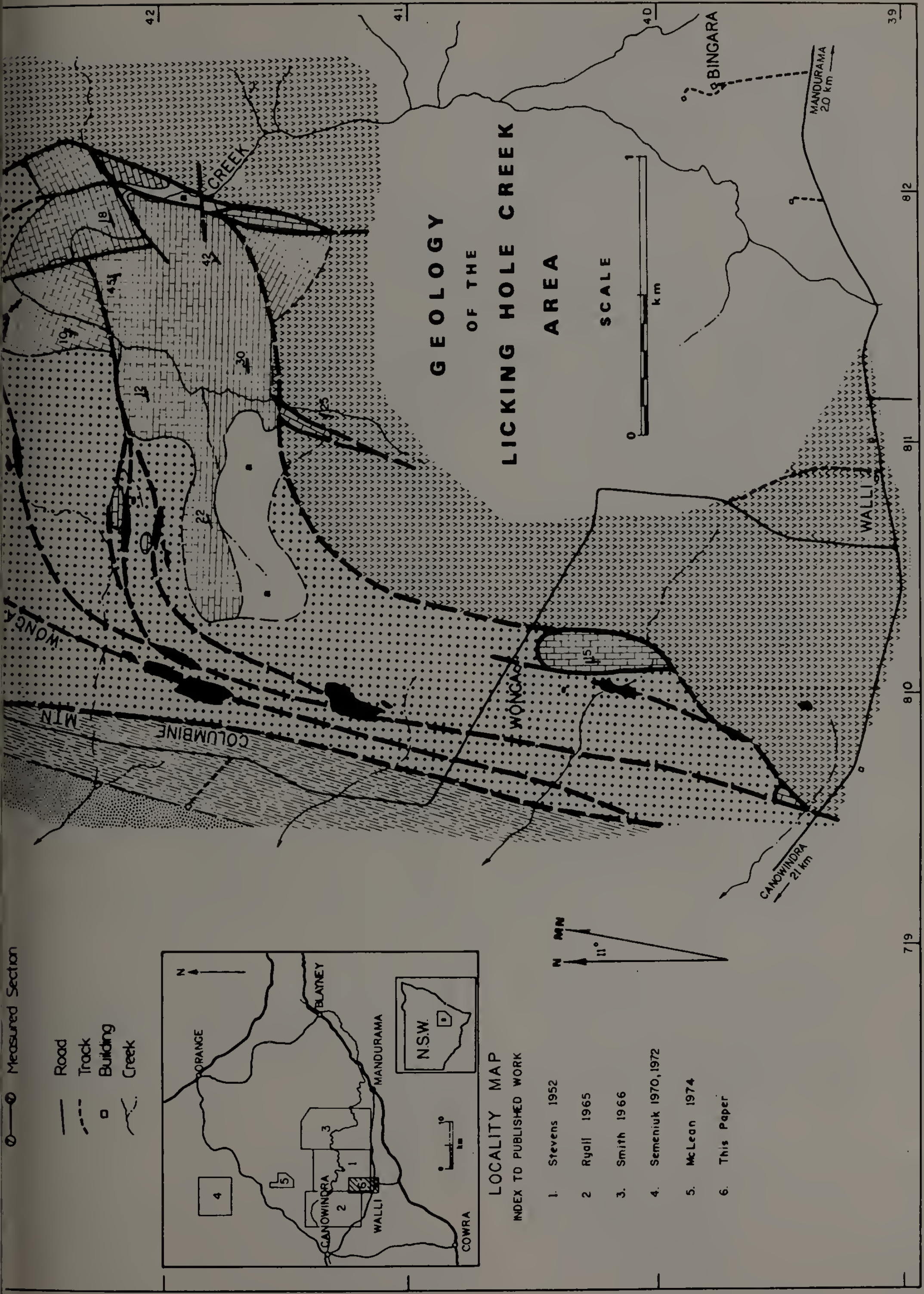

Fig. 2. Geology of the Licking Hole Creek area

the Cliefden Caves Limestone. Smith (1968), however, suggested either a disconformity or a faulted contact. In the Licking Hole Creek area, observed contacts between the two formations are either faulted (as around the southern margin of the main limestone outcrop, Fig. 2) or are of indeterminate nature. No internal palaeontological evidence for the age of the Walli Andesite is available, although Packham (1969) considered an Early-Middle? Ordovician age likely. A total probable thickness in excess of 1100 m is inferred by Smith (1966; 1967) to occur in the Davys Creek Anticline (east of Licking Hole Creek).

In the area studied, only the uppermost part of the Walli Andesite is exposed, consisting predominantly of porphyritic andesites, with minor basalt, volcanic breccias and crystal tuffs. Similar suites of volcanics have been described from the Cliefden Caves district by Stevens (1952), and Smith (1966; 1967; 1968). The andesites typically consist of 40-50% albitic plagioclase (about half of which occurs as phenocrysts), 10-20% augite phenocrysts, and minor amounts of chlorite, epidote, prehnite and pumpellyite. Subordinate rock types (tuffs and breccias) are interbedded with massive andesites in the upper part of the formation. The crystal tuffs are finely prophyritic to aphanitic, with albite laths forming at least half the rock; the remainder consists of quartz, epidote, chlorite, pumpellyite and opaques. The volcanic breccias contain fine to coarse angular lithic fragments (of crystal tuff, basalt and andesite) and phenocrysts, randomly dispersed through a groundmass of highly variable texture and composition. Basalt, several metres thick, overlies andesite at the top of the formation at GR 819340, although elsewhere in the area andesite directly underlies the Cliefden Caves Limestone. The basalt exhibits a pronounced trachytic texture, about 20% consisting of aligned plagioclase microlites; the interstices are occupied by opaques and chlorite.

The association of quartz, albite, chlorite, prehnite and pumpellyite in many of these lithologies is characteristic of Zone 3 of the burial metamorphic scheme proposed by Smith (1969).

CLIEFDEN CAVES LIMESTONE

Introduction

Stevens (1952) in naming the Cliefden Caves Limestone suggested that it could be divided into two or possibly three members in the vicinity of Cliefden Caves (east of the study area). In later detailed investigations, Webby (1969) and Webby and Semeniuk (1971) provided finer subdivision of the limestone into informal members and units characterised by distinct faunal associations and lithologies.

At Licking Hole Creek, the Cliefden Caves Limestone is about 363 m thick, and is informally divided into three members which correlate approximately with the three-fold division of the limestone at Cliefden Caves: a lower thinly bedded sequence, a middle massive unit, and an upper bedded member. The lower and upper members are each further divisible into two units. As at Cliefden Caves, these units are readily differentiated in the field on faunal and lithological characteristics. Although some facies differences are apparent between the two successions, the informal units used by Webby (1969) at Cliefden Caves have been applied where appropriate in the Licking Hole Creek area.

Tentative identifications of fossils and their occurrences through the limestone are presented in Table 1. Distribution of coral-stromatoporoid faunas (Webby, 1969) indicates that the Lower Member and lower portion of the Middle Member (below the 'E horizon') are of Fauna I age; the remainder of the Middle Member, and the Upper Member, are of Fauna II age.

Lower Member

The Lower Member consists of a predominantly thin-bedded sequence of interbedded lime mudstones, wackestones, and minor packstones and grainstones, of about 88 m thickness. The member and its subdivisions - big shell unit and overlying thinly bedded unit - are defined on the basis of measured sections 1 and 2 (Fig. 4). The contact between these two units is apparently conformable. Outcrop of the Lower Member is confined to discontinuous, broadly folded belts on the north-eastern and southern margins of the main limestone body (Fig. 3). In fossil content, lithological sequence, and field appearance, the Lower Member bears considerable similarity to the Ashton Member (McLean, 1974) of the Regans Creek Limestone to the north (Fig. 2).

Big shell unit

Shell banks (2.5-5 m thick), composed of the large inarticulate brachiopod cf. *Eodinobolus*, interbedded with yellow-brown lime mudstones and wackestones, characterise this unit. A total thickness of 43 m, measured in section 1 (Fig. 4) is approximate due to incomplete exposure of the shaly to rubbly basal beds. Up section outcrop is more continuous, though usually with low topographic relief. Only the upper beds occur in section 2 (due to faulting), but the unit here appears to be slightly more silt rich, with reduced development of shell banks compared to section 1 (Fig. 4). Thicknesses of individual beds range from 50 mm to 0.3 m.

Slightly over half the big shell unit consists of skeletal wackestone; lime mudstone (25%) is the other principal lithology, with grainstones and siltstones contributing about 15-20% of the total thickness. Lime mudstones are most common in the lower half of the unit. Fine-grained skeletal remains (of bryozoa, corals, trilobites, ostracodes, and brachiopods) form up to 10% of these mudstones, the matrix of which is dominated by yellow-brown terrigenous silt. In some mudstones ostracodes and brachiopods are often preserved articulated, while in other cases the sediment is extensively bioturbated and skeletal remains are fragmented.

Skeletal wackestones are interbedded with thin lime mudstones and poorly exposed siltstones above the initial mudstone sequence, and dominate the remainder of the unit. Pisolites and algal coatings on skeletal remains are rare to absent in these wackestones (cf. thinly bedded unit). The

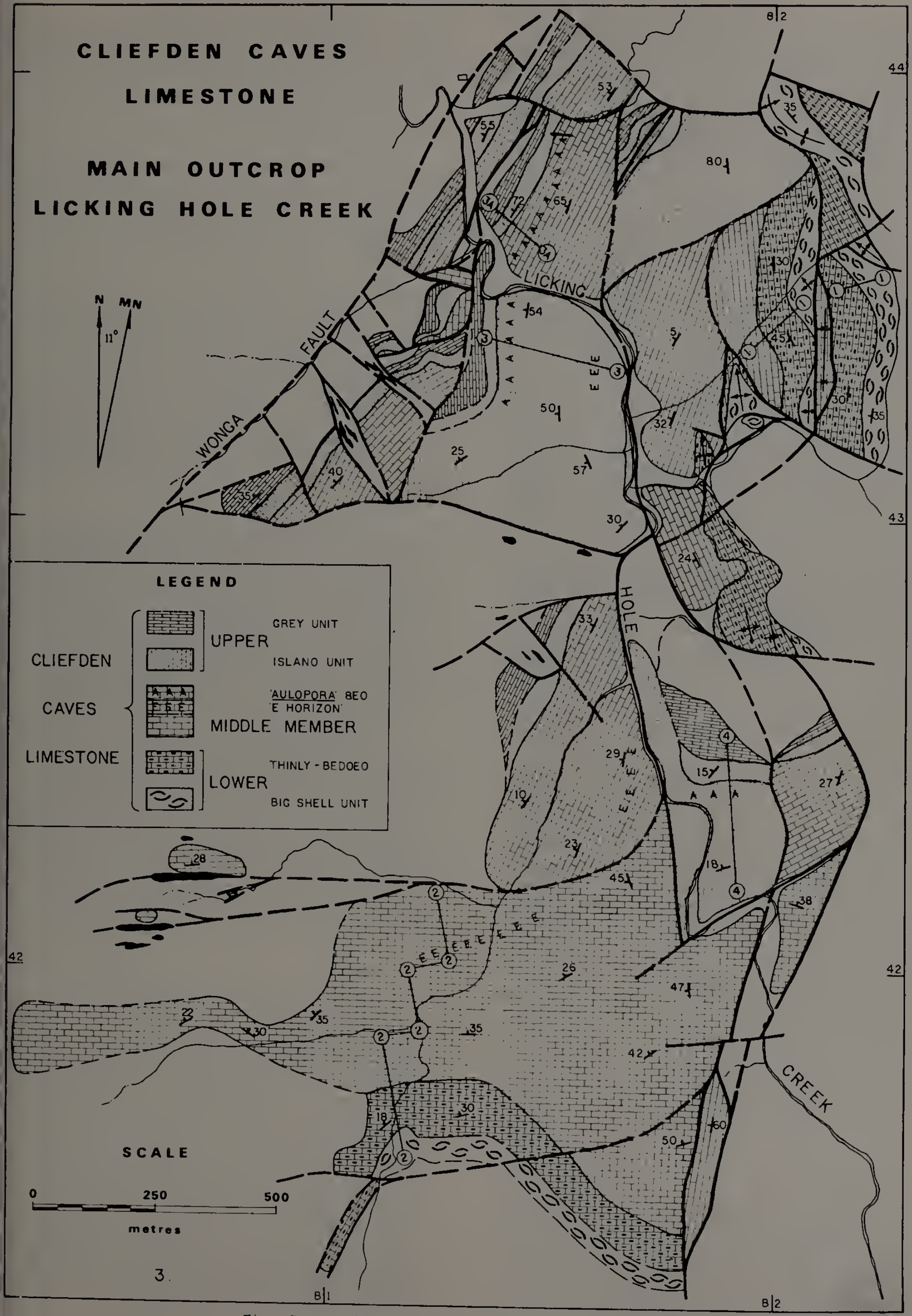

Fig. 3. Main Cliefden Caves Limestone outcrop

wackestones contain two distinct faunal associations: (i) cf. *Eodinobolus-Tetradium* - gastropod wackestones, and (ii) coral-stromatoporoid wackestones. In the former (which constitute the shell banks previously mentioned), little or no disturbance of the sediment by wave or current activity is indicated by the lack of fragmentation of the fossils and the frequent occurrence of conjoined cf. *Eodinobolus*. Often the uppermost part of each shell bank exhibits evidence of reworking, either by intensification of water turbulence (indicated by decrease in mud content with proportionate increase in fine fragmental skeletal debris, forming cf. *Eodinobolus-Tetradium* - gastropod packstones), or as a result of a probable combination of infaunal burrowing and water movement to produce bioturbated wackestones (containing disarticulated cf. *Eodinobolus* valves associated with *Vermiporella* and pelletal carbonate grains). In both sections 1 and 2 (Fig. 4), bioturbation is more extensive in the higher shell banks than in those lower in the unit. Diagenetic effects are more marked in the cf. *Eodinobolus-Tetradium* - gastropod wackestones than in other lithologies, and include leaching and recrystallization of skeletons by sparry calcite, enlargement and subsequent recrystallization of fossil moulds, and formation of geopetal structures (Semeniuk, 1971).

Coral-stromatoporoid wackestones are best developed overlying the lowest shell bed exposed in section 1 (the 'lower coral zone' of Webby, 1969), but similar sediments are associated with shell banks throughout the unit. The faunal assemblage is dominated by the tabulate corals *Coccoseris*, *Eofletcheria* and *Tetradium*, and stromatoporoids *Labechiella* and *Cystistroma*, preserved in growth position in a yellow-brown lime mud matrix.

Skeletal and lithoclastic grainstones, apparently formed in a turbulent, possibly nearshore, environment, overlie wackestones of the 'lower coral zone'. Skeletal grainstones contain fragmented and abraded trilobite, brachiopod, molluscan, and bryozoan debris of coarse sand to fine gravel size in a calcite cement. Lithoclastic grainstones are composed of angular lithoclasts of volcanic rocks, intraclasts of lime mudstone, skeletal fragments, and remanié fossil debris of coarse sand size. A 2 m thick accumulation of fine-grained pelletal grainstone, forming a prominent red-veined bed between shell banks in the upper part of section 1, may represent a high-energy sand concentration. This sand body is possibly lenticular as it does not occur in other exposures within the unit. A thin bed of terrigenous siltstone (containing sparse disarticulated lingulid brachiopods) is poorly exposed at the very top of the big shell unit in section 1.

Thinly bedded unit

This unit, 45 m thick, contains several thin cf. *Eodinobolus* horizons interbedded with grey, frequently burrowed limestones exhibiting varying degrees of silicification, and containing scattered chert nodules. Interbedded skeletal wackestones (comprising 50-60% of the unit) and lime mudstones (approximately 20% of unit), with minor skeletal grainstones (about 10%), occur in the lower and middle beds. Wackestones and lime mudstones are interbedded with pisolitic pelletal-skeletal packstones (10-20% of unit) in the upper part (Fig. 4). Individual beds (average thickness 0.1-0.5 m) are of more prominent outcrop than those in the underlying unit.

The lime mudstones are burrowed and contain sparse skeletal debris (brachiopods, ostracodes, gastropods, pelmatozoans). The yellow-brown terrigenous silt component, characteristic of big shell unit mudstones, is conspicuously absent from the dark-grey thinly bedded unit sediments.

Grey skeletal wackestones, similar to the cf. *Eodinobolus-Tetradium* - gastropod wackestones of the big shell unit but devoid of terrigenous silt, form thin shell beds in sections 1 and 2 (Fig. 4). These beds have been gently reworked in part (probably by burrowing activity, producing *Chondrites* burrows), resulting in the stacking of disarticulated, but unbroken, shells on each other. Other wackestones (which are also frequently bioturbated) are dominated by associations of (i) algae, gastropods and brachiopods, (ii) pelmatozoans and sponges, or (iii) intraclasts and skeletal remains.

A widespread horizon of pelletal-skeletal wackestones, containing *Girvanella* pisolites, faecal and accretionary pellets, lithoclasts, trilobite and brachiopod (*Sowerbyites*) skeletons, is found about 2-3 m below the top of the thinly bedded unit. *Sowerbyites* and *Girvanella* do not recur together in the limestone sequence until the level of the 'Island' unit some 200 m higher stratigraphically (although *Girvanella* ranges through the lower few metres of the Middle Member).

Irregular blocky chert nodules, 50-150 mm long and wide, occur sporadically throughout the unit, but are most common in skeletal wackestones. They are usually found on bedding surfaces where they are observed to replace tabulate corals, especially *Tetradium cribriforme* (Etheridge), and labechiid stromatoporoids. In thin section the chert nodules consist of orange-coloured translucent cryptocrystalline silica with minute dolomite rhombs suspended within. The means of formation of the nodules and their environment of development is unknown.

Middle Member

Overlying the thinly bedded unit with apparent conformity is the Middle Member, a thick accumulation of massive grey limestone (commonly exhibiting moderate silicification and development of chert nodules) with infrequent thin interbedded fossiliferous marls. The predominant lithology (75-80% of the member) is burrowed skeletal or pelletal wackestone; mudstone, packstone and grainstone comprise not more than 10% each of the total thickness. No internal subdivision is proposed for this member, although several horizons characterised by a particular fossil and lithological association can be recognised, enabling correlation between sections. A composite maximum thickness of 225 m was obtained in sections 2 and 3 (Fig. 4) using a datum, named the 'E horizon' for correlation. This contains a distinctive association of cf. *Eodinobolus*, *Ecclimadictyon* and cf.

Eofletcheria. In section 2, 94 m of massive limestone lies beneath this level; in section 3, 131 m of massive and thin-bedded limestone occurs above it. Corals and stromatoporoids diagnostic of Fauna 1 (Webby, 1969) are found beneath the 'E horizon', at which level the first clathrodictyids (represented by *Ecclimadictyon nestori* Webby) appear in the sequence, defining the commencement of Fauna 11 (Table 1).

The Middle Member occupies the largest area of outcrop in the limestone sequence; it is well-exposed in a broad belt extending from near Malongulli Trig, south-west to the Canowindra-Mandurama road (Fig. 2). Most of the massive limestone consists of wackestone, including the following varieties: pisolitic-pelletal (at base), pisolitic-skeletal, algal (dasycladacean), algal-skeletal, cf. *Eodinobolus*-coral-stromatoporoid, spicular, skeletal, and pelletal wackestones. Many of these lithologies display evidence of extensive infaunal burrowing activity. Fine to medium sand-size pellets, with a subangular to ovoid outline are particularly common in the wackestones.

Algae in the stratigraphically lowest wackestones form pisolitic nodules (composed of twisted tubules of *Girvanella*) and encrusting coatings on skeletal debris. Another group of algae - the dasycladaceans, represented mainly by *Vermiporella*- predominate in higher wackestones, but are conspicuously uncommon to absent in beds containing algal pisolites. Dasycladacean algae are most prolific in wackestones and packstones with a high pelletal content, and comprise up to 50% of some algal wackestones in the member. Upon death and disintegration, these algae probably contributed considerable quantities of carbonate mud to the sediment (Semeniuk, 1973). Semeniuk and Byrnes (1971) suggested that abundant *Vermiporella* flourished in a deeper water environment, offshore to the cf. *Eodinobolus* shell banks at Bowan Park. Certainly in the study area, whole *Vermiporella* does not occur in cf. *Eodinobolus* wackestones, although minor amounts of fragmentary, reworked dasycladacean algae are found in this lithology (presumably introduced from offshore).

Skeletal wackestones contain complete to fragmentary remains of, in order of decreasing abundance, brachiopods, trilobites, corals, bryozoa, echinoderms, and small gastropods. Wackestones containing cf. *Eodinobolus* are interpreted as representing *in situ* assemblages, as little or no reworking of these brachiopods has taken place. Such lithologies are developed only near the middle of the member (in the 'E horizon' and adjacent beds). This association of leached cf. *Eodinobolus* with rare *Tetradium* and gastropods in a grey lime mud matrix is analogous to shell bed wackestones previously described from the Lower Member. Significantly, the 'E horizon' faunal assemblage contains both an inferred inshore genus (cf. *Eodinobolus*) and the first appearance of a diagnostic Fauna 11 element (*Ecclimadictyon*). This suggests tentative correlation of the 'E horizon' with the base of the Davies Plains Limestone Member at Bowan Park, as at this level, Semeniuk (1972, 1973) recognised a major disconformity, above which Fauna 11 also commences.

With increase in pelletal content and decrease in proportion of mud matrix, together with reworking and abrading of the skeletal debris, the skeletal wackestones grade into cf. *Eodinobolus*-coral-stromatoporoid packstones and grainstones. Thin to thick beds of these coarser-grained sediments occur interbedded with massive wackestones in the upper part of the member. Near the top of section 3 (Fig. 4), at a level equivalent to the '*Aulopora*' unit of Webby and Semeniuk (1971) at Cliefden Caves, a coquina is developed which contains abundant closely stacked disarticulated valves of cf. *Eodinobolus*, in a coarse pelletal grainstone. Other textural indications of near-shore deposition (lithoclasts, remanié fossil grains, pronounced sorting and abrasion of skeletal constituents, scarcity or absence of mud) are exhibited by the packstones and grainstones in these upper beds. In section 3A (Fig. 4), massive pelletal grainstones (containing remanié fossil debris) of the Middle Member are overlain by thin-bedded pelletal grainstones, also with remanié fossils, of the 'Island' unit (Upper Member); the contact between the members is abrupt and traceable for many metres away from section. The top of the Middle Member is irregular, and thickness variations (to the extent of several metres) in the Upper Member are probably due to deposition on an erosional surface. In section 4 (Fig. 4), the boundary between the members is more gradational over 1-2 m of lithoclast-pelletal grainstone containing a tabulate coral breccia. Field evidence therefore suggests a probable disconformity in one area and sedimentation in a shallow turbulent water environment in another at about the same horizon.

Upper Member

The lower 20 m (the 'Island' unit) of the 50 m thick Upper Member consists of thin-bedded, richly fossiliferous brown limestone. Massive grey limestone, comprising the grey unit, forms the upper 30 m of the member. This facies is widely distributed in the region of the Molong High; a similar sequence occurs to the east at Cliefden Caves, and analogous strata are recognised as the Quondong Formation and basal Ballingoole Limestone at Bowan Park (Semeniuk, 1970; 1972), and as units 3 and 4 of the Checkers Member, Regans Creek Limestone (McLean, 1974).

At Licking Hole Creek, the Upper Member crops out in a series of folded and faulted blocks striking approximately north-easterly on the western margin of the main limestone exposure (Fig. 3). Strike faulting here has resulted in some parallel repetition of the sequence. An outcrop of the Upper Member, east of Licking Hole Creek, strikes across the trend of the main limestone belt. The sequence here (section 4 in Fig. 4) is slightly thinner than that to the west (section 3A), and is composed of a relatively higher proportion of coarser grained limestone. In the latter section excellent exposure of the 'Island' unit enables differentiation into lower sparsely silicified beds 13 m thick, and upper silicified more fossiliferous beds 7 m thick. Lower and upper beds could not be readily distinguished in other sections. The boundary between the 'Island' and grey units is entirely conformable with a vertical lithological change, over some 2 m, from thin-bedded abundantly fossiliferous brown limestone into massive

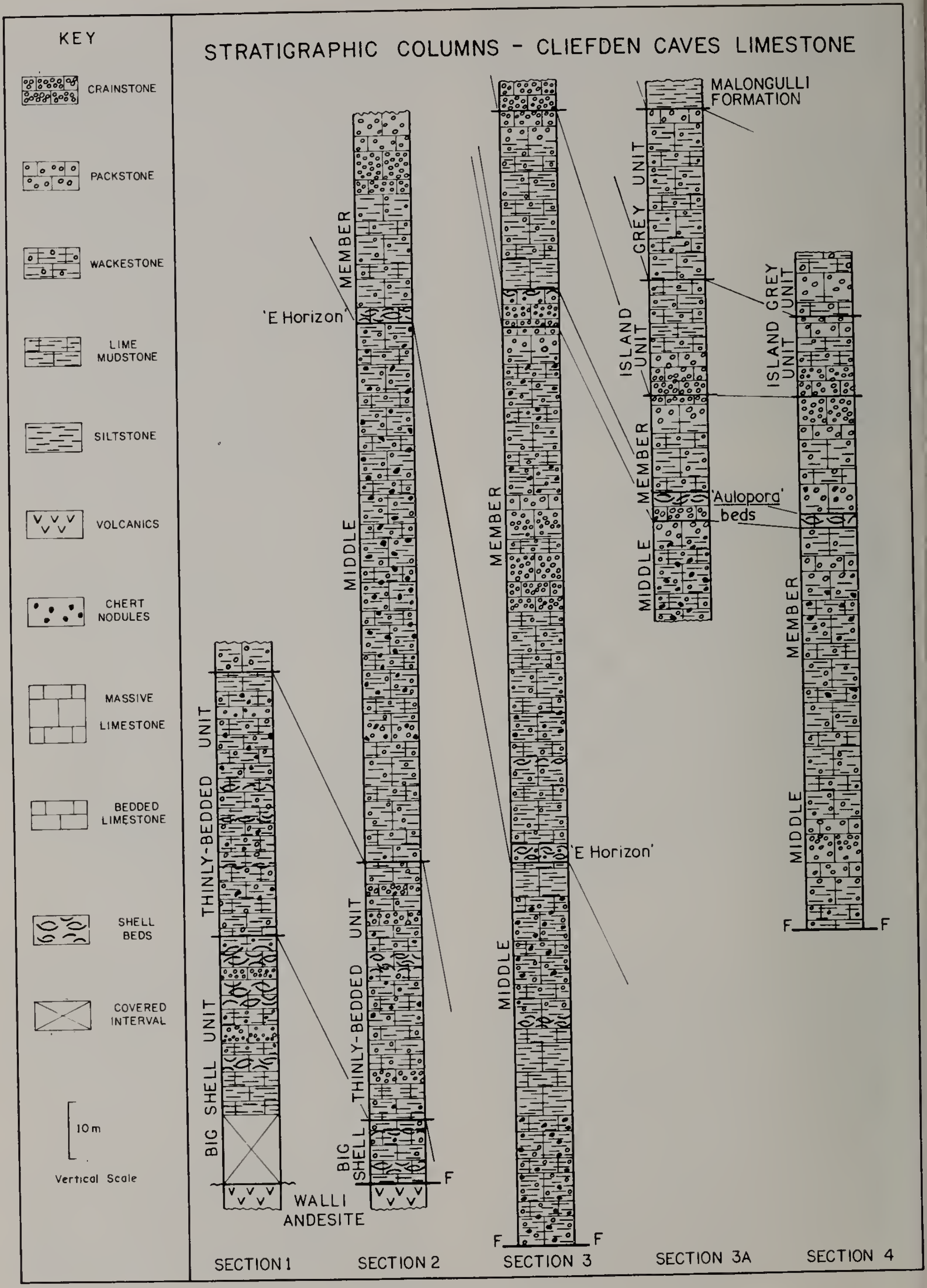

Fig. 4. Stratigraphic columns, Cliefden Caves Limestone

sparsely fossiliferous grey limestone.

'Island' unit

The main lithologies developed in this unit (the most fossiliferous in the limestone sequence) include pisolitic and skeletal wackestones (forming about half the sediments), pelletal packstones (about 30%), pelletal grainstone (10%) and lime mudstone (10%). The lower beds of the unit in section 3A consist of a gradational, upward-fining sequence from pelletal grainstone at the base, through pelletal packstone, pisolitic-skeletal wackestone, to lime mudstone. The upper, more fossiliferous, beds are predominantly pisolitic and skeletal wackestones, with minor interbedded skeletal packstones and grainstones. Bedding ranges from 50 mm to 0.3 m in thickness. A broadly similar sequence of lithologies occurs in section 4 (Fig. 4).

Pelletal grainstones at the base of the unit consist of fragmented skeletal debris of coarse sand to gravel size, with abundant remanié fossil grains (including *Vermiporella*, and shelly fragments, coated with iron-stained cryptocrystalline rinds) forming about 40% of the rock. Other constituents, each comprising about 10-20% of the sediment, include algal pisolites, lithoclasts of iron-stained lime mudstone, and complete to fragmentary brachiopods, bryozoa, corals, and echinoderm ossicles. The overlying pelletal packstone beds contain sand-sized accreted calcite grains, occasionally with skeletal nuclei (echinoderms, *Vermiporella*), in a matrix of lime mud forming about 20% of the rock. Up section, the packstones become finer-grained and show evidence of bioturbation.

Wackestones from both the lower and upper beds contain similar proportions (20-30%) of coarse sand size skeletal fragments (mainly cryptostome bryozoa, brachiopods, trilobites, tabulate corals, with few echinoderms). Larger skeletons are often thickly encrusted by algae, and pisolitic nodules comprise 10-15% of some wackestones. Brown lime mud occupies the remainder of the wackestones. Bioturbated lime mudstone, containing very fine skeletal debris, overlies the upward fining sequence in the middle of the unit.

A further, possibly palaeoenvironmental distinction between the 'Island' unit exposures in sections 3A and 4 is suggested by marked differences in faunal content (especially with regard to brachiopod distribution). The latter section contains an assemblage dominated by strophomenids, including *Sowerbyites*, cf. *Holtedahlina*, *Furcitella*, *Trigrammaria*, and cf. *Leptellina*. Glyptorthids (*Ptychopleurella* and *Eridorthis*) dominate the brachiopod content of the unit in section 3A.

Grey unit

Shelly macrofossils are rare throughout this unit, but dasycladacean algal remains are abundant in the packstones and wackestones of the lower beds, which contain up to 70% *Vermiporella* and *Dasyporella*, 20% lime mud matrix, with the remainder consisting of fine echinoderm debris. Bedding at the base of the unit is 0.3-1 m thick, but rapidly becomes massive up section, where wackestones dominate, comprising the majority of the grey unit. They contain *Vermiporella* (10-15% of sediment) and sponge spicules (5%) in a dark-grey lime mud. There is little or no evidence of burrowing activity in these lithologies. The massive limestone of the grey unit is of similar field appearance to the dominant lithology of the Middle Member, in its prominent outcrop; however, grey unit limestones are rarely silicified and lack the chert nodules present in the Middle Member wackestones.

MALONGULLI FORMATION

The Malongulli Formation (Stevens, 1952) is now restricted (Webby, 1973) to the 'calcareous facies' of Stevens (1956), exposed in the Cliefden Caves and Licking Hole Creek districts, because the 'siltstone-arenite facies' of the 'Malongulli Formation' in the Junction Reefs area (Stevens, 1956; Smith, 1966) constitutes "a distinct, older, Darriwillian-Gisbornian unit" (Webby, 1973, p.446). In the area studied, the Malongulli Formation occurs predominantly in a north-north-easterly trending belt, bounded to the east by the Cliefden Caves Limestone, and faulted along its western margin against the Silurian Millambri Formation (Fig. 2). North-east of Malongulli Trig, interbedded black impure limestones and siliceous siltstones of the Malongulli Formation conformably overlie massive limestones of the grey unit (Cliefden Caves Limestone).

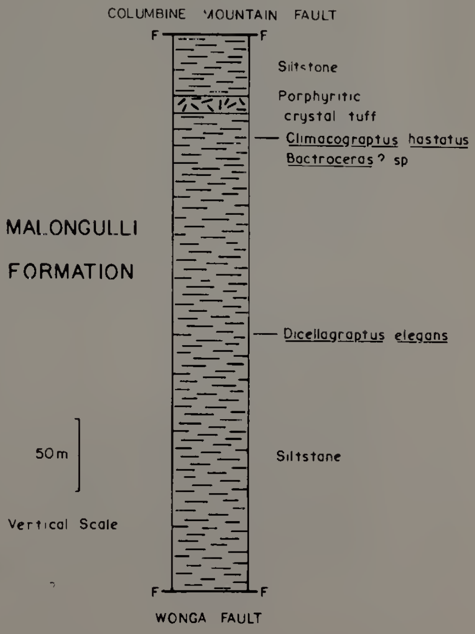

Fig. 5. Stratigraphic section 5, Malongulli Formation

TABLE 1

DISTRIBUTION OF ORDOVICIAN FAUNA AND FLORA IN THE CLIEFDEN CAVES LIMESTONE, LICKING HOLE CREEK

X = positive identification
? = questionable determination

	LOWER MEMBER		MIDDLE MEMBER		UPPER MEMBER	
	Big Shell Unit	Thinly Bedded Unit	Below E Horizon	Above E Horizon	Island Unit	Grey Unit
	1	2	3	4	5	6
ALGAE						
Vermiporella sp.	X	X	X	X	X	X
Dasyporella sp.				X		X
Girvanella sp.	X	X	X		X	
Solenopora sp.	X	X				
Hedstroemia sp.	X		X	?		
CORALS						
Tetradium cruciforme	?			?		
T. duplex	X	X				
T. cribriforme	X			X	X	
T. cf. *bowanense*				X		
T. sp. B Webby & Semeniuk				X		
T. sp.	X	X				
Eofletcheria gracilis	X					
cf. *Eofletcheria* sp.				X	X	
Aulopora sp.				X	X	
Nyctopora stevensi	X		?			
Coccoseris speleana	X		?		?	
Propora mammifera		X	X	X		
P. sp.	X	X		X	X	
Heliolites digitalis					X	
H. sp.		X	X	X	X	X
Hillophyllum priscum	X		X		X	
Hillophyllum sp.				X	X	
Palaeophyllum proliferum					X	X
STROMATOPOROIDS						
Labechiella regularis	X	X	X	X		
Cystistroma donnelli	X		?			
Stratodictyon ozakii	X	X				
Labechia variabilis				X		
Cystostroma cliefdenense				X		
Pseudostylodictyon inequale				X		
Ecclimadictyon nestori				X	?	
Clathrodictyon aff. *mammillatum*				X		
C. cf. *microundulatum*				X		
Cliefdenella etheridgei					X	
Alleynodictyon nicholsoni		X				

TABLE 1 (continued)

	1	2	3	4	5	6
BRYOZOANS						
Stictopora belubulensis	X					
S. sp.	X	X			X	
Homotrypa fenestrata	X					
Ulrichostylus sp.			?			
Prasopora sp.					X	
BRACHIOPODS						
cf. *Eodinobolus* sp.	X	X	X	X		
Obolus sp.	?					
Dinorthis sp.	?				?	
cf. *Doleroides* sp.		?	X	X	X	
Hesperorthis sp.			X		X	
Plectorthis sp.			X			
Ptychopleurella sp.			X	X	X	
Eridorthis sp.				X	X	
cf. *Leptellina* sp.		X			X	
cf. *Anoptambonites* sp.		X	X	X		
Sowerbyites sp. nov. a		X			X	
S. sp. nov. b					X	
sowerbyellid gen. nov.					X	
Christiania sp.					X	
Oepikina sp.		X				
Trigrammaria sp.					X	
Furcitella sp.					X	
cf. *Holtedahlina* sp.					X	
Bellimurina sp.					?	
Rhynchotrema sp.	X	X	X	X	X	
Hallina sp.		X		X	X	
Protozyga sp.		X	X			
cf. *Zygospira* sp.					X	
atrypid gen. nov.			X	X	X	
ARTHROPODS						
Pliomerina prima	X					
P. austrina					X	
harpid indet.					X	
ostracodes indet.	X	X				
MOLLUSCANS						
Loxoplocus (Lophospira) sp.	X	X	X	?	X	
Trochonema sp.		X				
Hormotoma sp.		X		X		
Maclurites sp.					X	
Gorbyoceras sp.					X	
MISCELLANEOUS						
sponge spicules		X	X			X
echinoderm ossicles	X	X	X	X	X	X
Chondrites		X	X			

Lack of continuous exposure and suitable marker beds prevented estimation of the total thickness of the Malongulli Formation in the area. The most complete section (section 5; Fig. 5) consists of about 380 m of siliceous siltstones, but is faulted at both its top and bottom. Discontinuity of outcrop also hinders description of superposition of component lithologies of the formation, but in general the sequence is as follows. The basal beds are graptolitic siliceous and calcareous siltstones. Siliceous siltstones and marls comprise most of the middle part, with minor interbedded limestone conglomerate (near the base, and in the middle to upper part of the formation), feldspathic greywackes and porphyritic tuff. In the upper beds, feldspathic greywackes are interbedded with marls, infrequent limestone, and limestone conglomerates. At the top of the formation (Fig. 6), siltstone and limestone conglomerate overlie graptolitic siltstones and shales. Marls and siltstones form an estimated 60-70% of the Malongulli Formation, with greywackes comprising about 20%; limestones and limestone conglomerates constitute most of the remainder.

The thin to medium-bedded marls and siltstones have a cherty appearance and conchoidal fracture. In general they are finely laminated, with graded bedding from medium to very fine grainsize. The detrital component (10-50% of these sediments) includes sponge spicules and quartz grains, with subordinate albite, epidote, prehnite and pumpellyite, in a carbonate-mud matrix. A porous fissile spiculite results from preferential leaching of the carbonate.

The feldspathic greywackes are medium bedded, generally fine-medium grained, and exhibit graded bedding from medium to very fine grainsize. Mineralogically the greywackes are variable, although most contain a significant percentage (35-80%) of angular quartz detritus, together with albite (10-30%) and minor hornblende, calcite, chlorite, biotite, epidote, prehnite and pumpellyite. Greywackes from the middle of the formation contain very little quartz however, the majority of the grains consisting of albite and augite in the ratio 2 : 1 (indicating probably an andesitic or doleritic provenance). All the greywackes contain a high proportion (30-50%) of matrix. Sorting varies from poor to fair texturally and mineralogically; all are markedly immature in regard to grain shape and composition, and appear to have been products of rapid deposition (probably resulting from turbidity currents).

Rectangular blocks of limestone up to 0.3 m by 1 m, randomly dispersed in a groundmass of subangular limestone fragments, form distinctive limestone conglomerates which probably represent slump deposits. These conglomerates are believed to be virtually contemporaneous with the shales in which they occur (Webby, 1975, p.61).

Porphyritic crystal tuff (in section 5; Fig. 5) contains a coarse-grained euhedral tabular mineral, pseudomorphed by chlorite and prehnite, forming nearly half the rock, the remainder of which consists of calcite (about 35%), quartz, albite, opaques, and lithic fragments.

The widespread distribution of colourless pumpellyite in the Malongulli Formation indicates that these rocks have undergone burial metamorphism, with the development of a Zone 3 mineral assemblage (Smith, 1969).

Fauna and Age Implications

Moors' (1970) revision of the age of the Malongulli Formation as Eastonian has been essentially confirmed in the present study; however, the discovery of a *Pleurograptus linearis* Zone fauna slightly below the base of the Angullong Tuff extends the age of the Malongulli Formation from late Eastonian into the early Bolindian.

The association of *Climacograptus missilus* Keble and Harris, and *C. hastatus* Hall (variety 2 of Berry, 1966) in the lower two-thirds of the formation indicates an age equivalent to the *Dicranograptus hians* Zone (late Eastonian) in Victoria. This age determination is reinforced by the occurrence in the same beds of *Climacograptus caudatus* Lapworth, *C. bicornis* (Hall), *Orthograptus amplexicaulis intermedius* Elles and Wood and *O. calcaratus vulgatus* Lapworth, which in Britain occur together in Zone 12 (*Dicranograptus clingani* Zone) strata of late Caradoc age. Other graptolites identified from the lower part of the formation include *Orthograptus apiculatus* (Elles and Wood), *O. calcaratus* (Lapworth)?, *O. quadrimucronatus* (Hall)?, *O. amplexicaulis pauperatus* Elles and Wood, *Climacograptus tubuliferus* Lapworth, *C. fusiformis* Moors, *Glyptograptus* cf. *tenuissimus* Ross and Berry, *Dicellograptus forchammeri* (Geinitz) and *D. elegans* Carruthers. The fauna from the uppermost beds includes *Climacograptus uncinatus* Keble and Harris, and *Leptograptus eastonensis* Keble and Harris, denoting an age not older than Zone 13 (*Pleurograptus linearis* Zone), equivalent to early Bolindian in the Victorian succession. This is believed to be the first record of the occurrence of *C. uncinatus* in New South Wales. Elsewhere this species is restricted entirely to Bolindian or equivalent strata, occurring with *P. linearis* in both Victoria (Harris and Thomas, 1954), and Idaho U.S.A. (Carter 1972). The uppermost beds also contain *Orthograptus amplexicaulis* (Hall), *O. amplexicaulis* cf. *pauperatus*, *O. calcaratus basilicus* Lapworth, *O.* cf *quadrimucronatus*, *Climacograptus tubuliferus*, *C. missilis* Keble and Harris, *Dicellograptus* cf. *pumilus* Lapworth and *D.* cf. *morrisi* Hopkinson. This assemblage indicates approximate age equivalence to Zones 12-13 in the British sequence.

Associated with graptolites at the base of the formation, at an horizon approximately correlative with that at Trilobite Hill near Cliefden Caves, occur the following: brachiopods *Pseudolingula* sp. and a sowerbyellid, and trilobites *Remopleurides exallos* Webby, *Malongullia oepiki* Webby Moors and McLean and *Encrinuraspis* sp. Limestone conglomerates have yielded the corals *Catenipora* sp., *Plasmoporella inflata* Hill and an indeterminate streptelasmatid (all from near the base of the formation). *Calapoecia* cf. *canadensis* Billings is recorded from near the middle of the formation. A limestone breccia immediately overlying *Pleurograptus linearis* Zone siltstones in the highest beds (section 6, Fig. 6) contains the following: hexactinellid sponge spicules, stromatoporoids *Ecclimadictyon* sp., and an actinostromid, tabulates

Heliolites sp., *Plasmoporella inflata* Hill, an indeterminate halysitid and an auloporid, rugosans *Favistina* sp., *Hillophyllum* ? sp., *Palaeophyllum* sp., and a streptelasmatid, bryozoans *Homotrypella* sp., *Favositella* sp., cf. *Glauconomella* sp., cf. *Phaenopora* sp., *Stictopora* ? sp., and a trepostome, brachiopods *Christiania* sp., *Strophomena* ? sp., and cf. *Skenidioides* sp., trilobites *Encrinuraspis* sp., *Pliomerina* sp., *Amphilichas* ? sp., and an unidentified odontopleurid, illaneid, and trinucleid, and the nautiloid *Bactroceras latisiphonatum* Glenister. In terms of the corals and stromatoporoids, this assemblage belongs to Fauna III (B. D. Webby pers. comm., 1975). The presence of *Catenipora* and *Calapoecia* in the lower and middle parts of the Malongulli Formation indicates that these genera appeared earlier than previously suggested by Webby (1972).

ANGULLONG TUFF

The Angullong Tuff (Stevens, 1952) is the uppermost Ordovician formation in the area (Fig. 1), and consists of a thick sequence of tuffaceous volcanics and derived sediments, exposed in a triangular area north and west of Malongulli Trig (Fig. 2). At GR 826458, the Angullong Tuff conformably overlies the Malongulli Formation (Fig. 6), and is unconformably overlain elsewhere by Late Devonian sediments. The lower 80 m (section 6; Fig. 6) consist of medium-bedded (0.2-1.5 m thick) crystal tuffs alternating with thin to medium bedded calcareous tuffaceous siltstones. Near the top of this section, feldspathic crystal tuffs appear, becoming more prominent with massive outcrop higher in the formation. The middle part of the formation mainly consists of thick beds of siltstone interbedded with the crystal tuffs. The upper beds are dominated by siliceous tuffaceous siltstones, with a thin concretionary horizon (consisting of boulder-sized blocks of silicified mudstone) extending laterally for several metres, interbedded in the siltstone sequence near the unconformity with Devonian sediments at GR 813457.

The calcareous tuffaceous siltstones exhibit alternating layers (10 mm thick) of calcareous mud and angular detrital quartz, feldspar and calcite. Siliceous siltstones of the upper beds are generally finely laminated with alternating bands (about 1 mm thick) of very fine quartz-feldspar detritus, and dark mud-rich layers. The crystal tuffs consist of 60-70% fine to medium sized crystals, mainly andesine laths, with subordinate amphibole, apatite, sphene and calcite, in a cryptocrystalline groundmass (in which chlorite may be extensively developed). Feldspathic crystal tuffs contain up to 90% medium to coarse-grained andesine laths (pink in handspecimen), set in a grey-green microcrystalline groundmass.

In the coarser grained lithologies in the Angullong Tuff, prehnite is occasionally present replacing feldspar, but no pumpellyite was observed in the thin sections examined. The constant association of andesine with amphibole in these rocks suggests that the pyroclastics are of andesitic composition.

Soft-sediment deformation, including small-scale slumping and drag-faulting, is well exhibited in the siliceous siltstones. Post-lithification deformation in these siltstones is indicated by small-scale low-angle reverse faulting. Most of the sediments are characterised by graded bedding, with erosive contacts between cycles of deposition, and occasional scour-and-fill structures. These features are commonly associated with hydroplastic contortion and sediment settling attributable to deposition by turbidity currents (Conybeare and Crook, 1968, p.23).

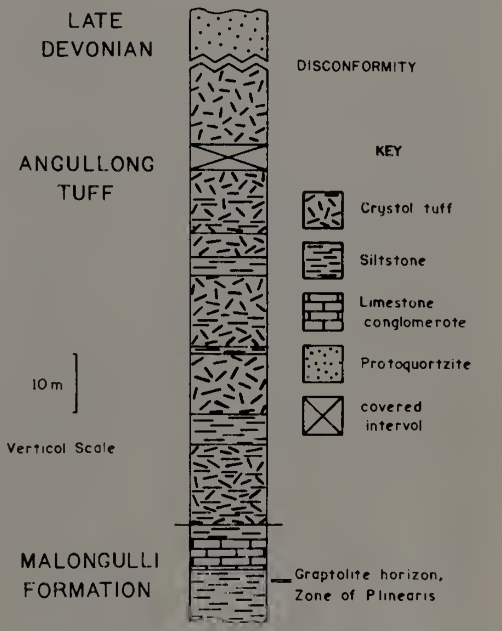

Fig. 6. Stratigraphic section 6, basal Angullong Tuff

The limited fauna found in the formation includes the graptolites *Climacograptus* aff. *scalaris* Hisinger, *Orthograptus calcaratus clavensis* Moors, *O. amplexicaulis* (Hall)?, coral *Palaeofavosites* sp. and an indeterminate orthid brachiopod. The fauna does not contain any elements diagnostic of a precise age, but is not older than early Bolindian.

ORDOVICIAN DEPOSITIONAL HISTORY

Extrusion of basalts and andesites, with explosive volcanic activity producing pyroclastic deposits (crystal tuffs), took place during the Early-Middle? Ordovician, forming the Walli Andesite. Following tilting, uplift and erosion of the volcanic pile, deposition of carbonate sediments commenced (during the early?, or late Gisbornian) with transgression from the east. Mud-free pelletal, skeletal and lithoclastic grainstones interbedded with cf. *Eodinobolus* shell banks in the lower limestone suggest proximity to the shoreline, and deposition in a moderately high-energy, apparently shallow-water environment. Transgression continued during deposition of the thinly bedded unit, with minor fluctuations in sea level indicated by the recurrence of shell beds in a sequence of burrowed dark grey wackestones. The presence of *Vermiporella* in some of these wackestones may indicate an offshore deeper water environment, below wave base (Semeniuk and Byrnes, 1971). Inferred inshore shallow water conditions again prevail at the top of this unit, with deposition of pelletal-skeletal packstones containing *Girvanella* pisolites and lithoclasts. Much of the massive limestone of the Middle Member was deposited in a quiet water environment (probably below wave base), inferred from the abundance of fine mud and *Vermiporella*. The 'E horizon' in the middle of the member may represent a regressional interval, with re-establishment of an inshore depositional environment. Accumulation of *Vermiporella* wackestones continues above this level, suggesting renewed transgression. Nearshore turbulent-water environments (indicated by grainstones, cf. *Eodinobolus* coquinas, and broken shelly debris) recur with increasing frequency towards the top of the Middle Member, where remanié-fossil grainstones underlie an irregular disconformity surface. Sediments of the 'Island' unit directly above this disconformity contain profuse lithoclasts, possibly eroded during the interval of non-deposition. An abundant marine fauna, associated with pisolite-forming algae, colonised the shallow shelf. Continuing transgression is reflected in the increasing *Vermiporella* content of wackestones of the overlying grey unit, and the appearance of a graptolitic fauna in the basal Malongulli Formation, during late Eastonian time. The Malongulli Formation probably accumulated towards the base of the continental slope, with deposition alternating between intervals of quiet sedimentation (of marls, spiculites and siltstones), and rapid deposition of greywackes with graded bedding (by turbidity currents) and limestone conglomerates (representing slump deposits from an adjacent shallow water carbonate shelf). Resumption of explosive volcanic activity in the early Bolindian resulted in deposition of pyroclastics and derived sediments of the Angullong Tuff in the offshore marine environment (slope or trough), again mainly as a product of turbidity current activity.

SILURIAN FORMATIONS

The Millambri Formation (Ryall, 1965) occurs immediately west of the Columbine Mountain Fault. On the basis of a sparse graptolite fauna, Ryall attributed an early Llandovery age to the upper beds of the formation. Graptolites found during the present study permit greater precision in the age determination and facilitate the recognition of a disconformity within the Llandovery. The Millambri Formation is here redefined to exclude the limestone immediately underlying the Lower Avoca Valley Shale (Ryall, 1965) east of 'Liscombe Pools' homestead. The limestone above the disconformity is here named the *Liscombe Pools Limestone*, after the property on which the majority of the formation is exposed.

Graptolites collected from the top of the redefined Millambri Formation (section 7, Fig. 7) include *Glyptograptus tamariscus* Nicholson, *Monograptus jonesi* Rickards (identified by C. Jenkins), *Pseudoclimacograptus* (*Metaclimacograptus*) *hughesi* (Nicholson), *P.* (*M.*) *undulatus* (Kurck) and *P.* (*Clinoclimacograptus*) *retroversus* Bulman and Rickards. These species indicate a middle Llan- dovery age for the top of this formation. From the Liscombe Pools Limestone, Pickett (1974) has obtained stromatoporoids, corals *Liscombea insole* Ross, *Halysites cratus* Eth. jr., *H. gamboolicus* E jr., *Favosites* sp., *Heliolites* sp., *Multisolenia* sp., and a large conodont fauna (comprising some twenty-three species, including *Aulacognathus kuehni* Mostler, *Neospathognathodus celloni* Wallis and *N. pennatus* Walliser) which fauna he conclude (p.4) "clearly indicates a late but not latest Llandovery age", suggesting tentative correlation with the Zone of *Monograptus greistonensis*. The disconformity between the Millambri Formation and the limestone may thus span up to four upper-midd to lower-late Llandovery graptolite zones, and is therefore probably attributable to the Panuara phase of the Benambran Orogeny (Packham, 1969).

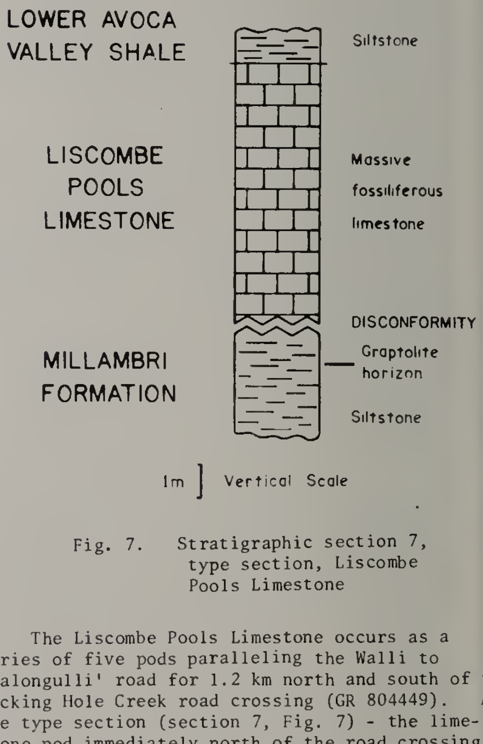

Fig. 7. Stratigraphic section 7, type section, Liscombe Pools Limestone

The Liscombe Pools Limestone occurs as a series of five pods paralleling the Walli to 'Malongulli' road for 1.2 km north and south of th Licking Hole Creek road crossing (GR 804449). At the type section (section 7, Fig. 7) - the limestone pod immediately north of the road crossing the formation is about 8 m thick. The limestone is typically thickly bedded to massive, grey in colour, fine grained, frequently silicified with a late Llandovery fauna (listed above, and in Picket 1974). The contact of the limestone with the overlying Lower Avoca Valley Shale is not exposed at the type section, but is thought to be conformable.

POST-SILURIAN STRATIGRAPHY

Late Devonian quartz-rich sediments (siltstones, arenites, protoquartzites, and conglomerates) unconformably overlie the Ordovician strata immediately east of the Columbine Mountain Fault, and also cap Malongulli Trig (Fig. 2), On the southern flanks of the latter is a scree slope (consisting of semi-consolidated material derived from the Late Devonian outlier) to which Adamson and Trueman (1962) ascribed a Tertiary age; no conclusive supporting evidence for this age (or any other) exists however.

IGNEOUS INTRUSIVES

Licking Hole Creek Diorite

A large irregular mass, up to 850 m long and 650 m wide, of deeply weathered diorite intrudes the Malongulli Formation south and west of Malongulli Trig (Fig. 2). This intrusion is here named the *Licking Hole Creek Diorite*, after the creek in which its southern extremity is exposed. Originally the rock type was identified by Stevens (1950) as a pyroxene lamprophyre, but he later suggested (Stevens, 1954) that the intrusion may be more closely related to the syenite-monzonite suite. The confusion over the classification of the rock arises from its intensely weathered nature; the intrusion consists almost entirely of a green-brown crumbly soil generally exposed only in creek banks. The rock, when sufficiently fresh for study, consists of 50% andesine plagioclase phenocrysts partly pseudomorphed by prehnite; the remainder contains phenocrysts of amphibole (probably hornblende) and epidote, with rare orthopyroxene and secondary calcite. The rock is therefore classified as a porphyritic diorite. The main intrusive mass is traversed by small discontinuous dyke-like bodies of red syenite between GR 820455 and GR 818451. Roof pendants of Malongulli Formation within the intrusion are only slightly contact metamorphosed. There is no conclusive evidence as to the age of the intrusion; however, it is apparent from field observations that it is confined within the Malongulli Formation, probably due to bedding and lithological characteristics of this formation which provided less resistance to intrusion in comparison to the overlying Angullong Tuff. It is unlikely that the intrusion was emplaced prior to the deposition of the Angullong Tuff as the contact between the formations is conformable, yet the diorite does not transgress this boundary although it intrudes the uppermost beds of the Malongulli Formation at GR 820450. Therefore it is suggested that the diorite intruded along weaknesses produced or accentuated within this formation by a post-Ordovician episode of folding or faulting.

Unnamed Quartz Porphyry

A small intrusive neck of dacitic quartz porphyry is exposed at GR 809445 on Licking Hole Creek (Fig. 2), and is surrounded by a 5-10 m wide cleaved and hydrothermally altered aureole in the enclosing Malongulli Formation. The quartz porphyry consists of about 60% cryptocrystalline to microcrystalline felsic groundmass, and 40% medium to coarse-grained crystals, mainly bipyramidal phenocrysts of embayed volcanic quartz with minor andesine feldspar, altered mafics and sparse red garnet phenocrysts. This porphyry is remarkably similar to the garnetiferous Canowindra Porphyry which crops out to the west of the Columbine Mountain Fault. These may be related, (a possibility also considered by Moors, 1966 unpublished), with the porphyry neck acting as a feeder pipe for the Canowindra Porphyry, described by Ryall (1965) as an extrusive body of Early to Middle Silurian age. Hence the age of the neck probably lies between late Eastonian (Late Ordovician) and Middle Silurian.

STRUCTURAL INTERPRETATION

The overall structure is fairly simple, although detailed mapping of the Cliefden Caves Limestone reveals a rather more complex pattern of small scale faulting. Deformation is not, however, of sufficient intensity to produce extensive cleavage in the sediments. The area lies on the west limb of a regional anticlinal structure, with the Ordovician sedimentary strata dipping (on average) at 40°-50° to the west. Limestone lenses in the Malongulli Formation outline the form of several large open flexures with north-easterly trending fold axes, in the Ordovician formations west and south-west of Malongulli Trig (Fig. 2). The folds are truncated to the south by a north-easterly trending fault which merges with the southern extension of the Columbine Mountain Fault in a shear zone (partly concealed by alluvium) about 0.5 km wide (Fig. 2). The north-easterly trending fault is the dominant structural feature in the area, and is here named the Wonga Fault (after 'Wonga' property GR 801406). The Cliefden Caves Limestone is not found west of the Wonga Fault; immediately east of the fault, however, the limestone has been extensively disrupted by cross-cutting and strike-slip faulting. Cross-cutting fractures in the western outcrop of the limestone (GR 809432) are characterised by the development of massive vein quartz. Where the Wonga Fault (and associated fractures) intersects the Malongulli Formation, fault zones are recognisable as resistant linear outcrops of intraformational ferruginous breccia, massive vein quartz, and massive prehnite.

The Ordovician sediments are faulted against the Silurian Millambri Formation to the west along the north-south Columbine Mountain Fault (Stevens, 1950; Ryall, 1965). To the east of the Cliefden Caves district, high-angle thrust faults such as the Wongalong Fault and Narambon Shear Zone (Smith, 1966) exhibit approximately parallel trends with the Columbine Mountain Fault. Horizontal stress axes acting on these thrust faults could well have resulted in transcurrent fracturing of the intervening block along a vertical sigmoidal fault. The Wonga Fault can be traced in a north-east direction to the Cliefden Caves district. G. H. Packham and B. D. Webby (pers. comm. 1974) have recognised in detailed mapping of the latter area that the north plunging anticlinal structure near Davies Creek has been displaced about 2.4 km to the east. This displacement implies a dextral direction of transcurrent movement along the Wonga Fault.

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Mylonitic Rocks in the Young Granodiorite, Southern New South Wales

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ABSTRACT. Discontinuous zones of steeply dipping mylonitic rocks occur along the western margin of the Young Granodiorite in southern New South Wales. The mylonitic zones are up to 300m wide and are best developed where the Young Granodiorite abuts against the Coolac Serpentinite. Mylonitic rocks grade through foliated into relatively massive biotite granodiorite.

Primary biotite and plagioclase in the biotite granodiorite undergo mineralogical breakdown during the mylonitization process, whereas quartz, microcline and muscovite appear simply to recrystallize. Plagioclase tends to be the phase most resistant to deformation. Microstructures developed progressively with increasing mylonitization suggest that ductile deformation, dynamic recovery and recrystallization were the major operative processes.

The mylonitic rocks were possibly formed during an episode in which rocks of the Yass-Canberra Rise were thrust at a high angle over an ophiolite suite forming the eastern boundary of the Cowra Trough. The thrusting may have been coincident with the final deformation and cratonization of the Cowra Trough in the early Devonian.

INTRODUCTION

Brief references on the occurrence and formation of mylonitic rocks in the Young Granodiorite close to its contact with the Coolac Serpentinite east of Tumut and Gundagai, southern New South Wales, have been made by Fraser (1961), Veeraburus (1963), Golding (1966; 1969) and Ashley et *al.* (1971). These investigations presented limited data on the field occurrence, petrography and development of the mylonitic texture, with Veeraburus (1963) attempting a tectonic synthesis. The present study is directed towards the geological setting and the progressive development of microstructures and mineralogical changes accompanying mylonitization. The tectonic implications of the mylonitic rocks are briefly discussed.

GEOLOGICAL SETTING

The Young Granodiorite (Ashley and Basden, 1973), is an elongate, biotite granodiorite-dominated composite batholith extending from near Canowindra in the north to near Yarrangobilly in the south (Fig. 1). The bulk of the batholith is considered late Silurian to earliest Devonian (410-420 million years (m.y.) ; Evernden and Richards, 1962; discussion by Richards et *al.*, 1972; Owen and Wyborn, pers. comm., 1975). An early Devonian age (397 m.y.) from 7 km northeast of Jugiong was reported by Basden (1974). The batholith has intruded and is in part overlain by chemically equivalent (possibly comagmatic) porphyritic rhyodacite, dacite and pyroclastic rocks of the middle to late Silurian Douro Volcanics, Goobarrangandra and Blowering Beds, and Canowindra Porphyry (Ashley, 1973; Basden, 1974). In the Micalong Swamp region about 30 km east of Tumut, the Young Granodiorite probably post-dates much of the Micalong Swamp Basic Complex dated at 425$\pm$9 m.y. (Owen and Wyborn, in prep.). Southwest of Burrinjuck Dam, the Young Granodiorite has been intruded by pink granite of the Burrinjuck Granite, dated at 406 m.y. (Owen and Wyborn, in prep.).

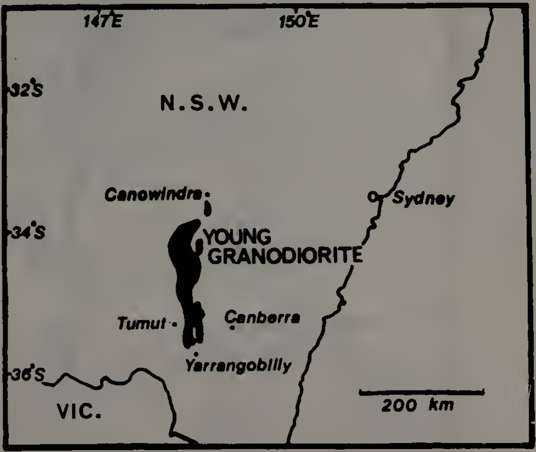

Fig. 1 Location of the Young Granodiorite, southern New South Wales

Mylonitic rocks are largely located along or near the western margin of the Young Granodiorite, although a few occurrences are more centrally located in the batholith (Fig. 2). The western margin of the batholith has been proposed to represent a major thrust (e.g. Veeraburus, 1963; Watts, 1971; Basden, 1974), the zone of dislocation having been termed the Mooney Mooney Thrust System by Basden (1974). The southern half of the batholith (within which most of the mylonitic rocks have been recognized) is bounded to the west by a suite of ophiolites, comprising from the base, the Coolac Serpentinite, the North Mooney Complex and equivalents, and the Honeysuckle Beds. The northern half of the Young Granodiorite is tectonically bounded to the west by the ?Cambrian-early Ordovician Jindalee Beds and in part is unconformably overlain by the early Devonian Illunie Rhyolite and the late Devonian Hervey Group.

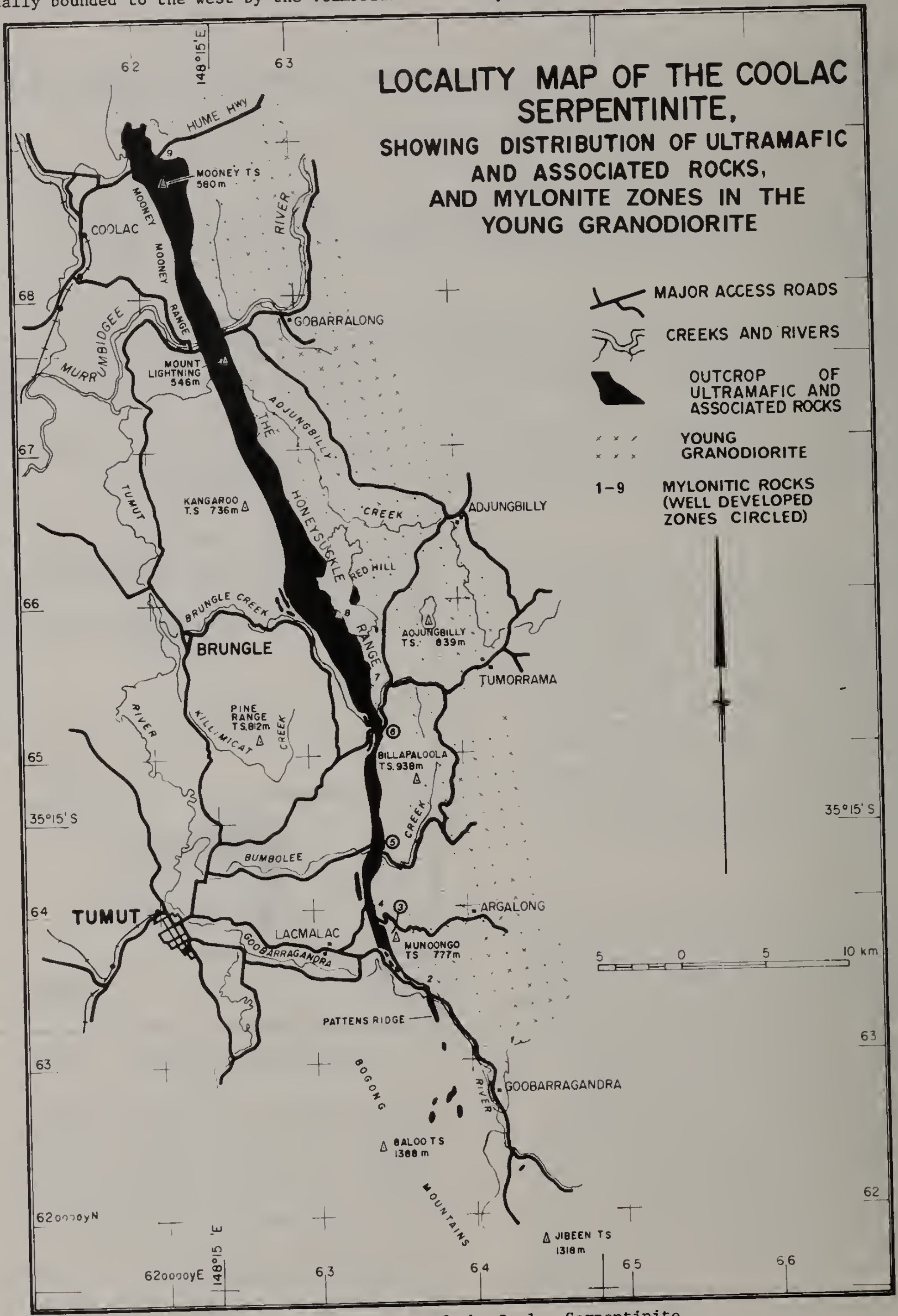

Fig.2 Locality map of the Coolac Serpentinite

FIELD DESCRIPTION

Mylonitic rocks have been found in the Young Granodiorite discontinuously southwards from 7 km northeast of Coolac to near Goobarragandra (Fig.2). Most of the occurrences are within 300m of the contact with the Coolac Serpentinite, although isolated mylonitic zones have been recognized well to the east. Where exposed, the actual contact between the Young Granodiorite and Coolac Serpentinite is sharp, with foliated to highly mylonitic granodiorite abutting schistose lizardite-clinochrysotile (± antigorite ± talc ± tremolite) serpentinite. Commonly, schistose serpentinite grades into the massive variety within a few metres of the contact.

The best exposures of mylonitic rocks are:

1. valley of Rough Gully close to the Wee Jasper road, 17 km northeast of Tumut (Australian Grid Reference 635652, Zone 7);
2. valley of Bumbolee Creek on the Canberra road, 15 km east-northeast of Tumut (G.R. 634643);
3. immediately west of Mundongo Trig. Station, 14 km east of Tumut (G.R. 635638).

In outcrop there is a notable gradation over distances of up to 300m from relatively massive biotite granodiorite into finely laminated mylonite. The former rock type constitutes the bulk of the batholith. It is medium to coarse grained and contains scattered ellipsoidal to angular xenoliths up to 60 cm across. Sparsely distributed dykes of microgranite and porphyritic microgranodiorite, and quartz-rich veins occur throughout the biotite granodiorite. A weak foliation is generally apparent in outcrops of biotite granodiorite, with a slight alignment of biotite plates, lenticular quartz aggregates and the long axes of xenoliths. The foliation becomes better defined closer to the mylonitic zones and is accompanied by a general decrease in grainsize, the alignment and elongation of xenoliths (Fig. 3) and dykes, and the development of a weak lineation, defined by preferred orientation of biotite plates and quartz aggregates, in the plane of the foliation. Within the mylonitic zones the rocks are fine to medium grained and finely laminated with light (quartz and feldspar) and dark (mica) laminae containing scattered plagioclase porphyroclasts (Fig. 4). Xenoliths lose their identity where their length/breadth ratio exceeds 25 to 40, but original dykes and veins may be represented by elongate segregations of quartz and feldspar. A weak lineation is commonly present in the plane of the foliation. The most mylonitic rocks resemble slates in hand specimen.

Fig. 3 Elongate medium grained quartz-plagioclase -biotite xenolith in strongly foliated coarse grained biotite granodiorite. Bumbolee Creek, G.R. 634643.

Fig. 4 Finely laminated granodiorite mylonite with light-coloured quartz-feldspar segregations and scattered plagioclase porphyroclasts. Bumbolee Creek, G.R. 634643.

The foliation in the mylonitic rocks closely parallels the attitude of the Coolac Serpentinite, i.e. dipping steeply to the east-northeast, and the poorly developed lineation generally plunges at high angles to the north and north-northwest (Fig. 5). Scattered lensoid tectonic inclusions of variably brecciated and mylonitized biotite granodiorite up to 100 m long and 30 m wide occur within schistose serpentinite close to the contact between the ultramafic belt and the Young Granodiorite.

PETROGRAPHY OF THE BIOTITE GRANODIORITE

The typical massive to slightly foliated biotite granodiorite of the batholith has an average grainsize of 3-4 mm. It contains 30-40 vol.% quartz, 25-40 vol.% plagioclase (average An$_{35}$, with normal and oscillatory zoning from An$_{40-55}$ to An$_{6-25}$), 5-15 vol.% perthitic microcline, 20-25 vol.% red-brown biotite and minor primary muscovite, apatite, zircon, rutile and ilmenite. Plagioclase is generally slightly altered to fine grained aggregates of muscovite, chlorite, clinozoisite and albite, and biotite to aggregates of muscovite, chlorite, clinozoisite, sphene and magnetite.

Xenoliths contain the same minerals as the enclosing granodiorite. They are finer grained (0.5 - 1.5 mm average) and may contain a higher proportion of biotite. Rare examples contain minor greenish-brown hornblende. Tectonic inclusions of biotite granodiorite within the Coolac

Serpentinite contain the same minerals as the Young Granodiorite, although progressive alteration of the primary minerals to reaction zone assemblages rich in Ca-Al silicates, tremolite and chlorite is prevalent (Ashley, 1973).

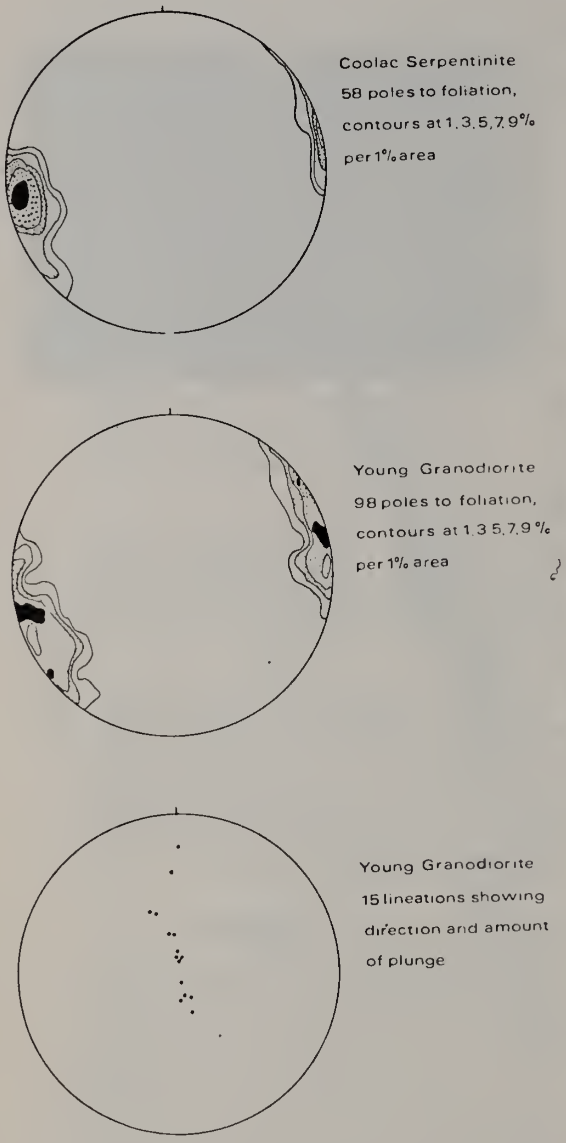

Fig.5 Stereograms showing poles to foliation in the Coolac Serpentinite and Young Granodiorite, and lineations in the latter

TEXTURAL AND MINERALOGICAL CHANGES ACCOMPANYING MYLONITIZATION

Macroscopically undeformed biotite granodiorite shows considerable deformation in thin section (*cf.* Bell and Etheridge, 1973). Quartz grains display undulose extinction, Boehm lamellae, subgrains and deformation banding, and serrated boundaries are developed between adjacent grains. Plagioclase and microcline grains are generally undeformed except for slight bending and fracturing whereas biotite plates are commonly bent or kinked.

In rocks which are macroscopically weakly to moderately foliated, quartz shows extensive deformation banding, with discrete subgrains formed in many areas. New, optically unstrained grains appear at sites of more intense strain. As pointed out by Bell and Etheridge (1973), the amount of strain influences the types of microstructures observed. For example, quartz inclusions in plagioclase are relatively unstrained, with weak deformation banding and/or undulose extinction (i.e. they are protected within the "strong" plagioclase), whereas less protected quartz grains show elongation, strong development of serrated boundaries, deformation bands, subgrains within deformation bands, and partial conversion to aggregates of new grains (Figs. 6 and 7).

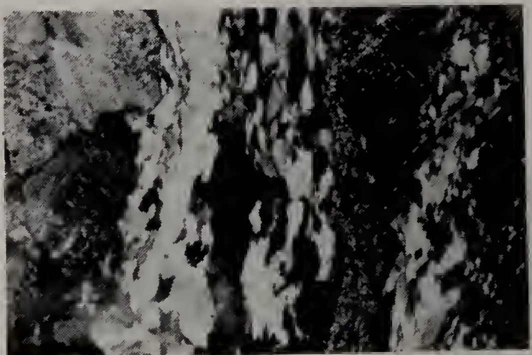

Fig. 6 Moderately foliated biotite granodiorite with quartz-rich lens showing development of elongate subgrains with undulose extinction and serrated boundaries. Adjacent plagioclase grains are relatively undeformed but partly altered to fine grained muscovite. Crossed polars, field of view approximately 4.5 x 3 mm.

Plagioclase grains commonly show fracturing and the bending and microfaulting of twin lamellae, but only minor recrystallization along grain boundaries and fractures.

Rocks which are macroscopically strongly foliated are typified by angular to subrounded plagioclase porphyroclasts in a strongly foliated, fine to medium grained groundmass. Most of the original quartz grains have been replaced by aggregates of new grains, the aggregates being parallel to the mylonitic foliation (Fig. 8). Original biotite grains are largely replaced by finer grained, elongate aggregates of secondary biotite, muscovite, sphene and magnetite. Plagioclase porphyroclasts are extensively fractured and microfaulted. "Beards" of recrystallized mica and quartz are common in "pressure shadows" fringing plagioclase grains (Fig. 9) (*cf.* Williams, 1972). Slight recrystallization of plagioclase has occurred along fractures and grain boundaries; the mineral is commonly flecked by muscovite and fractures may be partly filled by quartz, secondary biotite, muscovite and sphene. Microcline is partly converted to aggregates of new microcline grains. The foliation tends to wrap around relict, slightly fractured apatite and zircon grains.

Fig. 7 Moderately foliated biotite granodiorite with a quartz grain partly converted to an aggregate of polygonal subgrains, and surrounded by fine grained secondary biotite, muscovite, and quartz, with relict plagioclase grains. Crossed polars, field of view approximately 1.2 x 0.8 mm.

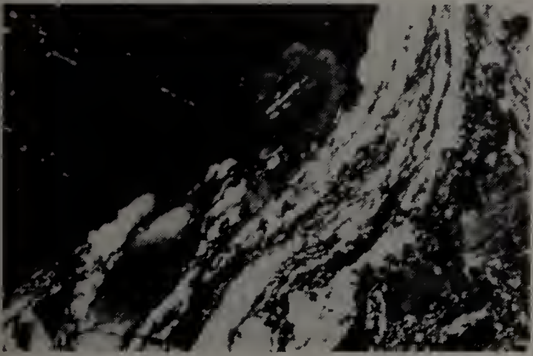

Fig. 8 Strongly foliated biotite granodiorite with recrystallized quartz aggregate defining the foliation beside a plagioclase porphyroclast showing slight marginal recrystallization. Crossed polars, field of view approximately 1.2 x 0.8 mm.

Strongly foliated granodiorite grades into mylonite with a decrease in the amount and grainsize of plagioclase porphyroclasts, and an increase in the amount of foliated, fine grained groundmass. Plagioclase porphyroclasts become more rounded with decreasing grainsize (Fig. 10) and finally recrystallize into lensoid aggregates. Highly mylonitized rocks are well laminated in thin section (Fig. 10), with laminae 0.1 - 0.5 mm wide rich in quartz or in secondary biotite + muscovite + sphene ± clinozoisite. Feldspar-rich lenses, together with trains of fine clinozoisite grains, are dispersed throughout the quartz- and mica-rich laminae (Fig. 11). The grainsize of these entirely recrystallized rocks generally averages 0.05 mm.

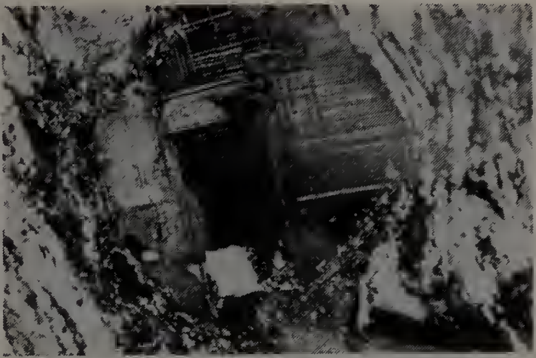

Fig. 9 Strongly foliated biotite granodiorite with ovoid plagioclase porphyroclast showing microfaulting, subgrain development and an unstrained quartz inclusion. Fine grained recrystallized quartz foliae surround the porphyroclast and fringing "pressure shadow beards" of secondary biotite and muscovite. Crossed polars, field of view approximately 1.2 x 0.8 mm.

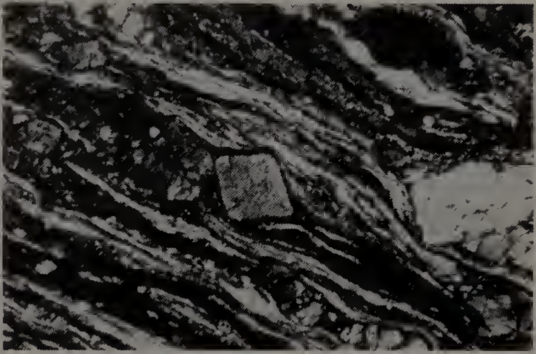

Fig.10 Granodiorite mylonite with plagioclase porphyroclasts in a fine grained foliated groundmass of quartz- and feldspar-rich laminae (light) and secondary biotite + muscovite + sphene ± clinozoisite laminae (dark). Crossed polars, field of view approximately 4.5 x 3 mm.

Accompanying the mylonitization process, quartz, microcline and primary muscovite appear simply to recrystallize, but biotite and plagioclase undergo more complex processes. Primary biotite from the biotite granodiorite is red-brown and strongly pleochroic with X = pale straw yellow, Y = Z = deep red-brown. Fine rutile needles oriented at about 60° to each other are abundant in the place of the (001) cleavage and small apatite and zircon inclusions are common. The mineral is characterized by $\Sigma FeO/MgO$ of approximately 2, a high FeO/Fe_2O_3 ratio and moderately high TiO_2 (Table 1). With mylonitization, primary biotite breaks down to the assemblages secondary biotite + muscovite + sphene ± magnetite and chlorite + sphene ± muscovite ± clinozoisite. Secondary biotite is pale

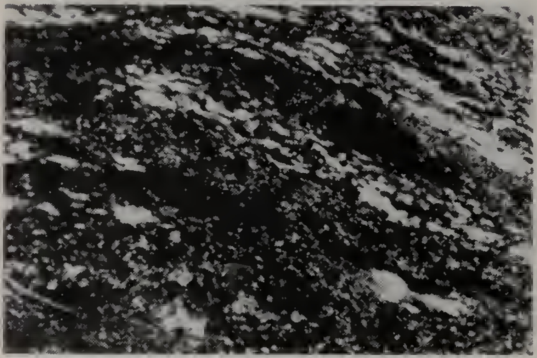

Fig.11 Granodiorite mylonite showing lensoid aggregates of recrystallized quartz and feldspar (light) with intervening fine grained secondary biotite and muscovite. Crossed polars, field of view approximately 1.2 x 0.8 mm.

brown, moderately pleochroic with X = pale yellow-colourless and Y = Z = drab brown. It is probably poorer in TiO_2 and Fe than the primary mineral, as well as having a lower FeO/Fe_2O_3 ratio. Such chemical changes in biotite have been demonstrated from hydrothermal alteration (e.g. porphyry ore deposit) systems (e.g. Moore and Czamanske, 1973).

As well as totally recrystallizing in the most mylonitic rocks, plagioclase generally breaks down to assemblages of albite (An_{5-10}) + clinozoisite + muscovite ± chlorite, or simply to muscovite. Calcic cores tend to be replaced first. Partial replacement along fractures and cleavage planes by muscovite and/or secondary biotite is also common. Feldspar-rich lenticles in the most mylonitic rocks consist dominantly of recrystallized albitic plagioclase with minor microcline.

CHEMISTRY OF THE MYLONITIC ROCKS

The biotite granodiorite forming the bulk of the Young Granodiorite shows the characteristics of the "S-type" granites of Chappell and White (1974) and White and Chappell (1974), with K>Na, $Na_2O + K_2O + CaO/Al_2O_3 < 1.1$, normative corundum, and containing inclusions derived from a metasedimentary source, as well as having a high FeO/Fe_2O_3 ratio and Rb/Sr approaching unity (Table 1). The "S-type" granites of southern N.S.W. are proposed to have been derived from the partial melting of Ordovician aluminous metasediments (e.g. Chappell and White, 1974; White *et al.*, 1974).

The formation of the mylonitic rocks from the biotite granodiorite is accompanied by only minor chemical changes, the most notable being slight decreases in the FeO/Fe_2O_3 ratio, TiO_2, K_2O, Rb, Rb/Sr ratio, Cu, Zn, and a slight increase in Na_2O and SiO_2 (Table 1). The above-mentioned decreases may be largely explained by the breakdown of primary biotite and the increases by the partial albitization of plagioclase. The chemical changes may require small additions and subtractions of components by a fluid phase during mylonitization.

Tectonic inclusions of foliated biotite granodiorite in the Coolac Serpentinite are chemically similar to equivalent rocks in the batholith (Table 1).

DISCUSSION

The textures and field occurrence of the mylonitic rocks in the Young Granodiorite agree with those in the definition of a mylonite as proposed by Bell and Etheridge (1973, p.347):- "A *mylonite* is a foliated rock, commonly lineated and containing megacrysts, which occurs in narrow, planar zones of intense deformation. It is often finer grained than the surrounding rocks, into which it grades". Bell and Etheridge (1973) proposed that all the microstructures they described from mylonites are typical of those formed during ductile deformation, dynamic recovery and recrystallization of a wide range of crystalline materials. It was strongly suggested that characteristics which apparently indicated processes of brittle deformation to previous workers (e.g. *inter alia* Higgins, 1971) were in fact formed, both naturally and experimentally, by ductile deformation and recrystallization (Bell and Etheridge, 1973; Etheridge and Hobbs, 1974; Vernon, 1974).

Although Bell and Etheridge (1973) recognized that some mylonitic rocks may be produced by brittle deformation (e.g. they quote Scott and Drever, 1953), they considered the process of ductile deformation is much more common in their formation. Since the microstructures described from the Young Granodiorite are identical with those reported by Bell and Etheridge (1973) and by Vernon (1974), it is suggested that the mylonitic rocks formed by one or more of the following processes:

1. Ductile deformation, dynamic recovery and recrystallization of phases.
2. Growth of new mineral grains at the expense of minerals of different composition (e.g. biotite and plagioclase) as a result of the change in conditions and movement of material accompanying 1. A decrease in grainsize generally follows.
3. Lenticular compositional layering in the more mylonitic rocks has probably formed due to the original rock being polymineralic and due to original grainsize being larger than the resultant mylonite (e.g. Vernon, 1974).

A locality on the western margin of the Young Granodiorite about 20 km northeast of Tumut (G.R. 634654) shows a limited outcrop of non-foliated cataclasite (using the nomenclature of Spry, 1969). The cataclasite contains subangular to angular fractured porphyroclasts of quartz and plagioclase, and granodiorite fragments up to 10 mm across in a fine grained matrix (up to 80 vol. %) of quartz, feldspar, chlorite and muscovite. As distinct from the more common mylonitic rocks, the cataclasite may have formed largely by brittle deformation.

TABLE 1
CHEMICAL ANALYSES

Sample	MU3831	MU3874	MU3948	MU3912	MU3825	MU3848	MU3802	MU3831B
SiO_2	69.05	68.76	68.61	69.87	70.41	69.92	71.58	35.15
TiO_2	0.69	0.63	0.64	0.55	0.56	0.60	0.52	2.76
Al_2O_3	14.02	14.14	14.51	14.21	14.14	13.58	13.29	18.06
Fe_2O_3	0.35	0.35	0.86	0.87	0.74	0.74	0.91	1.14
FeO	4.13	4.08	3.73	3.09	2.58	3.19	2.63	17.95
MnO	0.06	0.10	0.07	0.05	0.04	0.07	0.06	0.29
MgO	2.80	2.69	3.06	2.24	2.57	2.16	1.98	9.58
CaO	2.43	2.61	2.17	3.24	2.74	2.03	1.96	0.04
Na_2O	2.16	2.19	2.16	2.68	3.25	2.46	2.90	0.15
K_2O	3.18	3.03	2.82	2.33	1.16	3.70	3.08	9.65
P_2O_5	0.22	0.21	0.20	0.29	0.19	0.18	0.17	0.04
H_2O^+	1.09	0.97	1.01	0.68	1.62	0.75	1.79	3.02
H_2O^-	0.29	0.09	0.19	0.14	0.24	0.11	0.16	0.32
CO_2	0.03	0.10	0.15	0.00	0.00	0.02	0.01	0.00
F								0.31
Rb_2O								0.08
Less $O=F_2$								0.13
Total	100.50	99.95	100.18	100.14	100.24	99.51	101.04	98.41

Trace Elements

	MU3831	MU3874	MU3948	MU3912	MU3825	MU3848	MU3802	MU3831B
Cr	111		115	74	126	80	80	
Cu	28		27	10	8	21	18	
Ga	16	17	17	17				
Ni	36		34	23	137	24	25	
Pb	29	19	26	22				
Rb	167	154	132	123				
Sc	18		17	20	18	18	14	
Sr	129	135	136	155				
Th	14	14	17	13				
U	3	6	3	3				
V	64		74	62	59	59	51	
Y	35	33	34	41				
Zn	71		76	41	24	58	52	
Zr	195	191	189	179				
Rb/Sr	1.29	1.14	0.97	0.79				
FeO/Fe_2O_3	11.80	11.66	4.34	3.55	3.49	4.31	2.89	15.75

Analyses by P.M. Ashley (except MU3831B by R.H. Flood), using X-ray fluorescence spectrometry, flame photometry (Na_2O), titrimetry (FeO) and gravimetry (H_2O, CO_2).
Samples housed in the collection of the School of Earth Sciences, Macquarie University.

MU3831. Massive biotite granodiorite, Harden road, 2 km east of Wallendbeen. G.R. 619734.

MU3874. Massive biotite granodiorite, Billapaloola State Forest, about 20 km N.E. of Tumut and 3 km east of contact with Coolac

Serpentinite. G.R. 638653.

MU3948. Biotite granodiorite mylonite, Bumbolee Creek road, about 15 km east of Tumut, and 200 m east of contact with Coolac Serpentinite. G.R. 635643.

MU3912. Biotite granodiorite mylonite, 200 m west of Mundongo T.S. and 20m east of contact with Coolac Serpentinite. G.R. 634643.

MU3825. Altered, deformed biotite granodiorite, 1.5 m east of contact with Coolac Serpentinite, on Wee Jasper Road, 18 km northeast of Tumut. G.R. 635652.

MU3848. Tectonic inclusion of deformed, partly recrystallized biotite granodiorite in Coolac Serpentinite, about 20 km northeast of Tumut. G.R. 633655.

MU3802. Tectonic inclusion of deformed biotite granodiorite in Coolac Serpentinite, Wee Jasper Road, 18 km northeast of Tumut. G.R. 635652.

MU3831B. Primary red-brown biotite from MU3831.

TECTONIC IMPLICATIONS

It was suggested by Scheibner (1973) and Ashley (1973) that the ophiolite suite comprising the Coolac Serpentinite, North Mooney Complex and equivalents and the Honeysuckle Beds represents earliest Silurian oceanic lithosphere, and formed the basement of the Cowra Trough. During the deformation of the Cowra Trough, possibly around the Silurian-Devonian boundary, the ophiolite suite was obducted eastwards on the Yass-Canberra Rise. At this time the Yass-Canberra Rise may have had the characteristics of an Andean-type continental margin with abundant calc-alkaline rhyodacite-dacite volcanics and comagmatic granodioritic intrusives.

When initially obducted, the ophiolites may have formed a relatively low-angle sheet (*cf.* Coleman, 1971; Davies, 1971), but with increasing crustal shortening the sheet assumed a vertical to slightly overturned position. With further compression, the Yass-Canberra Rise was possibly thrust back over the ophiolites, with the development of the mylonitic rocks in the Young Granodiorite in proximity to the thrust plane. Tectonic inclusions of foliated to mylonitic granodiorite may have been mechanically incorporated into the ultramafic rocks of the Coolac Serpentinite at this stage.

Basden (1974) reported a narrow, subvertical north-south trending zone of deformation possibly extending from east of Tumut to near Murrumburrah (termed the Jugiong Shear Zone). She implied that this deformed zone separates an eastern, less eroded block of the Young Granodiorite (with abundant aplitic dykes and "roof pendants" of Douro Volcanics), from a western, more deeply eroded upthrust block. If this be so, the Jugiong Shear Zone and Mooney Mooney Thrust System may have acted as bounding faults in a large block movement. The early Devonian age (397 m.y.) reported by Basden (1974) from a somewhat deformed granodiorite sample from the Young Granodiorite probably reflects the time of thrusting and may coincide with the final deformation and cratonization of the Cowra Trough in this region.

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Potassium-Argon Ages of Igneous Rocks in the Wollar-Rylstone Region, New South Wales

J. A. Dulhunty

ABSTRACT. Potassium-argon age determinations are recorded for intrusive and extrusive alkaline intermediate rocks, and teschenite intrusions, and the significance of the results is considered in relation to the igneous chronology and geomorphology of the region. Late Triassic ages were obtained for teschenite intrusions; middle Jurassic ages for alkali microsyenite and phonolite sills and laccoliths, and late middle Triassic ages for trachyte and phonolite flows. Early Oligocene and middle Miocene basalt flows are correlated with dated flows in adjoining areas, and the significance of their mode of occurrence in relation to the development of the Goulburn Valley is noted.

INTRODUCTION

The purpose of this paper is to record K-Ar age determinations of igneous rock bodies in the Wollar-Rylstone region, and to consider their significance, together with previously recorded K-Ar ages, in relation to igneous chronology and geomorphology of the region.

PREVIOUS INVESTIGATIONS

The wide range of igneous rock types and variety of extrusive and shallow intrusive rock bodies outcropping in the Wollar-Rylstone region (Fig. 1) have attracted geological interest for many years. Carne (1903, 1908) first described laccoliths of alkaline rocks, other intrusions and flows of basalt. The general nature of the sills, laccoliths and flows, and their relations to the sedimentary rocks, were also noted by Jones (1926), Morrison and Kenny (1933) and Dulhunty (1938, 1940). The first comprehensive investigation of the geology of the region, and systematic petrographic study of igneous rocks was carried out by Day (1961). Previously, all post-Palaeozoic igneous rocks of the region had been generally, or traditionally, accepted as of Tertiary age. Day attributed the igneous rocks to five separate extrusive and intrusive episodes. Radiometric data and direct fossil evidence being unavailable, she suggested the following ages for the five groups, based largely on petrographic and field relations to each other and to a predominating erosion surface assumed to be Miocene by correlation with surfaces in other parts of eastern Australia.

1. Cretaceous -	Teschenite sills and other bodies intrusive into Triassic and Permian sediments.
2. Eocene -	Monchiquite and monchiquite-basalt neck residuals rising to 180 m above the Miocene erosion surface.
3. Eocene -	Olivine basalt and monchiquite flow residuals on old surfaces up to 240 m above the Miocene surface.
4. Eocene -	Alkali microsyenite and phonolite laccoliths and sills with denuded tops up to 250 m above the Miocene surface and associated phonolite and trachyte flow residuals on surfaces up to 150 m above the Miocene surface.
5. Oligocene -	Olivine basalt flows post-dating older igneous bodies but pre-dating the Miocene surface.

The numbering of Day's groups, from 1 to 5, has been adopted for the purpose of the present paper.

More recently, aerial photo interpretation with field studies was carried out by the Geological Survey of New South Wales, and published together with all other available data in the 1:250,000 Geological Series Sheets Singleton S1 56-1(1969) and Dubbo S1 55-4(1971). The probable Cretaceous age of Day's teschenite group 1, and the possible late Mesozoic age of some of the alkaline intermediate group 4, was recognised in the compilation of these geological maps and their legends. For detail outcrop geology of the region, reference should be made to the foregoing maps and Day (1961).

Between 1968 and 1970, the author obtained K-Ar dates for basalt flows in the Ilford-Mudgee-Gulgong district immediately to the south-west of the Wollar-Rylstone region (Dulhunty, 1971). Results revealed middle Miocene flows 13 to 15 m.y. old, lying on the floor of the Cudgegong Valley between Mudgee and Gulgong, and also residuals of late Eocene-early Oligocene flows, 33 to 41 m.y. old, lying on remnants of a presumed Eocene erosion surface between Ilford and Cudgegong. Similar investigations in the upper Castlereagh and Macquarie valleys (Dulhunty, 1972; 1973) revealed middle Miocene valley-fill basalts and high level residuals of late Eocene-early Oligocene flows.

Over approximately the same period, between 1968 and 1970, Wellman and McDougall (1974) dated some basalt flows within the Wollar-Rylstone region, as part of a wide study of Tertiary basalt ages in Eastern Australia. They obtained K-Ar ages of 34.1 to 41.2 m.y., equivalent to late Eocene-

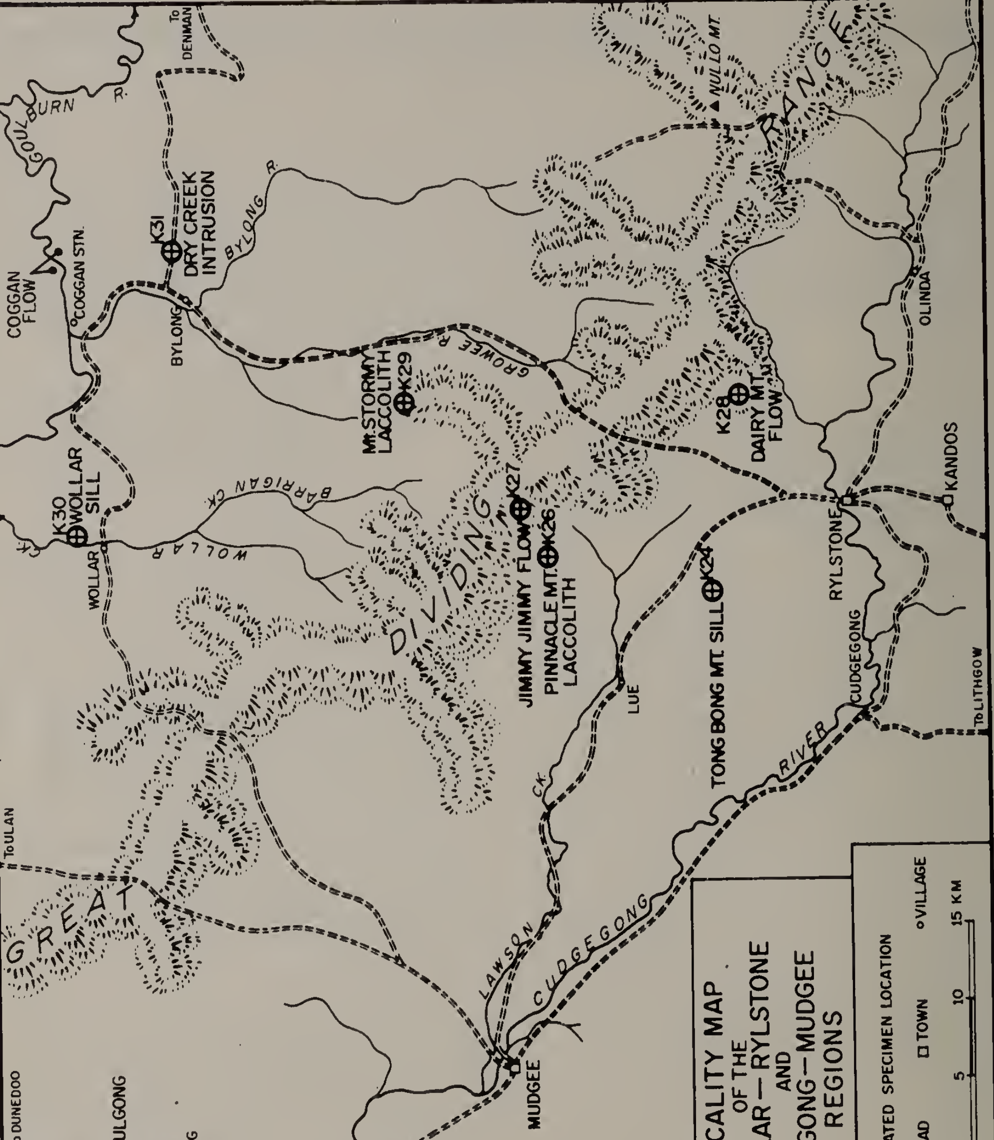

Fig. 1. Locality map of the Wollar - Rylstone and Gulgong - Mudgee regions

early Oligocene, for Nullo Mountain flows belonging to Day's group 3 of monchiquites and monchiquite-basalts. They also found ages of 11.9 to 12.6 m.y., equivalent to late middle Miocene, for flows in the Goulburn Valley, at Coggan Station. McDougall also obtained an age of 179 m.y. for an occurrence of nephelinite at Umbiella Creek, about 30 km to the south south east of Kandos (Harding, 1969).

PRESENT INVESTIGATION

Between 1972 and 1974 igneous rock specimens were collected from two occurrences of the teschenites of group 1, and five occurrences of alkaline intermediate intrusive and flow rocks of group 4, for the purpose of determining their positions in igneous chronology of the region. Localities from which the specimens were collected are shown by specimen numbers in Fig. 1. They are also given, in the following specimen descriptions, by grid references to the 1:250,000 Geological Series Sheets Singleton SI 56-1 and Dubbo SI 55-4 for New South Wales. Several rock specimens were collected at different points on each of the rock bodies within the localities shown. All were fresh in regard to atmospheric weathering, and free from macroscopic evidence of deuteric alteration. They were examined microscopically in thin section and those showing least feldspar alteration and smallest amounts of zeolitic material were selected for K-Ar age determinations by Geochron Laboratories, Cambridge, U.S.A., the results of which are set out in Table 1. The petrological nomenclature used in this paper is based on that adopted by Day (1961).

Specimen K-24. Tong Bong Mt. Sill, 10 km N-W of Rylstone. (SI 55-4, 287955). Age 185±8 m.y. Teschenite. Rock group No. 1.

Collected from western end of sill at approximately 30 m above its base. Coarse-grained and holocrystalline with olivine, titansalite, plagioclase, analcite, alkali feldspar and biotite. Very little feldspar alteration, but some zeolite.

Specimen K-31. Dry Creek Intrustion, 4 km E.N-E of Bylong. (SI 56-1, 313994). Age 198±8 m.y. Teschenite. Rock group No. 1.

Collected on Wollar-Sandy Hollow road, 0.3 km from western margin of intrusion. Medium-grained and holocrystalline with olivine, titansalite, plagioclase, analcite, alkali feldspar, and biotite. Minor feldspar alteration, and very little zeolite.

Specimen K-30. Wollar Sill, 2 km N of Wollar. (SI 56-1, 293000). Age 163±6 m.y. Aegirine microsyenite. Rock group No. 4.

Collected from prominent outcrop north of railway formation, 300 m east of Wollar Creek crossing. Medium-grained, holocrystalline with alkali feldspar, aegirine, analcite, calcite and chlorite. Moderately high feldspar alteration.

Specimen K-29. Mt. Stormy Laccolith, 16 km S.S-W of Bylong (SI 56-1, 302976). Age 179±7 m.y. Aegirine riebeckite phonolite. Rock group No. 4.

Collected from north-west face of laccolith,

TABLE 1
K-Ar AGES OF IGNEOUS ROCKS

Syd. Uni. Spec. No.	Geochron Anal. No.	Occurrence and Group No.	% K	Rad. 40-AR $(10^{-6}$Std.cc/gm$)$	% Rad. 40-AR	Calc. Age m.y. ± 1SD
K-24	R-2226	Tong Bong Mt. Sill. 1.	1.018 1.055	0.806	52.55	185±8
K-31	R-2852	Dry Ck Intrusion. 1.	2.306 2.316	1.928	90.40	198±8
K-30	R-2851	Wollar Sill. 4.	4.601 4.500	3.111	81.75	163±6
K-29	R-2806	Mt. Stormy Laccolith. 4.	4.810 4.821	3.617	90.70	179±7
K-26	R-2392	Pinnacle Mt. Laccolith. 4	4.841 4.789	3.606	89.25	178±7
K-27	R-2471	Jimmy Jimmy Flow. 4.	4.800 4.898	4.449	87.40	216±7
K-28	R-2482	Dairy Mt. Flow. 4.	4.704 4.672	3.946	84.75	199±7

Constants used: $\lambda_\beta = 4.72 \times 10^{-10}$/year; $\lambda_e = 0.585 \times 10^{-10}$/year; $K^{40}/K = 1.22 \times 10^{-4}$ g./g.

60 m above base of outcrop. Medium-grained, holocrystalline, with aegirine, riebeckite, sanidine, nepheline and analcite. Limited feldspar alteration and small amount of zeolite.

Specimen K-26. Pinnacle Mt. Laccolith, 10 km N-W of Lue. (SI 55-4, 292966). Age 178±7 m.y. Aegirine augite phonolite. Rock group No. 4.

Collected from north-western face of laccolith at base of outcrop. Medium-grained, holocrystalline, with aegirine-augite, olivine, riebeckite and nepheline. Limited feldspar alteration with some zeolite.

Specimen K-27. Jimmy Jimmy Flow, 13 km N-W of Lue. (SI 55-4, 294969). Age 216±8 m.y. Olivine trachyte. Rock group No. 4.

Collected from western face of flow, 28 m above its base. Fine-grained, holocrystalline with olivine, pyroxene, sanidine, nepheline, analcite and calcite. Moderate feldspar alteration and some zeolite.

Specimen K-28. Dairy Mt. Flow, 10 km N-E of Rylstone. (SI 56-1, 303954). Age 199±7 m.y. Olivine aegirine-augite phonolite. Rock Group No. 4.

Collected from north-west face of flow, 26 m above its base. Fine-grained, holocrystalline, with olivine, pyroxene, sanidine, nepheline, analcite and calcite. Some feldspar alteration and zeolite.

SIGNIFICANCE OF RESULTS

Further K-Ar dating and field investigations are necessary to establish the full and exact significance of the foregoing results, as the amount of radiometric data is small and argon contents may have been disturbed, however the following tentative conclusions may be drawn:

1. The K-Ar results of 185 to 198 m.y. for the teschenites of group 1 indicate that they are of late Triassic age, confirming Day's conclusion that they were pre Tertiary, but making them much older than Cretaceous.

2. The K-Ar dates of 163 to 179 m.y. for the Wollar Sill and Mt. Stormy and Pinnacle Mt. laccoliths, representing the intrusive microsyenites and phonolites of group 4, indicate an age of early to mid Jurassic. They were injected at, or near, the top of the Permian sediments, arching the overlying early to mid Triassic sediments, which could well have been lithified to sandstone by mid Jurassic time.

3. The dates of 199 and 216 m.y., averaging 207 m.y., for the Jimmy Jimmy and Dairy Mt. flows, indicate a late middle Triassic age, considerably older than the average age of 173 m.y. for the intrusive alkaline rocks of group 4 with which they could be grouped petrographically. Their K-Ar ages averaging 207 m.y., suggest that they were extruded before elevation of eastern New South Wales, on to a sedimentation surface of early to mid Triassic sands, rather than an early Tertiary erosion surface as previously assumed. Late Triassic sedimentation may have continued after extrusion of the lavas which would have become interbedded flows, in a manner similar to the embedding of the Garrawilla flows between late Triassic and early Jurassic sediments, in the Binnaway-Coonabarabran-Gunnedah district (Dulhunty, 1967; 1973). Elevation, commencing possibly in late Cretaceous time, would have first denuded the flows, and then reduced them to residuals during the development of successive Tertiary erosion surfaces.

4. The K-Ar dates by Wellman and McDougall (1974) of 34.1 to 41.2 m.y., averaging 36.8 m.y., for high-level basalt flow residuals near Nullo Mt., belonging to Day's group 3, provide an age of late Eocene-early Oligocene. This confirms the late Cretaceous-early Eocene, or Paleocene, development of the underlying erosion surface now standing only as residuals some 240 m above the predominating Miocene peneplain. The results also confirm correlation of the Nullo Mt. flows with high-level flow residuals on pedestals of country rock occurring along the Main Dividing Range to the south (Dulhunty, 1971; 1972; Wellman and McDougall, 1974).

5. Wellman and McDougall found ages of 11.9 and 12.6 m.y., averaging 12.3 m.y., for a basalt flow on the floor of the Goulburn Valley at Coggan Station, near Bylong (Fig. 1). Therefore the Coggan flow is of middle Miocene age (Berggren, 1972; Funnell, 1964) and equivalent to the valley-floor flows at and below, the Cudgegong river level at Guntawang, near Gulgong (Dulhunty, 1971) on the western side of the Main Divide (Fig. 1). Recent field investigations by the present author, established the fact that the Coggan flow lies on an old valley-floor (representing a former erosion surface) 80 m above the present bed of the Goulburn River. Large blocks of basalt, up to 2.5 m across, had slumped down steep slopes to present river level, and become partly buried in recent alluvium, but no flow basalt was found in-situ below 80 m above river level. The data suggest that the Goulburn River, flowing east from the Main Divide, has lowered its bed at Coggan by 80 m since the extrusion of the middle Miocene basalt, whilst the Cudgegong River, flowing west, has not lowered its bed at all, near Gulgong, since middle Miocene time.

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Structural Interpretation of New England Region—Discussion

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The paper, "Structural Interpretation of New England Region" by Dr. Emile Rod (1974), represents a criticism of the recent work of the Geological Survey of New South Wales compiled by Pogson (1972) and the suggested structural subdivision of the State by Scheibner (1972).

Although Rod (1974) rightly criticises the usage of the redundant term "Brisbane Block" (Scheibner, 1972), this was corrected before his criticism (cf. Scheibner, 1974), there are many points on which Rod (1974) himself should be corrected. Unfortunately, he has relied mainly on previously published geological maps and other published geological information (cf. Rod, 1974, p. 98). It is hazardous to rely solely on published information, because the rapid progress of geological investigations means that publications are outdated before they reach the reader. Geological maps become outdated during the process of drafting and printing, especially preliminary large-scale maps of the 1:250 000 series, and technical production cannot keep up with the flow of new information. This problem is being overcome by the updating of all available information at the Geological Survey of New South Wales and this is available on request. Therefore, Rod's remark (p. 90) that "Not one map agrees with the other on the age assignment" indicates that he does not appreciate this situation. If some of Rod's criticism is based on direct observation and field evidence, then he gives no reference to this work in his paper.

The State geological map was compiled on the basis of information available in December, 1971 which is still to a large extent unpublished or has been published only recently (for example Leitch 1974). This information was not considered by Rod and therefore his criticism is unjustified. The structural subdivision of New South Wales was first published by Scheibner (1972) and not Pogson (1972); hence, his criticism is wrongly directed. Rod, instead of approaching the State Survey with a request for an explanation (which is the normal procedure in the search for unpublished information), has made allegations of "guesswork" (Rod, 1974, p. 90). His criticism is not constructive. He has retreated even from the stage of knowledge achieved 15 years ago (Voisey, 1959), leaving the eastern part of the New England Fold Belt as an unnamed white "*terra incognita*" (Rod 1974, fig. 5).

The geology of the New England Fold Belt is very complicated and its explanation is hindered by the fact that the mostly flysch-like, metamorphosed and often structurally highly deformed, sequences contain few fossils. Despite this, it has been possible to establish several major lithological associations which have general stratigraphic validity. Recently, Leitch (1974) gave a brief description of these lithostratigraphic associations. More fossil evidence was gathered and reviewed by Fitzpatrick (1975), and the bio- and lithostratigraphy of Silurian sequences is reviewed in Pickett (in prep.). Further relevant data have been published by Runnegar (1974), McKelvey (1974) and Leitch (1974, where a useful list of published and unpublished sources is given).

In the light of the above facts, we have to refute the statements and arguments of Rod (1974) as unfounded in respect of stratigraphic position of lithological associations shown on the State geological map (Pogson 1972). This of course does not mean that changes and improvements have not been made or will not occur in the future.

Rod (1974), after firstly rejecting the stratigraphic value of major lithological associations, argued that the structural subdivision of the New England Fold Belt (Scheibner, 1972) is "ill-founded guesswork" (p. 90). Because Rod (1974, p. 90) based his argument on a false statement, we reject it. Our rejection of his argument is supported by the recently published structural subdivision of the New England Fold Belt by Leitch (1974), who also recognized a whole series of major blocks. However, it is fair to state that certain, in our opinion only minor, differences exist between the two structural subdivisions (Scheibner, 1972, in press, and in prep.; and Leitch 1974).

Based on published and unpublished data available in 1970-71, it appeared justified to replace the earlier structural scheme of Voisey (1959). The "Western Belt of Folds and Thrusts" and the "Eastern Belt of Folds and Thrusts" of Voisey (1959) have a similar geological history and are physically continuous, only part of them being separated by faults south of Taree. This was the reason for replacing the two structural units of Voisey (1959) by the term Tamworth Synclinorial Zone. To indicate the fact that the eastern part of this zone is fault bounded and separated from the rest of the zone by faults south of Taree, the term "Kempsey Block" was introduced (Scheibner, 1972). Later it was discovered that the eastern part of this block is more closely related to the Nambucca Block (Leitch 1974) and is fault bounded against the rest of the original "Kempsey Block" (cf. Letich, 1974; Harrington, 1974; Runnegar, 1974). It is suggested now that the name Kempsey Block be restricted to this eastern block which is related to the Nambucca Block on the north. The name Hastings Block (Leitch, 1974; Harrington, 1974) should be used for the rest of the original "Kempsey Block" of Scheibner (1972).

The terms "Central Complex" intruded by the "New England Granite Batholith" and the "Upthrust Blocks" of Voisey (1959), the "New England Massif" with the "Texas Structural High" of Hill and Denmead (1960), the "New England High" (Geol. Soc. Aust., 1971) were replaced by the more discrete structural terminology: Woolomin-Texas, Demon, Emu Creek, Brisbane (should be Beenleigh), Port Macquarie, and Nambucca Blocks. Some of these blocks are anticlinorial (elevated) consisting generally of early-mid Palaeozoic complexes, while others are synclinorial (depressed) and comprise late Palaeozoic complexes. These blocks differ in tectonic style, and Leitch (1974) indicated their properties in tabular form (Leitch, 1974, table 1). The boundaries of these blocks are faults and therefore they are well defined. It would appear that Rod is not aware of the existence of these faults. The only acceptable criticism is in respect of the redundant naming of the Beenleigh Block as discussed earlier.

It is considered unnecessary to repeat descriptions of the structure of the New England Fold Belt as outlines have recently been published (Leitch, 1974; Runnegar, 1974; Scheibner *in* Markham and Basden, 1975) and a more detailed description will be available soon (Scheibner in press and in prep.).

The structural terminology suggested for New South Wales (Scheibner, 1972) was published in the form of a map at a scale of 1:6,000,000 and only recently has some written explanation been published (cf. Markham and Basden, 1975). It is therefore surprising that Rod (1974, p. 91) states "The validity and wisdom of calling eleven structural units of New South Wales 'Synclinorial Zones' will not be discussed here." How well founded is such a statement if he does not know the background and reasons for the suggested terminology?

The terms *anticlinorial zone* and *synclinorial zone* denote major and composite regional structural units in fold or orogenic belts of anticlinal or elevated and synclinal or depressed character, and these zones are characterized by their tectonic style. Sometimes block tectonics is so important in a fold belt or in a sector of it that it is more convenient to distinguish regional structural blocks which again can be elevated and anticlinal or depressed and synclinal. The terms *anticlinorial* and *synclinorial zones* are used because these structural units are composite and often within them synclinoria and anticlinoria occur. Therefore, there is a need for the higher category term.

The above definition follows Shatski and Bogdanoff (1959) who stated that "The main structural elements in folded regions are anticlinoria and synclinora, which are often grouped in anticlinal and synclinal zones." They applied the term anticlinoria to "quite large complex folded structures, whose cores consist of the rocks of lower structural stages and which are generally characterized by a long period of usually inherited development." They applied the term synclinoria to "...large and complex synclinal downwarps, filled with the folded rocks of upper structural stage." It is necessary to clarify that the above folded regions of fold belts (=orogenic belts) develop from marginal mobile zones by interaction of lithospheric plates. For the pacific-type marginal mobile zones, anticlinorial and synclinorial zones and blocks are typical after the change of mobile zones into fold belts, while fold belts which develop from mediterranean-type marginal mobile zones are characterized by thrusts and nappe structures.

Shatski and Bogdanoff (1959) have written that synclinoria form in place of former troughs and anticlinoria in place of former uplifts. This is basically correct when the tectonic development is a straight forward process. However, many tectonic features (stratotectonic) change in character during their evolution, and tectonic inversion can occur before their final cratonization. After tectonic inversion a former trough behaves as an elevated zone and later after final cratonization it changes into an anticlinorial zone. Delineation of structural zones helps in the understanding of the tectonic history of the studied region.

Anticlinorial zones are composed of the oldest rocks and the more deeply eroded intrusions and metamorphics, while synclinorial zones contain the younger and youngest rocks, often with the rocks of the transitional tectonic provinces preserved in superimposed synclinoria. The boundaries between structural zones can be hinge lines, regional faults, reverse faults, thrusts, intrusive bodies etc.

We consider the employed structural subdivision of New South Wales a very useful framework for the description of various aspects of geology and tectonic development (cf. Markham and Basden, 1975).

Rod (1974), following some other geologists, replaced the term "thrust" by "fault" in the name Peel Thrust. It is possible to do this because any thrust is a fault. But it is well known that the Peel Thrust dips to the east and very different rock complexes are juxtapositioned along it. Oceanic lithospheric material occurs on the thrust (Great Serpentinite Belt) and the minimum indisputable displacement on the thrust must be from the base of the oceanic crust (Woolomin Beds with interbedded basalts) of the Woolomin-Texas Block to the high crustal levels of the Tamworth Synclinorial Zone, even if the serpentinites were emplaced as cold diapirs.

In many other orogenic belts thrust faults are often steeply dipping, especially if additional deformation and uplift have occurred. Compression and tilting will change the original dip. Therefore, in respect of Rod's criticism (Rod, 1974, p. 93) of the low dips of the Peel Thrust shown by Scheibner and Glen (1972) it is necessary to mention that these dips are on hypothetical palinspastic sections constructed for late Palaeozoic time and do not indicate the present situation. On the other hand (Rod, 1974, figure 3, section 9), there is no basis for showing a westerly dip of the Peel Thrust below 5 km.

Rod's statement (p. 91) that the Peel Thrust does not curve can be easily refuted by inspection of the satellite photo mosaic which is available at the Geological Survey, but curving is obvious also on the State Geological Map. Between Warialda and Moonbi the Peel Thrust describes an irregular arc with radius of about 250 km. A similar arc can be detected between Warialda and an area west of Yetman (Bourke, 1974; Runnegar, 1974; Scheibner, 1973), where the Peel Thrust was recognised on LANDSAT-1 (ERTS-1) images. The Peel Thrust and the Woolomin-Texas Block south of the New England Highway has been transversely offset, but the arcuate shape of the Peel Thrust is indisputable here also (cf. new mapping by Fitzpatrick, 1975). From the Hanging Rock area the Peel Thrust has been traced into the upper Manning Valley where it is displaced by numerous faults (cf. Pogson, 1972; Runnegar, 1974, fig. 2; Leitch, 1974, fig. 2; Scheibner, 1974). It is interesting to note that the larger map in figure 5 (Rod, 1974) has a tendency to show the Peel Thrust as a straight line, while the smaller map, an insert in figure 5, shows the curving nature quite clearly.

Rod's opposition to the curving of the Peel Thrust in plan stems from the fact that the geometry of the Peel thrust combined with its general easterly dip indicates that thrust or at least reverse dip-slip movement has occurred on it, and he is basically opposed to the thrust interpretation. The interpretation that the Peel Thrust is indeed a major thrust fault is not new (Benson, 1913) and it has been recently supported by others (cf. Runnegar, 1974).

Strike-slip movement along the Peel Thrust has been previously suggested by some authors (Crook 1963, Scheibner 1972 and Glen 1972, and also Voisey 1959 if the faults in the Manning River Valley are a continuation of the Peel Thrust), but all of them suggested right-lateral displacement, while Rod (1974, p. 93) wrote "it can be regarded as certain that it has a horizontal component with a left sense of displacement." Yet his arguments in support of the above quoted statement are insufficient and some, especially the secondary faults and the folds, support the earlier interpretations (cf. Crook, 1963).

With regard to the Mihi Fault, Rod has obviously overestimated its importance. Its position has been modified as a result of new mapping (cf. Leitch, 1974, fig. 2), and some authors even doubt its existence as is witnessed by its omission by Runnegar (1974, fig. 2). Rod (1974, p. 95) suggested that the Mihi Fault intersects the Peel Thrust 8 to 10 km southeast of Hanging Rock at an angle of 40°. Recent geological mapping by Fitzpatrick (1975) and Heugh (1971) in the critical area between the Mihi Fault and the Peel Thrust showed that many faults occur parallel to the Peel Thrust (cf. Pogson and Hitchins, 1973; Leitch, 1974, fig. 2), but none of these has the orientation predicted by Rod. The Tamworth Synclinorial Zone and the Woolomin-Texas Block Structures do not terminate on the projection of the Mihi Fault as suggested in figure 5 (Rod, 1974). Splay and radial faults occur not only in the area indicated in figure 5 (Rod, 1974, p.97) but in the whole area north of the Hunter Thrust (cf. Pogson and Hitchins, 1973; Pogson, 1972, Leitch, 1974, Scheibner 1974). It is possible, however, that some fracturing occurred at a later time along the projection of the Mihi Fault, as has been observed with many other faults in the State (cf. Scheibner, 1973).

The extension of the Demon Fault to the south is not questionable (Rod, 1974, p. 95) but real (cf. Letich 1974, fig. 2; Runnegar, 1974, fig. 2), and it is one of the most distinctive features observable on satellite imagery in this State (Scheibner, 1973). There are faults in the Nambucca Block in the projection of the Demon Fault (cf. Leitch 1974, fig. 2; Scheibner 1973), but there is indeed a substantial difference between the Demon Fault and the related fault in the Nambucca Block namely that major strike-slip displacement occurred along the Demon Fault (cf. Shaw *in* Packham, 1969).

Rod (1974, p. 95) suggested usage of the term "New England Block" in much the same sense as the earlier "New England Massif" or "New England High", but he forgot that the original meaning of those terms included not only areas defined by him but also those left blank in his figure 5. Besides this, some Queensland authors (cf. Stevens, 1969) used the term "Texas Block" for part of the area defined as the "New England Block" by Rod (1974). The reasons for the introduction of the term Woolomin-Texas Block, which is internally composite (cf. Leitch, 1974, fig. 2), was to separate out an anticlinorial crustal block composed mostly of the oldest complexes of the New England Fold Belt.

Rod (1974) used the term "Tamworth Fold Belt" for part of the Tamworth Synclinorial Zone. The term "fold belt" is used for large orogenic entities (cf. Dennis, 1967). The whole New England region is part of the orogenic belt - the New England Fold Belt (Packham 1969, Scheibner, 1972; Leitch, 1974). The Tamworth Synclinorial Zone is part of this orogenic belt. In Rod's terminology the Tamworth Synclinorial Zone appears to be an independent orogenic belt (Tamworth Fold Belt). Because he discarded the term New England Fold Belt, and referred to part of it as the "Tamworth Fold Belt", the rest of the main orogenic belt can be interpreted as being non-orogenic. In using this terminology, Rod has caused confusion in the clear hierarchy of structural categories.

A further discrepancy occurs in Rod's paper (1974, p. 95) where he stated that the Tamworth Synclinorial Zone is a 40-50 km wide fault zone; yet he named it the "Tamworth Fold Belt."

In conclusion, we would like to point out again that Rod's (1974) criticism was based on outdated information. Progress in the knowledge of the geology of the New England Fold Belt warranted publication of new maps (Pogson, 1972; Pogson and Hitchins, 1973) and a new structural subdivision

(Scheibner, 1972), and only further field work will show where improvement and changes to these should be made.

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Structural Interpretation of New England Region—Reply

EMILE ROD

I appreciate the opportunity provided by Pogson and Scheibner in their discussion of my paper (Rod, 1974b) to set right some misconceptions.

The scope of the paper under discussion - as stated in the introduction - was to present the results of a study of the geology and to set forth the conclusions of my investigations on the structural interpretation of the New England Region. Pogson and Scheibner allege in their introductory sentence that my paper "represents a criticism of the recent work of the Geological Survey of New South Wales compiled by Pogson (1972) and the suggested structural subdivision of the State by Scheibner (1972)." I disagreed with many structural interpretations of Scheibner as advanced by him in several publications and also shown on some maps issued by the Geological Survey of New South Wales. I found some deficiencies on maps and have commented on them previously. If the scope would have been to write a detailed criticism of the documentation which I had to use, it would have required a book.

In early 1973, when I started to scrutinize the geological maps of the New England Region in preparation of the paper under discussion, I found that on several maps the sections were not correctly constructed, that the effects of vertical exaggeration on angles of dip and on the distribution of the rock masses in cross-sections was not understood by some geologists compiling those sections. On nine adjoining sheets of the New England Region the sections were compiled at six different vertical exaggerations and on two sheets the ratio of vertical exaggeration shown on the maps was erroneous.

Prompted by my findings on those maps of the New England Region and by some observations on indiscriminate use of vertical exaggeration in geological sections in other publications, I decided to write a concise discussion on the use of vertical exaggeration in cross-sections (Rod, 1974a). This was a critical study which I wished to separate from the main body of my paper. However, for obvious reasons nobody from the Geological Survey had any comments to make up to now on this short paper entitled "Misrepresentations by indiscriminate use of vertical exaggeration in geological sections".

None of my critical remarks about the quality of some information shown on certain geological maps produced by the Geological Survey of New South Wales have been refuted. Merely a few weak excuses have been made.

However, if as a result of my comments the maps produced by the Geological Survey of New South Wales should one day reach the standards of excellence of the maps issued by the Geological Surveys of the neighbouring States of South Australia and Queensland (produced in Queensland in partnership with the Bureau of Mineral Resources, Geology and Geophysics), then my remarks will have served a good purpose.

In the opening barrage of arguments in their attack on my paper, Pogson and Scheibner more or less imply that I did not duly consider certain publications. It is a puzzle how the papers by Runnegar (1974), McKelvey (1974) and Leitch (1974) should have influenced my thinking when I was studying the geology of New England in early 1973.

I am not a wizard. How could I consider a paper which was published after I had completed the manuscript and submitted it to the editor? The manuscript of my paper (1974b) was received by the Royal Society of New South Wales on December 13, 1973 (see J. Proc. Roy. Soc. N.S.W., 107, 99). Leitch's article was issued in June 1974. Some other similar unreasonable claims are made by Pogson and Scheibner.

They also mention that "the bio- and lithostratigraphy of Silurian sequences is reviewed by Pickett (in prep.)." All my respects to Pickett. I am looking forward to read his paper which by July 1975, had not yet been published. But what has Pickett's study of 1975 to do with a criticism of my paper written in 1973?

After misquoting me on "ill-founded guesswork", a phrase I did not use, Pogson and Scheibner further state: "Because Rod (1974, p.90) based his argument on a false statement, we reject it." They omit to say what my "false statement" is. Then they continue: "Our rejection of his argument is supported by the recently published structural subdivision of the New England Fold Belt by Leitch (1974), who also recognized a whole series of major blocks".

The two sentences of Pogson and Scheibner quoted above are a distortion of the facts.

In Figs 1 and 2, some of the subdivisions crucial for this discussion of the New England Region are shown. Fig. 1 is a copy of Fig. 4, the same illustration published by me in the paper under discussion (Rod, 1974b). It is after the map entitled "structural units of New South Wales" in Scheibner (1972) and Pogson (1972). Fig. 2 is a new sketch map after Fig. 3 of Leitch (1974).

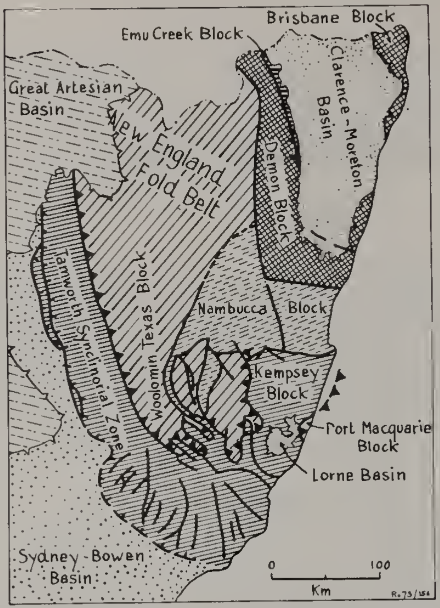

Fig. 1. Structural units of New England Region after portion of map called "Structural units of New South Wales" included in Geological Map of New South Wales 1 : 1 000 000 (Pogson, 1972). The colours of the original map have been rendered here by black and white patterns. After Scheibner (1972) and Pogson (1972).

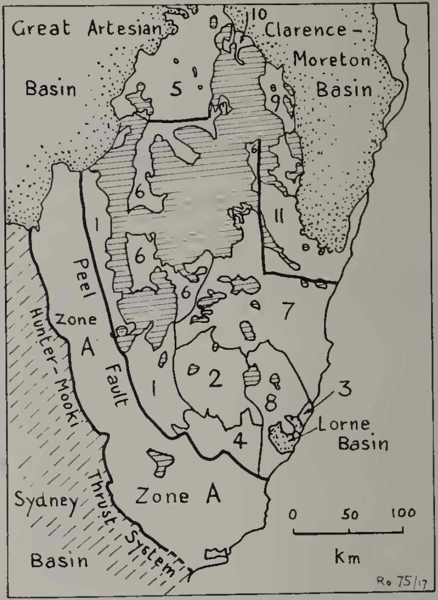

Fig. 2. Major blocks recognized by Leitch (1974) within Zone B of New England Region (after Fig. 3 of Leitch, 1974).
Key to names of blocks:
(1) Macdonald, (2) Yarrowitch, (3) Port Macquarie, (4) Manning, (5) Bonshaw, (6) Armidale, (7) Nambucca, (8) Hastings, (9) Tabulam, (10) Warwick, (11) Coffs Harbour. Horizontal lines: granitic rocks and Late Permian acid volcanics.

It should not be too difficult to see that the major blocks recognized by Leitch (1974) have very little in common with Scheibner's blocks of 1972, as Pogson and Scheibner later in the discussion also admit. Scheibner's Kempsey Block is taken up on Leitch's map by a portion of the Nambucca Block and the Hastings Block. The many finger-like lobes and tooth like protuberances assigned by Scheibner to his Woolomin-Texas Block and Nambucca Block (dove-tailed portion) west of his Kempsey Block, are separated under the names of MacDonald, Yarrowitch and Manning Blocks by Leitch (1974). Seven months after my paper was published Pogson and Scheibner are now making some corrections on the delineation and definition of Scheibner's blocks.

Leitch (1974) is honest about the definition of his blocks. He writes: "Recognition of the blocks is subjective". From his remarks and from an inspection of Table 1 (Leitch 1974), it should be obvious that Leitch's blocks are descriptive areal terms for certain lithologic associations. Thus Leitch's blocks have not been defined as structural units.

My remark on the validity of calling eleven structural units of New South Wales "Synclinorial Zones" gave Pogson and Scheibner the pretext to embark on a dissertation on the merits and definitions of anticlinorial and synclinorial zones. Pogson and Scheibner try to find support for their arguments in the definition and terminology used by Shatski and Bogdanoff (1959) in the tectonic map of Russia and the adjoining countries. What might be suitable for Russian conditions is not necessarily appropriate here. Moreover, from the sentence quoted below, it seems that Pogson and Scheibner simply mean "elevated" and "depressed" when they apply the terms "anticlinorial" and "synclinorial": "Some of these blocks are anticlinorial (elevated) consisting generally of early mid Palaeozoic complexes, while others are synclinorial (depressed) and comprise late Palaeozoic complexes".

Another instance of misinterpreting statements made by me can best be illustrated by the following sentence in Pogson's and Scheibner's discussion: "A further discrepancy occurs in Rod's paper (1974, p.95) when he stated that the Tamworth Synclinorial Zone is a 40-50 km wide fault zone; yet he names it the "Tamworth Fold Belt"."

What I said is "..... it might be suggested that the Peel Fault and the Mooki Thrust are actually just the border faults of one 40 km and to 50 km wide fault zone now known under its three main component parts, namely the Peel Fault, Tamworth Fold Belt and Mooki Thrust".

Pogson's and Scheibner's remarks on outdated information are difficult to understand in view of the fact that they themselves considered this problem at the beginning of their discussion. On very rare occasions only is it possible to have a short geological note or a discussion published within two to three months after it is submitted to the editor. Normally the delay is six months to two years. This delay is unavoidable. Scheibner (1973) should have some good first-hand experience in this matter. His manuscript was received by the Geological Society of Australia in May 1972 and the Journal containing his paper was issued in January 1974, thus 20 months later. Moreover, when Scheibner's manuscript was submitted in May 1972, less than 20 per cent of text and illustrations was original. Most of the text and 13 out of 16 figures had already been shown in the same form in one or more other publications.

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As for discussion by Pogson and Scheibner with the following change and additions.

Rod, E., 1974 becomes Rod, E., 1974b.

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The Early Carboniferous Marine Transgression in the Merlewood Formation, Werrie Syncline, New South Wales

DAVID MOORE AND JOHN ROBERTS

ABSTRACT. The Kyndalyn Member of the Merlewood Formation in the Werrie Syncline represents a marine transgression into a sequence of terrestrial sandstone, conglomerate, shale and interbedded volcanics. Lithologically the Kyndalyn Member consists mainly of mudstone, but has concentrations of oolitic limestone conglomerate and polymictic conglomerate in the south, and oolitic and skeletal limestone in the north. Analysis of the fabric of the oolitic limestone conglomerate and the distribution of sediment types suggests that the Kyndalyn Member was deposited on a shallow marine shelf east of a north-south trending coastline: the coast was marked by a pebbly beach in which the gravel was concentrated by wave action during the transgression; mudstone accumulated below wave base on the shelf; and oolitic and biohermal limestone accumulated on local banks, oolites occasionally being swept on to the beach forming oolitic limestone conglomerate. Geological mapping shows that the Kyndalyn Member incorporates the fossil horizons from Hill 60, Watts Babbinboon, and Wolli in a discrete unit within the Merlewood Formation, providing confirmation of Roberts' (1975) contention that faunas from all of these localities belonged to the same stratigraphic level: the *Gigantoproductus tenuirugosus* Subzone of the *Delepinea aspinosa* Zone. Consequently, the Namoi Formation, to which the Watts Babbinboon fauna was originally assigned, can confidently be dated as no younger than *Schellwienella* cf. *burlingtonensis* Zone, or late Tournaisian to early Visean; and the Merlewood Formation, which contains the Kyndalyn Member, as middle to late Visean.

INTRODUCTION

The Devonian and Carboniferous succession in the Werrie Syncline constitutes part of the Western Belt of Folds and Thrusts of Voisey (1959) or the Tamworth Synclinorial Zone of Scheibner (1973). The sediments represent a transition from moderately deep water conditions in the Devonian to shallow marine and then terrestrial conditions during the Carboniferous (Fig. 1). The Merlewood Formation in the Werrie Syncline was deposited in response to a regression following the onset of widespread volcanism in the middle Visean. Uplift of a high volcanogenic province in the west resulted in the accumulation of coarse lithic sandstone conglomerate, shale and interbedded volcanics. During the late Visean, towards the end of deposition of the Merlewood Formation, a transgression produced an intercalation of marine mudstone, sandstone, conglomerate and limestone in the upper part of the formation. Marine sediments had been mapped on the western side of the Werrie Syncline by Carey (1934) but were not known to have been as extensive as proved by recent mapping (Moore, 1974 unpubl.). This paper defines the marine intercalation as a new member, the Kyndalyn Mudstone Member, of the Merlewood Formation, and discusses the style of sedimentation.

The Werrie Syncline was mapped by Carey (1934), and further work on the northern part of the syncline was published by Voisey & Williams (1964), White (1964), and Roberts (1975). The most recent investigations were stimulated by a biostratigraphical study of Carboniferous faunas in eastern Australia by Roberts (1975). Roberts, from work in the Hunter-Myall district, N.S.W., realized that the rich coral and brachiopod fauna from Watts Babbinboon, described by Campbell (1957), had an anomalous age in relation to that of other faunas in the Namoi Formation. Faunas from the Namoi Formation on either limb of the Werrie Syncline, including localities almost immediately beneath the Merlewood Formation, belonged to the *Schellwienella* cf. *burlingtonensis* Zone (late Tournaisian to early Visean), whereas the Watts fauna was assigned to the upper part of the *Delepinea aspinosa* Zone (late Visean). The Watts fauna, however, had been used to date the upper part of the Namoi Formation in the Carboniferous correlation chart of Jones et al. (1973) because Campbell (1957), on the basis of field relationships on Carey's (1934) geological map, suggested that the fauna came from an horizon 30 m below the Merlewood Formation. Roberts (1975) demonstrated that the Merlewood Formation did not close around the axis of the syncline south of Babbinboon, as shown by Carey, but that it extended north of the Babbinboon - Somerton road and therefore enclosed the fossiliferous sediments at Watts. A number of important species from the Watts horizon were also shown to be present in the Hill 60 Member on the western side of the syncline, and in a marine intercalation in the Merlewood Formation at Wolli discovered by Wallis (1970, unpubl.), again suggesting that the Watts horizon was located stratigraphically within the Merlewood Formation. Moore (1974, unpubl.) subsequently mapped a marine member, the Kyndalyn Mudstone Member, extending from the Babbinboon region southwards on either side of the Werrie Syncline. The member is composed dominantly of mudstone with subordinate sandstone, conglomerate and limestone, and includes the well known Hill 60 Member, and the fossil localities at Watts Babbinboon, and at Wolli.

MERLEWOOD FORMATION

The Merlewood Formation in the Werrie Syncline was originally mapped by Carey (1934) and referred to the Lower Kuttung. Voisey & Williams

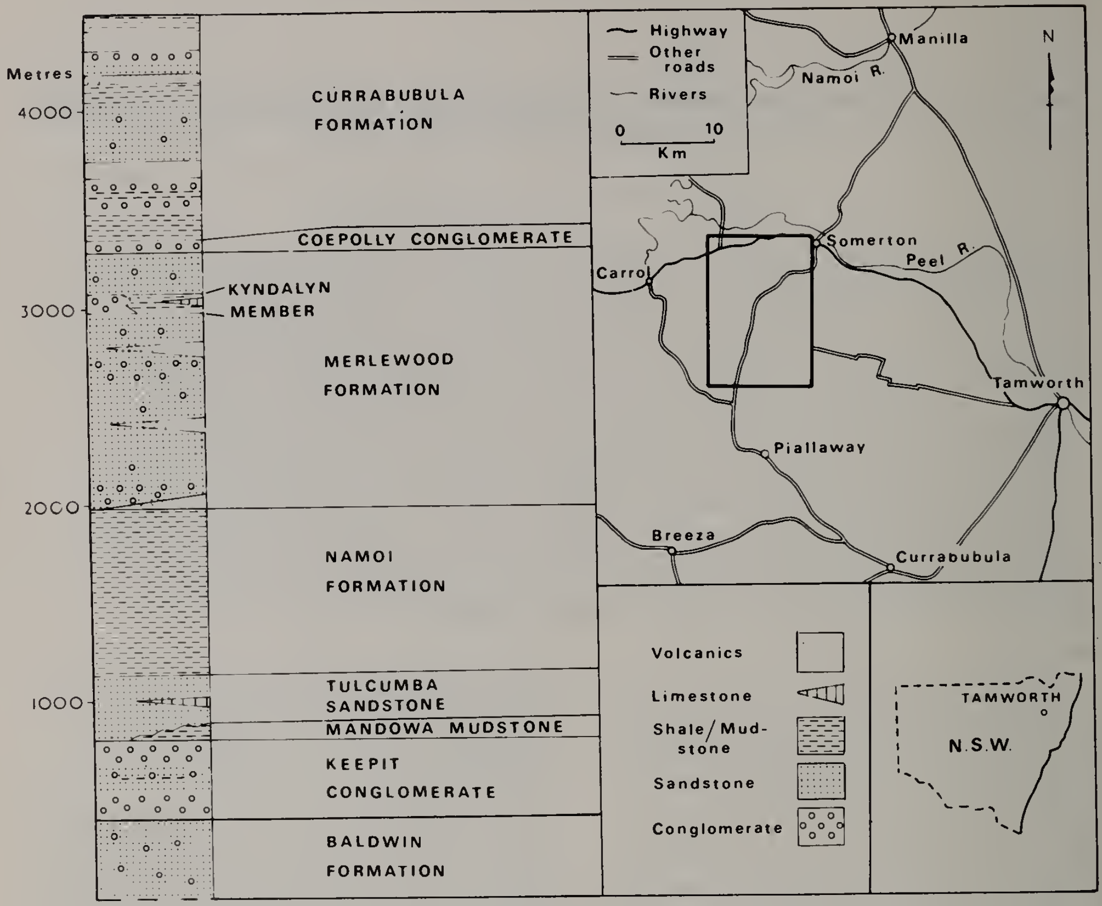


Fig. 1. Locality maps and stratigraphic succession in the northern portion of the Werrie Syncline

(1964) later introduced the name Merlewood Formation and recognized a number of members within the formation; two of their six formally named members, the Hill 60 and Myall Camp Members, and one unnamed pyroxene andesite, were mapped in the northern region of closure of the syncline. White (1964) in a map covering the Tamworth 1:100 000 sheet, also mapped the Hill 60 Member and unnamed andesites.

In the northern part of the Werrie Syncline the Merlewood Formation appears to overlie conformably the Namoi Formation. The contact between the two units appears to be mainly gradational as indicated by the change from shallow water limestones in the top of the Namoi Formation to beach and heavy mineral sands in the lower part of the Merlewood Formation, and the intertonguing of the two formations on the eastern limb of the syncline. Erosional contacts, demonstrated by the truncation of an andesite west of Glen Oak, are also present (Fig. 3). Crook (*in* Packham et al., 1969) has reported evidence of a low angle unconformity between the units on the eastern side of the syncline. The Merlewood Formation consists predominantly of coarse pink to buff lithic sandstone, which frequently has cross stratification and scour and fill structures; lensoidal polymictic conglomerate containing clasts of volcanics and plutonics, including a characteristic pink porphyry; and minor magnetite sand bodies and blue to brown silty mudstone. Pyroxene andesite flows are present at three horizons in the Merlewood Formation on the western limb of the syncline. The second and third flows were named Woodlands and Duri Andesite Members respectively by Voisey and Williams (1964).

Kyndalyn Mudstone Member

The Kyndalyn Mudstone Member is named after the property 'Kyndalyn' at Babbinboon. The type section, located in Donnellys Springs Creek (591594 - 595595 Winton 1:31 680 sheet) comprises 170 m of interbedded mudstone, siltstone and minor lithic sandstone. The sediments are buff to brownish green in colour, and consist of quartz, feldspar, oolite grains and rock fragments set in

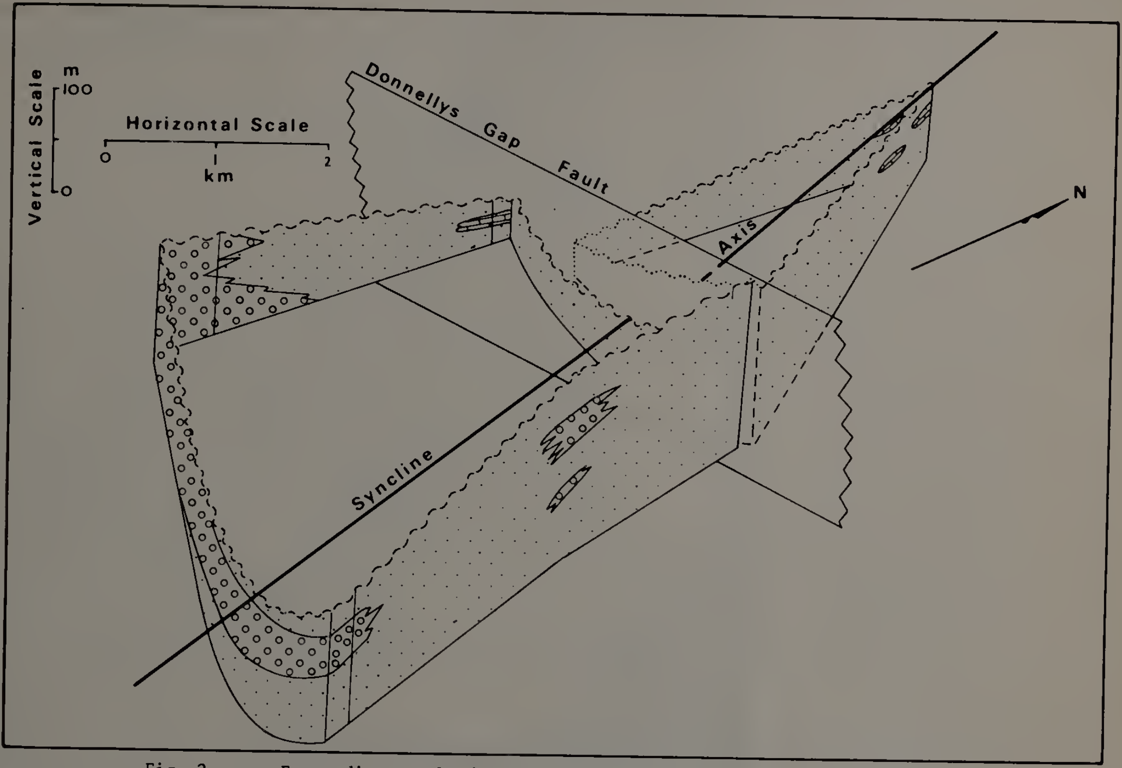


Fig. 2. Fence diagram showing the variation within the Kyndalyn Member

a chlorite or calcite-rich matrix; the silty beds have a rich marine invertebrate fauna. The contact with the underlying terrestrial sediments of the Merlewood Formation is gradational but there is an abrupt change from marine mudstone to pink lithic sandstone and conglomerate suggesting a disconformity on the upper surface of the member.

Lateral changes in lithology take place both south and north of the type section (Fig. 2). In the south, the member contains or is entirely represented by lenses of either oolitic limestone conglomerate or polymictic conglomerate. Both types contain well rounded and well sorted clasts of andesitic volcanics, plutonic rocks, quartzite and limestone. The limestone conglomerate, such as that 1.4 km east of Merlewood originally termed the Merlewood Beach horizon by Carey (1934), contains a large proportion (60% of clasts) of disc, blade and rod shaped pebbles set in a matrix of oolites. The oolites comprise between 30% and 70% of the rock and are frequently broken; those conglomerates with a high proportion of oolites are cross-bedded. The limestone conglomerate east of Merlewood is up to 60 m thick, extends laterally for about 1 km, and is overlain disconformably by terrestrial sediments of the Merlewood Formation. The polymictic conglomerates are less well sorted, have fewer disc, blade or rod-shaped pebbles, and contain less than 5% of carbonate in the matrix. The two types of conglomerate are not interbedded but are lateral equivalents.

North and west of the type section oolitic and bioclastic limestones are present within the Kyndalyn Member. The Hill 60 Member of Voisey and Williams (1964), in the west, consists of interbedded oolitic and bioclastic limestone up to 30 m in thickness; it is cut by the Donnellys Gap Fault in the north and lenses out in less than 1 km southwards. At the northern closure of the Kyndalyn Member near Babbinboon, scattered outcrops of oolitic limestone up to 5 m in thickness overlie a sequence of mudstone and sandstone and form caps on a number of low hills. The limestones probably belong to one horizon; they contain oolites 0.5 to 2 mm in diameter, and less than 5% of quartz and rock fragments set in a micrite cement. The northernmost limestone is overlain by mudstone and is also intruded by a basalt plug.

Environments of deposition in the Kyndalyn Member

(a) Fabric analysis of the limestone conglomerate

The high degree of rounding and sorting in the limestone conglomerate supports Carey's (1934) original suggestion that the sediment was deposited on a beach. Gravel on beaches is usually better sorted than that of fluvial origin (Pettijohn, 1957), and in addition tends to contain a predominance of disc or blade like pebbles (Bluck, 1967). Selective

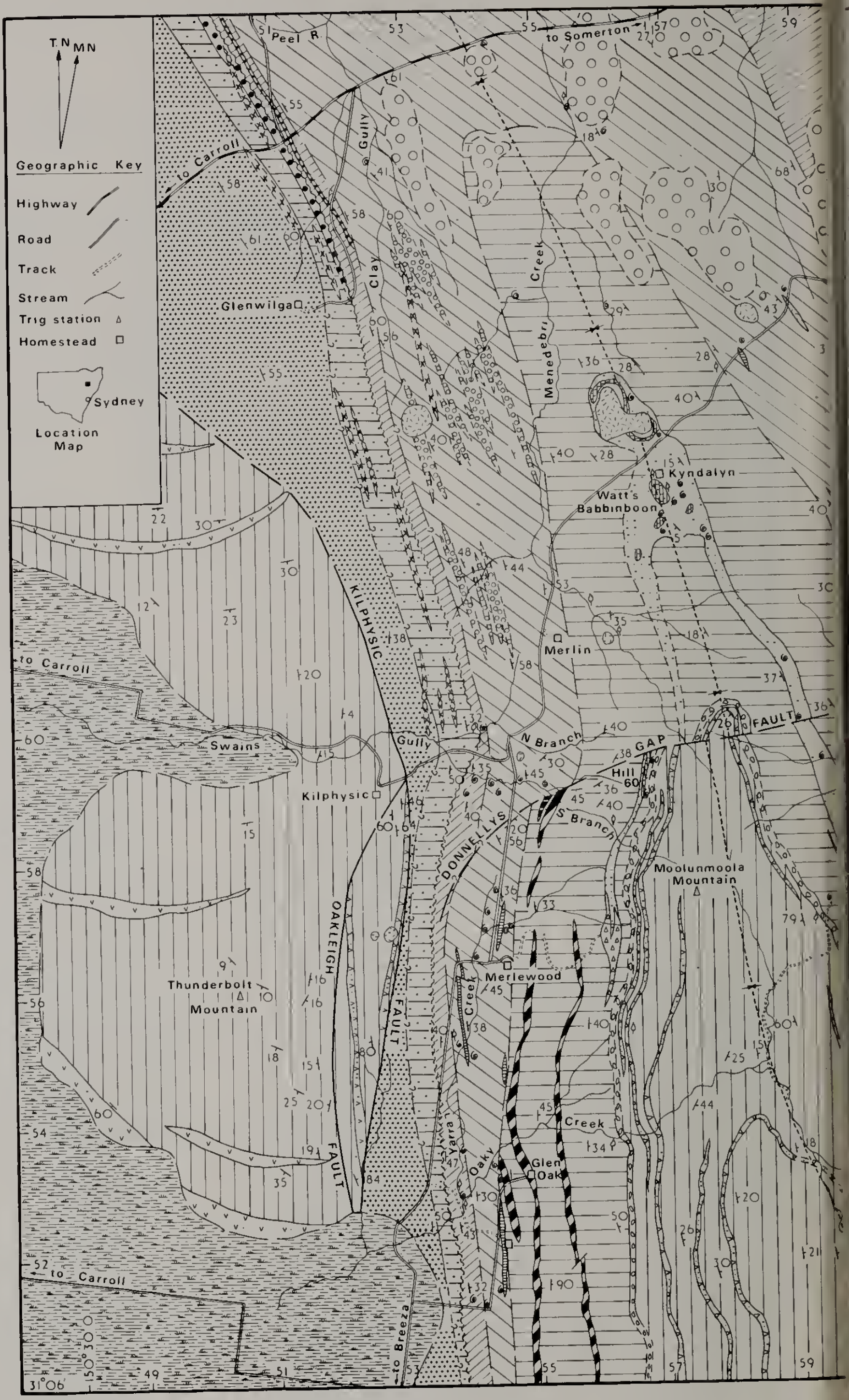
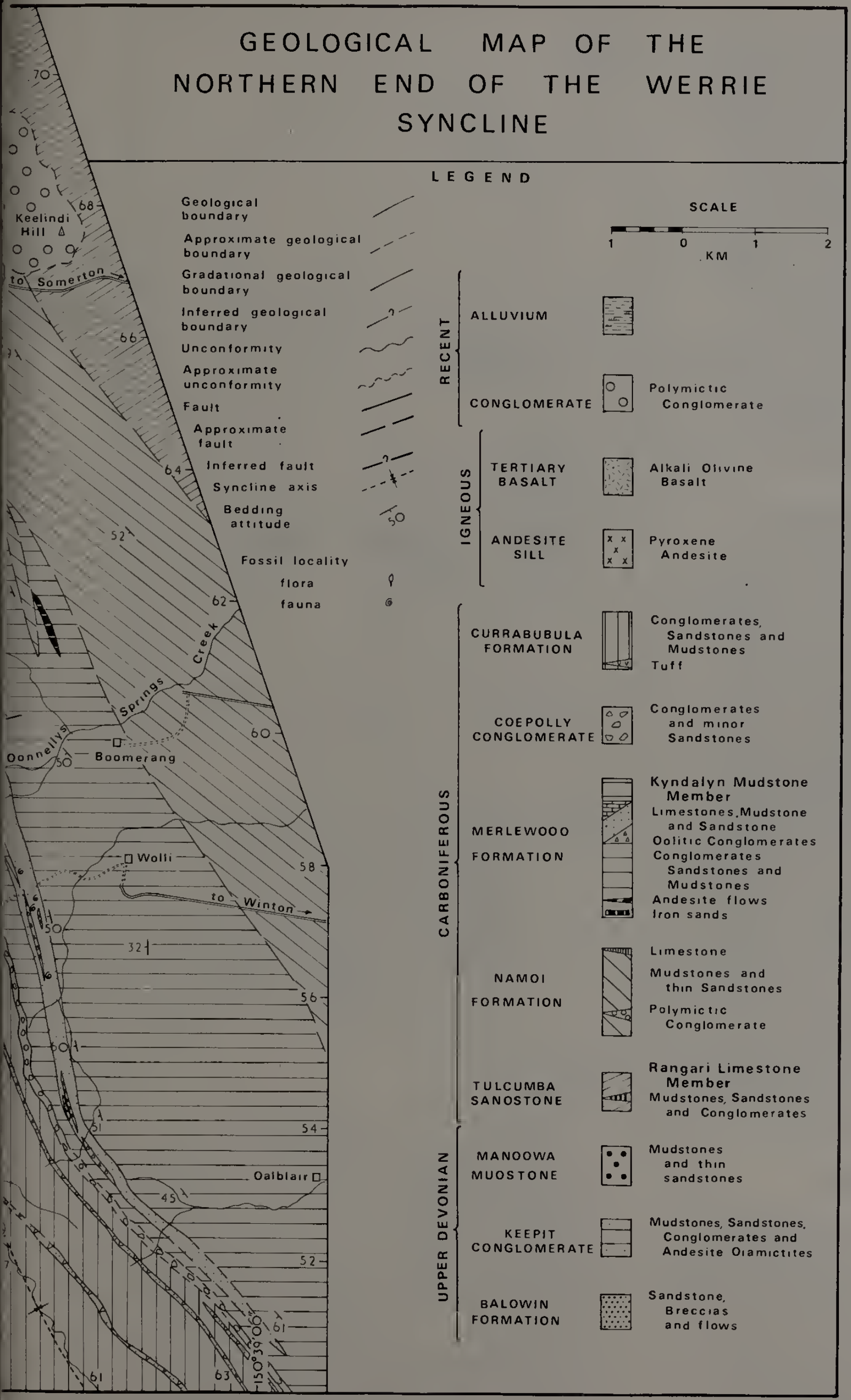


Fig. 3. Geological map of the



northern end of the Werrie Syncline

sorting is produced by waves throwing disc and blade shaped pebbles high on the beach, and rolling spherical pebbles back towards the sea. Bluck (1967), from work on beach gravels in South Wales, recognized four zones on a beach. From the back of the beach these are: 1. a large disc zone; 2. an imbricate zone with mainly disc shaped pebbles; 3. an infill zone of sand and minor pebbles; and 4. an outer zone of mostly spherical and ovoid pebbles. In the Kyndalyn Member, the limestone conglomerates correspond to Bluck's zones 2 and 3, and the polymictic conglomerate to zone 4. Fabric analysis of clasts in the limestone conglomerate indicates that flattened pebbles dip mainly to the east, towards the palaeoslope, and that elongate clasts have a north-south orientation (Fig.4). These observations support the interpretation of a beach environment in which flattened pebbles are inclined away from land and elongate pebbles are oriented parallel to the shoreline (Potter & Pettijohn, 1963).

The fabric analysis was carried out at four localities (A - D) in the limestone conglomerate east of Merlewood. Localities D, C and A, approximately 50 m apart, represent the lower middle and upper portions of the limestone near Merlewood; locality B was chosen close to A because it had an obviously different trend when compared with other localities. The azimuth of the long axes of rod and blade shaped clasts was measured at all localities, and the imbrication of disc and blade types recorded at localities, A, B and D; the measurements were corrected for tectonic tilt. Pebbles with an imbrication towards the west, or postulated landward area, are indicated by a dotted median line, and those imbricate towards the east with a heavy median line (Fig. 4). Except for locality B, the rod and blade like pebbles are oriented roughly north-south, and the major direction of imbrication is towards the east, suggesting a north-south shoreline and a palaeoslope towards the east. The limestone conglomerate near Wolli (Fig. 3) is obviously the remnants of a different shoreline to that near Merlewood: the clasts in the limestone at Wolli have approximately the same orientation as those from localities D, C and A. Data from locality B, which suggests an east-west strand line and southerly palaeoslope, may be explained by an embayment in the ancient coastline.

(b) Lateral lithological variation.

Lateral variations of lithologies within the Kyndalyn Member are shown in Figures 3 and 5. Conglomerate, the major component in the south, is replaced northwards by mudstone. Calcareous sediments (Fig. 5.2) are best developed in the west as the oolitic limestone matrix in the conglomerates, and elsewhere are present as lenses of oolite and bioclastic limestone. Limestone constitutes only a small part of the sequence, and terrigenous sediments predominate particularly on the eastern limb of the syncline. The percentage of sandstone is relatively constant throughout the unit.

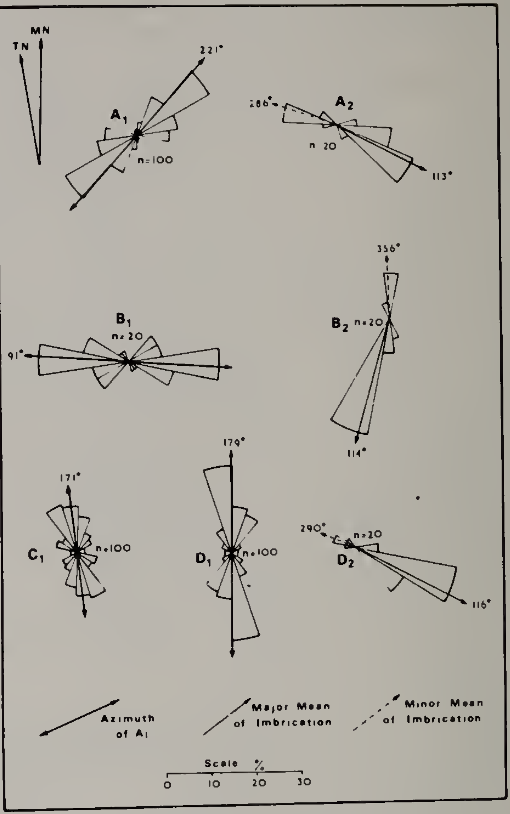


Fig. 4. Fabric data from oolitic limestone conglomerates in the Kyndalyn Member east of Merlewood. Localities D, C and A represent the lower, middle and upper part of the limestone. The suffix 1 indicates the azimuth of the long axis of clasts, and the suffix 2 the direction of imbrication; both measurements are corrected for tectonic tilt.

These data, and information from the fabric analysis of the conglomerates, suggest a shallow marine shelf east of a north-south trending coastline. The coast was marked by a pebbly beach in which the beach gravels were concentrated by wave action during the marine transgression; small remnants of conglomerate preserved in the east indicate the positions of early shorelines. On the shelf, mudstone and siltstone deposited below wave base supported a rich shelly fauna, and local banks provided suitable environments for oolitic and biohermal limestone deposition. Wave action swept oolites from the banks on to the shore, where they mixed with pebbles and formed the limestone conglomerate. Regression of the sea resulted in the erosion of the

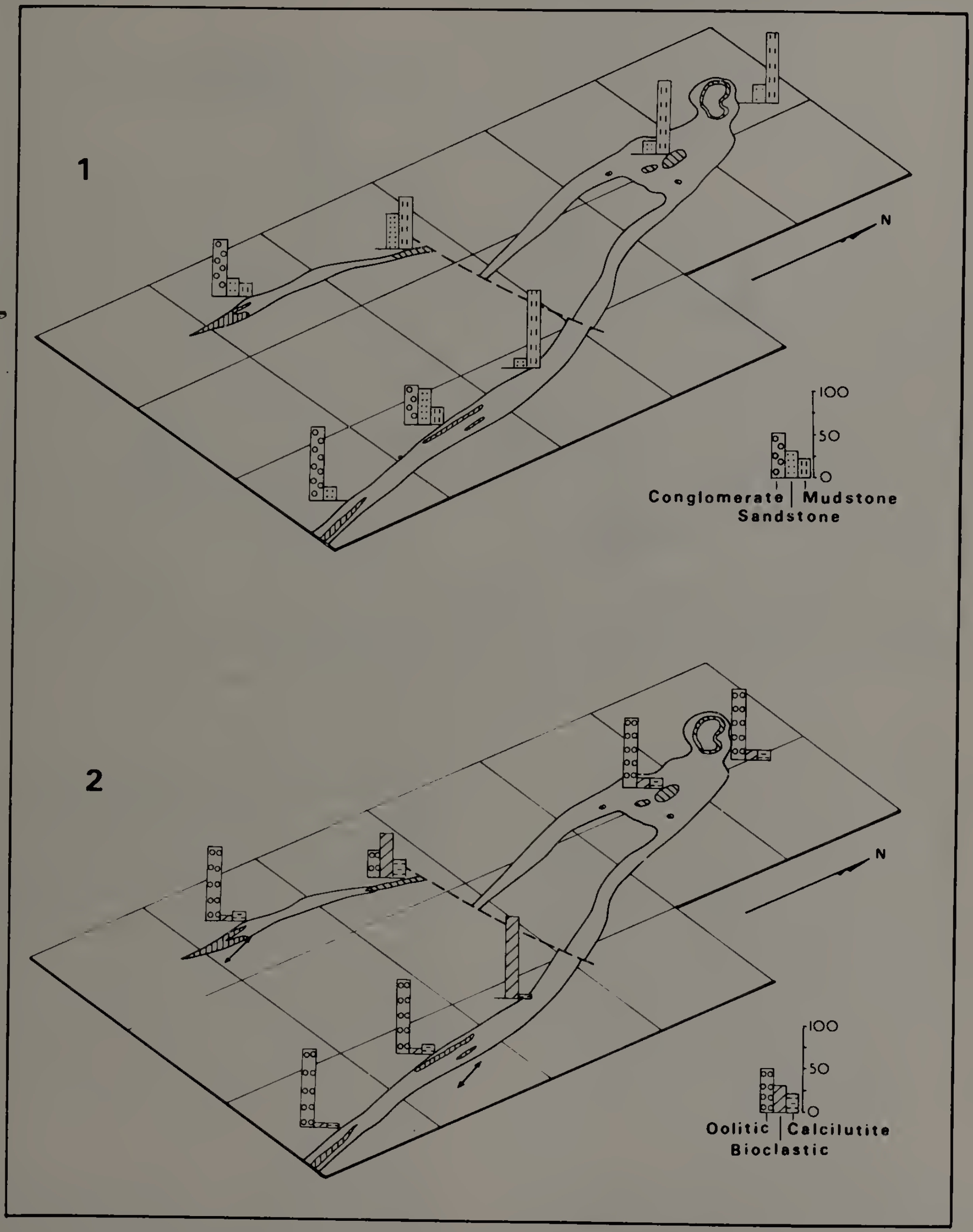


Fig. 5, parts 1 and 2. Lithological variation within the Kyndalyn Member

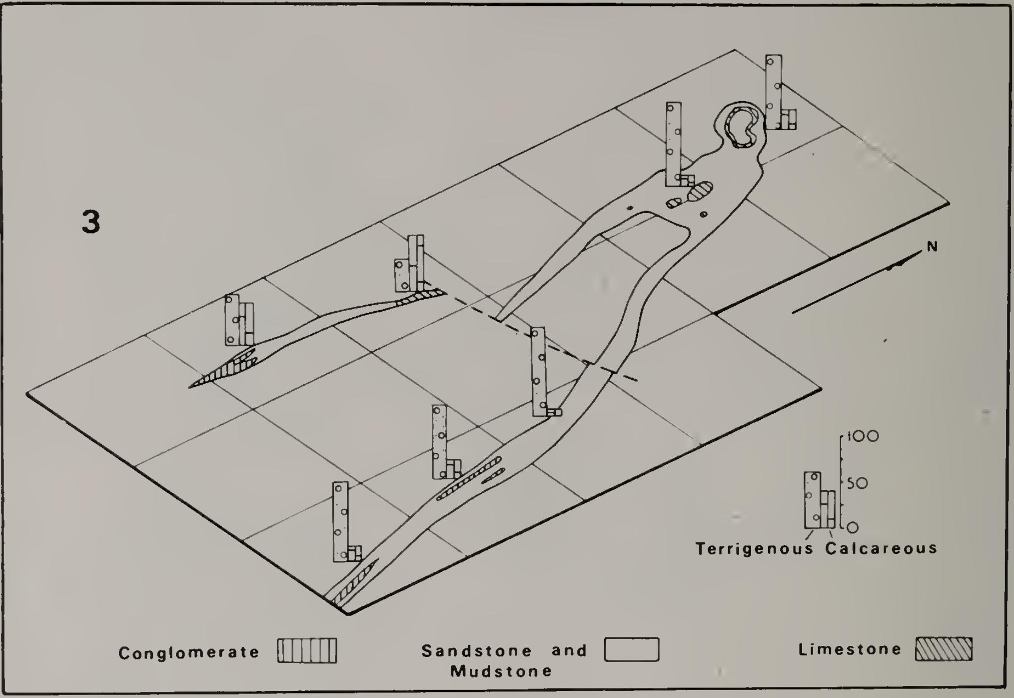


Fig. 5, part 3. Lithological variation within the Kyndalyn Member

upper surface of the member.

STRUCTURE OF THE NORTHERN WERRIE SYNCLINE

The Werrie Syncline is part of a synclinal axis which extends for a distance of 240 km from the Liverpool Range to the Surat Basin. Broad warps or areas of cross folding have formed three basin-like structures along the axis; the Werrie, Belvue and Rocky Creek Synclines. The structure of the Werrie Syncline and adjacent elements was described by Carey (1934). A warp in the synclinal axis in the northern part of the Werrie Syncline is demonstrated by an analysis of bedding attitudes. At the intersection with the Tamworth-Gunnedah road the axis plunges at 8° to 340°, whereas in the southern part of the map area (Fig. 3) the plunge of the axis has reversed to be 10° to 164°.

Two significant faults are recognized in the northern part of the syncline: the Kilphysic Fault which separates the western limb of the syncline from southerly dipping blocks (Carroll - Clifton blocks) of Upper Carboniferous Currabubula Formation; and the Donnellys Gap Fault, a smaller transverse fracture which displaces the axis and a number of stratigraphic units, and which truncates the Hill 60 Member. The Kilphysic Fault is a splay from the Hunter-Mooki fault system, mapped on the western side of the Carroll - Clifton blocks between sediments of the Currabubula Formation and alluvium of the Breeza plain (Carey,1934, Plate 17). Unpublished gravity data (Ramsay & Stanley, pers. comm.) suggest that the major fault of the Hunter-Mooki system, between flat-lying Permian and Triassic rocks and the more strongly folded Devonian, Carboniferous and Permian rocks, runs through the village of Carroll, slightly farther to the west. The Kilphysic Fault is a thrust fault in which the fault plane dips at approximately 45° to the east, north of Swains Gully, but steepens to 85° farther to the south. A precise estimate on the amount of displacement on the fault has not been made because the base of the Currabubula Formation is unexposed on the Carroll - Clifton blocks, and the base of the Baldwin Formation is not seen in the Werrie Syncline; the throw of the fault, based on the thickness of units on the western limb of the syncline, but not taking into account either of the latter formations, is greater than 3000 m.

The Donnellys Gap Fault cuts the syncline almost perpendicular to the axis, and then swings south-eastwards (Fig. 3). The fault plane was not observed in the field, but evidence for the existence of a fault is provided by disrupted bedding and shear zones in Swains Gully, and the truncation of the axis and limbs of the syncline. In the Swains Gully area sediments are sheared in a number of different localities, suggesting that the fault may have given off a number of splays. Bedding relationships adjacent to the fault indicate a small rotational component which has allowed the western limb of the syncline to drop lower than the eastern limb.

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Late Silurian (Late Ludlovian) Conodonts from the Kildrummie Formation, South of Rockley, New South Wales

PATRICK DE DECKKER

ABSTRACT. The Kildrummie Formation, previously known as Kildrummie Group, is redefined and a type section is selected and described. Fifty-eight limestone samples from two parallel sections were treated for the recovery of conodonts, thirty-eight of which yielded conodonts belonging to forty-six form-species. The occurrence of *Spathognathodus crispus*, *Ozarkodina jaegeri* and *Ozarkodina snajdri* in samples from the upper half of the Kildrummie Formation indicates a Late Ludlovian age (interval of upper *crispus* to lower *eosteinhornensis* zones). No short ranging conodonts have been recovered from the lower part of the formation but the occurrence of *Atrypoidea* cf. *australis* Mitchell & Dun, in approximately the middle of the lower half of the formation, also indicates a Late Silurian age.

INTRODUCTION

The Kildrummie Group (Stanton, 1956) occurs in the apical, southern part of the Hill End Trough and was described as a sequence of limestones, dolomitic limestones, marls and shales. The maximum thickness of the group, given by Stanton, was of 2000 m and its base was chosen at the lowermost occurrence of limestone. Corals (*Halysites, Favosites, Heliolites)* and brachiopods (including *Pentamerus knighti*) were reported to be common. The Kildrummie Group was given a Lower Silurian? age by Stanton. Subsequent workers attributed an age ranging from Llandoverian to Lower Devonian (Brown, Campbell & Crook (1968): Llandoverian to Upper Ludlovian; Scheibner (1970): Upper Silurian to Lower Devonian; Strusz (1972): Ludlovian).

Investigations performed since Stanton (1956) (e.g. Anderson, 1961; Nicholson, 1961; Brownlow, 1973) highlight the complicated structure, stratigraphy and facies relationships in this critical part of the Hill End Trough.

The following discussion is based on the study of an area South of Rockley. (A geological map of this area has been submitted by the author as partial fulfilment for the honours degree of Master of Science at Macquarie University).

THE KILDRUMMIE FORMATION

The Kildrummie Group is herewith changed to Kildrummie Formation. A change of status from group to formation is felt to be justified because the sequence consists predominantly of limestone with minor intercalations of tuffaceous arenite and shale and represents one natural field unit.

Definition of the Kildrummie Formation

The Kildrummie Formation consists predominantly of thinly bedded to massive impure limestones with intercalations of tuffaceous arenites and minor shale, quartzo-felspathic arenite, dolomite, argillaceous sandstone and breccia-conglomerate.

Lower boundary: base of lowermost limestone bed; the Kildrummie Formation is conformably underlain by metasiltstones of the Campbells Group (Formation ?).

Upper boundary: top of uppermost limestone bed; the Kildrummie Formation is conformably overlain by quartzo-felspathic arenites of the Burraga Group (Formation ?).

Age: Upper Ludlovian (interval of upper *crispus* to lower *eosteinhornensis* zones) for the upper half of the formation. The lower half is of Late Silurian age based on the occurrence of *Atrypoidea* cf. *australis* Mitchell & Dun in approximately the middle part.

Type section: Long. 149°35'00"E, Lat. 33°47'20"S. (Fig. 1) outcrops along the southern bank of the Campbells River in the Kildrummie Estate, 11 km south of Rockley.

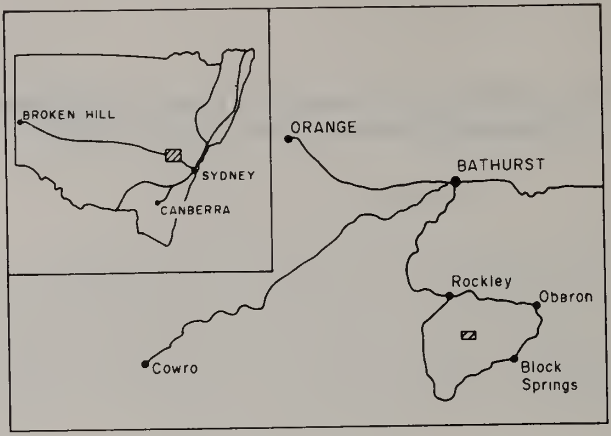
True thickness: 309 m (measured) + 0-15 m (basal part of type section covered by Tertiary basalt). Along the Campbells River, repetition of the beds is due to tight folding.

Description of the Type Section

The contact of the Kildrummie Formation with the underlying Campbells Group (Formation ?) is obscured by Tertiary basalt. Dip and strike orientations in the underlying shales of the Campbells Group (Formation ?) are, however, identical with those of the limestone beds of the lower part of the Kildrummie Formation indicating conformable relationship. In the type section, four units can be recognized, here referred to units 1 to 4 in ascending order. The sequence from bottom to top is described (in true thickness) in Fig. 2 and below the individual units are presented.

Tertiary Basalt Cover

Unit 1 (53 m): Shale, medium to dark grey, alternating with fine grained, medium to dark grey limestone, in places very fossiliferous. Percentage of limestone increasing



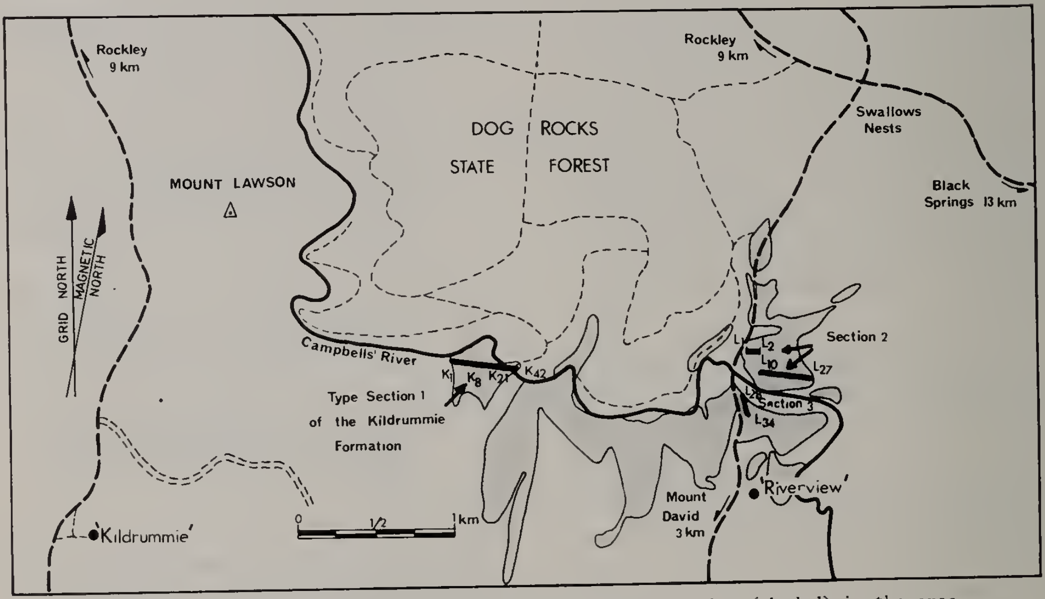


Fig. 1. Map showing the outcrops of the Kildrummie Formation (shaded) in the area south of Rockley, N.S.W., as well as the location of the measured sections

towards the top of the unit.

Unit 2 (25 m): Medium grey shale at the bottom which is grading towards the top into olive green, argillaceous sandstone, rich in mica; outcrop generally poor.

Unit 3 (95 m): Medium grey limestone, fossiliferous in places, alternating with medium grey shale in the first 30 m; above: massive, medium to dark grey, silty limestone.

Unit 4 (138 m): Tuffaceous shales arenites, limestones, dolomites, breccia-conglomerates, quartzo-felspathic arenites and in some places abundant fossils (mainly corals) in black, fine grained, limestone.

Above this a quartzo-felspathic arenite occurs (3.5 m thick) which is considered to be typical of the Burraga Group (Formation ?). On top, a breccia of quartzo-felspathic arenite with quartz and shales is present. A Tertiary basalt is covering the sequence. As the upper part of the Kildrummie Formation is approached, a decrease in limestone is noticed and this is compensated by an increase in quartzo-felspathic arenites showing

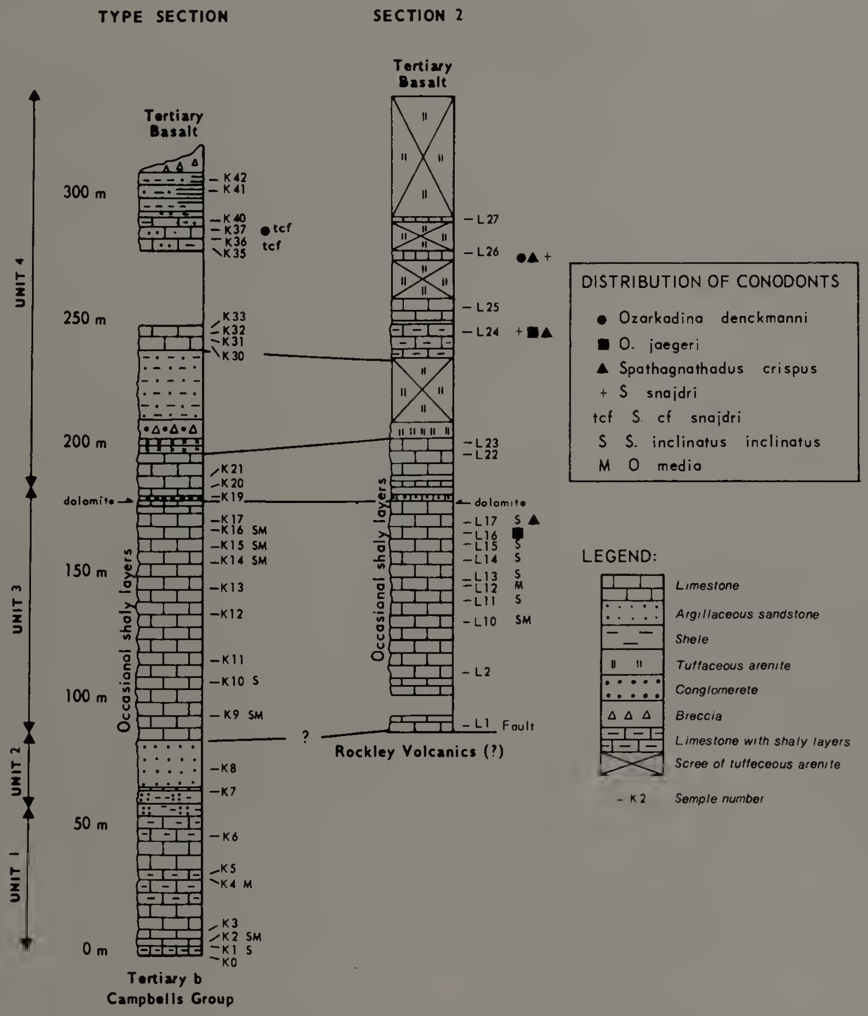


Fig. 2. Correlation of the type section and section 2 measured within the Kildrummie Formation showing also the distribution of conodont forms

therefore a transition (in respect of lithology) into the Burraga Group (Formation ?).

Other Sections

A second section (section 2, Figs 1, 2) was measured 2 km south of Swallows Nest. It can be correlated with units 3 and 4 of the type section.

Section 3 (Fig. 1) was not fully measured. However, it is similar in appearance to the massive limestone (unit 3) found in the adjacent section 2.

A correlation of these measured sections (Fig. 2) is only feasible on the basis of recognition of lithological units as some of the important conodont forms are missing from the type section.

Variation in the Kildrummie Formation

The basal conglomerate described by Scheibner (1970) in the Isabella District has not been observed in the type area. It is either hidden by the Tertiary basalt covering the contact between the Campbells Group (Formation ?) and the Kildrummie Formation or it is a localized phenomenon in the Isabella District.

TABLE 1
DISTRIBUTION OF CONODONT FORM-SPECIES FROM THE
SECTIONS MEASURED IN THE KILDRUMMIE FORMATION

SAMPLE NO. / CONODONT FORM-SPECIES	Section 2, near Swallows Nest														
	L10	L11	L12	L13	L14	L15	L16	L17	L19	L20	L22	L23	L24	L25	L26
Bellodella sp.indet.															x
Diadelognathus primus Nicoll & Rexroad															x
Distomodus curvatus Rhodes															x
Distomodus cf. *kentuckiensis* Branson & Branson															x
Distomodus sp.indet.													x		
Drepanodus curvatus Rhodes													x		
Drepanodus sp.													x		
Exochognathodus brassfieldensis Branson & Branson															x
gen. & sp.indet. Walliser															x
Gothodus ? sp.nov. Aldridge															x
Hindeodella equidentata Rhodes															
Hindeodella priscilla Stauffer															
Hindeodella spp.indet.								x							
Icriodus sp.															
Ligonodina aff.*elegans* Walliser															
Ligonodina salopia Rhodes													x		
? *Ligonodina* sp.b Walliser															
Lonchodina greilingi Walliser														x	x
Lonchodina walliseri Ziegler															x
Neoprioniodus bicurvatus Branson & Mehl															x
Neoprioniodus excavatus Branson & Mehl	x				x			x							
Ozarkodina denckmanni Ziegler															x
Ozarkodina cf. *denckmanni* Ziegler															
Ozarkodina jaegeri Walliser	x						x								
Ozarkodina media Walliser	x		x												
Ozarkodina spp.indet.	x	x		x			x							x	x
Paltodus fragilis Branson & Mehl															x
Paltodus spp.indet.															x
Panderodus gracilis Branson & Mehl	x	x	x	x	x	x	x	x	x	x	x				
Panderodus panderi Stauffer	x	x	x	x	x		x	x							
Panderodus cf. *panderi* Stauffer					x			x							
Panderodus recurvatus Rhodes	x	x	x	x		x		x							
Panderodus cf. *recurvatus* Rhodes															
Panderodus simplex Branson & Mehl	x	x	x	x	x	x	x	x							
Panderodus unicostatus serratus Rexroad							x	x							x
Panderodus unicostatus unicostatus Branson & Mehl	x	x	x	x	x	x	x	x		x	x				
Panderodus spp.indet.	x	x	x	x	x		x	x	x		x		x		
Plectospathodus extensus lacertosus Philip															
Plectospathodus flexuosus Branson & Mehl	x														
Spathognathodus crispus Walliser								x					x		x
Spathognathodus inclinatus inclinatus Rhodes	x	x		x	x	x		x							
Spathognathodus snajdri Walliser													x		x
Spathognathodus cf. *snajdri* Walliser															
Symprioniodina silurica Walliser	x													x	
Trichonodella excavata Branson & Mehl		x													
Trichonodella inconstans Walliser														x	
Trichonodella symmetrica Branson & Mehl															
Trichonodella cf. *brassfieldensis* Branson & Branson															x

Type section 1, near Campbells River																			Section 3, near Swallows Nest							
K1	K1A	K2	K3	K4	K5	K6	K9	K12	K13	K14	K15	K16	K17	K32	K33	K35	K37	K42	L28	L29	L30	L31	L32	L33	L34A	L34B
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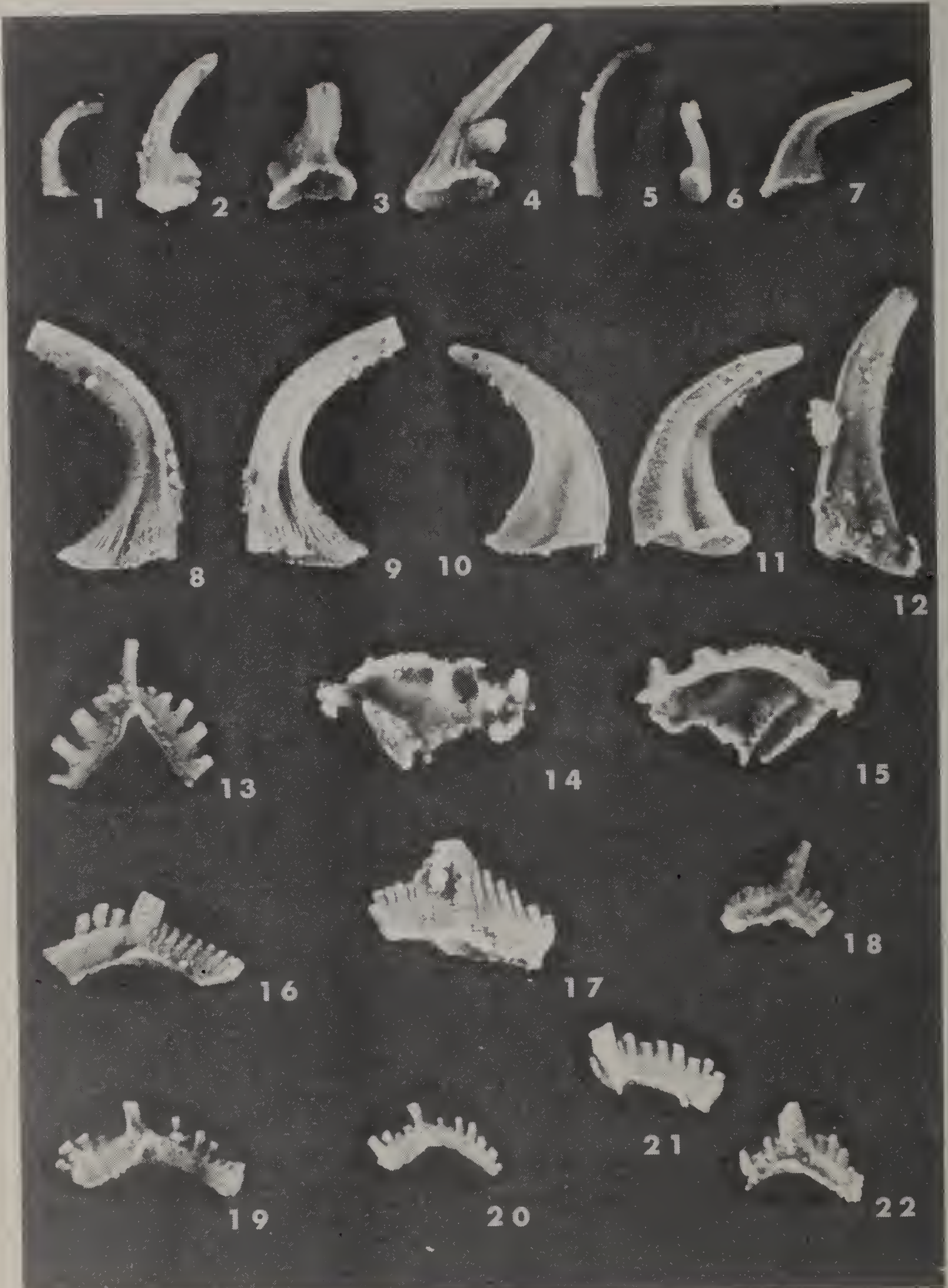
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FIGURE 3

All figures × 45

1 *Panderodus recurvatus* Rhodes, lateral view, sample L13.

2 Gen. & sp. indet. Walliser, lateral view, sample L26.

3 *Diadelognathus primus* Nicoll & Rexroad, lateral view, sample L26.

4 *Distomodus curvatus* Rhodes, lateral view, sample L26.

5 *Panderodus gracilis* Branson & Mehl, lateral view, sample L13.

6 *Drepanodus* sp., oblique posterior view, sample L24.

7 *Acodus* cf. *curvatus* Branson & Branson, side view, sample L26. (There is a denticle on the posterior edge, just above the posterior margin, which is almost invisible on the photograph because of being so small).

8, 9 *Panderodus panderi* Stauffer, both lateral views, sample L14.

10, 11 *Panderodus simplex* Branson & Mehl, both lateral views, sample L13.

12 *Panderodus unicostatus unicostatus* Branson & Mehl, lateral view, sample L13.

13 *Trichonodella inconstans* Walliser, posterior view, sample L25.

14, 15 *Icriodus* sp. (juvenile specimen), oral and aboral views, sample L28.

16 *Ozarkodina media* Walliser, lateral view, sample K15.

17 *Ozarkodina denckmanni* Ziegler, lateral view, sample L26.

18 *Ozarkodina jaegeri* Walliser, lateral view, sample L31.

19, 20 *Plectospathodus extensus lacertosus* Philip, lateral views, sample K9.

21 *Synprioniodina silurica* Walliser, (shorter process broken), lateral view, sample K16.

22 *Ozarkodina jaegeri* Walliser, lateral view, sample L24.

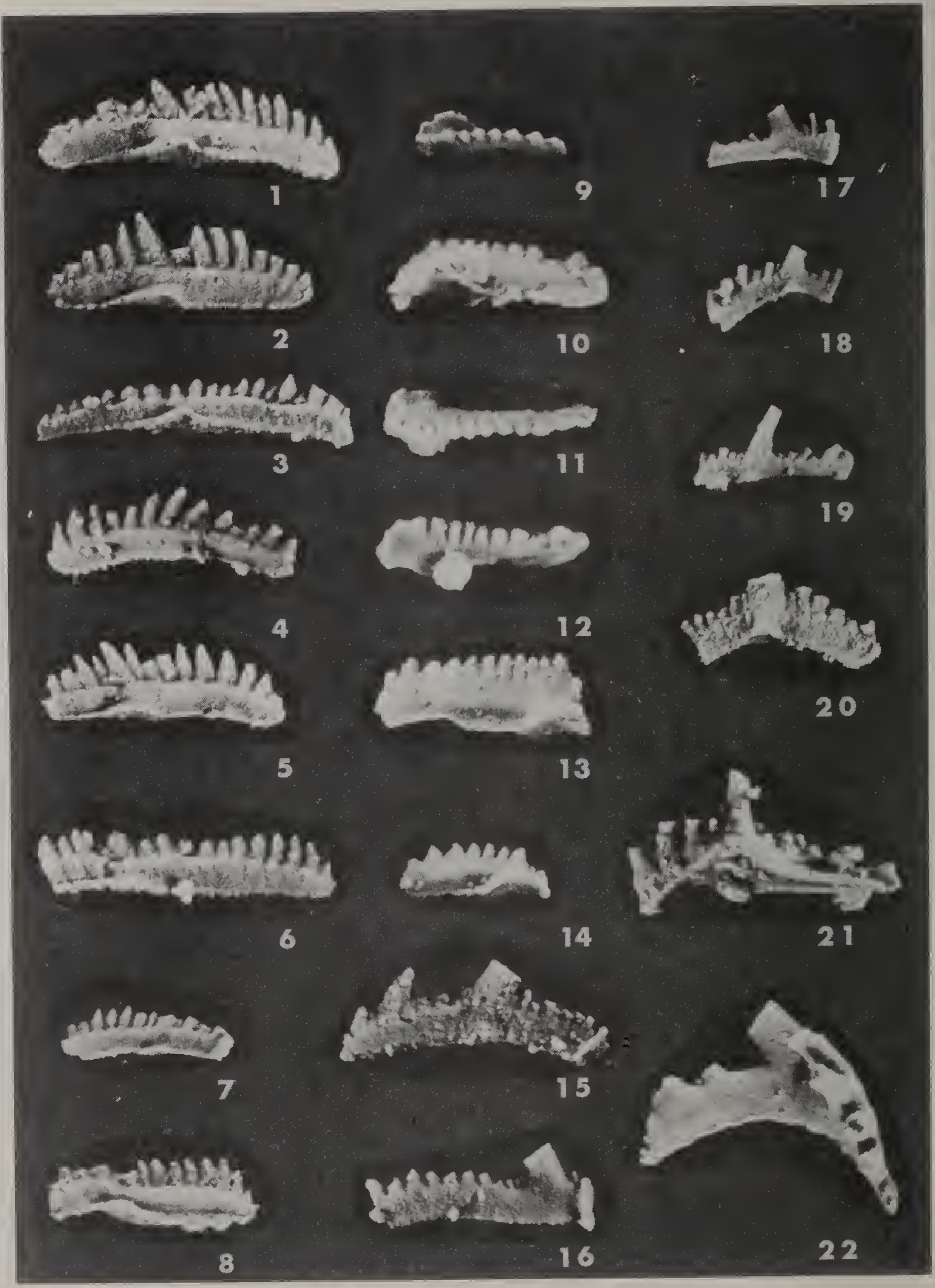
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FIGURE 4

All figures × 45

1-8 *Spathognathodus inclinatus inclinatus* Rhodes, all lateral views, samples L10, K14, K12, L31, L29, K17, L13, L10 (in numerical order as they are figured).

9, 14 *Spathognathodus* cf. *snajdri* Walliser, oral and lateral views, sample K36.

10-12 *Spathognathodus snajdri* Walliser, lateral view, sample L24.

11, 13 *Spathognathodus crispus* Walliser, oral and lateral views, sample L26.

15 *Ozarkodina* cf. *denckmanni* Ziegler, (pathological form with lateral branch near posterior end), lateral view, sample K12.

16 *Hindeodella equidentata* Rhodes, inner view, sample K15.

17 *Hindeodella priscilla* Stauffer, inner view, sample K9.

18 *Ozarkodina media* Walliser, lateral view, sample K9.

19 *Hindeodella equidentata* Rhodes, outer view, sample K9.

20 *Ozarkodina media* Walliser, lateral view, sample K14.

21 *Lonchodina walliseri* Ziegler, lateral view, sample L34A.

22 *Ligonodina salopia* Rhodes, inner view, sample L34B.

To the south-west, south of Burraga, Scheibner (1970) estimated a total thickness for the Kildrummie Formation between 1200 m and 1500 m. Stanton (1956) gave a figure of 2000 m for the formation in the type area but he overestimated it because of repetition of Campbells River. The formation thins from there to the west and is about 300 m thick (Dunnet, 1961) on the western limb of the Burraga Syncline.

AGE OF THE KILDRUMMIE FORMATION

Of forty-six recognized conodont form-species from the Kildrummie Formation (Table 1, Figs 3-4), only four species *(Spathognathodus crispus, S. snajdri, Ozarkodina jaegeri* and *O. denckmanni)* have a relatively short time range. According to Walliser (1964, 1970-71), the ranges for these forms are as follows:

- *Spathognathodus crispus* is the key fossil for the *crispus* zone and ranges into the basal part of the *eosteinhornensis* zone.
- *S. snajdri* is restricted to the *snajdri* horizon in the uppermost *siluricus* zone.
- *Ozarkodina jaegeri* ranges from the uppermost *latialatus* zone through the *eosteinhornensis* zone.
- *O. denckmanni* starts in the topmost part of the *crispus* zone and extends through the lowermost Devonian.

Ozarkodina jaegeri, O. denckmanni and *Spathognathodus crispus* thus occur only in a very short interval representing the uppermost *crispus* to the lowermost *eosteinhornensis* zone. *S. snajdri* found together with *O. denckmanni* (in samples L26, K37) and *S. crispus* (in samples L24, L26) from the upper part of the Kildrummie Formation, is, however, not supposed to be contemporaneous with these form-species. This apparent contradiction may be explained by *S. snajdri* having a longer range than previously thought or that *S. crispus* has a greater intraspecific variation including forms such as the one described by Walliser as *S. snajdri*. On the other end, *S. snajdri* may represent, like *S. ranuliformis* and *S. crispus*, a stage in a continuous lineage of spathognathid conodonts, characterized by a posterior dome-shaped basal cavity, ranging from Late Wenlockian to Late Ludlovian. This lineage is incompletely known and stratigraphical intervals, where morphological changes occur, have not been determined precisely.

At this stage it seems to be reasonable to use the association of *S. crispus*, probably representing the end member of the above mentioned lineage, with the early occurrence of *O. denckmanni* to date the upper half of the Kildrummie Formation as Late Ludlovian, uppermost *crispus* zone to lowermost *eosteinhornensis* zone, on the basis of Walliser's revised distribution chart (1970-71).

The lower part of the Kildrummie Formation has not yielded any indicative conodont form-species; at present, the age of this part of the sequence can only be determined on the basis of the occurrence of the brachiopod *Atrypoidea* cf. *australis* Mitchell & Dun (identified by Sherwin, 1973) in sample K8 as Late Silurian. According to Sherwin (1973) the genus *Atrypoidea* is restricted to Ludlovian and Pridolian.

Byrnes (1974) also identified corals from the type section (listed in Table 2) and suggested that they could indicate a post Llandoverian age for the formation.

TABLE 2
LIST OF CORALS IDENTIFIED FROM THE TYPE SECTION OF THE KILDRUMMIE FORMATION
(AFTER BYRNES, 1974)

Sample No	
K1	*Parachaetetes, Syringopora, Heliolites,* cf. *susmilchi,* stromatoporoid (fine).
K2	*Heliolites* (There is only the one form recognizable in the collection).
K5	*Coenites* cf. *juniperinus* with algal coating.
K9	*Syringopora, Syringoporinus, Heliolites, Coenites* sp. cf. *juniperinus, Halysites* sp. (cf. *australis* or *bellensis*), *Favosipora* sp. nov., *Diplostroma javorskii, Parachaetetes.*
K10	*Halysites* cf. *orthopteroides, Pseudoplasmopora* (subgen. nov.) sp., *Parachaetetes.*
K12	*Halysites chillagoensis.*
K20	*Parachaetetes, Quepora* sp. cf. *bellensis.*
K40	*Parastriatopora* cf. *coreanica.*

Byrnes (1974) pointed out that the species *Halysites bellensis, Halysites australis, Halysites chillagoensis, Favosipora* sp. and *Pseudoplasmopora* subgen. nov. could indicate a post Llandoverian age.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 109, pp. 71–76, 1976

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Precise Observations of Minor Planets at Sydney Observatory During 1975

T. L. MORGAN

ABSTRACT. Positions of 2 Pallas, 4 Vesta, 6 Hebe, 7 Iris, 389 Industria, 433 Eros and 532 Herculina obtained with the 23 cm camera are given.

The programme of precise observations of selected minor planets which was begun in 1955 is being continued and the results for 1975 are given here. The methods of observation are described in the first paper (Robertson 1958). All the plates were taken with the 23 cm camera (scale 116" to the millimeter). Four exposures were taken on each plate, except those for 389 Industria, 532 Herculina and the last plate for 433 Eros, which had two exposures. The plates for 4 Vesta were taken with a coarse wire grating in front of the lens. The side images were measured for the planet.

In Table 1 are given the means for all of the exposures for each of two separate groups of reference stars at the mean of the exposure times. The differences in results average $0^{s}.27$ sec δ in right ascension and $0''.33$ in declination for the plates on which four exposures were taken. For those plates on which there were only two exposures the corresponding differences were $0^{s}.051$ sec δ in right ascension and $0''.67$ in declination. This leads to probable errors for the mean of the two results from the one plate of $0^{s}.011$ sec δ and $0''.14$ for the case of four exposures and $0^{s}.022$ sec δ and $0''.28$ in the case of two exposures. The result of the first two exposures was compared with the last two by adding the motion computed from the ephemeris for those plates with four exposures. The means of the differences were $0^{s}.010$ sec δ and $0''.10$. Comparison of the first and last image on the plates with two exposures lead to mean differences of $0^{s}.035$ sec δ and $0''.35$. The images on the plates with two exposures were, in general, of poorer quality than the others, since they were of fainter objects. This, along with the fact that fewer measurements were meaned, explains the larger differences. It is expected that the two results will be combined before they are used. However, they are published in the present form so that any correction to the positions of the reference stars can be conveniently applied by using the dependances from Table 2.

No correction has been applied for aberration, light time or parallax, but the factors give the parallax correction when divided by the distances. The column headed "O - C" gives the differences between the measured positions (corrected for parallax) and the position computed from the ephemerides supplied by the Institute for Theoretical Astronomy in Leningrad. A precise ephemeris was not available for 433 Eros, thus no values are given for this planet.

In accordance with the recommendation of Commission 20 of the International Astronomical Union, Table 2 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 the proper motion correction applied to bring the catalogue position to the epoch of the plate. The column headed "Star" gives the number from the Smithsonian Astronomical Observatory Catalogue. The plates were measured by Mrs A. Brown, Miss J. Fitt and Mrs J. Saunders, who also assisted with the reductions. The observers at the telescope were T.L. Morgan (M), W.H. Robertson (R) and K.P. Sims (S).

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TABLE 1

POSITIONS OF MINOR PLANETS

No.		R.A. (1950.0)	Dec. (1950.0)	Parallax Factors		O - C		
		h m s	° ' "	s	"	s	"	
2 Pallas 1975 U.T.								
1309	July 09.78467	00 12 40.650	+06 19 54.38	-0.023	-5.67	+0.02	-0.4	S
1310	July 09.78467	00 12 40.649	+06 19 55.02					
1311	July 15.77185	00 14 51.674	+06 02 31.32	-0.017	-5.63	+0.11	+0.3	M
1312	July 15.77185	00 14 57.666	+06 02 31.12					
1313	Aug. 05.75056	00 17 58.572	+04 07 17.32	+0.077	-5.39	-0.03	-0.1	S
1314	Aug. 05.75056	00 17 58.554	+04 07 17.39					
1315	Aug. 18.68181	00 15 32.784	+02 09 10.84	-0.010	-5.16	-0.01	+0.2	R
1316	Aug. 18.68181	00 15 32.778	+02 09 11.56					
1317	Sept 09.62792	00 04 18.140	-02 27 37.18	+0.033	-4.57	+0.04	+0.2	M
1318	Sept 09.62792	00 04 18.168	-02 27 37.28					
1319	Oct. 02.53547	23 47 20.116	-07 59 55.80	-0.022	-3.83	-0.05	-0.1	R
1320	Oct. 02.53547	23 47 20.087	-07 59 55.87					
1321	Oct. 14.50102	23 39 14.030	-10 35 00.70	-0.010	-3.47	-0.03	+0.7	M
1322	Oct. 14.50102	23 39 14.062	-10 35 00.52					
1323	Oct. 27.47299	23 32 55.152	-12 49 37.78	+0.027	-3.15	-0.04	+0.5	R
1324	Oct. 27.47299	23 32 55.162	-12 49 38.34					
1325	Nov. 05.44861	23 30 33.361	-13 58 55.88	+0.033	-2.99	-0.02	+0.4	S
1326	Nov. 05.44861	23 30 33.324	-13 58 55.33					
1327	Nov. 10.43857	23 30 01.882	-14 28 52.08	+0.046	-2.92	-0.01	+0.5	M
1328	Nov. 10.43857	23 30 01.848	-14 28 52.60					
4 Vesta 1975 U.T.								
1329	July 07.78993	00 10 34.148	-06 30 01.88	-0.019	-4.03	+0.04	+0.4	S
1330	July 07.78993	00 10 34.176	-06 30 01.86					
1331	July 14.76841	00 15 17.476	-06 32 35.82	-0.037	-4.03	+0.00	-0.1	M
1332	July 14.76841	00 15 17.420	-06 32 36.01					
1333	July 30.73842	00 21 41.562	-07 11 31.96	-0.008	-3.94	+0.01	-0.4	M
1334	July 30.73842	00 21 41.586	-07 11 32.76					
1335	Aug. 13.69819	00 21 34.260	-08 23 26.18	-0.014	-3.78	+0.02	-0.7	M
1336	Aug. 13.69819	00 21 34.258	-08 23 25.70					
1337	Aug. 20.67596	00 19 24.072	-09 10 37.10	-0.019	-3.66	+0.00	-0.7	R
1338	Aug. 20.67596	00 19 24.118	-09 10 37.23					
1339	Oct. 02.55452	23 45 55.732	-14 07 53.49	+0.041	-2.97	+0.02	+0.2	R
1340	Oct. 02.55452	23 45 55.718	-14 07 53.48					
1341	Oct. 13.49409	23 37 49.496	-14 37 32.52	-0.038	-2.89	+0.01	+0.1	M
1342	Oct. 13.49409	23 37 49.529	-14 37 33.08					
1343	Oct. 27.45233	23 31 31.326	-14 33 30.99	-0.035	-2.90	+0.05	+0.1	R
1344	Oct. 27.45233	23 31 31.368	-14 33 31.00					
1345	Nov. 05.44861	23 30 15.213	-14 08 16.56	+0.032	-2.96	-0.01	+0.7	S
1346	Nov. 05.44861	23 30 15.240	-14 08 16.12					
1347	Nov. 10.41345	23 30 30.712	-13 47 42.41	-0.035	-3.01	+0.01	+0.5	M
1348	Nov. 10.41345	23 30 30.715	-13 47 42.72					
1349	Nov. 24.41607	23 34 38.608	-12 28 35.03	-0.046	-3.20	-0.05	+1.1	M
1350	Nov. 24.41607	23 34 38.504	-12 28 34.74					
6 Hebe 1975 U.T.								
1351	Apr. 01.68780	15 21 37.730	+02 40 55.36	-0.021	-5.20	+0.07	-0.2	R
1352	Apr. 01.68780	15 21 37.714	+02 40 56.22					
1353	Apr. 08.66349	15 18 19.460	+03 35 55.84	-0.011	-5.31	+0.02	-0.3	S
1354	Apr. 08.66349	15 18 19.484	+03 35 56.02					
1355	May 05.58219	14 57 28.853	+06 33 37.84	-0.009	-5.66	-0.01	+0.2	S
1356	May 05.58219	14 57 28.918	+06 33 37.91					
1357	May 27.50202	14 38 43.986	+07 21 27.84	-0.031	-5.75	+0.04	-0.1	R
1358	May 27.50202	14 38 43.976	+07 21 28.28					
1359	June 04.48525	14 33 24.184	+07 11 38.71	-0.004	-5.74	+0.03	+0.3	R
1360	June 04.48525	14 33 24.186	+07 11 38.52					
1361	June 09.48113	14 30 42.032	+06 58 31.94	+0.031	-5.71	+0.07	+0.2	M
1362	June 09.48113	14 30 42.087	+06 58 31.12					

TABLE 1 (cont.)

POSITIONS OF MINOR PLANETS

No.		R.A. (1950.0)	Dec. (1950.0)	Parallax Factors		O - C		
		h m s	° ' "	s	"	s	"	
6 Hebe (cont.)								
1363	June 30.41711	14 25 30.226	+05 15 08.78	+0.022	-5.51	+0.01	-0.6	M
1364	June 30.41711	14 25 30.276	+05 15 08.84					
1365	July 14.38877	14 27 35.563	+03 34 11.60	+0.047	-5.30	+0.01	-0.4	S
1366	July 14.38877	14 27 35.545	+03 34 11.84					
1367	July 24.35524	14 31 35.592	+02 12 19.53	+0.019	-5.13	-0.07	-0.1	M
1368	July 24.35524	14 31 35.592	+02 12 19.36					
7 Iris 1975 U.T.								
1369	Apr. 08.62894	14 07 31.485	-19 33 09.66	+0.015	-2.13	-0.02	-0.1	S
1370	Apr. 08.62894	14 07 31.458	-19 33 09.39					
1371	Apr. 28.55800	13 48 58.058	-17 40 20.20	+0.018	-2.41	+0.01	+0.1	R
1372	Apr. 28.55800	13 48 58.038	-17 40 20.96					
1373	May 05.53221	13 42 44.678	-16 55 02.92	-0.004	-2.51	-0.05	+0.1	S
1374	May 05.53221	13 42 44.692	-16 55 02.98					
1375	May 14.49670	13 35 42.600	-15 57 40.80	-0.023	-2.66	-0.02	+0.7	M
1376	May 14.49670	13 35 42.638	-14 57 40.46					
1377	May 27.46029	13 28 18.684	-14 44 27.40	-0.010	-2.83	-0.08	+0.6	R
1378	May 27.46029	13 28 18.708	-14 44 27.57					
1379	June 30.38125	13 27 13.110	-13 12 41.93	+0.036	-3.06	-0.02	+0.2	M
1380	June 30.38125	13 27 13.176	-13 12 42.46					
1381	July 07.36080	13 30 03.224	-13 13 11.60	+0.026	-3.05	-0.05	-0.2	M
1382	July 07.36080	13 30 03.218	-13 13 11.37					
1383	July 14.35549	13 33 47.194	-13 19 37.22	+0.061	-3.09	-0.02	+1.5	S
1384	July 14.35549	13 33 47.241	-13 19 37.05					
389 Industria 1975 U.T.								
1385	June 04.65593	18 25 49.716	-26 44 45.50	+0.028	-1.07	+0.06	+0.9	R
1386	June 04.65593	18 25 49.741	-26 44 45.98					
1387	June 11.62680	18 19 35.756	-26 29 06.80	+0.008	-1.10	+0.01	-0.2	S
1388	June 11.62680	18 19 35.732	-26 29 07.83					
1389	July 09.52767	17 52 11.202	-25 01 12.42	-0.004	-1.32	+0.07	-0.6	S
1390	July 09.52767	17 52 11.158	-25 01 11.96					
1391	July 14.52480	17 48 08.916	-24 42 59.11	+0.042	-1.38	+0.05	-0.2	M
1392	July 14.52480	17 48 08.977	-24 42 59.93					
1393	July 28.47876	17 40 08.184	-23 53 51.18	+0.034	-1.50	+0.10	+0.1	R
1394	July 28.47876	17 40 08.312	-23 53 50.33					
1395	Aug. 08.44366	17 37 40.381	-23 19 59.93	+0.022	-1.58	+0.11	-0.2	M
1396	Aug. 08.44366	17 37 40.376	-23 19 59.92					
1397	Aug. 14.43716	17 37 48.138	-23 03 50.57	+0.055	-1.63	+0.05	-0.4	R
1398	Aug. 14.43716	17 37 48.049	-23 03 51.86					
1399	Aug. 29.37954	17 42 22.910	-22 30 40.48	-0.011	-1.70	+0.05	-1.4	M
1400	Aug. 29.37954	17 42 22.801	-22 30 39.38					
433 Eros 1975 U.T.								
1401	Feb. 26.49263	07 47 28.373	-06 15 02.93	+0.060	-4.06			S
1402	Feb. 26.49263	07 47 28.376	-06 15 02.73					
1403	Mar. 03.48096	07 53 25.952	-08 23 00.27	+0.054	-3.75			M
1404	Mar. 03.48096	07 53 25.922	-08 22 59.54					
1405	Apr. 08.40863	08 58 58.882	-14 12 04.50	-0.007	-2.92			R
1406	Apr. 08.40863	08 58 58.904	-14 12 04.02					
1407	Apr. 24.38924	09 35 55.070	-14 47 40.19	-0.101	-2.83			R
1408	Apr. 24.38924	09 35 55.051	-14 47 40.71					
532 Herculina 1975 U.T.								
1409	Aug. 05.77710	01 26 52.990	-11 12 14.11	+0.023	-3.38	+0.00	+1.3	S
1410	Aug. 05.77710	01 26 52.929	-11 12 14.69					

TABLE 1 (cont,)

POSITIONS OF MINOR PLANETS

No.		R.A. (1950.0) h m s	Dec. (1950.0) ° ' "	Parallax Factors		O - C s	"	
532 Herculina (cont.)								
1411	Aug. 13.75484	01 27 53.855	-11 59 12.79	+0.019	-3.27	+0.02	+0.1	M
1412	Aug. 13.75484	01 27 53.912	-11 59 12,83					
1413	Aug. 18.73162	01 27 52.708	-12 31 58,73	-0.011	-3.18	+0.03	+1.2	R
1414	Aug. 18 73162	01 27 52.639	-12 31 58.91					
1415	Oct. 27.50815	00 46 39.288	-19 14 41.58	-0.01	-2.21	+0.03	+0.2	R
1416	Oct. 27.50815	00 46 39.277	-19 14 42.91					

TABLE 2

REFERENCE STAR POSITIONS AND DEPENDENCES

No.	Star	Depend.	R.A.	Dec.
1309	109060	0.421146	21,749	00.03
	109112	0.174018	54.564	03.29
	109118	0,404836	10.041	13.77
1310	109056	0.282500	57.727	11.92
	109089	0.332015	25.944	38.36
	109128	0,385485	36.870	25.67
1311	109089	0.295552	25,944	38.36
	109123	0.397900	20.144	56.05
	109139	0,306548	54.931	58.55
1312	109079	0.168610	16.917	24.71
	109118	0,481854	10.041	13.77
	109132	0.349536	27.046	26.66
1313	109103	0.358192	11.519	59.83
	109157	0.305605	39.857	51.61
	109180	0.336204	22.885	01.74
1314	109137	0,480864	46.568	38.63
	109143	0.159475	25.591	57.08
	109165	0,359661	49.621	54.62
1315	109083	0.366812	55.353	30.61
	109104	0,266544	14.781	25.45
	109166	0.366644	06.761	46.14
1316	109109	0,422190	45.239	57.32
	109117	0.223548	07.520	45.86
	109136	0.354262	45.411	49.08
1317	128559	0,372342	11.425	42.15
	128576	0,293476	56.665	55,43
	128630	0.334182	57.308	05.01
1318	128550	0.384064	13.293	42,27
	128596	0.297797	11,922	36.64
	128626	0.318139	23.256	09.43
1319	146902	0.347098	35.860	40,85
	146903	0.279292	39.885	33,66
	146967	0.373609	51,528	35.52
1320	146925	0.449134	15,052	27.91
	146926	0.296868	32.646	40.41
	146950	0.253998	11,312	24.58
1321	165812	0.319220	40.175	41.61
	165831	0.356271	52,114	33,52
	146883	0.324508	08,956	34,35
1322	146810	0.345461	18,039	09.66
	165847	0.361010	01.202	59,88
	165855	0.293528	41,010	42,83
1323	165736	0.331585	41.486	14.51
	165788	0.343675	09,365	54,52
	165816	0.324740	58.971	46.98
1324	165745	0.309362	34.219	56.95
	165793	0.330522	41,333	47.63
	165805	0.360116	05,785	42,74
1325	165744	0,386884	31.158	44.99
	165749	0.347602	43.236	51.61
	165788	0.265514	09.365	54.52
1326	165716	0.298942	19.654	15.11
	165753	0.299956	47.176	14.35
	165796	0.401102	16.303	05.46
1327	165737	0.347513	51.514	20.35
	165752	0.323390	46.799	40.20
	165770	0.329097	30.891	20.43
1328	165716	0.305438	19.653	15.11
	165741	0.325092	20.097	45.97
	165793	0.369468	41.333	47.63
1329	128617	0.290950	15.195	09.87
	128644	0.421076	38.729	11.76
	128672	0.287974	48.506	27.64
1330	128624	0.268731	11.295	57.38
	128641	0.459550	20.604	22.98
	128668	0.271720	18.354	45.63
1331	128644	0.308242	38.729	11.76
	128650	0.241587	36.853	36.87
	128728	0.450171	27.017	24.06
1332	128645	0.262319	46.339	14.44
	128693	0.290100	39.545	36.16
	128696	0.447582	03.247	01.87
1333	128696	0.302461	03.247	01.88
	128754	0.338536	49.637	46.06
	128765	0.359003	31.478	47.04
1334	128691	0.218364	09.684	19.60
	128730	0,425900	28.734	00.45
	128778	0.355736	32.921	46.18
1335	128691	0.265332	09.684	19.61
	128709	0.280427	36.943	34.60
	128778	0.454240	32.921	46.18
1336	128701	0.347078	46.363	54.48
	128754	0,371796	49.637	46.06
	128768	0.281126	35.115	10.93
1337	128687	0,341070	29.803	00.89
	128711	0.305212	40.360	31.79
	142774	0.353718	48.666	11.56
1338	128701	0,318924	46.363	54.48
	128706	0.374632	29.992	21.07
	128749	0.306444	11.851	41.95
1339	165871	0.390819	35.210	34.78
	165900	0.281412	20.706	14.07
	165917	0,327770	20.739	55.25
1340	165872	0.305403	43.748	32.15
	165903	0.334480	41.219	55.28
	165906	0.360116	05.803	21.65

TABLE 2 (cont.)

REFERENCE STAR POSITIONS AND DEPENDENCES

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
1341	165798	0.306996	28,083	22.53	1363	120422	0.288468	30.785	45.08
	165822	0.376116	38.375	54.05		120473	0.440016	15.411	06.64
	165850	0.316888	17,967	39.94		120528	0.271516	12.407	48.23
1342	165802	0.365910	49.369	36.83	1364	120454	0.311925	25.773	37.27
	165810	0.113124	57,900	22.18		120478	0.420484	27.516	09.06
	165844	0,520966	20.612	18.59		120503	0.267590	59.814	30.34
1343	165741	0,325561	20,097	45,96	1365	120475	0.303280	20.698	09.32
	165752	0,300446	46.799	40.20		120478	0.332463	27.516	09.06
	165802	0.373992	49,369	36,83		120532	0.364258	24.722	18.06
1344	165737	0.300254	51.513	20.35	1366	120477	0.169378	27.461	46.57
	165749	0.358910	43.236	51,61		120482	0.418544	04.055	08.91
	165809	0,340835	46.495	11.16		120518	0.412078	01.073	20.28
1345	165725	0.349824	39,018	11,38	1367	120509	0.182843	42.533	43.88
	165735	0,333052	38.730	27.85		120530	0,500656	19.767	40.15
	165802	0.317123	49,369	36,83		120555	0.316501	40.569	20.96
1346	165728	0,352436	09.617	46.64	1368	120495	0.384944	03.465	42.37
	165737	0.344622	51.513	20,35		120558	0.318043	00.550	20.26
	165796	0,302943	16,303	05.46		120567	0.297012	53.157	36.21
1347	165716	0.331673	19,653	15,11	1369	182250	0.364382	58.405	46.69
	165764	0,325290	47.915	27.56		158404	0.452972	13.277	32.15
	165796	0.343037	16,303	05.46		158450	0.182647	51.000	21.21
1348	165723	0,357182	21.924	08.36	1370	158364	0.310915	41.550	00.58
	165770	0.348429	30,891	20,43		182296	0.434705	49.950	38.38
	165788	0.294389	09.365	54.52		158447	0.254380	08.746	11.51
1349	165753	0.301567	47,176	14.35	1371	158179	0.422194	12.709	06.46
	165811	0,395422	32,007	39.79		158211	0,316008	05.336	38.69
	165816	0.303010	58.971	46.98		158227	0.261798	04.290	19.99
1350	165759	0,334872	23.344	47.70	1372	158164	0.260559	41.295	38.66
	165800	0.297100	45.593	54,03		158177	0.274292	07.882	54.14
	165826	0,368028	24.540	50.86		158240	0.465148	02.811	17.04
1351	120959	0.244450	15.219	09,34	1373	158130	0.396435	47.349	14.15
	120966	0,389876	10.782	54.09		158134	0.280984	00.971	47.90
	121006	0.365674	45.806	58,51		158162	0.322580	33.157	35.87
1352	120967	0,393286	12.486	30.97	1374	158123	0.441196	29.759	53.22
	120971	0.286964	34,493	25.65		158140	0.358282	23.353	40.06
	121004	0,319750	19.176	54.01		158177	0.200522	07.882	54.14
1353	120919	0.248131	58,047	32,38	1375	158042	0.321442	20.817	05.47
	120931	0,256242	57.189	58.39		158047	0.421186	45.072	30.76
	120993	0.495627	44.893	46.35		158091	0.257373	58.705	24.62
1354	120932	0,343486	58.735	35.32	1376	158026	0.182121	49.210	06.89
	120962	0.291572	54,441	41.93		158051	0.285510	16.845	00.50
	120967	0,364942	12.486	30.97		158073	0.532369	55.745	26.00
1355	120757	0.305675	56,383	17.61	1377	157933	0.267864	33.902	59.92
	120790	0,414674	09.021	39.15		157985	0.335511	14.373	26.52
	120799	0.279650	16.045	41,13		158005	0.396625	43.842	24.85
1356	120771	0,395508	27.014	10.46	1378	157936	0.286784	59.739	41.63
	120784	0,396747	45,420	23.73		157979	0.392816	34.991	10.41
	120796	0.207745	55.224	18.30		158015	0.320401	49.249	26.87
1357	120590	0.448680	06.970	18,64	1379	157944	0.399994	36.359	05.08
	120607	0,271380	35.057	16.92		157967	0.283117	18.338	37.00
	120619	0.279940	29.887	31,74		158002	0.316888	26.231	10.90
1358	120579	0,200032	42.228	54.46	1380	159735	0.256974	42.813	49.48
	120581	0.399333	49,170	36.37		157971	0.331226	46.786	42.74
	120644	0,400634	08.667	33.13		157982	0.411800	57.508	03.82
1359	120539	0.408473	52.863	28,41	1381	157979	0.352633	35.031	07.56
	120540	0,271296	20.258	13.55		157993	0.314174	48.532	12.82
	120584	0.320230	14,785	00,62		158016	0.333194	50.151	43.50
1360	120526	0,296573	06.377	32.41	1382	157969	0.463156	37.483	35.45
	120535	0.407099	40.224	33,42		157997	0.174865	08.233	40.55
	120596	0,296328	05.221	13.15		158031	0.361979	07.368	22.53
1361	120507	0,261181	35,424	10.73	1383	158016	0.263832	50.150	43.50
	120526	0,414742	06.377	32.41		158038	0.406922	48.399	06.37
	120539	0.324076	52,863	28,41		158052	0.329246	19.797	14.41
1362	120500	0,276604	36.812	28.71	1384	158000	0.453704	22.865	25,64
	120534	0.411250	32,303	24,55		158054	0.234144	20.778	17.60
	120540	0,312146	20.258	13,55		158079	0.312152	33.897	57.28

TABLE 2 (cont.)

REFERENCE STAR POSITIONS AND DEPENDENCES

No.	Star	Depend,	R.A,	Dec,	No.	Star	Depend,	R.A.	Dec.
1385	186780	0,226761	32,975	15,27	1401	135099	0,393274	34.968	36.62
	186884	0,415060	45,669	32.48		135169	0.331047	19.558	36.65
	186896	0.358150	28,206	52.34		135212	0,275679	34.147	01.64
1386	186803	0,315322	51.303	45.78	1402	135116	0.507852	37.364	25.84
	186818	0.320629	33,581	48,14		135165	0,143494	10.739	22.18
	186965	0,364049	24.609	31.77		135194	0.348655	52.932	30.22
1387	186628	0.323126	35,791	21,87	1403	135172	0.267412	28.440	34.00
	186747	0.358688	17.853	44.30		135298	0.445857	58.053	35.94
	186804	0.318186	52,452	23.98		135311	0.286731	40.350	59.96
1388	186671	0.303632	12.807	50.14	1404	135186	0.351029	23.117	50.22
	186705	0.453290	52,367	36.29		135307	0,247592	36.399	01.73
	186826	0,243078	54.450	14.87		135309	0.401378	38.279	57.73
1389	185902	0.411126	28,697	19,62	1405	154811	0.329135	11.398	52.96
	185915	0,309683	11.935	12.97		154847	0,394447	13,928	53.86
	186032	0.279191	48,920	43.05		154862	0,276418	45.624	17.94
1390	185897	0,380542	20.541	05.58	1406	154805	0.343898	26.611	40,98
	185933	0.372366	59,730	29,25		154822	0,368793	56.203	31.40
	186019	0,247091	20.340	18.06		154899	0.287309	22.213	50.41
1391	185777	0.294895	09,497	38.52	1407	155321	0,312158	10.916	43.32
	185854	0.308138	49,082	40,56		155373	0.318304	07,645	05.93
	185883	0.396968	51,302	16,57		155375	0.369538	11.415	55.54
1392	185809	0,368488	41.341	38.44	1408	155326	0.459450	39.225	03.93
	185819	0.303386	00.219	07,64		155385	0.271107	49.855	01.55
	185909	0,328127	50.745	18.03		155386	0.269444	51.075	28.85
1393	185602	0.328038	53.592	06,63	1409	147820	0,264272	34.999	47.50
	185648	0,316922	54,494	00,09		147833	0.408330	44.382	29.52
	185725	0,355040	21.675	22.08		147848	0,327400	06.823	57.36
1394	185625	0.337997	45,439	06.33	1410	147811	0.256427	10.282	26.78
	185639	0,350254	24.420	26.32		147835	0.370272	49.554	34.45
	185708	0.311750	27,517	40,33		147854	0.373302	47.811	32.84
1395	185574	0,313668	03.664	38.50	1411	147811	0.329153	10.282	26.78
	185618	0.364930	09.976	22,98		147853	0.348378	45.083	14.47
	185644	0,321402	39.394	46.73		147881	0.322469	47.264	54.46
1396	185580	0.388420	14,596	26,11	1412	147807	0.298111	44.486	27.16
	185616	0,299831	57.993	45.52		147848	0,353742	06.823	57.36
	185658	0,311749	23,882	32.62		147882	0.348146	14.323	06.92
1397	185572	0,370716	02.442	12.06	1413	147807	0.323106	44.486	27.16
	185616	0,316302	57,993	45,52		147865	0.320800	34.231	59.12
	185667	0,312982	54.806	25.05		147874	0,356094	06.633	32.61
1398	185592	0.301366	10,260	11,13	1414	147800	0.285590	53.248	05.52
	185617	0.365512	05.537	57.43		147849	0,313104	07.941	59.05
	185628	0.333122	56,732	23,14		147882	0.401306	14.323	06.92
1399	185617	0,314372	05.537	57.43	1415	147444	0,298178	22.557	16.31
	185737	0,341398	40,277	36,91		166573	0.344271	50.768	14.24
	185774	0,344231	59.250	32,12		147494	0,357550	17.104	51.47
1400	185658	0,295524	23,882	32,62	1416	147447	0.298614	29.156	03.60
	185675	0,405618	20.891	38,85		147455	0.392120	00.442	08.73
	185789	0.298856	46,547	42,95		147486	0.309264	34.774	38.93

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Proper Motions in the Region of NGC 6025

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ABSTRACT. Proper motions of stars in the region of the galactic cluster NGC 6025 based on plates taken with the 33 cm astrograph, are determined with the aim of identifying stars in the area of the cluster which are non-members.

INTRODUCTION

The galactic cluster NGC 6025, R.A. $15^h 54^m.6$ Dec. $-60^\circ 10'$ (1900.0), has been investigated photoelectrically by Hogg (1953) and Feinstein (1971). The purpose of the present investigation is to identify from their proper motions those stars which are not members of the cluster. As the motion of the cluster is very small relative to the field stars, no attempt has been made to determine its absolute proper motion.

THE PLATES

The plates were taken with the 33 cm standard astrograph (scale 1' = 1 mm) as follows:

	Plate No.	Date Taken	Exposure
1	1522s	1894 May 28	4 m
2	1522s	1894 May 28	2 m
3	379RH	1900 May 10	3 m
4	6566Sa	1972 Apr. 12	12 m
5	6580Sa	1972 Apr. 18	9 m
6	6579Sa	1972 Apr. 18	12 m

The observers at the telescope were J. Short, 1, 2, 3, W. Robertson, 4 and K. Sims, 5, 6. All plates are centred at R.A. $16^h 00^m$ Dec. $-60^\circ 00'$ (1900.0).

MEASUREMENT

The last three plates were taken through the glass and the plates were bound together in pairs, one old and one new, film to film, the three pairs being 1 - 4, 2 - 5, 3 - 6. The distances apart in x and y of the old and new images were measured in a short screw Repsold measuring machine. This has a square graticule at the focus of the microscope which can be adjusted to match the scale and orientation of one reseau square (5 mm x 5 mm) on the old plates. The orientation of the plate pair was then adjusted so that travelling the plate pair along the ways in the x direction kept the graticule aligned with a reseau line. There are two micrometers at right angles and the movable wires were set in turn on the old and new images. The scale of the micrometers was found by setting the movable wires on two adjacent reseau lines. Each plate pair was measured in both direct and reversed positions. The stars measured were selected from the published co-ordinates in the Astrographic Catalogue, (Sydney Observatory 1954) (Plate 379 RH) in the area between 18.0 - 26.0 in x and 37.0 - 46.0 in y. Each plate pair was measured twice as follows:-

1 - 4	Miss H. Saunders	W. Robertson
2 - 5	Miss J. Fitt	W. Robertson
3 - 6	Miss K. Luxton	Miss M. Telfer

REDUCTION

If X_1, X_2 are the measures of x on the new and old plates, μ is the annual proper motion and t is the time interval between the plates, then we can write:- $X_1 - X_2 = \mu t + ax + by + c + dm$ with a similar expression for $Y_1 - Y_2$ where x, y and m (image diameter) were taken from the Astrographic Catalogue. After preliminary trials without a magnitude term, a selection was made of 87 stars which had small relative motions. These included a large number of members of the cluster but also some from the surrounding field. A least squares solution without the proper motion term was then obtained using the same group of stars each time. The solution was performed for each set of measures with a Diehl Alphatronic programmable calculator. The solution gives the plate constants a, b, c, d and then the residuals from the original equations give the proper motions relative to the mean motion of the 87 stars, which is effectively the mean motion of the cluster. The residuals for the two measures of each plate pair were meaned and reduced to annual proper motions by multiplying by k/t where k is the scale factor to convert the measured differences to seconds of arc. The annual proper motions from the three plate pairs were then meaned and the standard error of the mean for each star derived from the residuals for each plate pair. The standard errors for individual stars were grouped by their image diameters and the mean of the standard errors σ_x σ_y determined for different groups are as follows:-

Diameter	σ_x	σ_y
	(Unit 0″.001/yr)	
2.2	2.4	2.3
2.4- 3.0	2.4	2.2
3.2- 4.0	2.1	1.8
4.2- 5.0	1.6	1.8
5.2-10.0	1.5	1.5

Table 1 gives the observational data. Those stars in the cluster area which can be considered as non-members on a proper motion basis, are marked. The criterion adopted is that the total proper motion $(\mu_x^2 + \mu_y^2)^{\frac{1}{2}}$ should exceed three times the average standard error $(\sigma_x^2 + \sigma_y^2)^{\frac{1}{2}}$ i.e. be greater than 0″.0085/yr. Those stars whose total motion approaches this are marked as doubtful. The cluster area is defined as a circle of radius 15 arcminutes centred at R.A. $15^h\ 54^m.6$ Dec. -60° 10' (1900.0) which certainly includes all the stars in the apparent area of the cluster. Some of the stars in the Astrographic Catalogue are omitted, mainly because the images were too faint to measure. Where a result was obtained on two plate pairs, the mean is shown but those from only one plate pair were rejected. The various columns are as follows:

No.	The number from the Astrographic Catalogue, Sydney Section ($16^h\ 00^m$ -60° centre)
Diam.	The diameter of the image from the same source.
R.A.) Dec.)	(1900.0) calculated from the astrographic place.
CPD No.	
Mag.	pPg from Hogg.
μ_x, μ_y	annual proper motion in units of 0″.001/yr. The axes are parallel to right ascension and declination.

Remarks
1 Non-member - in the area within a radius of 15' of the adopted centre of the cluster ($15^h\ 54^m.6$, -60° 10').
1: Doubtful case.
2 Only two plate pairs.

ACKNOWLEDGMENTS

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TABLE 1

THE OBSERVATIONAL DATA

No.	Diam.	R.A. (1900.0) 15h m s	Dec. ° ' "	CPD No.	Mag.	μ_x (Unit 0″.001/yr)	μ_y	Remarks
202	2.2	56 52	-60 27 03	-60°6382		-23	-26	
203	2.2	56 36	27 02	6378		+ 9	+ 5	
207	8.5	55 22	26 51	6353		-52	-67	
208	2.2	54 58	29 36			- 4	-16	2
209	2.2	54 19	28 12	6314		-28	-37	
210	4.8	54 08	24 54	6309		- 3	-10	
211	2.2	54 04	25 37	6307		- 2	+ 1	
236	4.0	56 58	22 35	6384		- 4	- 1	
237	2.2	56 40	22 49			+ 2	- 2	2
238	2.2	56 22	23 29	6373		+ 3	- 2	
239	2.2	56 14	21 11			+16	-20	
241	2.2	55 52	23 17	6367		+ 3	0	
244	3.0	55 44	24 10	6365		+ 3	0	
245	2.2	55 43	19 57			- 2	+ 3	
246	2.2	55 11	20 12			-14	- 4	1,2
247	3.0	54 52	24 07	6331	11.37	- 1	- 2	
248	3.0	54 31	21 49	6320	11.41	+ 2	0	
249	2.2	53 55	21 07	6304		- 4	- 1	2
251	3.5	53 11	21 27	6290		-13	-14	
252	2.8	52 18	21 33	6277		- 6	0	
286	2.2	56 53	19 02			- 3	- 7	
287	3.0	56 50	17 36	6381		+ 1	+ 4	
288	2.2	56 17	19 00			+ 2	- 4	2
289	2.2	56 03	17 13	6370	11.30	0	- 2	
290	3.5	55 34	18 36	6360	11.26	0	- 1	
291	3.5	55 34	15 18	6361	11.15	0	+ 2	
292	3.5	55 05	18 58	6342	11.44	0	+ 3	
293	3.5	55 02	14 54	6340	11.30	- 2	+ 4	
294	4.0	54 56	16 01	6335	10.90	- 2	- 3	
295	2.2	54 49	17 38	6328	12.41	+ 1	- 1	
297	4.5	54 09	19 02	6311	10.65	+ 3	- 1	
299	3.8	53 26	17 26	6296	10.87	- 3	+ 3	
300	2.8	53 08	18 49	6288		- 1	+ 1	
301	4.8	52 51	15 09	6283		- 1	0	
302	2.2	52 19	15 35	6278		+ 6	+ 4	
340	3.0	56 44	-60 10 36	6380		+21	+25	

TABLE 1 continued

No.	Diam.	R.A. (1900.0) 15h m s	Dec. ° ' "	CPD No.	Mag.	μ_x	μ_y	Remarks
						(Unit 0″.001/yr)		
341	2.2	56 42	-60 12 03			-21	- 7	2
343	2.2	55 46	12 14			- 8	+ 4	1,2
345	3.2	55 21	11 12	-60°6352	11.14	+ 1	+ 1	
346	8.5	55 14	14 01	6349	7.99	+ 6	- 2	1:
347	10.0	55 14	13 08	6348	7.01	+ 1	- 1	
348	3.5	55 11	10 49	6345	11.13	+ 1	- 2	
349	2.5	55 08	14 17	6344	10.84	+ 3	+ 1	2
350	8.5	54 59	12 24	6338	8.28	0	+ 3	
351	6.8	54 52	13 25	6332	9.62	+ 1	- 2	
352	3.8	54 49	13 17	6329		0	- 2	
353	7.0	54 47	10 07	6327	9.85	-12	-28	1
354	3.5	54 34	14 37	6321	10.90	- 1	- 4	
356	5.0	54 24	11 40	6316	10.21	+ 5	+ 1	
357	8.0	54 24	09 44	6317	8.83	+ 1	+ 2	
358	2.2	54 10	09 48	6310	12.51	- 4	+ 8	1
359	3.8	54 06	12 45	6308	11.22	- 4	- 1	
360	3.5	53 54	10 34	6303	11.54	- 5	- 3	1:
361	2.8	53 44	11 38	6300	11.26	0	- 1	2
363	3.2	53 39	14 21	6297	11.76	- 1	- 1	
364	8.0	53 23	13 35	6294	9.23	+ 1	+ 1	
365	2.2	52 58	10 47	6286		+ 1	+ 2	
366	2.2	52 10	09 42	6275		-20	-18	
401	3.5	56 40	07 03	6379		+ 2	- 1	
402	2.2	56 08	06 20			0	- 7	2
403	3.8	56 05	06 50	6371	11.02	- 5	+ 7	1
404	3.5	55 55	08 18	6368	11.38	+ 1	- 2	
405	2.5	55 45	06 59	6366	11.81	0	- 2	
406	4.5	55 34	06 54	6362	10.45	0	0	
407	3.5	55 14	06 04	6350	11.19	+ 2	+ 4	
408	3.8	55 05	09 37	6343	11.01	- 5	+ 3	1:
409	4.5	55 03	07 29	6341	10.37	-10	+ 1	1
410	5.0	55 00	09 30	6339	9.77	+ 4	+ 3	
412	7.0	54 54	05 47	6334	9.01	+ 1	+ 3	
413	3.8	54 50	06 27	6330	11.16	- 1	+ 7	1:
414	8.8	54 44	07 30	6326	7.93	+ 1	+ 2	
415	7.0	54 43	05 56	6325	8.77	+ 5	+ 4	1:
416	4.8	54 34	07 29	6322	9.75	+ 3	+ 4	
417	2.2	54 33	08 51			-10	+ 2	1,2
418	5.5	54 31	08 33	6319	9.93	+ 4	+ 2	
420	3.5	54 18	06 58	6313	10.81	+ 3	+ 3	
421	4.0	53 59	06 44	6305	10.25	0	+ 7	1:
423	3.2	53 02	08 53	-60°6287		0	- 4	
464	2.2	57 09	04 19			- 8	- 4	1,2
465	3.0	57 04	01 23	-59°6595		+18	+ 5	
467	3.0	55 49	03 47	6579	11.37	- 1	- 5	
469	3.0	55 33	01 03	6575	11.44	- 5	+ 4	1:
470	2.2	55 29	03 04			- 2	+10	1,2
471	2.2	55 26	00 14			- 1	0	
472	2.2	55 16	02 30			+ 2	0	
473	2.5	55 14	02 35	6569		+ 1	+ 2	
474	5.5	55 03	03 23	-59°6563	9.62	+ 2	0	
475	4.2	54 56	04 32	-60°6336	10.61	- 2	+ 1	
476	4.8	54 53	02 47	-59°6562	9.95	+ 3	0	
478	2.5	54 36	04 25	-60°6323	9.11	0	+ 2	
479	7.0	54 33	03 19	-59°6557	9.16	+ 2	+ 1	
480	8.8	54 25	03 15	6555		-12	-22	1
481	3.8	54 16	-60 03 32	6553	11.14	+ 2	0	
482	2.2	53 58	-59 59 57	6549	11.77	+ 2	- 2	
484	3.5	53 38	-60 01 29	6541	11.13	0	+ 1	
485	2.5	53 30	03 31	6539	12.00	- 2	- 1	
486	2.8	53 05	-60 00 47	6534		0	+ 2	
515	2.2	57 17	-59 59 51			+ 3	- 5	
516	3.5	56 18	-59 58 50	6584		- 7	-25	

TABLE 1 continued

No.	Diam.	R.A. (1900.0) 15h m s	Dec. ° ' "	CPD No.	Mag.	μ_x	μ_y	Remarks
						(Unit 0".001/yr)		
517	3.8	55 49	-59 58 06	-59°6578	10.40	+ 1	+ 4	
518	8.0	55 37	56 13	6576	8.40	- 2	-10	1
519	2.2	55 30	56 48			0	+ 1	
520	4.0	55 12	55 03	6568	10.61	+ 3	+ 5	
523	3.2	54 32	56 33	6556	11.45	+ 2	+ 2	
524	2.2	53 36	58 08	6540	11.87	0	0	2
525	2.2	53 11	55 23			+ 4	- 2	2
526	4.2	53 02	57 40	6533		+ 1	- 8	
529	2.2	52 06	57 19	6516		+ 9	+ 3	
530	3.5	52 06	54 56	6515		-19	-15	
559	2.2	57 10	54 20			-12	-11	
560	2.2	57 08	50 53			- 1	- 3	
561	2.5	56 41	54 02	6593		+ 3	- 2	
563	2.2	56 28	52 19			0	+ 2	
564	2.5	55 20	52 18	6571		+ 2	0	
565	4.5	55 04	51 46	6564		- 1	0	
567	2.2	54 49	52 07	6561		- 1	+ 4	
569	2.2	54 38	51 57			- 1	0	
570	5.0	53 43	51 19	6545		+12	+ 2	
571	2.5	52 26	49 48	6520		+ 1	- 2	
607	3.2	57 16	47 56			- 1	- 1	
608	2.4	57 15	49 24			- 2	- 1	
609	2.8	56 56	49 13	6594		- 6	-12	
610	2.2	56 31	48 15			- 2	+ 4	
611	2.2	56 31	46 12			-14	+ 8	2
612	2.8	56 24	49 07	6588		-25	+35	
613	2.2	56 03	45 57			-30	-43	2
615	4.5	55 08	49 20	6566		- 5	- 5	
616	2.5	54 39	44 53	6559		- 7	-15	
617	2.2	54 32	48 49			+ 4	- 3	
619	5.0	54 21	44 47	6554		+ 3	-22	2
620	2.2	53 51	49 11	6546		+ 6	- 3	
621	2.2	53 36	-59 47 17			- 5	- 1	

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Discharge of Sands by Sandy Bed Streams and the Regime of Leveed Rivers in Coastal Flood Plains with Special Reference to Rivers in Eastern New South Wales

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ABSTRACT. A formula is derived for the discharge of sands in a sandy bed stream. This formula is valid for all streams wherein the concentration of suspended sediment is less than 4000 parts per million. This formula is combined with a representative flood discharge hydrograph and a flood frequency relationship to obtain an expression for the average annual discharge of sand by an upland sandy bed stream without levees. The application of this expression requires only limited flood records and field observations.

The formation of leveed channels in flood plains is described. Relationships and formulae used above are extended to obtain expressions for the regime levels of the levee crests and the beds of the channels. These expressions are based on the assumption that the height of the levees and the width and depth of a leveed channel are determined by:-

(a) the average annual quantity of sand supplied by the upland stream and
(b) the proportion of fine sediment in the total average annual supply of sediment.

From these expressions changes in the levels of levee crests and the bed of a channel, due to changes in sediment supply, can be computed. In certain cases, the general trends of changes in sediment supply can be inferred from these expressions without computation. These general trends have been tabulated.

INTRODUCTION

A method is given for estimating the average annual quantity of sand discharged by an upland sandy bed stream without levees. Relationships and formulae associated with this method are used to obtain expressions for the regime levels of the crests of levees and of the beds of channels of rivers in coastal flood plains.

The expressions and relationships derived in this paper apply generally. Applications include the determination of sand yields from catchments, the accumulation of sand behind dams and the changes in the levels of levee crests and the beds of channels brought about by changes in sediment supply.

PART 1

The Average Annual Discharge of Sand by a Sandy Bed Stream

The method of determining the average annual discharge of sand by a sandy bed stream employs a formula for the discharge of sands, a representative flood discharge hydrograph and a flood frequency relationship.

These are now considered in turn.

1.1 The Formula for the Discharge of Sands.

The formula is derived from curves prepared by Colby (1964). Discharges computed from these curves are generally in closer agreement with field observations than those computed from the methods of other authors (Task Committee for Preparation of Sediment Manual, 1971). Colby defines sand as sediment particles that have diameters between 0.062 mm and 2.0 mm. The basic curves prepared by Colby give discharges of sand in tons per day per foot width of channel for various velocities and depths of flow. The curves are for median grain sizes ("D50") ranging from 0.1 mm to 0.8 mm, for velocities ranging from 0.3 m/sec. (1 f.p.s.) to 3 m/sec (10 f.p.s.) and for depths ranging from 0.3 m (1 ft.) to 30.5 m (100 ft.). In sand bed streams the velocity of flow is self-limiting and seldom exceeds 3 m/sec (Leopold et al, 1964) because of the resistance offered by the bed forms which are themselves fashioned by the flow.

The discharges given by these basic curves require corrections for temperatures differing from 16°C (60°F) and for the effects of concentrations of fine sediment. Colby defines fine sediment as sediment particles that have diameters less than 0.062 mm. Corrections for temperatures and concentration of fine sediments are given by curves in Colby's publication.

The maximum concentration of fine sediment in sand bed streams on the East Coast of Australia is generally less than 4,000 parts per million (McGlinn, J., 1976. Water Conservation and Irrigation Commission. Personal Communication) and temperatures do not depart greatly from 16°C (60°F). Hence the basic Colby curves apply to these streams without correction for these variables.

The median grain size diameters of sand in the streams in Eastern New South Wales are generally in the range 0.2 mm to 0.8 mm (Harbours and Rivers Branch, Public Works Department of N.S.W., 1945). The median grain sizes of sand in the Clarence and Hawkesbury Rivers (Scholer, 1961, 1974), the Hunter River (Nittim, 1966) and the Georges River (Munro et al, 1967) lie in the range 0.34 mm to 0.55 mm near the limit of tidal influence in these rivers.

The author has found by computation that the following formula gives a good fit of the basic Colby curves for median grain sizes ranging from 0.2 mm to 0.8 mm:-

$$Q_s = p_1 w\ d^{m_1} v^{n_1} + p_2 w\ d^{m_2} v^{n_2} \tag{1}$$

where Q_s is the discharge of sand; w is the width of the channel; v is the velocity of water flow; and p_1, p_2, m_1, m_2, n_1 and n_2 are constants.

The following expressions give, respectively, the channel widths and depths, at a station, in terms of the water discharge Q. They apply to observations on streams overseas (Leopold et al, 1964) and are assumed to apply to upland streams in Eastern New South Wales. They have been found by the author to apply to the Hawkesbury River and the Georges River. They apply to the Hunter River (Nittim, 1966):-

$$w = C_1 Q^{\alpha_1} \tag{2}$$

$$d = C_2 Q^{\alpha_2} \tag{3}$$

where C_1, C_2, α_1 and α_2 are constants.

In order to make use, subsequently, of the findings of Woodyer (1968), C_1 and C_2 are expressed in terms of the width and depth of flow corresponding to the discharge that is exceeded, on average, once a year (hereafter termed "the mean annual flood"). These widths and depths were deduced by the author from field observations of the positions of benches, described by Woodyer.

Let w_{ma} and d_{ma} be, respectively, the width and depth corresponding to the mean annual flood Q_{ma}.

Then (2) and (3) are replaced by the following expressions:-

$$w = \frac{w_{ma}}{Q_{ma}^{\alpha_1}} Q^{\alpha_1} \tag{3}$$

$$d = \frac{w_{ma}}{Q_{ma}^{\alpha_2}} Q^{\alpha_2} \tag{4}$$

Putting $v = \frac{Q}{bd}$ in (1) and substituting in the resulting expression the values of w and d given by (3) and (4), we obtain:-

$$Q_s = A_1 Q_{ma}^{-N_1}\ Q^{N_1} + A_2 Q_{ma}^{-N_2}\ Q^{N_2} \tag{5}$$

$$\text{Where } A_1 = p_1 w_{ma}^{1-n_1}\ d_{ma}^{m_1-n_1}\ Q_{ma}^{n_1} \tag{6}$$

$$\text{Where } A_2 = p_2 w_{ma}^{1-n_2}\ d_{ma}^{m_2-n_2}\ Q_{ma}^{n_2} \tag{7}$$

$$\text{Where } N_1 = n_1(1 - \alpha_1 - \alpha_2) + \alpha_1 + m_1\alpha_2 \tag{8}$$

$$\text{Where } N_2 = n_2(1 - \alpha_1 - \alpha_2) + \alpha_1 + m_2\alpha_2 \tag{9}$$

1.2 The Representative Flood Discharge Hydrograph.

The quantitiy of sand discharged by sand bed streams in dry weather flow is negligible compared to the quantity discharged in wet weather flow. Consequently, the sand transported in major and minor floods (including small rises and freshes) need only be considered.

For a given catchment, the shape of a flood discharge hydrograph is determined by the areal and temporal distribution of rainfall, as well as the magnitude of the total storm rainfall. Consequently, the construction of a discharge/duration curve (a feature of the usual procedure in estimating the discharge of sediments), which aspires to high accuracy, requires detailed records of floods extending over a long period of time. On the other hand, a representative flood discharge hydrograph which integrates meteorologic and catchment characteristics would be especially useful in cases where flood records are limited.

The surface runoff hydrograph described by Gupta and Moin (1974) has been adopted as the representative flood discharge hydrograph. Although the surface runoff hydrograph does not include base flows, as mentioned above, these do not transport significant quantities of sand and can therefore be validly ignored.

By inference from the equations in this Reference, the representative discharge hydrograph is given by the following expressions:-

$$Q = Q_{max}\phi(t) \tag{10}$$

$$\phi(t) = \left(\frac{t}{t_p}\right)^x e^{(1-\frac{t}{t_p})x} \quad \text{for } o \leq t \leq t_o \tag{11}$$

$$\phi(t) = \left(\frac{t_o}{t_p}\right)^x e^{(1-\frac{t_o}{t_p})x}\ e^{-(\frac{t-t_o}{d})} \quad \text{for } t>t_o \tag{12}$$

Where Q_{max} is the peak discharge and where, in the notation of Gupta and Moin, e is the base of Naperian logarithms, x is a parameter, t = time elapsing since the commencement of the river rise, t_p = time to peak discharge, t_o = time to the point of inflexion on the recession limb of the hydrograph and d is the recession constant. Representative values of x, d, t_p and t_o are obtained from flood observations.

The representive flood discharge hydrograph can be combined with the sand discharge formula given above, and the flood frequency relationship given below, to obtain an explicit formula giving the mean annual discharge of sand by an upland stream. As shown in Part 2 it can also be applied in obtaining an expression for the regime level of the levee crests of a leveed channel.

1.3 The Flood Frequency Relationship.

Floods with different recurrence intervals can be related (Woodyer and Fleming, 1968) by means of a frequency function F_y defined by the following equation:-

$$Q_{my} = F_y \, Q_{ma} \qquad (13)$$

Where Q_{ma} has been defined in Section 1.1 (see Eqns. (3) and (4)) and Q_{my} is the peak discharge that is equalled or exceeded once in y years.

In Eastern N.S.W. F_y is given by the following expression (Woodyer, K.D., 1974. Personal Communication):-

$$F_y = 1 + a \log_{10} y \qquad (14)$$

Where the value of the constant a is approximately 1.0 in Eastern N.S.W.

From (10) and (13) we obtain the following expression for the instantaneous water discharge Q:-

$$Q = Q_{ma} \, F_y \, \phi(t) \qquad (15)$$

Substituting the value of Q given by (15) in (5), we obtain the following expression for the instantaneous discharge of sand by the flood with a peak discharge equalled or exceeded once in y years:-

$$Q_s = A_1 F_y^{N_1} \, [\phi(t)]^{N_1} + A_2 F_y^{N_2} \, [\phi(t)]^{N_2}. \qquad (16)$$

Consequently, the total quantity of sand Q_{sty} discharged by this flood is given by the expression:-

$$Q_{sty} = A_1 F_y^{N_1} \int_0^{\infty} [\phi(t)]^{N_1} dt + A_2 F_y^{N_2} \int_0^{\infty} [\phi(t)]^{N_2} dt \qquad (17)$$

Now in any year, the probability Δp of occurrence of a flood with a peak discharge lying between Q_{my} and $Q_{m(y+\Delta y)}$ is, by definition of Q_{my} given by: $\Delta p = \frac{1}{y} - \frac{1}{y+\Delta y} \approx \frac{\Delta y}{y^2}$

Then ignoring higher powers of differentials, the average annual quantity of sand discharged $\Delta \bar{Q}_s$ by floods with peak discharges lying between Q_{my} and $Q_{m(y+\Delta y)}$, is $Q_{sty} \frac{\Delta y}{y^2}$, where Q_{sty} is given by Eqn. (17).

The average annual quantity of sand discharged by all floods, $\bar{Q}_s$ is given by :-

$$\bar{Q}_s = \int_{y_1}^{\infty} Q_{sty} \frac{dy}{y^2} \qquad (18)$$

Where y_1 is the value of y corresponding to $F_y = 0$.

Consequently, the value of the lower limit y_1 depends on the frequency function F_y. Adopting the expression for F_y given by (14) and a value of a = 1 then $y_1 = 0.1$ The value of a ranges from 1.0 to 2.0. For a = 2, $y_1 = 0.32$. At the worst, therefore, the use of (18) ignores the sand discharged by flows in very small rises with peak discharges exceeded about three times a year. The sand discharged by these flows is, however, relatively small and (18) can be adopted without significant error.

Substituting the value of Q_{sty} given by (17) in (18), we obtain the following expression for the average annual discharge of sand $\bar{Q}_s$ by an upland stream with a sandy bed:-

$$\bar{Q}_s = \{A_1 \int_0^{\infty} [\phi(t)]^{N_1} dt\} \int_{y_1}^{\infty} \frac{F_y^{N_1}}{y^2} dy + \{A_2 \int_0^{\infty} [\phi(t)]^{N_2} dt\} \int_0^{\infty} \frac{F_y^{N_2}}{y^2} dy \qquad (19)$$

PART 2

The Regime of Leveed Rivers in Coastal Flood Plains.

Figure 1 is an average cross section of the Hawkesbury River along Freeman's reach (the reach immediately downstream from Richmond Bridge). Here the crests of the levee banks are 7.6 m (25 feet) above the flood plain behind them. The levees of other large N.S.W. coastal rivers are of comparable heights.

In the case of the Hawkesbury River and other coastal rivers with drowned valleys, the present flood plains came into existence as deltas as the rivers filled their valleys with sediments in response to rises in mean sea level following periods of glaciation (Bird, 1964). This type of flood plain development is described by Strahler (1969), Sale (1967), Trewartha et al (1967), and the U.S. Army Corps of Engineers (1963). The mode of formation of these flood plains is modelled, in certain cases, by streams discharging into dams. The processes involved in the formation of the sedimentary deposits laid down by these streams, are a response to a rise in base level similar to the processes involved in the formation of sedimentary deposits laid down by a river during a period of rising sea level. An example of the processes which occur after a rise in base level, is the delta built up by Washita River behind the Denison Dam in Texas (Bondurant, 1955) within a decade after the filling of the dam. This delta is in the form of a floodplain wherein the river flows between levees.

The growth of the deltas is characterised by the advance of the levees which form spits that protrude into the standing water body on either side of the mouth of the stream. These spits are termed "deltaic spits". These spit forms are seen in the deltas of streams flowing into lakes

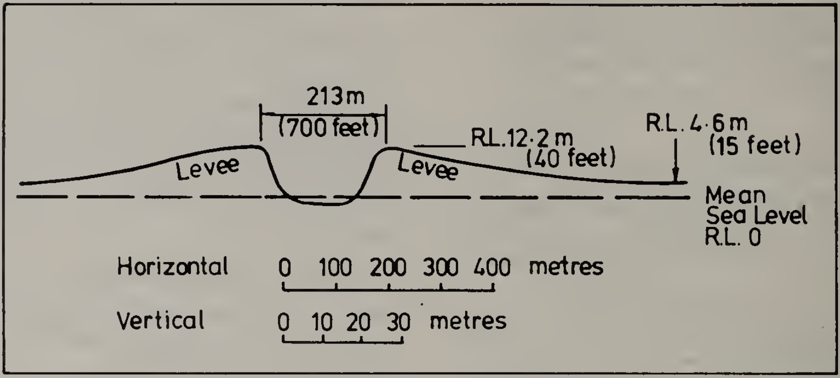

Fig. 1. Average cross section (diagrammatic) of Freeman's Reach, Hawkesbury River, showing the levee banks.

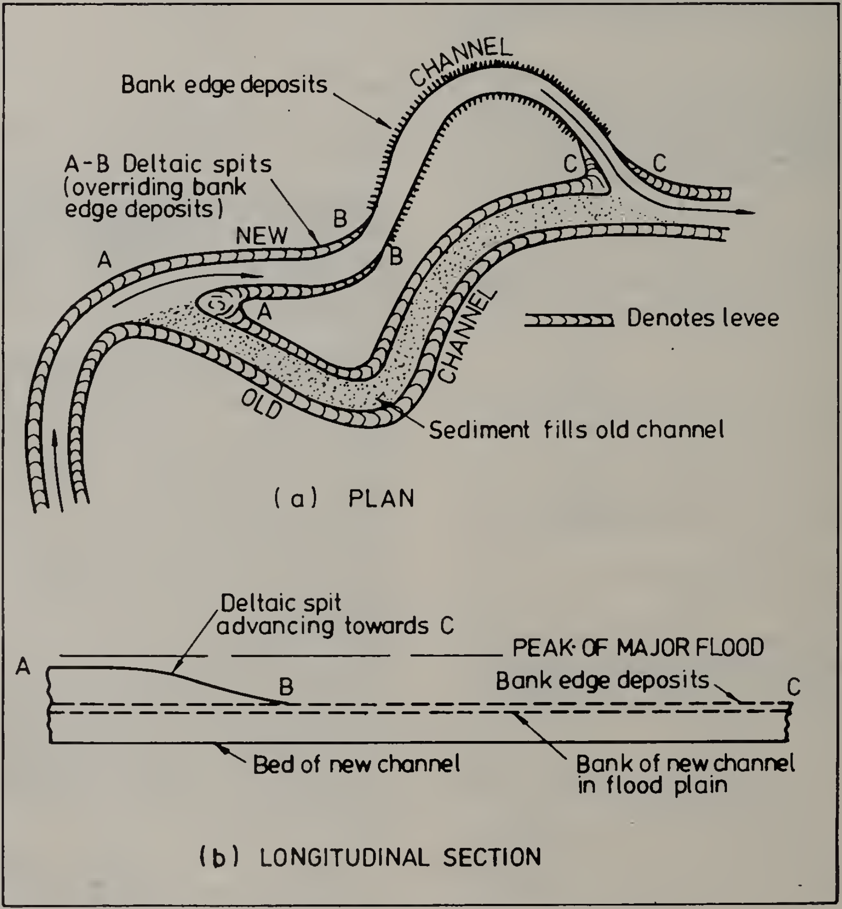

Fig. 2 Sketches illustrating the growth of levees.

such as Middle Creek entering Narrabeen Lake, Ourimbah Creek entering Tuggerah Lake and Macquarie Rivulet entering Lake Illawarra (Brown, 1969).

In its emergent flood plain a river changes its course by breaching its levee banks in floods ("avulsions"). Along its new course the river then proceeds to build new levees. This build up of new levees may be considered as being made up of two complementary processes: a process of bank edge deposition and a process of secondary deltaic growth. The term "secondary" has been used to distinguish the deltaic extension of the levee banks along the flood plain from the primary deltaic growth of the whole flood plain itself, referred to above.

In the process of bank edge deposition, the momentum transfer between the flow in the channel and the flow along the banks causes sediment to be transferred from the channel to the banks where, provided that the down valley slope is not excessive (Wolman and Leopold, 1957), the velocity is checked and the sediment is deposited. To quote from page 98 of this Reference: " ...... when the flow leaves the stream its velocity is checked, and as a result the stream is unable to carry its load and deposits material adjacent to the bank". Vegetation growing along the banks promotes this process (page 99).

In the process of secondary deltaic growth, the deposition of sediment is localised and occurs where the velocity of flood water in the channel is suddenly checked by the waters ponded in the flood plain. These deposits are in the form of deltaic spits and they advance downstream over the abovementioned bank edge deposits. Secondary deltaic growth is exemplified by the levees of Bardenarang Creek which connects the low lying areas of Pitt Town Bottoms with the Hawkesbury River. The sediment laden waters from the river in flood flow back along the creek into the ponded water of the Bottoms, depositing sediment to form these levees which taper spitwise back from the river. The levee crest level drops from R.L. 8.2 m (27.0 ft.) Standard Datum at the creek mouth to R.L. 3.6 m (12.0 ft.) in 2740 m (9000 ft.) while the bed is approximately horizontal over this distance at R.L. 1.0 m (3.0 ft.).

The two complementary processes involved in the growth of levees along a new river channel are illustrated by Figure 2. At A - A in Figure 2 (a) the leveed river has breached its banks and is flowing along a new channel to rejoin the existing channel at C - C. Originally the lower course of the new channel may, like Bardenarang Creek, have acted as an outlet for drainage and an inlet for floodwaters before the river breached its banks at A - A. Bank edge deposits have formed along the new channel and these deposits have channelised flows so that the secondary deltaic growths, advancing from the breached levee banks over the bank edge deposits, follow the sinuous course of the new channel. The advance of the secondary deltaic growths is shown in Figure 2 (b). When completed, these growths will form levees along the new channel of the same height as the levees of the abandoned channel.

Bank edge deposits are produced by floods as soon as they exceed bankfull stage and the higher portions of the deltaic spits are associated with the less frequent higher stage floods. Consequently, the rate of vertical growth of a levee at any location along a new channel diminishes with increasing height of the levee crest above the floodplain.

This hypothesis of levee growth not only explains the formation of levees along meandering rivers but also makes plausible the extension (see below) of regime relationships derived for non leveed rivers to rivers with natural levees.

Expressions are now obtained for the regime heights of levee crests at a location towards the upstream end of a leveed channel. This location, downstream from the location where the upland stream debouches into the floodplain is indicated by "X" in Figure 3. The discharge hydrograph between the levee banks at "X" is similar to the discharge hydrograph at the lower end of the upland stream.

Flow velocities and the transport of sand are checked when levees are overtopped and floodwaters mingle with the slow moving waters covering the floodplain (Wolman and Leopold, 1957). Hence, in order to maintain the continuity of transport of sand by the river through the flood plain, it is reasoned that the fully developed levees attain such a height as to confine the flows in a river reach so that, over many floods, a long term equilibrium of erosion and deposition is achieved. In other words, for a stable cross section to be achieved in a reach, the sand that is deposited when floodwaters are above levee crest level, must be balanced by the sand that is scoured when floodwaters are below the levee crests. The flow velocity diminishes abruptly when water levels are above the levee crests at "X".

It is assumed by the author that when the levels of the water ponded in the floodplain are above the levees at "X", there will be no movement of sand beyond point "X ", located a short distance downstream from "X".[1] This assumption is borne out by observations made by the author in 1972, at the University of N.S.W., Water Research Laboratory. This was a pilot model for preliminary studies related to a model of the development of a floodplain. The latter model is described by Scholer (1974). The implication is that all the sand carried past "X " in a flood occurs when floodplain water levels are below the levee crests at "X". Further, it is assumed that the discharges at "X$_1$" are not retarded by backwater effects when floodplain water levels are below the levee crests at "X".

This schematic model approximates the net movement of sand past "X " in the higher floods. When applied to the floods of widely varying magnitudes which occur over a long period of time the model gives a satisfactory approximation to the requirement of continuity, namely, that if equilibrium has been attained between erosion and deposition, the mean annual discharge of sand downstream equals the mean annual supply of sand from upstream.

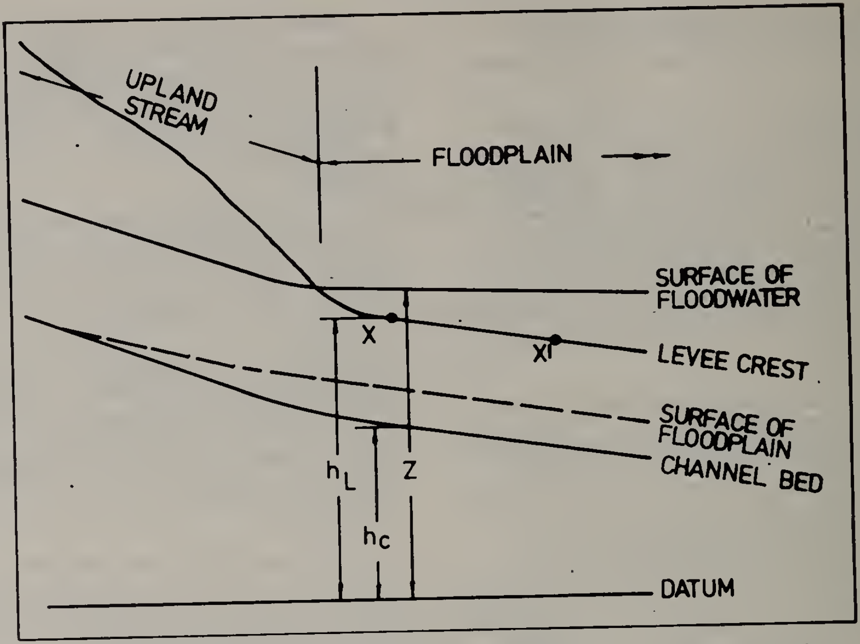

Fig. 3. Sketch of leveed stream at the upper end of its flood plain. Longitudinal Section. Not to scale.

Let Q = water discharge at a location near the lower end of the upland stream.
Let Z = water surface height at time t above datum at "X"
Let t = time since commencement of flood.
Let Q_o = water discharge at the downstream end of the floodplain.
Let S = storage at time t in the floodplain.

Then $$Q = Q_o + \frac{dS}{dt} \qquad (20)$$

Implicit in the use of equation (20) is the assumption that it is independent of the geometry of the leveed channel in the floodplain. This assumption is warranted by the fact that in nature there are openings in the levees at intervals along the channel permitting the ingress of water from the channel to the floodplain behind the levees. These openings suffice for the rapid filling up of the floodplain, so that when the levees are overtopped, the difference between water surface level in the channel and water surface level in the floodplain, is small. Otherwise when the levees were overtopped there would be heavy scour with the enlargement of existing openings and the formation of new ones.

Now generally there is a high degree of correlation between S and Z and Q_o and Z and hence we may consider S and Q_o as being functions of Z only. These functions, S = S(Z) and $Q_o = Q_o(Z)$ can be determined from observations of water levels and discharges made on actual floods, or on floods simulated by a hydraulic model.

In certain cases, where the geometry of the floodplain is relatively simple, S(Z) and $Q_o(Z)$ can be approximated to by the expressions

$$l_1(Z - Z_1)^{x_1} \text{ and } l_2(Z - Z_2)^{x_2}$$

where l_1, l_2, Z_1, Z_2, x_1 and x_2 are constants.

These expressions can be applied to the Hawkesbury River floodplain extending from the Grose River junction to Pitt Town, downstream of which the river is entrenched between sandstone hills. However, because of the backwater effects of the flood discharges of the Colo and Macdonald Rivers, which join the main river downstream from this floodpain, the degree of correlation between S and Z and Q_o and Z is not as high as it is for other coastal rivers.

Putting S = S(Z), $Q_o = Q_o(Z)$ and $Q = Q_{ma} F_y \phi(t)$ (see (15)), we obtain from (20) the following expressions for t in terms of the instantaneous level Z of the water in the floodplain at "X":-

$$t = t_1(Z, Q_{ma} F_y) \qquad (21a)$$

$$t = t_2(Z, Q_{ma} F_y) \qquad (21b)$$

Where (21a) is valid for the rising stage and (21b) is valid for the falling stage of the flood.

Also, we observe from (20) and (15), the peak level Z_{max} of the water in the floodplain at "X" is a function of $Q_{ma} F_y$, the peak discharge exceeded once in y years.

Let h_L be the height of the levee crests above datum at location "X" (see Figure 3). Then from (21a) and (21b), floodwaters are at levee crests level h_L at times $t_1(h_L, Q_{ma}F_y)$ and $t_2(h_L, Q_{ma}F_y)$.

The total quantity of sand discharged past "X_1" by a flood with a once in y years peak discharge exceedance, when the waters in the floodplain are below the levee crests at "X", is therefore, given by:-

$$Q^1_{sty} = \int_0^{t_1(h_L, Q_{ma}F_y)} Q_s dt + \int_{t_2(h_L, Q_{ma}F_y)}^{\infty} Q_s dt \qquad (22)$$

The limits in Eqn. (22) are such that if the peak Z_{max} of the water in the floodplain at "X" is less than h_L then $t_1(h_L, Q_{ma}F_y)$ and $t_2(h_L, Q_{ma}F_y)$ are both equal to $t(Z_{max})$. In this case $Q^1_{sty} = \int_0^{\infty} Q_s dt$. According to the above schematic model:-

$$\int_{y_1}^{\infty} Q^1_{sty} \frac{dy}{y^2} = \overline{Q}_s \qquad (23)$$

Where $\overline{Q}_s$ is the average annual quantity of sand discharged by the upland stream.

To derive from (1) an expression for the discharge of sands in a leveed channel, expressions for the instantaneous width w and depth d are required.

As a natural extension of (3) and (4), it is assumed that the following expressions give, for a leveed channel, the instantaneous channel widths and depths in terms of the water discharge Q:-

$$w = \frac{w_{ma}}{Q_{ma}^{\beta_1}} Q^{\beta_1} \qquad (24)$$

$$d = \frac{d_{ma}}{Q_{ma}^{\beta_2}} Q^{\beta_2} \qquad (25)$$

Where β_1 and β_2 are constants.

Expressions for w_{ma} and d_{ma} are obtained by assuming that they have the same form as the expressions developed by Schumm (1969) for the widths and depths of unleveed channels:-

$$w_{ma} = \frac{a\,Q_{ma}^{b}}{M^{c}} \qquad (26)$$

$$d_{ma} = g\,M^{1}\,Q_{ma}^{k} \qquad (27)$$

Where a, b, c, g, 1 and k are constants applicable to leveed channels and M is the percentage of sediment finer than 0.074 mm in the channel perimeter (Schumm, 1968). Here the channel perimeter is that of the waterway below the levee crests.

Schumm (1969) has given an expression for the inverse relationship that exists between M and the percentage of the total sediment load that is sand coarser than 0.074 mm, carried in the channel at mean annual discharge. This has been confirmed by the model study described by Scholer (1974). The manner in which the proportion of fine sediment in the banks and bed determines the channel geometry, is described by Schumm, 1960. Adopting Schumm's expression, we have:-

$$M = 0.55\,\frac{\overline{Q}_{s1} + \overline{Q}_F}{\overline{Q}_{s1}} \qquad (28)$$

Where $\overline{Q}_{s1}$ is the average annual discharge of sand coarser than 0.074 mm and $\overline{Q}_F$ is the average annual discharge of sediment finer than 0.074 mm. Note that $\overline{Q}_{s1}$ differs from $\overline{Q}_s$, the average annual discharge of sand coarser than 0.062 mm.

From (24), (25), (26) and (27) the following expressions are obtained:-

$$w = a\,Q_{ma}^{b - \beta_1} M^{-c}\,Q^{\beta_1} \qquad (29)$$

$$d = g\,Q_{ma}^{k - \beta_2} M^{1}\,Q^{\beta_2} \qquad (30)$$

Substituting in (1) the values of Q, w and d given by (15), (29) and (30), the following expression is obtained for the discharge Q^1_s of sands coarser than 0.062 mm.

$$Q_s = B_1 M^{r_1} F_y^{J_1} [\phi(t)]^{J_1} + B_2 M^{r_2} F_y^{J_2} [\phi(t)]^{J_2} \qquad (31)$$

Where $B_1 = p_1 a^{1-n_1} g^{m_1-n_1} Q_{ma}^{n_1+(1-n_1)b+(m_1-n_1)k}$ (32)

Where $B_2 = p_2 a^{1-n_2} g^{m_2-n_2} Q_{ma}^{n_2+(1-n_2)b+(m_2-n_2)k}$ (33)

Where $r_1 = (n_1-1)c + (m_1-n_1)1$ (34)

Where $r_2 = (n_2-1)c + (m_2-n_2)1$ (35)

Where $J_1 = n_1 + \beta_1 + m_1\beta_2 - n_1(\beta_1 + \beta_2)$ (36)

Where $J_2 = n_2 + \beta_2 + m_2\beta_2 - n_2(\beta_1 + \beta_2)$ (37)

$$\text{Put } I_1 = \int_0^{t_1(h_L, Q_{ma}F_y)} [\phi(t)]^{J_1} dt + \int_{t_2(h_L, Q_{ma}F_y)}^{\infty} [\phi(t)]^{J_1} dt \qquad (38)$$

$$\text{Put } I_2 = \int_0^{t_1(h_L,Q_{ma}F_y)} [\phi(t)]^{J_2}\,dt + \int_{t_2(h_L,Q_{ma}Fy)}^{\infty} [\phi(t)]^{J_2}\,dt \qquad (39)$$

Where the limits $t_1(h_L,Q_{ma}F_y)$ and $t_2(h_L,Q_{ma}F_y)$ are to be interpreted as in Eqn. (22).

Then from (22), (23), (31), (38) and (39) the following equation is obtained for the average annual discharge of sand coarser than 0.062 mm through the leveed reach:-

$$\overline{Q}_s = B_1 M^{r_1} \int_{y_1}^{\infty} F_y^{J_1} I_1 \frac{dy}{y^2} + B_2 M^{r_2} \int_{y_1}^{\infty} F_y^{J_2} I_2 \frac{dy}{y^2} \qquad (40)$$

Equations (28) and (40) can be used to predict changes in the height of the levee crests of leveed channels resulting from changes in the quantity and the nature of the sediment brought down from upstream sources.

In addition, changes in the levels of the channel bed h_c can be predicted if it is assumed that the depth $h_L - h_c$ of the waterway between levees can be expressed by a regime relationship similar to that developed by Schumm (1969) for unleveed channels:-

$$h_L - h_c = g_1 M^{l_1} Q_{ma}^{k_1} \qquad (41)$$

Where g_1, l_1, k_1 are constants and $l_1 > 0$.

The general effects of changes in sediment supply, when the water discharge statistics are unaltered, can be deduced without numerical computation from (28), (38), (39), (40) and (41). This is due to the fact that m_1 and m_2 are both positive, n_1 and n_2 are not greater than 2.0 and c and l are approximately equal and are less than 1.0.

These general changes in sediment supply are the result of changes in catchment land use (clearing, timber getting, burnoffs, reaforestation, etc.) or the building of dams that do not significantly alter flood discharge statistics.

General effects, which can be deduced from the above equations without computation, are listed in the table below. This table demonstrates how the depth of a leveed channel is dependent on the proportion of fine sediment less than 0.074 mm in the total annual sediment load. The table demonstrates how the height of the levees is primarily dependent upon the annual supply of sand. The height of the levees is dependent, to a lesser extent, on the proportion of fine sediment in the total annual sediment load because this affects the dimensions of the channel waterway area (see Equations 26, 27 and 28) and thereby affects flow velocities and the capacity of the channel to transport sand when the levees are not overtopped. The height of the channel bed, being the height of the levee crests less the depth of the channel, is dependent on both the annual supply of sand and the proportion of fine sediment in the total annual sediment load.

In the case of a river with a dam upstream which alters the water discharge statistics as well

EFFECTS OF CHANGES IN SEDIMENT SUPPLY ON LEVEED CHANNELS

Total Annual Sediment Load	Proportion of Sand $d > 0.062$ mm	Proportion of Fine Sediment $d < 0.074$ mm	Height of Levee Crest h_L	Height of Channel Bed h_c	Channel Depth $h_L - h_c$
Increases	increases	increases (1)	increases	(3)	increases
"	increases	unchanged (1)	increases	increases	unchanged
"	increases	decreases	increases	increases	decreases
Unchanged	increases	decreases	increases	increases	decreases
"	decreases	increases	decreases	decreases	increases
Decreases	decreases	increases	decreases	decreases	increases
"	decreases	unchanged (2)	decreases	decreases	unchanged
"	decreases	decreases (2)	decreases	(3)	decreases

(1) Implies that the proportion of fine sediment, with grain sizes between 0.062 mm and 0.074 mm, increases.

(2) Implies that the proportion of fine sediment, with grain sizes between 0.062 mm and 0.074 mm, decreases.

(3) Cannot be inferred (the changes in this column are inferred from the corresponding changes in the fourth and sixth columns).

as the sediment supply, a new representative flood discharge hydrograph and mean annual flood Q_{ma} must be computed, and estimates made of the sediments held back by the dam, before changes in h_L and h_c can be determined. In the Hawkesbury River, where the Warragamba Dam has radically reduced the supply of sediment available to the lower reaches of the river, approximate computations and estimates indicate an eventual lowering of the levee crests and channel bed in the floodplain extending below the Grose River junction.

Thus the levels of the levee crests and the channel bed of a river in a coastal floodplain have been found to be dependent on the average annual quantity of sand supplied by the upland river, the median grain size of the sand, the proportion of fine sediment <0.074 mm in the total average annual supply of sediment, the flood discharge statistics at a station just upstream from the floodplain and the relationship between the surface heights of the water ponded in the floodplain and the represtative flood discharge at this station.

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Holocene Aeolian Landforms in the Belarabon Area, S.W. of Cobar, N.S.W.

R. J. Wasson

ABSTRACT. A now relict dunefield and small sandsheets formed in the Belarabon area during the Upper Holocene. The origin of the Dunefield is suggested by comparing the Belarabon dunes in the Simpson Desert. The model of Simpson Desert dune development presented by Twidale (1972) applies to the Belarabon dunes. A phase of mid-Holocene alluviation occurred under climatic conditions which produced more runoff than is presently available. This alluvium was the source of the aeolian landforms which formed under dry conditions in the late-Holocene. The dunes have been stabilized by the present vegetation.

INTRODUCTION

The aim of this paper is to determine the origin and history of the aeolian landforms of the Belarabon area in western New South Wales (Figure 1). In order to fulfil this aim it is necessary to consider the fluvial landforms of the area, for the fluvial and aeolian landforms are intimately related. It will be shown that the aeolian landforms are relict and are of Holocene age, but it will be necessary to consider briefly sediments of Upper Pleistocene age so that the younger sediments can be placed in their stratigraphic context.

The Belarabon area lies about 100 km southwest of Cobar on the southwestern edge of an undulating plain which is cut across Palaeozoic rocks (Dury and Langford-Smith, 1964; Ongley, 1974). To the south of Belarabon lies the Murray Basin, and detritus derived from the Cobar plain thickens towards the basin (Packham, 1969). Strike ridges and low undulating hills of Devonian sediments rise within the Quaternary sediments of the Belarabon area, and sediments derived from these ridges mix with sediments deposited by Sandy Creek (sometimes called Crowl Creek), the largest drainage line in the area (Figures 1 and 2) The trace of Sandy Creek can be followed to the Talyawalka Anabranch, but local residents observe that Sandy Creek only flows as far as Lake Corinya, some 100 km from the anabranch. The remainder of the Creek's trace is unused.

The Belarabon area experiences a hot semi-arid climate, according to both the Koeppen and Thornthwaite classifications (Gentilli, 1972). The average annual rainfall is 361 mm at Cobar (83 year record, Records of Commonwealth Bureau of Meteorology) and is 330 mm at Belarabon homestead (unofficial 17 year record). There is no seasonality in rainfall. The average annual temperature at Cobar is 18.7°C, ranging between a mean annual maximum of 25.6°C and minimum of 11.9°C (29 year record, Records of Commonwealth Bureau of Meteorology). The area is highly susceptible to drought.

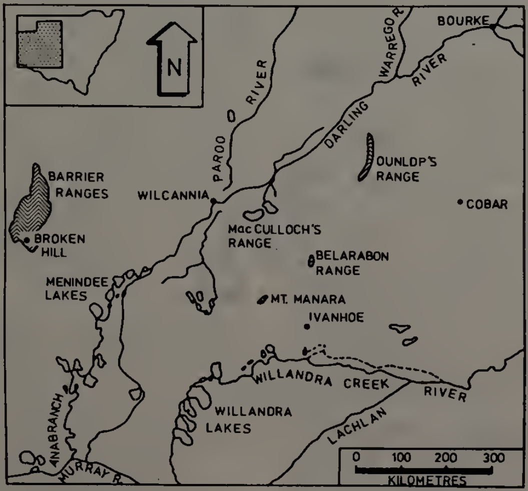

Fig. 1. Location of the Belarabon area

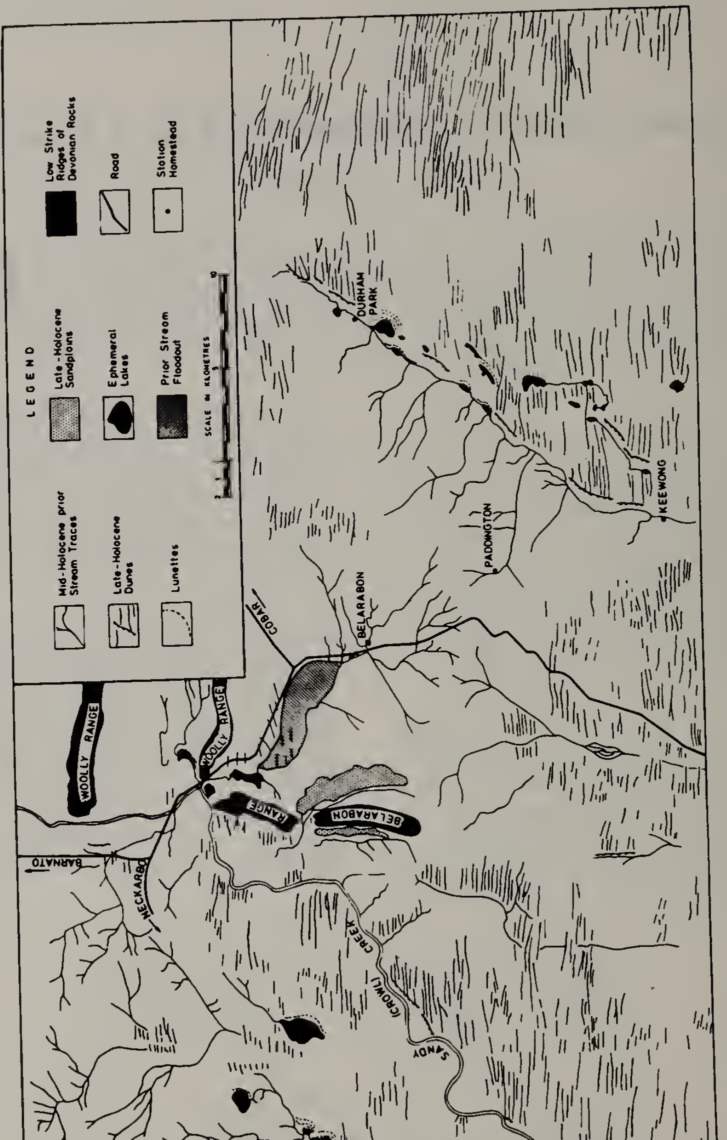

Fig. 2. Geomorphic Map of the Belarabon area

THE DUNEFIELDS

The dunefields primarily consist of longitudinal dunes of modest dimensions. The maximum measured height of the dunes is 8 m, and the maximum estimated height is about 10 m. The dunes mapped on Figure 2 range in length between 160 m and 6640 m. The spacing or wavelength of the dunes is commonly about 400m, but varies considerably. The dunes are asymmetrical; their southern flanks are steeper than their northern flanks. The dunes largely consist of fine sand (4.0 to 1.0 ϕ, Folk, 1968) and sub-dominant coarse sand (1.0 to -1.0ϕ). The graphic mean grain size of 11 samples is 2.67 ϕ with a standard deviation of 0.14 ϕ. The mean twenty percentile grain diameter is 0.84 ϕ, and, in combination with the common wavelength of 400 m, places the Belarabon aeolian bedforms within Wilson's (1972) dune category.

The direction of transport of sand in these dunes is demonstrated by convergence of dunes, or y-intersections. These y-intersections open to the west in the Belarabon dunes, and demonstrate a dominantly westerly dune-forming wind. Y-intersections have been noted in other Australian dunefields by Madigan (1946), King (1960), Wopfner and Twidale (1967), Mabbutt and Sullivan (1968), and Folk (1971). Folk's (1971) conclusions about the relationship between longitudinal dunes and wind direction follows Bagnold (1953), that is, longitudinal dunes are formed by dune-parallel helicoidal air flow. This argument is consistent with the evidence, and has an analogue in subaqueous bedforms (Cooke and Warren, 1973). The hypothesis appears to explain dune orientation, y-intersections, and also may explain a significant part of dune asymmetry (see Mabbutt, Wooding, and Jennings, 1969, and counter arguments by Clarke and Priestly, 1970).

There are four groups of longitudinal dunes within the area of Figure 2. The first consists of longitudinal dunes which are attached to and extend downwind from transverse dunes. The transverse dunes lie on the eastern (downwind) side of either Sandy Creek or the floodpains of prior streams (a term used in the sense of Butler, 1950). The transverse dunes are often slightly oblique to true transverse direction (cf. Cooke and Warren, 1973), but for convenience they are all classified together. Some lunettes in the area have the same relationship to the longitudinal dunes as do the transverse dunes. Where prior streams enter lakes from the north or south, the lunettes are sometimes continuous with transverse dunes which lie beside the streams. The lunettes have not been studied in detail, and so the following discussion is only concerned with the relationship between transverse and longitudinal dunes and streams.

The longitudinal dunes of the first group form a pattern identical with that described from the Simpson Desert by Twidale (1972), and earlier by Stannard (1962) from the Riverine Plains in N.S.W. This pattern has also been observed on a satellite image of the Abu Habl Fan, west of Kosti on the White Nile in Egypt. Twidale cogently argued that the transverse dunes, or leeside mounds as he called them, accumulate beside their sources of sediment (stream floodplains and channels, and lakes), and disrupt airflow over them. The airflow is channelled into linear zones - the helicoidal flow described by Bagnold (1953) - and forms longitudinal dunes downwind. The transverse dunes and associated longitudinal dunes are therefore source-bordering lee dunes according to Melton's (1940) classification. Twidale's hypothesis is applicable to the first group of longitudinal dunes at Belarabon.

Exploration beneath longitudinal dunes of this first group at Belarabon has shown that some rest directly upon gravel-rich alluvium. The low sand content of this substrate could not have provided sand for the creation of windrift dunes, that is, dunes which lie on residual features left by erosion of the interdune areas. Windrift dunes are expected to have alluvial cores, but none could be found within the Belarabon dunes overlying gravel-rich alluvium. For further discussion of the windrift hypothesis see Belknap (1972), King (1956), Mabbutt and Sullivan (1968), and Folk (1971).

Some longitudinal dunes of the first group extend downwind from very short transverse dunes. The transverse elements are not connected and appear to be remnants of formerly continuous transverse dunes. It is likely that the destruction of the transverse dunes was the result of one of two mechanisms. The first is that the longitudinal dunes grew at the expense of the transverse dunes as the sandflow rate from the sediment sources was reduced. The transverse dunes simply lost sand to the longitudinal dunes faster than they could trap sand from the streams. Wilson (1971) called this state the metasaturation point of dune evolution. The second mechanism follows Bagnold (1941) who argued that transverse dunes are inherently unstable because undulations along the line of their crests allow localised increases in sandflow rate. This instability permits blowouts to occur and eventually the transverse dunes are broken up. These two mechanisms will be further discussed below.

The second group of longitudinal dunes consists of features which lie a short distance downwind of, but detached from transverse dunes. This pattern was figured by Twidale (1972) from the Simpson Desert, and the longitudinal dunes seem to have migrated from the transverse dunes. The Belarabon dunes demonstrate that such migration can occur without the destruction of the transverse dunes, for many longitudinal dunes lie only a short way downwind of intact transverse dunes. Other longitudinal dunes appear in the act of breaking away from intact transverse dunes. One such dune is tenuously linked to a transverse dune by a sand saddle ca. 2 m below the top of the transverse dune. The saddle is not the result of flow separation of air passing across the transverse dune, for the distance between the points of separation and attachment in this case is 6 h, where h is the height of the transverse dune (Allen, 1970; Twidale, 1972). The transverse dune is 5.2 m high and therefore the point of attachment is only 31.2 m downwind of the crest of the transverse dune.

The third group consists of longitudinal dunes which lie a short distance downwind from a stream, but which have no associated transverse dunes. Examples of this group lie in the northwestern part of Figure 2. The position of these dunes just downwind from prior streams suggests that they were derived from these streams, particularly at sites where there is clear evidence that the dunes have migrated over a gravel-rich subaeolian floor.

Twidale (1972) recorded the pattern of the third group in the Simpson Desert. There are two possible explanations of the pattern. The first is that the dunes were initiated in the same way as the first group, but the transverse dunes have been destroyed by either a reduction in sandflow or by the inherent instability mechanism of Bagnold. The second is that the longitudinal dunes formed without the assistance of transverse dunes. Twidale (1972) drew attention to the production of linear vortices downstream of circular holes and transverse slots : Karman Trails. Here is a possible explanation of the third group, and, to the present author, the most likely explanation, for the total lack of evidence of transverse dune remnants demands the hypothesis that they never existed.

The fourth group consists of longitudinal dunes a long way from streams, and not attached to transverse dunes. Some of the dunes to the east of Sandy Creek fall into this group, and the dunes in the easternmost part of Figure 2 are examples of the group. Twidale (1972) argued that some of the Simpson Desert dunes have migrated from transverse dunes (synonym: leeside mounds) and this is one possible explanation of the fourth group. This explanation takes on great significance in areas where the dunes overlie gravelly sediments of low sand content (e.g. the small patch of dunes between Belarabon and Durham Park homesteads on Figure 2), but of course demonstrate migration but not the distance travelled. However, most of this fourth group consists of dunes which lie on sandy alluvium and there is no clear evidence of the origins of the dunes. Twidale (1972) suggested that some proportion of the Simpson Desert longitudinal dunes is the result of a local redistribution of alluvium and is unrelated to what he called"centres of initiation" (playas, alluvial flood plains and channels, and billabongs). The fourth group could be the result of either migration of dunes from transverse dunes or local redistribution of alluvium, but it is possible that both of these explanations are applicable. However, distinguishing dunes of the two possible origins within the two large dunefields of Figure 2. has not been attempted.

A small group of longitudinal dunes lies on the western piedmont of the Belarabon Range (Figure 2), and snouts of the dunes directly abut the foothills. of the range. Sand has been piled against the ranges in parabolic-like dunes between the snouts of the longitudinal dunes. The parabolic dunes could be interpreted as evidence of windrifting, but simple dune accumulation of dunes on an older

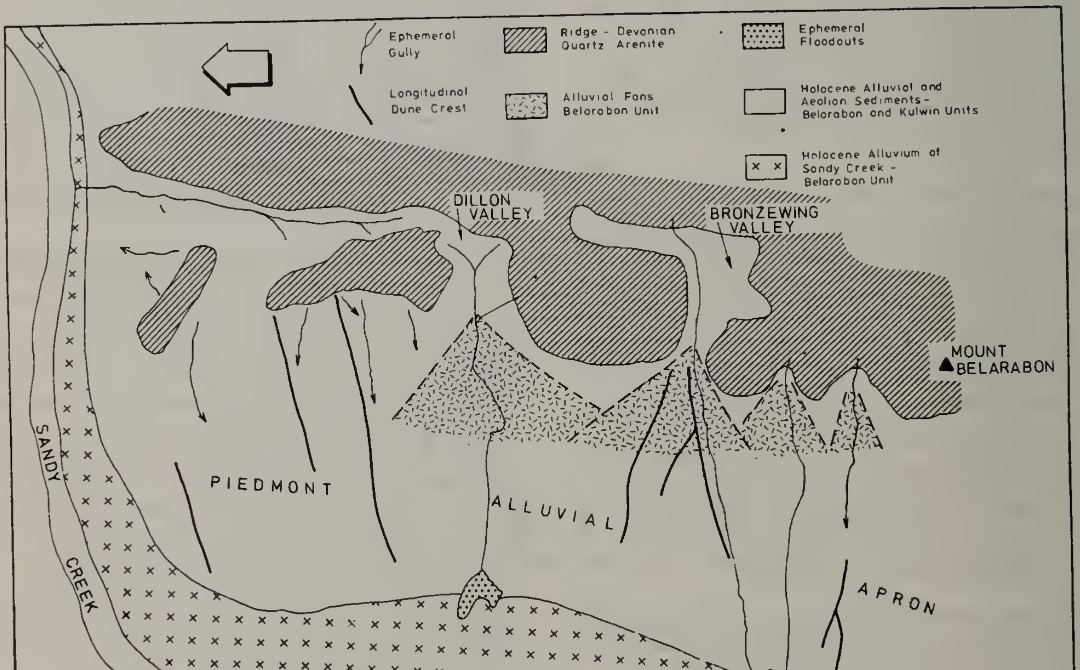

Fig. 3. Geomorphic Map of the northwestern part of the Belarabon Range and the adjacent piedmont

surface must involve some movement of sand within the swales. This movement is demanded by the helicoidal flow hypothesis. Natural exposures and pits dug within the longitudinal dunes and swales failed to provide evidence of alluvial cores in the dunes. The most likely origin of the longitudinal dunes is that they originated in the sediments of Sandy Creek and its floodplain, and migrated the short distance onto the piedmont.

SANDSHEETS

Small aeolian sandsheets occur within the dunefields and others occur as source bordering features leeward of prior streams in the southern Belarabon Range (Fig. 2). Here the sandsheets had climbed up onto the sides of the strike ridges up to 15 m above the general level of the valley floor. Only remnants of red fine sand can be found on these ridges, but they testify to relatively vigorous aeolian activity during the construction of these "climbing sandsheets". Systematic investigation of the sandsheets by the author is insufficient to consider the reasons for the development of sandsheets in the place of dunefields.

STABILITY OF THE DUNES AND SANDSHEETS

The dunes and sandsheets of the Belarabon area are well vegetated by two major formations of vegetation. The vegetation which covers the largest area is mallee (*Eucalyptus socialis, E. dumosa*), classified as open scrub with a hummock grass (*Triodia irritans*) understorey (Specht, 1972). The second formation is a low open-woodland dominated by *Callitris columellaris* (white pine), *Heterodendron oleifolium* (rosewood), and *Casuarina cristata* (belah). The understorey components of the woodland formation primarily consist of grasses of the genera *Eragrostis* and *Amphipogon, Dodonaea attenuata* and composites. The mallee understorey is dominated by *Triodia irritans* and other grasses. The amount of ground covered by the understorey plants in the two formations varies seasonally and is lower in summer as grasses and composites die back. Variation with drought is more significant than seasonal variation.

The author first visited the Belarabon area in 1969, at the end of a drought which had lasted for several years. Large areas of bare sand were visible on the dunes covered by woodland, but only small blowouts were active on the dune crests. The *Triodia irritans* beneath the mallee appeared to be unaffected by the drought, and there was no evidence of sand movement on either the dunes or in the swales.

If an "active longitudinal dune" is specified as one on which there is either evidence of significant movement of sand along its flanks and/or crest, or where there is evidence of significant sand movement from the adjacent swale onto the dune, then the Belarabon dunes are not active. It is interesting to compare the Belarabon dunes with longitudinal dunes near Andado homestead in the north-western Simpson Desert. Both the Belarabon and Simpson Desert dunes were visited during the period October-November 1974, after two years of exceptional rainfall and vegetation growth. The crests of the Simpson Desert dunes were obviously active, despite scattered shrubs of *Zygochloa paradoxa*. Sand was moving via slip faces which were oriented obliquely to the general trend of the dunes. The flanks of the dunes and swales were carpeted by *Triodia basedowii*, composites and numerous plants of other families. Sand on the flanks and in the swales was essentially stationary. According to the specification of an active dune, the Simpson Desert dunes near Andado are active, even though only the crests of these dunes are passing sand. At Belarabon the crests and flanks of the dunes and swales were completely covered by trees, grasses, composites and *Dodonaea*. Sand was not moving in any part of the aeolian landscape.

Therefore, it is concluded that the Belarabon dunefields and sandsheets are not actively forming under the present vegetation, and relict features.

STRATIGRAPHY

The Upper-Quaternary stratigraphy of the Belarabon area has been investigated with the aim of establishing both the environmental conditions under which the dunes formed and their age. Stratigraphically valuable sites occur in the western piedmont of Belarabon Range (Fig. 2 and 3). Part of the piedmont consists of small alluvial fans which coalesce to form a piedmont alluvial apron (Tuan, 1959). The across-fan stratigraphy is shown in schematic section through a fan apex (Fig. 4), and a measured section from the catchment of Dillon Fan (Fig. 3) into the fan apex is depicted in Fig. 5. From these two sections it is evident that the stratigraphy falls naturally into units above and below the carbonate layer (Bunda carbonate). It should be noted that the stratigraphic names are informal.

The sediments below the Bunda carbonate have been grouped into the Dillon unit which consists of generally gravelly facies, although sandy sediments do occur. The Bunda carbonate is developed in the top of the Dillon unit, and in the fine-grained fan sediments nodular and diffuse carbonate segregations occur with illuvial caly on prismatic peds. In the coarse-grained facies of the catchment the carbonate cements gravel particles and is segregated in platy, nodular and tubular forms (cf. Bogoch and Cook, 1974).

The clastic sediments of the Dillon unit are alluvial, as judged from their sedimentary

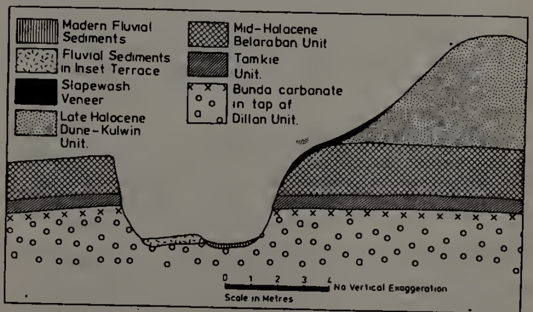

Fig. 4. Schematic transverse cross-section of the apical part of an alluvial fan in the Belarabon Range piedmont.

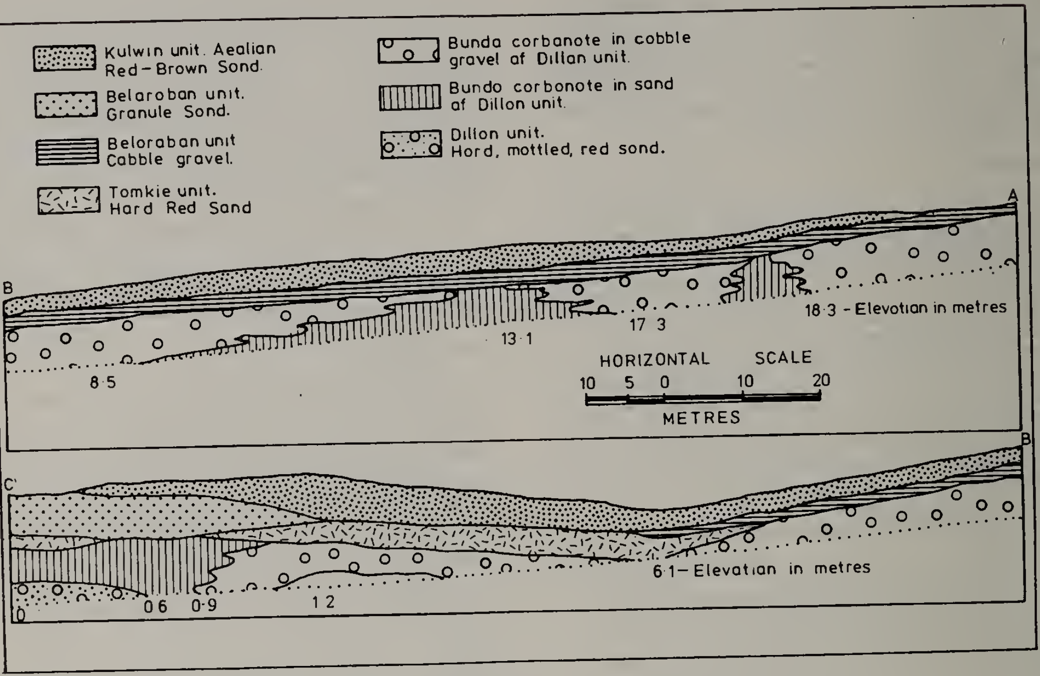

Fig. 5. Longitudinal section of the apex of the Dillon Fan and catchment

structures and textures. The Bunda carbonate is the result of the redistribution of carbonate of aeolian origin. The bedrock of the catchments of the fans, and the Belarabon Range is Upper Devonian quartz arenite of the Mulga Downs Group (Conolly, 1962; Packham, 1969). Petrography by Conolly and this author shows that there is no carbonate in the arenite, and there are no minerals which could weather to produce carbonate. There is no alternative to the argument that the carbonate was blown to the site and then re-precipitated.

At a number of sites the carbonate was deposited as a travertine towards the top, or on the top of the clastic sediments of the Dillon unit. The travertine resembles that described by Lattman (1973). The fact that the carbonate occurs only in the upper part of the Dillon unit shows that the aeolian accession of calcareous sediment occurred towards the end of depostion of the Dillon unit.

No dateable organic material has been found within the Dillon unit but two radiocarbon dates are available from the Bunda carbonate. The dated samples consist of hard nodules of micritic calcite and minor sparry calcite around voids and sand grains, with an average of 11 mol % $MgCO_3$ (determined by the x-ray diffraction technique of Müller, 1967); and soft diffuse ped coatings and adhesive nodules of pure calcite. A date on the hard nodules is 28,100 ± 900 years B.P. (SUA-279), and a date on the softer carbonate is 23,930 ± 470 years B.P. (SUA-328). These dates either approximate the true age of carbonate segregation, or they may be up to several thousand years too old (Williams and Polach, 1969, 1971). This is attributed to an initially low C^{14}/C^{12} ratio in soil carbonate, reflecting either the low C^{14} content of the source carbonate, or the low C^{14} concentrations expected in carbon derived from terrestrial waters (Broecker, 1965). The empirical work quoted above, and that by Bowler and Polach (1971), suggests that soil carbonate dates are generally within several thousand years of the age of initial precipitation. It is essential, however, that a large number of dates should be obtained from the Belarabon area before this discussion can be pressed further. The two dates support pedological intuition, that is, the soft powdery carbonate was believed to be younger than the hard nodules and the dates support this belief. It is, therefore, likely that the Dillon unit is older than ca. 28,000 years, and may have ceased deposition at about that time.

The Dillon unit and Bunda carbonate were trenched, and the carbonate was then overlain by a thin alluvial unit called the Tomkie unit. This last unit is undated. There is an erosional relationship between the Tomkie unit and the overlying Belarabon unit. The Belarabon unit is alluvial and is generally gravelly within the ranges and sandy in the piedmonts. Charcoal bedded within the centre of the Belarabon unit at the apex of Dillon Fan has an age of 4560 ± 95 years B.P. (SUA-166), and charcoal from about 15 cm below the top of the formation has an age of 2450 ± 110 years B.P. (SUA-327). Assuming a constant rate of deposition, the formation began its history ca. 6,500 years B.P.

It must be realised that charcoal within an alluvial sequence will reflect either the actual age of the mineral sediment in which the charcoal is bedded, or it will be older than that sediment. Sample contamination by younger carbon is here ignored, for there is no evidence of contamination, and the age difference is viewed only as the sum of the age of the vegetation from which the charcoal was derived (see Libby, 1952), and the time taken for the charcoal to reach its final point of deposition. The age of the alluvium can be estimated from a knowledge of the vegetation which produced the charcoal, and the period of transportation. As will be shown below, by pollen analysis, the most likely source of charcoal during the period of the radiocarbon dates was either *Callistris*, undifferentiated Myrtaceae, or *Eucalyptus*. It is unlikely that any trees of these taxa were more than 200 years old (Ogden, pers. comm.). The transportation time cannot be readily estimated, but it seems probable that, within the small catchments of the Belarabon Range, charcoal would have reached the fanheads within 200 years of its production.

It is now possible to estimate the probable error in equating the radiocarbon ages with "true" age of alluvial deposition within the Belarabon unit. The most important date for what is to follow is the youngest, and by taking two standard deviations of the counting uncertainty, and a 400 year (maximum) estimate of the difference between charcoal and alluvium ages, a result is obtained of 2450^{+220}_{-620} years B.P. for the age of the alluvium. That is, the Belarabon unit came to an end between 2670 and 1830 years B.P. For convenience, that part of the stratigraphy which postdates the Belarabon unit will be referred to as "less than ca. 2500 years".

The longitudinal dunes (constituting the Kulwin unit) of the piedmont overlie the Belarabon unit, and it is possible that the unit was superficially eroded during dune formation. It must be emphasised that the date from near the top of the Belarabon unit came from a site where the alluvium is buried directly beneath a dune, and exposed in a fanhead gully. The surface of the alluvium beneath the dune cannot have been seriously disturbed by aeolian action, and the date is a real indicator of the age of the upper part of the alluvium. The dunes are therefore less than 2500 radiocarbon years old.

The aeolian activity not only built dunes on the piedmont, but also piled sand into the fan catchments, covering slopes and stream channels. Some channels have not been exhumed and were discovered by augering. The period of aeolian activity was followed by gullying of the piedmont deposits, and, in some cases, the longitudinal dunes have been dissected.

Evidence of the minimum age of the dunes was gained by dating charcoal bedded within the slopewash veneers depicted in Figure 4. These veneers are clearly younger than both the dunes and gullies. Two dates are: 640 ± 110 years B.P. (SUA-329) from a veneer on the side of the gully in the Dillon Fan, and 260 ± 90 years B.P. (SUA-326) from a veneer on the flanks of a dune in the apex of Bronzewing Fan.

Applying the same reasoning as used earlier, these dates can be evaluated. The charcoal has clearly travelled only a few metres from the vegetation which produced it. It is therefore assumed that there is no transportation time. The oldest plants from which the charcoal was derived are *Acacia*, *Callitris*, and *Eucalyptus*, and so the 200 year number can be used for the maximum age of the vegetation. The oldest date for veneer formation is therefore 640^{+220}_{-420} years B.P.; once again using two standard deviations for the counting uncertainty. For convenience this age estimate will be referred to as "ca. 640 years B.P.".

The dunes on the piedmont are therefore younger than ca. 2,500 years B.P. and older than ca. 640 years B.P. The gullies are not related to European grazing pressure which began less than 200 years ago, but are natural features.

The prior streams shown in Figure 2 are really alluvial fills in shallow valleys, and channels no longer exist. The fills are poorly bedded, generally displaying parallel laminations, and consist of granule sand and sandy loam. The surfaces of these prior stream fills are covered by an open woodland of *Eucalyptus populnea* and *Callitris columellaris*, with an understorey of *Dodonaea attenuata*, *Eriostemon sp.*, *Cassia sp.*, and various grasses. During rare episodes of runoff in non-drought periods, clear water carries some organic debris down the prior streams. During droughts, when grasses are dead, runoff has been seen carrying minor quantities of mineral sediment. A similar situation has been described from an area just east of Cobar by Ongley (1974) and from the northern Cobar plain by Abrahams (1971). The streams are no longer active, that is, no longer transporting significant quantities of sediment. But sediment is certainly available on the slopes.

Sandy Creek is the only channelled drainage line in the Belarabon area, apart from minor gullies in the higher gradient alluvium of the Belarabon Ranges. The lower order Belarabon streams are no longer active, but the highest order channel in the area is ephemerally active. Sandy Creek is no longer depositing sediment outside its channel in the Belarabon area.

The prior stream alluvium is rarely more than 2m thick, and everywhere overlies calcareous alluvium, and (?) lacustrine sediments of gypseous clay. The sequence was particularly well exposed where the Gidgealpa-Sydney natural gas pipeline trench crossed Sandy Creek ca. 6 km northeast of the northern edge of the Woolly Range (Figure 2). Here the carbonate is segregated in the top of sandy alluvium. Longitudinal dunes overlie the uppermost alluvium on the sides of Sandy Creek.

It is quite clear that the Belarabon unit is the equivalent of the uppermost alluvial unit in both the prior stream fills and in the fill deposited by Sandy Creek. This equivalence has been proved by tracing the Belarabon unit in the Belarabon Range to the side of Sandy Creek (see Figure 3), and along various prior streams, in pits, by augering, and in gully exposures. It has been argued already that the Bunda carbonate is of aeolian origin, and therefore, it can be used as a chrono-stratigraphic unit. The alluvium (and ? lacustrine sediments) in which the carbonate is segregated, both in the ranges and beneath the prior streams, is assigned to the Dillon unit. The carbonate belongs to the Bunda carbonate, and the uppermost alluvial units constitute the Belarabon unit. The Tomkie unit has no equivalent in the prior stream stratigraphy.

The longitudinal transverse dunes overlie what is believed to be the Belarabon unit in all localities examined in the area of Figure 2. The Belarabon unit at the dated site has been shown to be physically continuous with the uppermost alluvial units in the prior streams and in the Sandy Creek fill in the area immediately surrounding the Belarabon Range. Identification of the Belarabon unit in other areas is based upon similarity of sediments and the nature of pedogenesis, as well as the stratigraphic relationships. That is, at all sites examined, only one alluvial unit could be found above the Bunda carbonate. This body of alluvium close to the ranges is the litho-stratigraphic equivalent and time-stratigraphic equivalent of the dated Belarabon unit, and therefore there is good reason for arguing that this uppermost alluvial unit in areas well away from the ranges is the same age as the Belarabon unit. While only one site has been dated, the time-stratigraphy has been extended well beyond that site using standard stratigraphic techniques. This extension can be considered a hypothesis which needs to be tested by radiocarbon dating at other sites.

The dunes and sandsheets are believed to be of the same age throughout the area of Figure 2. The sediments within these features are essentially the same, there is no evidence of pedogenesis in any of the deposits examined, and the morphology of the dunes is sensibly identical. The dunes and sandsheets, which have been grouped in the Kulwin unit (Figure 4), everywhere overlie alluvium which it is believed is the Belarabon unit. While the similar morphology of the features demonstrates very little, the lack of significant sedimentological or pedological differences between dunes is more convincing evidence of their contemporaneity. Once again, this argument can be considered a hypothesis which can be further tested. However, only one site has been found in the area where the age of dunes can be bracketed by radiocarbon dates; the Belarabon piedmont. If it is accepted that the dunes are all of the same age, then the palaeo-environmental implications are much greater than they are if the Belarabon piedmont dunes are believed to be of known age and the other dunes of unknown age.

It is the conclusion of this writer that the dunes and sandsheets of the area of Figure 2 are of the same age, that is, between about 2500 and 640 radiocarbon years B.P. While the age estimate will be re-examined in the next section, the argument for contemporaneity will be maintained.

ENVIRONMENT PRECEDING, DURING AND AFTER DUNE FORMATION

The prior stream sediments (Belarabon unit) are not accumulating at the present time. There is certainly insufficient runoff to produce the sedimentary structures seen within the prior stream sediments. The prior stream alluvium must have been deposited under competent runoff conditions, so providing the source of supply for dune formation.

In an attempt to describe the conditions under which the Belarabon unit was deposited, pollen was extracted from the formation in the downstream part of the section shown in Figure 5. Only one sample was taken from the sediment dated at ca. 4,500 years B.P. This sample was compared with modern pollen collected in samll "pinches" of sediment from the surface of the catchment of Dillon Valley (following a technique of Martin, 1963). Pollen counts were carried out by W.R. Sigleo, formerly of the University of Tasmania. The results of the counts are shown in Table 1. The surface of modern pollen represents not only the low open-woodland of the area of the surface sample, but the regional pollen rain as well.

The immediate conclusion to be drawn from Table 1 is that the vegetation 4,500 years ago was little different to the modern vegetation. Analysis of the fossil pollen does not suggest that conditions in the mid-Holocene were drier than they are now. Significantly drier conditions would surely be represented by a higher Chenopoliaceae count, produced by vegetation similar to that to the west of Belarabon.

The fossil pollen is difficult to interpret without ecological studies of the relationship between modern vegetation and pollen rain. However, both the postulated conditions necessary to produce the prior streams and the pollen analysis suggest that there was no less moisture in the landscape than there is today, and the prior streams required more runoff than is presently available. The precise climatic conditions for such an increase in runoff cannot be specified, but the conditions cannot have been dramatically different from those of today.

It was concluded earlier that the Belarabon dunes are relict under present conditions of climate and vegetation. It is most likely that drier climatic conditions prevailed during dune formation (cf. Hack, 1941; Flint, 1971; Cooke and Warren, 1973).

Climatic conditions at Belarabon were not drier 4,500 years B.P. (see Table 1), but they were drier ca. 2,500 years B.P. It is suggested that the climate responsible for run-off greater than the present switched to a climate which killed the woodland vegetation and promoted dune development. It is possible that dune development began while the prior streams were still accumulating sediment on floodplains and in channel bars, but at a time when the streams were becoming more and more incompetent. Such a possibility means that dune development in some parts of the Belarabon area may have begun a little before 2,500 years B.P., but certainly between 4,500 and 2,500 years B.P. The deposition of the Belarabon Formation had ceased by the time the bulk of the dunefield had been constructed, for

TABLE 1
MODERN POLLEN AND FOSSIL POLLEN FROM
THE BELARABON UNIT

Taxa	Surface Pollen %	Belarabon Unit Pollen %
ARBOREAL		
Mimosaceae (Acacia)	0.5	0.0
Proteaceae (Grevillea)	0.0	1.9
Cupressaceae (Callitris)	29.0	17.6
Myrtaceae (undiff.)	3.5	3.9
Myrtaceae (Eucalyptus)	13.0	3.9
Arboreal sum	46.0	27.3
NON-ARBOREAL		
Sapindaceae (Dodonaea)	0.5	5.8
Chenopodiaceae	4.5	1.9
Compositae		
High Spine	32.0	11.8
Low Spine	7.0	7.8
Potamogeton	0.0	27.4
Gramineae	4.5	27.4
Leguminosae	0.5	0.0
Polygonaceae	0.5	0.0
Umbelliferae	0.5	0.0
Non-arboreal sum	50.0	64.5
Unknowns	4.0	8.2

the dunes overlie the alluvium. In some places the dunes have disrupted the network of the prior streams (see Figure 2), suggesting that the construction of longitudinal dunes in these areas occurred when the streams were not competent to remove the encroaching aeolian sand.

As noted earlier, the longitudinal dunes at Belarabon are oriented approximately east-west. The orientation of 60 dunes has a mean of 272° and a standard deviation of 6°. Bowler (1975) has compared the orientation of longitudinal dunes and lunettes, formed during the arid phase 17,000 to 15,000 years B.P., with the seasonal resultants of sand shifting winds computed for Mildura and Broken Hill (Figure 1). He found a shift of 60° between the dune orientation (270°) and the lunette forming summer wind resultant (201°), and suggested that this shift is consistent with the summer anticyclonic system being at least 5° further north than it is today. It is interesting to note that the Late-Holocene Belarabon dunes show a shift of about 78° between the dune orientation and the summer wind resultant for Broken Hill (194°), the station nearest to Belarabon. The shift between dune orientation and the annual resultant for Broken Hill (243°) is about 27°. Bowler's evidence shows that the summer sand-shifting wind resultant is the most important for dune orientation, thereby suggesting that the wind pattern during the Late-Holocene was essentially the same as during the Late-Pleistocene deglacial arid period. This suggestion must be viewed cautiously until the regional significance of the Belarabon sequence is established.

The bulk of the dunefields was built in less than 2,000 years, according to the evidence available. This is a short period of time on the scale of the Quaternary, and intuitively suggests that the dunes formed quickly. Wilson (1971) has used Bagnold's (1941) work to produce a three-variable bedform reconstitution time diagram. The three variables are time, the potential sandflow rate, and the cross-sectional area of the bedform in the sandflow resultant direction. The bulk of the Belarabon dunes formed in less than 2,000 years and the maximum cross-sectional area of the longitudinal dune is 3,999m^2. When these two quantities are plotted on Wilson's diagram they indicate that the potential sandflow rate ($\overline{Q}_\sigma$) which formed the dunes could have been between 1000 tonnes/m.ann. and 5 tonnes/m.ann. Further inspection of the diagram shows the time taken to form the largest dune for various values of the potential sandflow rate:

$\overline{Q}_\sigma$ (tonnes/m.ann.)	Years
10^3	8
10^2	80
10	800
5	2000

The potential sandflow rate is rarely attained over significant distances in ergs (Wilson, 1971), and it is unlikely that the sandflow rate in the Belarabon dunefields was less than $\overline{Q}_\sigma$. Therefore, the actual sandflow rate was probably greater than 5 tonnes/m.ann.

The dunefield became stable before 640 years B.P., presumably as climate swung back towards that which prevailed during deposition of the Belarabon Formation.

The climatic inferences drawn from the Belarabon dunes oppose the argument of Ongley (1969) that more effective precipitation occurred in the area of the Cobar township between 2,420 years B.P. and the present.

HOLOCENE CLIMATE IN SOUTHERN AUSTRALIA AND THE BELARABON SEQUENCE

The most reliable evidence of Holocene climate in southern Australia comes from studies of lake sediments and pollen. Slight differences occur between the climatic interpretations from the lakes, but they are in general accord. Bowler and Hamada (1971) and Dodson (1974a) have presented data from Lake Keilambete in the sub-humid warm part of Victoria (Thornthwaite classification - see Gentilli, 1972). Dodson (1974b) has studied Lake Leake in the sub-humid warm part of South Australia, and Churchill (1968) has investigated a number of lakes in both sub-humid warm and humid warm parts of southwestern Western Australia. These studies show generally moist conditions from ca. 10,000 years B.P. to ca. 4,500 years B.P., with a peak ca. 6,500 to 5,500 years B.P. The authors agree on a dry period beginning ca. 4,500 years B.P. reaching a maximum of aridity between ca. 4,000 and ca. 3,000 years B.P., and then gradually ameliorating. A minor increase in moisture is reached in all of the lakes between ca. 2,500 and 1,000 years B.P. in Western Australia, between ca. 2,000 and 1,000 years B.P. at Lake Leake, and between ca. 1,500 and 500 years B.P. at Lake Keilambete.

The Belarabon record shows a moist landscape from ca. 6,500 years B.P. to ca. 4,500 years B.P., with dessication beginning at sometime between ca. 4,500 and 2,500 years B.P. The main period of aridity was between ca. 2,500 and ca. 640 years B.P., but climate began to ameliorate just before 640 years B.P.

The lacustrine records from both southern Australia and Belarabon show the same major changes of direction of climatic conditions, but they are not in phase. The lacustrine records are presumably out of phase with one another because of lag effects and local climatic fluctuations. The Belarabon record seems to be out of phase with the overall lacustrine picture, but this situation cannot be interpreted because the period of dry conditions at Belarabon cannot be resolved to a level of accuracy commensurate with the lacustrine records.

CONCLUSIONS

The Belarabon dunefield, sandsheets, and prior streams form a relict landscape of Holocene age. The dunefield is of composite origin and four groups of dunes have been identified. The first group consists of longitudinal dunes which originated by helicoidal air flow across transverse dunes as described by Twidale (1972). The transverse dunes formed on the leeward side of stream channels and floodplains. Longitudinal dunes of this group are largely constructional, that is, sand was transported across the upwind transverse dunes and deposited in linear zones. The second group of longitudinal dunes formed by migration of group one dunes a short distance downwind of the transverse dunes. The third group consists of longitudinal dunes which are not associated with transverse dunes. These dunes probably formed without transverse dunes by the formation of Karman Trails downwind of streams. The fourth group consists of longitudinal dunes which are a relatively great distance from stream channels. The origin of these dunes is obscure, but some may have migrated, while others may be the result of local redistribution of spreads of alluvium. The dunefields were built by moderate sandflow rates, probably greater than 5 tonnes/ m.ann.

The phase of alluvial deposition (represented by the Belarabon unit) which provided the sources of aeolian sediments occurred between ca. 6,500 and ca. 2,500 years B.P. Prior to this period alluvium had not been deposited in appreciable quantities for about 23,000 years: a long period of non-deposition.

Dunes and sandsheets probably began to form just before 2,500 years B.P. when climatic dessication began and stream competence decreased. The bulk of the dunes are believed to have formed within the period 2,500-640 years B.P. Climatic conditions during the time of the Belarabon unit increased runoff, but did not produce vegetation dramatically different from that which lives in the area today. The dunes and sandsheets formed during an arid phase which ended before ca. 640 years B.P. Dune-forming winds during this period were westerlies, the same as those operating during the Late-Pleistocene deglacial arid phase. The end of this arid phase was climatic amelioration which has allowed the present vegetation to invade the area and stabilize the aeolian landforms.

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Structural Analysis of the Albury District, N.S.W.

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ABSTRACT. A turbidite sequence of pelites, psammopelites and psammites in the Albury district of New South Wales has been subjected to three tectonic deformations. The first deformation produced easterly striking and gently plunging upright folds. The second deformation varied in intensity across the area studied. In the west the deformation was expressed as a simple overprinting which resulted in widespread lineation on the limbs of earlier folds. To the east, where the deformational intensity was strongest, the structure resulting from the first deformation was rotated and refolded into tight isoclinal superposed folds. A zone of transition defined by a shallow plunging reclined fold exists between the areas of imprinted lineation and superposed folding. The third deformation consisted of late-stage kinking. Low pressure regional metamorphism reached its peak between the first two deformations. The area is considered unique in that the trend of the first deformation in the western part of the Albury district is normal to the regional trend of the Lachlan Fold Belt. Evidence is provided for the existence of a major lineament which is possibly related to the south south-east trending faults in the Kiewa River district of Victoria.

INTRODUCTION

The Albury district is located within a belt of low pressure regional metamorphic rocks extending from Omeo in Victoria to north of Junee in New South Wales. Joplin (1944, 1947) recognised similarities between the metamorphism developed at Albury and that found at Cooma. No subsequent detailed geological studies have been published on the Albury district. It is proposed therefore to also discuss the metamorphic geology (elsewhere). It suffices to say that metamorphic grade increases to the south where a sillimanite isograde separates a zone of andalusite and cordierite from a zone of sillimanite. Most of the study area is within the andalusite and cordierite zone. This paper is concerned with analysing the relationships between deformational episodes and metamorphism in the vicinity of the City of Albury (Figs. 1, 2).

Joplin (1944) recognised several fold systems and summarised her observations by stating:-

> "Thus there appears to have been a great elongated dome or anticline pitching to the north-north-west, which may have been overfolded to the west, and upon this has been superimposed a series of intermediate folds or cross-warps which in their turn have been warped into a series of minor buckles". (p. 203).

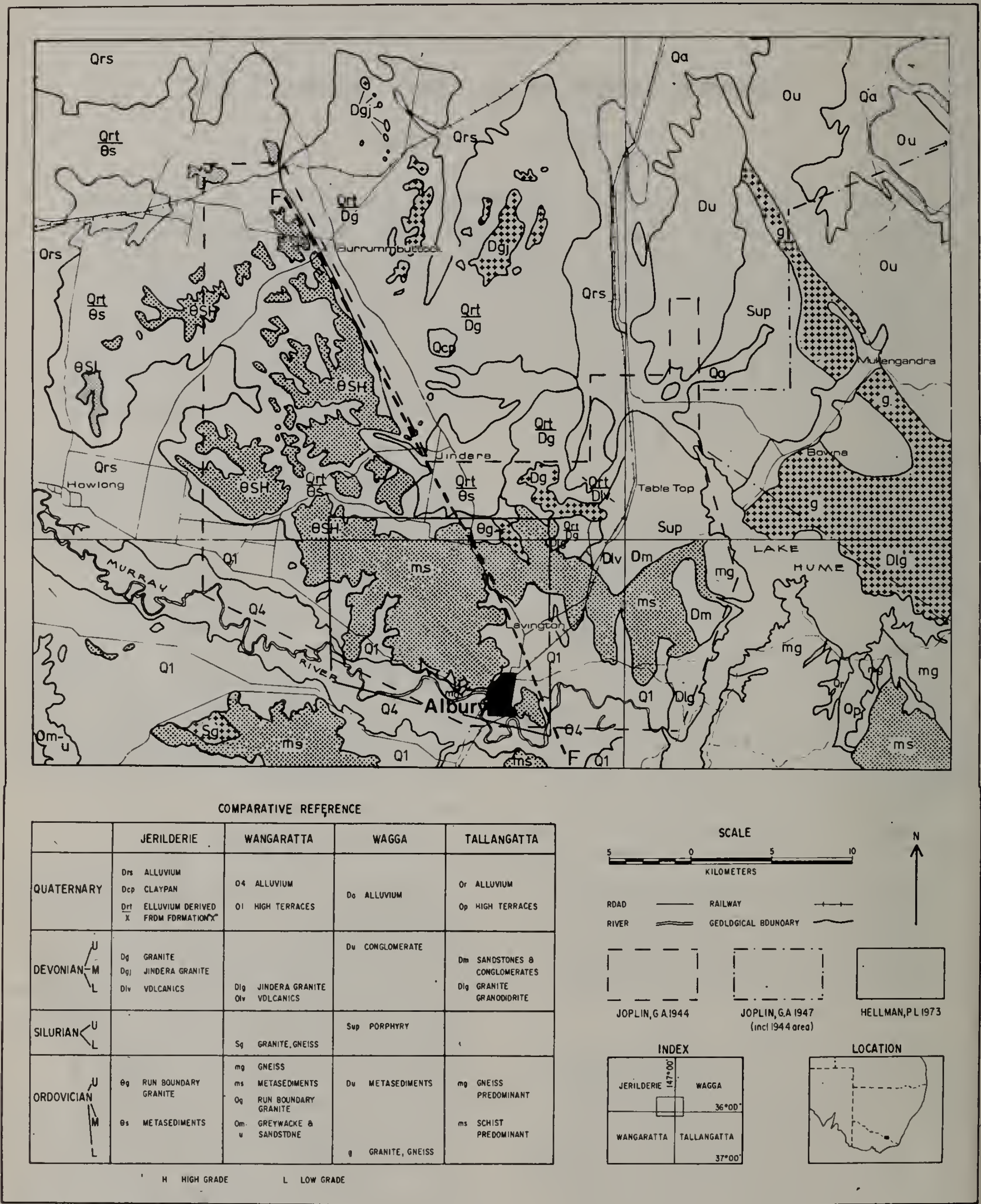
In the present work the effects of three deformations (D_1, D_2 and D_3) and one metamorphic episode can be recognised. Each deformation is treated in turn and related to macroscopic, mesascopic and microscopic structures produced. The thesis is presented that an early deformation (D_1) produced gently plunging upright anticlines and synclines in original bedding (So) which were subseqeuntly overprinted by a second deformation (D_2) which caused a widespread lineation (L_2) defined by the crenulation of S_1 (the cleavage which resulted from D_1). To the east of the area D_2 was most extreme and caused reorientation of the D_1 structure resulting in tight isoclinal folds. A late deformation resulted in widespread dextral kinking. For ease of presentation the area has been broken up into 16 domains (Fig. 3). All stereographic projections and orientation data are true north readings. In this paper "S" and "D" refer to strike and dip respectively.

The age of the sediments comprising the metamorphic rocks in the Albury district is thought to be Upper Ordovician on the basis of graptolites in lithologically similar rocks of the Jerilderie region (Hall and Whiting, 1959) and north-east Victoria (Joplin, 1947). The sediments are quartz-rich turbidites though rare felspar-quartz beds occur. No greywackes, gravels or conglomerates were found. Facing was determined by graded bedding and cross-stratification.

The First Deformation (D_1)

1. Macroscopic structure

Measurements of So in the western part of the area define a series of plunging upright (axial plane orientation of S.080 D.90) anticlines and synclines (Domains 1-7, Fig. 3). Due to poor outcrop, fold hinges cannot be seen except at one locality (Green Creek, Domain 2) where two limbs define a fold axis which plunges 10 degrees to 080. The So clusters (Fig. 4(A)) indicate the planar nature of the limbs and the cylindrical style of close folding. South dipping beds dominate to the south whereas north dipping beds increase in occurrence to the north. This feature may indicate the presence of a low plunging anticlinorium with axial surface trending to the east north-east. It should be noted that the orientation of S_1 to the N.W. of Albury contrasts remarkably with that of the meridional trends of the Lachlan Fold Belt. In fact, it is almost perpendicular to the metasedimentary and igneous trends observed in the surrounding region (see Jerilderie, Wagga, Wangaratta and Tallangatta geological sheets (1:250,000)).



COMPARATIVE REFERENCE

	JERILDERIE	WANGARATTA	WAGGA	TALLANGATTA
QUATERNARY	Drs ALLUVIUM Dcp CLAYPAN Drt/X ELLUVIUM DERIVED FROM FORMATION"X"	O4 ALLUVIUM O1 HIGH TERRACES	Do ALLUVIUM	Or ALLUVIUM Op HIGH TERRACES
DEVONIAN U M L	Dg GRANITE Dgj JINDERA GRANITE Dlv VOLCANICS	Dlg JINDERA GRANITE Olv VOLCANICS	Du CONGLOMERATE	Dm SANDSTONES & CONGLOMERATES Dlg GRANITE GRANODIORITE
SILURIAN U L		Sg GRANITE, GNEISS	Sup PORPHYRY	
ORDOVICIAN U M L	θg RUN BOUNDARY GRANITE θs METASEDIMENTS	mg GNEISS ms METASEDIMENTS Og RUN BOUNDARY GRANITE Om-u GREYWACKE & SANDSTONE	Du METASEDIMENTS g GRANITE, GNEISS	mg GNEISS PREDOMINANT ms SCHIST PREDOMINANT

H HIGH GRADE L LOW GRADE

Fig. 1 Location of study area compared with regional geology (compiled from Wagga, Jerilderie, Tallangatta and Wangaratta 1:250,000 geological sheets)

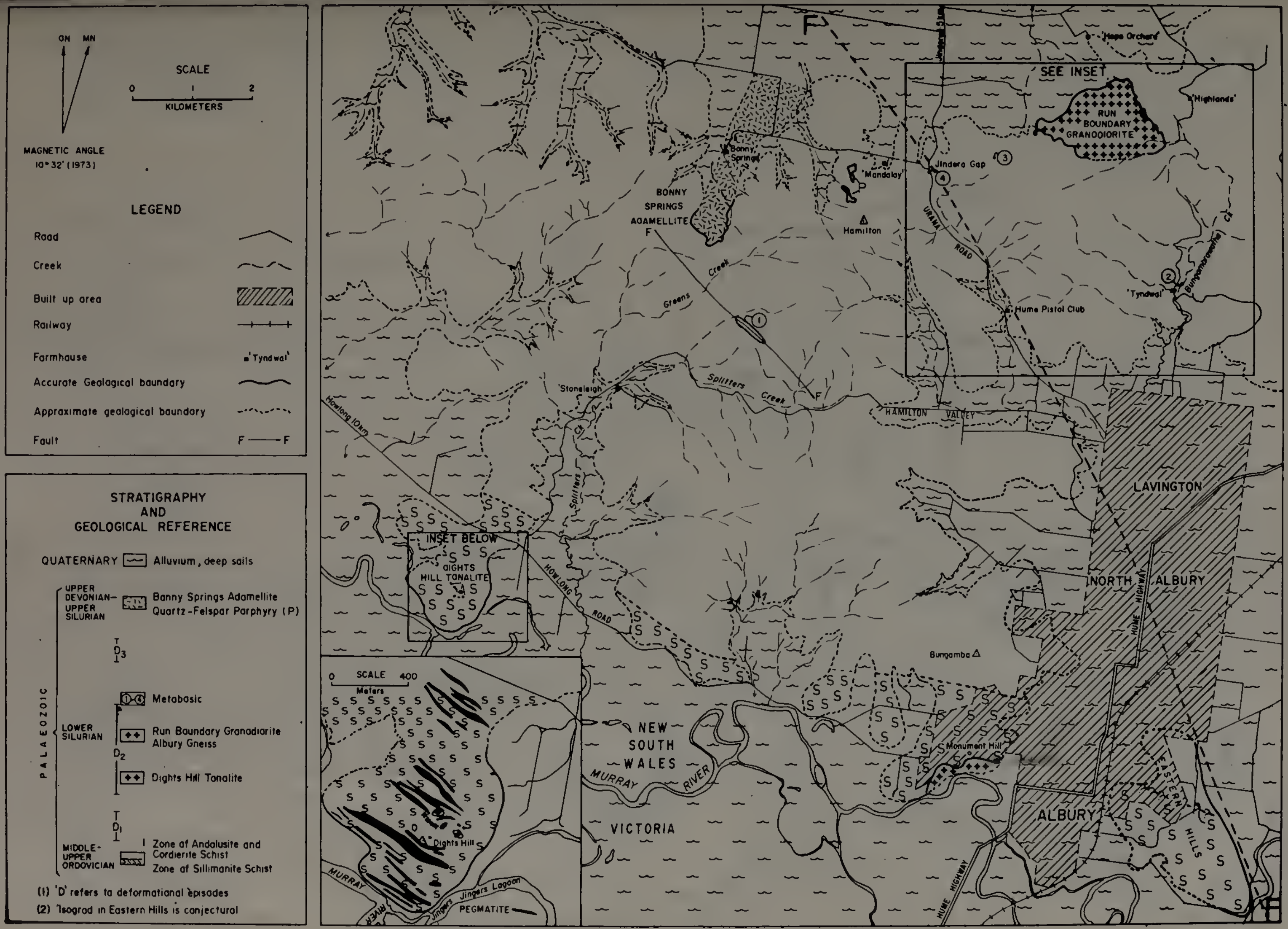


Fig. 2 Geological map of the Albury district. For Inset see Fig. 8

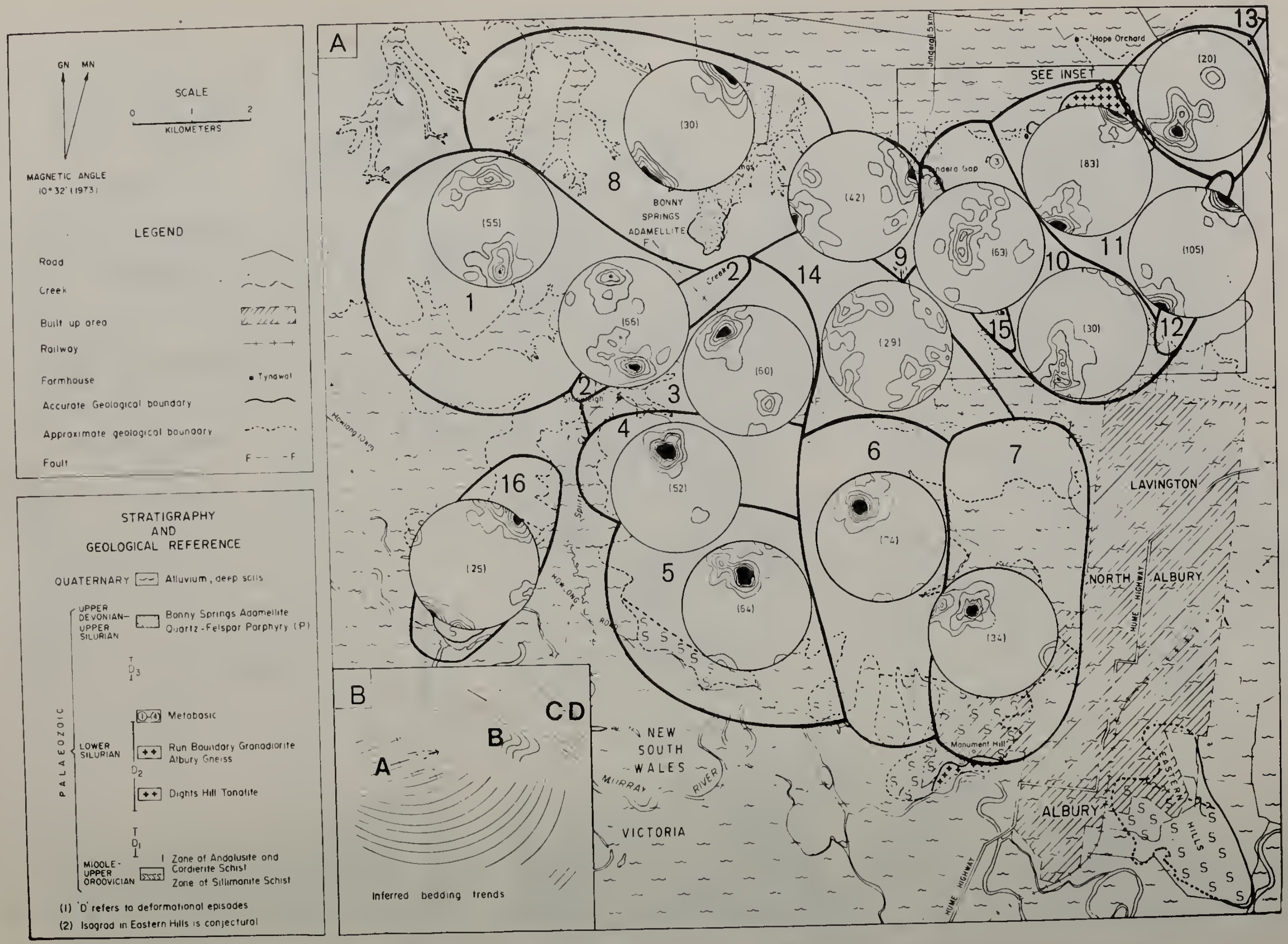

GN MN
MAGNETIC ANGLE 10° 32' (1973)
SCALE
0 1 2
KILOMETERS
LEGEND
Road
Creek
Built up area
Railway
Farmhouse
• Tyndwal
Accurate Geological boundary
Approximate geological boundary
Fault
F- - -F
STRATIGRAPHY AND GEOLOGICAL REFERENCE
QUATERNARY
Alluvium, deep soils
UPPER DEVONIAN– UPPER SILURIAN
Bonny Springs Adamellite
Quartz-Felspar Porphyry (P)
D_3
PALAEOZOIC
LOWER SILURIAN
①-④ Metabasic
Run Boundary Granodiorite
Albury Gneiss
D_2
Dights Hill Tonalite
D_1
MIDDLE-UPPER ORDOVICIAN
Zone of Andalusite and Cordierite Schist
Zone of Sillimanite Schist
(1) 'D' refers to deformational episodes
(2) Isograd in Eastern Hills is conjectural
A
B
A
B
CD
Inferred bedding trends
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
(55)
(66)
(30)
(60)
(52)
(64)
(42)
(29)
(74)
(34)
(63)
(83)
(30)
(105)
(20)
(25)
BONNY SPRINGS ADAMELLITE
Creek
Howlong 10km
HOWLONG ROAD
Jingerali 5km
Hope Orchard
SEE INSET
Gap
LAVINGTON
NORTH ALBURY
HUME HIGHWAY
ALBURY
EASTERN HILLS
Monument Hill
NEW SOUTH WALES
MURRAY RIVER
VICTORIA
S

Fig. 3.A. Structural domains (contours 0%, 5%, 10%, 15%, 20%, per 1% area). Stereographic plots are poles to bedding, bracketed numbers refer to number of measurements.

B. Trend surface of bedding. Speculative beddings trends are indicated by dashed lines. Sections A, B and C-D refer to fold styles in Fig. 7.

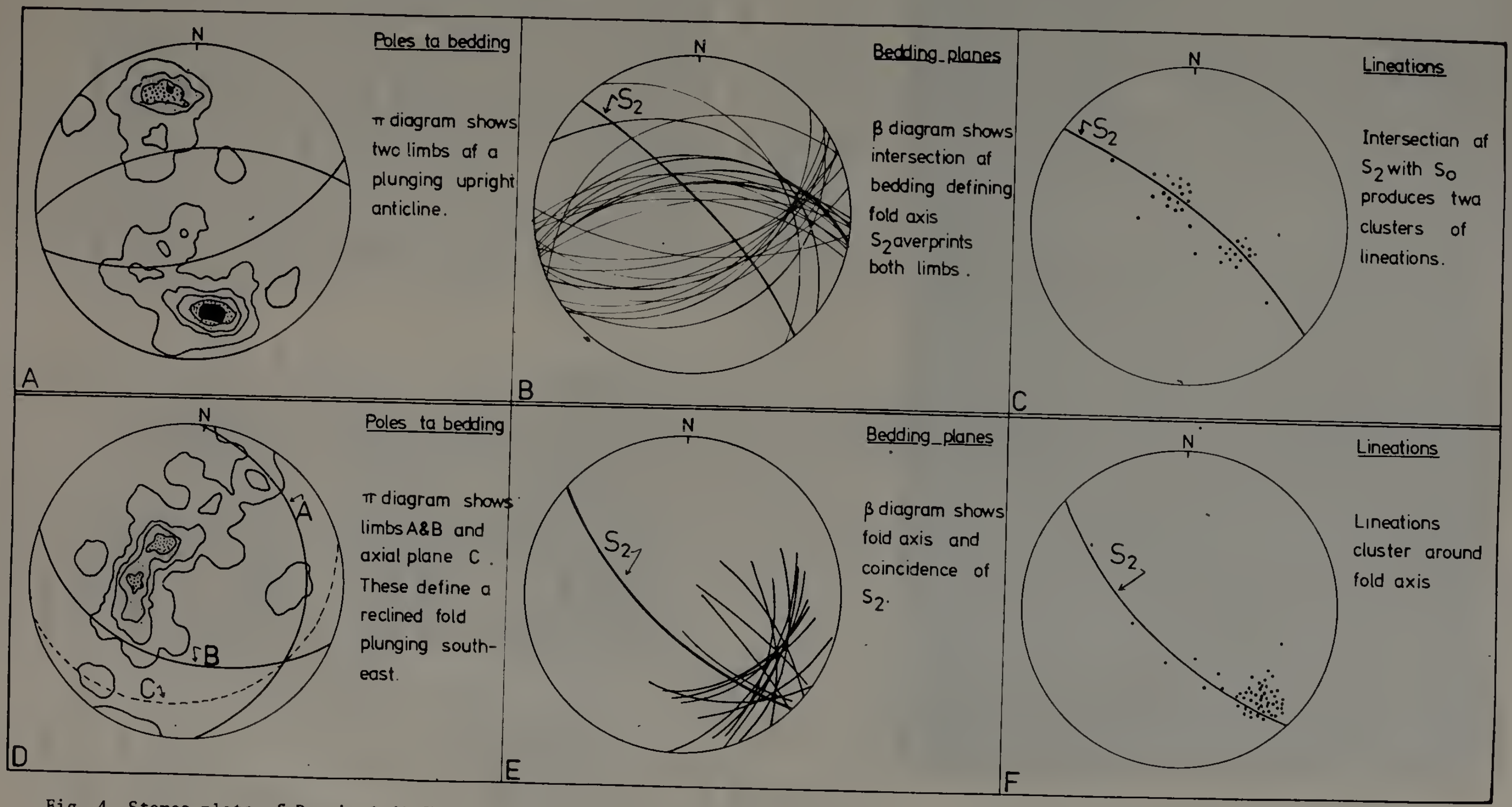


Fig. 4 Stereo plots of Domain 2 (A-C) and Domain 15, Urana Rd (D-F). Plot A and D represents 66 and 63 measurements respectively (contours as for Fig. 2)

2. Mesoscopic Structure

Lithology has exerted a strong control on mesoscopic structure. In pelitic and psammopelitic rocks D_1 caused a slaty cleavage (defined by a planar orientation of micas) which is now, because of metamorphic growth, a schistosity. In many psammitic rocks the morphological equivalent of this foliation is a non-uniform and non-penetrative micaceous segregation structure (Fig. 5). It consists of planar discontinuities which have imparted an irregular laminated appearance to the rock. This 'cleavage' is commonly refracted as it passes through a pelite into a sandier unit. Within actual beds the refraction appears as false cross-stratification defined by aggregates of micas. Structures appearing similar to sedimentary 'flame structures' have been found where psammites are in contact with pelites. These strongly lens shaped segregations are of uncertain origin and may be related to primary sedimentary processes or later metamorphic and tectonic activity. The origin of the S_1 segregations in the sand-rich units (Fig. 5) is certainly related to some mechanism of cleavage formation.

3. Microstructure and relationship to metamorphism

Schists containing modified detrital grains occur in the areas of lower metamorphic grades (to the N.W.) whereas recrystallised quartz-feldspar grains predominate in areas of higher grades. Larger clastic quartz grains displaying undulose extinction and a related deformation substructure occur in a matrix of relatively unstrained granular quartz. Ragged grain-boundaries and irregular grain boundary sutures are typical of this lower grade variety of quartz-muscovite schist. The S_1 foliation consists of a weak discontinuous planar preferred orientation of white mica and biotite. At higher grades a more continuous foliation results together with a more complete recrystallization of detrital quartz producing quartz-quartz triple points while muscovite and biotite plates lie along quartz grain boundaries.

Long axes of andalusite and cordierite porphyroblasts lie randomly within the S_1 schistosity plane and thus indicate controlled growth within that plane. Cordierite possesses an internal (S_i) quartz dimensional fabric whilst the external (S_e) schistosity wraps around the poikiloblasts. S_i is defined by a marked dimensional orientation of minute quartz blebs, which indicate that porphyroblastic growth took place after the formation of an early S-surface (possibly slaty cleavage). Towards the edge of the cordierite the quartz "trains" slightly curve creating a poorly developed snowball texture. This indicates that prior to the end of cordierite growth the porphyroblasts were slightly rotated by another deformation (D_2). These relationships provide evidence that the period of metamorphic mineral growth spanned the two deformations. The series of events envisaged leading to poikiloblastic textures is sketched in Fig. 6.

The Second Deformation (D_2)

1. Weak D_2 overprinting

Overprinting by a crenulation structure has affected the northern and western part of the area. This has resulted in the common appearance of crenulations in micaceous rocks. Stereographic plots of these indicate the constant orientation of S_2 (Fig. 3 (B, C)). Quartz veins and pegmatites show ptygmatic structures indicating plastic flow in response to D_2. A lineation is present in all pelitic rocks though weakens towards the west. The effect of D_2 upon the D_1 structure described above is represented in Fig. 7 (A).

2. Transition between overprinting and superposed folding

Along the Urana Road between Lavington and Jindera Gap a fold system is developed which is interpreted as being structurally intermediate between the overprinted D_1 structure to the west and the superposed D_2 folds to the east. Poles to S_o (Fig. 4(D)) form an imperfect girdle which defines a macroscopic fold axis plunging 20 degrees to 130. The main cluster of points delineates the shallow dipping limb A. The other limb (B) is exposed at only one locality and consequently does not appear significant on the stereographic plot. Both facing (based on graded bedding) and the cleavage indicate that the two limbs are part of a reclined fold with a closure of 40 degrees (Fig. 7 (B)). The geometry and orientation of this fold is interpreted as having resulted from a reorientation of a D_1 fold whose axial plane was rotated parallel to the S_2 trend with an associated decrease in the angle of closure. Consequently the lineations resulting from crenulation of S_o and S_1 are nearly coincident with the fold axis (Fig. 4 (E & F)).

3. Intense D_2 folding (see Fig. 8)

Isoclinal folds exposed along Bungambrawatha Creek (Domain 12) represent the product of the most severe deformational phase recognized in the Albury district. Although no macroscopic fold hinges can be observed, facing changes in vertically dipping beds, delineate isoclinal folds. Poles to S_o, in this region, plot as a point maximum and contrast with the stereographic plots of the western domains. Crenulations and mineral-streaks all plunge at low angles to the southeast and plot as a point maximum. Boudinage is extensively developed and a number of pegmatites and quartz veins have been ruptured and necked with subsequent flowage of the surrounding schist into the regions between the boudins. Minor structures include pinch-and-swelling of quartz veins, rootless intrafolial folds and minor folds of pegmatite and quartz veins. A foliation and lineation defined by muscovite plates exists in the finer grained pegmatites though the coarser-grained varieties apparently were more resistant to textural deformation. Exposed along the upper parts of Bungambrawatha Creek (Domain 13) is a less intense D_2 fold system. Poles to bedding and S_2 show a deviation from the point maximum of Domain 12 (Fig. 8). This variation of deformational intensity may have been a function of stress heterogeneity. Faulting may, however, have caused the coincidence of bodies of rock which were subjected to different intensities of stress. A fold hinge defined by symmetric crenulations was found in this less intense D_2 zone.

Fig. 5 Mesoscopic structure resulting from D_1 in psammopelite/pelite sequence, Urana Rd (Lens-cap diameter is 6 cm). Sedimentary structures such as graded bedding, scour-and-fill and laminations can also be seen

4. Microstructure

The mica-grains which define the crenulations have been mimetically adjusted and consequently form paracrystalline arrays rather than a kinked or bent S_1 cleavage. This indicates that metamorphic temperatures which reached their peak between D_1 and D_2 were sufficiently high to cause mimetic reconstruction during D_2. Further evidence for this drawn out metamorphic phase comes from the slight development of rotated andalusite porphyroblasts. These snowball shapes indicate that a small amount of rotation of the porphyroblasts resulted from D_2 as was discussed above with regards to the curved nature of quartz "trains" in cordierite poikiloblasts. In Domain 12 the most severe "wrapping around" textures occur. Here, the porphyroblasts have been substantially flattened (Fig. 9) and also aligned sub-parallel to the shallow southeast plunging lineations. Associated with this is a marked development of pressure shadows of quartz-grains. White mica plates

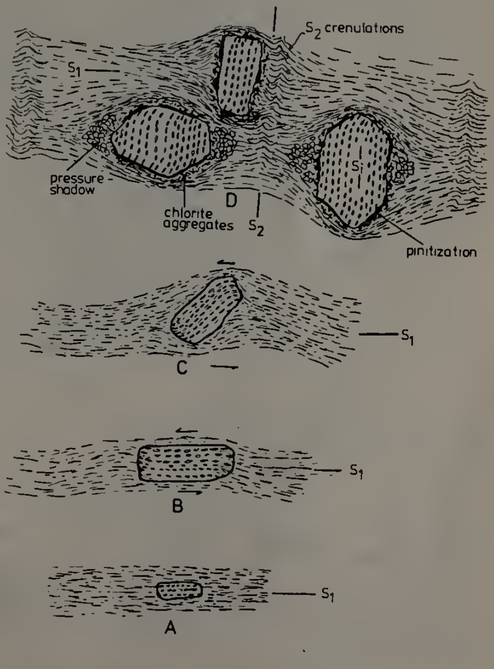


Fig. 6 Development of internal structures (S_i) in cordierite. Maximum metamorphic growth took place between A and C. Rotation began in B with the end result of D. Associated with this rotation was the wrapping-around of porphyroblasts by S_1 and development of pressure shadows of quartz grains (Based on Slide No. 50306, University of Sydney, Department of Geology and Geophysics Reference Collection).

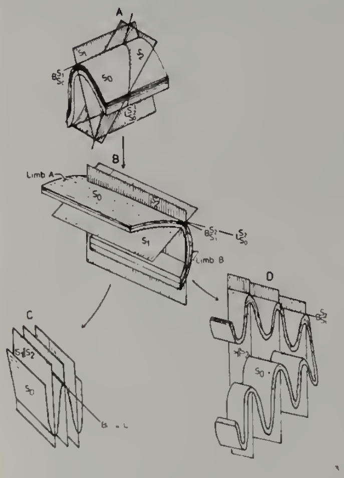


Fig. 7 Sketch of macroscopic fold systems found at Albury. The sequence A to C and D represents the structures found as one moves from the west to the east. Two alternatives present themselves for the intense D_2 zone.

display transgressive relationships to the schistosity indicating some post-D_2 growth.

5. Interpretation of the nature of D_2

The structural transition from the plunging upright folds due to D_1 to the intensely deformed isoclinal D_2 folds is depicted in Fig. 7 (A to D). Two possibilities exist for the transition from the reclined fold of Domain 15 (Fig. 7(B)) to the isoclinal folds of Domain 12 (Fig. 7 (C, D)). Firstly, the transition may have resulted from tightening of reclined folds together with rotation of the axial plane to the orientation of S_2. Secondly, it may have resulted from superposed isoclinal folds imprinted on both limbs of the reclined fold. The marked change of fold style as illustrated in this transition strongly suggests the presence of faulting. Examination of the outcrop pattern as marked on the relevant geological

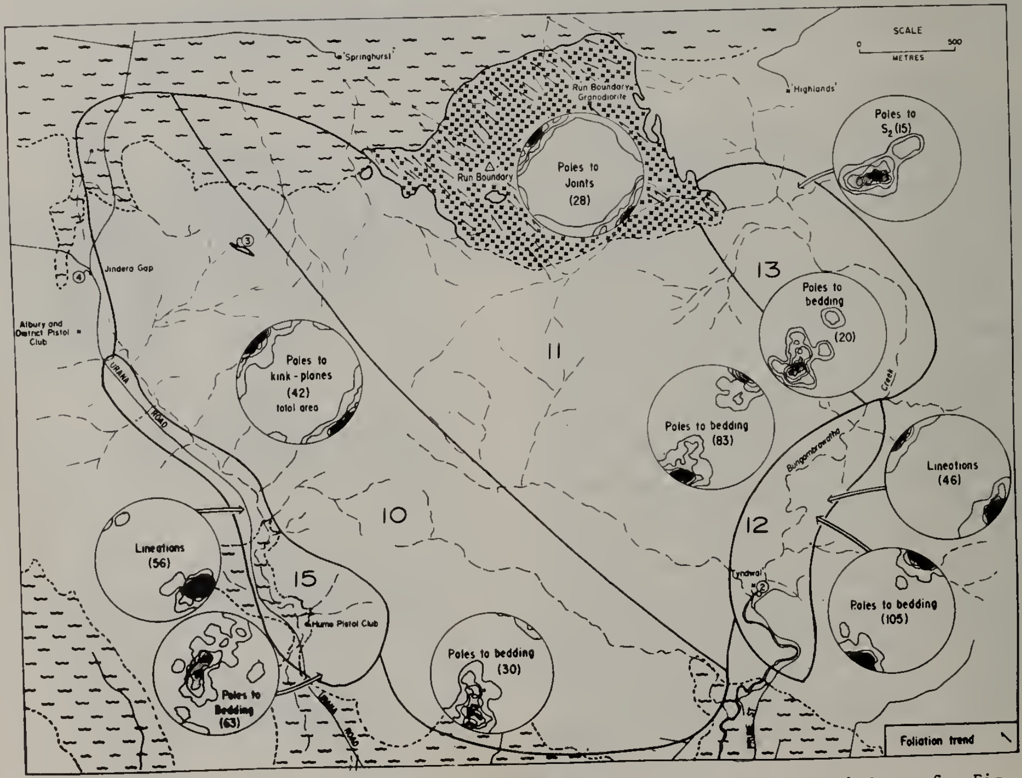


Fig. 8 Inset map of Fig. 2. Structural domains and contours as for Fig. 3. Symbols as for Fig. 2.

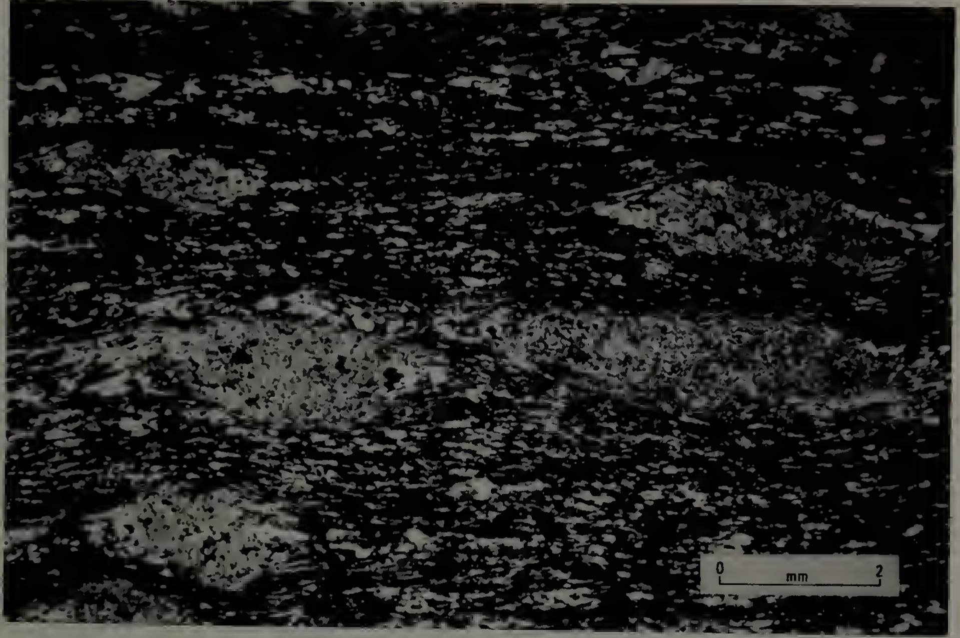


Fig. 9 Flattened andalusite (retrogressed) porphyroblasts showing strong wrapping-around and development of pressure shadows. (Crossed nicols, Slide No. 50316).

sheets together with ERTS photographs reinforce this observation. Thus a major fault is proposed to mark the structural transition discussed above. This lineament appears to have affected an area extending from Burrumbuttock to the Eastern Hills (Fig. 1) and possibly may be related to the various south south-east trending faults and thrusts in the Kiewa River region of Victoria. A related structure to this is the fault along which an altered gabbro is exposed (Fig. 2). Unlike the Kiewa thrust zone (Beavis, 1962) no evidence can be found for wide-scale mylonitization.

The Third Deformation (D_3)

An extensive system of dextral kink bands (orientation of S.045.D.90) is confined to those areas subjected to D_2 superposed folding. No sinistral kinks were found though at one locality a small left-handed bend-glide fold exists (orientation of S.169.D.90). The bands constituting these kinks occur in all thicknesses up to about 15 cm with the different stages of development commonly seen in a single outcrop (Fig. 10A). The presence of incipient kinks as predicted by the migrating axial surface model of kink formation strongly suggests that this was the active mechanism (Fig. 10B). Small-scale faulting along the axial surfaces of the kinks may be observed and indicates a later stage of kink fold development when 'the rocks pass from a ductile to a brittle state' (Ramsay, 1967, p. 453). The absence of conjugate kink systems indicates compression did not take place parallel to the foliation (Turner and Weiss, 1963). The average orientation for the axial planes of the kinks is at an angle of 90 degrees to S_2. Experimental work

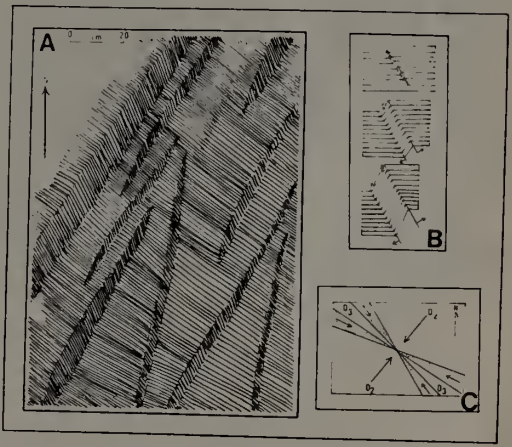


Fig. 10 A. Sketch of kink-bands, Urana Rd. Small incipient kinks are compared with fully developed bands, differential movement has resulted in small-scale faulting (plan view).

B. Mechanism which best fits the development of kinks at Albury - 'migration of axial surfaces' (after Ramsay, 1967, p. 452).

C. Directions of compression which resulted in kinking (D_3, stippled area) and superposed folding (D_2). The D_3 compression direction is parallel with that responsible for D_1.

indicates that such a relationship results when the angle between the maximum compressive stress (σ_1) and foliation is between 14 and 20 degrees (Weiss, 1968 p. 345, Plates 10 and 11). Joints in the Run Boundary Granodiorite have a similar orientation to the kinks. The directions of compression responsible for D_1, D_2 and D_3 are sketched in Fig. 10C.

Conclusions

The D_2 trend discussed above has been recognized in a number of other areas (Beavis, 1964; McKay, 1969; Rogerson, 1974; Singer, 1974; Wells, 1956). Reference to the geological sheets of Victoria and southern N.S.W. shows that this deformation has produced, in a vast tract of country, the north-west/south-east trend. The style of D_2 folding in Domain 12 appears more intense than that of the Kiewa district (Beavis, 1962, e.g. Fig. 7 A, D) and that of the Casterton district (Wells, 1956). No mention could be found in the literature of structures comparable to the Albury D_1 trend. Although multiple episodes of deformation have been recognized by Beavis (1964, 1965, 1968), McKay (1969), Rogerson (1974), Singer (1974) and Wells (1956), the early D_1 trend has not been recognized and has apparently been obliterated. Thus the Albury district might represent a rare occurrence in the Lachlan Fold Belt of an early deformation relatively unaffected by the dominant D_2 episode responsible for the present day geological trends.

Beavis (1964) has provided evidence for three periods of folding in the Beechworth district of Victoria where chevron folds and a strain-slip cleavage have affected an earlier foliation. In the Tawonga district he (Beavis, 1968) described two generations of folds and noted the existence of a rare crenulation cleavage. Rogerson (1974) and McKay (1969) also describe a crenulation cleavage in the Tallangatta district. Despite the widespread development of crenulations in the Albury district no such cleavage or parting has resulted.

Beavis (1964) attributes the three periods of folding in the Beechworth district to the Siluro-Ordovician Benambran orogeny. Brooks and Leggo (1972) provide geochronological evidence for a metamorphic and igneous phase related to the Benambran orogeny which gave rise to the regional aureole granites of the Corryong district, Victoria. Such observations are consistent with the Albury district where D_1, D_2 and possibly D_3 form deformational phases within the broad activity of the Benambran orogeny.

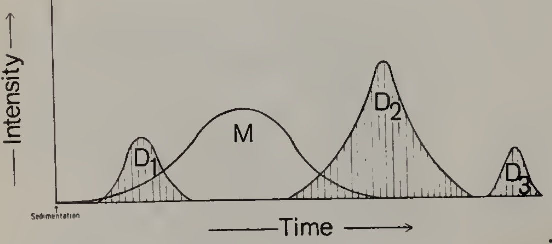


Fig.11 Intensity vs time graph for deformation [illegible] and metamorphism (M) in the Albury district

The following hypothesis for the structural evolution of the Albury district is presented (cf. Fig. 11).

(1) Deposition of an Upper Ordovician quartz-rich turbidite sequence.

(2) Deformation of bedding into upright, gently plunging close folds striking slightly north of east.

(3) Porphyroblastic metamorphic grain growth. This was initiated when the rocks possessed a slaty texture.

(4) Peak metamorphism resulting in maximum growth of andalusite and cordierite.

(5) Overprinting by D_2 in the western part of the area and refolding in the east during declining temperatures of metamorphism. Lineations, small folds and isoclinal folds thus resulted. Associated with D_2 was a major fault.

(6) Late kinking affecting areas most deformed by D_2.

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Seismic Risk in Australia

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ABSTRACT. The magnitude of an earthquake is a measure of the total elastic wave energy radiated by that earthquake. Attenuation of seismic waves in eastern United States and Australia is less than it is in southern California, and the magnitudes of some earthquakes in Australia have been overestimated. This paper presents the results of a correlation of published magnitudes of Australian earthquakes with the ground motion caused by these earthquakes at Riverview Observatory. From the resulting table of magnitudes of Australian earthquakes, some approximate estimates of seismic risk are made. An earthquake of magnitude 6.8 can be expected to occur under Perth less than once in a million years and an earthquake of magnitude 6.2 can be expected to occur under Sydney less than once in 500 000 years. An earthquake of magnitude 5.8 can be expected to occur close to Adelaide once in 100 years and an earthquake of magnitude 5.5 can be expected to occur in the region between Yass and Picton, New South Wales, once in 20 years.

INTRODUCTION

In order to estimate seismic risk in a region we need to know the energy released at the surface of the earth near the sources of the past earthquakes in that region. The magnitudes of these earthquakes are a measure of this energy. However, the magnitude of an earthquake is usually determined from measurements of ground motion made at distances of one or several hundred kilometres from the earthquake, and allowance has to be made for attenuation of the waves from the earthquake over these distances. This attenuation is not well known over much of Australia. Hence, before we estimate seismic risk in Australia, we need to examine methods of determining the magnitudes of Australian earthquakes.

MAGNITUDE AND SEISMIC RISK

The magnitude of an earthquake was originally defined (Richter, 1935) for shallow earthquakes in southern California as the logarithm (to base 10) of the maximum trace amplitude in micrometres recorded on a Wood-Anderson seismograph (static magnification 2800, period 0.8 s, damping 0.8 critical) 100 km from the epicentre of the earthquake. For situations in which there was no Wood-Anderson seismograph 100 km from the epicentre of the earthquake, Richter provided a table by which magnitudes of shallow earthquakes could be estimated in southern California up to epicentral distances of 600 km. This magnitude of an earthquake is now usually called the local magnitude (M_L). Gutenberg and Richter extended the magnitude scale to shallow earthquakes occurring outside southern California and recorded on other types of seismograph. They measured amplitudes of ground motion caused by surface waves, usually of period about 20 s. This magnitude of an earthquake is now called the surface wave magnitude (M_S), and is the magnitude given for shallow earthquakes by Gutenberg and Richter in *Seismicity of the Earth* (1954, p.10). Finally, since deep earthquakes do not radiate large surface waves, Gutenberg constructed tables for earthquakes of varying depths and epicentral distances by which their magnitudes could be estimated from the ground motion caused by P, PP and S waves from them. This magnitude of an earthquake is now called the body wave magnitude (m_B). Gutenberg tried to tabulate body wave magnitudes so that a deep earthquake of given body wave magnitude radiated the same seismic wave energy as a shallow earthquake of the same surface wave magnitude (Gutenberg and Richter, 1954, p.10). Later, a more accurate relation between body wave magnitude and surface wave magnitude was found to be (Richter, 1958, p.348)

$$m_B = 2.5 + 0.63\ M_S \qquad (1)$$

Gutenberg and Richter (1956) tentatively related body wave magnitude and local magnitude in California

$$m_B = 1.7 + 0.8\ M_L - 0.01\ M_L^2 \qquad (2)$$

Richter (1958, pp.353, 651) also related local magnitude in California with intensity in the region of greatest shaking and radius of perceptibility. Thus, an earthquake of local magnitude 5.5 has a maximum Modified Mercalli intensity of VII (Rossi-Forel VII-VIII) and a radius of perceptibility of 180 km, and an earthquake of local magnitude 6.0 has a maximum Modified Mercalli intensity of VIII (Rossi-Forel VIII) and a radius of perceptibility of 220 km.

It is worth noting that Gutenberg and Richter in *Seismicity of the Earth* gave most magnitudes to the nearest quarter unit and observed that the order of accuracy of well observed magnitudes was ±0.2 unit (1954, p.10). This still applies to magnitudes determined today on account of the irregular radiation pattern of earthquakes, irregular attenuation of earthquake waves, and the sometimes impulsive character of ground motion from which magnitudes of earthquakes must be estimated (cf. Denham, 1976).

From this brief historical survey, we can draw three conclusions.

First, the magnitude of an earthquake is an estimate of the total elastic wave energy radiated from the source region of the earthquake. It is of primary concern in the estimate of seismic risk. Other characteristics of an earthquake, for example its depth and the area of its fault plane over which fracture occurs, influence the wave energy radiated at the surface of the earth and the periods of earth vibration near the source of the earthquake (Adams, 1975; Evernden, 1975). However, for most Australian earthquakes these other characteristics are now known, and magnitude must be the characteristic used for the estimation of wave energy radiated from the earthquake at the surface of the earth near the source of the earthquake.

Second, if the attenuation of earthquake waves in the crust and uppermost mantle of a region is lower than it is in southern California, and if Richter's (1935) table is used, the local magnitudes of earthquakes will be overestimated. Nuttli (1973) has noted that the attenuation of earthquake waves in eastern United States is lower than it is in southern California, and Drake (1974) and White (1968) have made similar observations in New South Wales and South Australia. Richter's (1935) table has been used for the estimation of the magnitudes of some Australian earthquakes (Burke-Gaffney, 1952; Doyle *et al.*,1968). It is desirable to re-estimate the magnitudes of Australian earthquakes by other means than by Richter's (1935) table.

Third, these other means are available. Gutenberg and Richter (1954, pp.87, 225, 244) have given surface wave magnitudes for 12 important Australian earthquakes. Since for earthquakes of magnitude between 5 and 7.5 surface wave magnitude is not expected to differ from local magnitude by more than 0.2 unit (from equations 1 and 2), the estimates of Gutenberg and Richter can be used as estimates of local magnitude. Also, since 1964 the *Bulletin of the International Seismological Centre* has given body wave magnitudes (and sometimes surface wave and local magnitudes) of the more important Australian earthquakes. For earthquakes of magnitude between 6 and 6.5, body wave magnitude is often an acceptable estimate of local magnitude (equation 2). For earthquakes of magnitude between 5 and 5.5, local magnitude is expected to be smaller than body wave magnitude (equation 2). This is still found to be so in northern California (Bolt and Miller, 1975, pp.531-545). However, in New Zealand local magnitude is found to be larger than body wave magnitude (Gibowicz, 1972). Hence, for Australian earthquakes, body wave magnitudes given in the *Bulletin of the International Seismological Centre*, provided that they are based on the readings of at least two stations, can be expected to be approximate estimates of local magnitudes. Finally, detailed intensity data are available for at least 12 important Australian earthquakes. Although the radius of perceptibility of Australian earthquakes is greater than that of Californian earthquakes of the same magnitude (Drake, 1974), we can use Richter's (1958) relations between intensity in the region of greatest shaking and local magnitude as approximate estimates of the local magnitudes of Australian earthquakes.

This paper presents the results of correlating estimates of the magnitudes of Australian earthquakes made by the above three means with the ground motion that these earthquakes caused at Riverview Observatory. Tables have been drawn up of the magnitudes of Australian earthquakes that are consistent with their epicentral distances and the ground motion they caused at Riverview Observatory.

TABLE 1

EARTHQUAKES OF MAGNITUDE 5 IN NEW SOUTH WALES

	Date	Time (GMT)			Epicentre		Mag.	Region	Reference
		h	m	s	°S	°E	M_L		
1921	May 30	14	51	59	35.0	145.0	5.5	Hay, Tocumwal	Drake (1974)
1925	Dec 18	10	47	10	33.0	152.0	5.2	Sydney, Wingham	Drake (1974)
1930	Oct 27	02	03	51	34.5	149.0	5.0	Boorowa	Burke-Gaffney (1952)
1934	Nov 18	21	58	41	34.5	149.5	5.6	Gunning	Burke-Gaffney (1952)
1938	Mar 24	20	03	33	35.5	146.0	5.5	Berrigan	Burke-Gaffney (1952)
1949	Mar 10	22	30	33	34.8	149.2	5.5	Dalton, Gunning	Joklik (1951)
1959	May 18	06	12	59	36.2	148.7	5.3	Berridale, Cooma	Cleary *et al.* (1964)
1961	May 21	21	40	03	34.5	150.5	5.6	Bowral, Robertson	Cleary & Doyle (1962)
1968	Dec 31	16	08	33	31.0	149.3	5.0	Coonabarabran	Internat. Seismol. Centre
1973	Mar 09	19	09	15	34.2	150.3	5.5	Burragorang Valley	Gray (1974)

TABLE 2
EARTHQUAKES OF MAGNITUDE 5 IN VICTORIA AND TASMANIA

Date		Time (GMT) h	m	s	Epicentre °S	°E	Mag. M_L	Region	Reference
1903	Apr 06	13	52	00	38.4	142.5	5.4	Warrnambool	Barrachi & Hogben (1904)
1922	Apr 10	10	47	39	40.0	147.5	5.3	Flinders Island	Burke-Gaffney (1952)
1929	Dec 28	01	22	53	40.0	149.0	5.4	Flinders Island	Gutenberg & Richter (1954)
1946	Sep 14	19	48	42	40.0	148.0	5.7	Flinders Island	Gutenberg & Richter (1954)
1958	Jan 01	00	07	00	42.2	146.1	5.3	Queenstown	Doyle *et al.* (1968)
1960	Dec 24	16	42	08	39.0	143.5	5.3	Cape Otway	Doyle *et al.* (1968)
1965	Sep 14	12	34	33	38.7	144.2	5.0	Lorne	Internat. Seismol. Centre
1965	Sep 14	12	53	12	38.8	144.0	5.3	Lorne	Internat. Seismol. Centre
1966	May 03	19	07	54	37.1	147.2	5.0	Mt. Hotham	Internat. Seismol. Centre
1969	Jun 20	11	15	32	38.6	146.0	5.3	Gippsland	Internat. Seismol. Centre

TABLE 3
EARTHQUAKES OF MAGNITUDE 5 IN QUEENSLAND

Date		Time (GMT) h	m	s	Epicentre °S	°E	Mag. M_L	Region	Reference
1913	Dec 18	13	54	00	20.0	147.0	5.0	Charters Towers	Gutenberg & Richter (1954)
1918	Jun 06	18	14	24	24.0	152.0	6.2	Gladstone	Hedley (1925)
1935	Apr 12	01	32	24	26.0	151.0	5.2	Gayndah	Bryan & Whitehouse (1938)
1952	Jun 24	01	46	00	25.5	152.8	5.0	Maryborough	Jones (1959)
1954	Sep 19	10	37	13	28.5	148.5	5.0	St. George	Jones (1959)
1961	Dec 28	07	36	00	28.5	142.5	5.0	SW Queensland	Doyle *et al.* (1968)

TABLE 4
EARTHQUAKES OF MAGNITUDE 5 IN SOUTH AUSTRALIA AND NORTHERN TERRITORY

Date		Time (GMT) h	m	s	Epicentre °S	°E	Mag. M_L	Region	Reference
1897	May 10	04	55	00	37.0	139.6	6.5	Kingston, Beachport	Dodwell (1910)
1902	Sep 19	10	35	00	35.3	137.9	5.9	Warooka	Dodwell (1910)
1937	Oct 28	09	34	43	26.0	136.5	5.5	Simpson Desert	Bolt (1959)
1937	Dec 20	22	35	02	25.4	136.5	5.6	Simpson Desert	Bolt (1959)
1938	Apr 17	08	56	22	25.5	137.2	6.0	Simpson Desert	Bolt (1959)
1939	Mar 26	03	56	05	32.0	138.0	5.6	Quorn	Bolt (1959)
1941	May 04	22	07	30	26.3	136.9	5.9	Simpson Desert	Sutton & White (1968)
1941	May 04	22	31	50	26.3	136.9	5.3	Simpson Desert	Bolt (1959)
1941	May 04	23	23	57	26.3	136.9	5.6	Simpson Desert	Bolt (1959)
1941	Jun 27	07	55	51	25.7	137.8	6.5	Simpson Desert	Bolt (1959)
1948	Aug 06	03	29	45	36.9	139.9	5.6	Kingston	Denham *et al.* (1975)
1954	Feb 28	18	09	52	34.9	138.7	5.8	Adelaide	Kerr-Grant (1956)
1959	Nov 02	01	17	57	33.4	136.0	5.1	Eyre Peninsula	Sutton and White (1968)
1965	Mar 02	15	18	54	30.5	138.2	5.0	Flinders Ranges	Sutton and White (1968)
1971	Jul 26	07	50	33	31.4	138.8	5.0	Flinders Ranges	Stewart *et al.* (1973)
1972	Apr 18	22	20	39	31.4	138.5	5.2	Flinders Ranges	Internat. Seismol. Centre
1972	Aug 28	02	18	59	25.0	136.4	5.6	Simpson Desert	Stewart & Denham (1974)

TABLE 5
EARTHQUAKES OF MAGNITUDE 5 IN WESTERN AUSTRALIA

	Date	Time (GMT)			Epicentre		Mag.	Region	Reference
		h	m	s	°S	°E	M_L		
1929	Aug 16	21	28	22	17.0	120.9	6.2	NW of Broome	Bolt (1959)
1941	Apr 29	01	35	41	26.8	116.1	6.8	Meeberrie	Bolt (1959)
1961	Jun 18	16	13	58	20.1	119.3	5.6	Port Hedland	Doyle *et al.* (1968)
1961	Aug 23	18	01	33	18.5	119.0	5.4	W of Broome	Doyle *et al.* (1968)
1963	Jan 18	05	49	17	32.2	117.1	5.2	Beverley	Doyle *et al.* (1968)
1963	Aug 27	19	15	43	16.6	128.6	5.2	Ord River	Doyle *et al.* (1968)
1964	Mar 23	22	41	16	17.7	123.2	5.9	Derby	Internat. Seismol. Centre
1965	May 19	02	13	47	25.0	112.0	5.3	Carnarvon	Internat. Seismol. Centre
1965	Sep 10	12	24	01	18.1	122.2	5.0	Broome	Doyle *et al.* (1968)
1966	Apr 30	03	25	00	16.4	120.5	5.1	NW of Broome	Internat. Seismol. Centre
1966	Nov 13	03	41	48	24.2	111.9	5.4	Point Cloates	Internat. Seismol. Centre
1968	Apr 08	01	44	55	30.8	117.3	5.2	Beacon	Internat. Seismol. Centre
1968	Jun 19	05	55	43	19.4	125.1	6.0	Fitzroy Crossing	Internat. Seismol. Centre
1968	Jun 30	19	21	23	16.6	121.6	5.7	N of Broome	Internat. Seismol. Centre
1968	Aug 06	19	08	52	18.5	123.2	5.3	S of Derby	Internat. Seismol. Centre
1968	Oct 14	02	58	50	31.6	117.0	6.8	Meckering	Everingham *et al.* (1969)
1968	Oct 14	04	09	08	31.6	117.0	5.2	Meckering	Internat. Seismol. Centre
1968	Oct 15	03	30	07	31.7	117.0	6.0	Meckering	Internat. Seismol. Centre
1968	Oct 21	15	32	59	31.6	117.1	5.2	Meckering	Internat. Seismol. Centre
1968	Oct 26	04	22	30	31.7	117.0	5.4	Meckering	Internat. Seismol. Centre
1970	Feb 08	16	31	26	27.4	125.1	5.0	Officer Basin	Internat. Seismol. Centre
1970	Mar 10	17	15	17	31.0	116.7	5.5	Calingiri	Internat. Seismol. Centre
1970	Mar 24	10	35	13	22.1	126.6	6.1	Canning Basin	Denham *et al.* (1974)
1970	Mar 25	00	31	46	22.0	126.4	5.0	Canning Basin	Internat. Seismol. Centre
1970	Apr 04	14	09	36	21.9	126.6	5.3	Canning Basin	Internat. Seismol. Centre
1970	Jul 20	16	01	46	22.0	126.5	5.0	Canning Basin	Internat. Seismol. Centre
1972	Oct 21	02	33	42	24.8	115.8	5.3	Gascoyne Junction	Internat. Seismol. Centre
1973	Mar 11	16	04	13	21.9	127.4	5.0	Canning Basin	Internat. Seismol. Centre

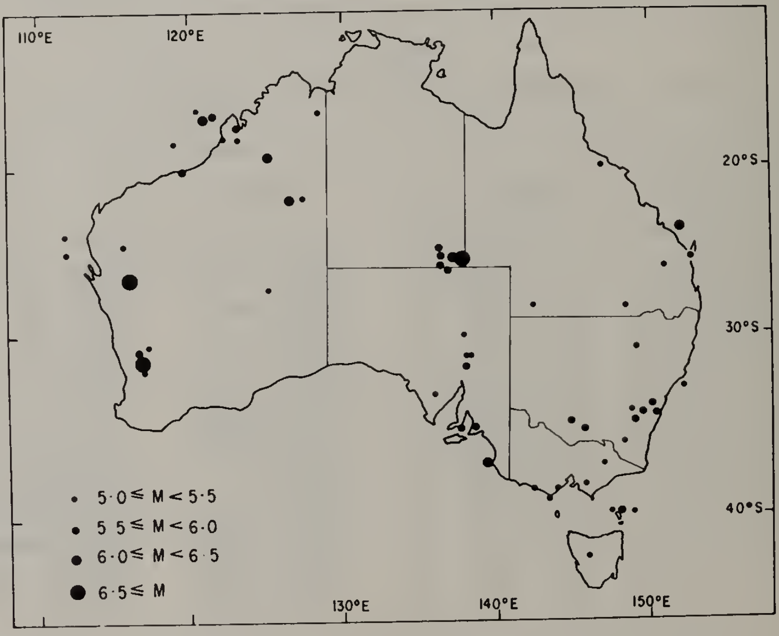

Fig. 1. Earthquakes of local magnitude 5 or larger, 1897-1973

MAGNITUDES OF AUSTRALIAN EARTHQUAKES

In Tables 1 to 5, the origin times, epicentres and local magnitudes of earthquakes of magnitude 5 or greater between 1897 and June 1973, within Australia or within 200 km of the Australian coastline are set out. Further information about these earthquakes and smaller earthquakes in the same region can be found in the accompanying references. The epicentres of the earthquakes in Tables 1 to 5 are plotted in Fig. 1.

The magnitudes of the earthquakes in Table 1 have been estimated previously (Drake 1974). The magnitude of the first earthquake in Table 2, that of 6 April 1903, near Warrnambool, was estimated from the description of damage. This estimate is subject to two uncertainties, namely how far the earthquake was from Warrnambool and the quality of the masonry in Warrnambool that was damaged.

With regard to the first and third earthquakes of Table 3, according to the Riverview seismograms, the magnitude of the earthquake of 18 December 1913 near Charters Towers, was three-quarters of a unit lower than that of the earthquake of 12 April 1935 near Gayndah. Bryan and Whitehouse (1938) assign a Rossi-Forel intensity of VIII in the epicentral region of the Gayndah earthquake, which suggests a magnitude of approximately 5.5. However, Gutenberg and Richter (1954, p.87) state that the Gayndah earthquake was not of magnitude 5.3, whereas the Charters Towers earthquake was. The first and the third magnitudes in Table 3 are thus a compromise of these various estimates.

The second earthquake in Table 3 of 6 June 1918, near Gladstone, according to the Riverview seismograms, is three-quarters of a magnitude larger than the Adelaide earthquake of 28 February 1954. Hedley (1925) assigns it the large radius of perceptibility of 400 km. According to the *International Seismological Summary* (Turner, 1923, p.74), the earthquake was under the town of Rockhampton. Perhaps because Rockhampton still stands, Denham *et al.* (1975) have omitted the earthquake. Since, according to the *International Seismological Summary*, the P arrival time at Batavia (Djakarta) was 8 s late, the earthquake was almost certainly east of Rockhampton. Gutenberg and Richter (1954, p.225) assign the earthquake a magnitude of 5.8. With regard to the Adelaide earthquake, Stewart *et al.* (1973) assign it a magnitude of 6. Kerr-Grant (1956) assigns a Modified Mercalli intensity of VIII in a small area in the epicentral region, which suggests a magnitude of close to 6. Again, the magnitude of the Gladstone earthquake in Table 3 and that of the Adelaide earthquake in Table 4 are a compromise of these various estimates.

The magnitudes of the first two earthquakes in Table 4 are assigned from carefully constructed isoseismal maps (Dodwell, 1910). The magnitudes of the Simpson Desert earthquakes in particular have been made consistent with ground motion at Riverview Observatory and the magnitudes of Gutenberg and Richter (1954) and of the *Bulletin of the International Seismological Centre*. Other magnitudes for earthquakes in South Australia have been taken from Sutton and White (1968), with the slight modification suggested by Stewart *et al.* (1973).

The second earthquake in Table 5, on 20 April 1941, near Meeberrie, has been assigned a surface wave magnitude of 6.8 by Gutenberg and Richter (1954, p.225). Gutenberg and Richter assign a depth of 60 km to this earthquake. This may explain why it was felt over so extensive an area (Bolt, 1959; Denham, 1976). The Meckering earthquake, 14 October 1968, has been assigned a body wave magnitude of 5.9 in the *Bulletin of the International Seismological Centre* and a surface wave magnitude of 6.8 by the United States Coast and Geodetic Survey. The surface wave magnitude has been retained in Table 5, since Gutenberg and Richter (1954) used surface waves to estimate the magnitude of shallow earthquakes, and, at this magnitude, surface wave magnitude and local magnitude are not expected to differ by much.

SEISMIC RISK IN AUSTRALIA

Seismic risk maps can be constructed from maps showing past earthquakes and their magnitudes. Expressions for the calculation of ground motion at various distances from earthquakes of various magnitudes and focal depths have been given by Esteva and Rosenbleuth (1964). Ground motion contours plotted on the risk map must be smoothed so that tectonically similar regions are included within the same contour (Whitham, 1975). Such a map has been constructed for Canada (Milne and Davenport, 1969), and one is in preparation for Australia (McEwin *et al.*, 1976).

Approximate estimates of seismic risk can be made from Fig. 1. Australia is well within the boundaries of a lithospheric plate (Lomnitz; 1974, p.272; Sykes and Sbar, 1973; Fitch *et al.*,1973). Experience in eastern United States and Canada has shown that the position of the release of intraplate stress has moved about, from the St. Lawrence River, in 1638, to New Madrid, in 1811 and 1812, to Charleston, in 1886, to Grand Banks, in 1929 (Howell, 1974). We must allow a similar possibility in Australia. Earthquakes are more likely to occur in the zones in which they have already occurred than in other places, because these zones are zones of weakness and of possibly accumulating stress. With this in mind, and considering the relative areas of Western Australia and Perth, we can estimate that an earthquake of the magnitude of those that occurred near Meeberrie in 1941 and at Meckering in 1968 might be expected to occur under Perth less than once in a million years, and, considering the relative areas of eastern Australia and Sydney, we can estimate that an earthquake of the magnitude of the one that occurred near Gladstone in 1918 might be expected to occur under Sydney less than once in 500 000 years. From the seismicity of the region near Adelaide, we must expect an earthquake of magnitude 5.8 or greater near Adelaide approximately once every 100 years, and, from the seismicity of the region between Yass and Picton, New South Wales, we must expect an earthquake of magnitude 5.5 or greater in that region approximately every 20 years.

We should note that risk maps which show ground velocities or accelerations that are to be expected within some time interval (e.g. 100 years) are subject to two strong qualifications. First, these ground velocities or accelerations marked on the risk map may be sharply exceeded, or exceeded for a period of many seconds. This may occur either because an earthquake of unusually large magnitude occurs in a region, or because an earthquake of moderate magnitude in a region causes unusually large ground motion (Bolt *et al.*, 1975, pp.49-55). Second, the risk map does not take account of local geological hazards, such as faults, ground of poor bearing capacity, weakly compacted alluvial soils, soil subject to liquefaction, or potential landslide areas (Steinbrugge, 1968, pp.11-36; Adams, 1975).

CONCLUSION

The magnitudes of Australian earthquakes are the best available measures of the energy radiated from these earthquakes at the surface of the earth near the sources of these earthquakes. Tables have been drawn up of the magnitudes of Australian earthquakes that are consistent with the epicentral distances of these earthquakes from Riverview Observatory and the ground motion that they caused there. Approximate estimates of seismic risk have been made for Perth, Sydney, the region near Adelaide and the region between Yass and Picton, New South Wales.

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Connected and Locally Connected Closed Subgroups of Products of Locally Compact Abelian Groups

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ABSTRACT. It is shown that any connected or locally connected closed subgroup of a product of locally compact abelian groups is topologically isomorphic to a product of locally compact abelian groups.

This paper is one in a series (Morris, 1972; Hunt et al, 1975; Brown et al, 1975) which attempts to expose the structure of closed subgroups of infinite products of locally compact abelian groups. In particular we mention the following Theorem (Brown et al, 1975):

THEOREM A

Let G be a closed subgroup of a product $\prod_{i\varepsilon I} R_i \times K$, where each R_i is an isomorphic copy of the topological group of real numbers, K is a compact abelian group and I is an index set. If G is connected or I is countable, then G is topologically isomorphic to a product $\prod_{j\varepsilon J} R_j \prod_{\ell\varepsilon L} Z_\ell \times K_1$, where K_1 is a compact group, each Z_ℓ is an isomorphic copy of the discrete group of integers, and J and L are some index sets. If G is connected, $L = \phi$; if I is countable, J and L are countable.

It should be noted that Theorem A would be false if the assumption that G is connected or I is countable were omitted. Indeed Leptin, 1955 showed that there is closed subgroup of an uncountable product of copies of Z which is not topologically isomorphic to a product of locally compact abelian groups.

We prove the following theorem:

THEOREM.

Let G be a closed subgroup of a product $\prod_{i\varepsilon I} L_i$ of locally compact abelian groups, for some index set I. If G is connected or locally connected then G is topologically isomorphic to a product of locally compact abelian groups. Indeed, if G is connected then it is topologically isomorphic to $\prod_{j\varepsilon J} R_j \times K$, where K is a compact connected group and J is some index set. If G is locally connected then it is topologically isomorphic to $\prod_{j\varepsilon J} R_j \times K_1 \times D$, where K_1 is a compact connected locally connected group and D is a discrete group.

PROOF.

Let G be connected. Define P_i, $i\varepsilon I$, to be the projection mappings of $\prod_{i\varepsilon I} L_i$ onto L_i. Then $p_i(G)$ is connected. So the closure of $p_i(G)$, $\overline{p_i(G)}$, is a connected locally compact abelian group. Further, G is a closed subgroup of $\prod_{i\varepsilon I} \overline{p_i(G)}$. As each $\overline{p_i(G)}$ is a connected locally compact abelian group, it is topologically isomorphic to a product $R^{n_i} \times K_i$, where n_i is a non-negative integer and K_i is a compact group. (Theorem 9.14 of Hewitt and Ross, 1963). So G is topologically isomorphic to a closed subgroup of a product $\prod_{m\varepsilon M} R_m \times K$, where M is some index set and $K = \prod_{i\varepsilon I} K_i$. As G is connected, Theorem A implies that G is topologically isomorphic to $\prod_{j\varepsilon J} R_j \times K_1$, where K_1 is compact. As G is connected, K_1 must be connected too.

Now let G be locally connected. If A denotes the component of the identity in G, then A is a closed connected subgroup of $\prod_{i\varepsilon I} L_i$ and so, by the above paragraph, is topologically isomorphic to $\prod_{j\varepsilon J} R_j \times K_1$. As K_1 is compact and connected, it is divisible (Theorem 24.25 of Hewitt and Ross, 1963). So A is an open divisible subgroup of G and 6.22(b) of Hewitt and Ross, 1963 implies that G is topologically isomorphic to A × (G/A); that is, G is topologically isomorphic to $\prod_{j\varepsilon J} R_j \times K_1 \times D$, where D is the discrete group G/A. Finally observe that as K_1 is a continuous open image of the locally connected group G, it too is locally connected.

COROLLARY

If G is a locally connected closed subgroup of a product $\prod_{i\varepsilon I} R_i \times K$, where K is a compact abelian group and I is an index set, then G is topologically isomorphic to a product $\prod_{j\varepsilon J} R_j \times K_1 \times Z^n \times F$, where K_1 is a compact connected locally connected abelian group, n is a non-negative integer and F is a finite discrete group.

PROOF

This is an immediate consequence of the above theorem and the fact, proved by Morris (1972), that a discrete subgroup of $\prod_{i\varepsilon I} R_i \times K$ is isomorphic to $Z^n \times F$.

REMARK

It would be interesting to know if a closed subgroup of a countable product of locally compact abelian groups is necessarily topologically isomorphic to a product of locally compact abelian groups. A positive answer would mean that Noble's result (1970), that every closed subgroup of countable product of locally compact abelian groups satisfies Pontryagin duality would follow from Kaplan's result (1948), that every product of locally compact abelian groups satisfies Pontryagin duality.

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New Ordovician Stromatoporoids from New South Wales

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ABSTRACT. Six species of stromatoporoids - three clathrodictyids and three cliefdenellids - are described from the late Ordovician of central New South Wales. Among the forms are new species *Cliefdenella perdentata, Ecclimadictyon cribratum* and *Plexodictyon*? *cascum*. The *Plexodictyon*-like forms are recorded for the first time from the late Ordovician. An outline of the stratigraphic distribution of the clathrodictyids and cliefdenellids in the N.S.W. Ordovician succession is also presented.

INTRODUCTION

Ordovician stromatoporoids have been described from central New South Wales by Etheridge (1895), Pickett (1970) and Webby (1969; 1971), and their distribution recorded by Webby (1975). The present paper completes the description of the faunas based on additional material collected from the limestones and limestone breccias of the late Ordovician succession during recent field sessions.

The first clathrodictyids in the sequence occur in the 'E' horizon, some 94 m above the base of the massive, middle member of the Cliefden Caves Limestone in the Licking Hole Creek area (Percival, 1976). They include *Ecclimadictyon nestori* Webby 1969 and *Plexodictyon*? sp. and define the base of Fauna II (Fig. 1). The interval of 94 m of massive beds below the 'E' horizon is poorly fossiliferous, but it is for convenience included, along with the lower, thinly bedded, member of the Cliefden Caves Limestone, in Fauna I - characterized by the labechiids, *Labechia regularis* Yabe & Sugiyama 1930, *Cystistroma donnellii* Etheridge 1895 and species of *Stratodictyon* Webby 1969. It may be suggested, on the basis of present correlations (Fig. 1) that the first clathrodictyids made their appearance about the beginning of the Eastonian.

An account of the stromatoporoid faunal distribution in the upper part of the Cliefden Caves Limestone and equivalents has previously been given (Webby, 1969; 1975). The occurrences belong to a Fauna II assemblage (Fig. 1) which immediately pre-dates the late Eastonian Zone of *Dicranograptus hians*. Towards the top of the Bowan Park Group, in the Clearview Limestone Member of the Ballingoole Limestone (Semeniuk, 1972), there is a fauna including *Clathrodictyon* aff. *mammillatum* (Schmidt, 1858), *C.* cf. *microundulatum* Nestor 1964, *Ecclimadictyon* aff. *nestori*, *E. amzassensis* (Khalfina, 1960) and *Plexodictyon*? *cascum* sp. nov. This is an assemblage of Fauna III age, probably correlative with the early Bolindian Zone of *Pleurograptus linearis* (Fig. 1).

At a similar stratigraphic level in a limestone breccia towards the top of the Malongulli Formation north-east of Malongulli Trig, the stromatoporoids *Ecclimadictyon cribratum* sp. nov. and *Cliefdenella* sp. have been found (Percival, 1976). No stromatoporoids have been found in the still higher limestone and limestone breccia near the top of the Malachi's Hill Beds (assigned a Fauna IV age on the basis of rugose and tabulate coral faunas - McLean & Webby, 1976; Webby, in press).

Doubts were originally expressed about whether close correlation was attainable between the Ordovician limestones of the Molong Rise and those of the Parkes Platform (Webby, 1969, p. 640). However with the present accumulation of faunal data it is possible to establish precise correlation of the Billabong Creek Limestone and the overyling unnamed limestone within the lower part of the Goonumbla Volcanics. The finding of *Ecclimadictyon nestori* and *Pseudostylodictyon inequale* Webby 1969 in beds towards the base of the Billabong Creek Limestone at Goonumbla suggests a correlation with the upper part of the Cliefden Caves Limestone and equivalents (Fauna II). *E. nestori* also occurs in the Billabong Creek Limestone at Billabong Creek.

The unnamed limestone of the lower Goonumbla Volcanics at Gunningbland exhibits *Cliefdenella perdentata* sp. nov. and *C.* aff. *etheridgei* but no clathrodictyids. Because the initial finds of *Cliefdenella* were made in the 'Island' unit of the upper part of the Cliefden Caves Limestone (Fauna II) these Gunningbland occurrences suggested the unnamed limestone had a similar age. However the recent addition of *C. etheridgei* from the middle part of the Cargo Creek Limestone, associated with *Quepora calamus* Webby & Semeniuk 1969, *Palaeophyllum crassum* Webby 1972 and *Helicelasma* sp. proved that the genus had a more extended upward range at least into Fauna III, and removed the objection of the Gunningbland horizons lying near the top of Fauna III (Fig. 1).

SYSTEMATIC DESCRIPTIONS

Order Stromatoporoidea

Family Cliefdenellidae Webby 1969

Relationships

Previous discussion of family relationships has been given by Webby (1969). Khalfina and Yavorsky (1973) included the Ordovician family in their new Superfamily Tienodictyeacea, presumably on the basis of the type species *Cliefdenella* exhibiting continuous, single-layered laminae, pillars of

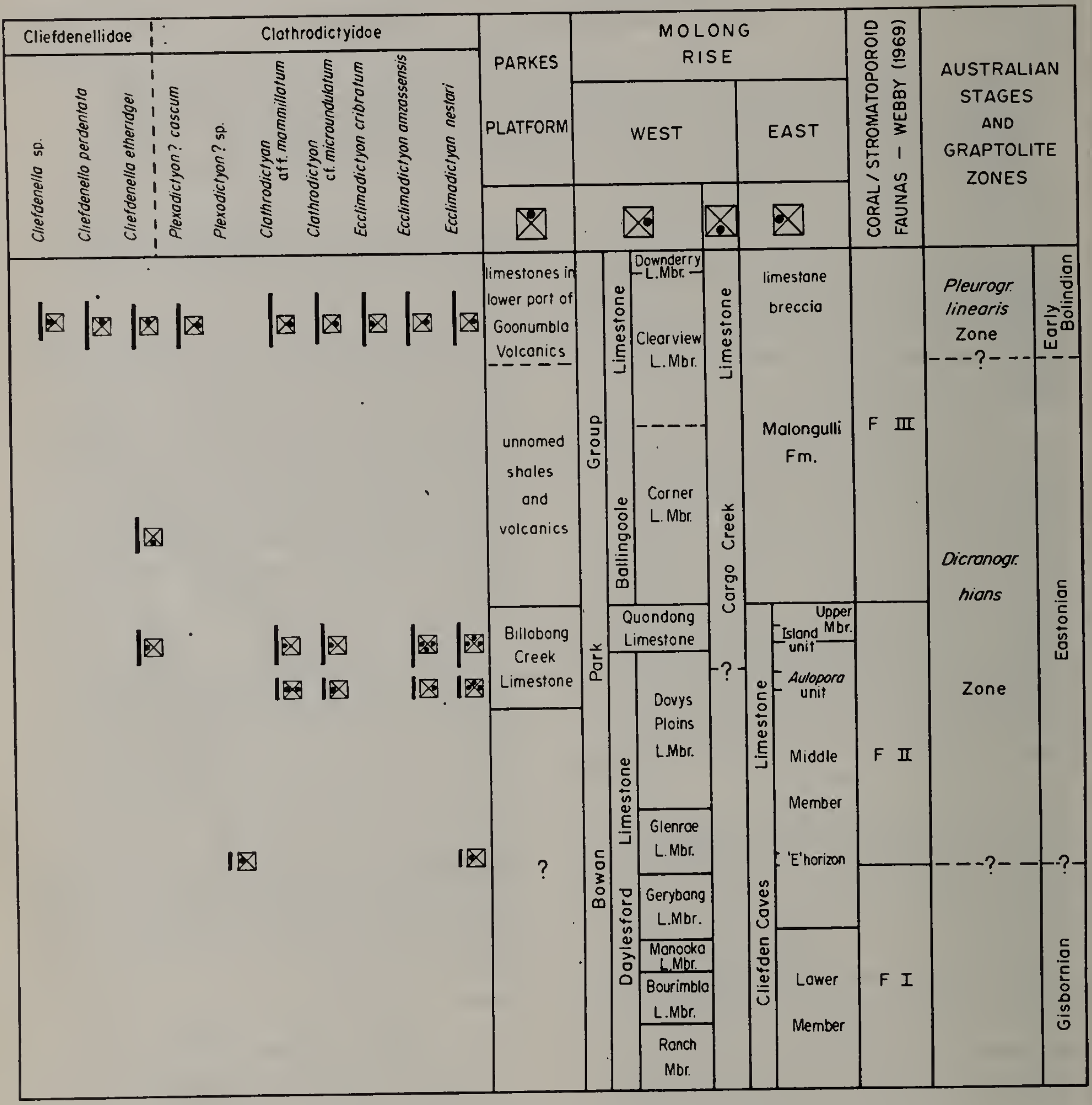


Fig. 1. Distribution of clathrodictyid and cliefdenellid stromatoporoids in the late Ordovician succession of central New South Wales. Species occurring in the succession of the Parkes Platform are shown by dot in top quarter of symbol; dots in other quarters of the symbol give distribution of species in different successions of the Molong Rise.

irregular or long, tubular kind and astrorhizae. However, there seems no justification for such a grouping. First, the laminae of *Cliefdenella* are not single layered, but comprise a darker, granulated, ?melanospheric middle layer intervening between upper and lower clear, compact layers; and secondly, the long, hollow, tube-like pillars (no irregular types) are not remotely comparable with the pillars of other representatives of the superfamily, such as *Tienodictyon* Yabe and Sugiyama 1941 and *Intexodictyon* Yavorsky 1963 (see Stearn, 1969). These latter forms have pillars which form complex meshworks confined to single interlaminar spaces. Thirdly, all the representatives other than the cliefdenellids come from much younger Silurian-Devonian horizons. Khalfina and Yavorsky's assignment of the cliefdenellids to the Superfamily Tiendictyacea is therefore rejected.

The probable association of *Cliefdenella* and *Forolinia* Nestor in 'lineage 1V' of 'morphological group A' of Kaźmierczak (1971) seems equally conjectural and untenable. *Forolinia*, as Kapp and Stearn (1975) have remarked, may be a junior synonym of *Labechia*, if the 'canals' of Nestor (1964) are recognized as altered pillars. No obviously close relationship exists between the Cliefdenellidae and Labechiidae.

Genus *Cliefdenella* Webby 1969

Type Species

C. etheridgei Webby 1969.

Diagnosis

To the features already given by Webby (1969) as characterizing the genus should be added the following: laminae three-layered, comprising lower and upper clear, compact layers separated by a darker, granular (?melanospheric) layer.

Discussion

No Ordovician or Silurian stromatoporoid genus shows close morphological similarities to *Cliefdenella*. The genus *Tubuliporella* Khalfina 1968 from the Devonian of south-west Siberia bears some resemblances but it too can be easily distinguished by its smaller size, and by exhibiting, in addition to long, tabulated, tube-like pillars, smaller, solid pillars confined to an interlaminar space (Khalfina, 1968; 1971; Ivaniya & Kosareva, 1968).

The genus *Cliefdenella* occurs in Faunas II and III of the N.S.W. successions, but has not been found in Tasmania despite a careful search. Khalfina, *in* Khalfina and Yavorsky (1974) has depicted a species of *Cliefdenella*, *C. permirum* from the Upper Ordovician of Salair, south-west Siberia, with an exceptionally large and complexly intermeshed vertical astrorhizal column.

Cliefdenella perdentata sp. nov.

Figs. 2A and 3A-B

vp. 1969. *Cliefdenella etheridgei* Webby, p. 655, pl. 125, fig. 5.

Material

Four specimens (SUP 29138-29140, 78265) from ridge top on south side of the Parkes-Bogan Gate road, and another (SUP 79151) from the 'piggery', Currajong Park, north of Gunningbland; horizons in unnamed limestone in lower part of the Goonumbla Volcanics. Note that specimens SUP 29138-29140 were previously (Webby, 1969, pp. 655-656) erroneously regarded as paratypes of *C. etheridgei*. Holotype of *C. perdentata* is SUP 29138; other specimens designated paratypes.

Description

Coenosteum massive; largest specimen (holotype) measures 100 by 80 mm across and 100 mm in height. Laminae, tubular 'pillars' and astrorhizae seen on weathered surfaces. Laminae continuous, flat to gently updomed, with prominent downward deflexions at junctions with individual 'pillars'; usually number from 3-8 per 5 mm vertically; thickness of laminae usually 0.1 mm. Denticles on upper surface of laminae typically about 0.2 mm in height. Interlaminar spaces usually from 0.5 to 1.8 mm wide, and filled with numerous inclined to subhorizontal undulating to convex cyst-like dissepiments and astrorhizal canals. 'Pillars' tube-like, from 0.35 to 0.6 (typically 0.5) mm in diameter, with numerous slightly updomed tabulae spaced from 5-8 in 3 mm vertically; normally continuous unbranching vertically, but one 'pillar' (SUP 29138) seen to bifurcate upwards. Lateral spacing of 'pillars' from 0.5 to 4 mm apart. Tube-like wall of 'pillar', like laminae, usually about 0.1 mm thick. Astrorhizal canals of interlaminar spaces tabulated, and with each successive bifurcation away from large vertical astrorhizal column there is a decrease in diameter of canal; adjacent to column the canals have diameters of from 0.5-0.8 mm, whereas in more distal parts they are from 0.2-0.4 mm; astrorhizal canals curve upwards into columns which have a diameter of 2.0-2.5 mm; occasional vertical rod-like structures are seen within astrorhizal columns. Microstructures of laminae and tube-like wall of 'pillars' composed of a middle, thin dark, dense ?melanospheric layer separated top and bottom (or by inner and outer in case of tube-like 'pillars') by lighter coloured, thicker compact layers (Fig. 2A). In contrast walls of astrorhizal canals, dissepiments and tabulae appear to be formed of single layer of compact tissue. Margins of all internal structures seem to be secondarily much corroded and altered with an additional layer of fine dark granular coating structures, and filling considerable amounts of interlaminar space.

Remarks

C. perdentata differs from the type species, *C. etheridgei*, in exhibiting on average more wide spaced laminae, less thickened 'pillars' with more prominent, close spaced tabulae, slightly larger and more conspicuous denticles, and wider astrorhizal canals in close proximity to astrorhizal columns. The interlaminar spaces also seem to be more fully occupied by dense, speckled material (?thickened dissepimental tissue) but this may be of secondary origin. Microstructure of better preserved specimens of *C. etheridgei* from the type horizon and locality in the Cliefden Caves Limestone shows the laminae (and 'pillars') composed of a middle, darker, speckled, melanospheric zone separated by less well defined upper and lower (or inner and outer in relation to tube-like wall of 'pillars') clear, compact zones (Fig. 2B). Denticles seem to be predominantly composed of the darker speckled tissue.

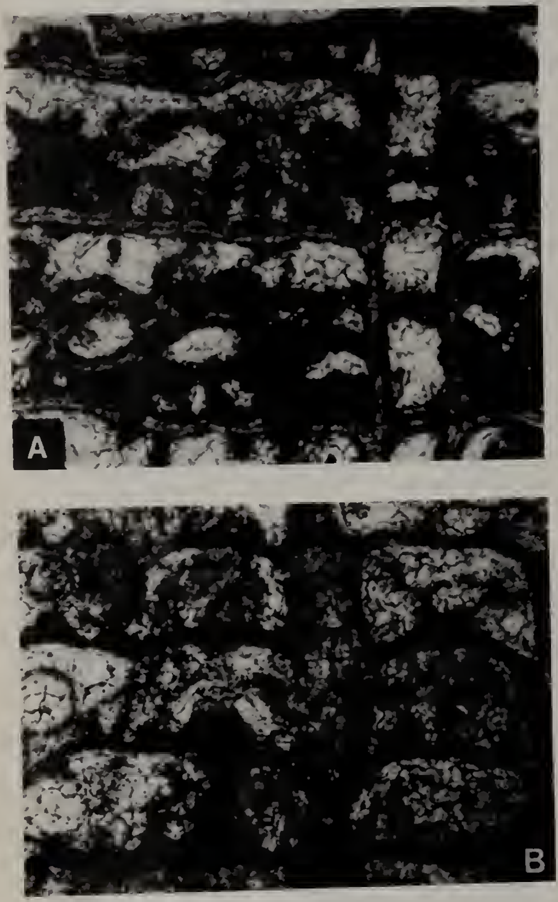


Fig. 2 Enlarged vertical sections of *Cliefdenella* to show nature of microstructure, x 20. A, *C. perdentata* sp. nov., holotype SUP 29138. B, *C. etheridgei* Webby 1969, paratype SUP 24154.

Cliefdenella aff. *etheridgei* Webby 1969

Fig. 3C-D

Material

One specimen (SUP 79150) from disused quarry, Currajong Park, north side of Gunningbland; horizon in unnamed limestone of lower part of Goonumbla Volcanics, probably stratigraphically just underlying 'ridge-top' and 'piggery' localities with *C. perdentata*.

Description

Coenosteum irregularly hemispherical, measuring 50 by 80 mm across and 50 mm in height. Laminae and long tube-like 'pillars' show on broken surfaces. Laminae continuous laterally, flat but for downward deflexions at intersections with 'pillars'; wall of laminae from 0.05-0.1 mm thick; vertical spacing of laminae from 7-8 in 5 mm. Prominent denticles arise from upper surface of laminae, usually 0.2 mm high. Interlaminar spaces from 0.4-0.8 mm in height exhibit numerous small cyst-like plates (dissepiments) forming a network with astrorhizal canals and denticles. 'Pillars' are hollow, tube-like structures from 0.35-0.55 mm in diameter and crossed by updomed and inclined cyst-like plates (tabulae). Wall thickness of tube-like 'pillars' from 0.1-0.15 mm. Astrorhizal columns are about 2 mm in diameter and spaced about 4-8 mm apart; with associated updoming of laminae, and upturning of astrorhizal canals as they intersect columns. A few vertical rod-like structures also occur within individual columns. Astrorhizal canals are typically confined within interlaminar spaces; they exhibit tabulae, and in proximity of columns usually have a diameter of about 0.4-0.5 mm.

Remarks

This specimen from Gunningbland bears close similarities to the type material of *C. etheridgei*. However, the denticles are markedly longer (0.2 mm high, as compared with 0.1 mm in *C. etheridgei*), and tube-like 'pillars' are less commonly thickened.

In addition to occurring in the upper part of the Cliefden Caves Limestone (Webby, 1969), *C. etheridgei* has also been found recently in the middle part of the Cargo Creek Limestone. The somewhat distorted, poorly preserved specimens (SUP 78262-78263) come from an horizon associated with *Helicelasma* sp., *Palaeophyllum crassum* Webby 1972 and *Quepora calamus* Webby & Semeniuk, 1969.

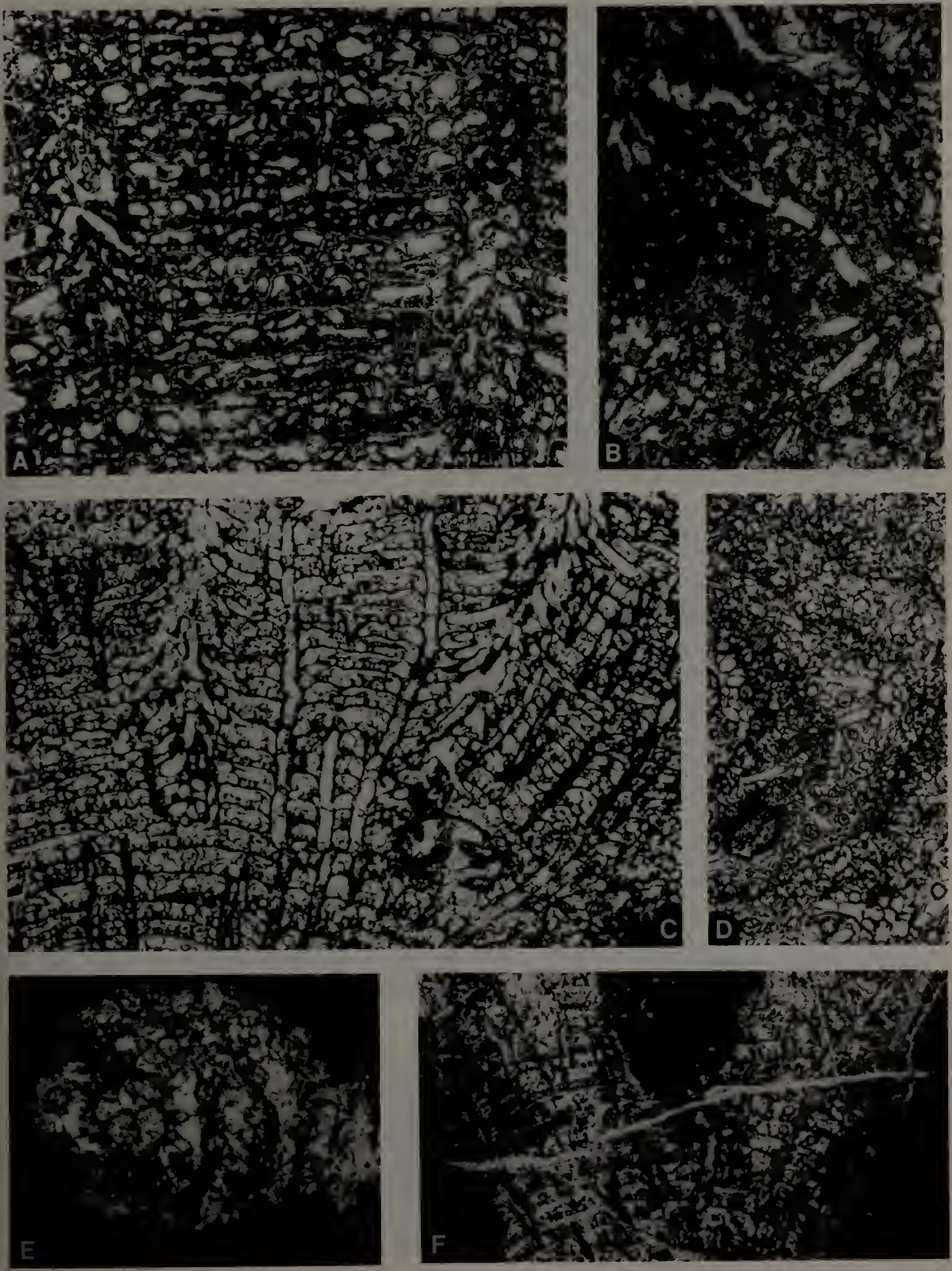
Cliefdenella sp.

Fig. 3E-F

Material

One partially silicified specimen (SUP 78268) from a limestone breccia at the top of the Malongulli Formation, north-east of Malongulli Trig.

Fig. 3 A-B, *Cliefdenella perdentata* sp. nov., holotype SUP 29138, x 5. A, vertical section. B, tangential section.
C-D, *Cliefdenella* aff. *etheridgei* Webby 1969, SUP 79150 x 5. C, vertical section. D, tangential section.
E-F, *Cliefdenella* sp., SUP 78268 x 5. E, tangential section. F, vertical section.


A
B
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D
E
F

Description

Coenosteum cylindrical with branching cylinders measuring about 6-12 mm in diameter; growing up to 40 mm in height. Laminae laterally continuous, numbering 8-9 per 4 mm vertically; usually 0.1-0.2 mm thick; downflexed at contacts with 'pillars'. 'Pillars' long, tubular, from 0.3-0.4 mm in diameter; usually spaced about 1 mm apart, and may be thickened (probably secondarily); rare domed tabulae. Recrystallization has caused alteration of elements in interlaminar spaces; astrorhizal canals from 0.2-0.3 mm in diameter may just be discerned, but dissepiments are not clearly seen. Denticles preserved on upper surfaces of laminae, usually 0.1 mm high. In tangential section of branching cylinder, there is a cluster of four thick-walled tubes, up to 0.7 mm across at the axis; these may represent elements of astrorhizal column.

Remarks

Judging from its markedly different growth form and stratigraphic occurrence at the top of the Malongulli Formation (*Pleurograptus linearis* Zone - early Bolindian), this cylindrical form probably represents a new species of *Cliefdenella.*

Family Clathrodictyidae Kühn 1939

Genus *Ecclimadictyon* Nestor 1964

Type species

Clathrodictyon fastigiatum Nicholson 1886

Ecclimadictyon nestori Webby 1969

Fig. 4D-E

1969. *Ecclimadictyon nestori* Webby, p. 660, pl. 128, fig. 1, pl. 129, figs. 1-6.

Additional material

One specimen (SUP 78259) from Billabong Creek Limestone at Billabong Creek, and another, poorly preserved specimen (SUP 78260) from base of Billabong Creek Limestone at Goonumbla; Parkes Platform.

Remarks

The specimen from Billabong Creek (Fig. 4E) is identical with *E. nestori* from the type locality at the 'Island' in the upper part of the Cliefden Caves Limestone. The Goonumbla specimen, (Fig. 4D), however, has a patchy preservation, with only small areas of the coenosteum clearly showing the typically spaced, chevron-spaced laminae and bunchy astrohizae.

Ecclimadictyon cribratum sp. nov.

Fig. 4A-C

Material

Two specimens (SUP 78266-78267) from the limestone breccia at the top of the Malongulli Formation, north-east of Malongulli Trig. Holotype is SUP 78266; other specimen designated paratype.

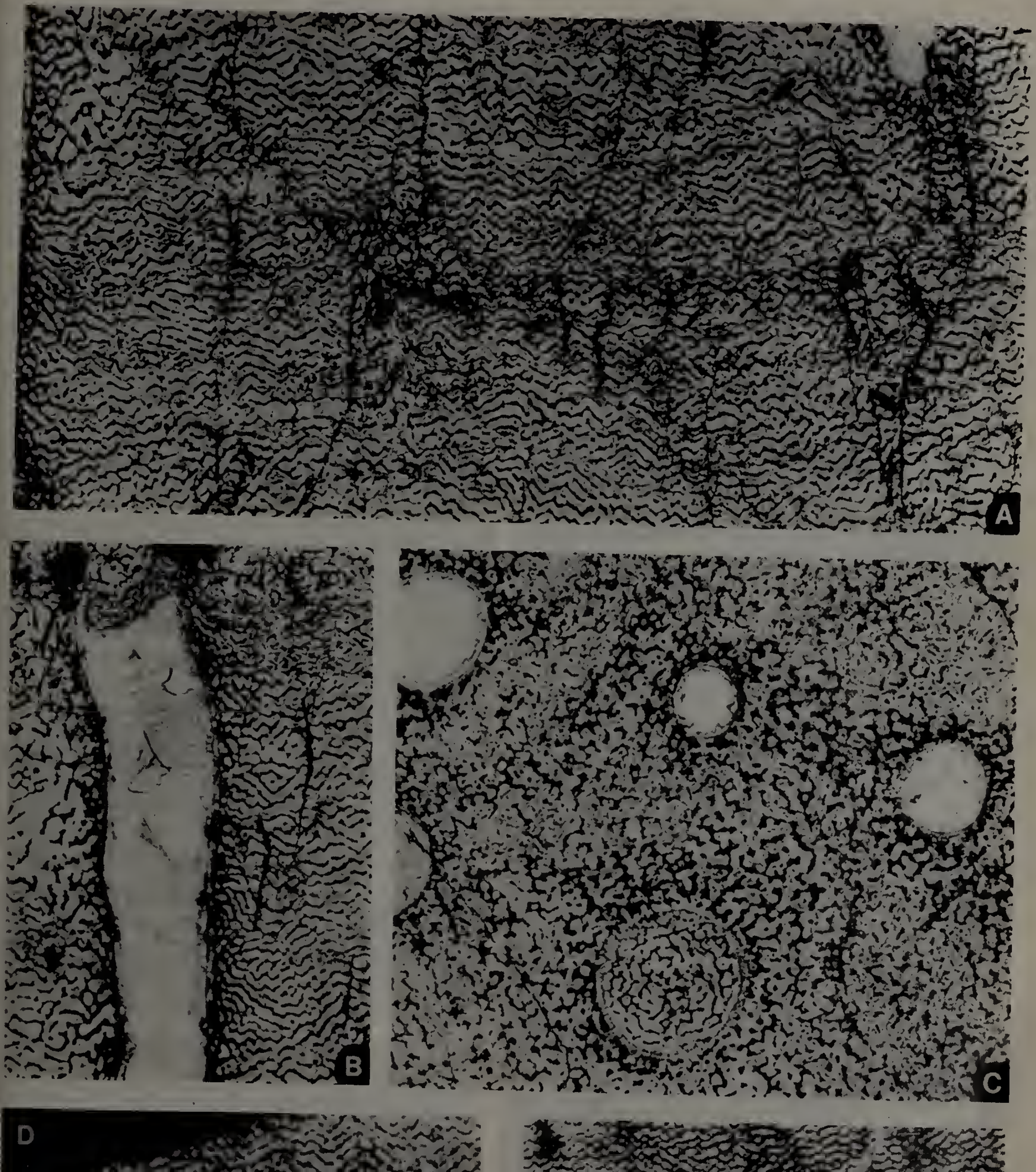
Description

Coenosteum irregularly hemispherical; largest specimen (holotype) measures 140 by 60 mm across and 90 mm in height. Laminae of sharply chevron-folded elements with some gaps in continuity as seen in both vertical and tangential sections; appears that in some areas laminar tissue is not sheet like, but forms rod-like radial processes; a type of 'hexactinellid' appearance in tangential section; usually about 12 laminae in 2 mm vertically. Thickness of laminae usually from 0.03-0.05 mm. Pillars developed from downward inflexions of laminae, confined to single interlaminar spaces; alternating rather than superposed vertically; pillars vary from 0.03-0.07 mm in diameter. Large vertical internally structureless caunopore tubes extend through coenosteum; range from 0.7 to 2.4 mm in diameter; more disordered *Ecclimadictyon* meshwork at contacts with these tubes; an occasional tube 'calice' is colonized by coenosteal tissue (Fig. 4B-C). No dissepiments seen. Astrorhizae not clearly differentiated, but there are a few scattered, ill-defined channel-ways, from 1½-3 times wider than an interlaminar space, which may represent them. Microstructure of compact type, and in a single layer.

Remarks

By exhibiting gaps in the continuity of laminae, *E. cribratum* may be readily distinguished from other species of *Ecclimadictyon.* It is not closely allied to either of the previously described N.S.W. species (Webby, 1969). With its spacing of laminae (12 per 2 mm), it is a coarser form than *E. nestori* Webby (15-16 in 2 mm), and is finer than *E. amzassensis* (Khalfina), this latter species typically having 10-11 laminae per 2 mm and, more fundamentally, long, slightly zig-zag shaped superposed pillars.

Fig. 4. A-C *Ecclimadictyon cribratum* sp. nov., holotype SUP 78266, x 10, Malongulli Formation. A, vertical section. B, vertical section showing 'calice' of caunopore tube colonized by disordered *Ecclimadictyon* meshwork. C, tangential section; note also disordered *Ecclimadictyon* infilling 'calice' of one caunopore tube.
D-E, *Ecclimadictyon nestori* Webby 1969, x 10, Billabong Creek Limestone. D, vertical section of SUP 78260 from base of limestone at Goonumbla. E, vertical section of SUP 78259 from limestone at Billabong Creek.


A
B
C
D
E

Genus *Plexodictyon* Nestor 1966

Type species

P. katriense Nestor 1966

Plexodictyon? *cascum* sp. nov.

Fig. 5A-C, 5E

Material

All specimens from Clearview Limestone Member, Ballingoole Limestone (Bowan Park Group); holotype (SUP 78258) from locality at Corner homestead, and paratypes (SUP 77277-79) from Malachi's Hill.

Description

Coenosteum massive with gently undulating laminae having wavelength of from 10-15 mm, to encrusting; holotype 70 mm across and 60 mm high; paratypes (SUP 77277-79) encrust rugose coral *Palaeophyllum*? *patulum* McLean & Webby 1976 (Fig. 5C). Skeletal structure consists of regular, continuous laminae (paralaminae of Nestor) with intervening interlaminar spaces containing irregularly crumpled, zig-zag shaped secondary laminae. Primary laminae number 7 to 9 per 5 mm vertically, usually 0.04-0.1 mm thick; secondary laminae of similar thickness. Shape of galleries round to elongate and crescentic; up to 0.3 mm in height and normally from 0.2 to 1.0 mm in width; occasional larger, elongated galleries where gaps in preservation of tissue along bottom of interlaminar space. Pillars are solid, isolated, vertical to inclined, cylindrical elements in lower part of interlaminar space, but do not cross space; branch and merge with downwardly inflexed secondary laminae to form an irregular meshwork in middle-upper parts of interlaminar space. Astrorhizae not clearly differentiated. Microstructure of laminae and pillars usually consisting of lighter, clear central layer bounded by narrow, darker, speckled margins; also a few areas of coenosteum, especially parts of primary laminae, show single, compact layer; appears likely that entire coenosteum originally exhibited a compact microstructure.

Remarks

The species is not positively assigned to the genus *Plexodictyon* Nestor 1966, because of doubts about the original nature of its microstructure. Also, Silurian species of *Plexodictyon*, except for *P. latilaminatum* (Bogoyavlenskaya, 1965) from the Ludlow of the Urals, tend to exhibit more rows of crumpled secondary laminae (3-6, according to Nestor, 1966) than in *P.*? *cascum*. The genus *Plexodictyon* has hitherto been restricted to rocks of Ludlow age (Nestor, 1966; Stearn, 1969; Bogoyavlenskaya, 1973).

Another, finer *Plexodictyon*-like form, found by I. G. Percival from the 'E' horizon of the middle part of the Cliefden Caves Limestone in the Licking Hole Creek area, and associated with *Ecclimadictyon nestori*, has a compact microstructure. It comes from the lowest level at which clathrodictyids occur in the N.S.W. succession (Fig. 1). As seen in vertical section (Fig. 5D), primary laminae are spaced 4-6 per 2 mm vertically; a few primary laminae are not persistent laterally, and appear to merge into crumpled zones of secondary zig-zag laminae; there is also a little irregularity in spacing of some primary laminae traced laterally. Thickness of laminae is from 0.03-0.05 mm. The interlaminar spaces are infilled by 1-3 rows of typical, very fine, zig-zag secondary laminae of the *Ecclimadictyon nestori* type. Pillars appear to merge into downwardly inflexed secondary laminae. Galleries from 0.1-0.2 mm high and 0.1-0.5 mm wide. No astrorhizae seen to be present.

A typical representative of *Plexodictyon* occurs in the New South Wales Silurian. It is *P. conophoroides* (Etheridge 1921) from the late Silurian of the Trundle area.

Whether the Ordovician representatives are homeomorphs, or ancestors of the Ludlow species of *Plexodictyon* remains uncertain. While similar gross structures may develop at different times and from different ancestors in the history of stromatoporoids (Stearn, 1966, p. 92), in this example, the same or similar *Ecclimadictyon* stock must have given rise to both the late Ordovician *Plexodictyon*-like forms and the late Silurian representatives. The *Plexodictyon*-type structure may have evolved from *Ecclimadictyon* twice or, as seems more likely, once, with the genus *Plexodictyon* having a more extended stratigraphic range from late Ordovician to late Silurian than previously thought (Nestor, 1966; Stearn, 1969; Bogayavlenskaya, 1973).

ACKNOWLEDGEMENTS

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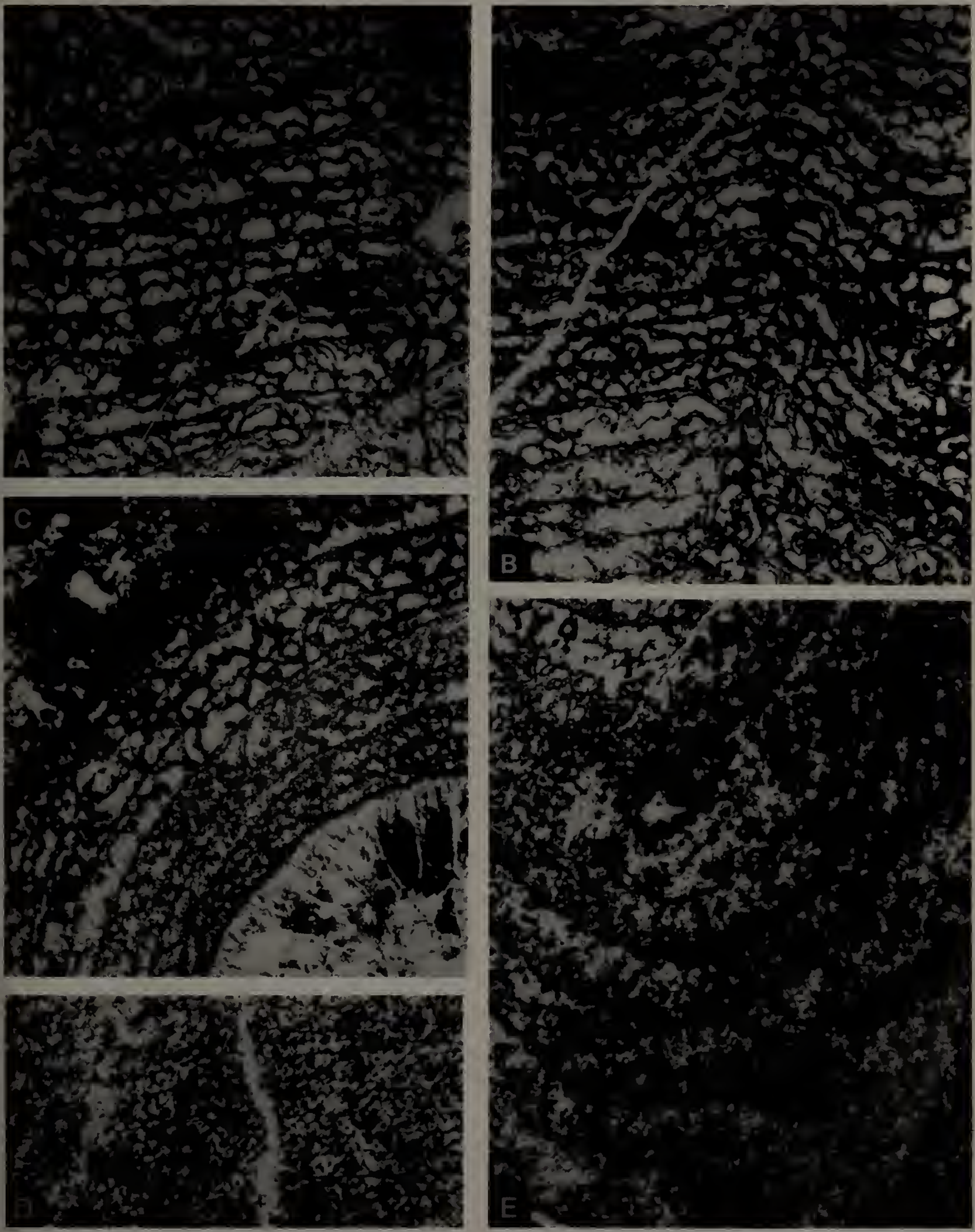
Fig. 5. A-C and E, *Plexodictyon*? *cascum* sp. nov. x 10. A-B holotype SUP 78258, vertical sections. C, paratype SUP 77277, vertical section of *P.*? *cascum* encrusting rugosan *Palaeophyllum patulum* McLean and Webby 1976. E, holotype SUP 78258, tangential-oblique section.
D, *Plexodictyon*? sp., x 10, SUP 77282, vertical section.


A
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Coordination, Topology and Structure in Transition Metal Oxides

RAYMOND L. MARTIN

ABSTRACT. The role of defects in the real structure of transition metal oxides which exhibit gross departures from simple stoicheiometries is reviewed. The classical notion of a randomized distribution of non-interacting point defects is no longer tenable being replaced by the emerging recognition that a high level of organization into discrete clusters or more extended assemblies of defects is an inherent feature of the real structure of defect solids. The concept of octahedral coordination of vacant oxygen sites, taken in conjunction with topological analysis, is shown to contribute considerable insight into the transformational and structural relationships between defect oxides of the fluorite type.

INTRODUCTION

It is a distinction indeed to be invited by the Royal Society of New South Wales to be their Liversidge Research Lecturer. The Lectureship honours Professor Archibald Liversidge who profoundly influenced the development of science in Australia. During a career of remarkable distinction he was appointed to the Chair of Chemistry and Mineralogy in Sydney at the age of 24 and was elected to the Fellowship of the Royal Society (London) at 34. He founded the Australasian Association for the Advancement of Science, the Faculty of Science, and the School of Mines in the University of Sydney and was the driving force behind the advancement of the Royal Society of New South Wales for many decades.

The field which I wish to evaluate this evening, structural inorganic chemistry of the solid state, has its origins in mineralogy. This is an appropriate association because Liversidge, as Professor of Chemistry and Mineralogy, brought together the greater part of the non-Australian mineral and geological collection at the Australian Museum in Sydney and published a significant survey of the minerals of New South Wales in 1888.

All crystalline solids contain imperfections. Semi-conduction, thermo-electric effect and transistor technology provide familiar examples of electronic properties which have their origin in deviations from perfect crystalline order. Oxides of the transition metals range from those which deviate from ideal stoicheiometric composition by an amount which is imperceptible chemically to those where departures from stoicheiometry are gross. Reduction in miniscule of TiO_2 yields $TiO_{1.9986}$ where the concentration of point defects could hardly exceed 10^{-4} (Bursill *et al.*, 1970); reduction in majuscule of CeO_2 yields the sesquioxide $CeO_{1.5}$ where 25% of the anion lattice sites become untenanted. Any theoretical analysis of thermodynamic equilibrium, transport and diffusion, reactivity, electronic and other properties of solids can only be based on an understanding of the structural role of defects and the nature of their interactions.

In this lecture attention will be directed to non-stoicheiometric oxides which possess structures either of the rock salt (NaCl) or the fluorite (CaF_2) type with emphasis on the means by which quite high concentrations of point defects are assimilated by the host lattice. If one considers a regular two-dimensional array with imperfections (*e.g.*, vacant lattice sites in Fig.1), the essential problem is to ascertain whether these are distributed randomly or are correlated in position.

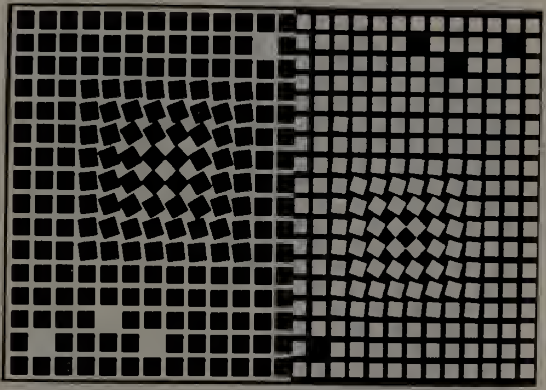

Figure 1. Point defects (vacant sites) introduced into ordered two-dimensional lattice array (with apologies to Victor Vasarely).

RANDOM *versus* ORDERED DEFECTS

At extremely low concentrations of point defects, the classical model (Schottky and Wagner, 1930) assumes that interactions between them are absent so that their distribution is random and the change in configurational entropy of the crystal is that for ideal mixing of the defects. However, as

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**The Liversidge Research Lecture, delivered before the Royal Society of New South Wales, 15th July 1976.*

the concentration of randomized point defects becomes higher, an increasing proportion of defects will move into juxtaposition so that the structural and thermodynamic implications can no longer be ignored. In a real crystal, interactions between point defects is present and the tendency for them to become ordered has important structural consequences (Bursill *et al.*, 1970). The traditional notion of randomized point defects as a basis for explaining gross departures from simple stoicheiometry must be abandoned and replaced by the concept of "correlated defects" as intrinsic structure-determining elements of the defective solid.

Ordering of Defects: Superstructure and Coherent Intergrowth

The structural consequences of correlation between interacting defects is exemplified by the monoxides of first-row transition metals (*e.g.*, Ti, V and Fe) which are derived from the rock salt structure. Although existence of the non-stoicheiometric δ-phase ($TiO_{0.7}-TiO_{1.25}$) has been recognized since 1939, evidence for the nature of the real defect structure of titanium oxides in this composition region was forthcoming only after a combined attack by the methods of electron microscopy, electron and X-ray diffraction some thirty years later (Watanabe *et al.*, 1970). Below 1000°C there are two distinct ordered phases at composition $TiO_{1.00}$ and $TiO_{1.25}$, the structures of both being superlattices based upon the rock salt type, with every occupied lattice site assignable to a site of the parent structure (Fig.2a).

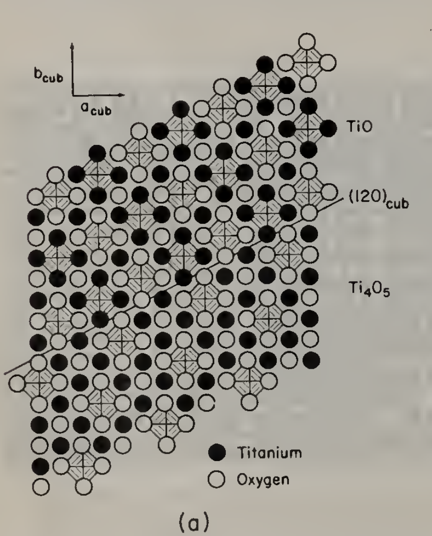


Figure 2. (a) The idealized structures of ordered TiO and Ti_4O_5 coherently intergrown across a $(120)_{cub}$ plane of rock salt structure; (b) Vacant cation and anion sites are octahedrally coordinated by oxygen and metal atoms respectively, and occur as extended strings of composition $\square_M O_5$ and $\square_O M_5$ to yield $Ti_{5/6}O_{5/6}$.

Surprisingly, the "stoicheiometric" phase $TiO_{1.00}$ is grossly non-stoicheiometric, the interpenetrating face-centred cubic (f.c.c.) arrays of titanium and oxygen having one-sixth of each type of atom formally missing, *i.e.*, $Ti_{5/6}O_{5/6}$. The vacant cation and anion sites are octahedrally coordinated by oxygen and titanium atoms respectively, the octahedra sharing *trans*-apices to yield extended strings of composition $\square TiO_5$ and $\square OTi_5$ (Fig.2b). In the oxygen-rich $TiO_{1.25}$, the high concentration of defects (∿20%) is confined solely to the cation sublattice, *i.e.*, $Ti_{4/5}O$. The structure is composed of extended $\square TiO_5$ strings blended with four titanium atoms giving the observed composition (Fig.2a). Interactions of point defects in both phases have led to the development of extended regions of long range order, *i.e.*, the generation of a superlattice of the rock salt structure.

There is a close relationship between the structural elements of the $TiO_{1.00}$ and $TiO_{1.25}$ phases which make them dimensionally compatible so that intergrowth between them can occur coherently at a common, defect-free $(120)_{cub}$ planar interface (Fig.2a). For oxides with compositions intermediate between $TiO_{1.00}$ and $TiO_{1.25}$, prolonged annealing generates lamellae comprised of alternate thin layers of the two boundary phases in the appropriate proportions.

Although the point defects are located at lattice sites of the parent rock salt structure, they are ordered geometrically so that the repeat unit of the new structure is larger than that of the parent and of lower symmetry. In a formal sense, the binary phases $TiO_{1.00}$ and $TiO_{1.25}$ can be regarded as a ternary system (anion, cation, defect), the defect being incorporated as the third component of the superstructure.

Ordering of Defects: Clusters

In the case of FeO, interactions between defects promote their organization into complex groups of correlated defects. This aggregate of defects or "cluster" becomes the new structural entity on which periodicity in the superstructure is based.

Ferrous oxide (rock salt type structure) is thermodynamically stable only above 570°C. Under ambient conditions the f.c.c. oxygen sub-lattice remains essentially complete but the cation sublattice is deficient of iron in the range $Fe_{0.85}O-Fe_{0.95}O$. To maintain electrical neutrality in the defect oxide, there are necessarily two Fe^{3+} ions for each vacant cation site,

$$2Fe^{2+} + \tfrac{1}{2}O_2 = 2Fe^{3+} + O^{2-} + \square_{oct} \qquad (1)$$

Since the ligand field stabilization of energy of Fe^{3+} (high-spin $3d^5$) in an oxygen lattice is zero, it has no preference for substitutional (octahedral) as opposed to interstitial (tetrahedral) sites. Indeed, magnetic neutron scattering and X-ray crystallographic studies establish that a substantial fraction of Fe^{3+} cations migrate to tetrahedral interstitial sites (Koch *et al.*, 1969),

$$Fe^{3+}_{oct} = Fe^{3+}_{tet} + \square_{oct} \qquad (2)$$

The two types of point defect, $\square_{oct}$ and Fe^{3+}_{tet}, interact strongly and coalesce to form a defect cluster comprising four tetrahedrally coordinated iron(III) atoms and thirteen octahedral vacant cation sites (Fig.3a). The $\{(Fe_4\square)\square_{12}\}$ clusters being dimensionally compatible, can intergrow coherently with defect free regions of the host

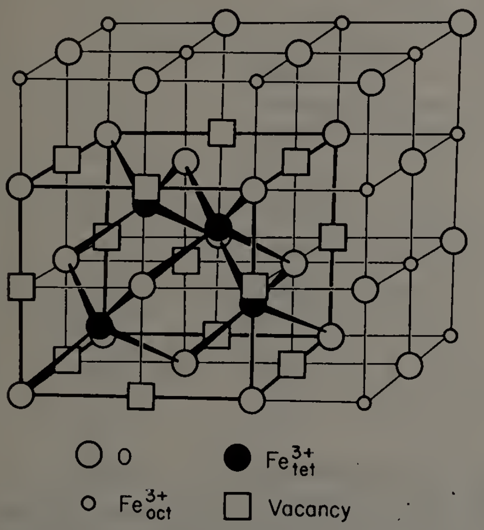


Figure 3. Fe_{1-x}. Koch-Cohen cluster comprising four tetrahedral iron atoms surrounded by thirteen vacant sites in rock salt structure;

rock salt structure. The structure of the cluster is much more complex than a simple aggregation of cation vacancies. It arises from both an aggregation process and a local modification of the rock salt matrix, and represents, indeed, the complete transformation of the contents of one unit cell of NaCl structure into one unit cell of zinc blende (ZnS) structure which is dimensionally compatible, both having f.c.c. anion lattices (Fig.4).

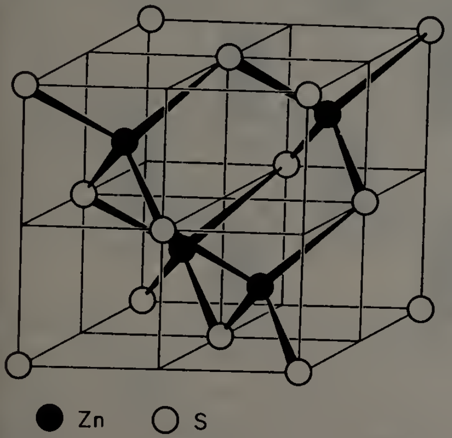


Figure 4. Zinc blende structure.

The clusters themselves tend to order under coulombic forces to develop a superstructure. The composition and configuration of this defect cluster is reminiscent of the polynuclear coordination compound, basic zinc(II) acetate, $\{Zn_4O(CH_3CO_2)_6\}$ (Koyama *et al.*, 1954).

Defect Elimination: Crystallographic Shear

The early transition metals in higher oxidation states (Ti^{4+}, V^{4+}, Nb^{5+}, Mo^{6+}, and W^{6+}) preserve octahedral coordination of the central metal ion in their binary oxides. Even though reduction of the metal to a lower oxidation state involves the removal of oxygen from the parent lattice, unlike rock salt and fluorite-type oxides, vacant anion sites are not retained in the non-stoicheiometric phase. Rather, the stoicheiometric change is accommodated by the elimination from the crystal of a complete plane of anion sites followed by a formal structural operation, crystallographic shear (CS), which restores octahedral coordination about the metal ion (Anderson *et al.*, 1967). There is a concomitant increase from two to three in the number of metal atoms coordinated to certain oxygen atoms. For example, the regular elimination of the CS plane (120) of oxygen atoms in MoO_3 (ReO_3 structure type; Fig.5a).

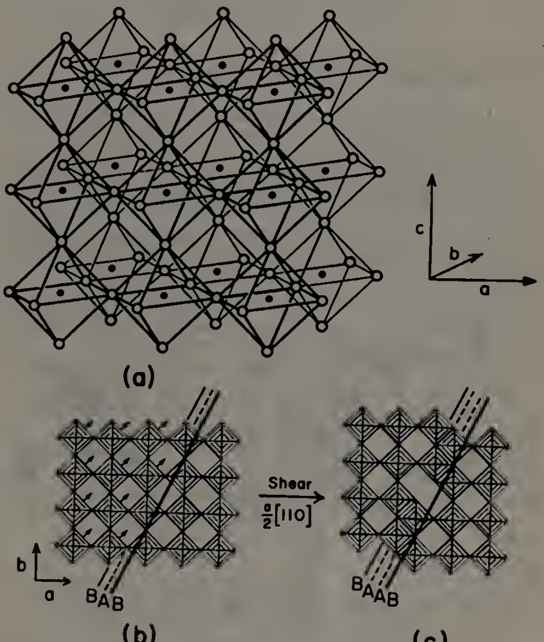


Figure 5. (a) ReO_3 structure type; (b) ReO_3 represented as apex-sharing ReO_6 octahedra and projected on the (011) plane; (c) formation of CS plane which occurs in Mo_8O_{23}.

generates the non-stoicheiometric oxide Mo_8O_{23}, the first member of the homologous series of ordered oxides M_nO_{3n-1} where $8 \leq n \leq 12$ (Fig.5c). In the MoO_3 parent (Fig.5b), the sequence of planes parallel to (120) is

····ABABAB····

(A = MoO_2; B = O). The regular removal of every *n*th B-plane of oxygen atoms from the parent structure yields the homologue of generic formula $(MoO_2)_nO_{n-1}$; *i.e.*, Mo_nO_{3n-1} (Fig.5c). The elimination of anion vacancies by crystallographic shear is also common in ordered phases based on the rutile (TiO_2) structure (*cf.* Table 1).

TABLE 1
CRYSTALLOGRAPHIC SHEAR IN THE ReO_3 AND TiO_2 STRUCTURES*

Parent Structure	Orientation of CS Plane	Series Formula	n	Examples
ReO_3	(100)	M_nO_{3n-1}	2	R-Nb_2O_5
			3	Nb_3O_7F
	(130)	M_nO_{3n-2}	20, etc.	$W_{20}O_{58}$, etc.
	(120)	M_nO_{3n-1}	$8 \leqslant n \leqslant 12$	Mo_8O_{23}
Rutile	(121)	M_nO_{2n-1}	$4 \leqslant n \leqslant 9$	Ti_4O_7—Ti_9O_{17}
				V_4O_7—V_9O_{17}
	(132)	M_nO_{2n-1}	$16 \leqslant n \leqslant 36$	$Ti_{16}O_{31}$—$Ti_{36}O_{71}$

*After Anderson (1974).

NON-STOICHEIOMETRIC OXIDES OF FLUORITE TYPE

In the terms of his bequest, Liversidge specified that emphasis "shall be upon recent researches and discoveries.....". Accordingly, I will now discuss some new concepts concerning the nature of defect solids of the fluorite type.

A distinguishing feature of the oxides of the early transition metals in high oxidation states (Ti^{4+}, V^{5+}, Nb^{5+}, Ta^{5+}, Mo^{6+}, W^{6+}) discussed earlier, is that the MO_6 coordination polyhedron remains intact in oxides which depart from a simple stoicheiometry. The oxygen lattice remains invariant in these phases and deviations in composition from the elementary MO_2 or MO_3 stoicheiometry are brought about by peripheral corner- or edge-sharing of the MO_6 octahedra. As we have seen, this enables the structure of compounds with complex compositions to be illustrated with precision in two dimensions by employing the conventional projections of an idealized MO_6 octahedron (Fig.5). Indeed, in favourable circumstances, the metal-centred octahedra are revealed directly by lattice imaging techniques in the electron microscope (Allpress, 1969) and this has produced new and deep insights into the real structure of the non-stoicheiometric oxides of the early transition metals (Allpress *et al.*, 1969).

A parallel development in the depth of our understanding of the nature of the defect oxides of the lanthanide and actinide elements and some of the larger transition metals (*e.g.*, Hf^{4+}, Zr^{4+}) has not been forthcoming. There are a number of reasons why their structural characterization has remained elusive. Oxygen can be transferred with extraordinary ease between the MO_x lattice and the ambient gas phase, even at relatively low temperatures (200-300°C) so that the synthesis of well-ordered crystals is inherently difficult (the remarkably high oxygen mobility inhibits the quenching-in of both composition and crystallographic order in samples equilibrated at even moderate temperatures). Of course, it is just this feature which leads to the hopeful expectation that fluorite-type oxides can be developed into successful refractory electrodes for fuel cells and other other technological uses. Although very small crystals of non-stoicheiometric praseodymium oxides have been grown by hydrothermal techniques, problems of crystallographic twinning, coherent intergrowth between homologous phases, absorption errors and large superstructures of low symmetry have all combined to make studies, even with single crystals, a formidable task.

The technique of lattice imaging, which has proved to be so incisive for CS structures which involve interstitial heavy metal atoms, does not produce the same marked contrast in images of the fluorite oxides. However, in the case of $Tb_{11}O_{20}$ periodicities imposed on the structure by oxygen vacancies appear to have been discerned in the bright field image (Kunzmann *et al.*, 1975). The vacancies are not imaged directly but the periodicity which they impose on the potential field may be discerned in the image.

Because of these difficulties, current efforts are being directed towards the neutron profile technique and the determination of superstructure lattice parameters from electron diffraction patterns taken in a high resolution transmission electron microscope from very small single crystals (average size; 1 µm). This enables the unit cell dimensions and possible space groups of the intermediate phases as well as the transformation matrices to be defined in terms of the fluorite substructure.

In defect oxides of the fluorite structure type (Table 2), the non-stoicheiometry is accommodated on untenanted anion sites, the cation sub-lattice remaining essentially intact. The central problem is to ascertain the superstructural pattern which reflects the ordering of anion vacancies in order that underlying structural principles may be defined. Unfortunately, the coordination sphere of the metal atom in dioxides such as CeO_2, HfO_2 and UO_2 is comprised of a cube of oxygen anions which precludestwo-dimensional projection of MO_6 octahedra along 2-, 3- and 4-fold axes which have proved to be so illuminating for TiO_2 or ReO_3 based structures. Attempts to represent the fluorite structure by the edge-sharing of MO_6 polyhedra are cumbersome(Fig.6) and provide

TABLE 2
SOME ORDERED FLUORITE TYPE OXIDES

Composition	Binary Oxides	Ternary Oxides
$M_{2.00}$	CeO_2, PrO_2, TbO_2, HfO_2, ThO_2, PaO_2, UO_2, NpO_2, PuO_2, AmO_2, CmO_2, BkO_2	
$MO_{1.857}$		γ-$Zr_{10}Sc_4O_{26}$
$MO_{1.833}$	β-$Pr_{12}O_{22}$	
$MO_{1.818}$	$Ce_{11}O_{20}$, δ-$Pr_{11}O_{20}$, $Tb_{11}O_{20}$	
$MO_{1.800}$	$Ce_{10}O_{18}$, ε-$Pr_{10}O_{18}$	ϕ_1-$CaHf_4O_9$
$MO_{1.778}$	Ce_9O_{16}, ζ-Pr_9O_{16}	ϕ-$Ca_2Hf_7O_{16}$
$MO_{1.760}$		ϕ_2-$Ca_6Hf_{19}O_{44}$
$MO_{1.750}$		pyrochlore, $La_2Ti_2O_7$, $Gd_2Zr_2O_7$
$MO_{1.714}$	Ce_7O_{12}, ι-Pr_7O_{12}, Tb_7O_{12}	UY_6O_{12}, $Zr_3Sc_4O_{12}$, $Zr_3Yb_4O_{12}$
$MO_{1.667}$	κ-Pr_6O_{10}	Sr_2UO_5, Cd_2UO_5
$MO_{1.600}$		
$MO_{1.50}$	Y_2O_3, Pr_2O_3, Sb_2O_3, β-Bi_2O_3, bixbyite(α-Mn_2O_3), In_2O_3, Te_2O_3	

only limited insight into the distribution of vacancies in oxides which deviate from elementary MO_2 composition (Sawyer *et al.*, 1965).

In an attempt to circumvent this problem, we can depart from our conventional metal-centred frame of reference and contemplate the fluorite lattice in terms of its anion-centred polyhedra (Martin, 1974). Examination of the MO_2 structure reveals that each oxide anion is coordinated tetrahedrally by four cations to form an octant of the fluorite cube with the composition $M_{0.5}O$. Eight such octants arranged in juxtaposition generate the fluorite unit cell of composition M_4O_8 and edge length a_F. A single layer of octants can be represented conveniently in projection by employing the square matrix illustrated in Fig.7 with oxygen sites envisaged at the centre of each square.

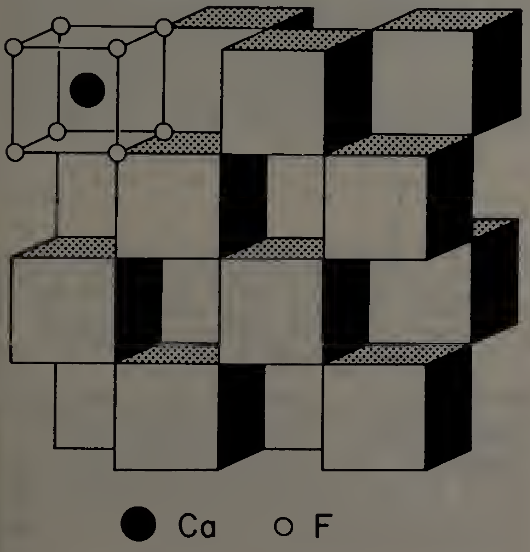


Figure 6. Fluorite structure represented as edge-sharing MO_8 cubes.

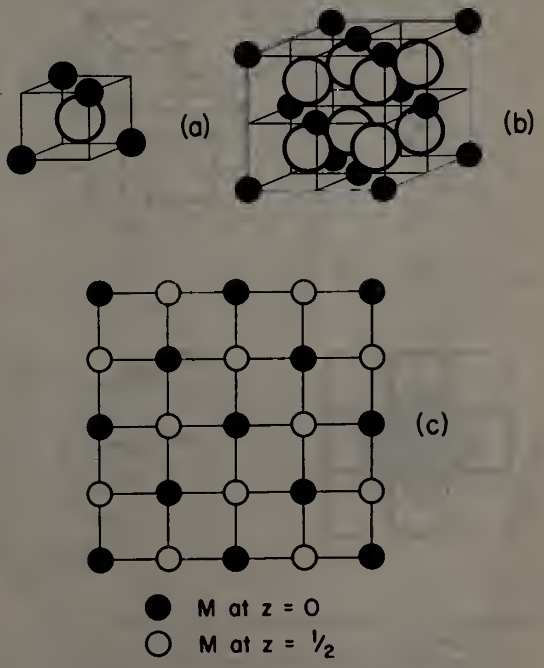


Figure 7. Fluorite structure. (a) octant of composition $M_{0.5}O$; (b) unit cell (8 octants) of composition M_4O_8; (c) matrix representation for layer of 16 octants (composition M_8O_{16}).

Non-stoicheiometric oxides MO_x (*cf.* Table 2) with compositions in the range $1.5 \leqslant x \leqslant 2.0$ result from the removal of oxygen from octant centres leaving vacant anion sites according to the equation:

$$\begin{aligned} 4M^{4+} + O^{2-}/\square_{an} \longrightarrow\ & 4M^{4+} + 2e^{-}/\square_{an} + \tfrac{1}{2}O_2 \\ & \quad \upharpoonleft\!\downharpoonright \\ & 2M^{4+} + 2M^{3+} + \square_{an} + \tfrac{1}{2}O_2 \end{aligned} \tag{3}$$

where the symbol $\square_{an}$ denotes an anion site denuded of oxygen. For binary oxides (CeO_x) imbalance between anionic and cationic charge is accommodated by changing proportions of the two oxidation states, Ce^{3+} and Ce^{4+}. Kinetic barriers to configurational rearrangements in binary oxides are small since inequalities of charge can be redistributed readily by electron transfer between metal cations. On the other hand, electron hopping between aliovalent ions (*i.e.*, solute cations of different oxidation state from the corresponding solvent cation) in ternary oxides such as CaO/ZrO_2 is precluded and the activation energy to ordering processes may be considerable. In these circumstances the distribution of aliovalent cations will pre-determine the location of the compensating defects in the anion sub-lattice.

The Coordination Defect: Topological Analysis

There are several single crystal X-ray structure determinations of fluorite type oxides which are of sufficient accuracy to confirm that every anion vacancy is circumscribed by the six nearest neighbouring oxygen atoms which are contracted inwards as though under the influence of a polarizing positive charge. In other words, the point defect $\square$ appears to have no independent existence but, in its coordinated state $\square O_6$ (Fig.8a), becomes a structural entity which places effective limitations on the number of alternative ways in which a given anion deficiency can be accommodated by the parent lattice. Furthermore, by employing our unconventional anion-centred reference frame, we can now depict a vacant anion site by the conventional projection of an octahedron along its four-fold symmetry axis (Fig.8c).

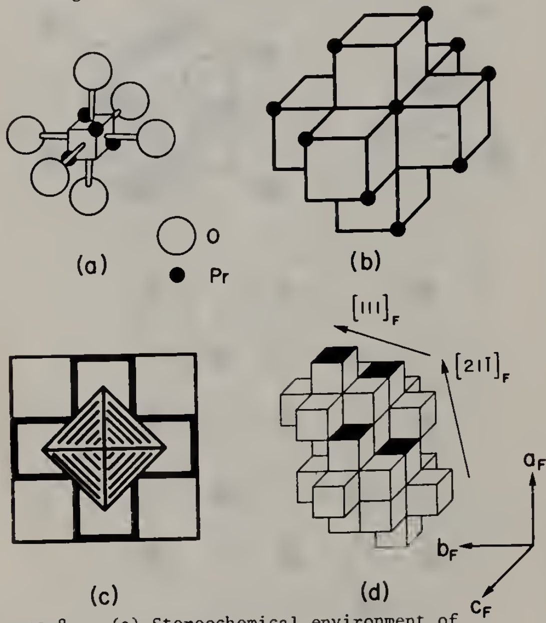


Figure 8. (a) Stereochemical environment of vacant anion site; (b) topology of coordination defect with composition $M_{3.5}\square O_6$; (c) octahedrally coordinated anion vacancy $\square O_6$ in projection on fluorite matrix; (d) cluster of four c.d's occurring in ι-Pr_7O_{12} showing important directions.

Before proceeding to explore the structural role played by the coordinated vacancy, $\square O_6$, it is necessary to establish its topology and chemical composition. Since the cation sub-lattice remains intact, the true coordination defect (c.d.) is comprised of the seven octants illustrated in Fig.8b which circumscribe the anion vacancy and each of its six nearest O^{2-} neighbours. The overall composition of the c.d. is $M_{3.5}\square O_6$ and its unique topology is consequent on the octahedral distribution of the six encapsulating octants.

In order to construct an oxide phase based on closest packing of c.d's, they need to be aligned in rows parallel to the $[0\bar{2}1]_F$ direction (Fig.9).

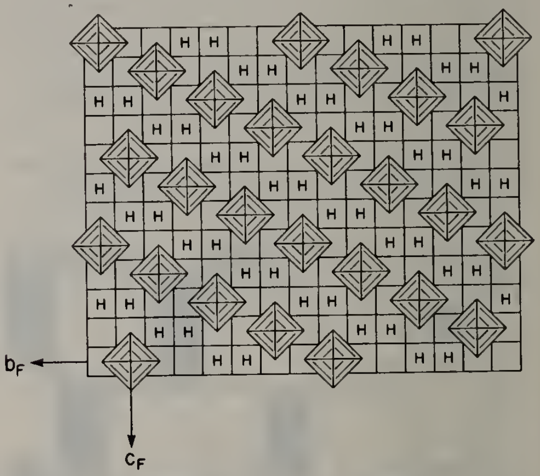


Figure 9. Idealized square-matrix representation of a $(100)_F$ layer of the fluorite lattice showing the location of vacant oxygen sites in ι-Pr_7O_{12} along $[0\bar{2}1]_F$ and $[0\bar{1}\bar{3}]_F$ directions. Mating holes for accommodating contiguous layers are designated by H.

Two mating holes (H) per octant must be incorporated in each $(100)_F$ layer to enable the topological requirement of c.d's in contiguous layers to be accommodated. The three-dimensional assembly of c.d's is uniquely determined by their topology and since it is space filling (Fig.8d), the overall composition of the phase is M_7O_{12} which corresponds to ~14% of untenanted anion sites.

A number of binary and ternary oxide phases with this composition are known (*e.g.*, ι-Pr_7O_{12}, $Zr_3Sc_4O_{12}$, $Zr_3Yb_4O_{12}$, ULu_6O_{12} and UY_6O_{12}) and in each case their structure conforms with that deduced from the above topological considerations. Since each vacancy along $[0\bar{1}\bar{3}]_F$ is related to another by the vector $\tfrac{1}{2}[21\bar{1}]_F$, they are gathered on oblique $(23\bar{1})_F$ planes and occur as metal-centred pairs in rows along the $[111]_F$ direction (Fig.8d). The detailed nature of the superstructure emerges clearly if the vacant anion sites in a $(111)_F$ plane of the ι-Pr_7O_{12} structure (Von Dreele *et al.*, 1975) are delineated by their oxygen polyhedra (Fig.10).

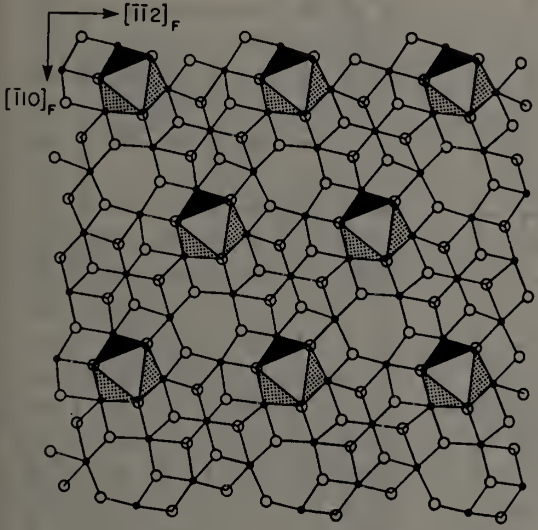


Figure 10. Section of ι-Pr_7O_{12} structure perpendicular to $[111]_F$ axis. Arrangements of vacant anion sites in a $(111)_F$ layer is shown by their coordination octahedra.

Attempts to visualize the planar ordering of vacancies in terms of the metal-centred representation of Fig.6 are less effective, the paired c.d. $M_7O_{12}\square_2$ having to be replaced by the much larger M_7O_{36} defect cluster (Thornber *et al.*, 1968) comprising the six MO_6 polyhedra (white cubes) which share edges with a central MO_6 polyhedron (black cube) which has a pair of vacant oxygen sites disposed across its [111] body diagonal (Fig.11).

In addition to $Zr_3Sc_4O_{12}$, there is a second more oxidized but closely related phase, γ-$Zr_{10}Sc_4O_{26}$, which occurs in the ZrO_2-Sc_2O_3 system. Once again, the vacant anion sites (7%) are ordered and structural features in common emerge when the distributions of coordination defects are viewed on an $(01\bar{1})_F$ plane (Fig.12). In both rhombohedral structures, the vacant anion sites lie along the $[111]_F$ direction occurring always as metal-centred pairs. The difference in composition between the two phases is seen to arise from the periodic annihilation along $[111]_F$ of a pair of c.d's by substitution of a pair of fluorite $Zr_{3.5}O_7$ entitites of identical topology which generates the composition of the γ-phase; *viz.*,

$$Zr_3Sc_4O_{12}\square_2 + Zr_7O_{14} = Zr_{10}Sc_4O_{26}\square_2 \quad (4)$$

Ternary oxides of the pyrochlore type (naturally occurring mineral, $CaNaNb_2O_6F$) also have interesting electrical, magnetic and refractory properties. This cubic M_4O_7 structure may be related to fluorite by deleting one-eighth of the anions in an ordered manner, the ternary oxides $La_2Ti_2O_7$ and $Gd_2Zr_2O_7$ providing examples (Table 2). Alternatively the pyrochlore composition can be achieved by incorporating one fluorite octant ($M_{0.5}O$) per c.d. into the close-packed assembly which comprises the M_7O_{12} phase; *viz.*,

$$M_{3.5}\square O_6 + M_{0.5}O = M_4\square O_7 \quad (5)$$

It is generally found that the larger M^{3+} cation lies at the centre of a deformed MO_8-cube while the smaller M^{4+} cation occupies the centre of a $MO_6\square_2$ cube where the missing anions lie along a [111] body diagonal. The resulting ordered arrangement of vacant anion sites in a $(100)_F$ layer is illustrated in terms of c.d's in Fig.13.

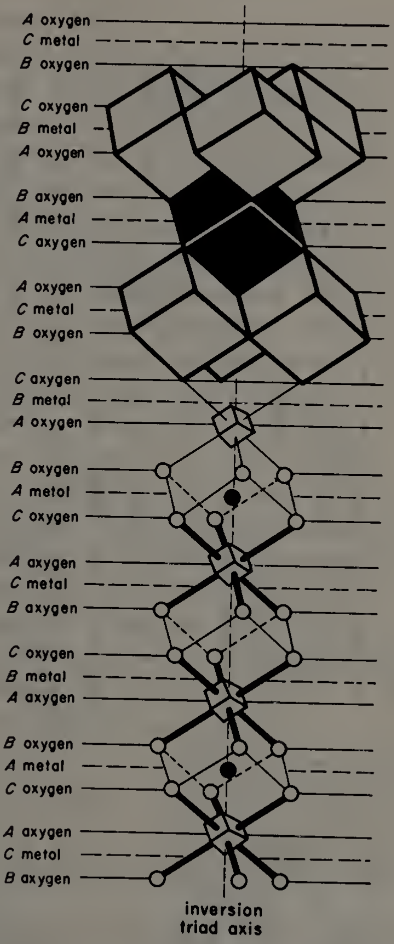


Figure 11. M_7O_{36} defect cluster and the octahedrally coordinated anion vacancies $\square O_6$ delineated along the same $[111]_F$ axis.

Homologous Series and Crystallographic Shear in Lanthanide Oxides

Several rare earth elements exhibit variable valency; in particular, cerium, praseodymium and terbium form both a tervalent and tetravalent sesquioxide M_2O_3 and dioxide MO_2. In the intervening composition regions $MO_{1.5}$—$MO_{2.0}$, the phase diagram (Fig.14) reveals a rich variety of non-stoicheiometric phenomena (Hyde *et al.*, 1966). At higher temperatures, non-stoicheiometric disordered

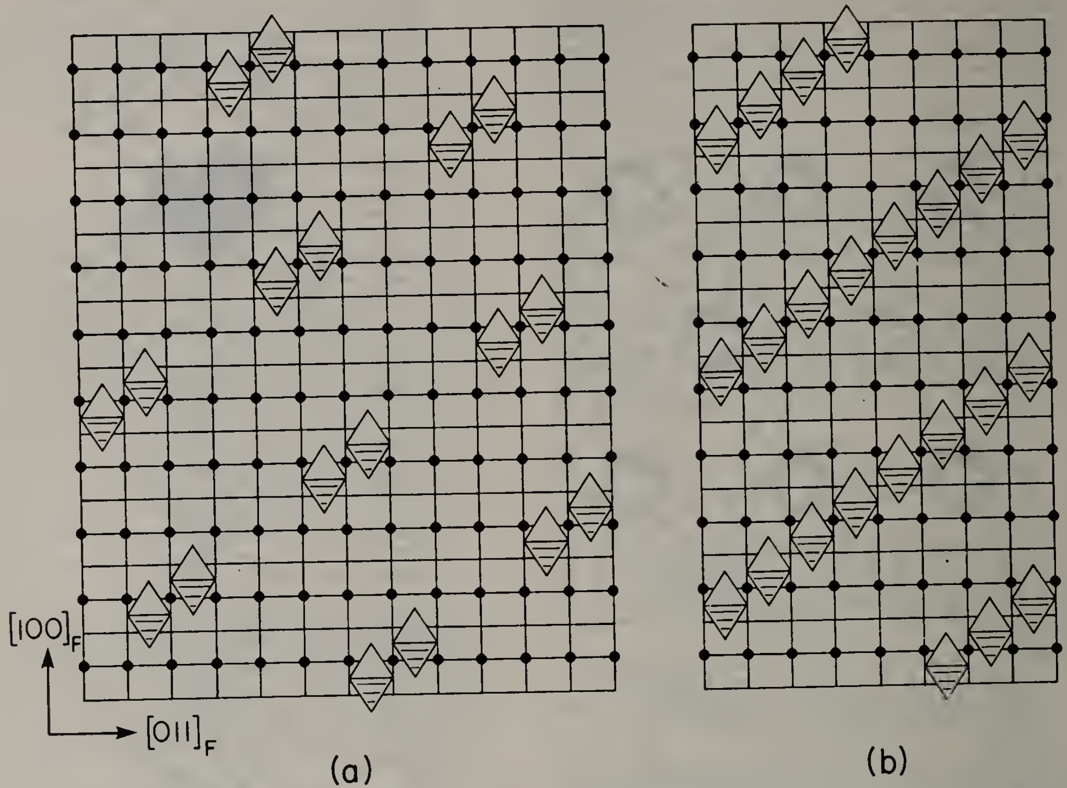


Figure 12. Structure of (a) $Zr_{10}Sc_4O_{26}$ and (b) $Zr_3Sc_4O_{12}$ shown on $(01\bar{1})_F$ planes. Note metal-centred pairing of c.d's along $[111]_F$ direction.

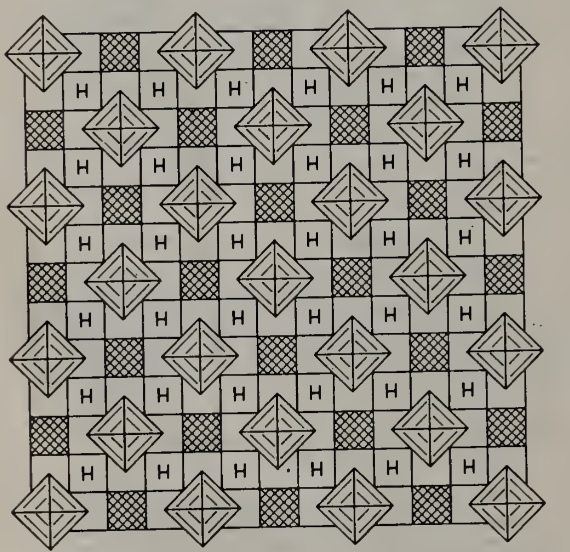


Figure 13. Pyrochlore structure M_8O_{14}. Idealized matrix representation of a $(100)_F$ layer showing location of vacant oxygen sites as c.d's. Additional $M_{0.5}O$ octants are cross-hatched.

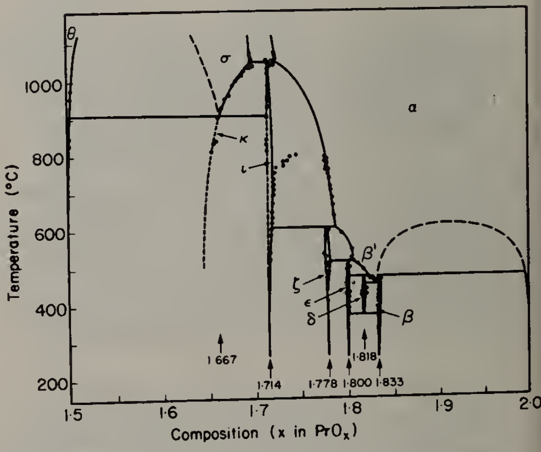


Figure 14. Projection of the PrO_x $(1.5 \leqslant x \leqslant 2.0)$ phase diagram on the temperature-composition plane. Compositions and designations of ordered phases are marked.

phases of widely variable composition MO_x occur. However, at lower temperatures a series of structurally ordered line phases of quite narrow composition range develop. Their composition is well-defined conforming to the homologous series Pr_nO_{2n-2} with n = 6, 7, 9, 10, 11 and 12 (*cf.* Table 2).

The detailed structural characterization of these intermediate phases has remained an elusive problem of significance in understanding the nature of fluorite related defect solids. Although the crystal structures are not known, the dimensions and symmetry of the superlattices have been obtained from high-resolution transmission electron microscopy of micro-crystalline materials (Kunzmann *et al.*, 1975). When combined with the topological restrictions imposed by the c.d., model structures can be devised which possess edge dimensions and directions which bear identical relationships to the parent fluorite structure as do the *a*, *b* and *c* axes of the observed unit cells.

The existence of the Pr_nO_{2n-2} series derives from blending y octants of composition $Pr_{0\cdot5}O$ with the c.d. progenitor $Pr_{3\cdot5}\square O_6$ to yield the homologue $Pr_{(3\cdot5+0\cdot5y)}\square O_{(6+y)}$; *i.e.*, Pr_nO_{2n-2} where $n = (y+7)$. This uniform progression suggests that the homologues might be inter-related, at least formally if not mechanistically, through a process of crystallographic shear (Hoskins *et al.*, 1976). The possibility of applying crystallographic shear to an oxygen-centred lattice is an advantage consequent on the persistence of the octahedral $\square O_6$ entity and the invariance of the f.c.c. metal lattice in the fluorite oxides. The crystallographic shear operation can be visualized conveniently by first cutting a drawing of a $(100)_F$ octant layer of ι-Pr_7O_{12} along the trace $[0\bar{3}5]_F$ of a $(1\bar{5}\bar{3})_F$ plane on $(100)_F$ (Fig.15a). The $(100)_F$ layer is now opened up by shearing in the $[0\bar{1}1]_F$ direction to create new oxygen sites. For example, the CS operation $[0\bar{1}1]_F$ enables two additional $(1\bar{5}\bar{3})_F$ planes of PrO_2 (*i.e.*, y=2) to be inserted coherently into the parent ι-Pr_7O_{12} matrix corresponding to the formation of a sheet of ζ-Pr_9O_{16} (Fig.15c). Similarly, the model which reproduces the unit cell characteristics of the δ-$Pr_{11}O_{20}$ phase can be generated from ι-Pr_7O_{12} by the CS operation $2[0\bar{1}1]_F$ as shown in Fig.14e. In this case, four new $(1\bar{5}\bar{3})_F$ planes of PrO_2 (*i.e.*, y=4) are introduced coherently into the ι-Pr_7O_{12} matrix to generate the composition $Pr_{11}O_{20}$.

The structural repeat units outlined in black in Fig.15 can be stacked along a_F to give triclinic unit cells which reproduce the $\frac{1}{2}[21\bar{1}]_F$ and $\frac{1}{2}[1\bar{1}2]_F$ vectors observed for the *a* and *c* axes of the super-structures respectively. Although the vacancies are grouped again as metal-centred pairs with a local $[111]_F$ axis, the pairs now lie along $[21\bar{1}]_F$ and $[1\bar{1}2]_F$ directions being gathered in $(1\bar{5}\bar{3})_F$ layers.

The CS operations $3/2[0\bar{1}1]_F$ and $5/2[0\bar{1}1]_F$ generate unknown triclinic polymorphs of the known

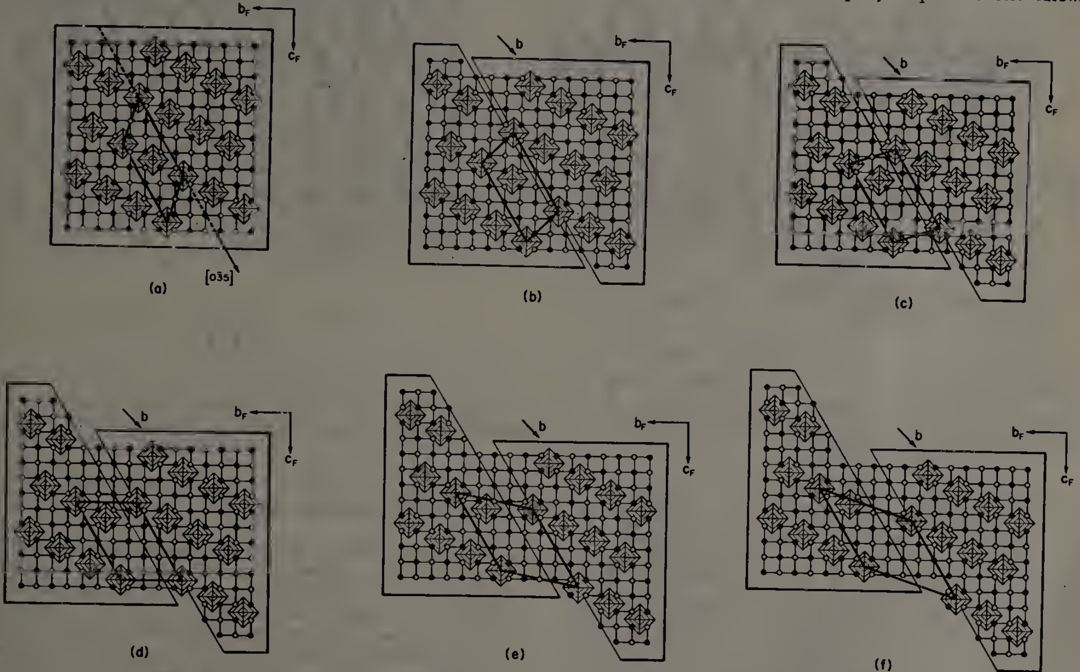


Figure 15. (a) an idealized $(100)_F$ structural octant layer of ι-Pr_7O_{12} showing the line in the $[0\bar{3}5]_F$ direction along which oxygen sites will be created using the shear operation $\frac{1}{2}[0\bar{1}1]_F$. The metal atoms can be regarded as invariant. (b) Formation of $(1\bar{5}\bar{3})$ $\frac{1}{2}[0\bar{1}1]_F$ shear plane corresponding to the production of a $(1\bar{5}\bar{3})_F$ sheet of composition Pr_8O_{14} inserted coherently into the parent ι-Pr_7O_{12} matrix (b = Burgers vector). (c) The formation of a $(100)_F$ octant layer of the ζ-Pr_9O_{16} phase by the incorporation of two additional $(1\bar{5}\bar{3})_F$ anion planes into ι-Pr_7O_{12} using the CS procedure above. (d) Conjectural triclinic modification of $Pr_{10}O_{18}$. (e) δ-$Pr_{11}O_{20}$; observed structural repeat unit outlined in black. (f) Conjectural triclinic modification of $Pr_{12}O_{22}$.

monoclinic homologues ε-$Pr_{10}O_{18}$ and β-$Pr_{12}O_{22}$. This suggests that the structural relationships between the odd- and even-membered phases are likely to be close. This topic has been discussed further elsewhere (Hoskins *et al.*, 1976).

Extended Defects: Corner and Edge-Sharing of Coordination Defects

The structures of $Zr_{10}Sc_4O_{26}$, pyrochlore and the Pr_nO_{2n-2} homologues are based on an ordered distribution of isolated coordination defects padded out with $M_{0.5}O$ fluorite octants. The most reduced fluorite-type structure based on the close-packing of isolated c.d's is M_7O_{12}. Any further reduction inevitably leads to corner- and/or edge-sharing of c.d's if the octahedral coordination about a vacancy is to be preserved (Hoskins *et al.*, 1975). The structures of two ternary phases of composition $MO_{1.667}$ (n=6) have been reported (*cf.*, Table 2) and both conform with the topological expectations of the c.d. model. For example, the structure of monoclinic strontium uranate (Loopstra *et al.*, 1969) involves strings of c.d's along $[100]_F$ which are joined by sharing corners (Fig.16b). The ordered vacancies are contained on every fourth $(01\bar{1})_F$ plane which has the composition $[UO\square]^{4+}$ (*cf.*, Fig.16b). This ordered vacancy plane is sandwiched between two $(01\bar{1})_F$ intact planes of $[SrO_2]^{2-}$ to complete the composition of the phase, Sr_2UO_5. The structure of cadmium uranate (Sterns *et al.*, 1964) is similar; the structure of κ-Pr_6O_{10} is not known.

Although more reduced oxide phases corresponding to n = 5 have not been characterized, there are many examples of metal sesquioxides (*i.e.*, n=4) with structures related to fluorite (*cf.*, Table 2). Examination of the cubic structures of β-Bi_2O_3 and type C-Ln_2O_3 (bixbyite or α-Mn_2O_3 type) has established that both are based on a f.c.c. metal lattice. Furthermore, in both structures, the 25% anions are omitted from fluorite sites in an ordered rather than a random manner. Each vacant oxygen site is surrounded by an octahedron of oxygen atoms so that the integrity of the c.d. remains preserved in these highly reduced phases.

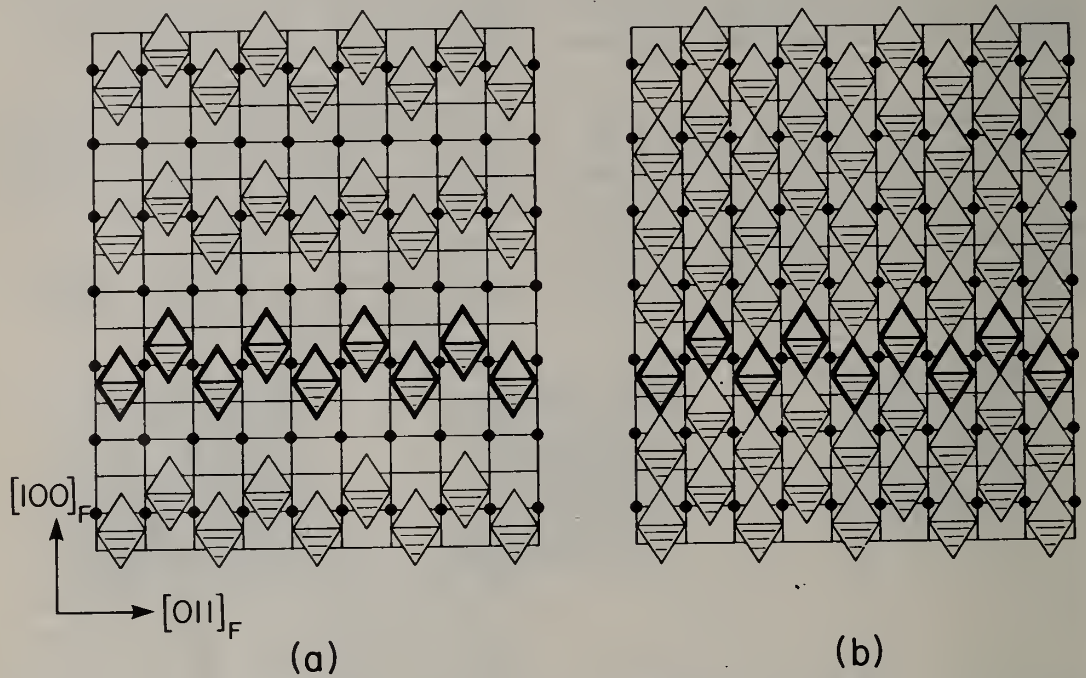


Figure 16. Structure of (a) pyrochlore and (b) Sr_2UO_5 (orβ-Bi_2O_3) on an $(01\bar{1})_F$ plane. The rows of c.d's along $[011]_F$ form "extended defects" (outlined), the anion vacancies being related by either $[111]_F$ or $[1\bar{1}\bar{1}]_F$ metal centred vectors.

In the cubic β-Bi_2O_3 structure (Gattow *et al.*, 1964) each c.d. shares all six apices with neighbouring c.d's to achieve the desired $\square O_3$ stoicheiometry (Fig.17a). The resultant $\square O_{6/2}$ infinite network is reminiscent of the metal-centred ReO_3 lattice (Fig.5a) except that the oxygen vacancies lie at the rhenium atom sites (N.B. there are actually two interpenetrating ReO_3-like sub-lattices in β-Bi_2O_3). If the cubic β-Bi_2O_3 structure is viewed on $(01\bar{1})_F$ planes, the arrangement of vacant anion sites is identical to that found on $(01\bar{1})_F$ planes in Sr_2UO_5 (Fig.16b). Each ordered vacancy plane of composition $[BiO\square]^+$ alternates with an oxygen intact $(01\bar{1})_F$ plane of composition $[BiO_2]^-$ to generate the

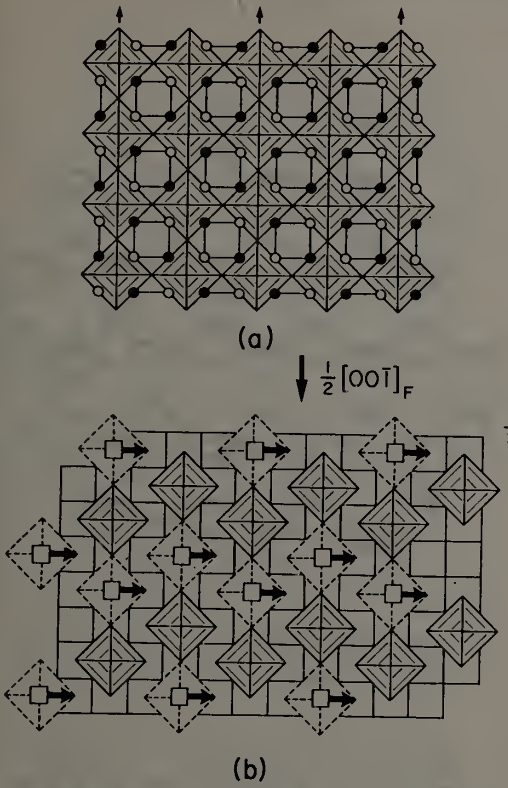


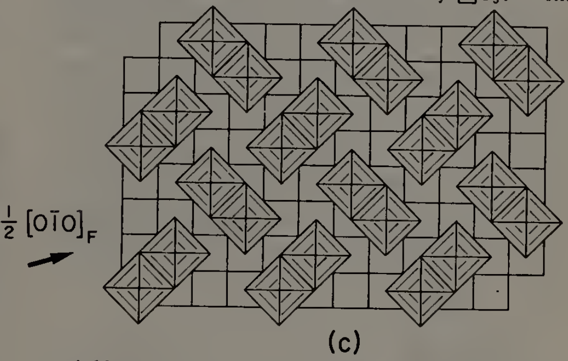
Figure 17. Transformation of β-Bi_2O_3 → type C-M_2O_3. (a) arrangement of c.d's in $(100)_F$ layer of β-Bi_2O_3 structure; (b) $(100)_F$ layer of type D-M_2O_3 generated by *c*/2 slip of alternate $[001]_F$ rows of c.d's in direction arrowed in (a); (c) $(100)_F$ layer of type C-M_2O_3 derived from type D by the *b*/2 slip mechanism depicted in (b).

sesquioxide composition and structure.

A close relationship between β-Bi_2O_3 and the cubic pyrochlore phase M_4O_7 also emerges on $(01\bar{1})_F$. The vacancy containing $(01\bar{1})_F$ plane in pyrochlore contains only one-half the density of vacant sites so that apex sharing between c.d's is no longer involved (Fig.16a). This plane of composition $M_2O_3\square$ alternates with an oxygen intact plane M_2O_4 to generate the pyrochlore composition. The rows of c.d's along $[011]_F$ form an "extended defect" with the anion vacancies being related either by $[111]_F$ or $[1\bar{1}\bar{1}]_F$ vectors. (This "extended defect" was originally termed a "duplex" row of c.d's by Martin, 1974.) These "extended defects" are also a characteristic of Sr_2UO_5 except that corner-sharing between them occurs along $[100]_F$. These transformational relationships correspond to the compositional sequence:

β-Bi_2O_3 ⟷ pyrochlore ⟷ fluorite
$M_{32}O_{48}\square_{16}$ $M_{32}O_{56}\square_{8}$ $M_{32}O_{64}$

The type C-M_2O_3 bears a different relationship to the fluorite structure. It also involves the regular omission of one-quarter of the oxygen atoms, a small distortion of the metal lattice from f.c.c., and a unit cell of b.c.c. symmetry with double the fluorite edge (Paton *et al.*, 1965). Again, every vacant anion site is coordinated by an octahedron of nearest oxygen neighbours to yield an ordered vacancy superstructure based on c.d's. However, unlike β-Bi_2O_3, each $\square_6$ octahedron shares three of its edges with three $\square O_6$ nearest neighbours to achieve the desired stoicheiometry $\square O_3$. These



neighbours, and hence the edges involved, are related by a three-fold symmetry axis passing through the centrally coordinated c.d., all four c.d's being situated on the same $(111)_F$ plane.

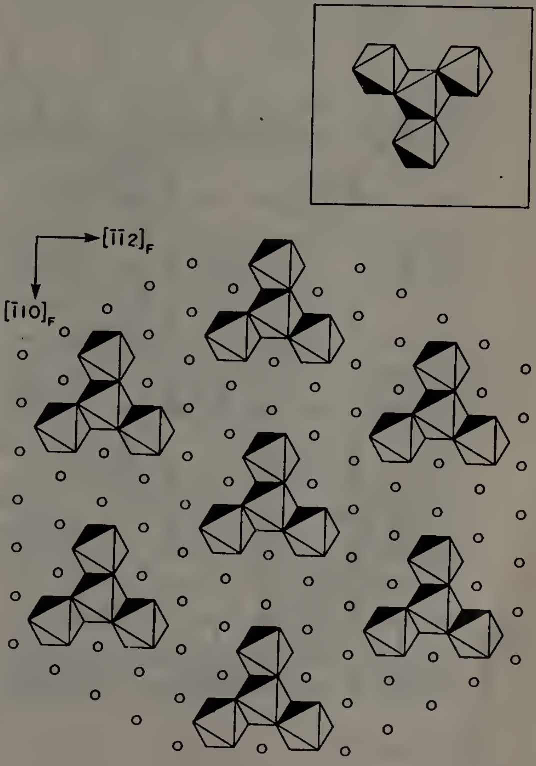


Figure 18. Type C-M_2O_3. Arrangement of vacant anion sites on a $(111)_F$ plane showing their coordination octahedra. The Λ chirality of the Y-shaped clusters in this plane is contrasted with the Δ configuration of adjoining $(111)_F$ planes shown in the inset.

Effectively, each c.d. is "tris-chelated" by its three neighbouring c.d's conferring on it the property of chirality, *i.e.*, Δ and Λ configurations occur in equal proportions in the structure (Hoskins *et al.*, 1975). The arrangement of vacancies on a $(111)_F$ plane is depicted in Fig.18.

The chiral properties of each $(111)_F$ layer determine the manner in which the Y-shaped clusters link up with their neighbours in next-nearest, rather than nearest, layers. Two interpenetrating, but unconnected networks of c.d's, each of opposite chirality, are generated throughout the type C-M_2O_3 structure, one involving the layers numbered 1,3,5 etc. (Λ chirality; Fig.18) and the other 2,4,6 etc. (Δ chirality). The Λ network which results from edge-sharing of c.d's between layers 1,3 and 5 is illustrated in projection on $(111)_F$ in Fig.19. Layer 7 exactly overlays layer 1 of this diagram, the pattern repeating itself throughout the lattice. The corresponding projection of the even-numbered layers, *i.e.*, those of opposite chirality, intermeshes perfectly so that the lacunae of the projection shown in Fig.19 disappear.

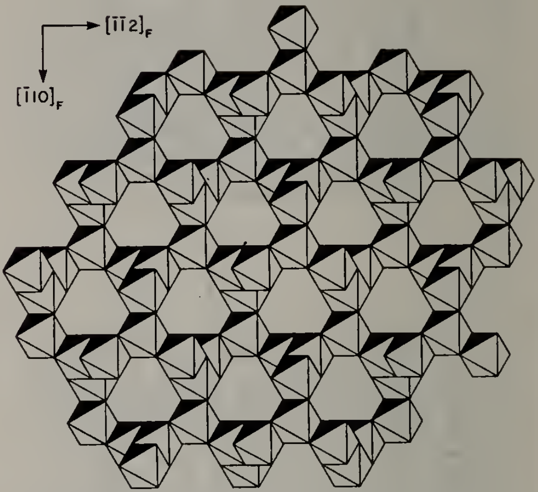


Figure 19. Type C-M_2O_3. One of the two interpenetrating networks of c.d's (Λ chirality) showing the edge-sharing involved between planes 1, 3 and 5.

The edge-sharing between c.d's within each single $(100)_F$ layer of the type C structure (Fig.17c) produces a pattern if isolated "pairs" which differs distinctively from the apex-sharing linkages of c.d's which characterize the β-Bi_2O_3 structure (Fig.17a). However, the relationship between the two structures is extremely close and

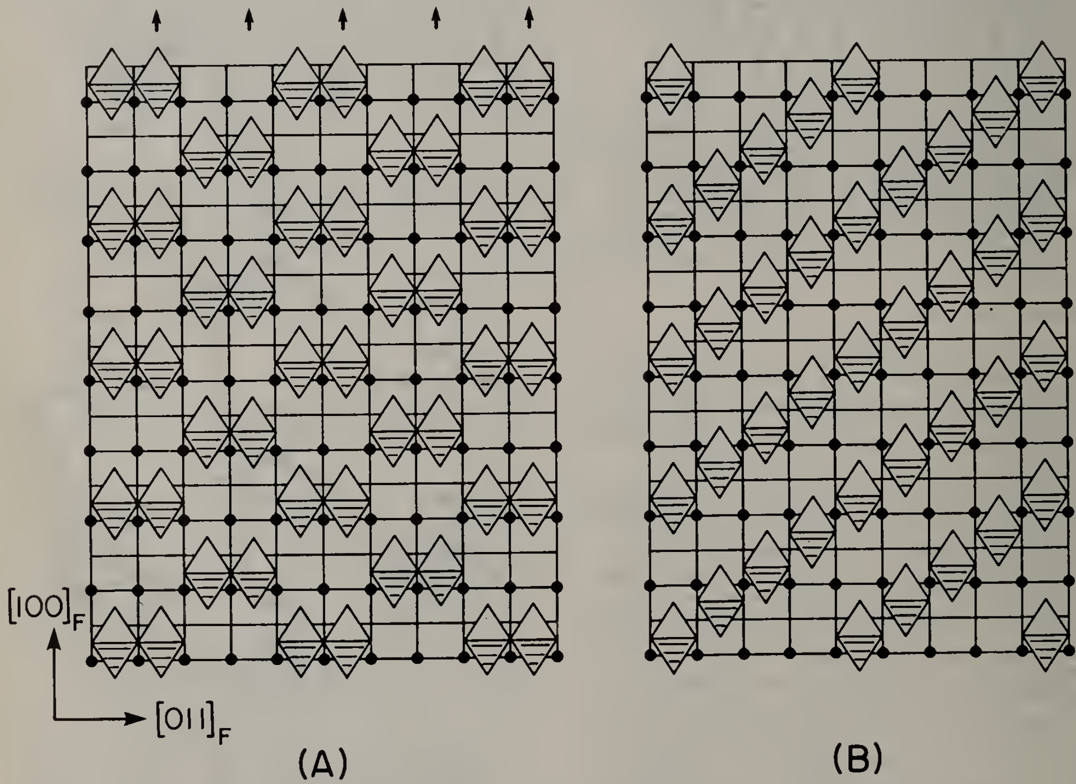


Figure 20. Type C-M_2O_3. Two $(01\bar{1})_F$ planes, denoted A and B, which alternate in the structure. Plane A is converted to plane B by *a*/2 slip of alternate $[100]_F$ rows of c.d's in the direction of the arrows.

the transformation

$$\beta\text{-}Bi_2O_3 \longleftrightarrow \text{type C-}M_2O_3$$

can be effected by a series of concerted oxygen/vacancy exchanges over minimal distances (of either *a*/2 or *a*√2); *viz.*,

$$O^{2-} + \square \rightleftharpoons \square + O^{2-} \qquad (6)$$

This transformation is illustrated schematically for the single $(100)_F$ oxygen plane in Fig.17a. The first step involves the translation by *a*/2 of every alternate $[011]_F$ string of apex-sharing c.d's to give the precursor shown in Fig.17b. This translation operation $\frac{1}{2}[01\bar{1}]_F$ is similar to introducing an antiphase boundary (a.p.b.) by crystallographic shear, the composition M_2O_3 remaining unchanged by the CS operation. The precursor structure differs, however, from β-Bi_2O_3 and C-M_2O_3 in that it is based on a combination of apex-sharing c.d's in *trans*-$[001]_F$ positions and edge-sharing of c.d's in the $[1\bar{1}0]_F$ direction. (This conjectural phase has not been observed experimentally and for convenience is referred to as type D-M_2O_3.) The second translation operation $\frac{1}{2}[0\bar{1}0]$ illustrated in Fig.17b is also a.p.b. in nature and generates a $(100)_F$ plane of unchanged composition with the type C-M_2O_3 structure (Fig.17c).

Unlike the β-Bi_2O_3 and pyrochlore structures, two types of vacancy plane, A and B, occur on $(01\bar{1})_F$ for type C, there being no oxygen intact planes. These are represented in Fig.20, both A and B having the same composition $M_4O_6\square_2$. A and B planes alternate throughout the type C structure generating the two interpenetrating sub-lattices of Δ and Λ chirality (*cf.*, Fig.18). Metal-centred pairing of c.d's along $[111]_F$ is evident in the B planes. An interesting feature of this beautifully ordered structure is that the sub-lattices of Δ and Λ chirality can be regarded as two independent giant extended defects which nevertheless are "paired" along $\langle 111 \rangle_F$ by six-coordinated metal atoms at the Δ/Λ interfaces.

CONCLUSIONS

Our concept of the real structure of a non-stoicheiometric solid has changed dramatically during the past 10-15 years. The classical idea of a random distribution of point defects has become unacceptable as a basis for explaining gross departures from simple stoicheiometry. Point defects in non-stoicheiometric oxide phases with either the rock salt or the fluorite structure undergo aggregation to more complex structural units which tend to be distributed throughout the host lattice in a regular periodic fashion. These may be discrete clusters or extended defects in two or three dimensions. This tendency to order when carried to completion generates a superlattice of the parent compound which for specific cation/anion ratios frequently defines a homologous series. The "cluster" and the "extended defect" become an integral component of the superstructural pattern, so much so that it can be argued that the ordered non-stoicheiometric phase is a new structure in its own right.

Recognition of the topology of the coordinated point defect enables common features of related crystal structures to be identified and their structural transformations to be better understood. This is especially important for materials such as oxides of the fluorite type where location of missing oxygen atoms by direct methods is inherently a formidable experimental task. Topological analysis of defect fluorite phases has wider implications of significance for other areas such as the magneto-optical properties of crystalline solids. For example, the green fluorescence of CaF_2 when doped with small amounts of uranium is observed only in the presence of oxygen and so has been attributed to U^{6+} coordinated by oxygen ligands. The polarized Zeeman spectra, which differ in character from those of uranyl (UO_2^{2+}) compounds, establish that the electronic transition occurs at a centre with trigonal and inversion symmetry (Manson *et al.*, 1975). These restrictions can be satisfied if the emitting centre is comprised of a metal-centred pair of c.d's of composition $UCa_6O_6F_6\square_2$ (*i.e.*, M_7O_{12} type) intergrown coherently in the host CaF_2 lattice (Fig.21).

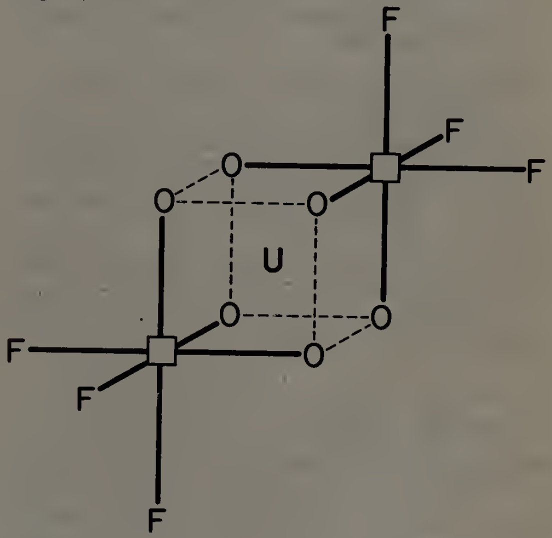


Figure 21. Conjectural structure of the emitting centre responsible for green fluorescence of fluorite doped with small amounts of uranium(VI). The uranium(VI) centred pair of c.d's has the overall composition $UCa_6O_6F_6\square_2$.

The growing demand for new materials in high temperature and electronic technology will ensure that the complex inter-relationships between composition, structure and properties, which form the basis of research into the defect solid state, will remain a vital field of chemical endeavour.

ACKNOWLEDGMENT

I am indebted to my colleagues, Dr. B. F. Hoskins and Dr. D. Taylor for many stimulating discussions.

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Sir Robert Robinson: A Contemporary Historical Assessment and a Personal Memoir

A. J. BIRCH

Seldom in a scientific discipline does the work of one man epitomise that of several generations. Sir Robert Robinson's long life spanned a vital period of organic chemistry when it was rapidly changing from a mostly empirical science into one soundly based on theory. To that change, he was an outstanding contributor in four most important areas: natural product structures, biosynthesis, organic reaction mechanisms and organic synthesis. For this reason his work belongs to the ages, and it is fitting to examine, for the future, not only the great deal which went right, but also what occasionally went wrong and why.

Although his work covered a number of fields, it was unified by his strong feeling for reaction mechanisms. His mechanistic theories were basic for his work on both synthesis and biosynthesis. They also greatly assisted his determinations of natural product structures at a time when such investigations involved interpretations of the results of reactions. To complete the circle, biosynthesis and structure determinations were mutually supporting.

MECHANISM THEORY

His contribution to the electronic theory of reactions is underlined by the fact that he invented the 'curly arrows' used to show how electrons move in bond breaking and bond making. He and Arthur Lapworth were the first to develop valid and useful ideas of organic reaction mechanisms based on dynamic views of what happens to bonding in the course of a reaction. The idea of fixed unitary valency numbers had been evolved by about 1870 to explain the composition of molecules. The theory did not automatically explain reactions, except that the resulting structures could be empirically related to reactions by experience; for example, in CH_3NH_2 the reactions of C-H are clearly quite different to N-H. Hypotheses preceding Lapworth and Robinson, which influenced them (Robinson, 1931; Robinson, 1932; Robinson, 1947; Ingold, 1934; Ingold, 1953), amounted to attempts to write the static structure of a molecule in a way which 'explained' its reactions. The formulae were empirical correlations of reactions, expressed in different conventions which indeed often contained varying aspects of the true situation. Electrical ideas were often involved, but until the discovery of the electron and its implication in joining atoms, suspected from about 1908, the bonding was vaguely considered in terms of 'tubes of force', diffusible in various ways. The conventions, such as the extra 'partial' valencies (Thiele, 1899) often did usefully rationalise reactivities, in this instance 1,4-addition to butadienes:

$$Br_2 \ + \ \text{---}CH_2{=}\overset{\frown}{CH\text{-}CH}{=}CH_2\text{---} \ \rightarrow \ BrCH_2CH{=}CHCH_2Br$$

The essential feature of the Lapworth-Robinson approach was their firm adherence to the idea of unitary principal valencies, which fractionate only as reaction proceeds, contrasting with the previous ideas of a permanent presence in the molecule of extra residual valencies, charged atoms or vaguely differentiated alternate bonds.

Although some ideas in particular cases had been put forward earlier, such as the influence of N in C=C-N, Lapworth added an important general concept with his theory of alternating polarities from a key atom such as O or N (Lapworth, 1920). Historically, this arose from his work on reactions of ketones, notably αβ-unsaturated ketones, C=C-C=O. The 'key atom' in this instance is oxygen (tending to acquire a negative charge). The resulting polarities shown below were not intended to represent complete charges, but to show how the primary valencies 'fractionate' as reaction proceeds:

$$C{=}C\text{-}C{=}O \ \rightarrow \ \overset{+}{C}\text{-}\overset{-}{C}\text{-}\overset{+}{C}\text{-}\overset{-}{O}$$

This idea amounts to acceptance of an extra unitary valency, not necessarily bonded to another atom, which can either be produced (such as the negative charge on oxygen) or utilised (the extra valency on nitrogen, for example). With the electronic theory this extra valency became immediately explicable as an unshared pair of electrons.

Reagents resembling anions will tend to react with positively charged carbons and those resembling cations with negatively charged carbons. This idea led to Lapworth's more conscious classification of reagents as 'anionoid' and 'cationoid' (Lapworth, 1925), (now 'nucleophilic' and 'electrophilic') even if they are not formally negatively or positively charged. The idea, as Robinson later said, was that "chemical reactions are preceded by a partial dissociation (*i.e.* of full normal into fractional valencies, *author*) leading to a slight polarisation of the molecules, formation or disappearance of all of the valencies being envisaged as a continuous and gradual process". The true relations between formal charged ions and the anionoid or cationoid reagents only became clear with the electronic formulations, the former possessing an unshared pair of electrons and the latter being capable of polarisation to accept a pair.

Robinson was greatly influenced by continuous discussions with Lapworth, both in his early period in Manchester (1909-12) and his later one (1922-27). This he acknowledges in a number of places, *e.g.*, (Robinson, 1974; Robinson 1949).

With the development of the Langmuir-Lewis theory of electronic valence (from about 1916) which was essentially a static explanation of the relation between atomic structures and the compositions of molecules, it became possible to translate the Robinson-Lapworth views immediately into electronic terms as pictures of the reactive interactions of molecules. The nature and validity of their fixed numerical valencies immediately became clear if these represent fixed numbers of electrons rather than diffuse electrical forces. Two papers (Kermack and Robinson, 1922; Lapworth, 1922) made the transition from the undefined valency pictures to the electronic pictures. Although published simultaneously, that of Robinson was written with Lapworth's in hand. Of the two papers, Robinson's is the more comprehensible in modern terms, since Lapworth's case is somewhat obscured by the symbolism which he had built up over a long period. Robinson's subsequent development of the subject is well known, including rationalisations of directive effects of substituents in aromatic substitution. He also noted and generalised the importance of the aromatic 'sextet' of electrons although he did not know then why it is important. At a time when these ideas were not fully accepted or understood, Robinson used them as guides to predict the outcome of reactions, to the awe of his contemporaries.

His weakness in the theoretical development was his essentially pictorial and non-rigorous approach. In a long forgotten controversy with Noyes (Noyes, 1934; Robinson, 1934; Wheeler, 1934) he demonstrated his clear visualisation of the reaction process. Noyes argued that an anion such as $CN^{\ominus}$ could add only to a fully developed charge in a 'radical' which could accept two electrons, for example to C=O in the form $^{+}C{-}O^{-}$ instead of $\overset{\curvearrowright}{C{=}O}$ as Robinson more correctly wrote the process. This ability to 'see' the processes was Robinson's great strength but also his weakness. When he had arrived at a valid picture he was satisfied. He did not think in terms of energies, mathematical symbols, or quantifiable theoretical concepts.

He did carry out quantitative experiments, for example on ratios of isomers in aromatic substitution, but he did not attempt to develop theoretical concepts of properties of substituents in quantitative terms which could lead to tests of detailed theories. If, for example, two opposing effects were involved, he qualitatively implicated as dominant the one which gave the observed result. He also did not examine reactions in ways calculated to lead to basic concepts like, for example, the contrast between SN-1 and SN-2 reactions. Unlike Lapworth, who eventually made a common front with Ingold, he had little feeling for physical chemistry. He liked the broad imaginative sweep of ideas, and having made a general point to his satisfaction would depart to new creative areas. He felt that he had solved a problem in principle with a general suggestion, and was impatient of the exacting and often boring experimental work then required to develop it quantitatively. This he left to others, notably Ingold. It is a pity that he and Ingold regarded each other with some hostility based probably on mutual incomprehension. They were in a sense complementary. Ingold, although also a man of great theoretical insight, was not willing to accept a general theory until he had quantitatively probed it and set up quantitative theoretical concepts. The contrast is between the painter who with a few broad imaginative strokes can convey the intense feeling of his subject, and the finely detailed portrait which completely defines an individual. Whatever the situation in art, there is no doubt that the second approach is necessary in science. Robinson's approach did lead however to basically valid ideas, which could be rapidly developed by others.

In his usual fashion, he started a number of ideas which he used only in individual problems without adequate generalisation. Among these were the type of delocalisation involved in the Wagner-Meerwein rearrangement which he discussed, in pre-electronic days (Robinson, 1920; *cf.* Ingold 1939) for the pinene-borneol type, and which could later be immediately written as a delocalised carbonium ion. He also distinguished, in particular cases, between kinetic and thermodynamic products of reactions, and clearly appreciated the general situation without developing it.

Robinson was not a writer of books and only a few substantial reviews on his mechanism theory exist, often published in rather obscure places (Robinson, 1931; Robinson, 1932). It is characteristic that Dewar's book (Dewar, 1949) was supposed to be a joint venture with Robinson, who eventually provided only the preface.

In his later years he made no attempt to absorb the developing ideas of quantum chemistry and molecular orbital theory although he accommodated readily enough to the more pictorial idea of resonance. Any criticism of his lack of development after the early 1930's recalls the Stone-Age cartoon "So, he invented the wheel, what has he done since?" Part of the reason was his wide range of interests and increasing involvement in outside affairs, but probably his temperament, which rejected the idea of a dull grinding of figures, was mostly responsible.

STRUCTURE DETERMINATIONS

Robinson coincided with the classical age of 'chemical' structure determinations, now gone forever with the development of physical methods. Although even today not entirely 'mechanical', much of the interest which appealed to Robinson's first-class chess and bridge-playing mentality has disappeared. Structures then depended on degradation to known molecules and on conclusions from reactivities. The results could be interpreted and assembled in all sorts of ways, depending on the exercise of judgement. In this Robinson excelled, his chief asset being his feeling for mechanism. He was not content to accept a mechanical and 'obvious' explanation if it violated his feeling for correct behaviour. He possessed a superb faculty of intuition.

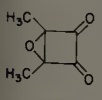
I recall, for example, finding him chuckling over a letter from a well known organic chemist concerning a degradation product, $C_6H_6O_3$, of a plant constituent, to which had been attributed the strange structure (1). Whilst not impossible, any such structure would clearly require very good evidence, particularly in favour of the clear presence of the unusual ring system. The evidence was:

(a) hydrogenation and oxidation with NaOBr gave 2,3-dimethylsuccinic acid (4);

(b) a derivative was formed with semicarbazide (interpreted classically as indicative of the presence of carbonyl group C=O);

(c) the only H present in the molecule was apparently in 2 CH_3 groups.

Robinson, in about 3 minutes, said "That is nonsense, the compound must be dimethylmaleic anhydride" (2). His reasons were: firstly the far higher chemical 'probability' of this structure (which he worked out initially, simply on the empirical formula including the 2 CH_3), then the interpretation of 'semicarbazone' formation as the imide (3). [*i.e.*, the diagnostic reaction for carbonyl was questioned, and anyway why should (1) not give a bis-semicarbazone since it has two C=O?] and finally the realisation that the 'oxidation' by NaOBr was not needed and indeed had not occurred, this reagent having merely supplied alkali for hydrolysis. This example, although simple, underlines two points: his ability to postulate a structure on minimal evidence, and then to disentangle significant from insignificant or obscuring evidence. Needless to say he was right.



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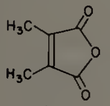

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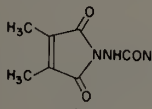

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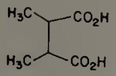


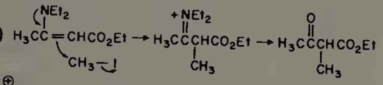
(4)

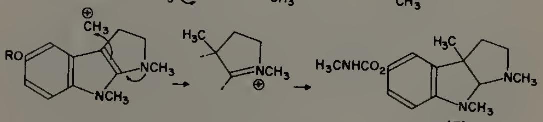
He was frequently consulted by chemists such as J.L. Simonsen and H. Raistrick who were very good experimental workers but did not have his theoretical insight.

He took considerable delight in the interpretation of published work in the literature and indeed directed less experimental work himself than might have been expected from his published conclusions. A classical case is his structural interpretation of experimental work on strychnine (Robinson, 1952) carried out notably by Leuchs. This structure was by certain criteria, the most complex ever determined before the days of physical methods, involving some 500 man-years of experimental work. Robinson claimed, correctly I believe, to have read every paper on the topic and to be able to remember all of the data published, although he carried out only a minor proportion of the work himself.

His biosynthetic ideas were of great assistance for structure work, although sometimes applied virtually subconsciously. I recall that he would say of a postulated structure "That looks right" (or "wrong") and further probing was required to reveal a biosynthetic correlation. One of his first major scientific results was the correction of the structure of the alkaloid berberine on conscious biosynthetic grounds (Perkin and Robinson, 1910). Sometimes it is rather difficult to disentangle now whether his biosynthetic ideas followed or preceded related structure determinations, and Robinson himself did not always remember. He probably did not regard the order of such ideas as significant anyway.

Characteristic examples of his more subtle use of biogenetic ideas for structures, in quite different ways, are the plant alkaloids physostigmine (5) (eserine) and the morphine group. Standard chemical work by Barger and others (Stedman and Barger, 1925) characterised much of the structure of physostigmine, with the notable exception of the placing of a methyl group. Robinson, following Lapworth's ideas, had been early interested in the alkylation of enamines, by processes mechanistically represented as below. The first experimental example was the methylation of diethylaminocrotonic ester (6) (Robinson, 1916).

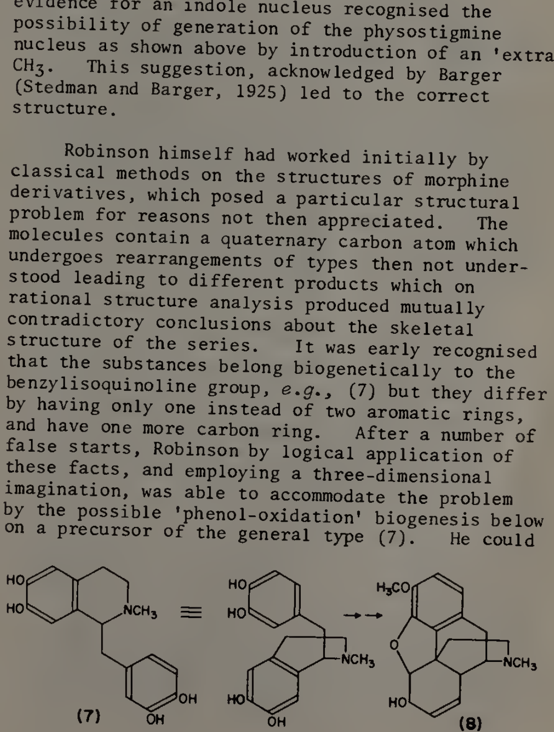
(6) 



(5)

Robinson on the basis of convincing evidence for an indole nucleus recognised the possibility of generation of the physostigmine nucleus as shown above by introduction of an 'extra' CH_3. This suggestion, acknowledged by Barger (Stedman and Barger, 1925) led to the correct structure.

Robinson himself had worked initially by classical methods on the structures of morphine derivatives, which posed a particular structural problem for reasons not then appreciated. The molecules contain a quaternary carbon atom which undergoes rearrangements of types then not understood leading to different products which on rational structure analysis produced mutually contradictory conclusions about the skeletal structure of the series. It was early recognised that the substances belong biogenetically to the benzylisoquinoline group, *e.g.*, (7) but they differ by having only one instead of two aromatic rings, and have one more carbon ring. After a number of false starts, Robinson by logical application of these facts, and employing a three-dimensional imagination, was able to accommodate the problem by the possible 'phenol-oxidation' biogenesis below on a precursor of the general type (7). He could



(7) (8)

then rapidly take account of the known reactions of morphine (8) and related alkaloids to produce detailed structures for them on the basis of the same molecular skeleton (Robinson, 1955; *cf.* Gulland and Robinson, 1923). The biosynthetic route was much later shown to be basically the correct one.

He did not classify himself as an 'adjectival' chemist such as an alkaloid, or a lignan, or a flavonoid etc. chemist. He was happy to tackle any problem which came his way, and this was part of his strength, since one area illuminated and supported another. He formulated many natural products of different structural types: brazilin, morphine, flavonoids and anthocyanins, many alkaloids including strychnine, etc. a list which marked in itself a great contribution. His originality lay in his ability to evaluate and interpret results, rather than in devising basically new experimental methods, but a major contribution in thinking in the area was his biosynthetic approach. He did not generalise this as a technique, but used the ideas in specific cases often without explanation at the time. This somewhat mysterious approach was probably a part of his 'magic' to his contemporaries, as indeed it was also to some extent with his mechanistic ideas; he produced the results frequently without indicating the reasoning involved, at least in print. He also had the related disconcerting habit of starting in the middle of a topic on the assumption that the interlocutor knew as much about what he was thinking as he did. The result was often dazed admiration, but some lack of understanding.

A great drawback from his students' point of view was that his approach was so personal and individual as to be largely inimitable.

An endearing but sometimes irritating characteristic was the ease with which he would write a new structure without inhibitions, and drop it with equal ease if he became convinced that it was incorrect. A classical case was his drastic modification of strychnine (on a fancied resemblance to quinine) which he published but abandoned almost immediately (Chakravarti and Robinson, 1947).

He also occasionally did not publish corrections, and became annoyed when he was corrected by others. He knew in 1939, for example, from work by H.L. Holmes that the size of a ring in his published structure of strychnine was not correct, and this was corrected by others in print to his initial annoyance (Prelog and Szpilfogel, 1945). If he knew a fact he tended to assume that everybody else did whether it was published or not.

PHYSICAL METHODS

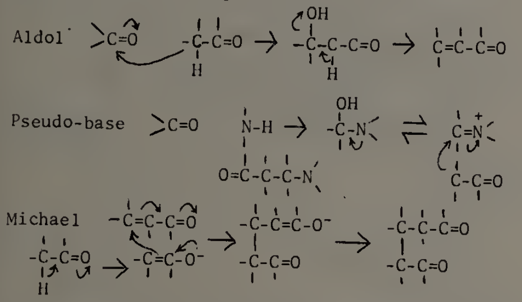
Robinson's practical techniques were of the simplest form, but astonishingly powerful in his hands. I recall methylating piperonylidene norequilenin methyl ether to what might have been either the unnatural *cis* or the natural *trans* C-D steroid derivative (Birch, Jaeger and Robinson, 1945). The product was optically inactive, and although we had the derivative of the natural (+)-hormone there were then no techniques for comparison of their identity. Robinson took the synthetic and the natural compounds and dissolved them in concentrated sulphuric acid: one went brown, the other green. He concluded that the synthetic product was the wrong isomer. Six months later, when I had prepared more material, I was able to show that he was correct. The use of colour reactions of this sort, in which he was very expert, was in a sense a primitive physical method based on producing visible light absorption. It was probably developed from his interest in anthocyanin pigments, where he and G.M. Robinson were able by partitioning the colours between solvents to derive considerable analytical and structural information.

Although not particularly enthusiastic about physical methods such as ultra violet and infra red spectra, he recognised their value and was prepared to use them, although he never thought primarily in terms of spectra. I recall, about 1941, proving by the ultra-violet spectrum that a synthetic steroid intermediate was an αβ- unsaturated ketone, although a 2,4-dinitrophenylhydrazone could not be prepared. He was delighted with this approach but still rather regretfully returned from time to time to the question of derivative formation. He never became an expert in subjects like n.m.r. or mass spectra, but he realised their advantages, and in his later years was much concerned with the latter topic in work with others on the origins of petroleum. What he did regret, as he frequently said, was the short-circuiting of chemical investigation by physical methods. Although this frequently led rapidly to the correct molecular structure, it also resulted in the loss of general and important chemical information. The methods also substituted by rather mechanical means the complex intuitive puzzle-solving processes in which he delighted. He used also to point out the extent to which chemical work on natural product structure had illuminated the whole area of organic reactions because of the complexities of structure which were not encountered in readily available synthetic substances.

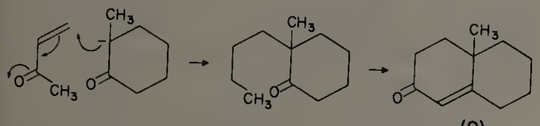
SYNTHESIS

Most of Robinson's syntheses were aimed at a scientific point: to exploit a novel reaction or sequence, to prove a structure, or to show that synthesis is possible. As a mountain climber, the argument "because it is there" probably appealed to him in the last connection. Synthesis in the anthocyanin area was particularly important in unravelling the complex situation of mixtures and closely related natural products. Occasionally he made substances for biological testing, such as anti-malarials, but even the synthesis of stilboestrol was initially undertaken to prove a scientific point.

His great assets in the general area were his 'feel' for mechanisms and his prodigious memory for published work. Organic synthesis involves chiefly C-C bond formation, and less frequently the production of C-N and C-O. Most synthetic chemists can be distinguished by habits of thinking and by favoured reactions. Robinson's characteristic reactions involved the generalised aldol condensation, which often leads to αβ-unsaturated carbonyl compounds, together with Michael-type reactions which involve the addition of carbanions (often as ketone enolates) to αβ-unsaturated carbonyl derivatives. Both can be generalised to involve analogous nitrogen compounds, such as pseudo-bases, and can lead to nitrogen-containing products.



Both reactions are useful for producing new C-C bonds in systems functionalised by carbonyl groups which are then available for further reaction. One classical example is the Robinson annelation which has been extensively used in the synthesis of terpenoids and steroids. Among other characteristics, it not only produces readily a six-membered ring from open-chain components, but can result in the presence of the 'angular methyl' groups which caused some problems in synthesis in these areas (*e.g.* 9).

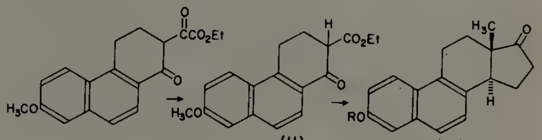


(9)

Michael reaction Aldol reaction

Robinson's strategy in synthesis, although he did not discuss it explicitly but merely used it when possible, was to construct separately fairly large pieces of a molecule and join them, usually by one of the reactions above. I have discussed this approach in more specific terms (Birch, 1953) and it now seems generally favoured. It was appropriate to his habitual experimental procedures as well as being theoretically desirable. The chief problem is that it often requires very considerable ingenuity, not only in the mechanism of junction of the pieces, but in the protection of reactive groups necessarily present in them which may be incompatible with desired processes. Some good examples from Robinson's work are the anthocyanin and some alkaloid syntheses.

Robinson's approach to the optimisation of reaction conditions was not helpful in long syntheses. He used the simplest of equipment himself, and complex equipment was not available in the Dyson Perrins laboratory. His approach to an experimentally difficult step was to depend on ingenuity to find a new way around it rather than to polish it experimentally. I recall that his remark on the Bachmann synthesis (Bachmann, *et al.*, 1939) of the first sex-hormone equilenin (10, R=H), which was the first in the now accepted manner, was "Walker and I thought of that in 1936!" This was true, but they were unable to consummate in the laboratory an important, superficially rather simple and expected reaction: the decarbonylation of the oxalyl ester to give (11). Bachmann succeeded in doing so by heating with powdered soft glass, and his yields in all of the steps have never been bettered. They were reached by extraordinarily close attention to experimental detail. Robinson's undergraduate laboratory record states, "a good student, but messy".



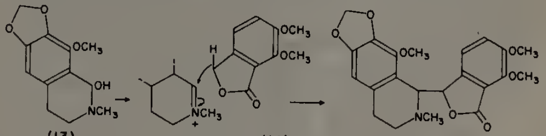
(11) (10)

Some years later, Robinson remarked to me of such syntheses in general: "These Americans are like cats trying to get over a wall, they scramble and scramble - I walk up and down until I find a hole I can get through". This is a very clear exposition of the contrasting attitudes; unfortunately holes are often not easy to find or are non-existent.

He could perhaps have supplemented his own gifts by choosing appropriate lieutenants. He did not often consciously do so although when more or less by accident he did come across the right people his ideas flourished. He was always an individualist rather than an organiser of the massive teams required nowadays for complex synthesis.

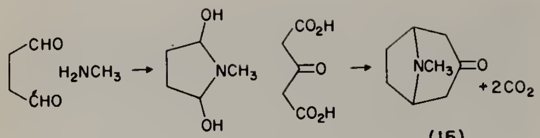
Only a few examples of his work can be quoted to illustrate general points.

His synthesis of narcotine (α-gnoscopine) (12) is an early one (Perkin and Robinson, 1910a) using the pseudo-base cotarnine (13) and the unsaturated lactone meconine (14). The former can react as the quaternary salt shown, and the latter might be expected to contain a reactive CH_2 activated by the lactone carbonyl, as Robinson notes on the basis of Lapworth's substitutions of crotonic ester $MeCH{=}CHCO_2R$ (Lapworth, 1901). He also considered that the presence of a five-membered ring would facilitate reaction. The condensation to (12) proceeded as he expected and the reasoning is a typical example of his creative extrapolation of known facts (known to him!) on an instinctive basis of feeling for reactions.



(13) (14) (12)

His most celebrated synthesis, which was described as *bewundernswerter Eleganz* by Willstätter (Willstätter, *et al.*, 1923), was the one-pot production of tropinone (15) by the reactions shown below. This synthesis of the nucleus of the cocaine alkaloids experimentally involved



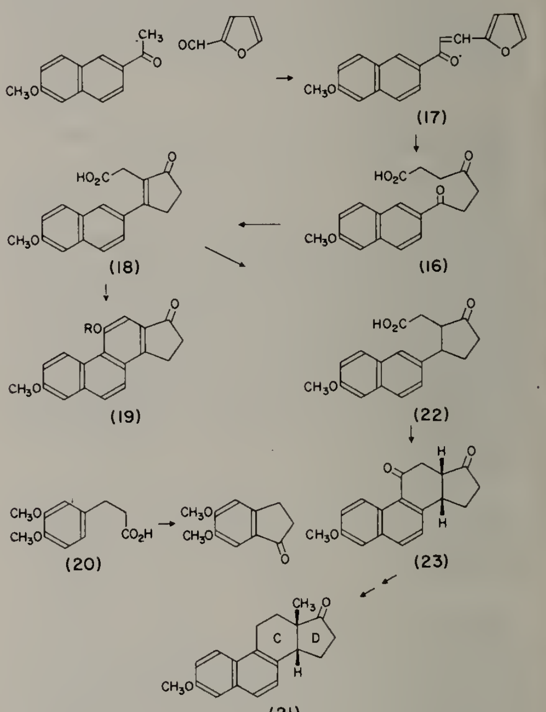
(15)

admixture of all of the components in water at room temperature, giving readily what was then regarded as a complex bicyclic molecule. The formulation of intermediates as pseudo-bases is his, although as Willstätter has noted that it is not the only possible sequence. This synthesis (Robinson, 1917), as he acknowledges, probably grew out of discussions with Lapworth during the first Manchester period (1909-12). As I note later, the process gave great support to some of his biogenetic theories, but probably itself arose from a dissection of the molecule in association with Lapworth's views (Robinson, 1974) on reactions of pseudo-bases.

A classical example of his synthetic approach resulted in the production of cyclopentenophenanthrenes with oxygenated substituents at the vital 3,11,17-(steroid) positions (Birch, *et al.*, 1945; Koebner and Robinson, 1938). The key to this work is the availability of diketo-acids of the type (16) through a rather strange and unpredictable hydrolysis of furans of type (17) which Robinson had remembered from the earlier German literature. The aldol-type ring-closure to give the cyclopentenone in (18) is another example of his favourite aldol-condensation, and the ring-closure of the acid on to the aromatic ring (19) goes back, as he mentions, to very early work of his (1908) on the phosphorus pentoxide closure of the acid (20).

Initial work gave the fully aromatic compound (19); later work went closer to natural steroids with production of the norequilenin structure (21) (Koebner and Robinson, 1938). Despite this simple and ingenious construction of the steroid ring system, with oxygenated substitutents appropriately situated to relate the product to natural hormones, the work was sterile for many years in terms of synthesis of genuine steroids because of problems associated with specific hydrogenation of the rings and insertion of the angular methyl group [compare the formula of equilenin (10)] which Robinson himself never solved. Two aspects of Robinson as a synthetic chemist are illustrated by this work and by other similar sequences. One is that he did not have the rather cold-blooded approach required to think a long synthesis through from beginning to end before starting it. Also, his emotional interest was caught by an ingenious solution to part of a problem and he had a considerable faith, sometimes, but not always justified, that he would eventually find his way out of an impasse by the exercise of further ingenuity. The later total synthesis of steroids (Cardwell, *et al.*, 1953) was given the correct approach by Cornforth rather than by Robinson.

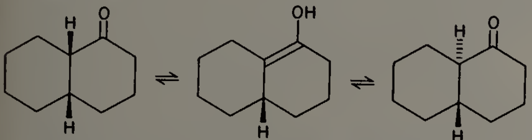
One interesting example of a new reaction was the accidental discovery of the cyclising potential of polyphosphoric acid (Birch, *et al.*, 1945; Koebner and Robinson, 1938) (then called a solution of phosphorus pentoxide in phosphoric acid). Robinson in 1908 had cyclised (20) with P_2O_5 in benzene in connection with brazilin work.



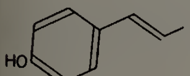
(17) (18) (16) (19) (22) (20) (23) (21)

This reagent was tried with (22) and at first was found to work to give (23). A later student could only produce a product resembling charcoal. Robinson, impatiently one day said "Nonsense, I know it works, I have done it!" He proceeded then to dissolve (22) in unpurified benzene in what was probably a damp flask and added phosphorus pentoxide without precaution. It did work! The correct deduction he made was the necessity for some water (*i.e.*, phosphoric acid). Further work justified this expectation (Birch, *et al.*, 1945). The student involved recounted the story in a seminar in the form."In his usual inimitable manner Sir Robert flung the things together and the reaction went". Sir Robert's comment was "I thank Dr X for the bouquet he has flung me, and I am still trying to dodge the brickbat inside it!" Indeed the moral of such stories is unclear, except that as Pasteur implied, chance is an important ingredient of scientific advances when its significance is correctly perceived. His sequence in this instance, stopped at *cis*-equilenin (21) with the wrong stereochemistry at the C-D ring-junction.

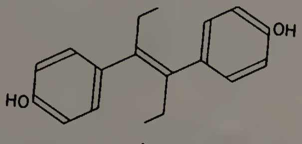
He was not insensitive to stereochemistry in synthesis, as were some of his contemporaries, but he suffered from the same relative lack of ability to predict the outcome until the formulation of conformational analysis. He did try to use what ideas he could, notably related to the attack of reagents from less hindered directions, and the thermodynamic stability of more sterically extended isomers and of *trans* decalin derivatives. The latter types, particularly important for steroids, he recognised could be obtained by equilibration through carbonyl enols, as shown below for the *cis* and *trans* decalones. He did not, however, consider this area in the same theoretical detail as he did electronic theories of bond formation.



The use of his favoured aldol and Michael reactions frequently led to new asymmetric centres adjacent to or vinylogous to carbonyl groups, permitting equilibration to the stable stereoisomers. Robinson recognised this as an advantage in the synthesis of a *trans-anti* series like the steroids, and it was an additional reason that he adhered to this type of reaction.



(25)



(24)

A very important example of a practically useful synthesis was that of the oestrogenic hormone substitutes, stilboestrol (24) and hexoestrol, although initially the work was undertaken to examine a structure. Dodds discovered biological activity as a female sex hormone of what seemed, from its mode of origin, to be a dimer of anole (25). Robinson and Golberg (Dodds, *et al.*, 1939) synthesised the most probable dimer (24). Robinson later rationalised a structural resemblance to natural steroidal oestrogens [compare formula (10)] by writing stilboestrol (24) as shown, but contrary to popular belief it was not this consideration which led to the synthesis. Industrial synthesis was later undertaken by various processes.

Robinson would very much have liked to synthesise strychnine, but although he made some beginnings, his temperament did not lead to a valid approach to the organisation of the extended sequence of reactions which would be required.

His influence in encouraging synthesis in organic chemistry was considerable. The 'inevitability' of his best syntheses set a good example, and his convincing application of mechanisms demonstrated the utility of such considerations.

BIOSYNTHESIS

Robinson was not the first to speculate on the biosynthetic origins of plant materials such as alkaloids. A remarkable book in 1910 (Winterstein and Trier, 1910), correctly formulated a number of the problems, and suggested in outline the solutions to some of these, for example, the involvement of ornithine and lysine in pyrrolidine and piperidine (including tropane) alkaloid origins. They correctly set out the origin of the benzylisoquinoline alkaloids from phenylethylamines and phenylacetaldehydes derived from tyrosine and its congeners. Pictet tried to formulate possible pathways as distinct from just molecular origins, but was not sensitive enough towards biochemically compatible processes and his uses of sulphuric acid as a catalyst and of red hot tubes, did not provide convincing models (Pictet, 1906; Pictet and Spengler, 1911). Willstätter also was considering the topic on authentic lines, but published little at the time (Willstätter, 1965).

Robinson's papers of 1917 were mainly responsible for the boost to the topic, and it is interesting to analyse why (Robinson, 1917; Robinson, 1917a). Surprisingly perhaps, it was not because his views were shown to be correct; they could not even be tested for another 30 years and many of the detailed suggestions turned out to be wrong. He was listened to because he was convincing, and he was convincing for two reasons. The first was that his relentless hammering of the idea that nature works by recognisable chemical processes is indeed correct in principle, and he was able to set out a number of impressive (although in the sequel often incorrect) suggestions on this basis. The second reason was the tropinone synthesis previously mentioned.

Although he clearly had had biosynthetic ideas under consideration from time to time, and was aware of Winterstein and Trier's book, which he quotes, all of the internal written evidence (discussed in detail elsewhere) (Birch, in press) suggests that the tropinone synthesis was undertaken initially as a purely chemical one. However, the ease and efficiency of a reaction in aqueous solution, using compounds from biochemically known or imaginable sources, appears to have stimulated the latent biosynthetic ideas which erupted in his second paper (Robinson, 1917a) submitted about one week after the first (Robinson, 1917). It was this experiment which was immediately recognised to provide support for the general theory. In retrospect it is puzzling that Winterstein and Trier (or Pictet, who actually did condense formaldehyde with tyrosine to obtain an isoquinoline) had not similarly supported their benzylisoquinoline idea. Schöpf later did this in convincing detail in his "synthesis under physiological conditions" (Schöpf, 1932).

Robinson produced many biosynthetic speculations, in the alkaloid and other areas. I recall congratulating him on the fact that his suggestion of 1927 that squalene is the precursor of steroids, had been confirmed. "But I have had six other ideas since then, they cannot all be right", was his response. The great contribution he made in this field was correctly to orientate thinking in terms of consideration of chemical mechanisms and of biochemical compatibility. Then when testing became possible, the alternatives were clearly visible.

Apart from sporadic reviews, *e.g.*, (Robinson, 1927), many of which contained ideas he would rapidly disclaim (although not often in print), his only book covered this area (Robinson, 1955; *cf.* Gulland and Robinson, 1923), but was written many years after the ideas were generated, and the historical origins of them are often not well exposed. The exposition is largely the usual scientific 'logical' one from the viewpoint of the time (1955) at which it was written. It is however a very interesting account showing how a jumble of apparently unrelated structures can be reduced to interrelated patterns.

Robinson showed no inclination to test his ideas even when after about 1947 it became possible; it was the pattern-making which apparently appealed to his chess-playing mind. "That must be right" he would say and go on to another problem.

TEACHER AND ORGANISER

I only knew Robinson from 1938 in Oxford, and the war, Presidency of the Royal Society, and other activities (he was on 37 committees at one stage during the war) may have affected unfavourably his academic activities. He was not, even in 1938, a good undergraduate teacher in the standard sense. He never gave the impression of having prepared a lecture, he just talked on the subject. This was fascinating for the best students, particularly as he was likely to have some new idea suddenly, and start to work it out on the spot. The not-so-good students complained, but under the Oxford system could always go back next year, although probably not to identical lectures. The students had to teach themselves largely by observing how a great mind coped, rather impromptu, with a topic, and this is probably the best way to learn. His formal scientific lectures could vary from being very good and exciting, if he was really interested, to embarrassingly bad if he was not. He made no concessions to his audience, and his lecture to the Royal Society of Arts in 1948 (Robinson, 1948) is an example of an extreme case where the ordinary members of the Society clearly had no idea what he was talking about.

His attitude to research students was defined by his interest in the work, and not by the progress of the student. If the work went well he followed it closely and with stimulating ideas; if it went badly he was not interested. Unfortunately his individualistic attitude did not lead to the logical solution to the organisational problems, which was to have lieutenants for closer supervision, particularly when he was not in Oxford.

As a laboratory organiser he was disastrous. Equipment in Oxford was surprisingly poor and there was no proper system to acquire it. In 1938 I recall that I only obtained basic equipment like stands and clamps through the kindness of Golberg and Openshaw, the flasks and condensers were mostly made of soft and ageing glass, and not even rubber bungs and filter pads were available, let alone ground glass. Robinson was also responsible for the 'design' of the early part of the new Dyson Perrins Laboratory. I recall protesting about the fume cupboards which were divided in such a way that they could not contain an ammonia cylinder, and there was also no power point within reach. His comment was "We do not often stir in fume cupboards do we?" His intense individualism inhibited delegation of authority, either academic or non-academic.

Administration was not made easier, during much of my time in Oxford, by the fact that his secretary typed badly and did not know shorthand at all. I once asked him why he employed her, "She was in the Red Cross you know" he said, as if this explained everything. A consequence was that most letters were written by him in his sprawling handwriting, and no copies existed. All sorts of interesting results followed, such as the arrival of students from the ends of the earth, whom nobody knew about, including Robinson who had forgotten.

His choice of research students seemed indeed to be very arbitrary and made without proper inquiry. He naturally had some very good ones, but he also had very bad ones, of whom there are many stories. A sample is the student who 'cleaned' some sodium with hot water, soap and a brush, burnt out a good deal of the laboratory and left it after a total residence of one day. Another was the student who evaporated a solution containing several litres of perhydrol, and demolished one of the laboratories. Laboratory safety precautions seemed to be non-existent, or at anyrate not enforced.

He also was very disinclined to dance the stately minuet required by the powerful Oxford Colleges, perhaps often justifiably but rather unrealistically.

However, although it is a pity that he did not allow others to supplement his deficiencies, the question about organisation is "organisation for what purpose?" The best organised laboratory can be sterile, the important factor is the excitement of ideas. The Dyson Perrins in Robinson's time was an exciting place. Even neglect has its advantages for those prepared to take the opportunities thus afforded. Perhaps academic life these days is too safe, too organised and too sterile. We need a few great individualists from time to time.

Robinson to the end of his long life of 83 years was dedicated to science, and it was this extreme personal dedication that produced both his good qualities and his bad ones. The greatest tribute to him as a scientist is that he began new projects in quite new areas at the age of 70, and despite developing blindness, continued this interest to the end. In our stream-lined, standardised, business-like laboratories, based on the work of the big battalions, we unfortunately shall probably not see his like again.

For details of his life and career and a list of his publications, reference may be made to his Royal Society obituary (Todd, in press).

I am indebted to Mrs Maureen Kaye for assistance in preparing this memoir.

ADDENDUM 21/9/76.

Since this memoir was written, the first volume of Robinson's autobiography has been published (Robinson, 1976). While adding detail on individual topics, his account does not contradict any of the conclusions above, nor does it illuminate further the origins of ideas except to re-emphasise the part played by Lapworth.

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Report of Council for the Year Ended 31st March, 1976

INTRODUCTION

The year has been one of increasing anxiety for your Council, for in spite of increased charges for services and a 10% increase in membership, income has fallen far short of the enormous increase in operating expenses. As is well-known, this condition is not unique to the Society and with no panacea for inflation in sight it is apparent that the next year or two may prove to be crucial in so far as the survival of the Society is concerned.

MEETINGS AND LECTURES

Attendance at all meetings and lectures held during the year was well maintained, the standard of the lectures was excellent and the interest sustained. Sir Marcus Oliphant, Governor of South Australia, was present at the August meeting when he was presented with the James Cook Medal awarded to him in 1974.

The following meetings and lectures were held in the Large Hall, Science House, 157 Gloucester Street, Sydney:

April 3rd: Annual General Meeting and Presidental Address, "Corals and Models of Continental Distribution for the Silurian", Dr. J.W. Pickett, N.S.W. State Department of Mines.

May 7th: "One Hundred Years of Oceanography", Dr. F.H. Talbot, Director, The Australian Museum.

June 4th: "Stability and Dynamism in the Australian Settlement Pattern", Professor A.J. Rose, Professor of Geography, Macquarie University.

July 2nd: "Of Mice and Men: What cultured cells can tell us", Professor N.G. Stephenson, Department of Biology, University of Sydney.

August 6th: "The Importance of Atomic Energy to Australia", Mr. K.F. Alder, Head, Nuclear Science and Technology Branch, Australian Atomic Energy Establishment.

September 3rd: "World Mineral Resources: Is there a shortage?", Dr. K.L. Williams, Senior Lecturer in Resource Geology, University of Sydney.

October 1st: Symposium, "Education in the Twenty-first Century", Dr. J. Vaughan, Director of Studies, N.S.W. Department of Education; Professor D. Cohen, Associate Professor, School of Education, Macquarie University; Dr. I.W. Paterson, Principal, Knox Grammar School.

November 6th: "Tides: Some theories old and new", Professor V.J. Buchwald, School of Mathematics, University of N.S.W.

December 3rd: "Nothing new under the Sun? A realistic view of the role of Solar Energy", Professor D.W. George, Vice-Chancellor, University of Newcastle.

In addition, the following lectures were held in association with the University of Sydney at that University:

July 10th: Clarke Memorial Lecture: "Phacopid Trilobites - Their Anatomy, Function and Distribution", Dr. K.S.W. Campbell, Department of Geology, Australian National University.

September 4th: Pollock Memorial Lecture 1975: "Tectonic Plate Movements relative to the Earth's Axis and Interior", Professor J. Tuzo Wilson, Director, Ontario Science Centre, Canada.

October 17th: Illustrated lecture entitled, "Alfred Wallace 1823-1913", Professor R.E. Bernstein, Inst. for Medical Research and School of Pathology, University of Witwatersrand, South Africa.

ANNUAL DINNER

The Annual Dinner was held in the Sydney Hotel on 17th March and was attended by 70 members and guests. The guest-speaker was Mr. R.R. Gray, Deputy Commissioner of Taxation, the title of his address being, "Filling the Royal Purse".

AWARDS

The following Awards for 1975 were made:

James Cook Medal:	Dr. A. Walsh
Edgeworth David Medal:	Dr. F.J. Ballard
Clarke Medal:	Dr. J.N. Jennings
The Society's Medal:	Mr. W.H. Robertson
Liversidge Research Lectureship:	Dr. R.L. Martin
Olle Prize:	No award

SUMMER SCHOOLS

The two Summer Schools held during January were highly successful and were attended by 103 fifth-form students. The school having Chemistry as its theme was entitled "Chemistry and Energy", and as on previous occasions was held at Macquarie University; the other having Astronomy as its theme and entitled, "Exploring the Universe", was held in Science House and included visits to Fleurs Radio Observatory, C.S.I.R.O. Radio Physics Laboratory, and the Sydney Observatory.

MEMBERSHIP

The membership at 31st March was: Hon. Members 9; Life Members 38; Members 378; Associates 57. The number of applications for Associate Membership following the Summer Schools was disappointingly small, only 4 being received.

PUBLICATION

Volume 108 of the Journal and Proceedings was published during the year. Mr. A.F. Day has completed the subject index covering the second fifty years of the Journal and Proceedings but unfortunately its printing has, of necessity, been deferred because of lack of funds. During the year the format of the Monthly Notice Paper was changed and is now entitled "Newsletter of the Royal Society of New South Wales". In addition to containing notices and reports of meetings, it includes a summary of the activities of the Associates as well as news of members and, when space permits, other items of interest.

LIBRARY

3068 items were received and processed. These comprised periodicals on exchange from some 353 societies and institutions, donations and periodicals purchased. 215 members, societies and organizations used the library facilities during the year. The re-cataloguing of the library which was commenced last year is nearing completion.

FINANCE

As mentioned earlier in this Report, the financial state of the Society continues to cause Council grave concern. Since the resumption of Science House by the Sydney Cove Redevelopment Authority all income derived from renting has been lost to the Society and this, combined with the greatly accumulated increase in operating expenses during the year, has resulted in a deficit for the 10 months ending 31st December amounting to $13,413.

In an effort to produce a balanced budget Council has elected to change the method of production of the Journal from that of letterpress to a process of "typeset-it-yourself" offset. Consideration is also being given to further reorganization of the office and services in order to effect the maximum economies possible.

SCIENCE CENTRE

Work on the alteration to the building is nearing completion in spite of some last-minute amendments having to be made to the plans to comply with fire-safety requirements.

ROYAL SOCIETY ASSOCIATES

Early in the year a number of Associates of the Society formed a new Group, The Royal Society Associates, operating within the Society and providing meetings, excursions etc., designed to meet the specific interests of those Associate Members under the age of 25. Membership of the group rose to 38, a total of 4 visits and lectures were held and a Newsletter was issued on a bi-monthly basis. The future of the group will depend entirely on the support it is given by the Associate Members of the Society.

ACKNOWLEDGMENTS

Mrs. V. Lyle has resigned from her position of Executive Secretary in order to join her husband in Iran early in April. During her three years with the Society Mrs. Lyle has reorganized the office procedures and contributed in no small measure to the substantial increase in membership during this period. Her absence from the office will be noted by all who have occasion to call there. Council wishes to record its sincere appreciation for the assistance she has given and extends its best wishes for a successful venture overseas. Council whishes to acknowledge the

Council wishes to acknowledge the considerable assistance the Society receives, at no cost, from Mr. A.F. Day who not only has been working on the subject index but also when necessary, deputizes for the Assistant Librarian. It also wishes to acknowledge the excellent work carried out during the year by the Assistant Librarian, Mrs. G. Proctor, and all concerned with the organization of the Summer Schools and monthly lectures.

ANNUAL REPORT OF NEW ENGLAND BRANCH OF THE ROYAL SOCIETY OF NEW SOUTH WALES

Officers:

Chairman: S.C. Haydon
Secretary-Treasurer: R.E. Gould
Committee: R.L. Stanton
N.T.M. Yeates
R.D.H. Fayle
N.H. Fletcher
Representative on Council: N.T.M. Yeates

The following meetings were held:

22nd April, 1975: "Shedding some light on the germination of seeds", Dr. R.D.B. Whalley, Botany Department University of New England.

5th October, 1975: "The role of animals in the epidemiology of influenza", Professor W.I.B. Beveridge, Professor of Animal Pathology, Cambridge University, England.

Financial Statement

Balance as at 31st March, 1975	$276.12	
Credit - Interest to 27.6.75	$4.83	
- Interest to 12.12.75	$5.60	$286.55
Debit - advertising, etc.	$8.07	$8.07
Balance as at 31st March, 1976		$278.48

ANNUAL REPORT OF THE SOUTH COAST BRANCH OF THE ROYAL SOCIETY OF NEW SOUTH WALES

Officers:

Chairman: B. Clancy
Secretary: G. Doherty
Representative on Council: G. Doherty

One function was held, in November 1975, sponsored jointly by the South Coast Branch and the University of Wollongong. At that function Mr. W. Peascod gave a stimulating tour, by slides and commentary, through some aspects of Japanese art and culture; Professor J.L. Griffith provided an illuminating, and humorously anecdotal, summary of the early history of the Royal Society and some of its prominent members; Mr. B. Doyle acquainted members with the state of the art in artificial insemination techniques, including in his talk some films on research in Australia and overseas. A buffet dinner was incorporated into the proceedings of the evening.

Financial Statement

Balance as at 31st March, 1975	$122.28
Credit : Accumulated interest	$ 4.29
Debit : Contribution to meeting and dinner	$ 80.37
Balance as at 31st March, 1976	$ 46.20

CITATIONS

THE SOCIETY'S MEDAL FOR 1975

The Society's Medal is awarded to a member of the Society for "meritorious contributions to the advancement of science. This may include administration and organization of scientific endeavour, and services to the Society".

The Award for 1975 is made to Mr. W.H. Robertson, Government Astrononer, Sydney Observatory.

William Humphrey Robertson joined the Society in 1948 and served on the Council of the Society from 1965 to 1975 and was always most active in its affairs.

The results of his scientific work have largely been published in the Journal and Proceedings to which he has contributed 33 papers. His work on minor planets reported in these papers is widely known and there has been comment on the reliable quality of the observations from Sydney Observatory, throughout the world.

Mr. Robertson is a member of the Organizing committee of the Commisssion concerned with this work in the International Astronomical Union. He is now Government Astronomer for New South Wales and his association with the Society continues a traditional association between the Observatory and the Society.

For the last two years Mr. Robertson has been actively involved in the Society's Summer Schools for Secondary School students in Astronomy.

THE JAMES COOK MEDAL FOR 1975

The James Cook Medal is awarded for outstanding contributions to Science and Human Welfare in and for the Southern Hemisphere.

The Award for 1975 is made to Dr. Allan Walsh, Assistant Chief, C.S.I.R.O., Division of Chemical Physics.

Although he spent the early part of his life in England, Dr. Allan Walsh has been with the Commonwealth Scientific and Industrial Research Organization since 1946, and he is now Assistant Chief of the Division of Chemical Physics. He is a versatile spectroscopist whose research has led to the development of a source unit for atomic emission spectroscopy, of multiple monochromators, of eschelette zone plates for far infra-red spectroscopy, and of microwave-powered Raman sources.

Dr. Walsh is, however, probably known best as the founder of atomic absorption spectroscopy, that branch of the science which has revitalized many segments of analytical chemistry. Wherever there is a need for trace-element analysis, this technique is used widely, especially in the fields of nutrition, food analysis, biochemistry, biomedicine, agriculture, mineral exploration and environmental science. In addition to a marked impact on research and development, it is estimated that atomic absorption spectrometry has been worth at least one hundred million dollars to Australia.

Dr. Walsh is an outstanding research scientist with a special gift for originality, with the tenacity necessary to overcome the many practical difficulties that have arisen during the past 21 years in atomic absorption spectroscopy, and with the personal qualities of leadership well recognized by his colleagues. In all his work, he shows an elegant simplicity, surely a mark of greatness.

Dr. Walsh has made profound contributions to science, and their applications in diverse fields are aiding human welfare. It has been said that "*spectroscopia est magister vitae*". It is equally true that Allan Walsh is a master of spectroscopy, and a worthy recipient of the James Cook Medal.

THE CLARKE MEDAL FOR 1975

The Clarke Medal is awarded for distinguished work in the Natural Sciences done in, or on, the Australian Commonwealth and its territories. It is considered annually and is awarded in the fields of Geology, Botany and Zoology in rotation.

The award for 1975 is made to Dr. J.N. Jennings, Professorial Fellow in Geomorphology, Department of Biogeography and Geomorphology, Australian National University.

Dr. Jennings has an international reputation as a geomorphologist for his studies of limestone Karst, of coastlines and of landform-shaping processes in cold climates. His reputation is no less as a teacher and supervisor of research at the Australian National University, where he has held his present position since coming to Australia from the United Kingdom in 1952.

Dr. Jennings' interest in the coast developed as a student of Alfred Steers at Cambridge. He established his own reputation with his studies of the Origin of the Broads. In Australia he continued his work on the coastline of King Island.

His interest in cold-climate landforms began at Cambridge, under W.V. Lewis, and developed with his taking part in expeditions to Jan Mayen and Iceland. It has been advanced in Australia with investigati investigations into the glaciation and periglaciation of the Snowy Mountains and Tasmania, and continues today in his 10 year study of snow action in Twynam Cirque.

Dr. Jennings is perhaps most widely recognised for his work on Karst in many parts of the world, first in his native Yorkshire and later in Europe, Turkey, the U.S., Malaysia, New Guinea, New Zealand and Zustralia. In this field too he has been most influential in promoting the work of others; he is a past-President of the Australian Spelaeological Federation, and of the Institute of Australian Geographers.

THE EDGEWORTH DAVID MEDAL FOR 1975

The Edgeworth David Medal is awarded for distinguished contribution by a young scientist, under the age of 35 years, for work done mainly in Australia or its territories or contributing to the advancement of Australian science.

The Award for 1975 is made to Dr. F.J. Ballard, Senior Research Scientist, C.S.I.R.O., Division of Nutritional Biochemistry.

After graduating with first class honours in biochemistry from the University of Western Australia, Dr. Ballard completed research for a Ph.D. He then went overseas to study at the Fels Research Institute, Pennsylvania, U.S.A., and was appointed an Assistant Professor there. In 1969 he returned to Australia as a Queen Elizabeth II Fellow, and in 1971 he joined the C.S.I.R.O. Division of Nutritional Biochemistry, where he is currently a Principal Research Scientist.

Dr. Ballard's research involves the study of the mechanisms and regulation of protein turnover in mammalian tissues. Following work on protein breakdown, a sequence of events has been established which permits measurements on the cellular factors responsible for regulation at each step. His research has led to the discovery that mammalian cells contain a system for the removal and degradation of abnormal proteins, such as may be formed by mutations, by or by the presence of abnormal amino acids.

Pathologically high rates of protein turnover are serious consequences of diabetes, dystrophic conditions and ischaemic heart disease, whereas rates are thought to be low during growth and in cancer tissue. Ballard's studies are aimed at modulating protein breakdown so that high or low rates may eventually be regulated by exogenous compounds.

Dr. Ballard has published widely in overseas and Australian journals, and he is held in high repute by his colleagues. Dr. Ballard's achievements mark him as an outstanding biochemist.

Obituaries

WILLIAM ROWAN BROWNE

William Rowan Browne, the most influential leader of geological research in New South Wales for a period of over fifty years was born in Lislea Co. Derry in December, 1884. He attended the Academical Institute, Coleraine, before coming to Australia for health reasons and taking up an appointment as tutor to country families in the New England and Goulburn districts. The change was evidently most beneficial as he remained active and intellectually stimulating up to the time of his death on 1st September, 1975.

Browne attended The University of Sydney from 1907 to 1909 gaining First Class Honours in Mathematics and Geology and the University Medal in Geology. In 1910 he was appointed First Assistant to G.F. Dodwell at Adelaide Observatory but was happy to receive Professor T.W.E. David's offer of the position of Junior Demonstrator in the Geology Department of The University of Sydney in 1911 departing however to become temporary Lecturer in mineralogy and petrology during the absence of Douglas Mawson who was exploring Antarctica. He returned to Sydney as Lecturer, becoming Assistant Professor in 1923 and Reader in 1939 retiring in 1950. For his work on the geology of Broken Hill he was awarded the degree of Doctor of Science with the University Medal.

Dr. Browne married Olga Marian Pauss, also a graduate in geology of The University of Sydney and they had two daughters Margaret Rowan and Helen Rowan (Mrs. F. Morley). After his wife's death in 1948 he married Ida Alison Brown a former student and Doctor of Science in Geology and during their last years in the department and for many afterwards they complemented each other's work and maintained a strong influence within the geological community.

Starting the geology course in 1929 I was fortunate to receive lectures from Professor L.A. Cotton on Tuesday and Assistant-professor W.R. Browne on Thursdays - the pair being known to us as Leo and Buster - the latter name being derived from our school-boy cartoon character, Buster Brown, the ancestor of the current Ginger Meggs. Though closely associated with them both for many years neither I - nor, I believe, their other academic colleagues ever used their Christian names. We were content with L.A.C. and W.R.B. and they likewise referred to Professor T.W.E. David as T.W.E.D. The affection we had for them was in no way diminished by this form of address.

I think we all held W.R.B. somewhat in awe when we were in first year and on our second year field excursions but the more we advanced and the more contact we had with him the closer we became and the more we appreciated his dedication to science and his command not only of petrology and geomorphology but of geology as a whole. His wide interests were well demonstrated by his contributions to "The Geology of the Commonwealth of Australia" which he took over on Professor David's death and after some years of painstaking work updating and editing the material saw through to publication in 1950.

For many years, both before and after retirement, Browne was editor or referee for most of the geological papers submitted to societies for publication and he insisted on the maintenance of high quality work. He was a fair but caustic critic and thereby did great service to many research workers who profited greatly by his advice. He served on the council or committee of many societies and organizations being President of the Linnean Society of New South Wales on two occasions (1928, 1944) and President of the Royal Society of New South Wales in 1932. He was awarded the Clarke Medal by the latter Society in 1942 and invited to give the Clarke Memorial Lecture in 1942. Seven years later the Council had the pleasure of awarding him the Society's Medal in recognition of his scientific contributions and services to the Society and conferring Honorary Membership upon him.

Browne was President of Section C of the Australian and New Zealand Association for the Advancement of Science in 1949. He was elected a Fellow of the Australian Academy of Science in 1954 and Honorary Life Member of the Geological Society of Australia in 1957.

Before and after retirement he was consultant to outside bodies such as the Sydney Water Board in connection with the Warragamba Dam project. He contributed greatly to the geomorphology of the Kosciusko area and worked for the preservation of a Primitive Area in the Summit region.

Apart from his scientific achievements and teaching ability W.R.B. will always be remembered by his students and associates as a delightful person with a dry and very quick wit which cannot be adequately expressed by repetition as its impact depended on the occasion when it was used. His reference to "the professor who shall be nameless, finding himself unable to afford the requisite underground installations for a new seismograph sought to solve his problem by acquiring a vault in the local cemetery where in a manner of speaking nobody happened to be living at the time" was produced while introducing Professor Bullen to the inaugural meeting of the Armidale branch of the Society.

Personally, I shall always remember the uncomfortable night we spent in the cell at Nowendo Police Station in 1939 - an event later explained to his Sydney colleagues as a result of our being caught after breaking into the till - the first strong evidence of Carboniferous rocks in the area.

There are many of us who treasure such memories of this fine gentleman who did so much in so many ways.

Alan A. Voisey

JULIUS WILLIAM HOGARTH

Julius William Hogarth died on the 19th September, 1975 at the age of 92 after a long and, in some respects, unusual career devoted to the service of chemistry.

His first publication, a short technical note communicated by J.A. Schofield, appeared in the Journal of the Royal Society of New South Wales in 1904. He began his university career at a later age than most students and in the middle of his under-graduate course became a personal assistant to Professor (later Sir) Robert Robinson. A further interruption to his university studies took place in 1914 when he joined the large body of chemists who were sent to Britain by the Commonwealth Government to help man the ammunition and explosive factories there. In his later years he often told stories of his experiences in the explosive factories during that period. After the war he returned to Sydney and in 1923 he was appointed as a teacher in chemistry at the Sydney Technical College. About this time he became a member of a group that carried out the chemical analyses of samples brought back by Mawson from the Antarctic. In 1928 he became Head Teacher of Chemistry at the College, a post he held for almost twenty years. Towards the end of this period he began to collaborate with F.P. Dwyer (later Professor of Chemistry at the Australian National University) on a study of cobalt amalgams. In 1948, at the age of 65, he retired. Then began what, in terms of chemical research, was the most productive period of his career. He moved to the University of Sydney to join Dwyer who, in the meantime, had become a member of the staff of the School of Chemistry. For the next three years his collaboration with Dwyer was eminently successful, so much so that he was persuaded to submit a thesis entitled "The Osmium Ammines" for a B.Sc. by research. The University was prepared to take an unusual step: on the strength of his unfinished degree course, begun nearly forty years earlier, and the thesis, it awarded him a B.Sc. by research. Much of the work was published in the Journal of this Society (vols. 84 and 85); some was published overseas. When in 1959, Dwyer became Head of the Biological Inorganic Chemistry Unit at the Australian National University, Hogarth moved to Canberra and, again in an honorary capacity, continued to work in the laboratory almost to his 80th year until finally his health failed him.

MAX RUDOLF LEMBERG

Max Rudolf Lemberg was born in 1896 in Breslau, the capital of Silesia, then a city of more than half a million almost entirely German inhabitants. He writes: "My mother's forbears had lived in Silesia, as manufacturers or wholesale merchants, from the time of Frederick the Great. My father's father had come to Breslau from the present Lwow in Galicia. In the liberal middle-class atmosphere of my parents' home adherence to the Jewish religion was more a matter of decent loyalty to one's forbears than a religious conviction.....Law, not science, was the family tradition. My father was one of the leading lawyers and notaries of Germany specialising in civil law.....Among my parents' cousins and relatives there were a number of scientists of repute, including Neisser, after whom the bacterial genus of the Neisseriae is named".

From school, a "liberal humanistic gymnasium", the young Lemberg went on to study chemistry, physics, mineralogy and geology at Breslau University. A few months later, war came. He volunteered, but then and on two later occasions was rejected as "too frail". Thus he was able to continue his studies in 1915 and 1916 at the Universities of Breslau, Munich and Heidelberg. His course was then interrupted for almost two years of military training and front line service in France as private, gunner and telephonist in the field artillery at the Chemin des Dames and in the Somme offensive of 1918. He wrote:- "I was wounded when this offensive, which we all knew would be our last effort, broke down in front of Montdidier. During the November 'revolution' (less an active revolt than a breakdown from complete exhaustion) I was in the Silesian garrison town to which I had returned after a severe attack of the influenza which spread like wildfire through the badly nourished civilian population, and which very nearly killed my wife-to-be. The war experiences had made me a convinced pacifist. I was not a coward and could face the dirt, danger, and death of the trenches, but what I found unbearable was the deliberate attempt to destroy human dignity, which the drill sergeants indulged in behind the front, encouraged by their officers. This *Schliff*, (polishing) was in fact the training school for the sadists of the concentration and extermination camps of Nazi days".

In 1919 Lemberg returned to Breslau University, where he passed his Ph.D. examination *summa cum laude* and accepted a position as private assistant to Biltz. But first he went for a three months' walking tour, sleeping in the hay or in peasant barns or in the few primitive Youth Hostels then in existence. This made a profound impression. He wrote (much later, in 1956): "A really satisfactory history of the Youth Movement has yet to be written. Even now, with knowledge of the immaturity and wistfulness of many of our dreams and the lack of concerted plans, I find it impossible to forget its magic power. It entirely altered the spirituality of its lower middle class members, giving its adherents a peculiar intensity to experience and live by commitment to one's own chosen values. Whosoever once belonged to it bears its stamp into old age and into foreign lands".

Lemberg was advised against an academic career because of the poor prospects for a scientist of Jewish descent at the German universities. So he accepted a position as an industrial chemist with a pharmaceutical firm of repute.

Of the next few years in Germany, he wrote: "It was an all-round dark period, with rampant inflation following the French occupation of the Ruhr. Our salaries were paid daily and had to be spent the same evening in town, because the next day their value had decreased by a factor of ten. I still own a tiny safety razor bought for two billion (10^{12} not 10^9) marks! The claim of the politicians that nothing could be done about it was demonstrated to be false when finally the currency was stabilized in a day - at the moment when it could be no longer avoided.........Thus the stage was set for the downfall of the Weimar Republic and for Hitler's rise".

Lemberg eventually realised that he "had not the makings of an industrial chemist" and managed to return to the University of Heidelberg in 1926 and to become a research worker. On Freudenberg's recommendation, he applied for a Rockefeller Foundation Fellowship to go to the Biochemistry Department of Hopkins at Cambridge. During his last year at Heidelberg, Lemberg and his wife were able to spend a summer climbing in the Alps. After this "the Nazi shadows began rapidly to gather". Lemberg was dismissed from his assistantship and, a few months later, when already at Cambridge, he was informed of his dismissal as a university lecturer by the letter of a German furniture removal firm offering its services! Restitution for the injustice then done was made in later years by appointment as an "Ordinary" Professor Emeritus of Heidelberg University and a Corresponding Member of the Heidelberg Akademie der Wissenschaften. The Lembergs settled in Cambridge in 1933, and Rudi continued to work on the bile pigments. Of course, not all the refugees could remain in Cambridge, but as Dr. Lemberg writes:..."leaving Cambridge was another serious crisis. The charm of English and particularly Cambridge life had had its effect. We had cycled through the southern parts of England and had seen the Lake District and Yorkshire and its old abbeys...Quakers of Cambridge had become our friends, long before we became members of the Religious Society of Friends in Australia". However, the third crisis was upon them, and in 1935 Dr. Lemberg accepted the position of research biochemist at the Royal North Shore Hospital, St. Leonards, Sydney, a position he was to hold and develop for the next 37 years. Before sailing he risked a last visit to his parents in Breslau, certain that he would not see them again. His mother, together with many other relatives, died in a concentration camp.

Apart from visits to Europe and to America, Lemberg was to spend the rest of his life, from 1936 until his death in 1975, in Australia.

E. Beatrix Durie.

Max Rudolf Lemberg, a member of the Royal Society of N.S.W. since 1936 and President in 1955, published several papers in the Journal of the Royal Society. In 1964 he was awarded the James Cook medal for services to science and human welfare in the Southern Hemisphere. In 1971 he was awarded the Walter Burfitt Price and Medal for his publications of highest scientific merit. He came to Australia in 1936 to take up the post of Biochemist at The Royal North Shore Hospital of Sydney. He was of part-Jewish descent and had fled Germany in 1933 for temporary haven and happiness in Cambridge which was at that time full of refugees from Nazi-ism.

Rudi was a man whom Australia particularly needed at that time. He came of a scholastic training having a mind capable both of intense and deep concentration on a scientific problem as well as of broad speculation on the place of science in human affairs and thought. In Sydney he submerged for a time into the job of establishing clinical chemistry at The Royal North Shore Hospital, emerging after the war as the founder of the Australian Biochemical Society and an initiater of ideas in the general Australian scientific scene. He became a foundation fellow of the Australian Academy of Science and a Fellow of the Royal Society (London) on the scientific side and a member of the Society of Friends (Quakers) on the philosophical side. As a Quaker he was prominent in public discussion of man's use of science. Being an idealist he was fearless in stating his opposition to misuse of science or, indeed, to any threats to the decency of man through war or political expediencies.

Lemberg is well known abroad and in Australia for a long series of scientific papers and several books (his most famous with Jack Legge). He was a long-time supporter of science in the clinical laboratories and did much to further their interests both at the hospital level and through the National Health Medical Research Council of whose various committees he was a member for many years. He will be remembered particularly by a large group of people who will recall with affection a basically gentle friend and scholar, sometimes roused to headlong action and occasionally exasperating - all because of his ideals and his deep concern for his fellow man.

D.B. Morell.

KATHLEEN SHERRARD

It is with regret, that the death on August 21st 1975, of Kathleen Sherrard (1898-1975) a valued member of the Royal Society of New South Wales is recorded.

Kathleen, the daughter of Dr. and Mrs. John McInerny of North Carlton, Victoria, had a tertiary education at the University of Melbourne, and graduated in 1918, majoring in geology and chemistry. As a Master of Science, she held the position of Assistant Lecturer and Demonstrator in the Department of Geology under Professor Skeats, until her marriage in 1928 with Howard Sherrard, an ex-serviceman of World War 1, a civil engineer, also a graduate of Melbourne University. After marriage the Sherrards made their home permanently in Sydney, New South Wales.

In 1929 and 1930, the first of Kathleen Sherrard's geological papers were published, one on the Victorian building stones of igneous type and the second on an occurrence of two Lansfield Lower Ordovician fossils: a phyllocarid and a brachiopod.

Kathleen Sherrard had many cultural interests besides geological research and during the following years projects included study of music, art and languages. When her sons were young, Max, the elder was born in 1935 and Owen in 1940, many charitable movements received her support, particularly those aiding the less-fortunate children. Nutrition and its effects on child growth was studied; systematic measurements were made on groups of school boys, providing useful data for the research by others.

Kathleen Sherrard enjoyed writing and her numerous contributions to magazines appeared in print from time to time. Their subjects varied widely; many focused on women's activities, careers, problems and involvements.

There was a life-long interest in earth sciences, particularly palaeontology. The scientific publications number fifteen; two of these were joint works; field work in Yass and adjacent areas of New South Wales provided material for several of the earlier reports of research work.

A large proportion of her papers describe graptolites and their occurrences in New South Wales. In 1950, a special visit of three months was made to Cambridge University, England, to study under Dr. Gertrude Elles, a world-famous graptologist. It is fitting, that a new monograptus, taken from the Forbes district of New South Wales and described recently should have been named sherrardae sp. nov., after Kathleen Sherrard, "in recognition of her pioneer work in the study of graptolites in New South Wales," (Sherwin, Records Geol. N.S.W. Vol. 16, Part 3, 1975).

In 1967, the Royal Society of Victoria (Vol.80, Pt. 2) published Kathleen Sherrard's work on Tentaculitids from New South Wales, Australia, research into which had begun some years before. Interest in Tentaculitids had been quickened by correspondence and later a visit to Moscow in 1963 to consult with Dr. Galina Ljaschenko, a Russian specialist palaeontologist.

Later there came the request to investigate Devonian Tentaculitids from North West Australia, and the results of this research were published this year. (Roy. Soc. Victoria Proceedings Vol.87, Pt. 1, 1975).

"Ancora Imparo" could well have been the maxim of Kathleen Sherrard, a person of fine intellect, a valued member of every society to which she belonged, who will be remembered for her generosity, forthrightness, humility and kindness and by her colleagues, in particular, for the warmth of her friendship.

The valuable assistance of Mr. Howard Sherrard in the preparation of this biographical sketch is gratefully acknowledged.

F.M. QUODLING

SIR ROBERT ROBINSON

A tribute has been paid to Sir Robert Robinson, an Honorary Member of the Society since 1948, by Professor Birch earlier in this Volume.

THE ROYAL SOCIETY OF NEW SOUTH WALES

BALANCE SHEET - 31ST DECEMBER 1975

1975 $		$	$
	RESERVES		
10,478	Library reserve (note 2 (i))		9,040
453,971	Resumption reserve (note 2 (ii))		424,564
5,214	LIBRARY FUND (note 2 (iii))		92,797
806	LONG SERVICE LEAVE FUND		806
16,793	ACCUMULATED FUNDS		37,822
$487,262	NET FUNDS		$565,029
	Represented by:		
	CURRENT ASSETS		
6,304	Cash at bank and in hand	9,826	
214	Cash at bank - Library fund (note 2 (iii))	297	
---	Debtors for subscriptions (note 3)	---	
1,394	Other current debtors and prepayments	1,409	
7,320	Short term deposits	9,282	
15,232			20,814
	Less		
	CURRENT LIABILITIES		
6,316	Sundry creditors and accruals	8,539	
366	Subscriptions paid in advance	2,093	
6	Life members subscriptions - current portion	4	
6,688			10,636
8,544	NET CURRENT ASSETS		10,178
	Add		
	FIXED ASSETS (notes 1 (b) and 5)		
2,208	Furniture and office equipment	2,122	
2	Lantern	2	
13,600	Library	13,600	
15	Pictures	14	
15,825			15,738
	INVESTMENTS (note 6)		
9,680	Commonwealth bonds and inscribed stock	9,680	
11,284	Short term deposits	---	
20,000	Loan secured by mortgage	20,000	
40,964			29,680
	ASSOCIATED CORPORATIONS (note 4)		
1	Shares	1	
421,990	Advances and loans - unsecured	509,490	
421,991			509,491
	TRUST FUNDS (note 7)		
7,000	Commonwealth bonds and inscribed stock	7,000	
3,396	Short term deposits	3,652	
10,396			10,652
497,720			575,739
	Less		
	NON-CURRENT LIABILITIES		
10,396	Trust funds (note 7)	10,652	
62	Life members subscriptions - non-current portion	58	
10,458			10,710
$487,262	NET ASSETS		$565,029

A. A. DAY
Hon. Treasurer

E. K. CHAFFER
President

THE ROYAL SOCIETY OF NEW SOUTH WALES

INCOME AND EXPENDITURE ACCOUNT FOR TEN MONTHS ENDED 31ST DECEMBER 1975

1975 $		$	$
(10,953)	NET SURPLUS (DEFICIT) for the period before bad debts		(13,413)
	Add		
641	REDUCTION in provision for bad debts		37
(10,312)			(13,376)
	Less		
430	SUBSCRIPTIONS written off		207
(10,742)	NET SURPLUS (DEFICIT) for period		(13,583)
	Add		
5,009	DONATIONS AND INTEREST to library fund (note 2 (iii))		87,583
---	SCIENCE HOUSE partnership (note 8)		3,767
1,645	TRANSFER from library reserve (note 2 (i))		1,438
---	TRANSFER from resumption reserve (notes 1 (c) & 2 (ii))		29,407
26,696	ACCUMULATED FUNDS brought forward from 1975		16,793
22,608	FUNDS AVAILABLE for appropriation		125,405
	Less		
5,009	TRANSFER to library fund (note 2 (iii))	87,583	
806	TRANSFER to long service leave fund	---	
5,815			87,583
$16,793	ACCUMULATED FUNDS - 31st December, 1975		$37,822

AUDITORS' REPORT TO THE MEMBERS

1. In our opinion (a) the attached Balance Sheet and Income and Expenditure Account, together with the notes thereon, have been properly drawn up so as to correctly show the state of the Society's affairs at 31st December, 1975 and the deficit for the ten months ended on that date.

   (b) the accounting and other records have been properly kept in accordance with the Rules of the Society.

2. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

65 York Street,
Sydney.
31st March, 1976

HORLEY & HORLEY
Chartered Accountants
Registered under the Public
Accountants Registration Act
1945 as amended.

THE ROYAL SOCIETY OF NEW SOUTH WALES
NOTES TO AND FORMING PART OF THE ACCOUNTS FOR THE TEN MONTHS ENDED 31ST DECEMBER 1975

1. SUMMARY OF SIGNIFICANT ACCOUNTING POLICIES

Set out hereunder are the significant accounting policies adopted by the Society in the preparation of its accounts for the 10 months ended 31st December, 1975. Unless otherwise stated, such accounting policies were also adopted in the preceding year.

(a) Accounting period

In order to rationalise the time between the close of the Society's financial year and the holding of the Annual General Meeting the Society's accounting period has been changed from 1st March - 28th February to 1st January - 31st December.

As a result of the above change in policy the figures for the current period represent 10 months operations while the comparative figures shown for 1975 represent 12 months operations.

(b) Depreciation

Depreciation is calculated on a written down basis so as to allow for anticipated repair costs in later years.

The principal annual rates in use are:		
	Furniture	7½%
	Office equipment	15 %

(Refer also note 5)

(c) Deficit from operations

The balance of the Resumption Reserve, after lending $416,990 to Science House Pty. Ltd., has been allocated to meet operating deficits.

2. MOVEMENTS IN PROVISIONS AND RESERVES

(i) LIBRARY RESERVE

1975 $		$	$
12,123	Balance at 1st March, 1975		10,478
	Less		
	Transferred to accumulated funds re		
1,058	Library recataloguing	1,292	
1,087	Typing & printing subject index	681	
2,145		1,973	
	Less		
500	Donation towards printing subject index	535	
1,645			1,438
$10,478	Balance at 31st December, 1975		$ 9,040
	Represented by:		
$10,478	Investments		$ 9,040

(See also note 6)

THE ROYAL SOCIETY OF NEW SOUTH WALES

NOTES TO AND FORMING PART OF THE ACCOUNTS FOR THE TEN MONTHS ENDED 31ST DECEMBER 1975 Cont.

2. MOVEMENTS IN PROVISIONS AND RESERVES Cont.

(ii) RESUMPTION RESERVE

1975 $		$	$
453,971	Balance at 1st March, 1975		453,971
	Less		
	Transferred to accumulated funds re		
---	- operating deficit - 1974	5,041	
---	- operating deficit - 1975	10,953	
---	- operating deficit - current period	13,413	
---			29,407
$453,971	Balance at 31st December, 1975		$424,564
	Represented by:		
1	Shares in associated corporations		1
416,990	Loans to associated corporations		416,990
18,604	Short term deposits		7,573
18,376	Investments		---
$453,971			$424,564

(See also notes 1 (c) and 4)

(iii) LIBRARY FUND

1975 $		$
205	Balance at 1st March, 1975	5,214
	Add	
5,009	Donations and bank interest	87,583
$ 5,214	Balance at 31st December, 1975	$ 92,797
	Represented by:	
214	Cash at bank	297
5,000	Loans to associated corporations	92,500
$ 5,214		$ 92,797

(See also note 4)

THE ROYAL SOCIETY OF NEW SOUTH WALES

NOTES TO AND FORMING PART OF THE ACCOUNTS FOR THE

TEN MONTHS ENDED 31ST DECEMBER 1975 Cont.

3. DEBTORS FOR SUBSCRIPTIONS

$		$
190	Owing by members	153
	Less	
190	Reserve for bad debts	153
---		---

4. ASSOCIATED CORPORATIONS

The Society has entered into a joint venture with the Linnean Society for the establishment of a Science Centre for New South Wales and to facilitate this, a company, Science House Pty. Limited, has been formed in which each Society has a 50% interest.

Advances and loans to the company have been made for an indefinite period on an interest free basis. No terms of repayments have been arranged. No material repayments are anticipated prior to 31st December, 1976.

1975 $		$
$421,990	Total amount advanced	$509,490
	Representing:	
416,990	Resumption reserve	416,990
5,000	Library fund	92,500
$421,990		$509,490

5. FIXED ASSETS

The basis adopted for the valuation of fixed assets is:

Furniture and office equipment - cost less depreciation
Lantern - cost less depreciation
Library - 1936 valuation
Pictures - cost less depreciation

6. INVESTMENTS

1975 $		$
10,478	Library reserve	10,478
18,376	Resumption reserve	---
806	Long service leave fund	806
11,304	General funds	18,396
$ 40,964		$ 29,680

THE ROYAL SOCIETY OF NEW SOUTH WALES

DETAILED INCOME & EXPENDITURE ACCOUNT FOR TEN MONTHS ENDED 31ST DECEMBER 1975

1975 $		$	$
	INCOME		
3,551	Membership subscriptions - ordinary		6,051
6	- life members		6
135	Application fees		158
3,692			6,215
1,325	Subscriptions to journals		1,950
1,750	Government subsidy		2,000
6,767	Total membership & journal income		10,165
5,872	Interest on general investments		4,136
---	Sale of reprints		1,924
4,723	Sale of back numbers		476
593	Sale of other publications		123
6	Donations - general		4
500	- printing journal & publications		705
97	Summer school surplus		---
18,558	TOTAL INCOME		17,533
	Less EXPENDITURE		
750	Accountancy		800
95	Advertising		---
518	Annual social		244
110	Audit		110
46	Branches of the society		---
167	Cleaning		142
199	Depreciation		187
121	Electricity		119
48	Entertaining		96
163	Insurance		213
315	Library purchases		409
73	Sale of reprints		---
1,058	Library recataloguing		1,292
261	Miscellaneous		463
427	Postages & telegrams		715
	Printing - Vol 108, parts 1 - 4	9,073	
	- Subject index	681	
	- Binding	175	
	- Postages	747	
9,327			10,676
861	Printing, general & stationery		822
5,058	Rent		4,006
150	Repairs		115
9,310	Salaries and superannuation		10,086
454	Telephone		451
29,511	TOTAL EXPENDITURE		30,946
$(10,953)	NET SURPLUS (DEFICIT) FOR TEN MONTHS		$(13,413)

THE ROYAL SOCIETY OF NEW SOUTH WALES

NOTES TO AND FORMING PART OF THE ACCOUNTS FOR THE

TEN MONTHS ENDED 31ST DECEMBER 1975 Cont.

7. TRUST FUNDS

1975 $		Clark Memorial	Walter Burfitt Prize	Liversidge Bequest	Olle Bequest	Total
$7,000	Capital	$3,600	$2,000	$1,400	$ ---	$7,000
	Revenue:					
607	Income for period	255	141	99	121	616
246	Less Expenditure	360	---	---	---	360
361		(105)	141	99	121	256
3,035	Balance from 1975	1,059	771	449	1,117	3,396
$3,396		$ 954	$ 912	$ 548	$1,238	$3,652

8. SCIENCE HOUSE PARTNERSHIP

The balance standing to the credit of the Society's capital and current accounts, previously written off at the time of the resumption of Science House by the Sydney Cove Redevelopment Authority, was refunded to the Society during the period as under:-

	$
Capital Account	3,005
Current Account	762
Total	$3,767

LOCATION

Large Hall, Science House, 157 Gloucester Street, Sydney.

APRIL 2ND

108th Annual General Meeting. The President Dr. J.W. Pickett was in the chair and 58 members and visitors were present. 3 new members were elected and Council announced the admittance of 16 new associate members. Council also announced the election by Council to Honorary Membership of Raymond James Wood Le Fevre.

The Clarke Medal was awarded to Dr. C.H. Tyndale-Briscoe; the James Cook Medal to Sir Mark Oliphant; the Walter Burfitt Prize to Dr. B.J. Robinson and the Archibald Olle Prize to David Ross Gray.

Messrs. Horley and Horley were elected Auditors.

The Presidential address "Corals and Models of Continental Distribution for the Silurian" was given by Dr. J.W. Pickett.

The incoming President, Mr. E.K. Chaffer, was installed and introduced to members.

MAY 7TH

883rd General Monthly Meeting. The President Mr. E.K. Chaffer was in the chair and 73 members and visitors were present. 11 new members were elected and Council announced the admittance of 6 new associate members.

An address "One Hundred Years of Oceanography" was given by Dr. F.H. Talbot, Director, The Australian Museum.

JUNE 4TH

884th General Montly Meeting. The President Mr. E.K. Chaffer was in the chair and 57 members and visitors were present. 9 new members were elected and Council announced the admittance of 3 new associate members.

An address "Stability and Dynamism in the Australian Settlement Pattern" was given by Professor A.J. Rose, Professor of Geography, Macquarie University.

JULY 2ND

885th General Monthly Meeting. The President Mr. E.K. Chaffer was in the chair and 27 members and visitors were present. 3 new members were elected and Council announced the admittance of 1 new associate member.

An address "Of Mice and Men : What Cultured Cells tell us" was given by Professor N.G. Stephenson, Zoology Department, University of Sydney.

AUGUST 6TH

886th General Montly Meeting. The President Mr. E.K. Chaffer was in the chair and 72 members and visitors were present. 3 new members were elected and Council announced the admittance of 1 new associate member.

Sir Mark Oliphant, Governor of South Australia, was present and accepted the James Cook Medal for 1974 from the President.

An address "The Importance of Atomic Energy to Australia" was given by Mr. K.F. Alder, Head, Nuclear Science and Technology Branch, Australian Atomic Energy Commission.

SEPTEMBER 3RD

887th General Montly Meeting. The President Mr. E.K. Chaffer was in the chair and 48 members and visitors were present. 6 new members were elected and Council announced the admittance of 2 new associate members.

Council also announced that commencing with Volume 109, the Journal and Proceedings of the Society would be produced by offset printing with the master typescript of contributed papers being prepared by the authors.

An address "World Mineral Resources - 1s there a Shortage?" was given by Dr. K.L. Williams, Senior Lecturer in Resource Geology, University of Sydney.

OCTOBER 1ST

888th General Monthly Meeting. The President Mr. E.K. Chaffer was in the chair and 75 members and visitors were present. 7 new members were elected and Council announced the admittance of 2 new associate members.

A symposium was held with the theme "Education in the Twenty-First Century". The panel of speakers comprised Dr. W.J.A. Vaughan, Director of Studies, N.S.W. Department of Education; Dr. I.W. Patterson, Principal, Knox Grammar School and Professor D. Cohen, School of Education, Macquarie University.

NOVEMBER 5TH

889th General Monthly Meeting. The President Mr. E.K. Chaffer was in the chair and 51 members and visitors were present. 4 new members were elected and Council announced the admittance of 2 new associate members.

An address "Tides; some theories old and new" was given by Professor V.J. Buchwald, School of Mathematics, University of New South Wales.

DECEMBER 3RD

890 General Monthly Meeting. The President Mr. E.K. Chaffer was in the chair and 60 members and visitors were present. 5 new members were elected and Council announced the admittance of 1 new associate member.

An address "Nothing New under the Sun; a realistic view of Solar Energy" was given by Professor D.W. George, Vice-Chancellor, University of Sydney.

LOCATION

Stephen Roberts Theatre, University of Sydney.

JULY 10TH

The Clarke Memorial Lecture was given by Dr. K.S.W. Campbell, School of Geology, Australian National University, the title of the address being "The Functional Anatomy of Phacopid Trilobites : Musculature and Eyes".

SEPTEMBER 4TH

The Pollock Memorial Lecture (in conjunction with the University of Sydney) was given by Professor J. Tugo, Director, Ontario Science Centre, Canada. The title of the address was "Tectonic Plate Movement relative to the Earth's Axis and Interior".

LOCATION

The Macleay Museum, University of Sydney.

OCTOBER 17TH

At a special meeting held with cooperation of Dr. P. Stanbury, Curator of the Macleay Museum, an address entitled "Alfred Wallace 1823 - 1913" was given by Professor R.E. Bernstein, a member of the Royal Society of South Africa.

MEMBERSHIP OF THE SOCIETY, APRIL 1976

During the year ended 31st March, 1976 the following changes in membership of the Society were effected.

ELECTION TO LIFE MEMBERSHIP

COHEN, Samuel Bernard, M.Sc.
CORTIS-JONES, Beverley, M.Sc.
HANLON, Frederick Noel, B.Sc.
MILLERSHIP, William, M.Sc.

ELECTION TO MEMBERSHIP

AQUILINA, Guy, B.Arch., 90/14 Blues Point Road, McMahon's Point, N.S.W., 2060 (1975).

BEAN, Judith May, B.Sc. (Hons), Ph.D. (UNE), P.O. Box 115, Rose Bay, N.S.W., 2029 (1975)

BEATTIE, Holford Ernest Rigel, B.V.Sc., M.A.C.V.Sc. (deceased 15.5.75).

BLACK, Peter Laurence, B.Sc., 39 Cummins Street, Broken Hill, N.S.W., 2880 (1975).

BROWN, Henry Emanuel, M.Sc., 9 Watford Close, Epping, N.S.W., 2121 (1975).

CAMPBELL, Kenton Stewart Wall, M.Sc., Ph.D., Geology Department, Australian National University, Canberra, A.C.T., 2600 (1975).

CHANDLER, Garry Anthony, 6 "Palomar" 49 Drumalbyn Road, Bellevue Hill, N.S.W., 2023 (1975).

CUDDY, Robert Graham, B.Sc. (Hons.) (Queens Uni.), M.Sc., (McMaster Uni.), Department of Geology, University of New England, Armidale, N.S.W., 2351 (1975).

D'ARCY, William Francis, B.Sc., c/- Department of Geology and Geophysics, University of Sydney, N.S.W., 2006 (1975).

DRUMMOND, David Gordon, M.Sc., Ph.D., F.Inst.P., 45 Albert Drive, West Killara, N.S.W., 2071 (1975).

FAYNE-SCOTT, Terence Graham, Chota Nalanda, Avoca Road, Grose Wold, N.S.W., 2753 (1975).

FINLAY, Cecily June, B.Sc., Minerals Research Laboratories, C.S.I.R.O., Box 136, North Ryde, N.S.W., 2113 (1975).

FISHER, John, FRAIA, ARIBA, 8 Glen Street, Milsons Point, N.S.W., 2061 (1975).

GHANIM, Ghanim Ali, B.Sc., 2/29 Bellevue Avenue, Greenwich, N.S.W., 2065 (1975).

GUNTHORPE, Robert John, B.Sc. (hons), Ph.D. (Uni. N.E.), Geology Department, Tsumeb Corporation Ltd., P.O. Box 40, Tsumeb, S.W. Africa, 9260 (1975).

HATCH, Marshall Davidson, B.Sc.(Hons.), Ph.D., F.A.A., Division of Plant Industry, C.S.I.R.O., P.O. Box 1600, Canberra City, A.C.T., 2601 (1975)

HAWKINS, David, 50 Beaumont Road, Killara, N.S.W., 2071 (1975).

JOHNSON, Brian David, B.A. (Hons.), 139 Adderton Road, Carlingford, N.S.W., 2118 (1975).

KELLY, John Charles, B.Sc.(Syd.), Ph.D.(Reading), D.Sc.(Uni.N.S.W.), F.Inst.P., 69 Yeramba Street, Turramurra, N.S.W., 2074 (1975).

KELLY, Peter, B.Sc., ASTC, M.Inst.P., MAIP, P.O. Box 307, Kings Cross, N.S.W., 2011 (1975).

KRAMER, Harold, M.B., Ch.B. (Uni. N.S.W.), D.Phil. (Oxon.), F.R.C.P.A., F.R.C.Path., F.A.C.M.A., F.A.A.C.B., The Institute of Clinical Pathology, and Medical Research, P.O. Box 108, Lidcombe, N.S.W., 2141 (1975).

KEMENY, Leslie George, B.E., M.I.E.(Aust.), 21 Westmeath Avenue, Killarney Heights, N.S.W., 2087 (1975).

McAULEY, William John Watson, B.Sc., 24 St. Niming Road, Brighton, Vic. (1975).

McGHEE, Moira Elizabeth, 28 Nielson Avenue, Carlton, N.S.W., 2218 (1975).

MICHELSON, Irvin, M.Sc. Ph.D., Professor of Mechanics, Illinois Institute of Technology, Chicago, Ill. 60616 U.S.A. (1975).

MOLLOY, Peter David, B.A., 16 Merriwa Street, Gordon, N.S.W., 2072 (1975).

MORGAN, Roger Paul, B.Sc.(Hons.) (Uni.W.A.), Mining Museum, 36 George Street, Sydney, N.S.W. 2000, (1975).

MOSKOS, Michael, B.E.(Mech.) (Uni.N.S.W.), 21 Baringa Road, Northbridge, N.S.W., 2063 (1975).

MURCH, Arthur James, 109 Palmgrove Road, Avalon Beach, N.S.W., 2107 (1975).

MURRAY, Richard Charles, 10 Rouse Street, Wingham, N.S.W., 2429 (1975).

NAZER, Roderick Eric, c/- Geology Department, University of Queensland, St. Lucia, Q'd., 4067 (1975).

PRASAD, Jean Veronica, Unit 32, 2-14 Pacific Street, Bronte, N.S.W., 2024 (1975).

PUTTOCK, Alan Maurice, A.C.A., 62 Margaret Street, Sydney, N.S.W., 2000 (1975).

RAMAGE, Bruce Robert, B.Sc., P.O. Box N121, Grosvenor St., Sydney, 2000 (1975).

STANBURY, Peter John Terence Cathcart, Administrator, Macleay Museum, University of Sydney, 2006 (1975).

STARLING, Hilda Phyllis Hargraves, 9 "Graydon Court", 221 Pacific Highway, Hornsby, N.S.W., 2077 (1975).

STEPHENS, Frederick Selwyn, B.Sc., Ph.D.(Uni.N.S.W.) School of Chemistry, Macquarie University, North Ryde, N.S.W., 2113 (1975).

ELECTION TO MEMBERSHIP CONTINUED

TAYLOR, Geoffrey Hamlet, D.Sc.(Melb.), 3 Palm Street, St. Ives, N.S.W., 2075 (1975).

TREAGUS, Roger Rowland, 4/6 McLeod Street, Mosman, N.S.W., 2088 (1975).

WALKER, Thelma Gwendolene, 44 Birtley Towers, Birtley Place, Elizabeth Bay, N.S.W., 2011 (1975).

WARD, Norman James, 19/41 Milray Avenue, Wollstonecraft, N.S.W., 2065 (1975).

WATERHOUSE, Michael Francis, B.E.(Hons.) Mech.Eng. (Uni.N.S.W.), M.Eng./Sc.(Uni.N.S.W.), M.App. Sc.(Uni.N.S.W.), 831 The Scenic Road, Kincumber, N.S.W., 2250 (1975).

WEATHERBURN, Charles, Dip.Arch.(Syd.), A.R.A.I.A., A.R.I.B.A., Unit 5, 6 Milner Crescent, Wollstonecraft, N.S.W., 2065 (1975).

WEATHERBURN, Gwynneth E., Unit 5, 6 Milner Crescent, Wollstonecraft, N.S.W., 2065 (1975).

WILD, Elizabeth Therese, 4 Eastern Avenue, Kensington, N.S.W., 2033 (1975).

WILD, John Joseph Berryman, B.D.S. (Syd.), 4 Eastern Avenue, Kensington, N.S.W., 2033 (1975).

WILLIAMS, Margaret Janet, 23 Parklands Road, Mt. Colah, N.S.W., 2079 (1975).

WRIGHT, Elaine, 3 Narena Close, Beecroft, N.S.W., 2119 (1975).

WRIGHT, Norbert Thomas, B.D.S.(Syd.), 3 Narena Close, Beecroft, N.S.W., 2119 (1975).

ELECTION TO ASSOCIATE MEMBERSHIP

CAWOOD, Peter Anthony, 75 The Boulevarde, Strathfield, N.S.W., 2135 (1975).

DAVIES, Philip Rhys, 21 Frederick Street, Gosford, N.S.W., 2250 (1975).

GIETZ, Timothy Charles, c/- International House, University of N.S.W., P.O. Box 1, Kensington, N.S.W., 2033 (1975).

GILL, Roderic, 61 Melaleuca Drive, St. Ives, N.S.W., 2075 (1975).

GRIFFITHS, David John, B.A., 70 Park St., Mona Vale, N.S.W., 2103 (1975).

HELLMAN, Phillip, 18 Banool Avenue, St. Ives,N.S.W. 2075 (1975).

JACKSON, Caroline Margaret, 23 Amy Road, Riverwood, N.S.W., 2210 (1976).

JOASS, Gregory George, 4 Gerroa Avenue, Bayview, N.S.W., 2104 (1975).

KEMENY, Anna Ruth, 21 Westmeath Ave., Killarney Heights, N.S.W., 2087 (1975).

KRUSE, Peter David, Dept. of Geology and Geophysics, University of Sydney, N.S.W., 2006 (1975).

LEAHEY, Trevor Allen, 8 Mason Avenue, Cheltenham, N.S.W., 2119 (1975).

LUCCHINI, Luke Paul, 5 Bunbury Avenue, Sutherland, N.S.W., 2232 (1975).

McMINN, Andrew, 80 Kissing Point Road, Turramurra, N.S.W., 2074 (1976).

MORAN, William Patrick, 20 Ruby Street, Gymea, N.S.W., 2227 (1975).

PENTECOST, Fred Edward, 51 Miowera Road, North Turramurra, N.S.W., 2074 (1975).

ROGERSON, Richard 52 Forbes St., Newtown, N.S.W., 2042 (1975).

SKRINJARIC, Marica Catherine, 6 Hereford Street, Botany, N.S.W., 2019 (1976).

SLADE, Rhonda Maree, 29 Irvine Street, Kingsford, N.S.W., 2032 (1976).

STEPHAN, Gina Dawn, 56 Eastern Road, Turramurra, N.S.W., 2074 (1975).

TAYLOR, Nancy Adrienne, 3 Palm Street, St. Ives, N.S.W., 2075 (1975).

TACHIBANA, Takashi James, 35 Waipori St., St. Ives, N.S.W., 2075 (1975).

THOMPSON, Denise Mary, 82 Awaba St., Mosman, N.S.W., 2088 (1976).

RESIGNATIONS OF MEMBERS

Margaret Beavis
Henry Roland Hoare
Maxwell Herbert McKay

MEMBERS WRITTEN OFF UNDER RULE 5(b)

Francis Edward Atkins
Norman Thomas Barker
Donald Westland Emerson
Brian Keith Hall
Anthony J. Irving
James Rhys Jones
Theodoor Seth Meijer Ranneft
Waclaw Szwidowski
Christopher John Lascelles Wilson

OBITUARY

Holford Ernest Rigel BEATTIE (1975) (deceased 25.5.75)

William Rowan BROWNE (1913; Pres. 1932) (deceased 1.9.75)

Julius William HOGARTH (1948) (deceased 19.9.75)

Max Rudolph LEMBURG (1936; Pres. 1955) (deceased 10.4.76)

Sir Robert ROBINSON (1948)

Kathleen Margaret SHERRARD (1936) (deceased 21.8.75)

Alexander STOCK (1961, New England Branch) (deceased 31.8.75)

Gilbert Percy WHITLEY (1963) (deceased 18.7.75)

THE ROYAL SOCIETY OF NEW SOUTH WALES

The Society originated in the year 1821 as the Philosophical Society of Australasia. Its main function is the promotion of Science through the following activities : Publication of results of scientific investigation through its Journal and Proceedings ; the Library ; awards of Prizes and Medals ; liaison with other Scientific Societies ; Monthly Meetings ; and Summer Schools for Senior Secondary School Students. Special Meetings are held for the Pollock Memorial Lecture in Physics and Mathematics, the Liversidge Research Lecture in Chemistry, and the Clarke Memorial Lecture in Geology.

Membership is open to any interested person whose application is acceptable to the Society. The application must be supported by two members of the Society, to one of whom the applicant must be personally known.

Membership categories are :

Ordinary Members : $18.00 per annum plus $3 application fee.

Absentee Members : $15.00 per annum plus $3 application fee.

Associate Members (spouses of members and persons under 25 years of age) : $5.00 per annum plus $2.00 application fee.

Associate Members (with Journal) : $12.00 per annum plus $2 application fee.

Subscription to the Journal, which is published in four Parts per year, issued twice yearly in May and November, for non-members is $22 p.a. plus postage.

For application forms for membership and enquiries *re* subscriptions, write to :

The Royal Society of New South Wales,
Science Centre,
35 Clarence Street,
Sydney, 2000, N.S.W.

The Society welcomes manuscripts of research (and occasional review articles) in all branches of science, art, literature and philosophy, for publication in the Journal and Proceedings.

Manuscripts will be accepted from both members and non-members, though those from the latter should be communicated through a member. A copy of the Guide to Authors is obtainable on request and manuscripts may be addressed to the Honorary Secretary (Editorial) at the above address.

THE ROYAL SOCIETY OF NEW SOUTH WALES SYDNEY
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