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Proper Motions in the Region of the Galactic Cluster NGC 6087

DAVID S. KING

ABSTRACT. Relative proper motions in the region of the galactic cluster NGC 6087 are determined with the aim of identifying stars which are non-members. The relative proper motions have an average standard error of 0".15/century and reveal 74 likely members and 83 likely non-members. Two probabilities of cluster membership are given, the first using only the proper motions and the second inserting positional information.

INTRODUCTION

The open cluster NGC 6087 (R.A. = $16^h14^m.7$, Dec. = $-57^o47'$; 1950.0) has been studied photometrically by Landolt (1963). The present investigation seeks to identify from both their proper motions and positions, those stars that are not members of the cluster.

THE PLATES

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

	Plate No.	Date Taken	Exposure	Plate Pair
1	21s	1892 Apr. 23	6 m	1
2	1402s	1894 Apr. 14	3 m	2
3	3346s	1897 May 1	30 m	3
4	N817	1923 May 19	4 m	4
5	N1111	1924 June 30	4 m	5
6	7846Sa	1979 June 25	20 m	4
7	8014Sa	1980 July 7	20 m	1
8	8146Sa	1981 Apr. 13	20 m	5
9	8150Sa	1981 Apr. 15	20 m	2
10	8166Sa	1981 June 3	20 m	3

Plate pairs 1, 4 and 5 were centred at R.A. 16^h12^m Dec. -58^o. Plate pairs 2 and 3 were centred at R.A. 16^h06^m Dec. -57^o (All 1900.0).

MEASUREMENT

The plates were each measured in a Grubb-Parsons photoelectric measuring machine in both direct and reverse positions. The reverse positions were converted into direct measures using plate constants and the average was recorded. All stars measured were selected from the published coordinates in the Astrographic Catalogue (Sydney Observatory 1954, plate N1111).

REDUCTIONS AND PROBABILITIES

The method of reduction and calculation of membership probabilities using only proper motions has been described in a previous paper (King 1979). In addition, the membership probabilities have now been calculated using a new method to be described fully in a future paper. This new method involves the introduction of an additional five distribution parameters apart from the nine parameters which describe the proper motion distribution.

The distribution parameters for the proper motion distribution in arc sec./century after eliminating 12 stars to obtain the best fit were:

$$\theta = 36^\circ.2 \quad N_f = 60 \quad X_f = -0.011 \quad \Sigma_x = 0.358 \quad X_c = -0.031$$

$$\sigma_c = 0.140 \quad N_c = 85 \quad Y_f = -0.564 \quad \Sigma_y = 0.708 \quad Y_c = +0.018$$

θ is the rotation angle of the observed proper motions ($+\mu$ to $+\nu$) into a new coordinate system defined by the principal axes of the apparent ellipsoidal distribution of field star motions. All the other parameters are defined in this new coordinate system. σ_c is the dispersion of the cluster star motions; N_f, N_c are the number of field and cluster stars. X_f, Y_f the centre of the field star proper motion distribution; Σ_x, Σ_y the field star proper motion dispersions; X_c, Y_c the centre of the cluster star proper motion distribution.

The distribution parameters for the total distribution taking proper motion and position into account after eliminating the same 12 stars to obtain the best fit were:

$$\theta = 36^\circ.5 \quad N_f = 71 \quad X_f = -0.008 \quad \Sigma_x = 0.337 \quad X_c = -0.037$$

$$\sigma_c = 0.130 \quad N_c = 74 \quad Y_f = -0.482 \quad \Sigma_y = 0.685 \quad Y_c = +0.024$$

$$\psi = 0^\circ.9 \quad \xi_c = 99.2 \quad R_\xi = 7.1$$

$$\eta_c = 102.3 \quad R_\eta = 7.9$$

The parameters in common with the proper motion distribution have the same meaning. The additional parameters are as follows. ψ is the rotation angle of the positions ($+\xi$ to $+\eta$) into new positional coordinates defined by the principal axes of the cluster. The remaining parameters are defined in this new coordinate system. ξ_c, η_c are the positional centre of the cluster in millimetres with 100.0, 100.0 being the star at $16^h14^m40^s.2$, $-57^o 47'13".8$. R_ξ, R_η are the cluster radii in millimetres containing half the stars in projection.

The centre of NGC 6087 is then R.A. = $16^h14^m 46^s$, Dec. = $-57^o46'30"$. Assuming a distance to the cluster of 910 pc as given by Landolt (1963), the linear diameter containing half the stars in projection would be 4.0 pc.

The standard errors for individual stars have been grouped by their magnitudes, and the mean of the standard errors σ_μ, σ_ν determined for different ranges are as follows:

Magnitude	σ_μ	σ_ν	No. of stars
	(Unit 0".01/cent)		
11.0 - 11.2	19.14	17.86	50
10.5 - 10.9	15.60	16.56	48
10.0 - 10.4	12.47	11.35	40
9.0 - 9.9	11.40	9.00	10
7.5 - 8.9	8.44	8.33	9
ALL	15.25	14.69	157

The absolute proper motion of the cluster NGC 6087 by comparison with 20 Cape Catalogue stars is +0".37 ± 0".10/cent. in R.A. and -1".70 ± 0".11/cent. in Dec. The proper motions used for this calculation were obtained from the differences between the 1945.6 epoch Cape positions and 1969.9 epoch Sydney Astrographic positions. The Sydney Astrographic positions were obtained from four plates taken through a Taylor, Taylor and Hobson lens giving a scale of 2' = 1mm. The plates are overlapped in R.A. and Dec. and were reduced using Perth 70 reference stars.

The observational data follows in Table 1. The various columns are:

- No. — The number from the Astrographic Catalogue, Sydney Section (centre 16^h12^m -58^o;1900.0)
- Mag. — The magnitude of the star taken from either the Cape Photographic Catalogue or the Sydney Astrographic Catalogue.
- R.A. — Right ascension (1950.0), all prefixed by 16^h.
- Dec. — Declination (1950.0).
- CPD No. — Cape Photographic Durchmusterung number.
- V — Photovisual magnitude from Mermilliod.
- M No. — Number as given in Mermilliod's Catalogue.
- μ, ν — Centennial proper motion in units of 0".01/cent. Motion of μ in R.A. and ν in Dec.
- σ_μ, σ_ν — Standard errors of centennial proper motion in units of 0".01/cent.
- P1 — Probability of cluster membership using motion only.
- P2 — Probability of cluster membershiip using motion and position.
- Notes — 1 - The Cepheid variable S Normae.
  6 - Not used in the calculation of distribution parameters.

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TABLE 1

THE OBSERVATIONAL DATA

No.	Mag.	R.A.	Dec.	CPD No.	V	M No.	μ	ν	σ_μ	σ_ν	P1	P2	Notes
1820	10.8	11 54.3	-57 40 21.0	7727			-51	-10	18	17	4	0	
1726	10.4	11 55.8	-57 43 19.5	7729			- 4	17	2	4	95	49	
1987	11.2	11 59.9	-57 28 51.6				37	-17	14	5	31	0	
1723	11.1	12 02.4	-57 45 58.6	7732			9	4	7	8	96	55	
1473	10.2	12 03.8	-57 56 00.6	7733			-303	-1019	12	8	0	0	6
1722	11.0	12 05.9	-57 44 52.2	7735			23	59	4	2	1	0	
1472	10.8	12 09.5	-57 53 03.5	7736			-80	-104	7	25	0	0	
1916	10.4	12 13.3	-57 35 13.2	7737			-13	- 7	16	6	92	35	
1721	11.1	12 13.7	-57 47 16.0				39	- 8	22	25	44	2	
1471	11.1	12 23.2	-57 53 26.1				-79	-120	32	16	0	0	
1357	10.8	12 23.6	-58 02 20.5	7741			-90	- 7	13	20	0	0	
1245	11.0	12 33.2	-58 04 11.3	7742			-81	-208	29	16	0	0	
1717	11.0	12 33.8	-57 46 44.8	7743			1	12	4	19	96	75	
1601	10.2	12 36.6	-57 48 20.5	7744			0	-20	14	10	85	36	
1984	11.2	12 38.8	-57 29 27.8				-111	-107	4	27	0	0	
1355	11.0	12 42.0	-57 57 53.3	7745			-46	-18	18	3	5	0	
1983	10.8	12 42.5	-57 30 24.1	7749			10	11	12	11	95	51	
1716	11.1	12 45.0	-57 46 53.1	7747			-24	-42	6	10	3	0	
1468	10.8	12 48.5	-57 55 03.7	7753			-106	17	16	23	0	0	
1467	10.8	12 48.8	-57 54 51.1	7752			31	27	11	27	44	6	
1982	10.4	12 55.5	-57 27 46.9	7755			-17	-94	9	19	0	0	
1465	10.4	13 09.4	-57 56 41.7	7757			-14	6	13	7	94	77	
1594	11.0	13 12.0	-57 52 03.2	7759			- 5	-39	7	15	19	3	
1239	10.8	13 13.3	-58 03 52.3	7758			-11	-50	18	20	1	0	
1814	10.8	13 16.2	-57 38 31.6	7761			-112	-110	15	5	0	0	
1351	9.9	13 21.0	-57 57 58.2	7762			- 7	- 3	6	7	95	81	
1980	11.1	13 23.3	-57 32 23.1				-127	-94	23	8	0	0	
1462	11.1	13 36.4	-57 55 49.5	7765			-101	-149	28	11	0	0	
1707	11.0	13 37.9	-57 45 38.5				4	-168	29	22	0	0	6
1812	11.1	13 38.5	-57 39 22.4				-19	- 4	10	39	90	81	

TABLE 1 continued

No.	Mag.	R.A.	Dec.	CPD No.	V	M No.	μ	ν	σ_μ	σ_ν	P1	P2	Notes
1706	10.8	13 38.7	-57 45 46.1	7766			-52	- 7	34	20	4	1	
1811	11.0	13 39.9	-57 40 44.1	7767			-12	75	17	21	0	0	
1590	10.8	13 42.7	-57 50 57.1	7768	11.90	106	5	- 5	13	4	95	94	
1589	8.6	13 43.7	-57 48 59.5	7769	7.49	12	- 6	-18	10	7	87	84	
1348	10.0	13 48.9	-57 58 57.1	7771			9	-13	4	10	91	74	
1907	10.6	13 49.0	-57 33 17.5	7774			4	- 3	9	11	96	84	
1588	10.0	13 49.5	-57 51 53.2	7773	8.71	16	-65	-36	11	8	0	0	
1906	11.0	13 49.7	-57 34 20.7	7776			-94	-192	30	23	0	0	
1235	11.0	13 50.9	-58 04 56.5	7772			-286	-51	16	22	0	0	6
1457	8.7	13 51.8	-57 55 49.2	7775	8.78	17	-22	-57	2	5	0	0	
1347	10.4	13 53.5	-58 02 17.9	7777			-117	-168	9	9	0	0	
1234	10.6	13 56.1	-58 05 15.4	7778			-21	12	13	10	90	53	
1705	10.0	13 57.3	-57 43 41:1	7779	10.18	15	- 7	- 2	15	3	95	97	
1904	10.8	14 00.9	-57 36 04.8	7781			47	27	22	6	4	1	
1585	10.2	14 01.7	-57 50 08.3	7780			-13	11	15	10	94	97	
1704	11.1	14 04.2	-57 45 51.2	7783			-24	16	27	29	86	93	
1233	10.8	14 05.7	-58 06 53.8	7784			-95	-108	7	21	0	0	
1584	10.6	14 07.0	-57 48 23.4	7786	10.31	44	14	4	9	19	94	97	
1805	10.4	14 07.6	-57 41 24.1	7788			- 3	12	10	6	96	97	
1583	10.6	14 09.0	-57 50 32.1	7789			- 8	4	6	10	96	98	
1903	11.0	14 11.4	-57 35 51.0	7790			-12	- 5	18	25	93	89	
1703	9.7	14 13.6	-57 44 10.5	7791	9.70	14	4	14	7	11	95	98	
1702	10.8	14 14.9	-57 46 23.4	7792			38	-16	11	18	29	38	
1801	9.2	14 15.8	-57 42 14.9	7793	9.31	13	6	13	12	5	95	98	
1580	10.4	14 19.7	-57 51 42.9	7794			7	37	8	23	68	79	
1700	10.4	14 20.9	-57 45 21.1	7796	11.39	41	6	11	8	14	96	99	
1579	11.1	14 21.3	-57 49 22.7				10	-14	21	42	90	96	
1699	10.8	14 25.5	-57 45 52.6	7798			- 3	20	9	29	94	99	
1226	11.1	14 26.5	-58 05 49.5				74	-63	25	38	0	0	
1800	11.0	14 27.8	-57 39 14.4	7802			18	-14	16	32	85	86	
1343	10.4	14 27.9	-57 58 44.5	7799			-30	-13	17	15	58	35	
1698	10.6	14 27.9	-57 43 51.0	7801			-28	7	20	11	82	94	
1342	11.0	14 28.0	-58 01 57.4	7800			-14	-44	8	13	4	0	
1577	9.3	14 28.3	-57 49 03.1	7803	9.39	11	12	9	8	7	95	99	
1902	8.1	14 28.9	-57 34 28.9	7804	8.31	1	8	- 8	5	2	94	88	
1975	10.6	14 30.7	-57 31 52.6	7805			7	- 2	6	18	95	86	
1799	11.0	14 34.6	-57 40 46.6	7808			-15	33	14	9	75	86	
1575	9.7	14 37.5	-57 49 28.1	7811			- 3	- 1	13	6	96	99	
1341	8.3	14 38.1	-58 00 50.3	7809	8.45	20	- 4	-17	8	10	88	71	
1452	10.8	14 38.5	-57 55 28.4	7814			-38	64	27	17	0	0	
1340	11.1	14 39.3	-57 57 48.8	7815			-38	-57	28	39	0	0	
1574	7.6	14 39.4	-57 48 35.0	7816	7.94	10	-10	-13	12	9	90	98	
1695	10.0	14 40.2	-57 47 13.8	7817	9.69	25	- 3	4	5	7	96	99	
1798	11.1	14 40.6	-57 39 05.6	7820			11	17	19	16	93	96	
1573	8.5	14 41.0	-57 49 23.1	7818			21	- 5	6	11	89	97	
1694	10.6	14 41.8	-57 44 41.7	7819			- 5	226	14	13	0	0	6
1693	7.5	14 42.4	-57 46 42.7	7821	6.11	131	4	- 4	14	18	95	99	1
1973	11.1	14 45.8	-57 29 39.5				9	24	14	25	90	63	
1571	10.8	14 46.6	-57 48 21.0	7823			15	20	9	5	90	98	
1570	11.0	14 47.2	-57 49 10.8	7822			6	17	20	8	94	99	
1900	10.6	14 47.7	-57 37 08.1	7827			-21	1	16	9	90	90	
1691	10.8	14 48.1	-57 44 37.4	7825			4	-13	27	20	92	98	
1449	11.1	14 48.8	-57 55 46.3	7824			- 4	- 6	18	22	95	96	
1899	10.2	14 48.9	-57 37 36.7	7829			-34	-29	7	6	8	4	
1689	10.8	14 49.9	-57 43 11.0	7830			- 5	4	13	27	96	99	
1336	10.2	14 51.3	-57 59 38.5	7828	10.63	50	- 1	1	13	8	96	93	
1796	10.6	14 51.5	-57 42 13.3	7831	11.45	38	5	- 5	7	11	95	99	
1971	10.4	14 53.4	-57 32 23.9	7834			-14	-31	7	6	40	11	
1448	10.4	14 53.5	-57 54 27.3	7832			-15	21	18	21	91	95	
1447	10.8	14 55.2	-57 57 30.4	7833			-14	-17	25	17	83	76	
1687	10.4	14 55.3	-57 43 05.6	7835	11.02	37	- 1	12	16	11	96	99	
1446	10.6	14 57.9	-57 54 29.1	7836			-52	-69	15	16	0	0	
1970	10.8	14 58.5	-57 31 14.4	7838			-14	10	8	20	94	83	
1568	11.1	14 59.2	-57 49 29.7	7837	12.09	66	- 6	10	16	5	96	99	
1897	10.2	15 03.4	-57 34 29.6	7841			-14	3	12	6	94	90	
1335	10.6	15 03.7	-57 59 07.9	7839			12	- 1	13	19	95	90	
1567	11.0	15 05.7	-57 51 09.5	7843			9	- 5	13	13	94	98	

TABLE 1 continued

No.	Mag.	R.A.	Dec.	CPD No.	V	M No.	μ	ν	σ_{μ}	σ_{ν}	P1	P2	Notes
1566	11.0	15 06.0	-57 49 59.6	7845			10	-50	18	11	2	2	
1895	11.1	15 06.6	-57 36 03.5				-14	-36	29	14	21	8	
1334	9.4	15 06.8	-57 58 14.1	7842	7.67	21	59	167	16	13	0	0	6
1565	11.1	15 07.1	-57 50 54.6	7846			7	-56	7	24	0	0	
1686	10.1	15 08.1	-57 46 05.0	7847			-117	-137	27	16	0	0	
1685	10.8	15 08.8	-57 45 58.3				40	- 8	19	27	34	54	
1894	11.0	15 08.9	-57 36 26.8	7849			- 4	43	11	5	49	35	
1684	9.0	15 08.9	-57 46 21.8	7848			- 2	35	15	6	77	93	
1683	10.0	15 10.8	-57 45 08.1	7850	10.38	36	- 4	- 3	4	14	95	99	
1682	10.0	15 11.7	-57 47 09.0	7851			-145	-134	15	7	0	0	
1892	10.6	15 13.1	-57 34 57.3	7853			- 2	4	16	7	96	94	
1563	10.4	15 14.6	-57 48 53.0	7852			- 6	7	11	12	96	99	
1681	8.8	15 15.6	-57 45 54.5	7854	8.97	8	- 7	2	7	3	96	99	
1792	10.8	15 15.9	-57 39 07.5	7856			- 5	20	19	7	94	96	
1562	11.1	15 26.4	-57 48 19.4				3	6	14	19	96	99	
1561	9.4	15 26.9	-57 48 52.0	7858	9.41	9	- 2	23	3	10	93	97	
1680	8.2	15 28.8	-57 47 09.4	7859	8.28	7	13	-15	12	10	88	94	
1557	10.4	15 36.1	-57 52 34.5	7861			- 5	27	4	10	90	91	
1556	11.0	15 36.5	-57 49 00.1	7862			8	-26	22	27	71	74	
1218	10.4	15 36.6	-58 07 02.1	7860			-210	-49	11	15	0	0	6
1554	11.0	15 41.0	-57 48 39.8	7864			44	-31	13	21	2	1	
1965	11.0	15 41.3	-57 29 31.9	7867			131	-232	23	18	0	0	6
1440	10.0	15 43.6	-57 55 57.9	7865			-22	17	8	9	88	79	
1217	9.7	15 44.9	-58 02 49.7	7866			-65	-29	20	11	0	0	
1791	11.0	15 45.1	-57 38 17.8	7869			10	-18	22	18	86	73	
1963	10.8	15 47.4	-57 32 29.7	7870			-37	-50	23	19	0	0	
1962	11.1	15 48.4	-57 32 26.5				-16	-15	31	13	84	47	
1789	11.1	15 49.0	-57 38 27.3	7871			-34	-35	29	22	3	1	
1678	10.0	15 49.7	-57 47 16.5	7872	10.29	5	-17	12	9	7	93	94	
1677	11.0	15 51.4	-57 44 50.6	7873			1	- 5	19	11	95	96	
1788	10.4	15 56.0	-57 38 17.6	7874			-107	89	25	3	0	0	6
1787	10.0	15 56.6	-57 37 46.7	7875			-12	3	4	4	95	89	
1888	11.1	15 56.6	-57 36 35.4				6	-34	28	5	40	11	
1215	9.6	16 00.2	-58 03 50.0	7876			- 7	13	14	14	95	73	
1214	11.0	16 04.0	-58 03 47.0	7877			13	12	29	4	94	64	
1672	10.6	16 06.7	-57 44 18.0	7878			-14	-45	26	22	4	1	
1330	11.0	16 07.7	-58 00 44.6	7879			- 5	8	12	23	96	82	
1549	10.8	16 08.9	-57 49 44.0	7883			-22	1	18	11	89	82	
1212	10.8	16 10.4	-58 05 10.1	7882			223	-267	5	22	0	0	6
1439	11.0	16 17.6	-57 54 54.3	7884			4	14	22	9	95	86	
1548	10.6	16 17.7	-57 50 20.4	7885			33	- 3	8	6	66	33	
1437	10.6	16 19.4	-57 57 11.1	7887			-47	- 5	23	21	11	1	
1547	10.6	16 22.2	-57 49 13.3	7890			- 2	10	22	12	96	91	
1784	10.8	16 25.2	-57 38 09.1	7893			-35	-49	16	19	0	0	
1436	10.8	16 26.5	-57 56 49.3	7892			- 1	-27	10	18	69	21	
1671	11.1	16 29.8	-57 44 45.2	7895			17	-79	42	20	0	0	
1957	10.0	16 35.2	-57 30 31.2	7896			1	20	12	17	94	56	
1545	10.8	16 38.6	-57 48 41.5	7897			-27	19	17	19	79	43	
1782	10.4	16 40.6	-57 37 52.2	7899			-30	5	10	17	78	30	
1668	10.2	16 44.0	-57 43 46.3	7901			-235	-249	21	19	0	0	6
1327	10.2	16 45.6	-57 59 14.6	7902			-14	52	18	21	11	1	
1665	10.8	16 49.0	-57 45 49.5	7904			5	-77	18	14	0	0	
1883	10.2	16 57.3	-57 36 12.9	7906			-112	-51	11	15	0	0	
1325	10.8	16 57.7	-58 00 35.4	7905			32	-22	28	27	36	2	
1881	11.0	17 05.0	-57 33 22.0	7908			-91	-136	29	21	0	0	
1540	10.0	17 11.1	-57 47 56.0	7909			-20	- 4	18	21	89	43	
1662	10.0	17 11.8	-57 44 43.8	7911			26	9	26	20	84	28	
1538	10.6	17 25.5	-57 52 19.1	7917			17	- 3	21	25	92	40	
1320	10.8	17 26.3	-57 57 44.4	7919			13	225	17	20	0	0	6
1207	10.0	17 27.3	-58 04 31.2	7918			1286	-620	24	10	0	0	6

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Precise Observations of Minor Planets at Sydney Observatory During 1981

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ABSTRACT. Positions of 3 Juno, 11 Parthenope, 18 Melpomene, 39 Laetitia, 51 Nemausa and 148 Gallia 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 1981 are given here. The methods of observation were described in the first paper (Robertson 1958). All the plates were taken with the 23 cm camera (scale 116" to the millimetre). Two or four exposures were taken on each plate, depending on the brightness of the planet. The number of exposures on each plate is indicated in Table 1.

In Table 1 are given the means of the positions for all the exposures using all six reference stars at the mean of the exposure times. The result for the first pair of images was compared with that for the last two by adding the motion computed from the ephemeris for the plates with four exposures. The r.m.s. differences were $0^s.009$ Sec δ in right ascension and $0''.19$ in declination.

No correction has been applied for aberration, light time or parallax, but the factors give the parallax correction when divided by the distance. 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. The ephemeris for 51 Nemausa was obtained from L.K. Kristensen (University of Aarhus, Denmark).

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 six star dependences. The reference star positions were converted to standard coordinates for the calculation of six star 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 of the star in the SAO catalogue or the zone and number of the star in the AGK3 catalogue. The column headed "Vol." gives the volume of the SAO or AGK3 in which the star is listed. The first column gives a serial number which cross-references Table 1 and Table 2 and also the catalogue from which the reference stars were taken.

All plates were reduced by both the method of dependences and by first order plate constants using the same six reference stars. Equal results were obtained in each case, as could be expected due to the formal identity of the two methods. The r.m.s. residuals of the reference stars were obtained by taking for each star the mean residual from the plate constants fitted to the first and last pairs of images, summing the squares of these residuals in right ascension and declination for all stars on all plates with four exposures and dividing the result by the appropriate number of degrees of freedom. For AGK3 stars the r.m.s. residual was $0''.38$ (3 plates) while for SAO stars it was $0''.83$ (22 plates).

Using six star dependences instead of two sets of three star dependences, as had been employed in reducing observations from years previous to 1978, has the disadvantage that a direct measure of the uncertainties in the measured positions is no longer available and the uncertainties have to be found by indirect means. The method used was described in a previous paper (Lomb 1980). The standard errors calculated in this way are listed in Table 3.

The plates were measured by Mrs J. Close, Miss D. Teale and Miss R. Skeers. The observers at the telescope were D.S. King (K), N.R. Lomb (L), W.H. Robertson (R) and K.P. Sims (S).

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TABLE 1

POSITIONS OF MINOR PLANETS

No.		R.A. (1950.0) h m s	Dec. (1950.0) ° ' "	Parallax Factors s	"	O - C s	"	No. of Exp.	
	3 Juno 1981 U.T.								
1756	Mar. 03.75613	14 31 00.474	-05 24 57.75	+0.057	-4.15	-0.021	+0.16	4	L
1757	Mar. 09.71344	14 30 08.423	-04 50 32.51	-0.022	-4.22	-0.044	+0.28	4	R
1758	Mar. 16.72342	14 28 07.599	-04 05 26.28	+0.071	-4.33	-0.058	+0.83	4	S
1759	Apr. 09.63250	14 14 23.482	-01 10 36.67	+0.023	-4.70	-0.014	-0.11	4	R
1760	Apr. 15.61899	14 09 48.993	-00 27 04.87	+0.041	-4.80	-0.014	+0.06	4	S
1761	May 25.48098	13 42 23.837	+02 37 30.09	+0.011	-5.18	-0.011	+0.31	4	R
1762	June 09.43689	13 37 56.368	+02 42 10.78	+0.011	-5.19	+0.022	+0.06	2	R
	11 Parthenope 1981 U.T.								
1763	May 05.78735	19 57 27.777	-17 27 14.46	-0.014	-2.47	-0.007	+0.96	4	L
1764	June 03.72735	20 11 08.462	-17 04 26.79	+0.017	-2.53	-0.084	+0.78	4	S
1765	June 10.71350	20 10 49.247	-17 13 34.92	+0.034	-2.51	-0.129	+0.34	4	K
1766	June 29.65304	20 02 37.145	-18 10 46.12	+0.025	-2.36	-0.096	+0.62	4	L
1767	July 09.63222	19 54 42.012	-18 56 28.31	+0.064	-2.27	-0.020	+0.55	4	R
1768	July 30.55067	19 35 35.521	-20 42 25.81	+0.029	-1.99	-0.011	+0.28	4	S
1769	Aug. 20.47257	19 22 53.290	-22 07 16.65	-0.011	-1.77	-0.002	-0.18	4	R
1770	Aug. 27.45436	19 21 32.576	-22 26 57.65	-0.005	-1.72	-0.018	-0.13	4	R
1771	Sep. 02.45414	19 21 42.011	-22 40 08.75	+0.049	-1.70	+0.032	-0.21	4	S
1772	Sep. 15.39966	19 26 05.682	-22 56 48.74	-0.024	-1.65	+0.029	+0.12	4	R
1773	Sep. 22.39261	19 30 35.588	-22 59 08.11	+0.005	-1.64	+0.017	-0.17	4	L
1774	Sep. 28.38409	19 35 30.956	-22 57 20.53	+0.020	-1.65	-0.037	-0.03	4	K
	18 Melpomene 1981 U.T.								
1775	June 03.78480	21 51 39.708	-05 47 54.82	-0.021	-4.13	-0.005	+0.50	2	S
1776	July 29.66981	22 16 17.969	-06 49 52.01	+0.043	-3.99	+0.064	-0.36	4	S
1777	Aug. 25.58231	22 00 18.802	-12 09 11.99	+0.035	-3.25	+0.007	+0.32	4	L
1778	Sep. 01.54359	21 55 13.999	-13 43 17.82	-0.015	-3.02	-0.041	-0.08	4	R
1779	Sep. 18.50288	21 46 19.516	-17 01 43.76	+0.023	-2.54	-0.027	-0.54	4	L
1780	Sep. 28.47617	21 45 04.873	-18 22 57.30	+0.027	-2.34	+0.018	-0.42	4	K
1781	Oct. 06.44022	21 46 42.731	-19 05 17.47	-0.022	-2.24	-0.010	+0.01	4	R
1782	Oct. 22.41046	21 56 51.737	-19 31 30.26	+0.001	-2.17	+0.038	-0.72	4	R
	39 Laetitia 1981 U.T.								
1783	Mar. 04.75796	14 32 59.523	-04 56 12.83	+0.067	-4.21	+0.046	-0.53	2	L
1784	Mar. 12.71755	14 32 18.007	-04 14 45.35	+0.011	-4.30	+0.008	+0.41	2	R
1785	June 02.45400	13 44 43.958	+02 17 12.33	-0.009	-5.14	+0.043	-0.38	2	R
1786	June 24.39586	13 43 18.431	+01 31 23.83	-0.001	-5.04	+0.009	+0.21	2	K
	51 Nemausa 1981 U.T.								
1787	Jan. 13.45102	04 01 29.234	+06 09 52.70	+0.048	-5.64	+0.030	-0.06	2	L
	148 Gallia 1981 U.T.								
1788	July 29.64787	21 36 56.878	-07 56 49.20	+0.060	-3.84	-0.004	+0.46	2	S
1789	Aug. 25.54536	21 16 34.450	-14 18 37.20	+0.015	-2.93	-0.003	+0.32	2	L
1790	Sep. 01.51343	21 11 40.558	-15 57 49.84	-0.015	-2.69	-0.007	+0.77	2	R
1791	Sep. 18.47069	21 03 40.682	-19 27 37.87	+0.014	-2.18	+0.042	+0.65	2	L
1792	Sep. 22.46460	21 02 50.451	-20 08 26.77	+0.032	-2.08	+0.058	+0.54	2	L

TABLE 2

REFERENCE STAR POSITIONS AND DEPENDENCES

No.	Vol.	Star	Depend.	R.A.	Dec.	No.	Vol.	Star	Depend.	R.A.	Dec.
1756	3	139958	0.105690	04.780	23.08	1767	3	163065	0.176886	27.272	20.44
SAO	3	139967	0.189176	04.355	38.75	SAO	3	163096	0.197455	39.615	23.66
	3	139983	0.068525	42.778	16.09		3	163109	0.130258	45.079	37.02
	3	139994	0.276000	42.517	59.75		3	163161	0.196127	22.666	14.95
	3	140025	0.113798	34.114	49.72		3	163176	0.137158	52.128	36.99
	3	140048	0.246810	55.523	52.56		3	163217	0.162117	58.543	48.39
1757	3	139958	0.166783	04.780	23.08	1768	3	188324	0.165336	54.666	59.11
SAO	3	139967	0.178633	04.355	38.75	SAO	3	188345	0.144826	54.224	17.20
	3	139983	0.155264	42.778	16.09		3	162834	0.126143	07.229	23.65
	3	139994	0.185710	42.517	59.75		3	188406	0.209222	46.323	17.87
	3	140028	0.165739	43.786	44.61		3	188413	0.191876	56.293	14.40
	3	140040	0.147872	10.674	17.56		3	188418	0.162597	05.539	49.54
1758	3	139947	0.146683	25.443	54.28	1769	3	188032	0.172975	16.354	11.51
SAO	3	139963	0.212641	32.488	48.99	SAO	3	188053	0.174528	13.014	42.59
	3	139971	0.101831	32.592	38.48		3	188072	0.166725	06.916	25.01
	3	139983	0.133469	42.778	16.09		3	188154	0.166434	02.122	11.11
	3	139984	0.236726	14.852	37.88		3	188155	0.159823	03.027	37.45
	3	139996	0.168650	47.285	29.33		3	188205	0.159514	10.776	57.73
1759	8	- 1°1818	0.192071	29.050	43.12	1770	3	188028	0.157479	56.262	29.71
AGK3	8	- 1°1819	0.195288	22.897	04.68	SAO	3	188042	0.229116	40.744	30.55
	8	- 0°1902	0.176222	48.616	06.89		3	188068	0.227084	00.518	04.13
	8	- 0°1906	0.141251	02.144	02.79		3	188076	0.106747	11.780	13.59
	8	- 1°1829	0.154345	18.810	14.83		3	188155	0.114859	03.027	37.45
	8	- 1°1830	0.140823	10.162	20.18		3	188157	0.164715	08.682	21.97
1760	8	- 0°1895	0.173400	33.130	42.14	1771	3	187976	0.097088	45.240	06.60
AGK3	8	+ 0°1721	0.154112	29.692	32.02	SAO	3	188019	0.110133	46.661	56.88
	8	- 1°1815	0.180309	50.175	38.22		3	188032	0.172140	16.354	11.51
	8	+ 0°1729	0.153453	16.735	11.15		3	188100	0.147453	07.117	19.23
	8	- 1°1821	0.177363	31.781	18.46		3	188120	0.248822	20.167	29.23
	8	- 0°1903	0.161363	30.307	01.83		3	188155	0.224364	03.027	37.45
1761	8	+ 2°1692	0.245941	11.190	16.99	1772	3	188076	0.159149	11.780	13.59
AGK3	8	+ 2°1694	0.212087	09.751	37.57	SAO	3	188107	0.178171	36.397	28.39
	8	+ 1°1577	0.170148	31.267	35.85		3	188166	0.149566	25.571	13.05
	8	+ 3°1735	0.166285	22.221	50.04		3	188207	0.184730	22.492	22.75
	8	+ 2°1696	0.117023	46.839	59.52		3	188253	0.156110	22.873	04.09
	8	+ 3°1737	0.088516	17.059	05.99		3	188273	0.172273	25.791	44.22
1762	8	+ 2°1678	0.176133	48.312	00.23	1773	3	188155	0.157553	03.027	37.45
AGK3	8	+ 3°1727	0.224370	43.383	29.35	SAO	3	188207	0.196717	22.492	22.75
	8	+ 1°1568	0.117455	53.499	36.74		3	188226	0.139307	04.235	42.21
	8	+ 1°1576	0.108619	47.187	36.27		3	188331	0.135418	19.268	13.51
	8	+ 2°1695	0.152776	26.630	09.18		3	188352	0.203316	20.334	09.94
	8	+ 3°1735	0.220648	22.221	50.04		3	188366	0.167689	57.014	51.26
1763	3	163109	0.122427	45.078	37.02	1774	3	188310	0.216966	10.484	45.31
SAO	3	163120	0.096014	31.441	20.43	SAO	3	188342	0.255789	50.083	52.28
	3	163142	0.180218	10.285	20.75		3	188356	0.128750	29.956	23.29
	3	163174	0.142212	45.576	13.92		3	188441	0.108714	06.722	15.10
	3	163205	0.245289	56.251	44.35		3	188461	0.121925	53.904	37.62
	3	163216	0.213841	49.285	19.51		3	188463	0.167856	02.007	56.09
1764	3	163317	0.193512	17.746	03.10	1775	3	145692	0.212738	24.202	13.57
SAO	3	163320	0.171659	24.560	16.19	SAO	3	145700	0.171668	03.258	01.22
	3	163363	0.150820	07.774	39.83		3	145730	0.196008	19.466	05.06
	3	163366	0.188959	22.954	49.94		3	145740	0.138146	22.455	25.15
	3	163415	0.139219	17.852	57.61		3	145793	0.122139	53.153	51.48
	3	163417	0.155831	33.142	53.23		3	145794	0.159300	01.447	48.84
1765	3	163317	0.153769	17.746	03.10	1776	3	145978	0.193567	03.086	47.00
SAO	3	163320	0.183028	24.560	16.19	SAO	3	145983	0.193974	22.907	05.85
	3	163324	0.118746	36.858	52.16		3	146011	0.170486	56.732	08.02
	3	163370	0.211179	35.595	47.62		3	146015	0.170742	31.477	58.53
	3	163389	0.143055	40.860	32.95		3	146056	0.144470	52.386	36.00
	3	163415	0.190224	17.852	57.61		3	146072	0.126762	49.736	11.41
1766	3	163194	0.130132	07.398	23.25	1777	3	164800	0.202524	24.027	28.69
SAO	3	163217	0.164501	58.543	48.39	SAO	3	164804	0.195812	39.647	06.35
	3	163224	0.148479	30.120	15.09		3	164815	0.184069	31.510	03.24
	3	163244	0.177569	19.231	04.98		3	164845	0.150164	59.752	36.89
	3	163278	0.177250	52.379	35.97		3	164864	0.141519	07.879	23.73
	3	163284	0.202069	18.221	45.35		3	164877	0.125912	25.884	41.80

TABLE 2 (Cont.)

REFERENCE STAR POSITIONS AND DEPENDENCES

No.	Vol.	Star	Depend.	R.A.	Dec.
1778	3	164736	0.211525	08.803	57.61
SAO	3	164747	0.166961	07.689	56.19
	3	164770	0.188003	14.853	45.00
	3	164789	0.133020	27.852	57.03
	3	164806	0.172313	42.947	38.88
	3	164812	0.128178	26.710	50.52
1779	3	164605	0.136842	46.679	00.16
SAO	3	164620	0.127611	57.048	26.12
	3	164635	0.130059	32.845	34.13
	3	164685	0.196726	27.134	51.61
	3	164702	0.194576	49.600	39.71
	3	164705	0.214186	56.756	07.41
1780	3	164611	0.161448	14.385	39.39
SAO	3	164619	0.146774	43.902	29.33
	3	164655	0.188215	54.530	25.65
	3	164676	0.185619	46.843	42.96
	3	164685	0.148001	27.134	51.61
	3	164690	0.169944	53.596	53.06
1781	3	164655	0.214465	54.530	25.65
SAO	3	164664	0.188680	31.425	00.87
	3	164670	0.210859	06.459	43.10
	3	164690	0.126920	53.596	53.06
	3	164694	0.133661	37.793	04.98
	3	164700	0.125414	21.632	07.64
1782	3	164739	0.180634	32.255	35.22
SAO	3	164741	0.148002	36.728	39.31
	3	190791	0.184570	26.932	00.60
	3	164796	0.143219	50.235	25.66
	3	190849	0.184584	25.838	12.67
	3	164847	0.158990	07.159	07.42
1783	3	139984	0.193050	14.852	37.88
SAO	3	139992	0.196709	30.101	33.49
	3	140018	0.185199	49.196	54.03
	3	140025	0.140401	34.114	49.72
	3	140048	0.158254	55.523	52.56
	3	140070	0.126386	31.702	56.45
1784	3	139984	0.104705	14.852	35.94
SAO	3	139996	0.089963	47.285	29.33
	3	139999	0.196887	11.588	59.58
	3	140008	0.091760	57.053	08.44
	3	140025	0.204471	34.114	49.72
	3	140028	0.312213	43.786	44.61
1785	8	$+1^{\circ}1576$	0.111728	47.187	36.28
AGK3	8	$+2^{\circ}1693$	0.129700	01.246	37.17
	8	$+3^{\circ}1735$	0.189512	22.221	50.04
	8	$+1^{\circ}1578$	0.155494	02.077	29.83
	8	$+1^{\circ}1582$	0.184328	56.645	32.21
	8	$+2^{\circ}1701$	0.229237	53.955	36.09
1786	8	$+1^{\circ}1573$	0.168721	05.201	33.13
AGK3	8	$+2^{\circ}1693$	0.167228	01.246	37.17
	8	$+0^{\circ}1678$	0.167641	45.822	57.88
	8	$+2^{\circ}1696$	0.165296	46.839	59.53
	8	$+0^{\circ}1684$	0.166260	21.980	13.77
	8	$+1^{\circ}1582$	0.164855	56.645	32.21
1787	7	$+6^{\circ}\ 410$	0.161384	35.349	01.75
AGK3	7	$+5^{\circ}\ 423$	0.142284	06.249	42.50
	7	$+6^{\circ}\ 414$	0.187825	50.696	27.41
	7	$+5^{\circ}\ 430$	0.146784	54.936	56.97
	7	$+6^{\circ}\ 421$	0.187950	06.526	19.06
	7	$+6^{\circ}\ 425$	0.173771	36.695	45.08
1788	3	145530	0.196355	27.577	27.48
SAO	3	145561	0.149947	21.462	06.30
	3	145563	0.196992	35.039	27.46
	3	145565	0.146485	53.918	19.73
	3	145585	0.178240	25.830	39.18
	3	145602	0.131981	54.777	12.42
1789	3	164259	0.210968	44.088	36.07
SAO	3	164283	0.262473	48.473	45.00
	3	164298	0.118493	07.116	11.37
	3	164331	0.085035	44.241	08.64
	3	164339	0.203470	05.268	44.93
	3	164370	0.119561	51.719	45.00
1790	3	164199	0.077949	24.822	57.20
SAO	3	164200	0.190343	27.298	54.88
	3	164201	0.148752	35.569	52.17
	3	164245	0.089977	56.031	11.02
	3	164270	0.186777	03.274	30.31
	3	164278	0.306202	28.263	06.91
1791	3	164065	0.135505	36.396	50.48
SAO	3	164105	0.204650	00.133	02.14
	3	164113	0.110301	24.088	20.95
	3	190037	0.254565	59.269	17.20
	3	164179	0.119453	41.745	25.20
	3	164197	0.175525	11.396	26.59
1792	3	189931	0.122196	03.416	48.77
SAO	3	189955	0.081162	26.476	58.00
	3	164105	0.220220	00.133	02.14
	3	190022	0.097068	09.549	15.26
	3	164148	0.300126	24.491	05.95
	3	190067	0.179227	34.404	38.89

TABLE 3

STANDARD ERRORS

		R.A.	Dec.
AGK3	4 image	$0^{s}.011 \sec\delta$	$0''.18$
AGK3	2 image	$0^{s}.012 \sec\delta$	$0''.21$
SAO	4 image	$0^{s}.024 \sec\delta$	$0''.36$
SAO	2 image	$0^{s}.024 \sec\delta$	$0''.37$

Sydney Observatory,
Sydney, N.S.W., 2000.

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The Kempsey Earthquake of 6 September 1979

J. M. W. RYNN AND C. J. LYNAM

ABSTRACT. At 1308 hours UTC (1108 pm EST) on 6 September 1979 the Kempsey-Macksville area on the central New South Wales coast experienced the effects of an earthquake. This event, recorded by several seismograph stations in eastern Australia, was located about 25 km north-northeast of Kempsey (30.87°S, 152.98°E). Its magnitude was M_L 3.3 (Cooney Observatory). The earthquake was felt over an area of about 1000 km^2 with a maximum intensity of MM V reported from Eungai Rail - South West Rocks - Stuarts Point region between Kempsey and Macksville.

GENERAL SEISMICITY

Earthquake activity in Australia as a whole is much less than that in the neighbouring Pacific Islands and indeed is quite low when compared with the rest of the world. Within Australia, one of the most active regions is located in south-eastern New South Wales between the Sydney Basin and the Victorian border (Denham, 1976). The central coastal region to the north of Sydney, however, exhibits a very low level of seismic activity for all magnitudes.

The seismicity of New South Wales, up till 1973, has been discussed by Drake (1974). His data, which include the results of studies of several particular seismic areas, together with the Earthquake Data File of the Bureau of Mineral Resources (B.M.R.), Canberra, up till the end of 1977, show that only three earthquakes have been located in the central region since instrumental recording began in New South Wales at Riverview College, Sydney in 1909 (Table 1 and Fig. 1). Historical records for the area are almost non-existent, the only information being available in early issues of the "Queenslander" newspaper (S. Colliver, personal communication, 1980) (Table 1). Enquiries made through newspapers and residents of the central coast region did not reveal any information on earthquakes additional to those previously noted.

From this past data, the central coastal region of New South Wales is thus considered to be one which possesses a low level of seismic activity. Such a conclusion, however, may be due in part to the lack of seismological detection for the region. The only local station is that at the Cooney Observatory (COO) near Armidale, which began operating in August 1974. Prior to this time, the seismic coverage was such as to record only those earthquakes whose magnitudes were greater than M_L = 4.0. These regional stations included Riverview (RIV, in Sydney; installed 1909), Brisbane (BRS, installed initially in the city in 1937, then transferred to Mt. Nebo in 1963), the Australian National University southeast Australia network which includes Jenolan, Werombi and Avon (JNL, WER, AVO, respectively; Sydney Water Board stations installed in the late 1950's),

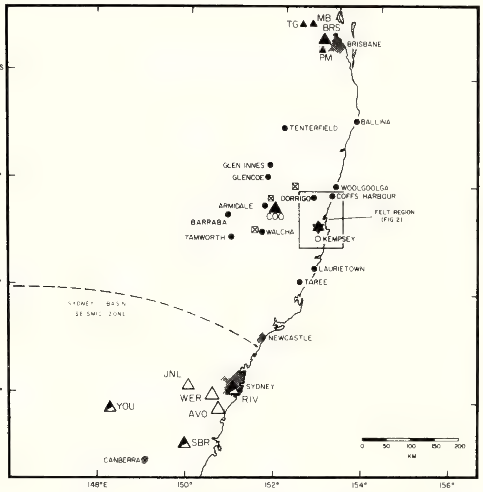

FIG. 1 Map of coastal region of central eastern Australia showing epicentre of the Kempsey earthquake of 6 September 1979 (star), felt region related to the Kempsey earthquake, and towns which did not feel this event (solid circles). Seismograph stations of the region used in this study, are shown by triangles (filled - stations used in hypocentral determination; half-filled - stations recording surface waves only; open - stations not recording earthquake. Earthquakes previously located in the region (as listed in Table 1 are shown by the cross-in-square symbol. The northern limit of the Sydney Basin seismic zone (taken from B.M.R. Earthquake Date file) is indicated by the dashed line.

Young (YOU; installed 1971) and stations in the Snowy Mountains area (installed since 1956). The locations of these stations is shown in Figure 1.

Although the establishment of the COO station has lowered the detection threshold for seismic activity in the region, attempts to deduce the level of seismic activity in more detail are now

TABLE 1

EARTHQUAKES ALONG CENTRAL COASTAL NEW SOUTH WALES REGION

Date	Origin Time (UT) hr min sec	Epicentre °S Lat °E Long	Depth km	Magnitude[1] M_L	Locality	Maximum Intensity MM	Reference
1938 JUN 27	22 38 47	30.4 151.8	(33)	4.7 (RIV)	Armidale-Guyra		Burke-Graffney (1951)
1959 OCT 12	21 23 40	31.0 151.5		4.7 (RIV)	Uralla-Tamworth		Doyle et al. (1968)
1973 JUL 29	13 58 14.3	30.17 152.33	10	4.5 (BRS)			BMR Earthquake Data File
1979 SEP 06	13 07 59.0	30.87 152.98	(10)	3.1 (COO)	Kempsey-Macksville	V	This paper

(1) Magnitudes given as local magnitudes (M_L) at a particular seismograph station: RIV - Riverview; BRS - Mt. Nebo; COO - Cooney

beset with an additional problem. This concerns man-made blasting related to quarries, coal mines and the like. Many events within 150 km of COO having magnitudes M_L less than 3.0 have been recorded but their identification (whether earthquakes or blasts) is extremely difficult from such single station data. Until detailed studies of the occurrence of blasting, local microearthquake surveys and/or in situ stress measurements are undertaken the level of seismic activity and the present tectonic stress distribution in this region will remain unknown.

Seismic activity for the region appears to be low. Consequently infrequent earthquakes, particularly those whose effects are felt throughout the region are of interest to both the local population and seismological community.

GEOLOGY AND TECTONICS

Geologically the part of the central New South Wales coast in the epicentral region of this earthquake is quite complex. The region of interest lies in the southern part of the New England Fold Belt within the Nambucca and Kempsey Blocks (Scheibner; 1974, 1976). This is a composite synclinorial block bounded on the east by the continental margin, on the west and south by the southermost part of the Demon Fault (a complex series of faults in this area) and on the north by the Crossmaglan and Demon Faults (shown as the Kempsey Area Fault in Packham, 1969). The region is highly deformed, being composed of many smaller blocks of Palaeozoic rocks; each block is in fault contact with the next. Details of the geology and tectonic nature of the region can be found in, for example, Korsch (1977) and Leitch (1974, 1975).

EARTHQUAKE OF 6 SEPTEMBER 1979

Hypocentral Details

The earthquake was located using readings from the seismograph stations COO, BRS, Toogoolawah, Somerset Dam and Pine Mt (near Ipswich). These latter three stations, TG, MB and PM, form part of the Wivenhoe Dam seismic surveillance microearthquake network in the Brisbane Valley (Rynn et al, 1982; Fig. 1). Surface waves only from this event were also recorded at stations RIV (L.Drake, personal communication, 1981), YOU and SBR (South Black Range; J. Weekes, personal communication, 1979) (Fig. 1). The other seismograph stations shown on Figure 1, JNL, WER and AVO, did not record the earthquake.

The hypocentral solution determined by the use of local travel times from the B.M.R. crustal model (I. Everingham, personal communication, 1980), is

Origin time : 6 SEPTEMBER 1979 13h07m59.0s UT

Epicentre : 30.87°S, 152.98°E

Focal Depth : 10 km (assumed)

Magnitude : 3.3 (M_L COO)

Because of the poor station distribution for this event, the epicentral error is most probably of the order of 10 km. No aftershocks associated with this earthquake were observed.

Estimates for the magnitude of this earthquake were computed by three different methods. Firstly, the Richter local magnitude value, M_L, was determined for COO and the Wivenhoe network stations PM, TG and MB from the formula for non-standard seismographs adapted by McGregor and Ripper (1976)

$$M_L = \log A - \log Ao - \log R$$

where A = maximum trace amplitude (mm) measured from zero-to-peak on

a non-standard seismogram,

Ao= trace amplitude of the reference earthquake (magnitude zero) at the same distance (tabulated by McGregor and Ripper, 1976),

R = ratio of the magnification of the non-standard seismogram to that of the Wood-Anderson at the same period.

This yielded M_L (COO) = 3.3 with $\overline{M}_L$ (Wivenhoe network) = 3.1. Secondly, the magnitude formula based on duration, M_D, As currently used in the Wivenhoe Dam project (Preston Institute of Technology, Victoria: G. Gibson, person communication, 1979; Rynn et al, 1982).

$$M_D = -1.06 + 1.04 (\log T)^{1.612} + 0.003 D$$

where T = time from onset of P-wave arrival to where coda first decreases to the background noise level (sec),

D = hypocentral distance (km),

was used for the three stations of the Wivenhoe network. The average value was $\overline{M}_D$ = 3.6. Thirdly, the magnitude based on the radius of perceptibility (Rp) of the isoseismal zone M (McCue, 1980),

$$M = 1.01 \ln Rp + 0.13$$

was computed to be M = 3.4 for Rp = 25 km.

All of the above magnitude computations suggest that the local magnitude for this earthquake was between 3.0 and 3.6. The local magnitude based on the COO seismogram, M_L (COO) = 3.3, was considered to be the most reliable estimate for the following reasons:

(a) the COO seismogram afforded the best recording of the event (amplitude about 25 mm for the S-wave arrival) whereas those for the Wivenhoe network had maximum amplitudes (zero-peak) of less than 1 mm;
(b) the formula for M_D was not locally derived;
(c) in the empirical determination of McCue's (1980) formula, the isoseismal parameters fall at the extreme low-value end of the data range (McCue, 1980). There is, however, some degree of consistency in the three different determinations implying that a direct comparison can be made (in this case at least) between the instrumental and macroseismic effects.

Isoseismal Effects

The University of Queensland seismology group initiated an isoseismal study as soon as the approximate location of the earthquake was determined. With the assistance of the local media in Kempsey (viz. Kempsey ABC radio and the Kempsey "Macleay-Argus" newspaper), earthquake questionnaires were distributed throughout the central coastal region and New England Tableland from Taree to Coffs Harbour and west to Glen Innes, Armidale and Tamworth; 90 questionnaires were returned, 25 of which stated that event was not felt. To ensure that this event was not the result of man-made blasting, enquiries were made to the local authorities in the epicentral zone (Shire Councils and N.S.W. Department of Public Works offices) on this subject. All reports were negative.

The region over which this earthquake was felt and centres which did not feel the effects are shown in Figure 1. The detailed isoseismal map is given in Figure 2. The felt area covered about 1000 km^2, extending approximately 30 km to the

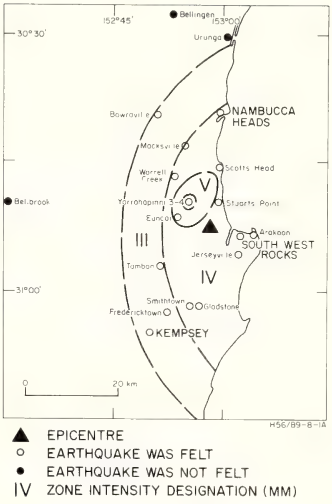

Fig. 2. Isoseismal Map - Kempsey earthquake, 6 September 1979. Felt intensities based on the Modified Mercalli Scale of Intensity (MM) assigned to replies from earthquake questionnaires. Isoseismals shown delineate the boundaries between zones marked. Small figures beside open circles indicate intensity (MM) is different from zone designation.

north and south and 20 km to the west of the epicentre. The region of maximum intensity, MM V (based on the Modified Mercalli Intensity Scale of 1931) was centred in the region of Eungai Rail and Scotts Head. Questionnaires received from these areas stated that hanging objects swung, objects on shelves were shifted slightly and trees and bushes were strongly shaken. No reports of serious damage were received. In many cases people were awakened and quite disturbed thinking that a very large explosion had occurred.

It is also noted that several questionnaires contained information of similar effects which might have been related to other possible "earthquakes" having occurred in the region. These included reports from Dorrigo (Fig 1) for 6 September 1979 at about 1200 hours (EST) and 8 September 1979 at about 1100 hours (EST) and from the Kempsey area for late January 1978. Analysis of the COO seismograms and enquiries into man-made blasting for each of these reported times showed that, other than at about 1200 (EST) on 6 September 1979, these events were neither recorded nor related to blasts. For the 6 September 1979 an event was recorded at COO and subsequent enquiries revealed the cause to be a blast at the Wood's Reef mine near Barraba.

DISCUSSION

Earthquakes in the central eastern New South Wales region that can be reliably located, including those which may be felt by the local population, are fairly infrequent. Thus the occurrence of such an earthquake as discussed herein is significant. The earthquake indicates some release of tectonic stress. For the inhabitants of the region macroseismic effects caused some concern about the stability of the region. In addition, the epicentral location and isoseismal data have provided further information for the on-going study of the seismic risk in Australia.

Also small earthquakes may manifest the release of stress related in some way to "block" tectonics. Such a relationship conforms, in general, to that suggested by Denham (1969) for the eastern part of Australia whereby earthquakes are indicative of the release of regional stress in the Tasman Geosyncline. Such stress release is an inherent part of the movement of the Australian continent northwards as prescribed in the plate tectonics model of the earth's crust.

ACKNOWLEDGMENTS

We wish to acknowledge the efforts and assistance of the Kempsey media, in particular Ms. B. Landers of Kempsey ABC and Mr. C. Haughton of the "Macleay-Argus" newspaper, in distributing the earthquake questionnaires and to the Editor of the "Macleay-Argus", Mr. P. Riggs, for publishing a copy of the questionnaire in the newspaper. Our thanks are also extended to the many civilians and police in the central coast and New England Tableland areas who replied to the earthquake questionnaires. Mr. S. Colliver drew our attention to the historical report in the "Queenslander" newspaper. We thank the Director, Bureau of Mineral Resources, Geology and Geophysics and his drafting section staff for drafting the isoseismal map. Data obtained from the Wivenhoe Dam network seismograms were from the project undertaken for the Co-Ordinator General's Department, Queensland State Government. This research was carried out as part of the Tasman Fold Belt Project under a grant from the Australian Research Grants Committee. Our thanks are also extended to Dr. J.P. Webb, Mr. I.B. Everingham and Dr. L.A. Drake for valuable comments during this study and suggested improvements to the original draft.

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The Dummy Creek Association: Rim Syncline Deposits

R. J. Korsch

ABSTRACT. The Dummy Creek Association in the New England Orogen consists predominantly of conglomerate derived from local basement highs. It is proposed that the highs were produced by a doming effect of the landsurface associated with high level intrusion of the granitic plutons. The conglomeratic sediments were deposited in rim synclines which formed in association with the granitic intrusions. The best example is the Dummy Creek Conglomerate and adjacent Mt. Duval Granite. Volcanic rocks, probably derived from material similar to the granite, covered the conglomerate. Further rise of the pluton brought its top to above the level of the original land surface. Erosion of the thin cover exposed the pluton, which has been more resistant to erosion than the surrounding land surface which is over 300m below the present exposed top of the pluton. A diapiric mechanism is preferred for the rise of the pluton into the highest levels of the crust.

INTRODUCTION

The New England Orogen in eastern Australia consists of Palaeozoic sedimentary rocks and associated acid volcanic and plutonic igneous rocks (Fig. 1). In many places the Palaeozoic rocks are masked by a cover of Tertiary basalt which, occasionally, is up to 400m thick. A recent synthesis by Korsch (1977) provides a framework for the Palaeozoic geology. Granitic rocks in the New England Orogen consist of over 150 individual mappable plutons or plutonic complexes (Pogson and Hitchins, 1973). They have a total exposed area of at least 16 500km^2 and comprise one of the largest of the numerous batholiths which make up a major proportion of the Palaeozoic to early Mesozoic orogens which developed in eastern Australia (Chappell, 1978). The majority of previous work on the granites in the New England Orogen has been concerned with detailed descriptions of the chemical characteristics of various plutons within the orogen, and little attention has been paid to emplacement mechanisms, structural setting, tectonic or geomorphic significance of the plutons.

Most workers had not questioned the prevailing opinion that the granitic intrusions continued down to mid-crustal (20-30km) depths. However, a gravity study of part of central New England by Green and Kridoharto (1975) showed that the Banalasta Granite was a lenticular (or mushroom-shaped) body with a maximum thickness of 4km. Runnegar (1974) considered that a layer of rock 1-2km thick must have covered the granitic intrusions over the whole of New England during the late Permian and that much of the rock probably consisted of subhorizontal, terrestrial Permian sediments and acid volcanics and pyroclastics. Korsch (1977) included the Permian terrestrial rocks in his Dummy Creek Association and suggested that the rocks were deposited in rim synclines associated with the granitic intrusions. Therefore the aim of this paper is to interpret the geological setting of the Dummy Creek Association as sediments deposited in rim synclines which formed due to a doming effect of the land surface by high level intrusions.

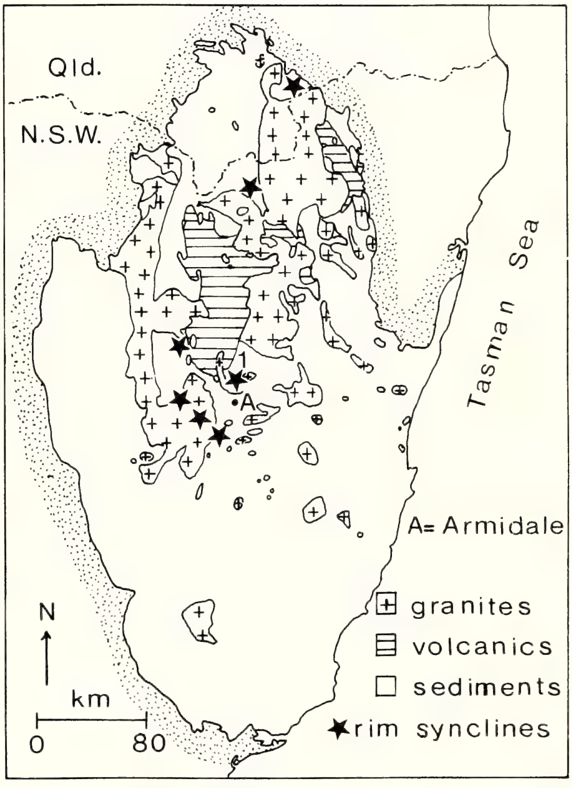

Fig. 1. Distribution of Palaeozoic granitic, sedimentary and volcanic rocks in the New England Orogen. Tertiary and Quaternary rocks have been omitted for clarity. Stars represent inferred rim synclines associated with the granites, and 1 is the rim syncline associated with the Mt. Duval Granite.

GEOLOGICAL SETTING OF THE DUMMY CREEK CONGLOMERATE

In the Mt. Duval area, just to the north of Armidale, the oldest exposed rocks are the Late Devonian-Carboniferous Sandon beds (Fig. 2), a deepwater marine sequence consisting of turbidites, chert, jasper and basic volcanics (see Sandon Association in Korsch, 1977). These rocks were

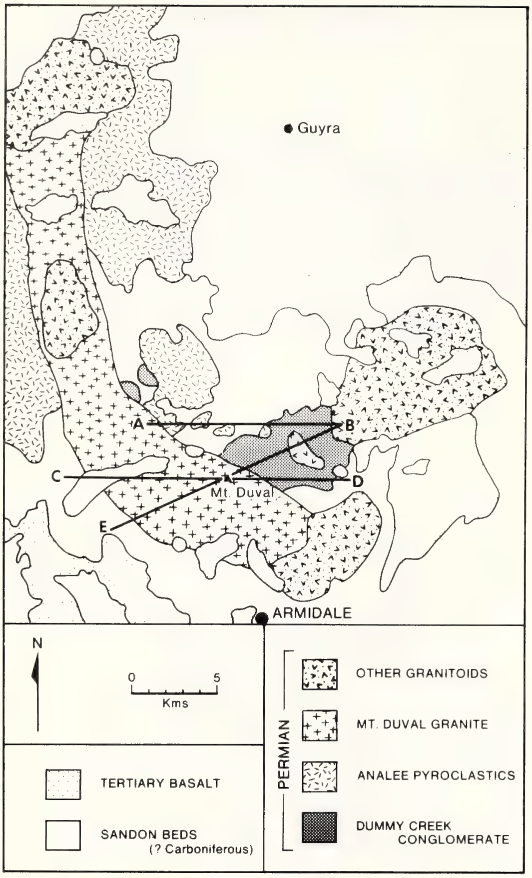

Fig. 2. Geological map of the Mt. Duval area, modified from Leitch *et al.* (1971). Also shown are location of the cross sections of Fig. 3.

complexly deformed and intruded by small acid porphyries prior to deposition of the Dummy Creek Conglomerate, which consists of pebbly conglomerate, sandstone and mudstone. McKelvey and Gutsche (1969) found floras indicative of a Permian age, but specific index fossils were not observed. The unit has a thickness of up to 150m.

The conglomerates are mostly paraconglomerates although minor orthoconglomerates occur also. They are poorly sorted, with subangular to subrounded clasts of chert, greywacke and intermediate-acid plutonic rocks derived from the underlying basement. The rocks were deposited in a terrestrial environment with coarse breccia-like conglomerates being fluvial and restricted in extent to valley-fill in the basement rocks.

The Dummy Creek Conglomerate has an exposed basal relief of 220m and the variation from the lowest exposed topographic point to the highest topographic point is 240m. However, because of the uneven nature of the depositional surface, this does not necessarily represent the true thickness of the sequence. The highest elevation at which the Dummy Creek Conglomerate crops out is 1240m. By contrast, the highest point of the Sandon beds in the vicinity is 1320m, indicating that either the Dummy Creek Conglomerate has had at least 80m eroded off the top, or that the basement contained topographic highs where no Dummy Creek Conglomerate was deposited in the first place.

Overlying the Dummy Creek Conglomerate are the Analee Pyroclastics which are also Permian. Basal trachytes are overlain by dacitic to rhyodacitic ash flow to ash fall tuffs and reworked volcaniclastic sandstones. A disconformity between the Dummy Creek Conglomerate and Analee Pyroclastics was proposed by McKelvey and Gutsche (1969) because the base of the pyroclastics is irregular. In places the pyroclastics overlie the basement Sandon beds with angular unconformity. McKelvey and Gutsche assumed that the Dummy Creek Conglomerate was eroded prior to deposition of the Analee Pyroclastics, to produce the disconformable contact. Within the Dumaresq 1: 25 000 topographic sheet (Number 9237-III-S), topographic variation of the exposed base of the Analee Pyroclastics ranges from 1020m to 1310m suggesting a relief of about 300m from the base.

In contrast to the steeply-dipping Sandon beds, both the Dummy Creek Conglomerate and Analee Pyroclastics have suffered only minor deformation. In places, the beds are essentially horizontal, whereas elsewhere broad, gentle folds occur, with maximum dips in the pyroclastics being only about 15^{o}.

Following eruption and deposition of the Analee Pyroclastics, the rocks of the Mt. Duval area were intruded by the Mt. Duval Granite, a coarse-grained plutonic mass which has an isotopic age of 249 Ma (M.J. Neilson, pers. comm.). The pluton is a member of the New England Batholith (Korsch, 1977). Contact metamorphic effects occur in the Dummy Creek Conglomerate and Analee Pyroclastics as well as the Sandon beds. Because of the lithologies, the effects are usually limited to the growth of fine white mica and the recrystallisation of biotite. However, Binns (1965) records evidence for hornblende-hornfels facies in basaltic rocks adjacent to the granite and for the threshold of pyroxene-hornfels facies being reached at the contact with the Mt. Duval Granite. Mt. Duval is the dominant topographic feature of the Armidale area (Figs. 3 and 4), rising to a height of 1393m, which is over 300m higher than the surrounding landscape.

Following the intrusion of the Mt. Duval Granite in late Permian time, a long interval occurred for which there is no rock record. In the Tertiary, huge volumes of basalt covered much of the New England Orogen. Isotopic ages range from 70 Ma to 13 Ma, but locally K-Ar ages of 31 Ma and 21 Ma have been determined by Wellman and McDougall (1974).

In the Mt. Duval area, the basalt has a base which varies in elevation from 1030m to 1150m, but even so, these elevations are 370m to 250m below the summit of Mt. Duval, indicating that this

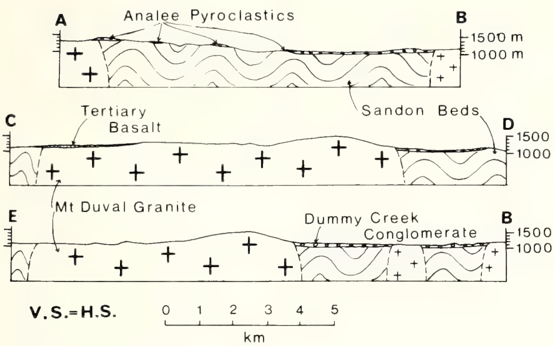

Fig. 3. Geological cross sections across the Mt. Duval area, along the lines shown in Fig. 2. Note that the folding pattern in the Sandon beds is schematic only.

granitic mountain must have occupied a similar topographic relationship to the surrounding landscape in Oligocene to earliest Miocene time, as it does today.

The conventional interpretation of the geological development of the Mt. Duval area up until now is one of a series of discrete events. The basement was exposed, eroded and then covered by deposits of the Dummy Creek Conglomerate. This was followed by further erosion, then deposition of the Analee Pyroclastics. The rock units were then intruded and contact metamorphosed by the Mt. Duval Granite. A long period of erosion was followed by basalt outpouring over much of the area. This was followed by further erosion, continuing to the present day. The alternative, novel interpretation presented below, suggests that the Dummy Creek Conglomerate and Analee Pyroclastics were genetically associated with the intrusion to a high level of the Mt. Duval Granite.

Fig. 4. Photograph of Mt. Duval Granite dominating the central New England skyline. Note the steeper NE slope (right-hand side) of the pluton. View looking towards the NNW.

DEVELOPMENT OF RIM SYNCLINES AROUND PLUTONS

Korsch (1977) grouped the Dummy Creek Conglomerate and other units in the New England Orogen considered to be its equivalent into the Dummy Creek Association. All deposits of this association occur exclusively in the near vicinity of granitic plutons. He suggested that rocks of the association were deposited in a rim syncline which developed at the margin of a rising granitic diapir. Ramberg (1967, 1970) has described in detail the method of formation of "sinks" which he termed rim (marginal) synclines and which result from the intrusion into the country rocks of material such as salt or magma. Field examples of granite diapirism have been described by Stephansson (1975), Bridewater *et al.* (1974) and Stephansson and Johnson (1976). According to Ramberg's models, as the diapir intrudes upwards due to density contrasts, the flow of material from around the root of the dome results in a thinning of the source area and a collapse of the overlying sediments forming rim (marginal) synclines (Fig. 5). This can often lead to buckling and downwarping of adjacent material with folds developing in the overburden. The folds can vary from simple, upright structures to complex overturned folds. Korsch (1981) has suggested that a possible mechanism for the overturning of a large area of rocks at Rockvale, about 25km to the east of Mt. Duval, could be related to the diapiric intrusion of the Abroi Granodiorite.

Rim synclines tend to form at a short distance away from the root of the diapir, due to drag which tends to uplift the immediately adjacent portion of the overburden to some distance away from direct contact with the diapir (Fig. 5).

As the diapir rises, the roof above it is domed, stretched and thinned (if able to yield) or otherwise fragmented. In extending the models of Ramberg (1967), the rising roof of the dome would create a source area for material to be transported to the rim syncline which then become sites of deposition. Thus, sediments found in the rim synclines could have been derived from the material being intruded by the diapir. Material, derived from the same source as the diapir, which penetrates the overburden and reaches the surface would be extruded as volcanic debris.

Rim synclines do not necessarily form completely rimming structures around diapirs (Ramberg, 1967, Fig. 76). In plan the diapirs can be arcuate as well as circular (Ramberg, 1967, Figs. 44 and 71) and they can have a nonplanar upper surface (Fig. 5A) which can be quite irregular (Ramberg, 1967, Figs. 55 and 77).

Ollier and Pain (1980) have described actively-rising surficial gneiss domes from the Papua New Guinea region. The gneiss domes are cored with granites which rise diapirically through the lower rocks. Eventually the gneiss domes emerge at the ground surface. In the case of Goodenough Island, the summit of the dome is now over 2000m higher than the surrounding land surface. The driving force for the rise of the gneiss dome is considered to be a large granitic batholith beneath the dome. Small intrusions of granodiorite are now exposed in the centre of the dome on

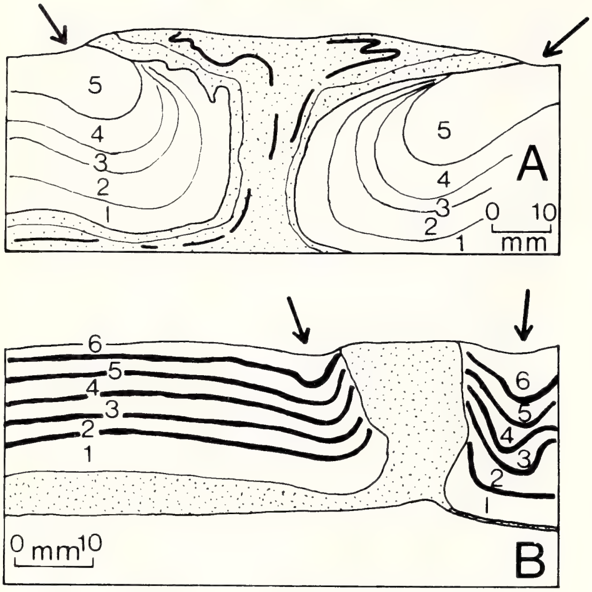

Fig. 5. Centrifuged models of diapirs and associated structures. Note the development of rim synclines (arrowed). A: Dome of silicone (stippled and containing layers) penetrating an overburden of layers (1-5) of putty. B: Dome of silicone (stippled) which has risen through alternating layers of putty (layers 1-6) and modelling clay (thick black lines). After Ramberg (1967): A-Figure 35 and B-Figure 78.

Goodenough Island. In proposing this new type of landform, Ollier and Pain (1980) have shown that intruding granite diapirs can be responsible for the production of a dome with a relief of at least 2km above the former land surface.

The Mt. Duval Granite is a typical epitectonic diapir (Stephansson, 1975) being discordant with the Sandon beds, and with no obvious foliation or lineation developed in the contact aureole.

GEOLOGICAL DEVELOPMENT OF THE MT. DUVAL AREA

The geological development of the Mt. Duval area presented below is based on an interpretation of the Mt. Duval Granite as a rising diapir which produced structures similar to that obtained in the centrifugal experiments of Ramberg (1967). Although I prefer a diapiric model for emplacement of the Mt. Duval Granite and development of the associated structures, other mechanisms related to high level intrusion of plutons possibly could produce features similar to rim synclines.

1. The original landsurface after deposition and deformation of the Sandon beds is represented as horizontal (Fig. 6A). Minor small quartz porphyries intruded the Sandon beds as precursors to the diapir proper. There is no evidence which allows a picture of the nature of this surface to be developed, and hence whilst it is shown as horizontal, this may not be so, particularly over a large surface area.

2. The Mt. Duval Granite member of the New England Batholith formed and started to move diapirically-upwards due to a density contrast between it and the Sandon beds. The Sandon beds, with densities for individual rock types of about 2.65 gcm^{-3} (greywacke), about 2.79 gcm^{-3} (jasper consisting of cryptocrystalline quartz and hematite) and about 2.96 gcm^{-3} (basalt), have an average density greater than that of the Mt. Duval Granite (around 2.67 gcm^{-3}). A density contrast as low as 0.05 to 0.1 gcm^{-3} is sufficient to initiate diapiric rise and the driving force of the diapirism becomes the density difference between the intruding body and the surrounding rock (Stephansson, 1975; Stephansson and Johnson, 1976). As the Mt. Duval pluton intruded the upper levels of the crust it caused the land surface to dome upwards (Fig. 6B). As diapirism proceeds, depressions (rim synclines) form around the dome. Hence the effects of the diapir are observed on the land surface a long time before the diapir intrudes the highest levels of the crust.

3. As the dome continues to rise, it provides a source area or "high" from which material is eroded, to be deposited in the rim syncline as the Dummy Creek Conglomerate (Fig. 6C). These deposits possibly were derived partly by gravity-sliding or slumping, which might have contributed to the slightly deformed state of the rocks. Davis (1975), Gastil (1979) and Ollier and Pain (1980) have suggested that gravity sliding is associated with domal uplifts. Mt. Duval at present has an asymmetric shape (Figs. 3 and 4) with a gentle slope to the SW and a steeper slope to the NE. The Dummy Creek Conglomerate is only found to the NE of the Mt. Duval Granite. The asymmetry could have been present early, and might be related to rise of the pluton.

4. The Dummy Creek Conglomerate, which only occupied the depressions and not the highs in the area, was covered by extensive deposits of the Analee Pyroclastics which also covered parts of the Sandon beds (Fig. 6D). This volcanic material is considered to be derived from the magma of the diapirically-rising pluton.

5. Upward movement of the diapir (Fig. 6E) through the denser Sandon beds continued until the mass reached the interface with the overlying Analee Pyroclastics, which are less dense (around 2.56 gcm^{-3}) than the diapir. At this stage the diapir might have spread laterally at the interface, but even if this did not occur it would have come in contact with the Dummy Creek Conglomerate and produced the contact metamorphic effects now seen in the Sandon beds, Dummy Creek Conglomerate and Analee Pyroclastics. The sharp contacts and the presence of a contact metamorphic aureole around this epitectonic diapir indicates that it intruded as a hot diapir. Contact metamorphic effects in the Dummy Creek Conglomerate and Analee Pyroclastics

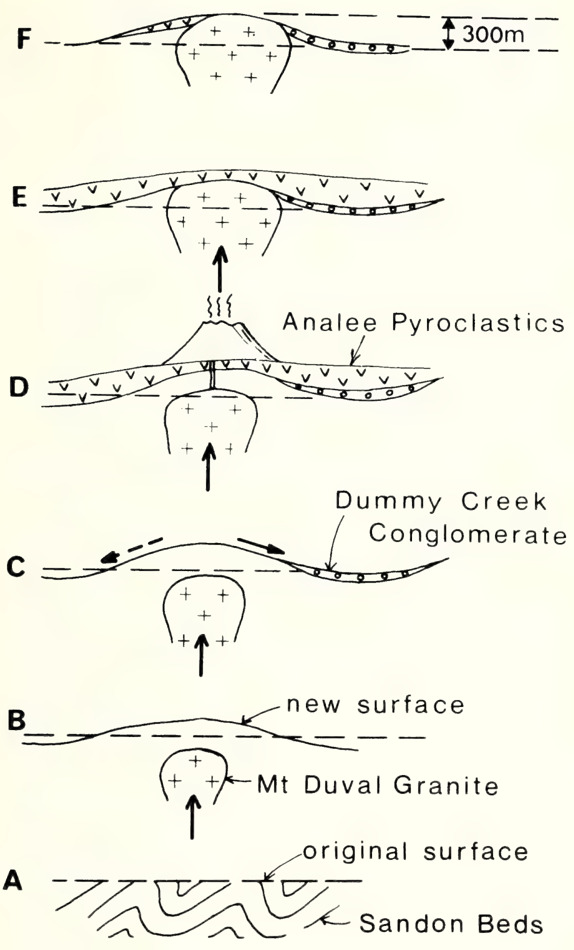

Fig. 6. Schematic representation of the development of the Mt. Duval granitic diapir, along NE-SW cross sections. The folded pattern of the Sandon beds in A has been omitted for clarity in B-E. A: Original horizontal (?) surface. B: Initial rise of the Mt. Duval diapir and doming of the overburden. C: Dome becomes source area for Dummy Creek Conglomerate which is deposited in the rim syncline. D: Eruption of Analee Pyroclastics derived from magma of the diapir. E: Continued rise of the Mt. Duval diapir to interface with Analee Pyroclastics. F: After erosion to expose the Mt. Duval Granite.

suggest that the diapir was still relatively hot as it intruded the uppermost levels of the crust. This is in contrast to the relatively cool, solid-state diapiric processes implied by Stephansson (1975) and Ollier and Pain (1980) for the plutons they descirbe. Nevertheless, the Mt. Duval diapir has produced similar effects in the overburden to the effects produced by the cool diapirs. Also, the minor deformational effects observed in the Dummy Creek Conglomerate and Analee Pyroclastics probably developed at this stage. As inferred in Fig. 6E, the upper surface of the diapir is now higher than the former land surface, and also higher than the upper surface of the Dummy Creek Conglomerate and the base of the Analee Pyroclastics located above the Dummy Creek Conglomerate in the rim syncline.

Wilkinson (*in* Runnegar, 1974) suggests that at least 1km of overburden is necessary to crystallise the granitic bodies. However, as Ollier and Pain (1980) have shown, domes can emerge at the ground surface by shouldering the bounding rocks aside, and the 1km of overburden suggested by Wilkinson is probably unnecessary. A maximum thickness of about 500m for the Analee Pyroclastics or its equivalents has been recorded in central New England to date.

Thus, the intrusion of the Mt. Duval Granite into high levels of the crust has domed the land surface and produced a topography which had a greater relief than previously. Removal of the volcanic overburden exposed the pluton at a level higher than that of the previous land surface. The pluton remained as a topographic high during the Oligocene to earliest Miocene when basalts were erupted onto the land surface over 250m below the summit of Mt. Duval, and the pluton remains as a topographic high today.

INTERPRETATION OF THE DUMMY CREEK ASSOCIATION AS RIM SYNCLINE DEPOSITS

Over 150 individual granitic plutons have been mapped in the New England Orogen (Pogson and Hitchins, 1973); the formation of rim synclines around the granitic plutons is not universal but it is not unique to the Mt. Duval Granite. Korsch (1977) recognised rocks of similar age and lithology to the Dummy Creek Conglomerate scattered throughout the New England Orogen and he grouped these as the Dummy Creek Association. Some of these localities, shown on Fig. 1, are: east of Uralla, Wilsons Creek to the west of Uralla, near Yarrowyck, south of the Tingha Granite, Gibraltar Range near the Mole Granite, the Ashford area and the Warwick area. The typical rock type of the Dummy Creek Association is conglomerate deposited in a terrestrial environment. The composition of the boulders indicate that the source area was the basement rocks in the vicinity of the present sites of the conglomerates. In each case the conglomerates occur in the vicinity of plutons. For descriptions of the geology of the above areas refer to the references listed in Korsch (1977).

Previous interpretations have inferred that much of the New England was covered by conglomerate units of the Dummy Creek Association, most of which have been removed by subsequent erosion (e.g. Runnegar, 1974). However, it is considered here that the Dummy Creek Association was deposited predominantly in rim synclines which were localised at the margins of some of the plutons in the New England Orogen. As the models of Ramberg (1967) have shown, rim synclines do not necessarily develop around every rising dome. Hence, I consider that several rim synclines developed in New England during the Permian and they were associated with surficial domes or topographic highs produced by the rising granitic plutons. Most of these granites were as susceptible to erosion as their surrounding rocks and hence now exert only a limited influence on the present topography, and are not as dominant as the Mt. Duval Granite.

Korsch (1977) considered that two other granitic belts in the New England Orogen (the Hillgrove and Bundarra belts) have features possibly produced by diapirism. The Hillgrove Belt has pronounced shearing and a foliation developed at the edges of individual plutons (see Fig. 3 in Korsch, 1977) which could be the equivalent to the faults found around the surficial gneiss domes in Papua New Guinea by Ollier and Pain (1980). The Hillgrove and Bundarra belts represent different stages of domal development from the New England Batholith, but there is no major topographic expression at present associated with them.

CONCLUSION

Previous workers on the granites of the New England region of Australia have concentrated on the geochemical characteristics of various plutons. Here I have examined the geological setting of the Mt. Duval Granite and I interpret it and other late Palaeozoic granites as high level plutons which have domed the land surface and formed rim synclines. Conglomerate units of the Dummy Creek Association were deposited in the rim synclines. In the case of the Mt. Duval Granite, debris derived from the dome in the overburden has been transported into the depressions surrounding it and covered by a blanket of volcanic material derived from the rising granitic magma. Further upward intrusion of the pluton to the interface with the volcanic material at a level higher than the original land surface has occurred. Erosion of the thin overburden has revealed the pluton as a topographic high, which has survived from the Permian to the present day.

Over 150 individual plutons have been mapped in the New England Orogen, and it is considered that many plutons had a profound influence on the form of the land surface during the Permian to the early Triassic. Rim synclines developed in association with many of the plutons. Some plutons which still remain as topographic highs (e.g. Mt. Duval, Round Mountain) have continued to exert an influence on the land surface to the present day. Hence the Permian granitic plutons and associated rim syncline deposits have exerted a considerable geologic and geomorphic influence on the New England region.

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Description and Interpretation of a Useful Leucogneiss Stratigraphic Marker in the Willyama Complex, Broken Hill Block, N.S.W.

I. L. Willis

ABSTRACT. A leucocratic quartzo-feldspathic gneiss (leucogneiss) has been recognized as a useful stratigraphic and structural marker in parts of the Willyama Complex of the Broken Hill Block. The microcline-quartz-albite/oligoclase-biotite ± garnet leucogneiss occurs as extensive thin, continuous, conformable horizons within Suite 3 of the stratigraphy of Stevens et al (1980). It has the chemistry and field relations of a rhyolite, and probably formed during a brief period as a series of pulses of air-fall tuff. It can therefore be used as a time-stratigraphic marker. The leucogneiss occurs in a narrow stratigraphic interval which can be traced for many kilometres in the Thackaringa and Triple Chance areas, and which stratigraphically underlies the sequence containing the orebodies at Broken Hill in the Broken Hill Synform. The leucogneiss is associated with garnet- and pyroxene-rich basic gneisses, and with quartz-feldspar-biotite-garnet ("Potosi"-type) gneiss, an association which has similarities with the overlying "mine sequence" at Broken Hill and its regional equivalents (Suite 4).

INTRODUCTION

Recent work by the Geological Survey of N.S.W. has shown that, despite high grades of metamorphism and multiple deformation (Vernon 1969, Phillips 1978, Marjoribanks et al 1980), a consistent stratigraphic succession can be recognized in the Early-Middle Proterozoic Willyama Complex of the Broken Hill Block (Stevens et al 1980) (see table 1). Numerous lithostratigraphic markers can be recognized within this succession which have varying degrees of persistence and distinctiveness. These include felsic gneisses (quartz-feldspar-biotite or "granite" gneiss, megacrystic or "augen" gneiss, and quartz-feldspar-biotite-garnet or "Potosi" gneiss), various "lode" rocks (e.g. quartz-gahnite rock, quartz-magnetite rock), calc-silicate rocks, and extensive bodies of basic gneiss. Interpretations of pre-metamorphic rock types in the Willyama Complex have tended to favour a volcano-sedimentary model, with the felsic and basic gneisses interpreted as acid and basic volcanics respectively (Johnson and Klingner 1976, Stevens et al. 1980).

This paper describes a recently recognized acid metavolcanic from the Willyama Complex, which is a valuable stratigraphic marker in the central and southwestern Broken Hill Block. The rock is a leucocratic feldspar-quartz-biotite ± garnet gneiss ("leucogneiss"), which has the chemistry and field relationships of a metarhyolite. It occurs as a single thin horizon, or as multiple adjacent horizons. The leucogneiss is a distinctive and persistent unit which is confined to a narrow stratigraphic interval of wide distribution within Suite 3 (see table 1). It is therefore an excellent datum within the sequence and is of considerable value in determining stratigraphic position and in delineating meso- and macroscopic structures.

DISTRIBUTION OF THE LEUCOGNEISS

The known distribution of the leucogneiss is shown in figure 1. The rock has been studied in detail only in the Thackaringa (Willis 1980a, b) and Triple Chance (Stroud in prep.) areas. Less well known occurrences are found in sequences extending northeastwards from the Thackaringa area, and in the Broken Hill Synform. It is expected that further investigation will reveal other occurrences particularly in the southwestern and southcentral areas of the Block.

LITHOLOGY AND FIELD RELATIONSHIPS

The leucogneiss is a fine- to medium-grained (0.2-1 mm) microcline-quartz-plagioclase-biotite ± garnet gneiss (figures 2, 3). The rock is white or pale yellow to pale or dark grey. It has a prominent, thin (1-5 mm) layering/gneissosity defined by laminae of quartz + feldspar and of biotite, paralleled and accentuated by thin, planar quartzo-feldspathic segregations (figures 2, 3). The laminae are planar, regular and continuous. The segregations commonly contain clusters of fine- to medium-grained garnet, or biotite clots after garnet (figure 3).

The typical leucogneiss contains only 0.5-5% biotite, but commonly grades along and across strike to variants which contain 8-10% biotite. These are grey to dark grey rocks which resemble fine-grained "granite" gneiss. Less commonly the leucogneiss grades laterally into a leucocratic, weakly to strongly foliated granitoid to pegmatoid. The leucogneiss also rarely grades to poorly to well-layered sodic plagioclase - quartz rocks (the "quartz-albite rocks" of Vernon 1961). The transition is marked by an increase in thin layers of fine-grained saccharoidal leucocratic plagioclase-quartz rocks (Willis 1980b).

Despite these variations, the leucogneiss horizons form relatively homogeneous quartzo-feldspathic units over their extensive strike lengths. They contain no metasediment or amphibolite intercalations, and variations are in terms of mafic mineral content and/or proportions of plagioclase to K-feldspar.

TABLE 1. GENERALIZED STRATIGRAPHIC SEQUENCE FOR THE BROKEN HILL BLOCK after Stevens et al (1980).

Stratigraphic Unit (metamorphic suite)	Component Metamorphic Rock Types
7 (youngest)	Fine-grained quartz-albite-rich psammite and minor graphitic meta-siltstone and interlayered micaceous psammopelite.
6	Graphitic chiastolite or sillimanite-bearing pelite/psammopelite; graphitic metasiltstone; calc-silicate rock. Also contains a variable proportion of micaceous psammopelite.
5	Pelitic to psammopelitic schist with variable psammite. Zoned calc-silicate nodules.
4	Metasediment, amphibolite, garnet-rich quartzo-feldspathic gneiss, quartz-gahnite rock, BIF, calc-silicate rock, zoned calc-silicate nodules.
3	Large, discontinuous bodies of quartzo-feldspathic gneiss or quartz-albite rock, plus metasedimentary composite gneiss, amphibolite.
2	Metasedimentary composite gneiss, amphibolite, minor quartz-albite rock.
1 (oldest)	Quartzo-feldspathic composite gneiss to migmatite, contains both quartz-albite and metasedimentary layers.

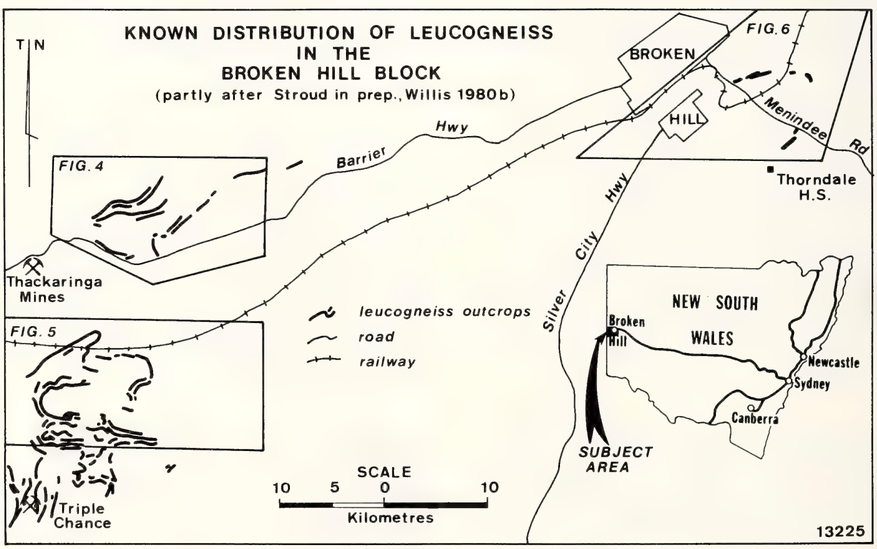

Fig. 1. Known Distribution of Leucogneiss in the Broken Hill Block (partly after Stroud in prep., Willis 1980b)

The "granite" gneiss (about 5% of the units), the leucocratic granitoid (about 2-3%) and the plagioclase - quartz rocks (2-5%) are significant, but volumetrically minor, components of the leucogneiss as a whole.

The leucogneiss occurs as tabular, continuous horizons, which are generally only 1-3 m wide, rarely 5-10 m. At least three distinct horizons are known, two of which are most commonly observed. They may be separated by as little as 3 m, or as much as 100 m, but all lie within a restricted stratigraphic interval (200 m or less). The horizons are concordant, and probably conformable, with bedding in adjacent rocks, and with regional lithological trends (figures 4-6). The margins of the horizons tend to be regular and sharp.

Each leucogneiss horizon is constant in thickness, without significant attenuation or thickening

Fig. 2. Fine lamination with parallel quartzo-feldspathic segregations, in leucogneiss 2 km west of Old Coolgardie Tank.

Fig. 3. Leucogneiss, showing garnet concentrated in segregations.

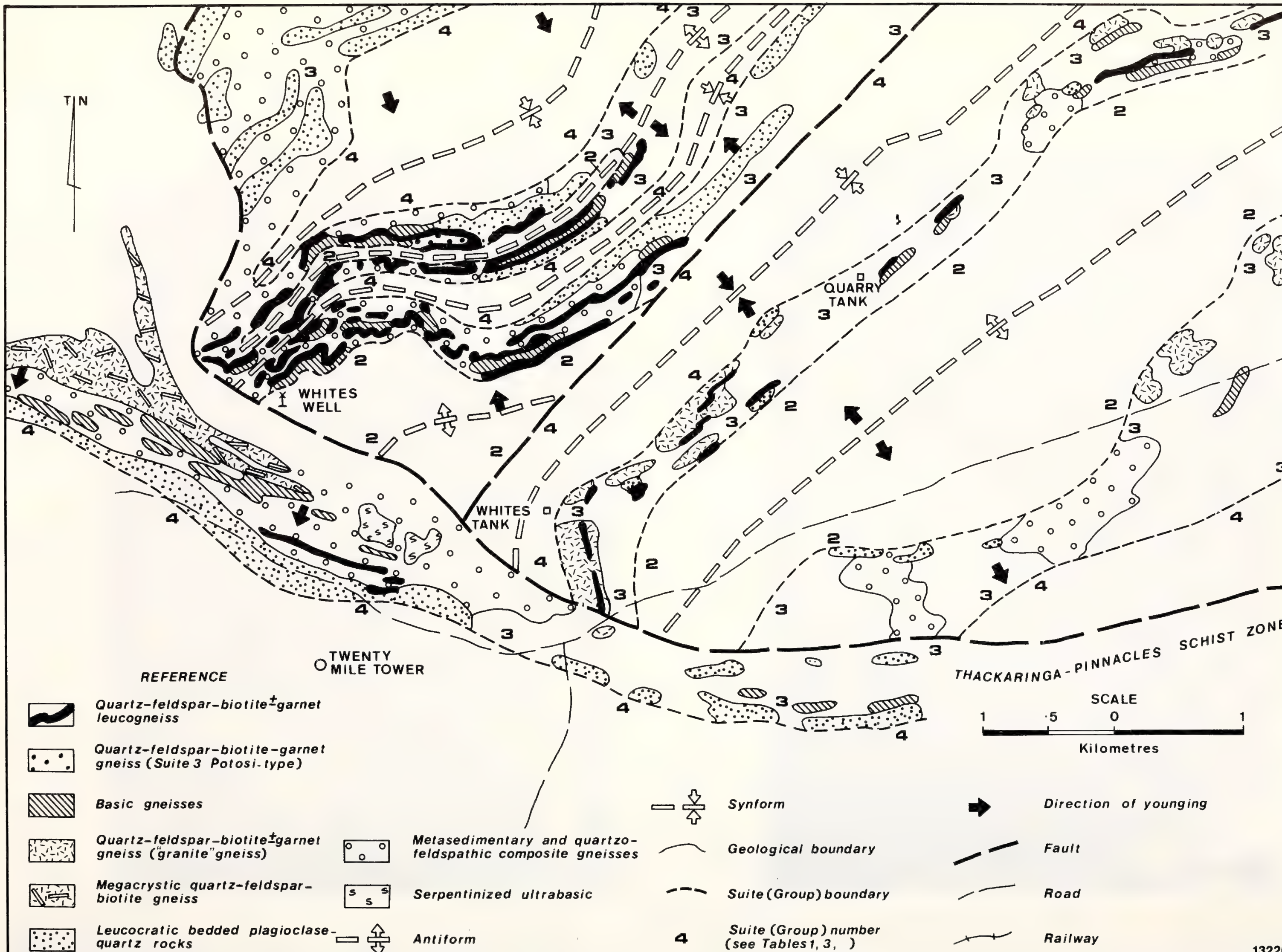

Fig. 4. Stratigraphic interpretation and simplified geology of Suite (Group) 3 in the north Thackaringa district. The leucogneiss and associated basic gneisses and garnet-bearing quartzo-feldspathic gneisses consistently underlie Suite (Group) 4.

Fig. 5. Simplified geology of Suite (Group) 3 in the south Thackaringa district, showing distribution of the leucogneiss and associated basic gneisses and quartz-feldspar-biotite-garnet gneiss (Formation 3 III). Formation boundaries are not shown.

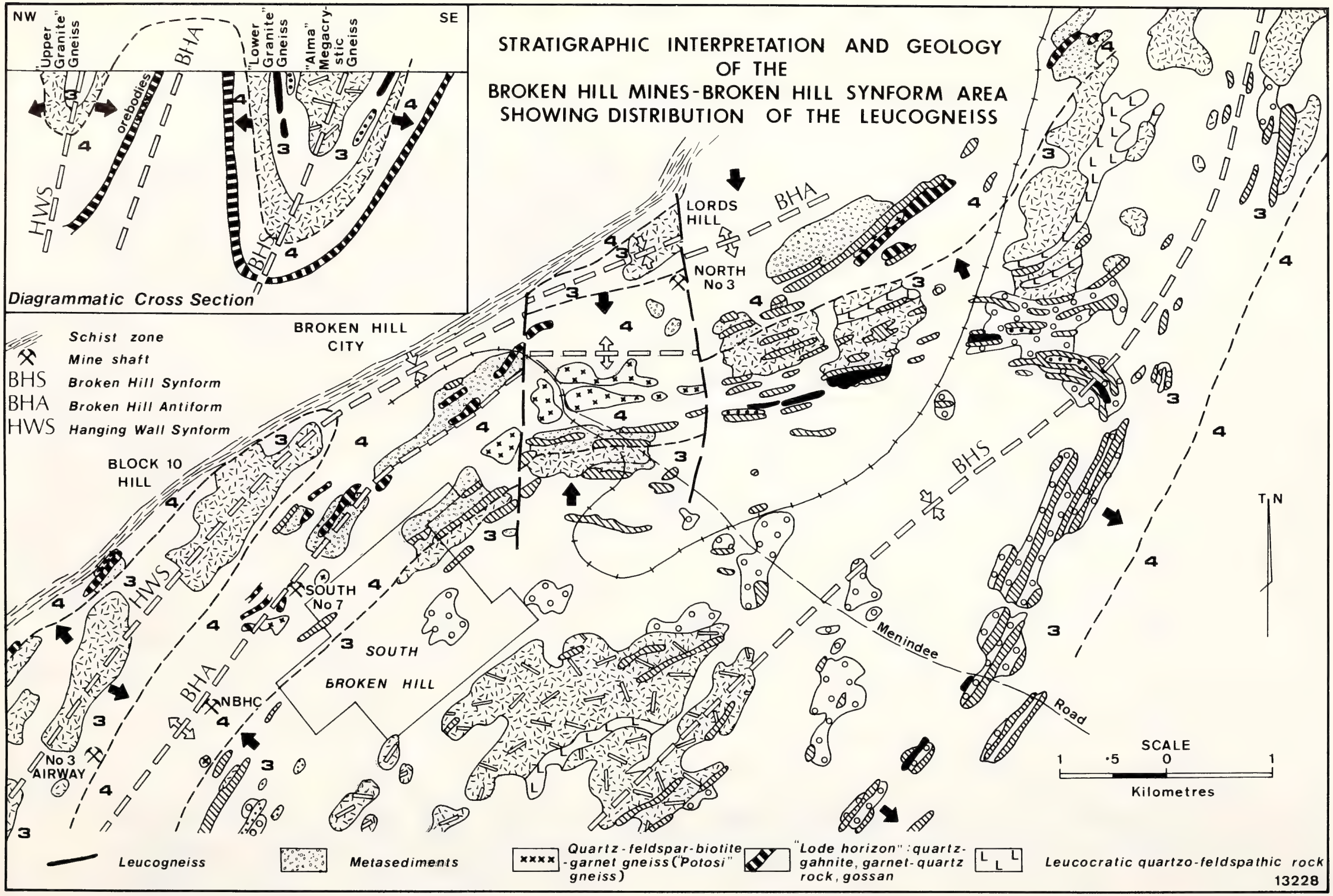

Fig. 6. Stratigraphic interpretation and geology of the Broken Hill mines - Broken Hill Synform area showing distribution of the leucogneiss. The leucogneiss underlies the "Lower Granite gneiss" and the Broken Hill orebodies. Geology after Bradley 1978, 1980, Brown 1980, Laing et al 1978, Laing 1980. See figure 4 for additional reference.

due to deformation. With tight or open mesoscopic folding, the leucogneiss has behaved competently, being offset by small faults or shears in the fold hinges, usually by only a few metres. Repetitions of the horizons in the limbs of tight or isoclinal folds can be traced by careful mapping in the dislocated fold hinges, where outcrop permits.

PETROGRAPHY

The typical leucogneiss is a microcline-quartz-albite/oligoclase-biotite ± garnet gneiss, but some thin layers are plagioclase rich. An average mode is given in table 2.

In thin section, the laminae are defined by quartz + feldspar domains separated by biotite grains and foliae, or by variations in plagioclase relative to microcline. A relict medium-grained (0.5-1 mm) granoblastic-polygonal microstructure is present in most samples. This is overprinted by recrystallization to a finer grained (0.1-0.5 mm) irregular aggregate of quartz and feldspar, with abundant subgrain development.

The tartan-twinned microcline is xenoblastic, and commonly microperthitic, with braided and planar exsolution lamellae. The plagioclase averages oligoclase An_{11}, and is well twinned and xenoblastic to subidioblastic. The quartzo-feldspathic segregations comprise mainly medium- to coarse-grained (1-3 mm) xenoblastic microcline and quartz, with xenoblastic garnet poikiloblasts (1-3 mm diameter).

TABLE 2: AVERAGE MINERAL MODE OF 23 SAMPLES OF LEUCOCRATIC QUARTZ-FELDSPAR-BIOTITE ± GARNET GNEISS.
Visual volumetric estimates only. Data from Willis 1980b. The range is given in brackets.

MICROCLINE	47%	(20-69)
QUARTZ	35%	(23-51)
PLAGIOCLASE	13%	(5-30)
BIOTITE	3%	(0-7)
MUSCOVITE	1%	(0-10)
GARNET	1%	(0-10)

Accessory OPAQUE, APATITE, ZIRCON

An CONTENT OF PLAGIOCLASE: An_{11} (An_0-An_{17})

GEOCHEMISTRY

Major element analyses of the leucogneiss are presented in table 3. The leucogneiss is a SiO_2-rich rock characterized by low total Fe and CaO, moderately high alkalis, and Na_2O about equal to, or in excess of, K_2O.

TABLE 3: GEOCHEMISTRY OF LEUCOGNEISS SAMPLES FROM THE THACKARINGA AREA, COMPARED WITH OTHER QUARTZO-FELDSPATHIC GNEISSES FROM THE BROKEN HILL BLOCK, AND WITH AVERAGE RHYOLITE.
Total Fe as Fe_2O_3 in columns 5-7.

Rock Unit	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	H_2O^+	H_2O^-	No. of analyses
1. LEUCOGNEISS	73.8	13.6	0.73	1.31	0.01	0.38	0.49	3.4	4.72	0.28	0.12	0.64	0.09	1
2. " "	75.2	13.9	0.52	0.56	0.01	0.31	0.22	4.3	3.58	0.21	0.12	0.72	0.31	1
3. " "	75.0	13.5	0.49	1.18	0.02	0.38	0.54	3.7	4.41	0.27	0.11	0.28	0.15	1
4. " "	75.5	13.6	1.10	1.42	0.01	0.48	0.63	4.6	1.31	0.30	0.11	0.77	0.20	1
5. LEUCOCRATIC GNEISS	71.1	14.6	2.74	--	0.03	0.43	0.76	1.25	7.20	0.36	0.24	1.14	0.26	3
6. "UPPER GRANITE GNEISS	68.4	15.4	4.9	--	0.1	1.2	2.1	2.8	3.6	0.6	0.1	0.5		26
7. "LOWER GRANITE GNEISS"	69.6	14.3	5.1	--	0.1	1.2	2.9	2.4	3.0	0.6	0.1	0.7		7
8. AV. "RHYOLITE"	72.81	13.20	1.45	1.24	0.06	0.42	1.13	3.54	4.17	0.29	0.08	1.23	0.59	448
9. AV. "RHYOLITE"	74.85	12.79	0.97	0.58	0.04	0.21	0.81	3.64	4.44	0.15	0.05	1.15	0.64	66

1. Sample G80-809, N.S.W. Dept. of Mineral Resources, GR 1515 5013, Thackaringa 1:25,000 sheet.
2. Sample G80-812, N.S.W. Dept. of Mineral Resources, GR 1462 5014, Thackaringa 1:25,000 sheet.
3. Sample G80-813, N.S.W. Dept. of Mineral Resources, GR 1446 5022, Thackaringa 1:25,000 sheet.
4. Sample G80-814, N.S.W. Dept. of Mineral Resources, GR 1455 5030, Thackaringa 1:25,000 sheet.
5. Leucocratic quartzo-feldspathic gneisses, data published in Stevens (1978).
6.,7. Data from Johnson and Klingner (1976).
8. Average rhyolite from CLAIR file, Le Maitre (1976).
9. Average "rhyolite", as specifically defined by De la Roche et al (1980), using data from CLAIR file.

The four leucogneiss analyses are essentially similar. The main variation is in total Fe, which is reflected in the variable biotite and garnet contents of the leucogneiss. CaO shows minor variation. Total alkalis average about 8% in three of the samples and drop to about 6% in sample 814, due entirely to a major depletion in K_2O. This is reflected in a more plagioclase-rich leucogneiss variety.

The chemistry of the leucogneiss shows only broad correspondence with, and some significant variations from, most other quartzo-feldspathic rocks from the Broken Hill Block (table 3). Leucocratic quartzo-feldspathic gneisses from Suite 4 in the Nine Mile area (Stevens 1978) are K_2O-rich and Na_2O-poor compared with the leucogneiss. Leucocratic sodic plagioclase-quartz rocks (Vernon 1961, Brown et al in prep.) have high Na_2O and Al_2O_3 compared with the leucogneiss. The leucogneiss bears no chemical resemblance to the quartz-feldspar-biotite gneisses which are interpreted to overlie it in Suite 3 i.e. the "Upper" and "Lower" granite gneisses" and their equivalents (Johnson and Klingner 1976, Brown et al in prep.). These gneisses are significantly richer in total Fe, CaO and MgO, and poorer in SiO_2, Na_2O and total alkalis.

ASSOCIATED ROCK UNITS

On a broad scale, the leucogneiss and associated rocks occur in a sequence dominated by two separate quartzo-feldspathic facies. In the south-western Broken Hill Block, the sequence mainly contains abundant leucocratic sodic plagioclase-quartz rocks e.g. south Thackaringa (figure 5), Triple Chance. Elsewhere the plagioclase-quartz rocks are minor to absent, and the sequence is dominated by quartzo-feldspathic gneisses ("granite" gneisses) with abundant to minor basic gneisses e.g. north Thackaringa, Broken Hill Synform (figures 4,6).

In detail, the leucogneiss is typically enclosed by metasedimentary rocks. These are psammitic to psammopelitic quartz-feldspar-biotite-sillimanite-garnet schist and gneiss, some with abundant quartzo-feldspathic segregations (composite gneiss in the terminology of Stevens et al (1980). The metasedimentary rocks also contain interbedded basic gneisses: garnet-bearing amphibolite and/or hornblende granulite. The basic gneisses are typically thinly layered, in some cases with unusually well developed planar feldspathic layers (Stroud, in prep.).

The leucogneiss and basic gneiss are commonly associated with discontinuous thin lenses of a dark grey, medium-grained garnet-rich quartz-andesine-biotite ± K-feldspar gneiss (Willis 1980b, Stroud in prep.) (figures 4,5,6). This gneiss is similar in outcrop and identical in mineralogy (Willis 1980b), to garnet-rich quartzo-feldspathic gneisses ("Potosi" gneiss) which occur in Suite 4 adjacent to the orebodies at Broken Hill and elsewhere throughout the Block (Stevens et al 1980). However, the Suite 4 garnet-rich gneisses generally occur in much larger and more persistent bodies.

At Whites Tank (figure 4), the leucogneiss is interlayered with a quartzo-feldspathic gneiss which is similar in lithology and mineral content (quartz-microcline-oligoclase/andesine-biotite ± garnet) to the "Upper"- and "Lower granite gneisses" which stratigraphically underlie the orebodies at Broken Hill (Laing et al 1978). The gneiss at Whites Tank is a medium- to coarse-grained quartz-feldspar-biotite gneiss with garnet-rich phases (garnet-rich "granite" gneiss).

STRATIGRAPHIC RELATIONSHIPS

In all the areas in which it has so far been recognized, the leucogneiss occurs within Suite 3 of the Broken Hill Block succession (table 1), below the stratigraphic level of the Broken Hill-type mineralization (Suite 4) (figures 4,5,6,7). In most of these areas the leucogneiss is associated with other quartzo-feldspathic lithologies which are characteristic of Suite 3 throughout the Broken Hill Block: leucocratic sodic plagioclase-

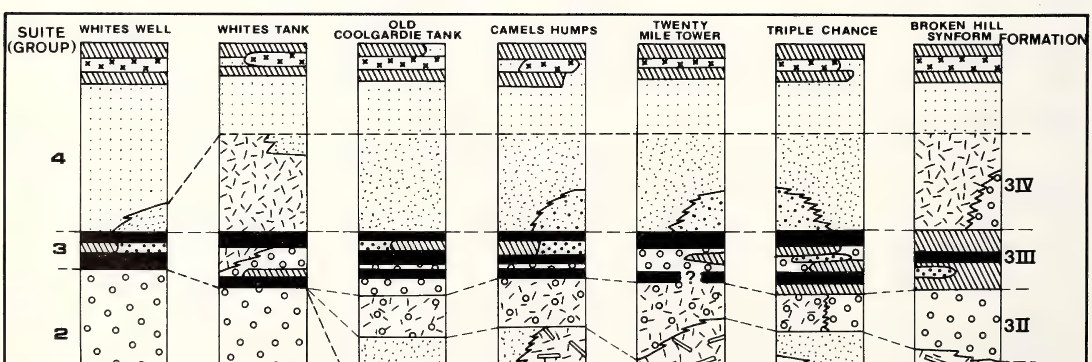

Fig. 7. Schematic stratigraphic sections through the stratigraphy of Suite (Group) 3 from locations in the Thackaringa area (figures 4,5), the Broken Hill Synform (figure 6) and the Triple Chance area (after Stroud, in prep.). The sections are diagrammatic only and not to scale. See figures 4,6 for additional reference.

quartz rocks, quartzo-feldspathic gneisses, and metasedimentary and quartzo-feldspathic composite gneisses (figures 4,5,6,7). In areas where these characteristic lithologies are absent, the leucogneiss can be accepted as diagnostic of Suite 3 (Willis 1980b, Stroud in prep.).

The Leucogneiss and Subdivision of Suite 3

In the Thackaringa area, Willis (1980b) assigned informal group status to Suite 3 and recognized four formations using the continuous and extensive leucogneiss as an important marker unit (table 4). The leucogneiss occurs in Formation 3 III* of this succession (figure 7), usually in two main levels: a thin horizon at or near the top of the formation, and a lower level at the middle or base comprising a single thick horizon, or two thin to thick horizons. Formation 3 III also comprises a wide variety of other lithologies - see table 4. The amphibolites and associated quartz-feldspar-biotite-garnet gneiss generally occur as lenses and tabular bodies between the two leucogneiss levels in the formation (figure 7). Layered amphibolites also occur below the basal leucogneiss horizons; some of these are felsic and very well layered (Stroud in prep.). Small, but laterally persistent units of garnet-quartz rock and quartz-iron oxide rock also underlie the basal leucogneiss.

Formation 3 III equivalents are present throughout the Broken Hill Block within Suite 3, and are being mapped in work in progress. However, in this stratigraphic interval, the leucogneiss has so far only been definitely recognized in the Thackaringa and Triple Chance areas, and in the Broken Hill Synform, south of Broken Hill. In the Triple Chance area (Stroud in prep.), the equivalents of Formation 3 III are identical to those at Thackaringa: extensive development of continuous leucogneiss horizons, with layered garnet- or pyroxene-bearing basic gneiss, and sporadic development of quartz-feldspar-biotite-garnet gneiss with garnet-quartz and calc-silicate rocks. In the Broken Hill Synform, however, the equivalents of Formation 3 III appear to contain only one thin discontinuous horizon of leucogneiss in a thick sequence of pyroxene-rich basic gneiss and garnet-rich psammitic to psammopelitic metasediments and metasedimentary composite gneiss (figure 6). Thin layers and lenses of quartz-feldspar-biotite-garnet gneiss are interlayered with the basic gneisses (Bradley 1978) (figure 6).

TABLE 4: INFORMAL STRATIGRAPHIC SUBDIVISION OF SUITE (GROUP) 3 IN THE THACKARINGA AREA

(After Willis 1980b).

SUITE 4	See table 1
SUITE 3	FORMATION 3 IV Bedded leucocratic plagioclase-quartz rocks, quartz-feldspar-biotite ± garnet ("granite") gneiss, minor amphibolite.
	FORMATION 3 III Quartz-feldspar-biotite ± garnet leucogneiss, amphibolite and hornblende granulite, quartz-feldspar-biotite-garnet gneiss, metasedimentary composite gneiss, garnet-quartz rock, garnet-epidote calc-silicate rock, granular quartz-iron oxide rock.
	FORMATION 3 II Quartzo-feldspathic composite gneiss, minor amphibolite.
	FORMATION 3 I Bedded leucocratic plagioclase-quartz rocks, megacrystic quartz-feldspar-biotite gneiss, minor amphibolite.
SUITE 2	See table 1

The association of a "Potosi"-like quartz-feldspar-biotite-garnet gneiss with garnet- and pyroxene-rich basic gneisses in Formation 3 III, has some similarities with the typical "mine sequence" association in Suite 4 throughout the Broken Hill Block (table 1) (Stevens et al 1980). In Suite 4, these rocks are spatially related to Broken Hill type Ag-Pb-Zn mineralization, quartz-gahnite rock and garnet-quartz rocks (Stevens et al 1980). Although no Ag-Pb-Zn mineralization has thus far been recognized in Formation 3 III or its equivalents, the leucogneiss is associated with a Suite 4 type rock unit association which may have potential for Broken Hill - type mineralization.

Formation 3 III is generally overlain by an extensive unit of well-bedded sodic plagioclase-quartz rocks (Formation 3 IV - table 4) in the south Thackaringa (Willis 1980b) (figures 4,5,7) and Triple Chance (Stroud in prep.) areas. The basal rocks in Formation 3 IV, immediately overlying the uppermost leucogneiss horizon, are commonly pyritic plagioclase-quartz rocks including the significant cobaltiferous pyrite deposits at Big Hill and Pine Ridge (Vernon 1961, Plimer 1977). In the north Thackaringa area, the plagioclase-quartz rocks are only sporadically developed in the sequence above the leucogneiss. Their lateral equivalent in Formation 3 IV in this area is garnet-bearing "granite" gneiss which has been equated with the "Upper" and "Lower granite gneisses" at Broken Hill (Willis 1980b) (figure 4). At Thackaringa and the Broken Hill Synform, the "granite" gneiss occupies a similar stratigraphic position: above the leucogneiss, and immediately below Suite 4 (figures 4,6,7) (Willis 1980b, Laing 1980, Brown 1980). In parts of the succession at Thackaringa, the upper leucogneiss occurs towards the base of, and interbedded with, the "granite" gneiss (figures 4,7).

The sequence immediately below the leucogneiss and associated rocks in the south Thackaringa area comprises quartzo-feldspathic composite gneisses (Formation 3 II) (figure 7, table 4). The equivlent sequence in the Broken Hill Synform comprises mainly feldspathic psammitic to psammopelitic metasedimentary composite gneisses (Bradley 1978) (figure 7).

The base of Suite 3 occurs well below the

* To be formally named Cues Formation in a publication in preparation.

leucogneiss datum and is defined by megacrystic quartz-feldspar-biotite gneiss at Thackaringa, Triple Chance (Stroud in prep.) and the Broken Hill Synform (the "Alma augen gneiss") (Laing 1980, Bradley 1978, Brown 1980) (figure 7). In the Thackaringa area, the megacrystic gneiss is interlain with, and laterally equivalent to, well-bedded leucocratic sodic plagioclase-quartz rocks in Formation 3 I (figure 7, table 4). This lower interval of plagioclase-quartz rocks also occurs in the Triple Chance area (Stroud, in prep.) but is absent in the Broken Hill Synform (figure 7).

Formations 3 I and 3 II and their equivalents are absent in some cases and the leucogneiss immediately overlies Suite 2 metasedimentary composite gneisses (figure 7) (Willis 1980 a, b, Stroud in prep.).

The Leucogneiss as a Time-Stratigraphic Marker

Individual leucogneiss horizons are extremely thin compared with their extensive distribution, they maintain a consistent stratigraphic position over tens of kilometres of strike length, and they occur together in a very narrow stratigraphic interval. They are interpreted to have been deposited rapidly as individual volcanic pulses (see below) over a wide area, and therefore represent time-stratigraphic units.

STRUCTURAL SIGNIFICANCE

The leucogneiss is a distinctive, extensive, and usually competent structural datum within the sequence. Individual leucogneiss horizons about a metre wide can be traced continuously for several kilometres, and the narrow interval containing the multiple horizons can be traced for many kilometres (figures 1, 4, 5) (Willis 1980b, Stroud in prep.). The leucogneiss is therefore very useful for delineating mesoscopic and macroscopic structures.

In the Broken Hill Block, at least three regional deformations (D_1,D_2,D_3) are recognized (Rutland and Etheridge 1975, Laing et al. 1978, Marjoribanks et al 1980). The prominent gneissosity in the leucogneiss corresponds to S_1 (generally parallel to bedding, S_0), which is believed to be axial planar to very large isoclinal folds (F_1) formed during D_1. In all cases observed S_1 has been folded with the leucogneiss, defining F_2, F_3 and possibly F_4 (Willis 1980b), folds.

At a detailed scale, individual leucogneiss horizons provide an excellent opportunity to consistently trace out meso- and macroscopic folds, in some cases recording structures which would otherwise be unobserved. Two kilometres west-southwest of Old Coolgardie Tank (figure 5), the leucogneiss defines tight to open, angular, north-plunging mesoscopic F_3 folds on the northern limb of an east-plunging F_2 synform. The only other convincing evidence of this deformation observed is a weak north-trending schistosity (S_3) in adjacent plagioclase - quartz rocks. One kilometre southwest of Old Coolgardie Tank, the leucogneiss defines tight to isoclinal, angular, east-plunging F_2 folds of about 5 m half-wavelength and 10-20 m amplitude, in composite gneisses and amphibolites which otherwise appear to be unfolded.

The leucogneiss is more significant, however, as a form surface for larger macroscopic folds (Willis 1980b, Stroud in prep.) (figures 4, 5). In areas of structural repetition of an otherwise relatively undistinguished sequence (Suite 3) the leucogneiss is commonly the only reliable structural datum. In the Camels Humps-Old Coolgardie Tank area the leucogneiss horizons trace out a series of macroscopic F_2 fold repetitions with superimposed macroscopic F_3 structures (figure 5). In the Whites Well area (figure 4), the leucogneiss horizons define a series of isoclinal F_2 folds, which might otherwise have been confused for a continuous sequence (Willis 1980a). In the Triple Chance sheet area, the leucogneiss defines a complex fold interference pattern in a sequence otherwise lacking in reliable structural markers (Stroud in prep.).

ORIGIN OF THE LEUCOGNEISS

The quartzo-feldspathic composition of the leucogneiss is more compatible with an igneous progenitor than with a typical sedimentary rock. A feldspathic sediment (e.g. an arkose) may approximate the leucogneiss composition, but the regular, extensive thinly-layered horizons are not indicative of an arkosic sediment. The extensive development of thin horizons, conformability, stratigraphic consistency and thin layering are more compatible with an extrusive, rather than intrusive, origin. In fact the leucogneiss has the chemical composition of a rhyolite (columns 8, 9, table 3, and figure 8). Submarine deposition is indicated by the enclosing marine sedimentary sequence (Stevens et al 1980, Willis 1980b). Because rhyolitic lavas usually have restricted mobility, and the leucogneiss was deposited in such thin, homogeneous bodies over such a wide area, it can be concluded that the progenitor was a water-lain rhyolitic air-fall tuff. A submarine mass flow may also have produced a similar distribution and

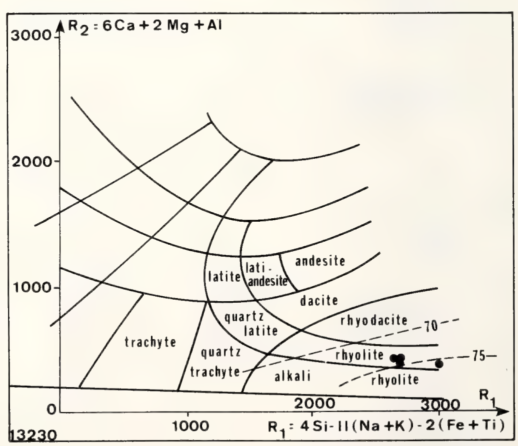

Fig. 8. Analyses of leucogneiss plotted on R_1R_2 diagram for the chemical classification of igneous rocks (De la Roche et al. 1980). The leucogneiss plots within the field of rhyolite, stradding the 75% weight percent silica contour (dashed lines).

geometry, but the laminations and thin, multiple horizons of the leucogneiss are more compatible with an air-fall origin. No relict igneous textures have been observed in thin section.

CONCLUSIONS

The leucogneiss is interpreted as a metamorphosed rhyolitic air-fall tuff which can be used as a time-stratigraphic marker in parts of the central and southwestern Broken Hill Block. As a consistent stratigraphic marker it can be used to subdivide Suite 3 in critical areas (e.g. Thackaringa) and to correlate Suite 3 in the Thackaringa and Triple Chance areas with the sequence underlying the Main Lode at Broken Hill. As a coherent structural marker it is useful in outlining meso- and macroscopic folds in areas of extensive Suite 3 outcrop.

Rock units associated with the leucogneiss are similar to lithologies which commonly accompany stratiform basemetal mineralization in Suite 4 (garnet- and pyroxene-rich basic gneisses, garnet-rich quartzo-feldspathic "Potosi"-type gneiss) (Stevens et al 1980, Barnes 1980). The presence of these units in Suite 3 raises the possibility that stratiform basemetal mineralization of the Broken Hill type (Barnes 1980) may occur stratigraphically below the level of the Main Lode, at the stratigraphic level of the leucogneiss.

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On the Growth and Evolution of Continental Crust: A Comparative Tectonic Approach

R. W. R. Rutland

ABSTRACT. Aspects of present continental crustal structure and composition, and of the geological record, are examined which bear on hypotheses concerning the volume, structure, composition, and stability of continental crust through geological time. The records of both platform covers and orogenic provinces are considered with particular reference to the concept of chelogenic cycles (global thermal cycles during which large areas of continental crust were stabilised as shield areas).

Major unconformities at about 2400 and 1000 Ma (10^6 years) following episodes of basic dyke injection are of similar character and mark the beginning of new chelogenic cycles when cratonic areas were of maximum extent. The continents were emergent before the development of these unconformities, which were followed by long periods of progressive subsidence. Thus the sea level changes do not support theories of general continental emergence consequent upon rapid continental growth and thickening, either at the end of the Archaean or later.

True cratons were present earlier in the Archaean, but reduction of cratonic areas by remobilisation was much more widespread in the Proterozoic than in the Phanerozoic. These cratonic areas were least extensive during the peaks of thermal activity within the chelogenic cycles, at about 1900-1700 and 400-200 Ma.

It is argued that the areally most extensive Precambrian provinces, both Proterozoic and Archaean, are more closely analogous to Palaeozoic Hercynotype orogenic belts than to the Mesozoic-Cenozoic belts which have generated the more popular models. The Hercynotype orogenies are characterised by areally extensive granitic plutonic episodes which correspond to the peaks of thermal activity within the chelogenic cycles. They are allocated to a tectonic environment between the contemporaneous craton and arc-trench complex and are regarded as largely, if not wholly, ensialic. The role of the Wilson cycle in the development of these provinces is still obscure but it seems doubtful whether the closure of large oceans is a critical factor. These Hercynotype provinces are regarded as being of major significance in the development of continental crust.

In these provinces the present structure and composition of crustal layers has been developed by multi-stage processes. Older provinces have been built on Archaean basement by Proterozoic deformation and plutonism of Proterozoic mobile belt sequences and by subsequent platform deposition, while younger provinces have developed on Precambrian basement through similar processes in the Phanerozoic. During the orogeny the crust may become underplated by basaltic material. These processes of vertical accretion produced a grossly layered crust which can be correlated with deep seismic structure.

Circum-Pacific-type processes of lateral accretion of ensimatic arc-trench complexes may be mainly important for the development of the lower crust, whereas Alpine-Himalayan type collision orogeny is important for crustal thickening in relatively narrow belts and the provision of source areas for platform deposition.

The analogies between the post-Archaean chelogenic cycles suggest that ocean floor spreading was active throughout the Proterozoic and that mantle convection produced widespread intracontinental (ensialic) orogeny as well as circum-Pacific-type orogeny on continental margins. It is not clear, however, whether a major phase of continental fragmentation and dispersal followed the thermal peak at 1850-1650 Ma in the same way as Mesozoic fragmentation and dispersal followed the late Palaeozoic thermal peak.

Archaean granulite-gneiss belts show some analogies with younger Hercynotype provinces, although the protoliths of the granitoids were probably closer in age to the plutons themselves, and more uniformly mafic, than in the younger provinces. Granite-greenstone belts are developed on tectonically highly evolved crust immediately prior to stabilisation as cratons, and are best regarded as more mobile equivalents of younger platform covers. They provide no support for theories requiring numerous microplates in the Archaean.

The major peaks of plutonism during the Archaean are analogous to the peaks in the younger chelogenic cycles. They represent growth of the upper crust at the expense of the lower crust.

The isotopic evidence for a major episode of continental growth at the end of the Archaean is better interpreted as evidence for growth of the upper crust by plutonism derived from a thick basaltic lower crust during a global thermal peak. In the post-Archaean cycles there is increasing likelihood that the lower crust was both chemically differentiated and much older than the upper crust. Thus isotopic signatures of plutonic rocks are likely to reflect increasing contamination by evolved older crust in younger orogenic belts.

In view of the absence of the earmarks of subduction in older Precambrian terrains, the time of commencement of ocean-floor spreading and subduction remains conjectural. It may, however, have occurred before the deposition of the earliest granite-greenstone belts and thus assisted in the tectonic thickening of the early globe-encircling protocrust to form the earliest granulite-gneiss provinces.

INTRODUCTION

"As we increase our demands on the earth and seek to increase our ability to predict or investigate the instabilities, we must improve our knowledge of the basic tectonic framework and processes involved in the formation and modification of continental crust."

U.S. National Research Council paper on Continental Tectonics, 1980.

The theory of plate tectonics elegantly explains the broad features of the Earth's near-surface dynamics at the present day. It requires that oceanic crust be generated and consumed at such a rate that no oceanic crust is older than about 200 Ma. Continental crust on the other hand resists subduction because of its greater buoyancy and preserves a record of geological history dating back almost 4000 Ma. Much attention is currently being given to the question of how far this geological record can be interpreted in terms of the operation of the plate tectonic system in the past (e.g. Kroner, 1981a).

Strict uniformitarianism is clearly not applicable to the Precambrian, since radioactive heat generation, and presumably geothermal gradients, were higher. Actualistic principles can be applied, however, and careful analysis is required to determine whether the different thermal regime, and perhaps different volume, area, and thickness of continental and oceanic lithosphere, resulted in significantly different configurational processes than in the later Phanerozoic.

Geological and palaeomagnetic evidence (e.g. Morel and Irving, 1978) strongly suggest that plate-tectonic processes have operated in the Late Proterozoic and Phanerozoic and there is a strong body of opinion that plate-tectonic processes have operated throughout the Proterozoic, although various qualitative differences have been proposed to explain features of the geological record (e.g. Rutland, 1973b; Hargraves, 1976; Kroner, 1977b).

In particular a thinner and more mobile continental lithosphere may have favoured continental thinning, as a response to extensional processes, rather than rifting and drifting. Thus ensialic orogeny may have been relatively more important and the "Wilson Cycle" of ocean opening and closing relatively less important. Palaeomagnetic evidence is still not conclusive in this regard (e.g. Piper, 1976; Irving and McGlynn, 1981).

Some authors have also argued for an essentially uniformitarian interpretation of Archaean tectonics, while others have proposed a variety of other tectonic schemes (see e.g. Windley, 1977a). The interpretation of the early thermal history and of the earliest differentiation of the earth is a critical factor in this debate (e.g. Hargraves, 1976; 1981; McKenzie and Weiss, 1975; McKenzie and Richter, 1981). The geological constraints are few, the most important being the presence of peridotitic komatiite lavas in the Archaean which were extruded at temperatures around 1600°C, implying higher temperatures in the upper mantle and probably a significantly thinner lithosphere than at present (e.g. Green, 1975, 1981).

There can be no doubt that, if the earth passed through an early high-temperature phase (e.g. Shaw, 1976; Tarling, 1978), then the earliest crust was physically quite different from that of the present day and was probably similar over the whole earth. One possibility is that fractional crystallisation and gravity differentiation of anorthitic plagioclase would occur from the molten upper mantle (Shaw, 1978; Fyfe, 1978) but this is disputed (Taylor and McLennan, 1981a). In any case, the earliest crust would have been subject to recycling by vigorous mantle convection and to modification by volcanism and meteorite impact. The oldest preserved crustal rocks (> 3700 Ma) are similar chemically and in their lithological complexity to those of the Archaean generally (> 2500 Ma) (Taylor and McLennan, 1981b).

Assuming higher geothermal gradients, Hargraves (1978, 1981) has developed a model in which viscous drag subduction caused vigorous recycling of the earliest buoyant crust. Subsequently a buoyant, possibly continuous, global scum crust would have developed, and later again negative-buoyancy-powered subduction, like that of the present day, began at the end of the Archaean (Fig. 1). Other authors (e.g. Windley and Smith, 1976; Windley, 1977a) have inferred that subduction processes similar to those of the present day also operated in the Archaean.

Plate tectonics has also given new stimulus to the hypothesis of continental growth by accretion at convergent plate boundaries, and this raises the questions of the rate and amount of growth, and of recycling, by these processes. Evidence from various isotopic systems has been used to construct a number of models. Hurley and Rand (1969) inferred from the apparent age patterns of continental basement rocks that the rate of production of continental crust has been increasing.

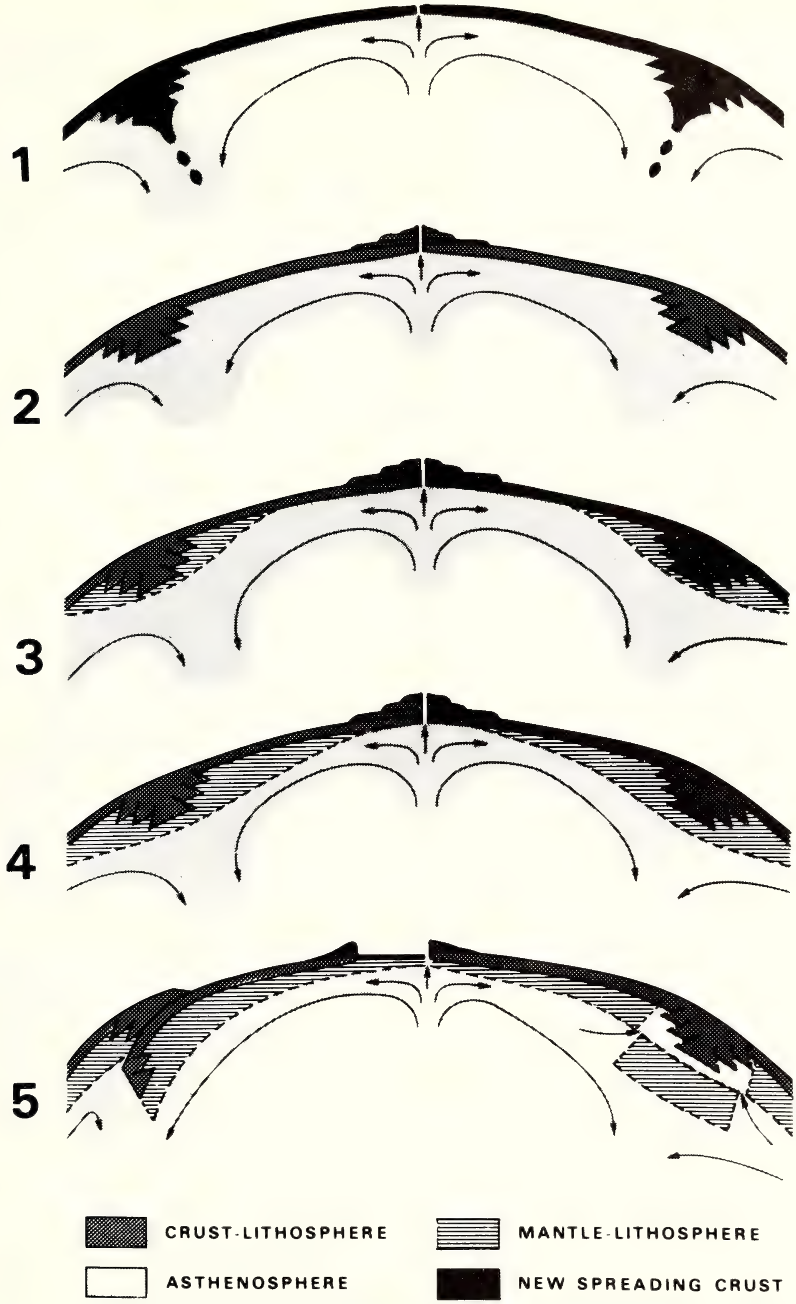

Fig. 1. Pictorial cartoon illustrating postulated evolution of tectonic style. (1) Viscous drag subduction stage: newly formed basaltic crust (= lithosphere) formed above upwelling hot-spot zones is dragged down at convergent zones, but partial remelting distills more sialic material. (2) Progressive accumulation of sialic differentiates concomitant with decreasing heat flow and viscous drag leads to globe-encircling, positively buoyant, scum crust (= lithosphere) decoupled from mantle asthenosphere below. (2-3) Eruption of basalt above upwelling zones (hot-spots?) is no longer accompanied by lateral spreading as buoyant scum-crust is continuous: outpouring of basalt onto scum-crust causes thickening and remelting at base; this stage is characteristic of Archaean crustal evolution. (3-4) With further slowing of convection lithosphere thickens to include denser mantle above cooler downwelling zones, causing progressive change in buoyancy from positive toward negative. (5) This thickening culminates in (left) buoyancy-powered subduction, with concomitant growth of new basaltic (= oceanic) crust, and (right) decoupling of mantle lithosphere from overlying crust causes intracontinental type orogeny. From Hargraves (1981), *in* PRECAMBRIAN PLATE TECTONICS (ed. A. Kröner), *Elsevier, Amsterdam.*

Moorbath (1977), McCulloch and Wasserburg (1978), and Jacobsen and Wasserburg (1981) have also developed isotopic models which suggest that progressive continental growth has occurred. Thus in the models of Jacobsen and Wasserburg the mean age of the crust is about 1800 Ma. In contrast, other authors have emphasised the importance of recycling and reworking processes, which would have allowed most of the volume of the earth's crust to be formed in the Archaean (Armstrong, 1968; Fyfe, 1978; O'Nions et al., 1979). As discussed below, this view is more consistent with the geological evidence (e.g. Rutland, 1973b; Wise, 1974; Kröner, 1977a; Windley, 1977b; Allègre and Ben Othman, 1980). Fyfe (1980) emphasises the importance of potassium fixation and other chemical exchange during the spilitisation of oceanic crust and, since spilite subduction about balances ocean crust production, he suggests that continental removal rather than continental growth may be occurring at present.

A major episode of continental crust generation in the late Archaean (2700-2500 Ma) has been postulated from the study of neodymium-samarium systematics (McCulloch and Wasserburg, 1978), of rare-earth abundances and patterns in sediments (Taylor and McLennan, 1981a), and of $^{87}Sr/^{86}Sr$ ratios in carbonates (Veizer and Jansen, 1979). This draws particular attention to the possibility of changes in tectonic style at the Archaean-Proterozoic boundary.

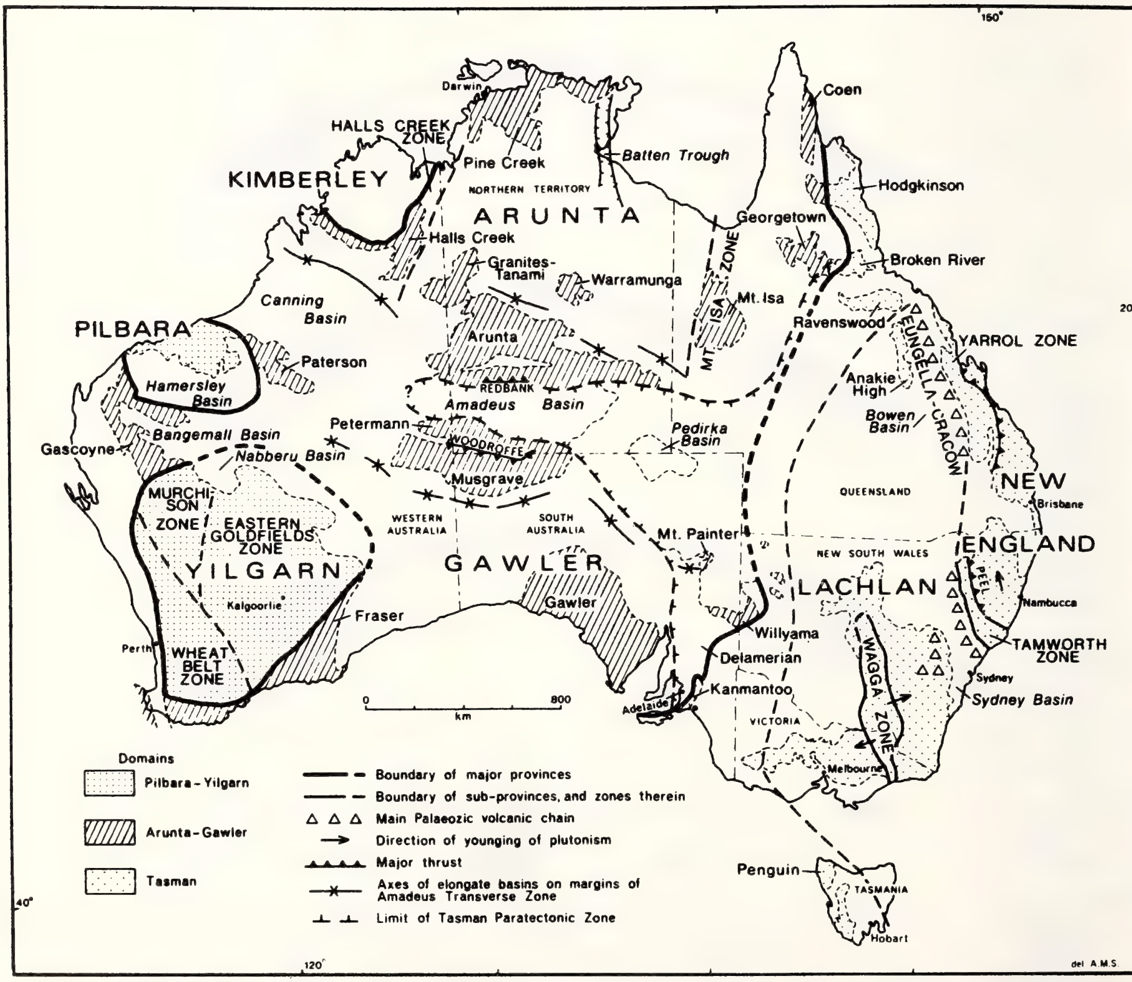

Fig. 2. Map showing the principal exposed orogenic domains in Australia. The ornamentation of the domains indicates their allocation to three super-provinces, corresponding to three chelogens. From Rutland (1976, Orogenic evolution of Australia. *Earth Sci. Rev.*, *12*, 161-196).

In this paper I wish to discuss some of the geological evidence, especially from Australia, which places constraints on these models.

PRESENT STRUCTURE AND COMPOSITION OF THE CONTINENTAL CRUST

The continental crust is readily divided into major provinces on the basis of its age and geological history. In Australia three super-provinces occur, corresponding to crustal evolution during three chelogenic cyles (Fig. 2; Rutland, 1973b; 1976; 1981), and similar provinces of broadly similar age have been identified in other continents (e.g. Sutton, 1963; 1967). A chelogenic cycle is a global thermal cycle of the order of 1000 Ma, during which large areas of continental crust are stabilised as shield areas. As Runcorn (1962) first suggested, the chelogenic cycle may reflect periodic changes in the convective system in the mantle. Each chelogenic cycle is characterised by a major peak of metamorphic and granitoid intrusive activity occupying a limited time span but having wide areal extent. Thus the temporal limits of the Proterozoic chelogenic cycle in Australia are marked by major phases of basic dyke emplacement at about 2400 and 1050 Ma while the major peak of granitoid intrusive activity occurred at about 1900-1700 Ma. Eastern Australia is the product of an, as yet, incomplete chelogenic cycle, encompassing an assemblage of Late Proterozoic and Phanerozoic fold belts, which display varying degrees of morphotectonic rejuvenation in the Neogene. Thus Eastern Australia is not yet a true craton with steady-state heat flow (see below), as are the Archaean and Proterozoic chelogens. It should be emphasised, therefore, that stable continental crust is the product of a lengthy geological history. The crust formed in the early stages of this history is better described as proto-continental crust.

If there are major secular changes in tectonic processes and crustal evolution it might be expected that these would be expressed by differences in the crustal structure and composition of Phanerozoic, Proterozoic, and Archaean chelogens. Unfortunately currently available geophysical evidence is not sufficiently unambiguous to enable reliable generalisations to be made. It will be a major task of the International Lithosphere Project to provide clearer analyses of the differences between chelogens and between the smaller tectonic units within them.

Broad geophysical differences between the lithosphere and upper mantle of Precambrian shield areas and Phanerozoic provinces have been reasonably well established (e.g. McElhinny, 1973; Finlayson et al., 1974; Finlayson, 1982; for Australia). These however are largely due to the long time scale of global heat flow decay (Sclater et al., 1981). The Phanerozoic provinces show a large scatter and high mean of heat flow values, reflecting the influence of transient tectonic and erosional processes, whereas the Precambrian shield areas show a smaller scatter about a lower mean, indicating steady-state conditions. Thus it is not possible to infer that there are any more fundamental structural or compositional differences between Phanerozoic and Precambrian crustal provinces. No general distinction was recognised by Sclater et al. (1981) between Precambrian provinces older and younger than 1700 Ma. In Australia however the Archaean chelogen shows distinctly lower heat flow than the Proterozoic chelogen (Cull, 1982) and significant differences in crustal composition can be inferred.

Recent seismic refraction studies have provided more refined models of crustal structure than were hitherto available (Finlayson et al., 1980; Finlayson, in press; Drummond, 1982). Three depth-velocity diagrams taken from the three main chelogens or super-provinces in Australia are presented for comparison in Figure 3. It is notable that there is close similarity between the curves for Phanerozoic and Proterozoic Australia and this is consistent with the close geological analogy between the two chelogenic cycles (Rutland, 1973b, fig. 3 and pp.1017-1022).

It will be argued below that the upper crust in each case probably corresponds to rocks of the relevant chelogenic cycle including both platform cover and orogenic basement rocks, while the normal-velocity lower crust probably corresponds to reworked rocks of the preceding chelogenic cycle. There is good evidence elsewhere that such lower crustal layers can be attributed to Precambrian granulite-facies rocks of variable composition produced by deformation and metamorphism in orogenic zones (Smith and Bott, 1975; Tarney and Windley, 1977; Smithson et al., 1980). Many of these granulites were apparently derived from igneous intrusions, but they also include supercrustal metavolcanics and metasediments (e.g. Collerson et al., 1972; McGregor, 1973).

The Pilbara profile apparently lacks the relatively high velocity layers that are present in the lower crust in the Proterozoic and Phanerozoic chelogens. This probably reflects a simpler history of crustal evolution and possibly more effective recycling of restites from granitic plutonism back into the mantle, than in later epochs. The lower crust is interpreted as felsic granulite (Drummond, 1981). However, higher-velocity layers (Vp 6.9-7.0 km/s) are present in the Archaean of the Yilgarn province which includes both older and younger Archaean elements (Figs. 4 and 11). Drummond and Shelley (1981) combined the seismic and gravity data, and suggested that some chemical layering was possible, with garnet granulites becoming more basic downwards.

It should be stressed that the correlation between seismic velocities and composition indicated above is highly generalised. Jones (1981) has considered the nature of the lower crust for regions where geomagnetic or geoelectric as well as seismic studies have been undertaken. He considers that 'normal' Precambrian lower crust with P wave velocities around 6.6 km/s has high electrical resistivity and can be modelled by anhydrous quartz diorite compositions in the granulite-eclogite facies. However, he considers that Precambrian lower crust with relatively high P wave velocity (6.8-7.3 km/s) and a moderate resistivity are better modelled by hydrous rocks in the amphibolite facies. The former 'normal'

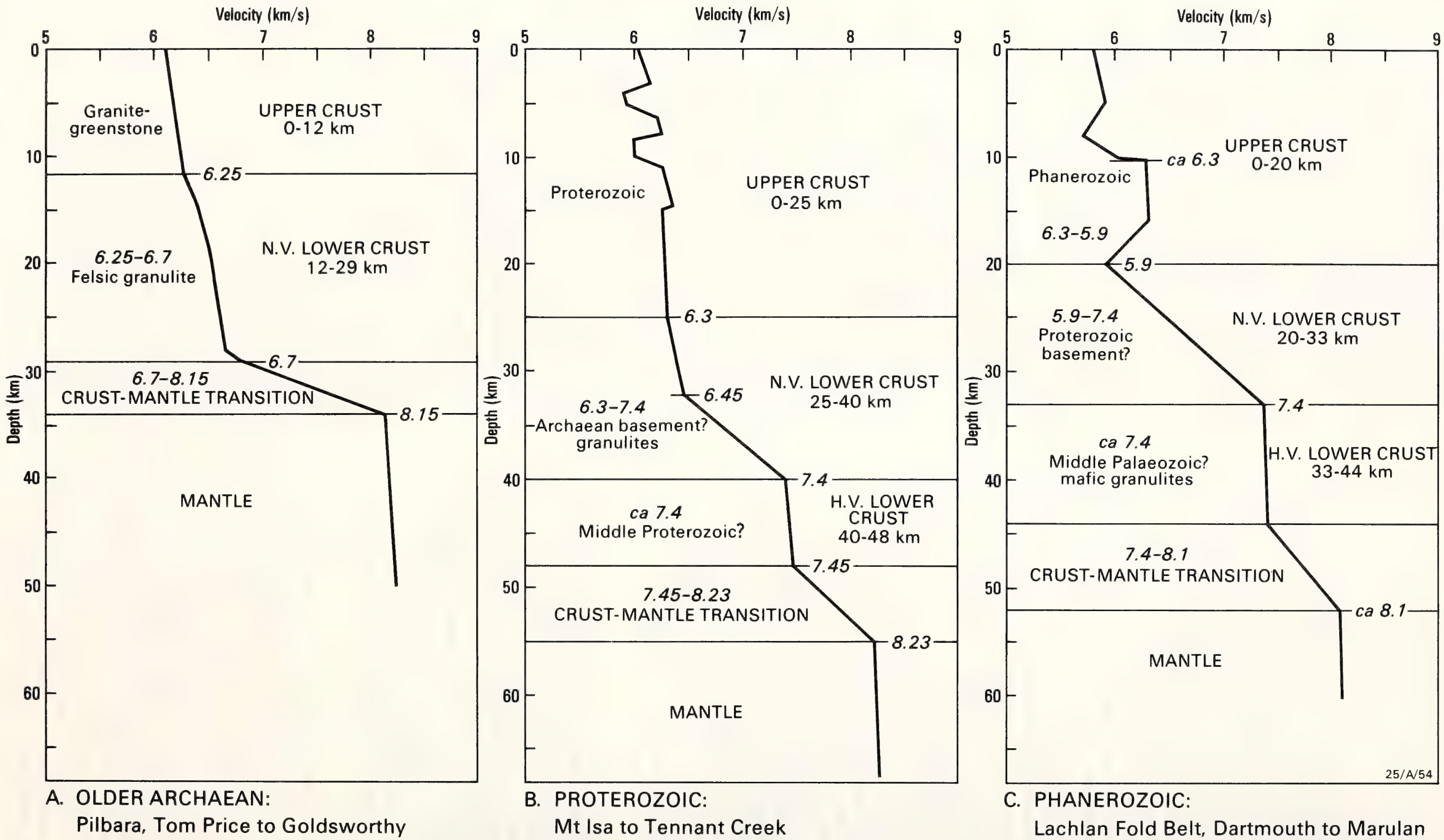

Fig. 3. Velocity-depth functions for Phanerozoic, Proterozoic and Archaean provinces in Australia, indicating their possible interpretation in terms of crustal structure and age (see text). N.V. = normal velocity; H.V. = high velocity. Velocity-depth functions from: (A) Drummond (in prep.), (B) Finlayson (in press), (c) Finlayson et al. (1980).

type is regarded as characteristic of the central part of shield areas while the latter type is regarded as a shield 'edge' effect. He also observes that layers with velocities between 6.6-7.7 km/s may often not be recognised in less sophisticated analyses. Consequently the present data base is inadequate for confident regional comparisons. Berry and Mair (1980) emphasise that seismic reflection data are needed to complement seismic refraction data. Smithson et al. (1980), for example, have demonstrated the presence of folded structures in the deep Archaean crust (24 to 31 km) in Wyoming, and it seems likely that, although the crust shows a gross layering, second-order lateral heterogeneity is characteristic of both the upper and lower crust.

It should also be noted that crustal P-wave velocities are normally regarded as falling below 7 km/s so that higher values are attributed to transitional crust-mantle boundaries (Prodehl, 1977; Bamford and Prodehl, 1977). The layers labelled 'H.V. lower crust' in Figure 3B and C with velocities greater than 7.4 km/s can probably be attributed to rocks of basaltic and more mafic composition in the granulite facies. This view is supported by the evidence of mafic nodules in kimberlite pipes (Fig. 5; Ferguson et al., 1979). The upper part of this zone could correspond to oceanic crust produced by ocean floor spreading but much of this zone is probably produced by underplating of the crust at an early stage of local crustal evolution. There is little direct evidence that the lower crust consists of the refractory residues from partial melting.

GROSS COMPOSITION OF THE CRUST

The isotopic models noted above depend on estimates of the relevant elemental and isotopic ratios both in the crust and also in depleted and undepleted mantle reservoirs. Using these estimates it is possible to calculate the consequences of particular models of mass transfer between the reservoirs. These models can be developed independently of assumptions concerning the bulk composition of the crust or of specific mechanisms of differentiation or recycling (e.g. Jacobsen and Wasserburg, 1981). Since this talk was prepared an excellent general discussion of 'Chemical Geodynamics' has been presented by Allègre (1982).

Direct estimates of the average chemical composition of the upper continental crust of the Canadian Shield have been made by Eade and Fahrig (1971, 1973) and by Shaw et al. (1967, 1976), and a granodioritic composition is suggested. A similar composition for the upper crust has been inferred by Taylor (1977, 1979) and Taylor and McLennan (1981a) from the uniformity of rare-earth-element (r.e.e.) patterns in post-Archaean sedimentary rocks. This uniformity is interpreted to indicate that the sediments preserve and record the average rare-earth abundance pattern of the upper crust, which is taken to be 10-15 km thick in average crust of about 40 km.

In order to calculate the composition of the lower crust a model for total continental crust must first be assumed. Taylor (1967) concluded that island arc volcanism was the only presently observable viable source for continental growth and therefore, on uniformitarian grounds, used the average composition of young island-arc rocks to establish the bulk composition of the continental crust (the andesite model). Assuming that the lower crust constitutes two-thirds of the total, its composition can then be calculated. The normative composition of the lower crust thus calculated has about 80% plagioclase, and average lower-crust samples should have positive Eu

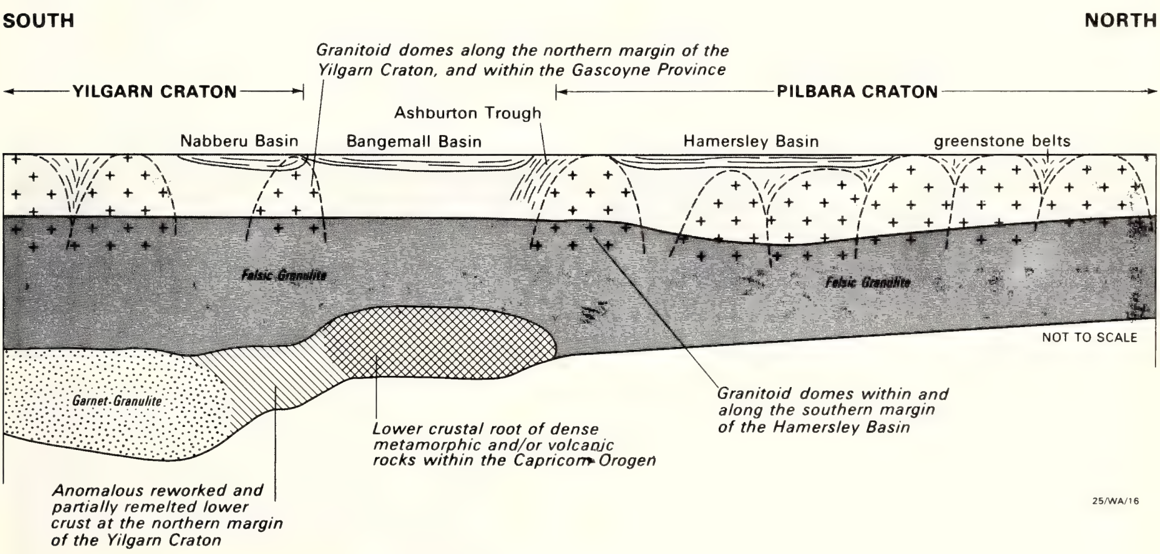

Fig. 4. Cartoon sketch of a north-south section from the Pilbara to the Yilgarn cratons (Fig. 2) giving a geological interpretation of refraction seismic models. From Drummond (1981).

anomalies (Taylor & McLennan, 1981a). The model is plausible but the assumptions involved are open to question.

Firstly, it is doubtful whether the average composition of island arc assemblages used in the andesite model gives adequate weight to the more

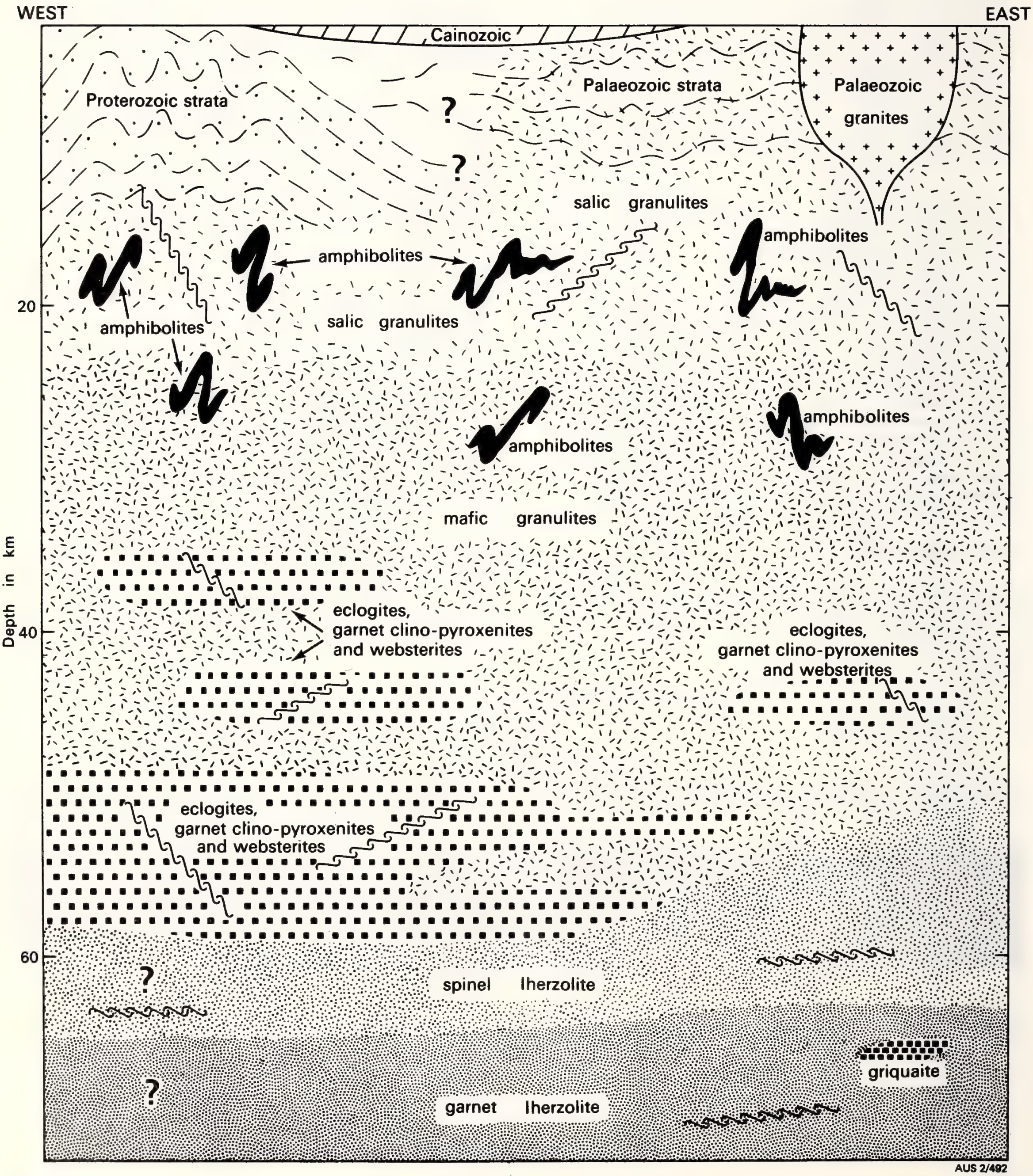

Fig. 5. Idealised cross-section from Port Augusta (SA) to Jugiong (NSW) with inferred crust-upper mantle lithologies. From Ferguson et al. (1979).

basaltic components (e.g. Arculus, 1981) and, as already noted, differential recycling is ignored in the model. Furthermore, the upper crust composition derived from the sediment rare-earth patterns is an average from the exposed area of crust and cannot be correlated with a particular thickness or volume of the crust defined by geophysical means, so that the assumed upper crustal thickness is mainly constrained by heat-flow considerations. Finally, there are difficulties with the compositional characteristics of the lower crust predicted from the model.

Tarney and Windley (1977, 1979), in particular, have argued that Precambrian granulites are representative of the lower continental crust and that they are of intermediate average composition. They regard the dominant process of crustal growth as similar to that giving rise to modern Cordilleran granodioritic and tonalitic batholiths and they consider that the continental crust completed a "substantial part" of its growth by 2500 Ma ago.

Some support for such an alternative model may be found in the conclusion of Taylor and McLennan (1981a) that "the parallel r.e.e. patterns in sedimentary rocks since 2.5 Ga [2500 Ma] B.P. indicate no fresh input from other than 'granodioritic' material over this period. For the andesite model, this would require that differentiation into upper and lower components must occur before significant input is made to the sediments. Tarney and Windley (1979) have pointed out that the energy source for this differentiation process is not readily discerned. In any case the important inference from the sediment rare-earth data appears to be that the net input to the upper crust since 2500 Ma B.P. has been of granodioritic composition.

Taylor and McLennan (1981a) also use the rare-earth patterns and abundances of Archaean sediments (from granite-greenstone terrains) to infer that the composition of the upper Archaean crust resembles that of the total post-Archaean crust, and is close both to average island arc compositions and to a mixture of tholeiite and tonalite-trondhjemite suites. Since bimodal basaltic and tonalite-trondhjemite suites are so common in the Archaean (both in granite-greenstone terrains and in granulite-gneiss terrains) they accept that Archaean crustal growth did not occur by means of island arc volcanism and follow the model developed by Tarney et al. (1979). In this model the tonalites and trondhjemites are developed by partial melting of basalts at depths where garnet is stable (cf. Arth and Hanson, 1972). Deficiencies in this model, as applied to particular tonalitic bodies in the Yilgarn Archaean, have been discussed by Foden et al. (in prep.).

A direct indication of lower crustal composition in the Archaean is given by the exposed areas of Archaean granulite-gneiss belts, in which tonalitic rocks are often a dominant component (Fig. 6; Bridgwater et al., 1978). These terrains include the oldest crustal rocks known (> 3700 Ma) and show phases of tonalitic and granodioritic intrusion at about 3700 and 3000-2800 Ma, as well as relatively minor phases of potash-rich granites at about 2500 Ma. The

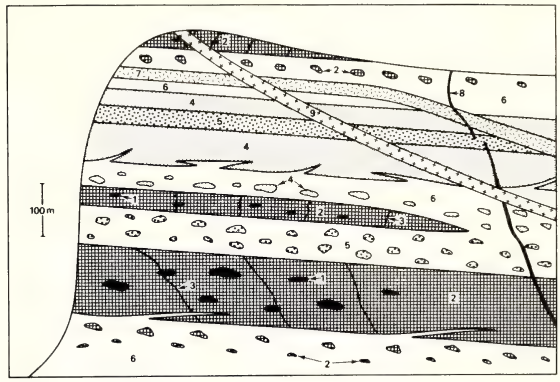

Fig. 6. Hypothetical vertical section through part of the Archaean gneiss complex compiled largely from field observations in the Godthab district and Saglek fjord, Labrador. Note that all the contacts shown are either tectonic or intrusive. Individual rock units except for the youngest granites are highly deformed and their conformable nature is largely due to tectonic rotation. This pattern is typical for the whole craton except that in most areas the old gneiss units are missing.

(9) Late to post tectonic potash-rich granites and pegmatites (e.g. Qôrqut 2520 ± 90 Ma).

(8) Basic and intermediate dykes. Can be confused with (3) in areas in which there is insufficient isotopic control.

(7) Igneous complexes emplaced at least in part under granulite facies conditions; andesine anorthosites, monzonites and porphyritic granites (e.g. Ilivertalik, 2835 ± 10 Ma).

(6) Tonalite, granodioritic and locally granitic gneisses emplaced as sub-concordant sheets into the gneiss complex. In West Greenland they make up 50-80% of the gneiss complex (e.g. Nûk gneisses 2800-3000 Ma). In the Saglek area these rocks form a much smaller percentage of the gneiss complex.

(5) Layered anorthosite complexes (2800 ± 200 Ma), locally intrusive into (4). Similar rocks in Saglek area may pre-date (2).

(4) Amphibolites, ultrabasic rocks, metavolcanics and metasediments (e.g. Malene supracrustals 2900 ± 200 Ma) and Upernavik supracrustals (older than 3100 Ma). No primary depositional contacts preserved, not seen to be intruded by (3).

(3) Amphibolite dykes cutting old gneisses (Ameralik dykes in Godthab district, Saglek dykes in Labrador).

(2) Tonalitic and granodioritic gneisses (grey Amîtsoq and Uivak gneisses), porphyritic granites and iron-rich diorites 3700 ± 100 Ma.

(1) Amphibolites, layered basic complexes, ultrabasic masses, metasediments. Isua supracrustals (3760+ Ma) pre-Uivak and pre-Amitsoq inclusions.

With permission from Bridgwater et al. (1978), *in* EVOLUTION OF THE EARTH'S CRUST (ed. D.H. Tarling), *Academic Press, London*.

various components have been strongly deformed and interleaved in tectonic episodes prior to 2800 Ma which have been likened to Phanerozoic collision orogeny.

In the Aldan Shield (Moralev, 1981) the oldest Archaean gneiss-granulite basement (> 3000 Ma) consists of meta-basaltic rocks (mainly hypersthene and two-pyroxene-plagioclase schists), up to 5 km thick, at the base, overlain by a varied suite of gneisses and schists, about 2-3 km thick. The latter begin with high-alumina-garnet and sillimanite gneisses with beds of quartzite and lenses of corundum. This is regarded as a meta-sedimentary suite formed as a result of weathering and disintegration of a mafic basement. The over-lying higher parts of the granulite-gneiss complex are also dominantly mafic, with subordinate marbles and quartzites, and apparently belong to the younger Archaean. These in turn are overlain by greenstone belts of late Archaean or Early Proterozoic age. The mafic gneiss-granulite complex also contains granite-gneiss domes but neither the volumetric nor age relationships are clearly defined. Apparently tonalitic-grano-dioritic intrusion terminated the development of the granulite-gneiss basement and preceded development of the greenstone belts, but the main granitic emplacement in the region was in the Early Proterozoic (and in the Cretaceous!). In any event the present crustal density is greatly influenced by the granitic rocks.

Thus the evidence generally supports the view that the Archaean crust is made up of a mixture of tonalitic-granodioritic and basaltic rocks.

Taylor and McLennan (1981a) attribute the change in sedimentary rare-earth patterns at about the Archaean-Proterozoic boundary, and the inferred difference in average exposed upper-crustal com-positions, to unroofing of the large volumes of K-rich granitic rocks intruded into most shield areas. They calculate that about $^1/3$ K-rich granite must be added to the upper Archaean crust to produce typical post-Archaean sedimentary patterns. They further infer that the production of these K-rich granites by intracrustal melting would require an Archaean crust perhaps 40 km thick. Such an episode of intracrustal melting can also explain the isotopic data of McCulloch and Wasserburg (1978) and Veizer and Jansen (1979) referred to above. Thus, although these data imply rapid growth of the upper crust at the end of the Archaean, they do not necessarily imply a major phase of growth of the total continental crust, if the lower crust was basaltic.

I will return to the question of the tectonic significance of the Archaean-Proterozoic boundary after a brief review of tectonic changes through time, dealing first with platform-cover evolution and then with orogenic evolution.

PLATFORM COVERS AND CONTINENTAL EMERGENCE

The continental crust and the oceanic crust today correspond to two isostatic levels, the continental generally less than 1 km above sea level and the oceanic generally 4-6 km below sea level. The volume of the oceans is such that the lowest parts of the continental surface (the continental shelves) are flooded. An increase in ocean volume (or a decrease of ocean basin volume) of only 13% would flood most of the continents. It is therefore one of the more remarkable features of earth history that large parts of the surface of the continents have been near sea-level, and subject to transgressions and regressions, since at least the beginning of the Proterozoic. Wise (1974) has used this evidence, on uniformitarian grounds, to argue that continental area and thick-ness have not changed significantly for the last 2500 Ma. This assumes that the present contrast between continental and oceanic crust has existed throughout that time, and implies that ocean floor spreading (and subduction) was probably operative to generate the oceanic crust.

This is consistent with the evidence from Archaean terrains that parts of the continents had achieved stability as cratons by, or before, the end of the Archaean. Extensive basic dyke swarms, which were emplaced at the end of the Archaean, and which have remained undeformed since, testify to the Archaean stabilisation of the lithosphere in these regions. Windley (1977b) has reviewed various lines of evidence which support the view that normal present day crustal thicknesses were achieved in the Archaean.

Other scenarios are possible if the uniformitarian assumptions are not made. Thus Hargraves (1976) argued for progressive thickening of continents and increase of oceanic crustal area through the Precambrian, so that continents were not generally emergent until 1400 to 1000 million years ago. As Hargraves pointed out, a critical question is whether the preserved geological record at any time is typical or atypical of crustal conditions then obtaining. Glikson (1979a) was dissatisfied with uniformitarian explanations of the Proterozoic record and in particular by the scarcity of signatures of closed ocean domains and of the accreted volcanic products of continent-ocean convergent margins. He therefore considers the expanding earth hypothesis as a possible explanation.

These discussions tend to neglect the demonstrated periodicity of tectonic processes and of relative movements of sea level on various time scales. In particular the study of platform sediments has revealed major variations in the rates of accumulation and distribution of platform sediments on the time scale of the chelogenic cycle (e.g. Sloss, 1976; Garrels and Mackenzie, 1971; see also review by Williams, 1981). The sea level changes show a correlation with orogeny and this may be partly due to reductions in continental area by compressional thickening (e.g. Grasty, 1967; Rutland, 1973b; Hallam, 1977). The major control is usually regarded as tectono-eustatic owing to variation in the volume of the oceanic ridge system caused by variations in spreading rates and ridge length (e.g. Hays and Pitman, 1973). However, this must be supplemented by epeirogenic effects within the continents them-selves. In Australia, for example it is clear that the emergence of the craton during the Cenozoic, following the Cretaceous marine trans-gression, is related to the formation of a broad tectonic arch so that the Cretaceous unconformity rises from below sea level at the north and south

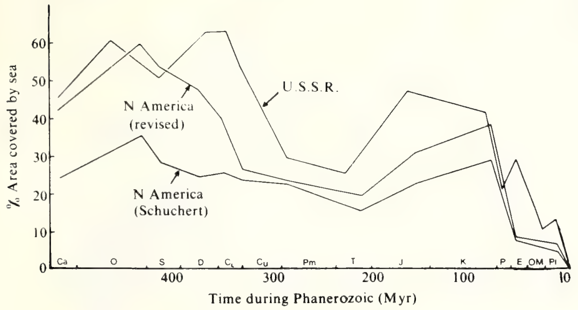

Fig. 7a. Maximum degree of marine inundation for each Phanerozoic geological period for USSR and North America. From Hallam (1977).

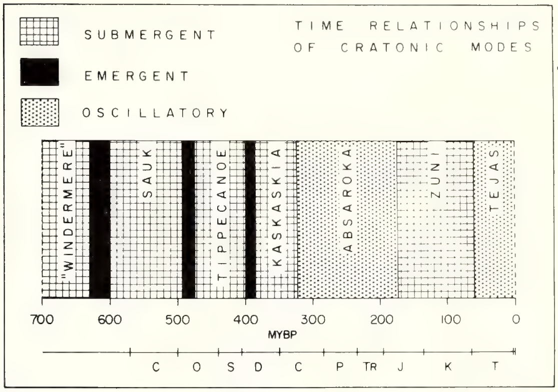

Fig. 7b. Time distribution of three tectonic modes in the cratons. Relationships to Phanerozoic periods, to the isotopic timescale, and to the episodes of deposition of the North American stratigraphic sequences are shown. From Sloss and Speed (1974).

coasts of Australia to around 1000 m near Alice Springs. Similar morphotectonic effects are well documented in other shield areas of the world, while the amount and rate of differential vertical movements in Phanerozoic fold belts during the Neogene has been much greater. These effects must be attributed to a global thermal cycle having significant effects in both continents and oceans (e.g. Rutland, 1973a; Sloss and Speed, 1974; Sloss, 1976). The importance of these thermally induced processes within the continents is emphasised by the fact that the new oceans which have grown by spreading in the last 200 million years were initiated by rifting, in the interiors of relatively stable regions of continental crust. Thus it appears that major transgressions and regressions are caused by tectonic effects of a global thermal cycle in both ocean basins and continents.

Whatever the precise cause of fluctuations in the continental freeboard the evidence for them is reasonably well documented. Fig. 7a shows the maximum degree of marine inundation for USSR and North America during the Phanerozoic. Sloss and Speed (1974) have identified three tectonic modes in the cratons: emergent, submergent, and oscillatory. While the first two are characterised by broad epeirogenic movements, the third is accompanied by intracratonic faulting leading to significant relief, and is marked by "pulsatory vertical movements leading to general net elevation of the cratons". Fig. 7b shows the pattern of these modes through the late Precambrian and Phanerozoic. Sloss (1976) has also demonstrated correlations between the volumes accumulated per unit time of preserved Palaeozoic-Mesozoic strata on the Russian platform and on the western part of the North American craton.

The later Precambrian to Palaeozoic platform covers in Australia are divided into two main groups with quite different regional distribution (G.S.A., 1971). I have suggested (Rutland, 1973; 1981) that these two groups (Fig. 8) correspond to two main stages of the chelogenic cycle. The older, late Precambrian-Palaeozoic, cover ('Central Australian') is the cratonic equivalent of the mobile-belt sequences which were deformed within the assemblage of Palaeozoic fold belts. The younger, largely Mesozoic, cover ('Trans-Australian') formed after the formation and stabilisation of the Palaeozoic fold belts from the mobile belt sequences and thus extends across the newly consolidated Palaeozoic crust as well as the previously existing Precambrian craton. This younger platform cover is equivalent in age to mobile belts formed during the main period of continental fragmentation and dispersal in the Mesozoic. Clearly the main deformation, plutonism, and metamorphism (the thermal peak of the chelogenic cycle) occurred in the diachronous interval between these two platform-cover stages and broadly corresponds to the oscillatory cratonic mode recognised by Sloss and Speed (1974). It seems likely that the mafic underplating of the mobile belts recognised on seismic and petrological grounds, occurred during this thermal peak.

The basal sediments of the older platform-cover stage (ca. 1000 Ma) often, but not invariably, rest with profound unconformity on platform basement rocks belonging to the preceding chelogenic cycle, as for example where Adelaidean rocks rest on highly metamorphosed Proterozoic rocks of the Broken Hill orogenic domain. As noted above, the transition between these two chelogenic cycles is also marked by a major phase of basic dyke emplacement at about 1050 Ma. It seems likely, from the

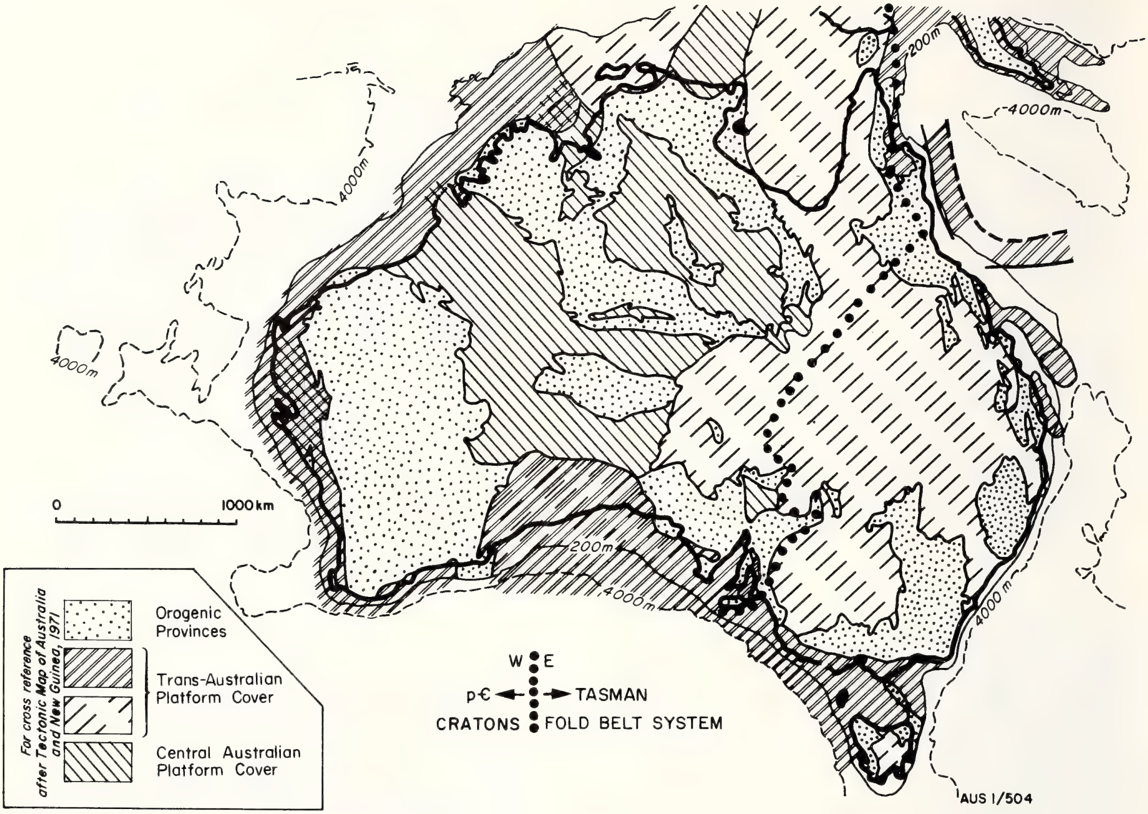

Fig. 8. Distribution of older and younger stages of the platform covers of the Late-Proterozoic-Phanerozoic chelogenic cycle. Modified from Doutch and Nicholas (1978).

geological record of Late Proterozoic sequences (e.g. Preiss et al., 1981), that the area of continents covered by sea was at a minimum at the beginning of the chelogenic cycle and gradually increased to the Palaeozoic maximum indicated in Figure 7a.

This general scheme can be successfully applied (Rutland, 1973b; 1981) to recognise a Proterozoic chelogenic cycle in Australia (Fig. 9), and consequently a general scheme for elevation of the continents with respect to sea level since the Archaean can be inferred, as in Table 1.

The analogy between the two chelogenic cycles clearly suggests that the regional unconformity at the base of the Early Proterozoic platform cover (ca. 2500 Ma) is similar in character to the unconformity at the base of the Adelaidean (ca. 1000 Ma) and both mark the beginning of a period of progressive submergence of continental area. Both unconformities probably reflect changes in tectonic pattern rather than a fundamental change in tectonic process. In this connection it is notable that although the unconformity at the base of the Lower Proterozoic is of great regional significance, it is not necessarily a large angular unconformity. In the Nullagine area of the Pilbara, for example, there is very little angular unconformity between the Fortescue Group and the underlying sediments and volcanics of the Archaean.

On the Kaapvaal craton of Southern Africa there are yet older platform sequences in the age ranges 2500-2800 Ma (Witwatersrand Group) and ca. 3000 Ma (Pongola Group). The Pongola group contains stromatolitic dolomites indicative of deposition in the intertidal zone, and cyclic sedimentation of arenite-argillite lithofacies has also been interpreted in terms of shallow-marine to tidal-flat environments. It has been suggested that the implied large tidal range is indicative of "exceptionally large shelf-widths, which is in keeping with the large size of the Gondwanan super-continent" (Button, 1981). Iron formations indicative of low relief occur in both the Pongola Group and the Witwatersrand Group and shallow marine conditions are again indicated, whereas the upper part of the Witwatersrand group displays fluvial and lacustrine sedimentation.

TABLE 1
CONTINENTAL ELEVATION DURING THE EARLY AND MIDDLE PROTEROZOIC CHELOGENIC CYCLE

	Emergence/ Submergence	Ma B.P.
. Late Archaean	Continental emergence	ca. 2700-2500
. Major phase of mafic dyke emplacement (change of global tectonic pattern)		ca. 2500
. Regional unconformity of Proterozoic older platform cover on Archaean platform basement		
. Early platform-cover stage (West Australian Platform Cover of G.S.A. 1971) and laterally equivalent Early Proterozoic mobile belt sequences	Progressive submergence	ca. 2500-2000
. Main deformation, plutonism and metamorphism in diachronous interval between platform stages	Oscillatory cratonic mode	ca. 1900-1700
. Late platform-cover stage (North Australian Platform Cover of G.S.A. 1971), formed after stabilisation of the main Proterozoic fold belts	Progressive emergence	ca. 1900-1400
. Continental uplift with orogenic and taphrogenic reactivation of the chelogen		ca. 1400-1050
. Mafic dyke emplacement and establishment of new chelogenic pattern		ca. 1050

The Pongola and Witwatersrand Groups are only mildly folded and it therefore appears that true cratons, formed during an Archaean chelogenic cycle, existed from about 3000 Ma ago. Thus there is no strong evidence from platform tectonics of a major change in tectonic processes at about the Archaean/Proterozoic boundary, and true cratons had similar freeboard in the Late Archaean as in the Proterozoic. Continental emergence at both 2500-2700 and 1400-1000 Ma ago is apparently related to a stage in the chelogenic cycle, and was followed by periods of progressive submergence. Consequently there is little justification for relating either of these periods to the first general emergence of the continents as a result of continental growth and thickening (Hargraves, 1976; Windley, 1977b).

In the Late Proterozoic-Phanerozoic chelogenic cycle there is an overall emergence of the continents, following maximum submergence during the Palaeozoic (Fig. 7a). This trend is temporarily reversed by the major Cretaceous transgression associated with rapid growth of ocean ridges and continental dispersal, during a period of low continental relief. The apparent lack of a similar major marine transgression on the late platform-cover stage of the Proterozoic may be an indication that no such phase of rapid continental dispersal occurred, in keeping with the concept of a coherent Proterozoic super-continent (e.g. Piper, 1976). However, the sabkha-type carbonate facies (Muir, 1979) of the McArthur River Group does indicate a phase of low continental relief, close to sea level. It should also be emphasised that ocean floor spreading may have occurred in large oceanic areas, with subduction on continental margins, even if thermal activity did not lead to rifting and dispersal of continents.

THE INTERPRETATION OF PRECAMBRIAN OROGENY

a) Phanerozoic Models

The contemporary association of both volcanism and seismic activity with plate boundaries has led to the plate-tectonic concept that tectonic activity is essentially confined to the margins of rigid plates. This concept applies specifically to the Neogene configuration of arc volcanism when the continents have been strongly emergent. Other concepts of Cordilleran orogeny on the convergent margins derive from the Mesozoic record of ophiolites and subduction complexes. In general, the climax of orogenic deformation was in the Mesozoic in the arc-trench complexes (eutectonic zones), and in the Cenozoic in the sedimentary belts between the arc-trench complexes and the cratons; but the controls of episodic orogenic deformation by continuous subduction processes are not well established.

I have argued elsewhere (Rutland, 1973a; 1981) that the concepts of plate tectonics and of the "Wilson cycle" need to be placed in the perspective of the longer-term chelogenic cycle. Thus the models of Mesozoic-Cenozoic cordilleran and collision orogeny, and of continental accretion thereby, may not be fully applicable to older orogenic belts.

I will confine myself here to some points which are of particular significance for concepts of continental growth.

Arc complexes (and their erosional products), formed above subduction zones in Cordilleran belts, clearly represent a potential accretion to the continents, whether or not recycling is involved. Insofar as the accretion process operates on an oceanic rather than earlier continental crust, lateral continental accretion, involving an increase in continental area, may occur. However, it is by no means clear that such accreted arc complexes form a substantial proportion of Phanerozoic orogenic belts generally (e.g. Rutland, 1973a).

As already indicated, the Phanerozoic orogenic belts have not yet reached the thermal steady state exhibited by the older Precambrian shields, and they have displayed much more tectonic mobility than the shields during the Neogene. During the Palaeozoic it appears that large areas of the crust, which gave rise to the Palaeozoic fold belts, were mobile simultaneously, and tectonic activity was not closely confined to the margins of rigid plates. Thus the late Palaeozoic orogeny (Hercynotype) has distinctly different characteristics from circum-Pacific orogeny. It is argued below that this Hercynotype orogeny provides a closer analogue of many Precambrian orogenic provinces than do the younger circum-Pacific and Himalayan (collision) orogenies.

The broad Palaeozoic mobile belts, in western Europe, western North and South America, and Australia, are dominated by non-volcanogenic sedimentation from older continental crust rather than from arc-trench complexes. These belts appear to have developed as back-arc basins between the craton and any subduction-controlled volcanic arc. It is possible to envisage complex models in which, as a result of progressive fore-arc accretion of subduction complexes, the back-arc basins are built over subduction complexes accreted during an earlier phase of progressive fore-arc accretion (e.g. Crook, 1980). Hoever, I remain unconvinced that large scale fore-arc accretion has taken place, and prefer the simpler models in which back-arc deposition occurs on oceanic crust in marginal basins of West Pacific type, or on thinned older continental crust (e.g. Rutland, 1973a).

These mobile belts have been subjected to strong compressional deformation and to widespread granitic plutonism. Zwart (1967) clearly distinguished these Hercynotype (Variscan) orogenic belts from both Alpinotype (collision) and circum-Pacific belts and he pointed out that "... a very large amount of heat has to be introduced into the Hercynotype orogen, especially because of the very large regions involved" (op. cit., p.306). In spite of a proliferation of plate tectonic interpretations, his separation of a distinctive Hercynotype orogeny remains valid.

Thus Zwart and Dornsieper (1980), while accepting that both Alpine and Variscan orogenies were probably due to collision, consider that the former occurred in a low, and the latter in a high, heat-flow regime. They suggest that the Variscan orogeny occurred at the end of a period of high heat flow and orogenic activity lasting about 300 Ma, and caused by a major mantle plume.

These authors also emphasise that, in spite of the collision interpretations, the Variscan belt does not exhibit the crustal thickening of the Alpine-Himalayan belt. Indeed seismic studies show that the Variscan areas of Europe have relatively thin crustal sections above a well-defined Moho (Bamford and Prodehl, 1977). In this connection it should be noted that the structural characteristics of asymmetry and nappe tectonics, attributed to plate collision, develop only in the collision stage. Their presence does not distinguish between a collision orogeny following a full Wilson cycle of opening and closing of a major ocean, from an orogeny following upon much more limited separation of continental plates. Indeed, in a high-heat-flow regime, it is conceivable that thinning of continental crust, and basin development without the formation of oceanic crust, could lead to intracontinental orogeny with collisional characteristics (Rutland, 1973b; Kroner, 1977b). The former presence of oceanic crust must be judged from the presence of deep oceanic sedimentary facies, of ophiolite sequences, and of volcanism inferred to be generated by subduction of oceanic crust. In any case, if oceanic crust is eliminated by subduction, it does not make a contribution to continental accretion.

If the preserved Variscan belts are largely underlain by older continental crust (e.g. Cogné and Slansky, 1980), and their sedimentary sequences are largely recycled older continental material, then they clearly did not, in general, contribute to continental growth. The main sialic component of continental growth is the granitic plutonism insofar as it may be derived from the mantle (Allègre and Ben Othman, 1980). In addition, underplating of basaltic material may occur during orogenic evolution.

The Lachlan Fold Belt was formed in the circum-Pacific setting but, like the European Palaeozoic belts, it was a wide zone of crustal mobility in an area of largely non-volcanogenic sedimentation. The view that it is largely underlain by older continental crust (Rutland, 1973a) has recently been supported by geochemical and isotopic evidence from the widespread granitoid intrusions (e.g. White and Chappell, 1977; Compston and Chappell, 1979).

Thus the Variscan orogeny with its widespread granitic plutonism can be seen as the thermal peak of the world-wide long-term chelogenic cycle. The development of high heat flow and of orogenic activity within the continental areas was apparently associated with a decrease in the area of the continents covered by sea, and led to the initiation of the main period of rifting and continent dispersal during the Mesozoic (Fig. 7a).

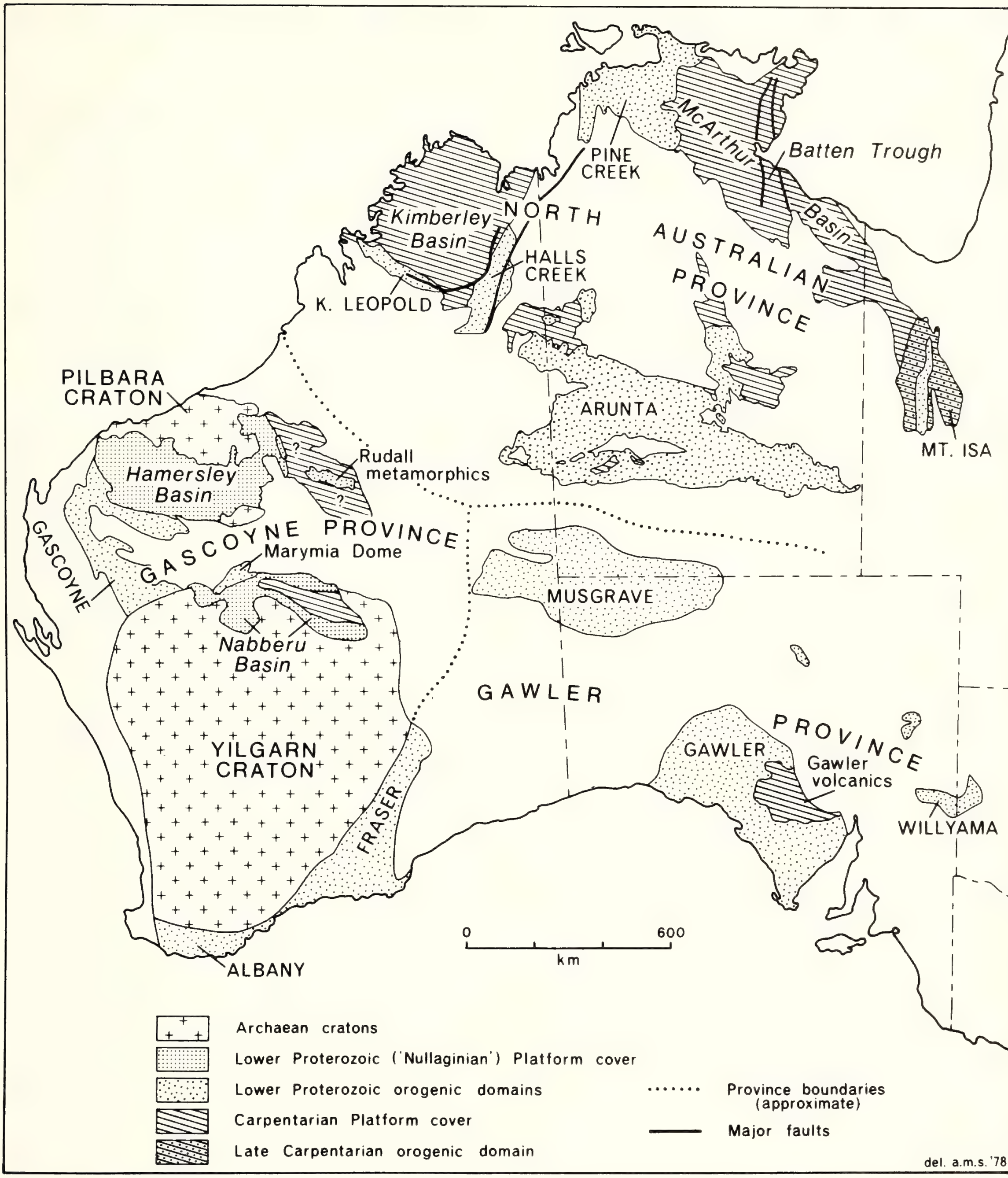

Fig. 9. Principal exposed tectonic elements of the Early and Middle Proterozoic chelogen (2400-1400 Ma, excluding reactivation features, 1400-1000 Ma). The earlier, Archaean, provinces formed stable cratons during this period. The areas described in the legend as Carpentarian Platform Cover are more correctly described as North Australian Platform Cover. After G.S.A. (1971).

This was preceded by a long period in the younger Proterozoic when the area of continents covered by sea was increasing. At this time continental margins around the Pacific and in Western Europe were generally passive (e.g. Rutland, 1973a; Preiss et al., 1981), while others, especially in N. Africa and Arabia (e.g. Gass, 1981), were apparently active plate boundaries, perhaps of circum-Pacific type, providing evidence of volcanic arc accretion.

b) Early and Middle Proterozoic orogenic provinces

Zwart (1967, p.302) suggested that the Proterozoic Svecofennian-Karelian belt in Scandinavia is a typical Hercynotype orogenic belt, and it has also been shown (Rutland, 1973b) that there are close analogies between the Lachlan Belt and the Australian Proterozoic orogenic provinces (Fig. 9) which are broadly equivalent to the Svecofennian-Karelian or to the Churchill province in Canada. On the other hand, orogenic belts with the characteristics of Cordilleran or Alpine-Himalayan orogenic belts are areally of much lesser significance in the preserved Proterozoic record.

The Hercynotype Proterozoic orogenic provinces include geosynclinal regions such as the Svecofennian, or the Pine Creek Geosyncline in Australia (e.g. Plumb et al., 1981). These regions are probably largely ensialic, but, as with the Lachlan Belt, development as ensimatic basins well behind the contemporaneous continental margin can also be argued. If the lithosphere was generally thinner, and the geothermal gradient higher, in the Proterozoic than in the Phanerozoic, crustal extension by thinning, rather than by rifting and oceanic crust formation, would have been favoured. In any event they were not analogous to circum-Pacific or Alpine-Himalayan orogenies. The provinces also include reworked regions of platformal or miogeosynclinal character such as the Gawler province in southern Australia (Glen et al., 1977) or the Karelian belt in Scandinavia. These regions contain thinner, more mature sedimentary sequences (including quartzites, carbonates and ironstones) and were clearly developed on older Archaean basement rocks.

The reworked platformal regions in particular also provide evidence that the Archaean cratons were much more extensive before the Proterozoic orogenic belts developed (Rutland, 1973b; Kroner, 1977a). They demonstrate that the process of stabilisation of continental crust into cratons is not irreversible. During the thermal peak of the Proterozoic chelogenic cycle (ca. 1900-1700 Ma) the areas of mobility encroached onto extensive areas which previously had cratonic character (in the latest Archaean and Early Proterozoic) and which reverted to cratonic character following the Hercynotype orogeny. The deformation and metamorphism of these platformal areas took place under high geothermal gradients, and granulite-facies conditions were reached at the base of relatively thin structural successions (e.g. Glen et al., 1977; Rutland et al., 1981).

As with the Phanerozoic Hercynotype belts, the role of horizontal plate movements and closure of ocean or marginal basins is difficult to evaluate (e.g. Kroner, 1981b). It is clear however that in the extensive Proterozoic Hercynotype provinces, crustal thickening of Himalayan-Alpine proportions did not occur, and the higher parts of sedimentary sequences of low metamorphic grade are still preserved (e.g. Rutland, 1973b; Watson, 1976).

It can be concluded that, although large areas of continental crust evolved and were established during the Proterozoic chelogenic cycle, they do not in the main, represent new additions from the mantle. The lower part of much of the Proterozoic crust was formed in the Archaean and apparently stabilised then. It was reworked by Hercynotype orogeny after deposition of geosynclinal sedimentary sequences in some provinces, and of platformal sequences in others. Thus the upper part of the present platform basement belongs to an Early to Middle Proterozoic stage of accretion on top of an Archaean stage. This platform basement has since been modified by various phases of erosion and platform-cover deposition. These platform covers form the highest levels of the present continental crust.

Since the sedimentary sequences involved in the Proterozoic Hercynotype orogenic provinces were derived largely from pre-existing continental crust, the provinces can be regarded essentially as Archaean crust reworked by exogene and endogene processes. Consequently the areas and isotopic ages of these provinces do not give a measure of new crustal accretion from the mantle, as supposed for example, by Hurley and Rand (1969). As with the Phanerozoic Hercynotype belts, these Proterozoic provinces provide little evidence of accretion, other than through their widespread granitic plutonism, and limited, often bimodal, volcanism. The evidence from Hercynotype belts suggests in fact that much of the area of Proterozoic orogenic provinces was previously underlain by Archaean continental crust and much of the area of the Palaeozoic orogenic belts was previously underlain by Proterozoic crust. This is shown diagrammatically in Figure 10.

Thus, the crust is made up of stages of different age that produce a gross horizontal layering. The rocks of the lower crust (normal velocity in Figure 3) are inferred to belong not only to a different orogenic cycle from the upper crust, but to a different chelogenic cycle. However, if basaltic underplating occurs, the lowermost crust (high velocity in Figure 3) may be made up of mafic granulites of the younger chelogenic cycle. These concepts have been used to make a tentative interpretation of the crustal layers in Figure 3.

c) The lower crust of Hercynotype provinces

It is notable that the major Early Proterozoic Hercynotype provinces occur near the margins of the Proterozoic supercontinent envisaged by Piper (1976), although the reality of such a supercontinent is by no means well established (Irving and McGlynn, 1981). In Australia the tectonic evidence suggests a continental margin to the east (e.g. Rutland, 1973b; 1976), while on the west the Proterozoic mobile belts interdigitate with Archaean cratonic remnants. Further west, in

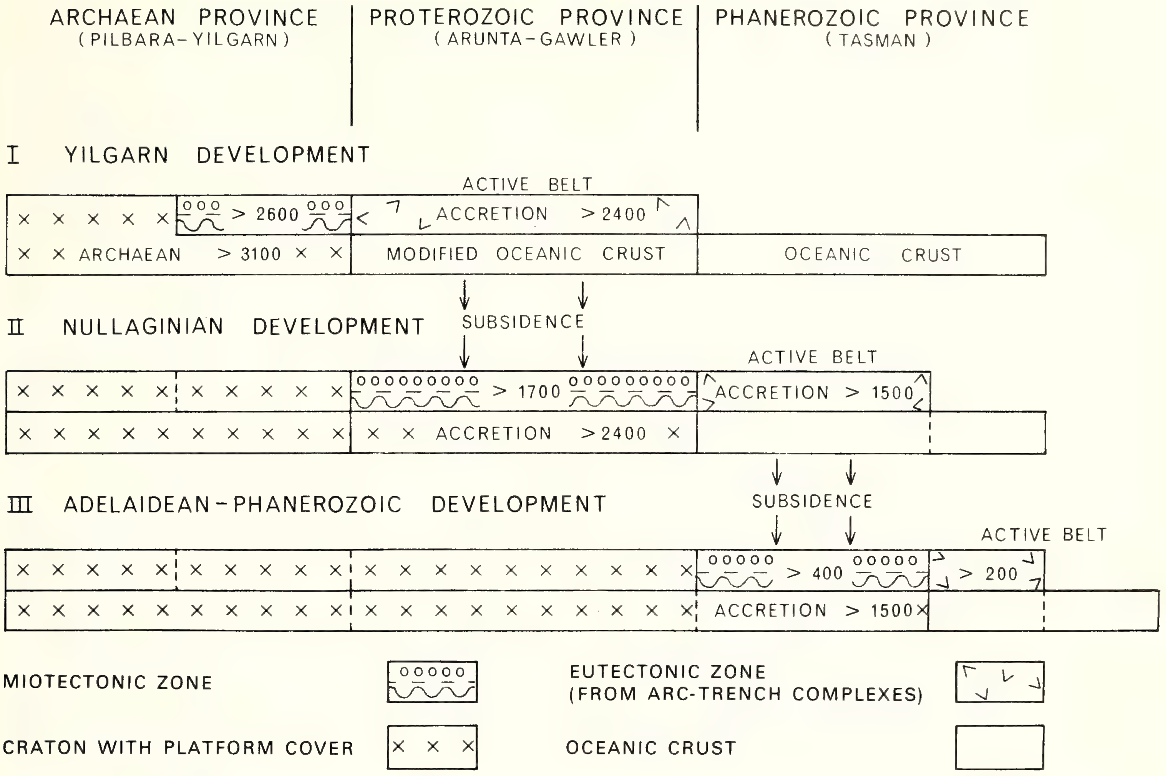

Fig. 10. A model for continental accretion. The lower parts of the areas described in the legend as miotectonic zones correspond to the Hercynotype provinces of Proterozoic and Phanerozoic age. It is suggested in the text that the Archaean granulite-gneiss terrains may be of similar character. The upper parts of the miotectonic zones correspond to the platform cover developed in the later part of the chelogenic cycle. After Rutland (1973a; 1974).

southern Africa (presumably in the central part of the inferred supercontinent) the Early Proterozoic provinces are more limited, occurring as a network of relatively narrow belts of orogenic reactivation, such as the Limpopo and Irumide belts, separating Archaean cratonic remnants (see e.g. Kroner, 1977a and b). They appear to be marked by stronger deformation and greater vertical and horizontal shear movements than obtained in the broader Hercynotype provinces. Thus the general distribution of Early Proterozoic tectonic provinces tends to support the idea of a supercontinent which became increasingly mobile in broad belts along its margins. This provides a further analogy with the distribution of Palaeozoic Hercynotype belts.

It is envisaged (Rutland, 1973b; 1976) that active margins, with arc-trench complexes, may have operated throughout the Proterozoic. However, by analogy with the Late Proterozoic-Phanerozoic cycle, such activity was probably greatest during the later part of the chelogenic cycle, and was confined to the outer edges of the Proterozoic supercontinent or continents, beyond the Hercynotype provinces. It is suggested that remnants of this activity are only rarely preserved (e.g. Hoffman, 1973) since these arc-trench complexes are inevitably largely buried beneath younger mobile belts. However, in the Scandinavian Shield a record of orogenic activity over the whole Early-Middle-Proterozoic chelogenic cycle has been preserved. A succession of relatively narrow linear belts occurs, which has been interpreted in terms of repeated collisions on the margins of the Proterozoic continent after the stabilisation of the Svecofennian province (Berthelsen, 1980). Substantial telescoping and crustal thickening is inferred for these collision belts and they clearly provide an excellent upper crustal source for younger platform covers.

It seems possible that the end of a chelogenic cycle corresponds to the end of a major cycle of ocean floor spreading. If so, it may be expected that the eroded arc-trench complexes formed on circum-Pacific margins will subside as the geothermal gradient declines and the underlying upper mantle assumes more cratonic characteristics (Rutland, 1973c; 1974). These accreted arc-trench complexes and any basaltic material underplated at the base of the crust may therefore form part of the basement of the mobile belts of the next chelogenic cycle and are not generally exposed at the surface. Thus it is reasonable to assume that arc-trench complexes accreted in the late Archaean will form part of the basement of the Proterozoic Hercynotype provinces along with reworked older Archaean crust, and arc-trench complexes accreted in the later Proterozoic will form part of the basement of the Palaeozoic Hercynotype belts, along with the reworked older Precambrian crust.

Thus the 'andesite model' of accretion may be directly relevant to the accretion of substantial parts of the lower crust of Proterozoic and Phanerozoic provinces. The age of this lower crust, however, will be much greater than that of the higher levels of the crust, which are largely made up of continentally derived material. As already noted, such accreted and eroded ensimatic arc complexes are likely to be considerably more mafic than suggested by the andesite model. This concept of accretion of the lower crust is also incorporated in Figures 10, 3b and 3c. Clearly, during orogenic episodes affecting the upper crust, partial melting of the lower crust may occur, leading to accretion of the upper crust by granitic plutonism. Because of its composition, and the possibility of isotopic exchange with the mantle, such lower crustal material may not be readily distinguished from mantle sources by isotopic methods.

It will be evident that if accreted arc-trench complexes are generally buried beneath younger mobile belts, the paucity of signatures of closed oceanic domains in the Proterozoic record is to be expected and there is no need to consider explanations involving earth expansion (e.g. Glikson, 1981). Indeed, the similarities of the Early-Middle Proterozoic chelogenic cycle to the Late-Proterozoic-Phanerozoic chelogenic cycle strongly suggest that very similar processes operated and that the areas of continental and oceanic crust were also very similar.

ARCHAEAN TECTONIC PROVINCES

The general distinction between high-grade Archaean granulite-gneiss terrains and relatively low-grade granite-greenstone terrains (Windley and Bridgwater, 1971) is widely accepted, but interpretations of tectonic relations between them are controversial. Three principal groups of hypotheses can be distinguished:

(1) the two types of terrain represent two areally distinct types of crustal environment (e.g. Windley and Smith, 1976; Bridgwater et al., 1978);

(2) the two main types of terrain represent different levels within the same crustal environment, the granite-greenstone terrains lying above the granulite-gneiss terrains, which represent either

(a) an older re-worked sialic basement on, or within, which the greenstones were deposited (e.g. Annhauser et al., 1969; Windley, 1973), or

(b) new sialic crust, generated below the greenstones after the deposition of the latter in an ensimatic environment (e.g. Glikson and Lambert, 1976; Glikson, 1979b).

Clearly, if hypothesis (1) is correct, gneissic terrains that were formed in an early tectonic episode might become the basement of greenstones formed in a later episode. Thus it is possible to combine hypothesis (1), either with 2(a) or with the view that greenstone belts are ensimatic in origin. Hypothesis 2(b), however, excludes the other hypotheses.

The view which I wish to outline is that the Archaean gneissic terrains correspond most closely to the gneissic terrains of Proterozoic and Phanerozoic Hercynotype belts, whereas the greenstone belts correspond most closely, not to younger orogenic provinces, but to platform cover.

Attempts to interpret the gneissic and greenstone terrains in plate-tectonic terms have appealed to models based on Mesozoic-Cenozoic tectonics. Thus Windley and Smith (1976) compare greenstone belts with Andean marginal basins and the high-grade terrains with deep-seated granitic batholiths located along the axes of 'modern' arcs. They regard the two tectonic types as complementary environments on the margins of continental plates in circum-Pacific type orogenic belts. Bridgwater et al. (1973, 1978) emphasise the horizontal tectonics of the granulite-gneiss terrains and suggest analogy with Alpine tectonics and collision models (see Fig. 6).

These analogies imply, however, that both high-grade gneissic terrains and greenstone belts should be developed as relatively narrow linear zones on the margins of older cratons. In fact both types of terrain are of wide areal extent, and comparison with the Proterozoic record suggests more plausible analogies.

Granulite-gneiss terrains

Windley and Smith (1976) note that the carbonate (dolomitic marble) -orthoquartzite-K-rich pelite (sillimanite-schist) association is typical of most high-grade regions. They suggest that it is best explained by deposition on a shallow-water continental margin and note that such an assemblage is known in association with one Cordilleran Mesozoic batholith. It has been pointed out above that similar platformal assemblages are well known in Proterozoic Hercynotype orogenic provinces that are areally extensive. Some of these provinces are also characterised by granulite-facies metamorphism consequent upon high geothermal gradients, and early recumbent isoclinal folding is also present (e.g. Glen et al., 1977; Laing et al., 1978). The metasedimentary sequence is heavily intruded by granitic plutons and the older basement is only rarely detected (e.g. Rutland et al., 1981).

It is therefore suggested that the Archaean granulite-gneiss terrains find their closest analogies in Proterozoic high-grade terrains such as the Gawler Province in South Australia, which in turn can be compared with Palaeozoic Hercynotype belts. The significance of this analogy is that the Archaean gneissic terrains can then be regarded as areally extensive and they do not need to be

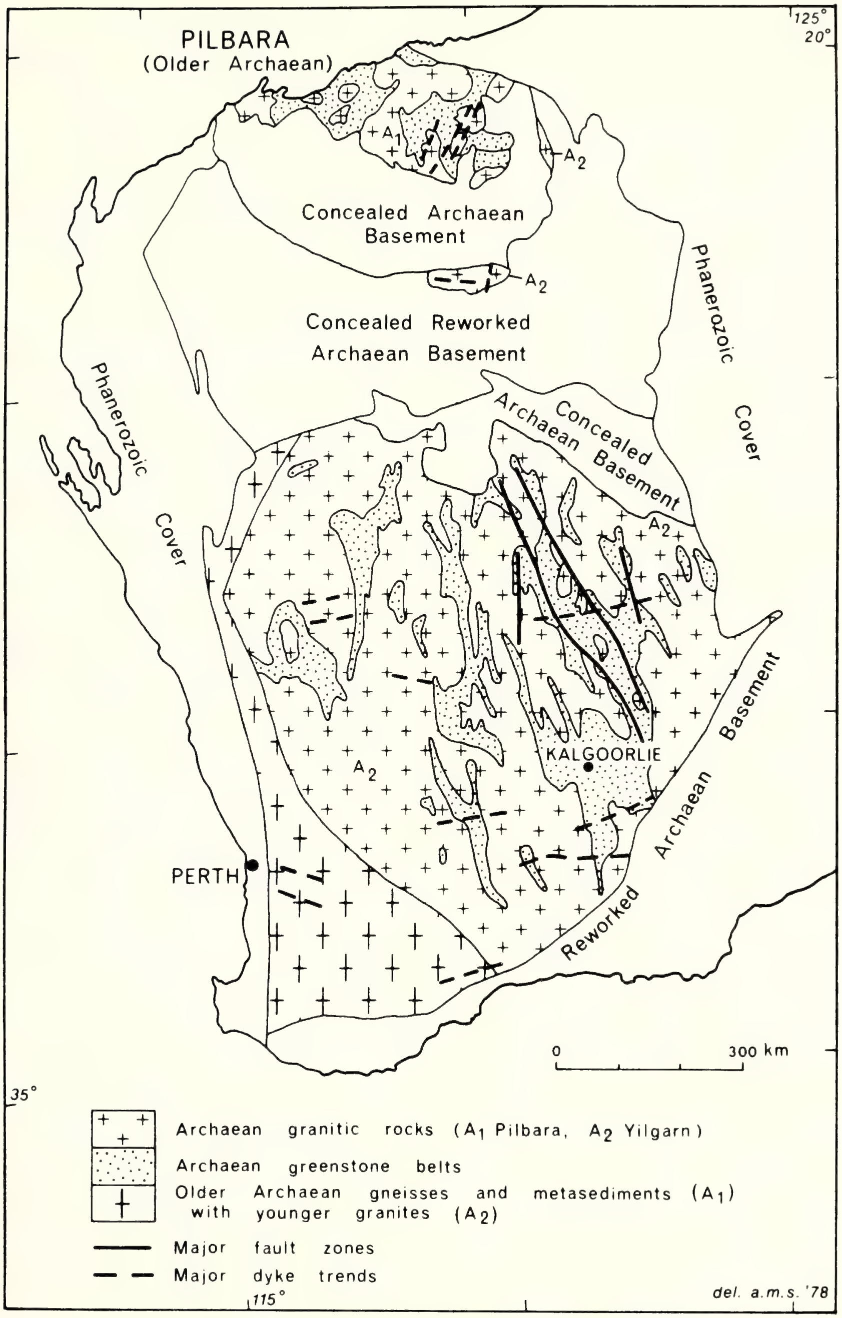

Fig. 11. Principal tectonic elements of the Archaean chelogen in Western Australia. Note that the older greenstone belts of the Pilbara province are overlain by a sedimentary sequence (Gorge Creek Group and Mosquito Creek Formation) which may in part be the age equivalent of the younger greenstones of the Yilgarn province. From Rutland (1981), *in* PRECAMBRIAN OF THE SOUTHERN HEMISPHERE (ed. D.R. Hunter), *Elsevier, Amsterdam.*

closely related to subduction zones or subduction-generated volcanics (which are present in Cordilleran Mesozoic belts but not in the Archaean granulite-gneiss terrains).

One major difference between Archaean and younger, Hercynotype, terrains must however be remarked. It has been suggested above that both Proterozoic and Phanerozoic Hercynotype terrains were developed on older sialic basements: an Archaean basement is inferred for the Proterozoic provinces and a Proterozoic basement for the Phanerozoic provinces. In the Archaean, however, and especially in the pre-3000 Ma granulite-gneiss belts, the protolith for the granitic plutons may have been very much closer in age to the plutons themselves. It is also likely to have been of generally mafic composition, as indicated, for example, by the occurrences in the Aldan Shield (Moralev, 1981) referred to above. The presence of an extensive suite of gneisses attributed to the weathering and disintegration of the mafic basement in the Aldan Shield may indicate that the basement was relatively stable prior to the main deformation and plutonism which occurred at about 3000 Ma.

Other differences between the Phanerozoic, Proterozoic, and Archaean Hercynotype terrains can be attributed to two factors: first, the higher radioactive heat production, explaining higher mobility and more extensive granitic plutonism in the older provinces; and, secondly, a lower availability of terrigenous clastic material in the Archaean mobile belts. Both of these factors suggest a thinner and more mobile lithosphere in the Archaean.

Granite-greenstone belts

Perhaps the most popular plate-tectonic model for granite-greenstone belts, such as those of the Pilbara or Yilgarn provinces in Australia (Fig. 11), is the marginal-basin model (Tarney et al., 1976) illustrated here in Figure 12. These authors saw the greenstone belt development as ensialic, behind a contemporaneous calc-alkaline volcanic arc. Such a paired arrangement does not in fact occur in Archaean terrains, which instead are characterised by areally extensive greenstone stratigraphies.

Tarney et al. (op. cit.) attempted to explain this characteristic by appealing to lateral accretion, causing the continental arc and trench to migrate. This however is scarcely consistent with the evidence of coeval greenstone deposition over wide areas (e.g. Rutland, 1973b; Binns et al., 1976; Gee, 1979). Moreover, in older Archaean terrains such as the Pilbara of Australia, the greenstones are not arranged in linear belts. Rather, the greenstones form a network of relatively uniform stratigraphy between granitic domes. Platt (1980) emphasised that the marginal-basin hypothesis cannot explain the voluminous pre-tectonic (but post-greenstone) tonalitic magmatism of Archaean greenstone belts. The continued refinement of both ensialic and ensimatic models for greenstone belts, unrelated to plate margins, is illustrated by Goodwin (1981) and Annhauser (1981).

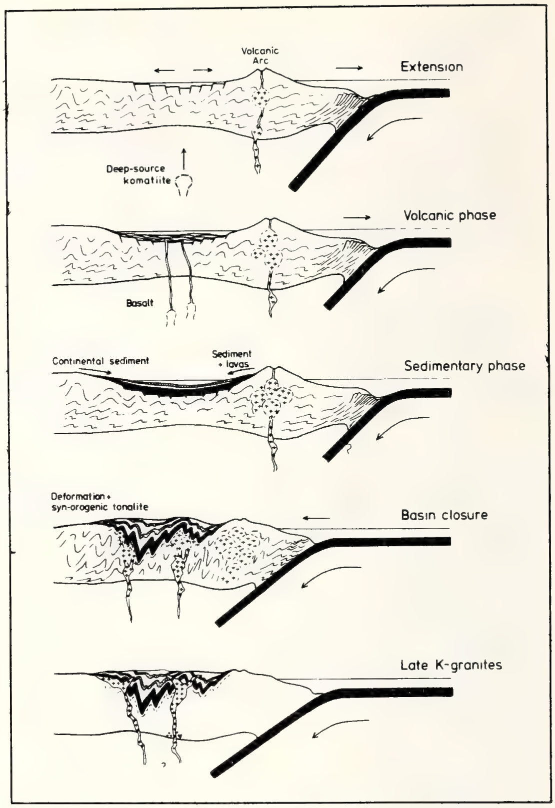

Fig. 12. Possible development of Archaean greenstone belts according to the 'rocas verdes' model derived from a Mesozoic marginal basin in southern Chile. Back-arc extension is inferred to take place by crustal thinning rather than by crustal rifting. From Tarney et al. (1976), *in* THE EARLY HISTORY OF THE EARTH (ed. B.F. Windley), *Wiley, London.* Copyright 1976 John Wiley & Sons Ltd.

It is also notable that, although the greenstone belts are associated with widespread granitic plutonism so that the basement on which they were deposited is rarely seen, they have not been subjected to the more extreme types of orogenic deformation. Moreover, the greenstone belts were essentially converted to stable cratons soon after their relatively short history of plutonism and deformation, and it must be assumed that their present crustal structure was already established at that time. Thus it is difficult to countenance models in which any part of the greenstone belts is postulated to originate as primitive oceanic crust (i.e. resting directly on the mantle).

The lack of tectonic complexity of greenstone belts is surprising in the context of the evidence for high geothermal gradients and thin lithosphere provided by komatiitic lava flows in the greenstones, and by the extreme deformation in Archaean granulite-gneiss terrains. The paradox is resolved if the greenstone belts are regarded as

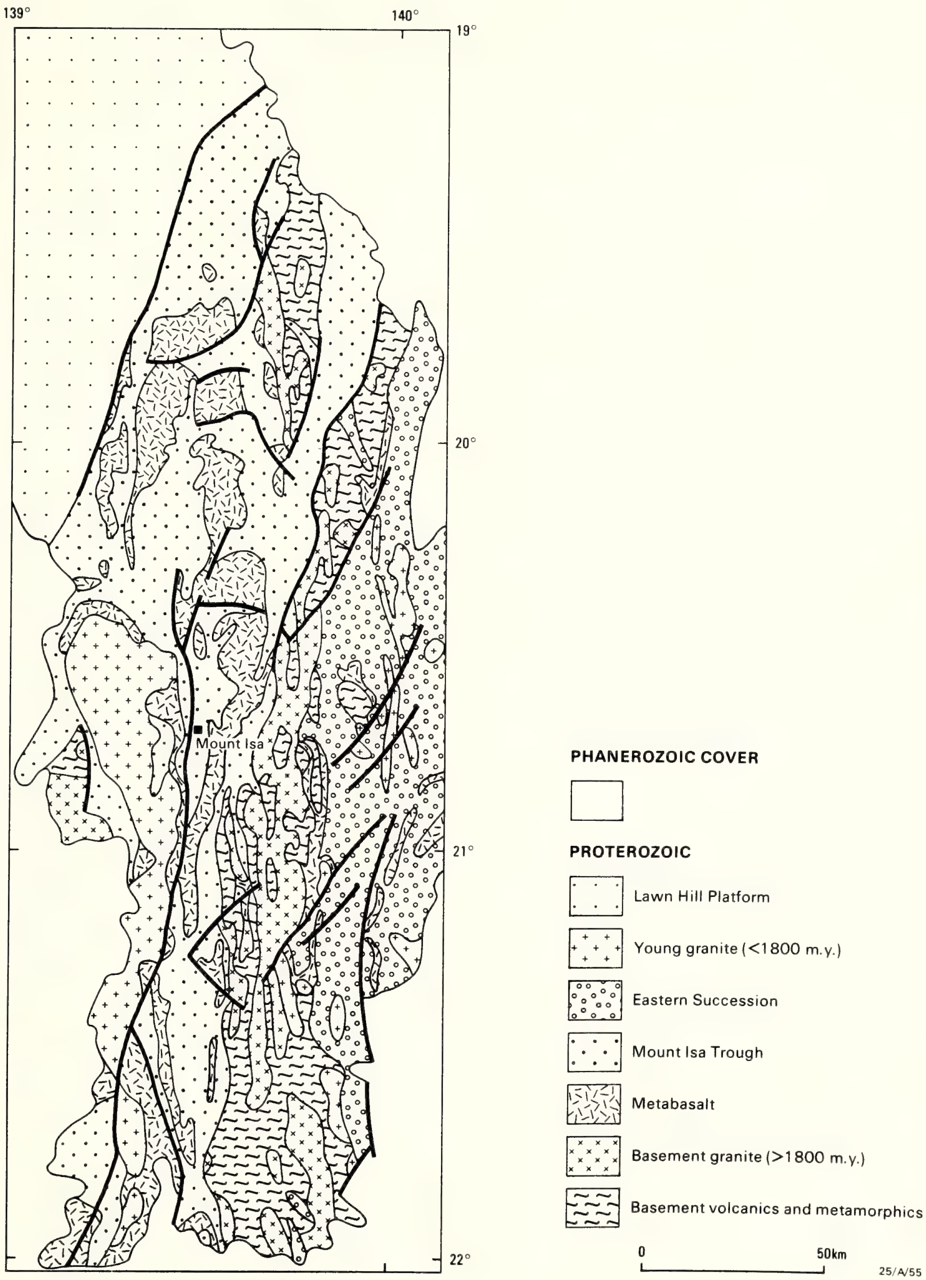

Fig. 13. Distribution of meta-basaltic formations, granitic intrusions, and 'basement' rocks in the Mount Isa region, illustrating the general similarity with the tectonic style of Archaean greenstone belts.

the analogues of post-Archaean platform sequences rather than of orogenic belts.

The lack of an identifiable basement to the greenstone belts has often been regarded as a severe problem. However, this is not a unique feature of Archaean greenstone terrains. In the Hercynotype Proterozoic Gawler province, where the metasedimentary sequence is clearly of platformal or miogeosynclinal character, synorogenic granitic plutons, intruding the lower part of the sequence, are so extensive that the older Archaean basement has only recently been distinguished and dated (Cooper et al., 1976). Thus it appears that where lower crustal partial melting is extensive, granitic plutons tend to spread out at the base of the overlying sedimentary succession.

The closest Proterozoic analogue for Archaean greenstone belts is to be found, perhaps, in deformed platform sequences such as those of the Mount Isa region (Fig. 13). Over most of northern Australia the North Australian platform cover is relatively undeformed and unmetamorphosed. But in the Mount Isa region this same platform cover, with generally similar sedimentary facies, became involved in a later fold episode. The lower part of the sequence includes extensive basaltic formations, which can be compared with synclinal Archaean greenstone belts. The anticlinal basement regions in particular are intruded by granitic plutons. Moreover, as in the Archaean greenstone belts, the deposition of the supracrustal sequence is closely related in time to the granitic plutonism (Page, 1978). Granite intrusion occurred both before and after eruption of the basaltic sequence in a total time span of little more than 200 Ma. The development of Archaean greenstone belts and their associated plutonism is similarly restricted in time. The principal episodes of plutonism in the Archaean can be related to the thermal peaks like those in the post-Archaean provinces. They represent periods of growth of the upper crust at the expense of the more mafic lower crust, rather than periods of rapid growth of the crust as a whole.

The Archaean belts display more extensive plutonism and they lack the close association with sediments of continental derivation which is present at Mount Isa, but these are features which can reasonably be attributed to the higher geothermal gradient and thinner lithosphere in the Archaean.

Thus the Archaean greenstones can be regarded as sequences developed late in the crustal evolution of the regions in which they occur. They can be regarded as platformal or "miogeosynclinal" sequences, more deformed than their Proterozoic counterparts, rather than as "eugeosynclinal" sequences which are less deformed than those of younger orogenic belts. A consequence of this interpretation is that the greenstone belts can be expected to be areally extensive and they do not need to be closely related to subduction zones. Another consequence, if the analogy with younger belts is pursued, is that the greenstone belts should be underlain by more highly deformed orogenic complexes, of not much greater age than the greenstone belts themselves. The granulite-gneiss belts are obvious candidates.

No specific relationship between granite-greenstone belts and ocean floor spreading and subduction can be inferred (c.f. Goodwin, 1981). However, such relationships are also obscure for Hercynotype provinces and their covers in post-Archaean times. Neither can the presence of ocean basins with ocean-floor spreading and subduction be definitely inferred from the sea level relations of the established Archaean cratons. Deep ocean basins may have been present if continent and ocean areas were similar to those of the present day. But if protocontinental crust such as that underlying the greenstone belts was very extensive, ocean waters may have been shallower over the large areas of protocontinental crust.

At present it seems possible that ocean-floor spreading and subduction may have begun before the deposition of the earliest greenstone belts. In any case, it is quite clear that the greenstone belts themselves were not formed as oceanic crust by processes similar to those operating at the present day.

The changes of tectonic style in the continental crust since the Archaean (Table 2) are therefore attributed to the supposed secular decline in geothermal gradient and increase in lithospheric thickness towards the present, rather than to the absence of ocean-floor spreading in oceanic areas.

CONCLUDING DISCUSSION

It will be evident from the above discussion that growth of continental crust must be clearly distinguished from stabilisation of continental crust; and that growth of lower crust must be distinguished from growth of upper crust.

Although only a small percentage of present crustal structure was finally stabilised in the Archaean, the growth of crustal volume was probably largely complete by the end of the Archaean, since it has been argued that most Proterozoic provinces are underlain by Archaean crust. The plutonic episodes seen in the Archaean at about 3700, 3100, and 2600 Ma represent periods of growth of the upper crust at the expense of the mafic lower crust, rather than growth of the crust as a whole.

The present crustal structure of post-Archaean regions has been established by processes of tectonism, erosion, and deposition operating during two major post-Archaean chelogenic cycles, which are apparently related to major cycles of ocean-floor spreading and subduction. During these cycles, areas of pre-existing continental crust, perhaps produced by lateral accretion of arc-trench complexes, have been modified and overlain by sedimentary accumulations.

During the Early and Middle Proterozoic, mobile belt and platformal sedimentary accumulations have been developed above thinned Archaean lower crust. Plate edge and collision orogeny provided the sedimentary source areas by local thickening of pre-existing crust. The sedimentary geochemistry reflects that of the chemically differentiated upper crustal source areas. Further differentiation of the Archaean basement occurred during the main Proterozoic thermal peak, so that heat-producing elements were highly concentrated in the upper part of the Proterozoic crust.

TABLE 2
SECULAR CHANGE IN HERCYNOTYPE OROGENY

Archaean		Proterozoic		Phanerozoic
Granite-greenstone terrains	→	mildly reworked platform covers	→	little-deformed platform covers
Granulite-gneiss terrains	→	strongly reworked platformal or miogeosynclinal regions	→	Hercynotype geosynclinal terrains

Decreasing geothermal gradient
→
Increasing lithospheric thickness

The question arises whether the Archaean areas which have been preserved as cratonic nuclei are simply a random selection, dependent on the configuration of mantle dynamic processes, or whether they were different in character from those which became remobilised in the Proterozoic. It is possible that the reworked areas were zones of higher heat flow, due to higher concentration of heat-producing elements, and therefore more readily thinned during extensional processes. Certainly the Proterozoic provinces are notable for uranium concentrations both within the sedimentary sequences and in the post-orogenic granites. It is also possible that the reworked areas are largely those which grew by lateral accretion during the younger Archaean, as indicated in Figure 10. In some case, however, relatively narrow zones of reactivation have developed along the boundary between younger and older Archaean provinces both in Australia and South Africa. This may reflect control of deeper, mantle, processes by the crustal inhomogeneity.

Similar questions arise concerning the areas of Proterozoic crust which became involved in late Precambrian and Phanerozoic mobile belts. Again it seems possible that these are largely areas which grew by lateral accretion during the Proterozoic, as indicated in Figure 10. If so, they give a measure of growth of continental area since the Archaean. The upper crustal layers of these areas, however, consist largely of reworked older continental material. Consequently, the growth of crustal volume since the Archaean is apparently less than the apparent growth of continental area, and is probably less than 25%. Thus the crust of the post-Archaean cycles shows a gross layering (Fig. 3) in which the upper crust consists largely of orogenic and platformal metasediments derived from repeated recycling of chemically differentiated Archaean and younger upper crustal rocks. The change from upper crust to normal-velocity lower crust in the post-Archaean provinces is interpreted as the unconformity between rocks of younger and older chelogenic cycles. The latter may often be eroded remnants in the granulite facies. Thus a geophysical discontinuity is to be expected and this unconformity probably corresponds to the Conrad discontinuity where that has been identified.

By contrast, the Archaean crust lacks such thick upper crustal layers and its sediments are largely first-cycle, derived from the associated volcanic rocks. Thus the contrasts in composition and age between upper and lower crust are not so pronounced in the Archaean as in the younger cycles. It follows also that the isotopic signatures of granitic rocks are likely to reflect increasing contamination by evolved older crust in younger Hercynotype belts.

Stabilisation of continental crust, as distinct from growth, is clearly related to the chelogenic cycles. Much of the Archaean crust was reworked in the Early and Middle Proterozoic, so that stabilisation of the Precambrian shields was not achieved until approximately 1000 Ma ago. Some reworking has occurred since, and the Phanerozoic mobile belts have not yet been fully stabilised.

Thus, cratonic reworking, or ensialic orogeny, were clearly much more extensive in the Proterozoic than in the Phanerozoic, presumably because the geothermal gradient was generally higher. However, this does not imply the absence of ocean-floor spreading and subduction, which may have operated in pre-existing oceanic areas even if new oceans were not produced by rifting and drifting. The analogy between the two major post-Archaean chelogenic cycles in both platformal and orogenic evolution strongly suggests that plate-tectonic processes were indeed operating in the Proterozoic oceans.

In the Archaean, the continental crustal areas were even more mobile than in the Proterozoic, prior to the development of the granite-greenstone belts. As discussed above, neither the granulite-gneiss terrains, nor the granite-greenstone belts, require close association with subduction zones for their development, but it remains possible that ocean-floor spreading and subduction began before the deposition of the earliest greenstone belts. If so it may have assisted in the tectonic thickening of the early globe-encircling proto-crust to form the earliest granulite-gneiss provinces.

The model presented here for the growth and stabilisation of the earth's crust is undoubtedly imperfect. However, in placing emphasis on the vertical accretion of the continental crust over very long periods it may provide a sounder geological basis for interpretation of future studies than models based simply on lateral continental accretion of arc-trench complexes.

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Molecular Crystals and Light: Chemical Reactions in Cages*

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ABSTRACT. The kinetics, mechanisms, and stereochemistry of solid state photochemical reactions are different in fundamental ways from reactions in fluids, and constitute a distinct set of problems. Molecules in crystals below the melting point are confined by intermolecular forces to sharply defined regions, or 'cages'. Reactions take place between molecules within such cages in positions and orientations known from crystal structure analysis or in positions related to the perfect crystal structure by dislocations or local disordering.

New concepts are being developed to advance understanding in this field. The best known is that of 'topochemistry', which is that static lattice constraints restrict the products of a photochemical reaction to those preformed in the parent crystal. Also recent theory leads to the proposal that there may be impulsive molecular displacements following light absorption and lasting only a few picoseconds that bring neighbour molecules close together and promote chemical change or excimer formation. The theory of this concept of 'dynamical preformation' is described and possible examples discussed.

INTRODUCTION

The Will of Archibald Liversidge is the source from which we seek the true intention of these lectures. From Professor David Mellor's splendid biographical note (Mellor, 1957) we learn that '... the lectures shall not be such as are termed popular lectures dealing with generalities and giving mere reviews of their subjects nor such as are intended for the ordinary class or lecture room instruction ... but shall be such as will primarily encourage research ...'. The lectures are to be about new knowledge, and not generalities but generalizations are called for because they so often mark new insights and newly recognized connections between observations. In research we aim to replace isolated observations, often seemingly mysterious, by a network of facts fitting together straightforwardly, leading to general conclusions, and enabling the working of a physical system to be understood in terms of accepted principles. The advances in knowledge of photochemical reactions in solids provide just such possibilities.

Photochemical reactions in crystalline solids have exceptional interest in that the processes of light absorption, energy transfer to the reactants and the reactions themselves occur under conditions made simpler by reason of the ordered structure of the crystal. Of leading importance is the elimination of collisions, which so complicate the understanding of chemical reactions in fluids.

The replacement of collisions as the mechanism by which energy is made available at a reacting site has profound consequences for the nature of chemical change in solids. In a particular way it makes thermal reactions harder to study than in solution or in the gas and gives a special advantage to photochemical reactions. If there are no collisions to activate a molecule, the activation of a thermal reaction must come by the chance accumulation of vibrational motions of the lattice and of the molecule. There is no collisional kinetic energy for conversion to potential energy. For this reason a thermal reaction in a crystal rarely occurs at isolated single locations at a controlled rate. When a crystal is heated to induce a thermal reaction, thermal activation often occurs at a large number of sites almost at the same temperature. Autocatalysis is common, as the result of a thermal reaction at one site releasing heat to activate the same reaction at neighbouring sites.

On the other hand in a photochemical change it is possible to control the rate of activation of molecules in the solid by varying the light intensity. This varies the rate at which energy is supplied to produce the activation necessary for a chemical change. Also energy collection is highly efficient. When light falls on a crystal it excites it as a whole and, as a second stage, the available energy is trapped at sites at which chemical change is possible. The available energy is 'scavenged' by molecules capable of reaction and can be used with high efficiency. This contrasts with photochemical reactions in gases and liquids in which a molecule can react only by itself absorbing a photon. Solid state photoreactions are in many cases cooperative in this sense.

It is at once obvious that the range and variety of chemical reactions is very limited compared with other phases. Because the molecules in a solid are in fixed positions chemical reactions tend to be confined to molecules which are nearest neighbours, and for a reaction between two different molecular species the molecules must have been combined in a mixed crystal as host and guest. However one should not underestimate the possibilities. Wegner and colleagues (1972)

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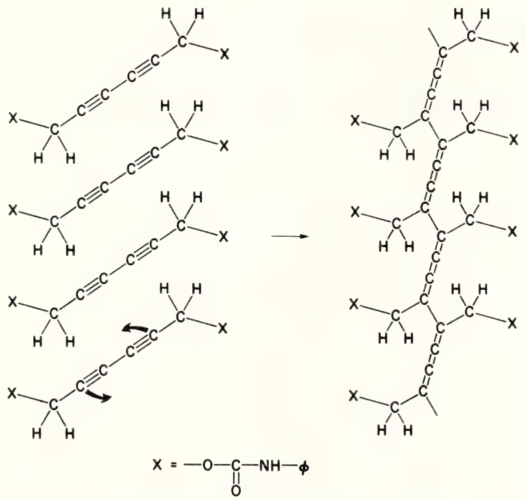
synthesized photochemically and thermally long chain stereoregular polymers which up to the present have not been made by any other means. This reaction does not go in solution and in the crystal goes only in that crystal modification in which the molecules are stacked as shown in Figure 1. Here the polymer is preformed and small rotations only about the centres of mass are required to achieve the precise structures essential for polymerisation. Such polymers are important technically, possessing interesting semiconducting properties. The structural characteristics of the starting crystals, apart from preformation of the product, are that the triple bonds of adjacent molecules are very close (about 0.3 nm) and thermally induced vibrations can bring the reacting entities close enough to combine. Photochemical activation is also



Wegner, ***Die Makromoleculare Chemie*****, 154, 35, (1972).**

Fig. 1

facile. The central idea in this example is that of topochemical preformation, namely that the molecules which will react together are already held in the original lattice in a configuration which is a natural precursor of the product.

TOPOCHEMICAL PREFORMATION

The systematic study of photochemical reactions in solids began in the late thirties. Its first major result was the generalization deduced from a range of studies by Schmidt and coworkers (1964) which they called the principle of topochemistry, to which reference has just been made. One of its clearest examples is the solid state photochemistry of p-substituted cinnamic acids (Figure 2). These acids for various substituents in the p-position of the phenyl group form crystals with a range of molecular packings, with variations in the relative orientations and separations of nearest neighbours. The photochemical reactions, where they occur, are dimerisations proceeding to form one or other of the two structures shown on the left hand side of

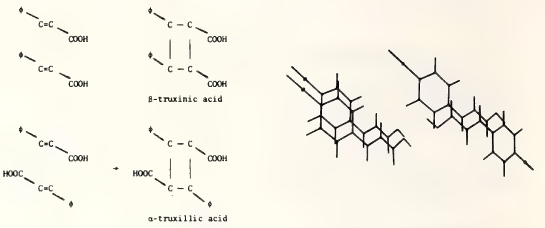


Fig. 2. Dimerisation of the cinnamic acids showing the chemical products (left-hand) and structural registry in the crystals (right-hand) for *cis*- and *trans*-dimers

Figure 2 and in their approximate crystal registrations on the right-hand side. The reaction is the cyclisation of the pair of double bonds. Where the separation of these bonds exceeds a critical value there is no photochemical reaction; where the separation is less than the limiting value there is photodimerisation, leading in every case to the dimer performed by the crystal packing of the parent. This remains one of the classic studies of topochemistry.

Later findings have added much to this general understanding of solid state reactivity. It was shown that even in cases where a dimer was preformed in the monomer crystal, and the packing was close and in correct registration, there need be no reaction if opposing steric constraints were strong enough. Thus in the crystal of 9-cyanoanthracene there is preformation of the *cis*-dimer, in which the 9 and 9' carbons, and 10 and 10', are expected to bridge as in the well known dimer of anthracene itself. No *cis*-dimer forms. Instead, in a remarkable variant, in a slow and auto-catalysed reaction, there is formation of the 'wrong', i.e. the *trans*, dimer (Craig and Sarti-Fantoni, 1966).

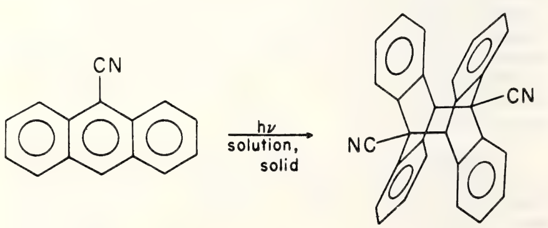


Fig. 3. Monomer and *trans*-dimer structures for 9-cyanoanthracene. The *cis*-dimer is not known

This is the first of many examples of non-topochemical reactions, for which a general explanation has become accepted. The initial rate of such reactions is increased in crystals lacking perfect crystalline order. The reactions can often be shown to have occurred at these zones of imperfection and at surfaces. Their autocatalysis has in a few examples been connected with the growth of dimer bodies, causing increasing disturbances to the host structure, and thus inducing further loss of order.

Consideration of the course of photoreactions not taking place in the ordered crystal bulk is incomplete without reference to their highly selective and localized nature. After irradiation, the absorbed energy is transferred within the crystal and trapped at 'reactive' sites, which, as in the examples already referred to, may be misoriented molecules in a pure crystal, or may be chemical impurities in a doped crystal. Cases are known of photoreactions confined to impurities present only in parts-per-million concentrations. In anthracene crystal for example 2-hydroxy-anthracene (2-OHA) is a photoreactive impurity, forming with one molecule of anthracene a pair compound joined in the 9-9' and 10-10' positions to give a structure similar to the 9-cyano-anthracene dimer in Figure 3 (Craig and Rajikan, 1977). The reaction can be followed in some detail, because the radiation absorbed at the wavelength characteristic of the host anthracene crystal, even at 2-OHA concentrations of less than 10 parts per million, is largely trapped by the impurity. At low temperatures the radiation is emitted at frequencies characteristic of 2-OHA; at higher temperatures the energy is dissipated in processes leading to formation of the pair

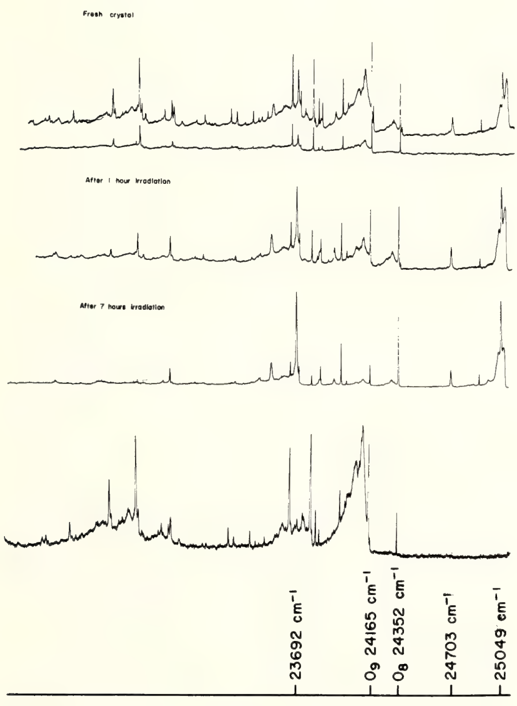


Fig. 4. Fluorescence spectra at 5 K of anthracene crystal doped at <10 ppm with 2-hydroxyanthracene. In the two orientations of 2-OHA there are different emission origins, at O_8 and O_9. Under suitable conditions, irradiation depletes O_9 only, by photochemical reaction. The bottom spectrum is of a fresh heavily doped crystal. Taken, with permission, from *Chem. Phys. Lett.* 1977, *47*, 20

molecule. On closer study the details contain much information illustrated in Figure 4. In a crystal of the anthracene space group $P2_1/a$ replacement of a host molecule by an impurity of symmetry C_{1h} may be made in two distinct ways. The local atom-atom contacts between impurity and host make different contributions to the total crystal energy. The consequences are that one packing orientation is more probable than the other, and that the energy of the radiation required to excite them is different. Thus an easy experimental method, the measurement of fluorescence frequencies and intensities, is available to find the relative concentrations, and the rates of photoreaction. As shown in Figure 4 both orientations trap radiation absorbed by the host anthracene crystal but photoreactivity is confined to one only. The explanation is not known. Calculations of the local packing do not agree with the idea that there is topochemical preformation in either case (Craig and Markey, 1980). Probably both impurity packings are disordered, one but not the other preforming the reaction product.

STATIC AND DYNAMIC TOPOCHEMICAL PREFORMATION

Preformation is a more complex concept than at first appears. It is well established by measurements of lattice vibrations, and supported by calculations of the force system holding a molecule in place at its lattice site, that the 'cage' in a lattice containing a molecule is a stiff structure, limiting its motion to small excursions from a mean position and orientation even at temperatures within a few tens of degrees of the melting point. There are obvious exceptions to this statement, as in molecules with an axis of rotation (CO_2) and also where there is an axis of high order (C_6H_6), but in molecules like naphthalene and anthracene the centres of mass oscillate with amplitudes of only a few tens of picometres and axes of inertia by a few tenths of a radian. How this picture changes when the molecule is electronically excited is not known experimentally but calculations suggest that while there may be a change in the equilibrium positions the motional amplitudes, which depend on the same cage as in the ground state, are not much changed. Thus in a broad sense one has no difficulty in rationalizing the topochemical principle. It is not so easy to understand the steps following excitation in a dynamical context. The atoms of adjacent molecules which are to be bonded to one another (9,9' and 10,10' in the anthracene dimers) have to get much closer than they are in the crystal. If the crystal distance is too great, as noted in Section 2 for the cinnamic acids, there is no reaction even if the molecules are favourably registered. Thus it is not possible to avoid analyzing motional and dynamic aspects as well as the static problems of cage structure and local packing.

INSTABILITIES AS AN ASPECT OF DYNAMICAL PREFORMATIONS

The force system maintaining the local packing in a molecular crystal is well described by summing the dispersion attractions and the closed shell repulsions due to electron exchange. These two are often referred to jointly as van der Waals forces, although sometimes the term is applied to the dispersion force alone. The repulsion energy is fairly well represented over a range of interatomic separation R by an exp(-cR) dependence. The dispersion energy between molecules a and b, denoted by D_{ab}, is accounted for on the Heitler-London theory in terms of the intermolecular coupling of virtual transitions according to equation (1)

$$D_{ab} = - \sum_{i(a)} \sum_{j(b)} \frac{\underset{\sim}{M}^2_{oi}\ \underset{\sim}{M}^2_{oj}}{\Delta E_{oi} + \Delta E_{oj}} (I^{ij}_{ab}) \qquad (1)$$

where, in the notation Craig *et al.* (1965) $\underset{\sim}{M}_{oi}$ is the transition moment and ΔE_{oi} the excitation energy for the transition to the i-th excited state from the ground state of the molecule. I^{ij}_{ab} is a geometrical factor depending on the positions of the two molecules and on the polarization directions of the $i \leftarrow 0$ and $j \leftarrow 0$ transitions. The energy (1) varies with the distance ρ separating the molecules as ρ^{-6}. Where the total interactions are represented as sums of interatomic parts, the dispersive terms are empirically set to obey an R^{-6} relation between atomic centres. In that case, in what has become the usual treatment of intermolecular forces in studies of crystal packing, the potential energy is the sum of interatomic terms of the 'exp-6' form

$$V_{ij} = - a(ij)R^{-6}_{ij} + b(ij)\ \exp\{-c(ij)R_{ij}\} \ (2)$$

With the help of some rather crude approximations the dispersion energy can be written as a function of the polarisabilities of the coupled molecules. The polarizabilities are measured quantities, and allow comparison of actual and computed dispersion energies. Computations based on measured polarizabilities rarely give more than 60% of the true values, but are still of great value. In particular, by using the polarizability of an <u>excited</u> molecule, we get a measure of the forces acting to move and reorient it within the cage. In most crystals electronic excitation increases the attractive forces (dispersion forces) so that the excited molecule is more tightly bound to its environment. It is quite a good approximation to say that the closed shell repulsions are not altered, inasmuch as the excitation affects the states of electrons not much involved in the repulsions. Thus excitation of the π-electrons in an aromatic molecule leaves the hydrogen-hydrogen atom repulsions more or less unchanged, and these are mainly responsible for the repulsive, structure-maintaining, forces in the crystal.

There are examples, notably in crystals of pyrene and perylene, where the structure consists of eclipsed pairs of molecules, which on excitation form excimers, or close-spaced excited molecule-pairs, with characteristic spectral properties, but with no tendency to form chemical dimers. The increased attractive force on excitation accounts for the movement of molecules closer together in such structures. In others such as 9-cyano-anthracene the structure is not by pairwise molecular association; the molecules are in stacks, and it is not at once easy to see how excimers, which are observed, would form. In yet other cases there are similar problems in accounting for the formation of photochemical products.

Some of these difficulties would be removed if it were the case that, following excitation, impulsive forces were generated which, over short time intervals, caused displacements of molecules, or perhaps only the excited molecule, away from the ground state equilibrium positions, so predisposing the molecules for excimer or dimer formation in a process that one can describe as dynamical topochemical preformation. After the impulsive motion is damped out, the excited molecule and its neighbours settle into a new equilibrium, in which the packing may be unsuitable for excimer or dimer formation. We may readily show that such short-term instabilities are feasible by taking a simple model system of three molecules in a straight line, held in equilibrium by balanced dispersive and repulsive forces. The repulsive term will be given by a power law, rather than an exponential, dependence on distance so that the attractions and repulsions vary with distance respectively as R^{-6} and R^{-12}. The pairwise potential is thus

$$V = - \alpha/R^6 + \beta/R^{12} \qquad (3)$$

α and β being constants for the scale of the attractive and repulsive energy functions. If the equilibrium separation is at $R = \rho$, β can be eliminated, giving

$$V = - \alpha/R^6 + \alpha\rho^6/2R^{12} \qquad (4)$$

and if on excitation the dispersive constant is changed to α^* we have for the excited state potential function

$$V^* = - \alpha^*/R^6 + \alpha\rho^6/2R^{12} \qquad (5)$$

given in terms of ρ, the ground state equilibrium spacing. To test the consequences for the 3 molecule system

$$\overset{\bullet}{1} \qquad\qquad \overset{\bullet}{2} \qquad\qquad \overset{\bullet}{3}$$

one can take two extreme assumptions. If molecule 2 is excited, and atoms 1 and 3 allowed to relax freely, the system will come to a new symmetrical equilibrium structure with separation changed from ρ to ρ^*,

$$\rho^* = \rho(\alpha/\alpha^*)^{1/6} \qquad (6)$$

The other extreme is to follow the motion of the central atom in the short period before molecules 1 and 3 can move. Figure 5 shows how the potential for the central atom depends on the ratio α^*/α. For small changes in α^* the centre position remains the equilibrium position. For larger changes there is instability, the central atom being driven away from its site at the centre to one of two equivalent displaced configurations with close approach to one or other neighbour. There is thus preformation of a dimer pair, in the short term, which could prepare the system for chemical change or excimer formation. If there is no chemical change long term equilibration would follow to the symmetrical structure described before.

While the three molecule system gives a useful view, a much more detailed picture can be had by taking a one-dimensional 'crystal' consisting of equally spaced atoms (Figure 6)

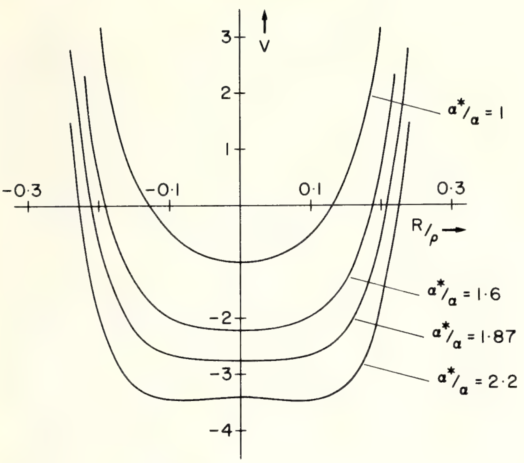


Fig. 5. Potential curves for an excited atom in a triatom configuration with fixed outside atoms. R is the displacement from the ground state equilibrium. α*/α is the ratio of excited state to ground state dispersive constants in equations (4) and (5) Taken, with permission, from *Chem. Phys.* 1982, *65*, 129

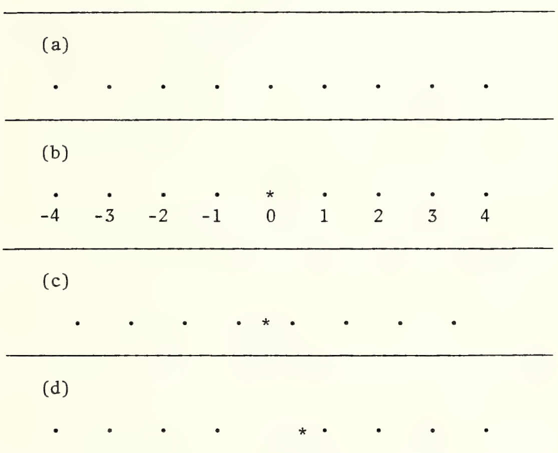


Fig. 6. One-dimensional atomic lattice: (a) ground state, (b) excited atom shown as * in ground state configuration, (c) symmetrical long-term relaxation, (d) asymmetrical short-term distorted lattice

in which one molecule is to be excited. The force system controlling the response of the excited system can now be followed realistically, taking account of the propagation along the chain of the impulsive forces caused by excitation. The extremes are shown in Figure 6; there can be a symmetrical contraction (c) (or, in principle, expansion) about the excited atom, and after sufficient time this will certainly be the result. In short periods an unsymmetrical (dimer preforming) motion (d) is a possibility. Also it is necessary to simulate in the calculations another feature of real systems, which is that, depending on temperature, there will be vibrational motion in the initial state of the system.

Calculations (Craig and Collins, 1981) of the one-dimensional system by classical mechanics (semi-classical method) are illustrated by the results in Figure 7. The calculations are made for a range of initial motions of the inner (u_0) and one of the outer (u_1) atoms, and the time development of the system after excitation of the atom labelled 0 in Figure 6. In (a), with initial motion of atoms 0 and 1, those atoms oscillate as a pair over long periods, atom -1 being more or less unaffected. This is the typical dynamical

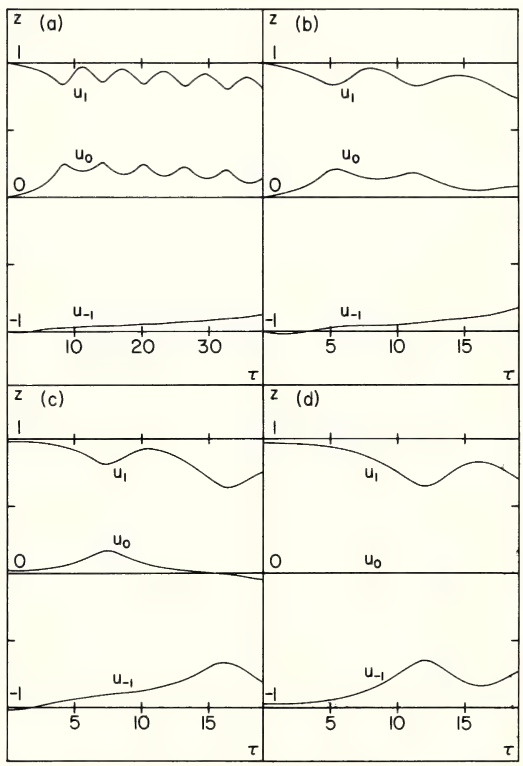


Fig. 7. Motions of the inner (u_0) and outer (u_1 and u_{-1}) atoms in the excited atomic chain. Taken, with permission, from *Chem. Phys.* 1981, *54*, 305

preformation of the dimer pair. In (b) with small initial velocities the same behaviour is found. Successively, in (c) and (d), the dynamics changes to symmetrical collapse. It is thus confirmed that the unsymmetrical short-term displacement, reflecting instability, occurs in a range of circumstances.

INSTABILITIES IN REAL CRYSTALS

The extension of such kinematic arguments to three dimensional systems is difficult, though possible in atomic lattices of simple structure, such as crystalline argon (Collins and Markey, 1982). For molecular crystals calculations of the kind sketched for the three-atom system can be made, leading to potential energy functions. One can predict instabilities and the magnitudes of short-term and equilibrium displacements, but cannot follow the time-evolution leading to these configurations with present theories.

There are well established procedures for calculating the equilibrium properties, structural and dynamic, of the crystals of simple molecules especially, but not only, hydrocarbons. The starting point is a set of atom-atom potentials of the 6-exp form in which the repulsive part of the potential is an exponential function. Given atom-atom potentials found by fitting a few known crystal structures, other crystal structures can be accounted for with good accuracy. The potentials used are of the form given in equation (2) and in the following work the constants are taken from Williams set IV (Williams, 1966). Early efforts to account for known structures were in many cases based on observed lattice spacings, and minimized the total atom-atom potential energy with respect to angles of orientation. Later, lattice dimensions were included as variables, again with good results. To deal with the effects of excitation of one molecule on local structure is much harder, and is similar to finding the effect on local packing of an impurity molecule or of a vacancy. All three can be done only if local structural relaxation can be allowed for, with loss of the simplifying features that come from translational symmetry of a lattice, and permitting independent position and angle variations of molecules in a neighbourhood of the foreign molecule (Craig and Markey, 1980). In the present problem of calculating the forces produced by molecular excitation the calculations are of two types. First, the energy is minimized with respect to centre-of-mass movement and orientation changes of the excited molecule only, the environment being kept fixed. This simulates the short-term energetics, and brings to light any instabilities, in the manner of the three-atom system in Section 4. In the second calculation the energy minimization includes relaxation of the environment molecules, and simulates the long-term energetics, after any instability has been damped out.

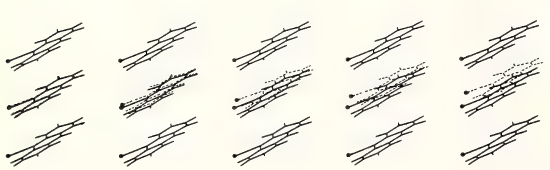


Fig. 8. The effect of allowing an excited molecule of 9-cyanoanthracene (dashed line) to relax in a fixed lattice for a range of excited-unexcited coupling strengths. The nitrogen atom is shown by a full circle. The coupling strengths increase from left to right; even for rather small values the excited molecule is unstable at its equilibrium position and moves towards one neighbour. The projection is along the a-axis of the crystal. Taken, with permission, from *Chem. Phys.* 1982, *65*, 129

The procedures and results are well illustrated in the crystal of 9-cyanoanthracene, one molecule of which is assumed to be excited. The excitation is known to delocalize to a greater or less degree, moving from site to site, but we shall assume it to be trapped. The polarizability of the excited molecule exceeds that of the normal molecule, as is known from the spectral red shift that takes place between solution and crystal. The magnitude of the increase is taken to be equal to that of anthracene, which has been measured (Liptay and Schlosser, 1972; Liptay *et al.* 1971; Mathies and Albrecht, 1974), but because the measured quantities is an average over three components, its composition over these components must be treated as a variable, and calculations of structure made for a range of values. The results show that for a large part of the range the excited molecule in a fixed environment is unstable at its normal equilibrium position and is displaced towards one or other of its neighbours in the stack, in a manner to perform an excimer. This finding is illustrated in Figure 8, in which the initial molecular positions are shown in full lines, and the energy minimized positions by dashed lines. The right-hand diagram, for the largest changes of the force system on excitation, shows a large asymmetric displacement of the excited molecule in a manner predisposing its participation in excimer formation with one neighbour.

Figure 9, giving the results including relaxation of the environment, shows quite large displacements of near neighbours of the excited molecule, but in a nearly symmetric manner, as expected.

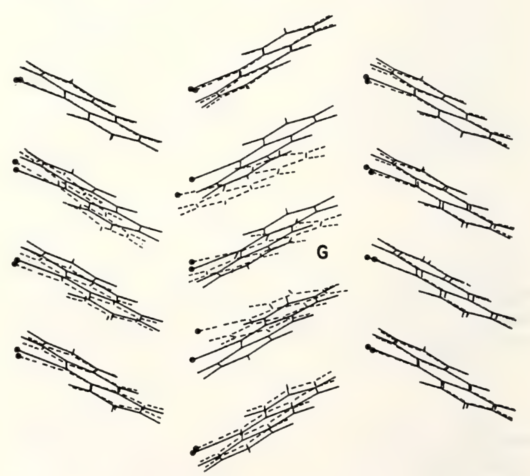


Fig. 9. 9-cyanoanthracene crystal structure as modified by the presence of an excited molecule (shown as G) with allowance for environment molecules to relax. The crystallographic structure is shown by full lines, and the relaxed structure by dashed lines. The nitrogen atom is shown by a full circle. Taken, with permission, from *Chem. Phys.* 1982, *65*, 129

CONCLUSION

The instabilities that arise in the model three-atom system, and in the example of 9-cyano-anthracene in Section 5, are not general, and not essential as a step in the formation of excimers or chemical dimers. They do not appear in calculations on crystalline anthracene either in the normal $P2_1/a$ structure or in the metastable $P\bar{1}$ structure, nor in 9-methylanthracene (Craig and Mallett, 1982). Excimers in the classical examples of perylene and pyrene are associated with pair-wise stacking in the normal crystal, and not with dynamic instabilities, though perhaps with other dynamic features. However in structures with stacks of translationally equivalent molecules like 9-cyanoanthracene instabilities can be expected in many cases, and their occurrence provides a new insight into excimer formation, which was puzzling before. There is another and varied class of mixed crystals, not discussed in this lecture, in which instability will be a common feature. An example studied by methods like those described (Craig and Mallett, 1982) is that of 9-methoxyanthracene as an impurity in 9-cyano-anthracene. The calculated instability gives a useful clue to the nature of excimer formation recently found experimentally (Berkovic and Ludmer, 1981). In the more general context one sees that the dynamic properties of lattices must be included in theories of photochemical change in crystals, as well as already recognized static properties, and that we need to reckon with dynamic topochemical preformation as a newcomer to the array of concepts that help understanding of the radically new features of chemical change in solids.

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Presented at the 115th Annual General Meeting of the Royal Society of New South Wales held on 7th April, 1982.

INTRODUCTION

A continuing review of 11 the Society's activities is taking place and the necessity of certain changes in the method of functioning of the Society is becoming apparent because of financial stringencies.

The Society and its Journal have a useful role to play in the scientific community in the state. To this end Council decided to provide a forum for publication in our Journal for abstracts of M.Sc. and Ph.D. theses from research carried out in New South Wales, in disciplines traditionally represented by papers in the Journal. This will be at a nominal cost to the student.

In November the President and Secretary of the Society expressed in person the appreciation of the Society to the Governor of New South Wales, Air Marshal Sir James Rowland, K.B.E., D.F.C., A.F.C. for his acceptance of the office of Patron.

MEETINGS

Council held 11 meetings during the past year. Attendance of members of Council ranged from 10 to 15. On 16th December the President entertained the Council at a small function to commemorate the centenary of the Act of Incorporation assented to on 16th December, 1881.

Nine general monthly meetings were held during the year together with the Clarke Memorial Lecture by Dr. R.W.R. Rutland on "The Growth of Continental Crust: a Comparative Tectonic Approach" (23rd July, 1981) and the Pollock Memorial Lecture (with Sydney University) by Professor E.Salpeter "Galaxies, Clusters and Invisible Mass" (30th July, 1981) (J. and P., vol. 114, pp. 53 - 58).

A special lecture entitled "Is God Left-Handed?" given by Professor R. Gillard at Macquarie University was jointly sponsored by the Royal Australian Chemical Institute and our Society on 11th February, 1982.

Abstracts of the lectures at the monthly meetings have been published in the Society's Newsletter. The average attendance at the meetings was 37 (range 24 - 76).

ANNUAL DINNER

The Annual Dinner was held at the Sydney Hilton Hotel on Tuesday, 9th March, 1982, and was attended by 52 members and guests.

We were entertained by an amusing and informative talk by Mr. Graham White, Assistant General Manager for A.B.C. Television. He spoke on "Television Programming - an Inexact Science."

PUBLICATIONS

Volume 114, Parts 1 - 4 were published in two issues during the year.

There were 9 issues of the Society's Newsletter. Council appreciates the contributions of the authors of the short articles that appear in the Newsletter from time to time.

MEMBERSHIP

The membership of the Society at 31st March, 1982 was:

Honorary Members	13
Life Members	35
Company Member	1
Ordinary Members	326
Associate Members	42

LIBRARY

Members of the Society, students of the Universities and others have used the library on various occasions during the year.

The library is being kept up to date, by the continual receipt of overseas journals in exchange for our Journal. However, this is causing a space problem and it will be necessary, in the near future, to dispose of some of the local material easily available elsewhere in Sydney.

Members are reminded that photocopying by the Society is now subject to the new Copyright Act. All requests for photocopying should be made in writing.

Council is moat grateful to Mrs. Proctor who has continued in her work for the Society as Librarian in an honorary capacity. Mrs. Proctor is in attendance on Tuesdays and Thursdays. Readers requiring to use the Library should contact her by phone, beforehand on these days.

During the year there were 98 requests for copying from the library. Some 2254 items were received and processed from 376 institutions.

Members are reminded that donations to the Library are deductible for Taxation purposes.

AWARDS

The following awards for 1981 were made:

Clarke Medal: Professor William Stephenson
Edgeworth David Medal: Dr. Martin Andrew Green
The Society Medal: Associate Professor William Eric Smith
Archibald D. Ollé Prize: Dr. Helene A. Martin for her paper entitled "Stratigraphic Palynology of the Castlereagh River Valley, N.S.W."
Clarke Memorial Lectureship: Dr. R.W.R. Rutland

SUMMER SCHOOL

The Summer School on Materials Science entitled "Improve your Game - Science in Sport", was held from January 25th to 29th, 1982, in conjunction with the Department of Materials Science at the New South Wales Institute of Technology. The School consisted of lectures and tutorials at the N.S.W. Institute of Technology with a site visit to QANTAS.

Twenty seven students attended from high schools distributed over a wide area.

FINANCE

The Society's annual accounts for 1981 show a surplus of $776.

The principal ingredients in this result were (i) the generous action of our Librarian, Mrs. G. Proctor, to act in a voluntary capacity from February; (ii) a reduction in postal charges achieved through bulk-posting and any other cost-saving measures that might arise, and (iii) a reduction in the cost of printing the Journal which was not deliberate policy but the result of fewer papers being printed than usual. The Annual Dinner and Summer School both broke even, although Entertainment increased due to the cost of entertaining the Governor-General and his party at the Annual Dinner.

Council is grateful to the New South Wales Government for its grant through the Division of Cultural Activities in the Premier's Department.

SCIENCE CENTRE

A Science Centre Foundation was established in May, 1981, but by the end of the year had not succeeded in raising funds to the extent originally anticipated.

Council's representatives on the Board of Science House Pty. Ltd. continued to be Mr. Puttock (Chairman), Mr. Chaffer, Mr. Humphries and Associate Professor Smith. They gave considerable attention to the financial difficulties of the Company and warned Council that in 1982 substantial changes in arrangements would probably be necessary.

The Science House Pty. Ltd. Secretariat serviced 24 scientific societies during the year - a benefit which they greatly appreciated.

ACKNOWLEDGEMENTS

Mrs. Judith Day and Mrs. Grace Proctor in the past year have continued to give great assistance and service to the Society and its members.

Council would also like to record its thanks to all those who contributed to the success of our activities especially to Drs. R. MacMillan and G.M. Renwick of the New South Wales Institute of Technology who organized the Summer School.

ANNUAL REPORT OF THE NEW ENGLAND BRANCH OF THE ROYAL SOCIETY OF NEW SOUTH WALES

Officers for 1981

Chairman	S.C. Haydon
Secretary/Treasurer	T.O'Shea
Committee	R.D.H. Fayle
	C.D. Ollier
	R.L. Stanton
Branch Representative on Council	S.C. Haydon

MEETINGS

April 27	Professor L. Phillips, Canterbury University Atmospheric Pollution in the 21st Century.
May 28	Dr. B. McKelvey, University of New England Probing a Frozen Land
June 15	Professor H.C. Freeman, University of Sydney. Electron Transfer in "Blue" Proteins.
August 6	Professor C.D. Ollier, University of New England Making Mountains, the origins of the Eastern Highlands of Australia.
October 22	Dr. G.S. Gibbons, N.S.W. Institute of Technology History in Walls.

FINANCIAL STATEMENT

Balance in C.B.C. Sydney Ltd., University of New England Branch December 31st, 1980	$439.70	
Credit - Interest to June 30	7.55	
- Interest to December 31	6.29	
- Cheque from Council		
	$553.54	
Debit - advertising		4.50
- accommodation for visiting speakers		82.79
- fare for visiting speaker		123.00
		$210.47
Balance at December 31st, 1981		$343.07

ABSTRACT OF PROCEEDINGS 1981 - 1982

The Annual General Meeting and eight General Monthly Meetings were held in the Science Centre. Abstracts of the proceedings of these meetings are given below. In addition the Clarke Memorial Lecture was delivered by Dr. R.W.R. Rutland on 23rd July, 1981 at Sydney University.

APRIL 1st

114th Annual General Meeting. Location: the Auditorium, 1st Floor, Science Centre. The President, Dr. G.S. Gibbons, was in the Chair and 76 members and visitors were present.

The Annual Report of Council and the Annual Statement of Accounts were adopted. 1 paper was read by title only.

The Cook Medal was awared to Professor Robert John Walsh; the Walter Burfitt Medal and Prize to Professor Hans Adolph Buchdahl; the Edgeworth David Medal to Dr. Michael Anthony Etheridge and the Society Medal to Mrs. Maren Krysko von Tryst.

Messrs Wylie and Puttock, Chartered Accountants, were elected Auditor.

The Presidential Address "History in Walls" was delivered by Dr. G.S. Gibbons.

The incoming President, Professor B.A. Warren, was installed and introduced to members.

MAY 6th

931st General Monthly Meeting. Location: Room H, 2nd Floor, Science Centre. The President, Professor B.A. Warren, was in the Chair and 24 members and visitors were present. 2 new members were elected. 1 paper was read by title only.

An address "Land and Sea Satellite Surveillance" was delivered by Dr. John Huntington of the C.S.I.R.O. Division of Mineral Physics, North Ryde.

JUNE 3rd

932nd General Monthly Meeting. Location: Room H, 2nd Floor, Science Centre. The President, Professor B.A. Warren, was in the Chair and 38 members and visitors were present. 2 new members were elected. 1 paper was read by title only.

An address "Invertebrates and the Evolutionary Origin of Vertebrates" was delivered by Professor D.T. Anderson, FRS, Professor of Biology, The University of Sydney.

JULY 1st

933rd General Monthly Meeting. Location: Room H, 2nd Floor, Science Centre. The President, Professor B.A. Warren, was in the Chair and 27 members and visitors were present. 1 new member was elected. 1 paper was read by title only.

An address "Drugs and the Law" was given by Mr. Robert Woellner, Chairman, Department of Legal Studies, Kuring-gai College of Advanced Education.

AUGUST 5th

934th General Monthly Meeting. Location: Room J, 2nd Floor, Science Centre. The President, Professor B.A. Warren, was in the Chair and 21 members and visitors were present. 2 new members were elected. 2 papers were read by title only.

An address "Electricity Generation in New South Wales" was delivered by Mr. Garth Coulter of the Electricity of N.S.W.

SEPTEMBER 2nd

935th General Monthly Meeting. Location: Room H, 2nd Floor, Science Centre. The President, Professor B.A. Warren, was in the Chair and 41 members and visitors were present. 4 new members were elected. 1 paper was read by title only.

An address "Astronomical Photography - a Very Peculiar Business" was delivered by Mr. David Malin, Research Photographer, Anglo-Australian Observatory.

OCTOBER 7th

936th General Monthly Meeting. Location: Room H, 2nd Floor, Science Centre. The President, Professor B.A. Warren, was in the Chair and 30 members and visitors were present. 1 new member was elected. 1 paper was read by title only.

An address "Polar Wander, Sea-Floor Spreading and Earthquakes" was given by Dr. L.A. Drake, Director, Riverview College Observatory.

NOVEMBER 4th

937th General Monthly Meeting. Location: Auditorium, 1st Floor, Science Centre. The President, Professor B.A. Warren, was in the Chair and 29 members and visitors were present.

A symposium was held with the theme "Ethical Problems of Modern Science and Technology". The panel of speakers comprised Mr. W.J. Orme, Executive Member of N.S.W. Privacy Commission; Dr. John Pollak, Reader in the Department of Histology and Embryology, University of Sydney; and Mr. Terry Muldoon, Public Service Association of N.S.W.

DECEMBER 2nd

938th General Monthly Meeting. Location: Room E, 2nd Floor, Science Centre. The President, Professor B.A. Warren, was in the Chair, and 44 members and visitors were present. 1 new member was elected. 1 paper was read by title only.

An address "Plants of Sand and Sandstone" was delivered by Associate Professor Roger Carolin of the School of Biology, University of Sydney.

CITATIONS

THE CLARKE MEDAL

Professor William Stephenson graduated from King's College, Newcastle-on-Tyne, and after spending several years at the Dove Marine Laboratory, he became Professor of Zoology at the University of Queensland in 1949.

In the 1950s he worked on the systematics of portunid crabs, which include some commercially important species. These papers are still widely used and he is recognized as one of the leading authorities in this area. He also undertook some general faunistic surveys on the Great Barrier Reef.

Since the 1960s he has been involved in major benthic surveys in estuarine areas and has radically changed the methodology of such ecological surveys. Together with Professor Bill Williams he has devised computer programmes to analyse this data. These programmes are widely used throughout Australia and have been a major contribution to benthic studies. Recently, he has travelled overseas, lecturing on these methods which are now being used in the States and in England. He has written a text book on these methods. Apart from having and continuing to have a very active research programme, he was Chairman of the Zoology Department for many years. He is a lucid and enthusiastic lecturer, and has supervised many graduate students, many of whom have become successful scientists.

Perhaps the major facet of Professor Stephenson was his ability in later years to completely change fields and to become a leader in the developing field of computer analysis and its application to zoology.

EDGEWORTH DAVID MEDAL

Dr. Martin Andrew Green is awarded the Edgeworth David Medal for outstanding work in physics and engineering with particular emphasis on the development of solar cells.

Dr. Green is a senior lecturer at the University of New South Wales and graduated from the University of Queensland. His doctorate was earned at McMaster University, Canada. Over the last seven years he has built up a dynamic research group with a strong reputation for achievement.

He is able to attract significant funding for his researches into Metal-Insulator-Semiconductor solar cells. These cells have both high efficiencies and voltages; their application has led to significant advances in his field with commercial implications for Australia.

Dr. Green has published widely with close on fifty technical and scientific articles, in addition to reports and conference presentations. He has also written a monograph on the subject of Solar Cells. He has combined researches into the underlying physics of semiconductor phenomena with practical developments of these phenomena. He is a worthy recipient of the Edgeworth David Medal for 1981.

ARCHIBALD D. OLLE PRIZE

Dr. Helene Martin is awarded the Archibald D. Ollé Prize for 1981 for her paper entitled "Stratigraphic Palynology of the Castlereagh River Valley, New South Wales".

Dr. Martin studied both Botany and Geology at Adelaide University, but as a student her interests turned more towards Botany because, as she said "plants are lighter than rocks!" She became interested in spores while at the University of British Columbia, and later gained her Ph.D. at the University of New South Wales. At present she is a Research Fellow in the School of Botany at the University of New South Wales, working under a grant from the Water Resources Commission of N.S.W.

Dr. Martin became a member of the Royal Society in 1976 and has contributed five papers on Tertiary palynology to the Society's Journal. She was President of the Linnean Society of N.S.W. in 1981/82.

THE SOCIETY'S MEDAL

The Society's Medal for 1981 is awarded to Associate Professor William Eric Smith for research in Applied Mathematics, Education, Administration and Teaching in Mathematics and for service to the Society.

Professor Smith was born in Ryde, N.S.W. in 1931 and was educated at the Sydney Technical High School (where he was dux) and at Sydney University, where in 1952, he graduated B.Sc. with First Class Honours and the University Medal in Theoretical Physics.

CITATIONS

He worked first, at the C.S.I.R.O. National Standards Laboratory in the Division of Electrotechnology, on precision electrical measurement and microwave spectroscopy. A C.S.I.R.O. post-graduate scholarship enabled him to do further work on microwave spectroscopy at the Clarendon Laboratory at the University of Oxford.

In 1960, he joined the newly formed Department of Applied Mathematics at the University of New South Wales, to participate in its development. He has made considerable contributions to administration, teaching, research and scholarship at the University of New South Wales. He was appointed Associate Professor in 1969 and Deputy Head of the School in 1970.

His research publications include important papers in the fields of electrical measurements, microwave spectroscopy, acoustics, electromagnetism, radiation pressure, plasma confinement, and numerical analysis which is his current major research interest. He is author of 45 publications (three being in the Journal of the Royal Society). He holds the degrees of M.Sc. from the University of Sydney and Oxford, and Ph.D. from the University of New South Wales.

He joined the Society in 1963, and was first elected to the Council in 1968, and has served continuously to the present, being Hon. Treasurer in 1969, President in 1970 and Vice President thereafter. He has served as Chairman of the Science House Management Committee and as a Director of Science House Pty. Ltd. since its foundation in 1973, to purchase and establish the present Science Centre. Over this period, he has worked for the Society in almost every aspect of operations. He is also active in the Appled Mathematics community, and is Associate Editor and Editor-elect for 1982 of the Journal of the Australian Mathematical Society Journal (Series b, Applied Mathematics).

OBITUARY

ROBERT JACKSON NOBLE

Robert Jackson Noble C.B.E., B.Sc.Agr., M.Sc., Ph.D, a most distinguished member of the Royal Society of New South Wales died on 21st May, 1981 after a short illness, at the age of 87. He was a Life Member of the Royal Society of New South Wales which he joined in 1920, serving as Council Member, Honorary Secretary and Editor of Proceedings from 1929 to 1934, and as President in 1934. Dr. Noble was a former Under-Secretary and Director of the New South Wales Department of Agriculture of which he was Permanent Head for a record 19 years.

Robert Jackson Noble was born at Five Dock, Sydney, and educated at Sydney High School and the University of Sydney. In 1915 he graduated Bachelor of Science of Agriculture with first class honours and was awarded the University Gold Medal, the Belmore Scholarship for Chemistry and Geology, and the J.H. Maiden Prizes for Agriculture, Botany and Forestry.

Dr. Noble first joined the New South Wales Department of Agriculture as a cadet in 1913, and after graduation and service with the A.I.F. in Egypt and France from 1916 to 1919 returned to that Department as an Assistant Biologist in 1920. In 1921 he was awarded the first Sir Benjamin Fuller post-graduate travelling scholarship and undertook research of cereal diseases at the University of Minnesota, U.S.A., where he was awarded the degree of M.Sc. in 1922 and Ph.D in 1923. The University of Minnesota later awarded him (1951) its "Outstanding Achievement Award, Medal and Citation" made "in recognition of noted professional achievement as an internationally celebrated plant pathologist and as an administrator". He was the author of some 66 scientific papers, which dealt mainly with plant diseases, especially cereal smuts, plant viruses, and many aspects of agricultural history and production. His major contributions led to recognition of the importance of plant diseases in agriculture, laid the guidelines for effective plant quarantine, and started the mushroom industry in Australia.

Dr. Noble's membership of scientific and other organizations makes an impressive list. Besides the Royal Society of N.S.W. he was a member of the Linnean Society of N.S.W., a foundation member of the Australian Institute of Agricultural Science in which he served as federal council member and President of the N.S.W. Branch. He was a fellow of the Royal Institute of Public Administration since 1940 and a member of its N.S.W. council. Since 1940 also, he was a Fellow of the Australian and New Zealand Association for the Advancement of Science. In 1933 he was appointed a member of the N.S.W. Committee of the Council for Scientific and Industrial Research (now the C.S.I.R.O.). To these must be added his membership of the Sir Benjamin Fuller Scholarship Trust, Taronga Zoological Park Trust, the British Colonial Service Appointments Committee, Australian Museum Board of Trustees, the Inter-Departmental War Service Land Settlement Panel (1947-1949), Fauna Protection Panel, and the Board of Trustees of the McGavie Smith Institute. He also served as Chairman of the Farrer Memorial Trust, of the Board of Trustees of the Royal Botanic Gardens, and of the Standing Committee on Agriculture of the Australian Agricultural Council.

Dr. Noble led the Australian Commonwealth delegation at the inaugural meeting of the Food and Agriculture Organization of the United Nations at Quebec, Canada, in 1945 and was appointed a member of the executive committee of the conference. His report on that conference was published as a white paper by the then Commonwealth Government which, along with the State Governments adopted his recommendations for the co-ordination of health, fisheries, agricultural production, and marketing services.

Dr. Noble received royal recognition of his scientific achievements with the award of Commander of the Order of the British Empire in the Queen's 1957 birthday honours list. This followed his earlier awards of the Coronation Medals in 1937 and 1953, and the Jubilee Medal in 1953. He was awarded the 1959 Farrer Memorial Medal by the William Farrer Memorial Trust in the year of his retirement after 46 years of outstanding public service including a record term of office for any departmental head in New South Wales.

Dr. R.J. Noble whose wife Joan died some years ago is survived by his two sons Dr. Neil Noble, a surgeon, and Dr. James Noble, an agricultural scientist, and by seven grandchildren.

R. Meadows has written a more detailed biography of the work and achievements of the late Dr. R. J. Noble in the Agricultural Gazette of N.S.W. Vol. 92 No. 6, December 1981.

H.D.R. Malcolm

THE ROYAL SOCIETY OF NEW SOUTH WALES

FINANCIAL STATEMENTS

For the Year Ended 31 December 1981

AUDITORS REPORT TO THE MEMBERS

In our opinion:

(a) the attached Balance Sheet and Income and Expenditure Account, which have been prepared under the historical cost convention, are properly drawn up in accordance with the Rules of the Society and so as to give a true and fair view of the state of affairs of the Society at 31st December 1981 and of the results of the Society for the year ended on at date; and

(b) the accounting records and other records, and the registers required by the Rules to be kept by the Society have been properly kept in accordance with the provision of those Rules.

WYLIE & FUTTOCK
Chartered Accountants.

By ALAN M. FUTTOCK
Registered under the Public Accountants Registration Act, 1945 as amended.

BALANCE SHEET as at 31/12/81

	RESERVES			
7310.57	Library Reserve (note 2(i))			7310.57
416991.00	Resumption Reserve (note 2(ii))			416991.00
2305.57	LIBRARY FUND (notes 1(c)(d) and 2(iii))			2708.13
14206.36	TRUST FUNDS (note 4)			17455.36
74258.59	ACCUMULATED FUNDS			75084.52
515072.09	TOTAL RESERVES & FUNDS			519549.58
	Represented by:			
	CURRENT ASSETS			
18.39	Petty Cash Imprest		23.64	
801.26	Debtors for Subscriptions	1049.50		
680.26	Less Provision For Doubtful Debts	1049.50		
2483.91	Other Debtors & Prepayments		1977.04	
2840.72	Cash at Bank		6230.96	
5464.02				8231.64
	Less: CURRENT LIABILITIES			
4911.97	Sundry Creditors & Accruals	5217.74		
19.37	Life Members Subscriptions - Current Portion	19.37		
209.55	Membership Subscriptions Paid in Advance	94.44		
906.00	Subcriptions to Journal Paid in Advance	965.84		
6046.89				6297.39
(582.87)	NET CURRENT ASSETS			1934.25
	Add: FIXED ASSETS			
6652.66	Furniture, Office Equipment, etc.- at cost less Depreciation	6073.66		
13600.00	Library - 1936 Valuation	13600.00		
10.00	Pictures - at cost less Depreciation	10.00		
20262.66				19683.66
19679.79				21617.91
	Add: INVESTMENTS			
35580.00	Commonwealth Bonds & Inscribed Stock	8100.00		
40000.00	Loans on Mortgage	20000.00		
-	Interest Bearing Deposits	50000.00		
75580.00				78100.00
	Add: ASSOCIATED CORPORATIONS (note 3)			
1.00	Shares - at Cost	1.00		
419994.61	Advances & Loans - Unsecured	419994.61		
419995.61				419995.61
515255.40				519713.52
	Less: NON-CURRENT LIABILITIES			
183.31	Life Members Subscriptions - Non-Current Portion			163.94
515072.09	NET ASSETS			519549.58

B. A. WARREN President

A. A. DAY Honorary Treasurer

NOTES TO AND FORMING PART OF THE ACCOUNTS
for the year ended 31st December, 1981

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 year ended 31st December, 1981. Unless otherwise stated, such accounting policies were also adopted in the preceding year.

(a) Basis of Accounting

The accounts have been prepared on the basis of historical costs.

(b) Depreciation

Depreciation is calculated on a written down value basis so as to allow for anticipated repair costs in later years.

The principal annual rates in use are:

Furniture	7.5%
Office Equipment	15.0%

(c) Library Fund

During the 1980 year an amount was transfered from the Library Fund to Accumulated Funds as a contribution to the cost of printing & mailing those copies of the Journal & Proceedings involved in the exchange programme whereby the publications of other Societies are aquired for the Library. This procedure was last adopted in the current year.

(d) Library Facilities

Certain donations to the Society's Library Fund have been paid to Science House Pty Limited (see also note 3) towards the cost of providing library facilities for the Society. Such payments represent donations specifically designated by the donor as being for that purpose.

2. MOVEMENTS IN PROVISIONS AND RESERVES

(i) Library Reserve

	1980 $	1981 $
Balance at 1st January	7300	7310
Add		
Sale of Books	10	-
	-----	-----
Balance at 31st December	$7310	$7310
	=====	=====

NOTES TO AND FORMING PART OF THE ACCOUNTS
for the year ended 31st December, 1981

2. MOVEMENTS IN PROVISION AND RESERVES Contd.

(ii) Resumption Reserve

	1980 $	1981 $
Balance at 1st January	416991	416991
Less		
Movements	-	-
	-------	-------
Balance at 31st December	$416991	$416991
	=======	=======
Represented by:		
Shares in associated corporation	1	1
Loans to associated corporation	416990	416990
	-------	-------
	$416991	$416991
	=======	=======

(iii) Library Fund

	1980 $	1980 $	1981 $	1981 $
Balance at 1st January		2346		2305
Add Donations and bank interest		759		5453
		-----		-----
		3105		7758
Less Library purchases	800		50	
Library fittings & equipment	-		-	
Paid re library facilities	-		5000	
	-----		-----	
		800		5050
		-----		-----
Balance at 31st December		$2305		$2708
		=====		=====
Represented by:				
Cash at bank		760		462
Commonwealth Bonds		2300		2300
Owing to general funds		(755)		(54)
		------		------
		$2305		$2708
		======		======

NOTES TO AND FORMING PART OF THE ACCOUNTS
for the year ended 31st December, 1981

3. ASSOCIATED CORPORATIONS

The Society has entered into a joint venture with the Linnean Society for the establishment and operation 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 50% interest.
Advances and loans to the company have been on an interest free basis repayable at call. No material repayments are anticipated prior to 31st December, 1982

	1980 $	1981 $
Balance at 1st January,	419995	419995
Less Movements	-	-
Balance at 31st December	$419995	$419995
Representing:		
Resumption reserve	416991	416991
Accumulated funds	3004	3004
	$419995	$419995

4. TRUST FUNDS

	1980 $	Clarke Memorial $	Walter Burfitt Prize $	Liversidge Bequest $	Olle Bequest $	Total $
Capital						
Balance at 1st January	11100	4800	3000	2000	1300	11100
Bequest Capital Received	-	-	-	-	2461	2461
Capitalisation of accumulated revenue	-	-	-	-	239	239
Balance at 31st December	$11100	$4800	$3000	$2000	$4000	$13800
Revenue						
Revenue income for period	1328	545	341	227	366	1479
Less Expenditure	524	475	187	30	-	692
	804	70	154	197	366	787
Add Balance from 1980	2303	1173	1079	(13)	868	3107
	3107	1243	1233	184	1234	3894
Less Capitalisation	-	-	-	-	239	239
Total Revenue	$3107	$1243	$1233	$184	$995	$3655
Total Trust Funds	$14207	$6043	$4233	$2184	$4995	$17455

FUNDS STATEMENT FOR THE YEAR ENDED 31ST DECEMBER 1981

	1980 $	1980 $	1981 $	1981 $
SOURCE OF FUNDS				
Operating surplus for the year	-		776	
Add:				
Items not involving the outlay of funds in the current period:				
Depreciation of fixed assets	-		579	
Provision for doubtful debts	-		921	
Funds derived from operations		-		2276
Donations and interest to library fund		759		5452
Library sales		10		-
Trust fund income		1328		1479
Trust fund bequests - Olle Estate		-		2461
Reduction in working funds		4998		-
		$7095		$11668
APPLICATION OF FUNDS				
Operating deficit for the year	2899		-	
Less:				
Items not involving the outlay of funds in the current period:				
Depreciation of fixed assets	(640)		-	
Provision for doubtful debts	(308)		-	
Funds applied to operations		1951		-
Reclassification of life members subscriptions in advance		20		19
Increase in investments		4600		2520
Trust fund expenses		524		692
Library facilities		-		5000
Increase in working funds		-		3437
		$7095		$11668

THE ROYAL SOCIETY OF NEW SOUTH WALES

INCOME AND EXPENDITURE ACCOUNT
For the Year Ended 31 December 1981

	INCOME			
7130.90	Membership Subscriptions - Ordinary			7450.50
19.37	Membership Subscriptions - Life Members			19.37
54.00	Application Fees			57.40
7204.27				7527.27
3186.59	Subscriptions to Journal			3127.38
1500.00	Government Subsidy			1600.00
43.20	Donations - Printing Journal & Publications			-
11934.06	Total Membership & Journal Income			12254.65
7377.59	Interest Received			7598.15
154.35	Sale of Reprints			-
179.60	Sale of Back Numbers			350.00
34.00	Sale of Other Publications			55.60
51.74	Annual Dinner Surplus			25.94
302.50	Summer School Surplus			29.15
136.52	Other Income			282.11
20170.36				20595.60
	Less: EXPENSES			
867.00	Accountancy Fees		867.00	
443.00	Audit Fees		443.00	
22.36	Branches of the Society		100.00	
149.00	Cleaning		205.50	
640.00	Depreciation		579.00	
282.90	Electric Light & Power		356.20	
66.80	Entertainment Expenses		320.25	
176.62	Insurance		177.86	
	Journal Publication Costs			
4983.00	Printing - Current Year Volume	4132.00		
1158.40	Wrapping & Postage	1037.85		
			5169.85	
241.20	Legal Costs		-	
50.06	Library Purchases		49.80	
4448.92	Library Accession, Cataloguing & Reader Services		125.00	
412.54	Library Insurance		425.74	
49.28	Miscellaneous Expenses		279.38	
892.45	Monthly Meeting Expenses		563.05	
1603.27	Newsletter Printing & Distribution		1253.27	
266.96	Postage		269.58	
301.50	Printing & Stationery - General		481.54	
308.38	Provision for Doubtful Debts		921.00	
2781.28	Rent		2781.24	
-	Repairs & Maintenance		196.70	
-	Reprints - Loss on Sale		243.70	
2691.12	Salaries		3783.07	
13.88	Secretarial Services		-	
219.12	Telephone		227.74	
23069.04				19819.47
(2898.68)	SURPLUS for the year			776.13

STATEMENT OF ACCUMULATED FUNDS
For the Year Ended 31 December 1981

(2898.68)	SURPLUS for the year		776.13
759.33	Donations & Interest to Library Fund		5452.36
800.06	Transfer from Library Fund		5049.80
76357.21	Accumulated Funds-Beginning of Year		74258.59
75017.92	AVAILABLE FOR APPROPRIATION		85536.88
759.33	Transfer to Library Fund	5452.36	
-	Payment for Provision of Library Facilities (Note 1(d))	5000.00	
759.33			10452.36
74258.59	ACCUMULATED FUNDS-Current Year		75084.52

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Royal Society of New South Wales

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Date of Publication:
Parts 1 and 2: September, 1981
Parts 3 and 4: December, 1981

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GENERAL

Manuscripts should be addressed to the Honorary Secretary (address given above).

Manuscripts submitted by a non-member must be communicated by a member of the Society.

Each manuscript will be scrutinised by the Publications Committee before being sent to an independent referee who will advise the Council of the Society on the acceptability of the paper. In the event of rejection, manuscripts may be sent to two other referees.

Papers, other than those specially invited by Council, will only be considered if the content is substantially new material which has not been published previously, has not been submitted concurrently elsewhere, nor is likely to be published substantially in the same form elsewhere. Well-known work and experimental procedure should be referred to only briefly, and extensive reviews and historical surveys should, as a rule, be avoided. Letters to the Editor and short notes may also be submitted for publication.

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Spelling follows "The Concise Oxford Dictionary".

The Systeme International d'Unites (SI) is to be used, with the abbreviations and symbols set out in Australian Standard AS1000.

All stratigraphic names must conform with the Australian Code of Stratigraphic Nomenclature (revised fourth edition) and must first be cleared with the Central Register of Australian Stratigraphic Names, Bureau of Mineral Resources, Geology and Geophysics, Canberra. The letter of approval should be submitted with the manuscript.

Abstract. A brief but fully informative abstract must be provided.

Tables should be adjusted for size to fit the format paper of the final publication. Units of measurement should always be indicated in the headings of the columns or rows to which they apply. Tables should be numbered (serially) with Arabic numerals and must have a caption.

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