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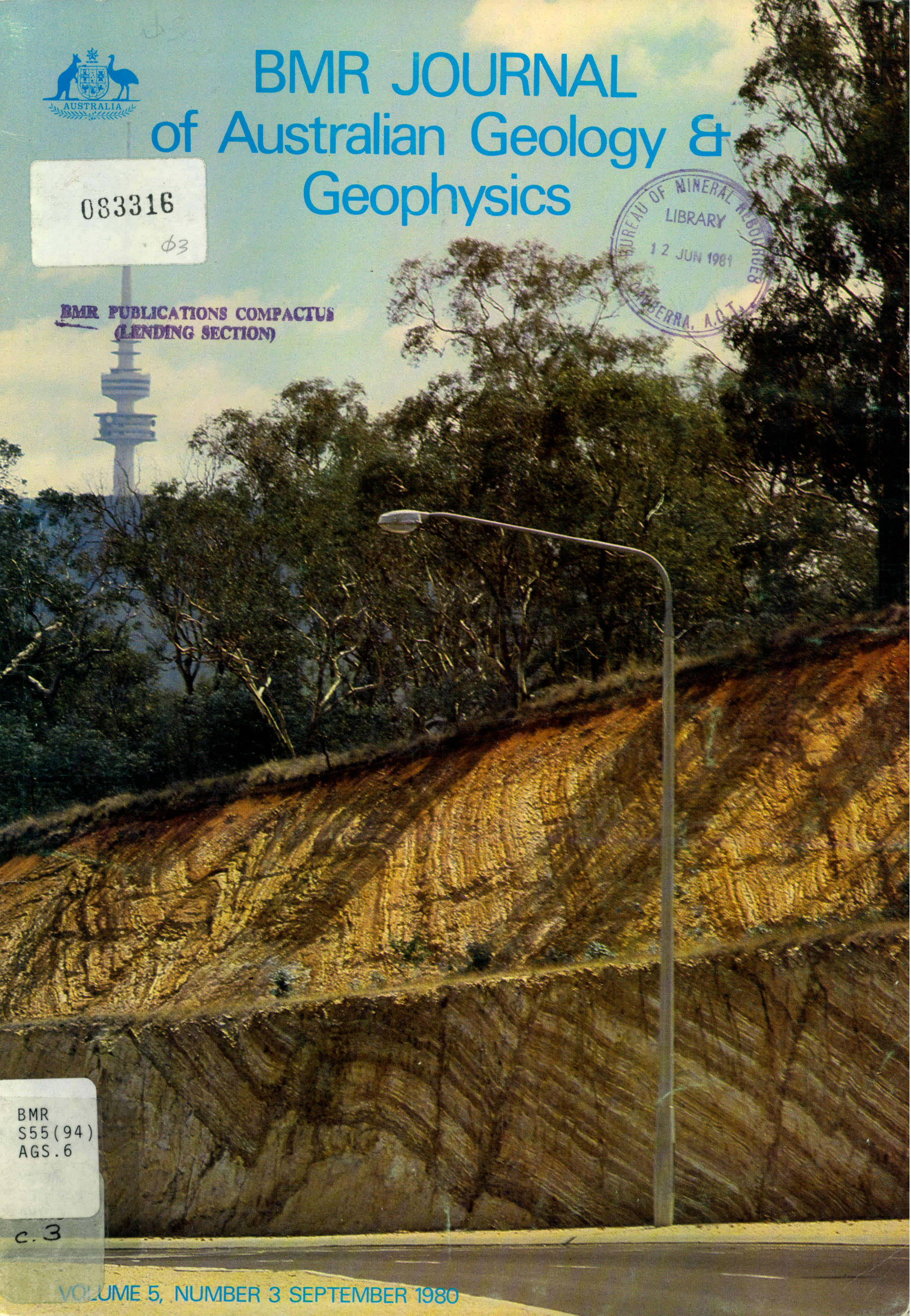

VOLUME 5, NUMBER 3 SEPTEMBER 1980

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Front cover:

A familiar sight to Canberra residents and tourists is this benched cutting in State Circle, near the site of the proposed new Parliament House. The exposure is classified as a geological monument.

The pale wedge of rock in the lower left of the photo is Lower Silurian State Circle Shale, which is unconformably overlain by the well-bedded Camp Hill Sandstone Member of the Middle Silurian Canberra Formation.

Photograph: W. H. Oldham.

The text figures in this issue were drawn by a cartographic team of J. Mifsud, R. Bates, I. Hartig, R. Anderson, and C. Fitzgerald.

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Archaeocyatha of the Amadeus and Georgina Basins

P. D. Kruse[1] & *P. W. West*[2]

The Todd River Dolomite (Amadeus Basin) and Mount Baldwin Formation (Georgina Basin) are a part of the Early Cambrian platform cover of the central Australian craton. Marine dolostones of these rock units preserve a limited archaeocyathan-radiocyathan fauna, including *Aldanocyathus greeni* Kruse sp. nov., *Coscinocyathus bilateralis* (Taylor), '*Dictyocyathus*', *Aruntacyathus toddi* Kruse gen. et sp. nov. (Metacyathidae), and *Radiocyathus minor* (Bedford & Bedford). *?Aruntacyathus rossi* Kruse sp. nov. and *Beltanacyathus* Bedford & Bedford are known traditionally from the Todd River Dolomite. On the basis of the common occurrence of elements of Faunal Assemblage No. 2 (Daily, 1956), the Todd River Dolomite and Mount Baldwin Formation can be correlated with the lower part of the Ajax and Wilkawillina Limestones of South Australia. The central Australian and corresponding South Australian archaeocyathan faunas appear to be coeval with those of the Atdabanian and possibly early Lenian stages of Siberia.

This paper documents an archaeocyathan fauna common to both the Amadeus and Georgina Basins of central Australia. Kruse is responsible for the description of the fauna and review of Amadeus Basin stratigraphy, and the synthesis, while the contribution on the Georgina Basin is the result of fieldwork by West in support of the Bureau of Mineral Resources' Georgina Basin project.

The Amadeus Basin is an east-west-trending intracratonic trough or aulacogen spanning the central portion of a much larger elongate zone of relative crustal mobility ('Trans-Australia Zone' of Austin & Williams, 1978). The Georgina Basin, presently separated from the Amadeus Basin by the Arunta Block, represents a more stable region of the ancient continental platform. In both basins deposition commenced in mid to late Adelaidean time (Wells & others, 1970; Smith, 1972; Marjoribanks & Black, 1974; Mayne, 1976; Shergold & others, 1976; Burek & others, 1979). Palaeogeographic reconstructions of the Australian craton by Veevers (1976) and Webby (1974, 1978) depict the two basins united as a single marine embayment of variable extent throughout their Cambro-Ordovician depositional phase. Preiss & others (1978) have suggested that there was interconnection between these basins in the Adelaidean also.

In the Amadeus Basin, archaeocyaths are present only in the Todd River Dolomite (Wells & others, 1967) of the Pertaoorrta Group, and in the Georgina Basin, the Mount Baldwin Formation (Smith, 1964) of the Mopunga Group. Both occurrences were first reported by Madigan (1932), and represent elements of a shallow marine fauna developed in Early Cambrian continental platform successions on the Australian craton.

Amadeus Basin

The Todd River Dolomite is an Early Cambrian rock unit cropping out over an extensive area of the northeastern Amadeus Basin, covering portions of the ALICE SPRINGS, RODINGA and HALE RIVER 1:250 000 geological map sheets. The type section is in the Ross River gorge (on the present northeastern margin of the basin), where a maximum thickness of 155 m is preserved (Fig. 1). In the present study the archaeocyathan fauna was sampled both here and on the southern limb of the Ooraminna Anticline, some 60 km to the southwest, where the formation is only 66 m in thickness. Spot samples in the collections of the Bureau of Mineral Resources from several intervening localities were also examined.

The type section, as defined by Wells & others (1967), consists of a basal unit of thin-bedded sandstones, siltstones, and dolostones (83 m), overlain by 72 m of thick-bedded to massive yellow-brown dolostone (Fig. 2). Daily (1972) has recorded a fauna of *Pelagiella, Chancelloria, 'Micromitra' etheridgei* Tate, brachiopods, hyoliths, Problematica, and archaeocyaths, indicative of his Early Cambrian Faunal Assemblage No. 2 (Daily, 1956), from the 'thick-bedded unit'. The archaeocyaths are here identified as *Aldanocyathus greeni* Kruse sp. nov., *Coscinocyathus bilateralis* (Taylor), '*Dictyocyathus*' spp., *Aruntacyathus toddi* Kruse gen. et sp. nov., *?Aruntacyathus rossi* Kruse sp. nov., *Beltanacyathus* Bedford & Bedford and the radiocyathan *Radiocyathus minor* (Bedford & Bedford); they are present only in the lowermost 50 m of the 'thick- bedded unit' (Fig. 3). The upper limit of the range of the archaeocyaths is represented by a prominent band of silicified fossiliferous dolostone crowning the scarp on the western side of the gorge. No fossils have been recovered from the 'thin-bedded unit'.

The Todd River Dolomite is overlain with apparent conformity by the Giles Creek Dolomite (Wells & others, 1967). The rich biota recorded from this unit, of hyoliths (including *Biconulites*), brachiopods, gastropods, trilobites (including *Redlichia amadeana* Öpik 1970), and the alga *Girvanella*, is considered to be Ordian (earliest Middle Cambrian) in age (Gilbert-Tomlinson *in* Wells & others, 1967, 1970).

Conformably underlying the Todd River Dolomite is the Arumbera Sandstone (Prichard & Quinlan, 1962), which in its upper parts (informally termed Arumbera II and III) contains trace fossils considered to be Early Cambrian (Gilbert-Tomlinson *in* Wells & others, 1967, 1970; Glaessner, 1969) (Fig. 4). Daily (1972, 1976a-c) has regarded the Arumbera II and III interval (his Box Hole and Allua Formations respectively) as equivalent to a part of the earliest (Tommotian) stage of the Siberian Early Cambrian (Zhuravleva & others, 1969; Banks, 1970; Alpert, 1977).

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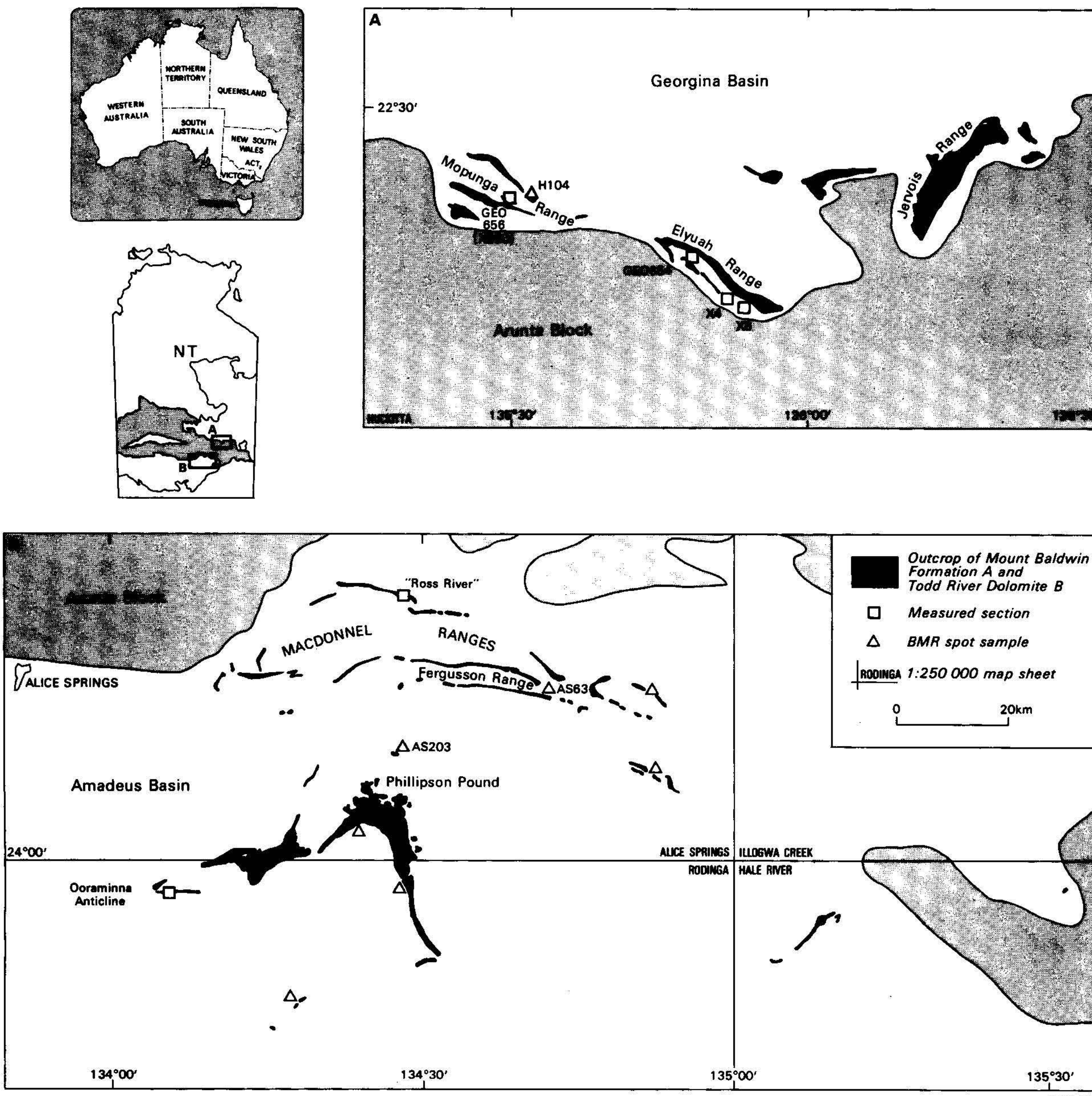

Figure 1. Location map.
Prefixes: AS—BMR spot samples; GEO—measured or remeasured sections of this study; X—section designations of Smith (1964).

In the Ooraminna Anticline section (Fig. 5) the Todd River Dolomite is overlain by the Chandler Limestone, an unfossiliferous sequence of evaporites and grey laminated and contorted limestones tentatively referred to the Early Cambrian by Wells & others (1967, 1970). *Coscinocyathus bilateralis* (Taylor), *'Dictyocyathus'*, and *Aruntacyathus toddi* Kruse gen. et sp. nov. have been identified from lenses of pink dolostone in the uppermost 10-12 m of the section (Fig. 6), in association with elements of Faunal Assemblage No. 2 (Daily, 1972). This more restricted archaeocyathan fauna is also encountered in the Todd River Dolomite of intervening areas between Ross River and the Ooraminna Anticline.

Georgina Basin

Exposure of the archaeocyath-bearing Mount Baldwin Formation is confined to the environs of the Mopunga, Elyuah and Jervois Ranges on the HUCKITTA 1:250 000 Sheet. The type section (X4 of Smith, 1964) is in the Elyuah Range, where the formation is of the order of 300 m thick (Fig. 1). (PWW considers the sandstones above the archaeocyathan horizon in the type section (Smith, 1964, fig. 15) to be a faulted repetition of lower beds of the Mount Baldwin Formation.)

Three broad lithological divisions recognised within the formation are: a basal red-purple siltstone shale unit (90-150 m); a resistant red sandstone unit (140-210 m); an uppermost dolostone unit (60-80 m) capped by a single dolostone archaeocyathan horizon of 1-2 m thickness. This horizon, with its fauna of *Aldanocyathus greeni* Kruse sp. nov., *Coscinocyathus bilateralis* (Taylor), *'Dictyocyathus'*, *Aruntacyathus toddi* Kruse gen. et sp. nov., and *Radiocyathus minor* (Bedford & Bedford) can be traced discontinuously through the Mopunga and Elyuah Ranges. For the present study, the horizon was sampled at four separate localities, altogether some 50 km apart (Fig. 7).

Figure 2. Type section of Todd River Dolomite, western side of Ross River gorge.
Arumbera III ('Allua Formation') at right; vegetated area at centre represents the 'thin-bedded unit' of the Todd River Dolomite; upper part of cliff scarp (above dark stratum) is the 'thick-bedded unit', with Archaeocyatha; Giles Creek Dolomite at left background.

The dolostones of the overlying Arthur Creek Beds (Smith, 1964) in the Mopunga and Elyuah Ranges are sparsely fossiliferous, with only localised occurrences of hyoliths and possibly Ordian trilobites and brachiopods (Casey & Gilbert-Tomlinson, 1956; Smith, 1964). However, equivalent shales, limestones, and sandstones of the Arthur Creek Beds in the Jervois Range have yielded abundant faunas of trilobites, brachiopods and sponge spicules, spanning much of the Middle Cambrian (Smith, 1964, 1972; Gatehouse, 1968; Shergold, 1969; Öpik, 1970).

At present the archaeocyathan horizon, located in a continuous sequence of dolostones, constitutes the boundary between the Mount Baldwin Formation and Arthur Creek Beds in the Mopunga and Elyuah Ranges. Revision of the stratigraphy is necessary in order to bring the nomenclature into conformity with current stratigraphic practice.

Two algal occurrences were recorded from dolostones of the Mount Baldwin Formation below the archaeocyathan horizon in the Mopunga Range by Smith (1964). The stratigraphically higher of these contains the columnar stromatolite *Georginia howchini* Walter (1972) of 'early Cambrian or Vendian age' (Fig. 7). An abundant and diverse trace fossil fauna is also known from sandstones in the middle part of the Mount Baldwin Formation in the northeastern Jervois Range. These traces are of similar aspect to those from Arumbera II and III of the Amadeus Basin (M. R. Walter, pers. comm., 1978).

Systematic palaeontology

Specimens bearing the prefix SUP are deposited in the collection of the Department of Geology and Geophysics, University of Sydney; those bearing the prefixes CPC or F are deposited in the collection of the Bureau of Mineral Resources, Canberra.

The following abbreviations are used in the accompanying tables: *holotype. *Cup*: ø, cup diameter; w, intervallum width; loc, ratio of sides of interseptal loculi in transverse section; SC, Septal Coefficient = number of septa/cup diameter; GPC, General Porosity Coefficient = porosity coefficient for inner wall/porosity coefficient for outer wall. *Walls, septa and tabulae*: n, number of vertical pore rows (per intersept for walls; across intervallum for septa); ø, pore diameter; l, lintels (horizontal distance between adjacent rims of neighbouring pores); ø/l, Porosity Coefficient; t, wall-septum-tabula thickness; r, number of radial pore rows per intersept; p, number of pores per radial row.

Phylum ARCHAEOCYATHA Bornemann, 1884

Class REGULARES Vologdin, 1937

Family AJACICYATHIDAE Bedford & Bedford, 1939

Genus **ALDANOCYATHUS** Voronin *in* Debrenne & Voronin, 1971

Type species: Ajacicyathus sunnaginicus Zhuravleva, 1960; OD Voronin *in* Debrenne & Voronin, 1971.

Diagnosis: Outer and inner walls with simple pores, septa completely porous.

Remarks: Aldanocyathus is a cosmopolitan genus ranging throughout the Tommotian, Atdabanian, and Lenian stages (*sensu* Rozanov, 1973; Rozanov & Debrenne, 1974) of Siberia. The genus is distinguished

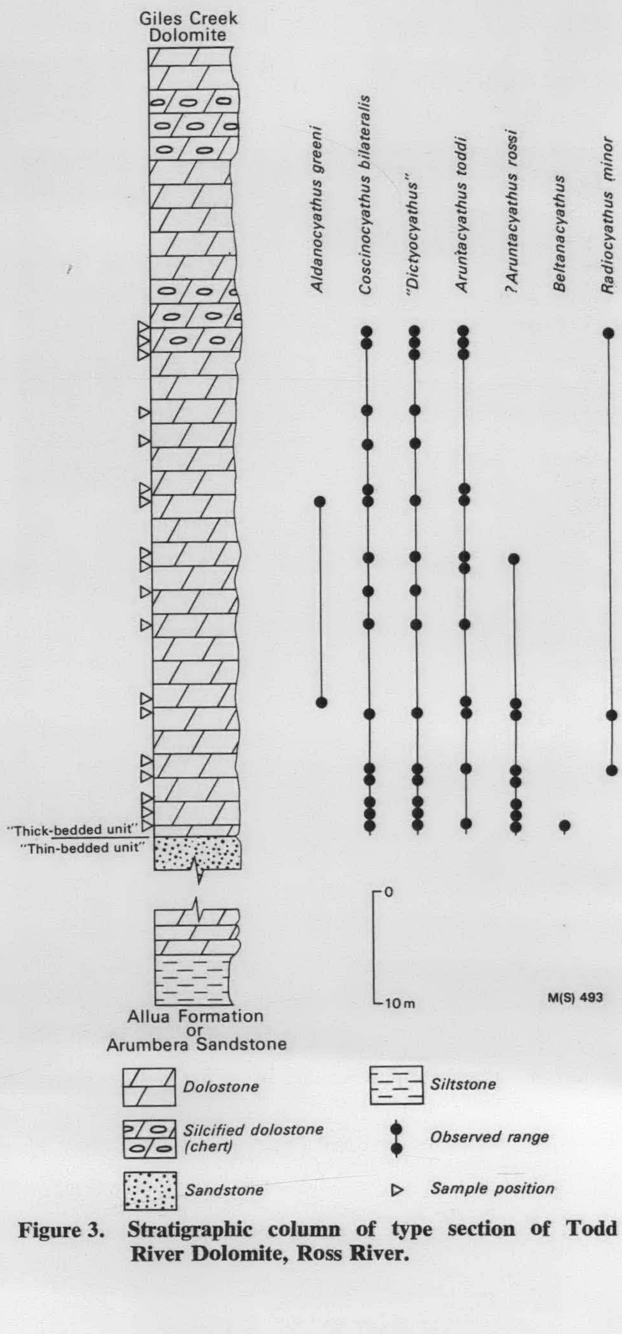

Figure 3. Stratigraphic column of type section of Todd River Dolomite, Ross River.

from *Ajacicyathus* Bedford & Bedford (1939) by the completely porous nature of the septa and by the absence of true stirrup pores.

True stirrup pores are formed by the union of a wall pore with an adjacent septal pore, such that the septal pore constitutes a hemispherical indentation in the septal margin. In genera showing this feature, true stirrup pores are consistently present along the entire length of each septal margin, on either the inner wall, outer wall, or both walls. By contrast, false stirrup pores represent the occasional or sporadic amalgamation of a septal pore with a wall pore. There is no consistent pattern of occurrence. Resultant indentations of the septal margin may be a variety of shapes, as determined by the shape of the component septal pore.

ALDANOCYATHUS GREENI Kruse sp. nov.
Fig. 8A-F

Name: After Mr Gil Green, co-manager of Ross River tourist camp.

Material: 10 specimens: holotype CPC18354, paratypes SUP86201-86203, CPC18684, additional material F24097-24098, 24120-24122. Ross River, Phillipson Pound (AS203), Mopunga Range (GEO656), Elyuah Range (GEO654).

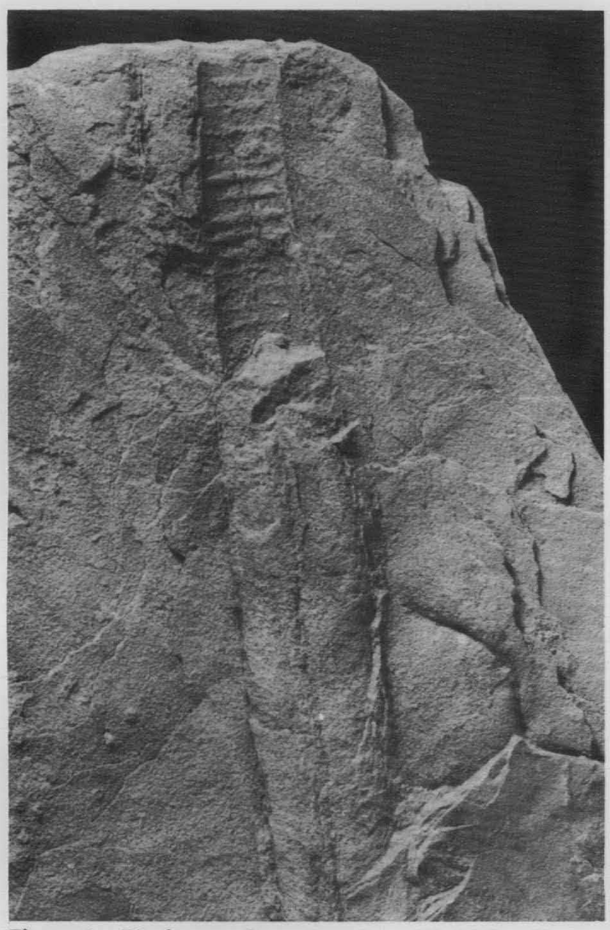

Figure 4. Plagiogmus from Arumbera III ('Allua Formation'), Ross River.
The upper surface (lower half of photo) is comparable to specimens figured by Glaessner (1969, fig. 9C) as 'molluscan trails'. These forms must now be included in *Plagiogmus*. Glaessner's reconstruction of *Plagiogmus* (p. 387, fig. 8) requires modification to allow for a median longitudinal groove on the upper surface.

Diagnosis: Septa with 6-8 pore rows, pores in centre of intervallum being somewhat larger. False stirrup pores present on both walls.

Description: Cup conical, diameter up to 11.1 mm, with intervallum 1.8 mm in width. Outer wall with 2-3 rows of simple rounded pores per intersept (diameter 0.10

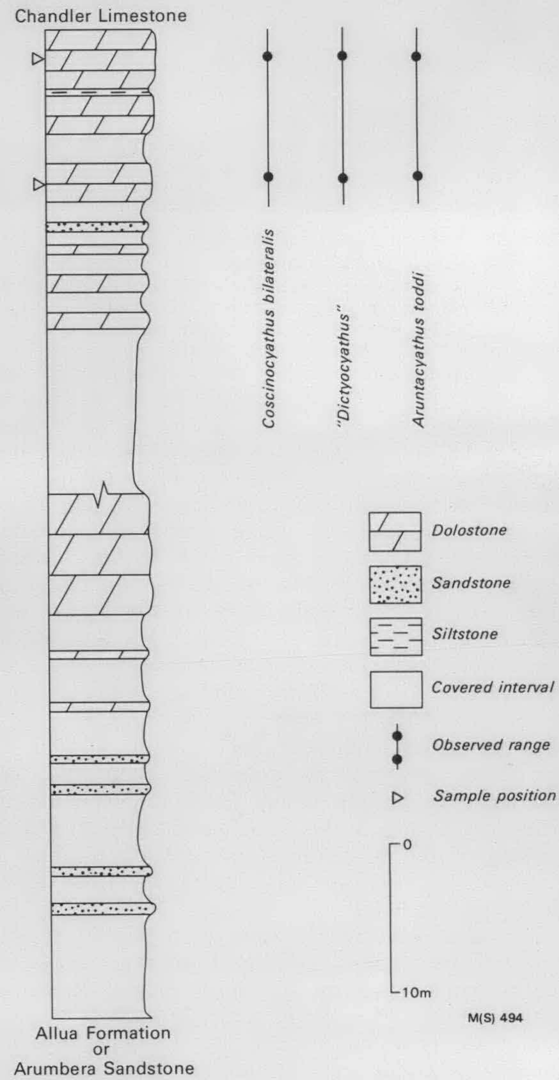

Figure 5. Stratigraphic column of section of Todd River Dolomite, southern limb of Ooraminna Anticline.

Figure 6. Archaeocyath-bearing dolostone lens in uppermost Todd River Dolomite, southern limb of Ooraminna Anticline.
Lens about 1 metre in size.

mm, lintels 0.09 mm, wall thickness 0.1 mm), and rare false stirrup pores. Inner wall with 2-3 rows of simple, rounded pores per intersept (diameter 0.11 mm, lintels 0.07 mm, wall thickness 0.1 mm); false stirrup pores common. Septa with 6-8 rows of rounded to elliptical or ovoid pores (diameter 0.12 mm, lintels 0.11 mm). Septal pores in centre of intervallum may be larger and more elongate (up to 0.18 mm diameter) than those nearer the walls. False stirrup pores are formed where a septal pore row converges with either wall; this takes place more commonly at the inner wall (Fig. 8C). Septal coefficient 6.3-7.4. Ratio of sides of interseptal loculi 1/3.8-1/5.0.

Remarks: A. grandiporus (Taylor, 1910) from the Ajax Limestone of the Ajax Mine, South Australia shows comparable variation in septal porosity, but lacks the false stirrup pores of *A. greeni*. As well, septa are more widely spaced in *A. grandiporus*. No other Australian species of *Aldanocyathus* is known.

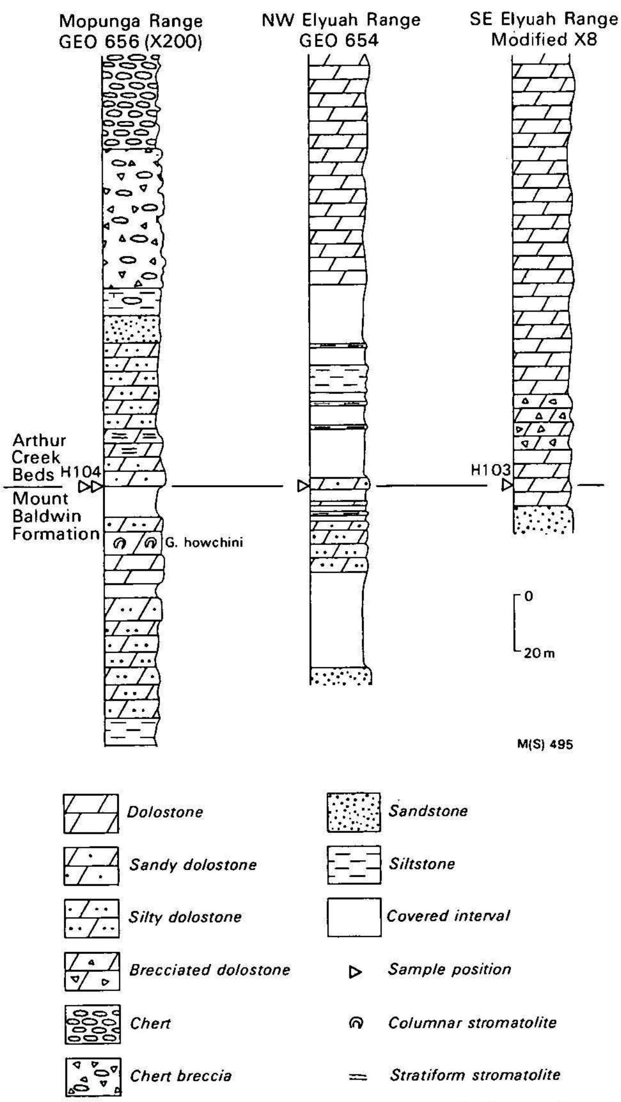

Figure 7. Stratigraphic columns of upper (dolostone) portion of Mount Baldwin Formation and lower portion of Arthur Creek Beds.
Sections measured or remeasured in this study are prefixed GEO; X and H refer to sections and localities respectively of Smith (1964). Archaeocyathan horizon is used as a datum and is not necessarily considered to be isochronous.

	* *CPC 18354*	*SUP 86203*	*SUP 86201*	*CPC 18684*	*SUP 86202*
ϕ	7.6	11.1	10.9	9.7	8.2
w	1.3	1.7	1.5	1.8	1.6
loc	1/4.2	1/3.8	1/4.1	1/4.6	1/5.0
SC	7.4	6.6	6.3	6.6	7.4
GPC	1.4	1.1	1.8	1.0	1.6
Outer wall:					
n	2(3)	2–3	2(3)	2–3	~2
ϕ	0.09	0.11	0.10	0.10	0.12
l	0.10	0.07	0.09	0.08	0.10
ϕ/l	0.9	1.6	1.1	1.3	1.2
t	0.1	0.1	0.1	0.1	0.1
Inner wall:					
n	2	2–3	2(3)	2–3	2
ϕ	0.12	0.09	0.10	0.10	0.13
l	0.09	0.05	0.05	0.08	0.07
ϕ/l	1.3	1.8	2.0	1.3	1.9
t	0.1	0.1	0.1	0.1	0.1
Septa:					
n	6	7	6–8	6–8	~6
ϕ	0.12	0.14	0.10	0.12	0.10
l	0.09	0.10	0.12	0.09	0.13
ϕ/l	1.3	1.4	0.8	1.3	0.8
t	0.07	0.07	0.07	0.07	0.09

Family Coscinocyathidae Taylor, 1910

Genus **COSCINOCYATHUS** Bornemann, 1884

Type species: Coscinocyathus dianthus Bornemann, 1884; ICZN plenary powers; ICZN, 1974; Debrenne, 1970a.

Diagnosis: Outer and inner walls with simple pores, septa and tabulae completely porous.

Remarks: Coscinocyathus is a common genus of the upper Tommotian, Atdabanian, and Lenian stages (*sensu* Rozanov, 1973; Rozanov & Debrenne, 1974) of Siberia.

COSCINOCYATHUS BILATERALIS (Taylor)
Figs. 8G-J, 9A-B

v*1910 *Coscinoptycha bilateralis* Taylor, p. 142, pl. 2, fig. 6, pl. 6, fig. 32, pl. 11, figs. 61-63, text-fig. 6.

1937 *Coscinocyathus fultus* Gordon; Ting, pl. 11, fig. 1.

1960 *Coscinoptycta bilateralis* (Taylor); Debrenne & Debrenne, p. 699, pl. 19, figs. 10-13, pl. 20, fig. 6.

non1964 *Coscinoptycta bilateralis* (Taylor); Hill, p. 614, fig. 2(14-18).

1979 *'Coscinoptycta' bilateralis* Taylor; Walter & others, p. 308.

Lectotype chosen herein: South Australian Museum T1550 Z-23, Early Cambrian, Ajax Limestone, Ajax Mine area, South Australia.

Material: 124 specimens: SUP86204-86288; CPC18355; F24097-24103, 24123-24153. Ross River, Fergusson Range (AS63), Phillipson Pound (AS203), Ooraminna Anticline, Mopunga Range (GEO656), Elyuah Range (GEO654, X8).

Diagnosis: Intervallum narrow, rarely exceeding 1.1 mm in width. Septa with 3-5 widely spaced pore rows. Tabulae widely spaced.

Description: Cup conical until early maturity, becoming irregular in very large cups (Fig. 9A); cup diameter up to 12.9 mm, with intervallum width constant at 0.8-1.1 mm. Outer wall with 2-4 rows of simple, rounded pores per intersept (diameter 0.13 mm, lintels 0.09 mm, wall thickness 0.1 mm). Inner wall with 2-3 rows of simple, rounded pores per intersept (diameter 0.13 mm, lintels 0.08 mm, wall thickness 0.1 mm). Septa with 3-5

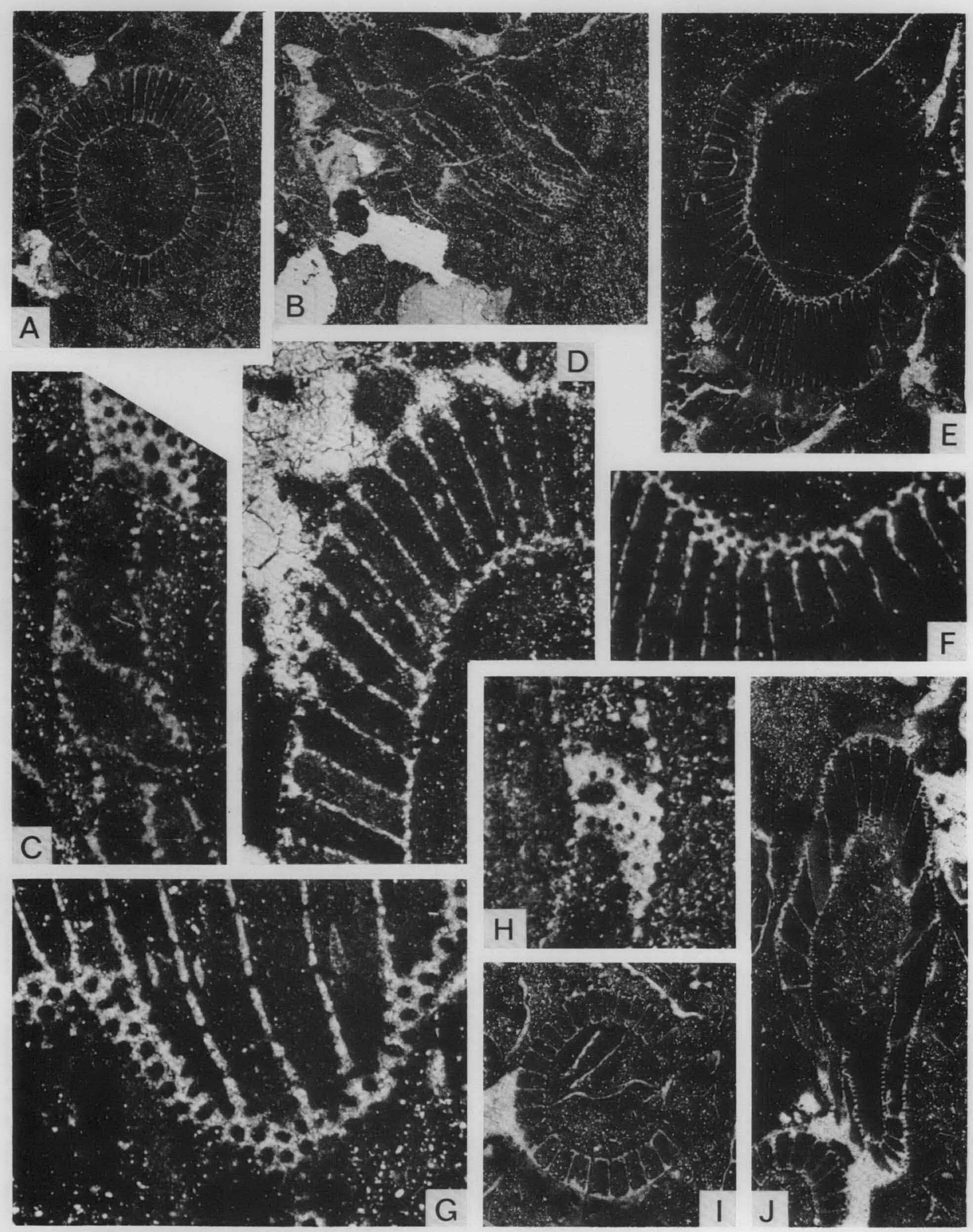

Figure 8. Aldanocyathus greeni Kruse sp. nov.
A-C. Holotype CPC 18354. A. Transverse section X4. B. Longitudinal section X4. C. Detail of longitudinal section showing septal porosity X12. D. Paratype SUP 86203, detail of transverse section showing false stirrup pores on outer wall X12. E-F Paratype SUP 86201. E. Transverse section X4. F. Detail of transverse section showing false stirrup pores on inner wall X12.
Coscinocyathus bilateralis (Taylor).
G. Specimen SUP 86225, detail of longitudinal section showing outer wall X12. H. Specimen CPC 18355, detail of longitudinal section showing septal porosity X12. I-J. Specimen SUP 86220. I. Transverse section X4. J. Longitudinal section X4.

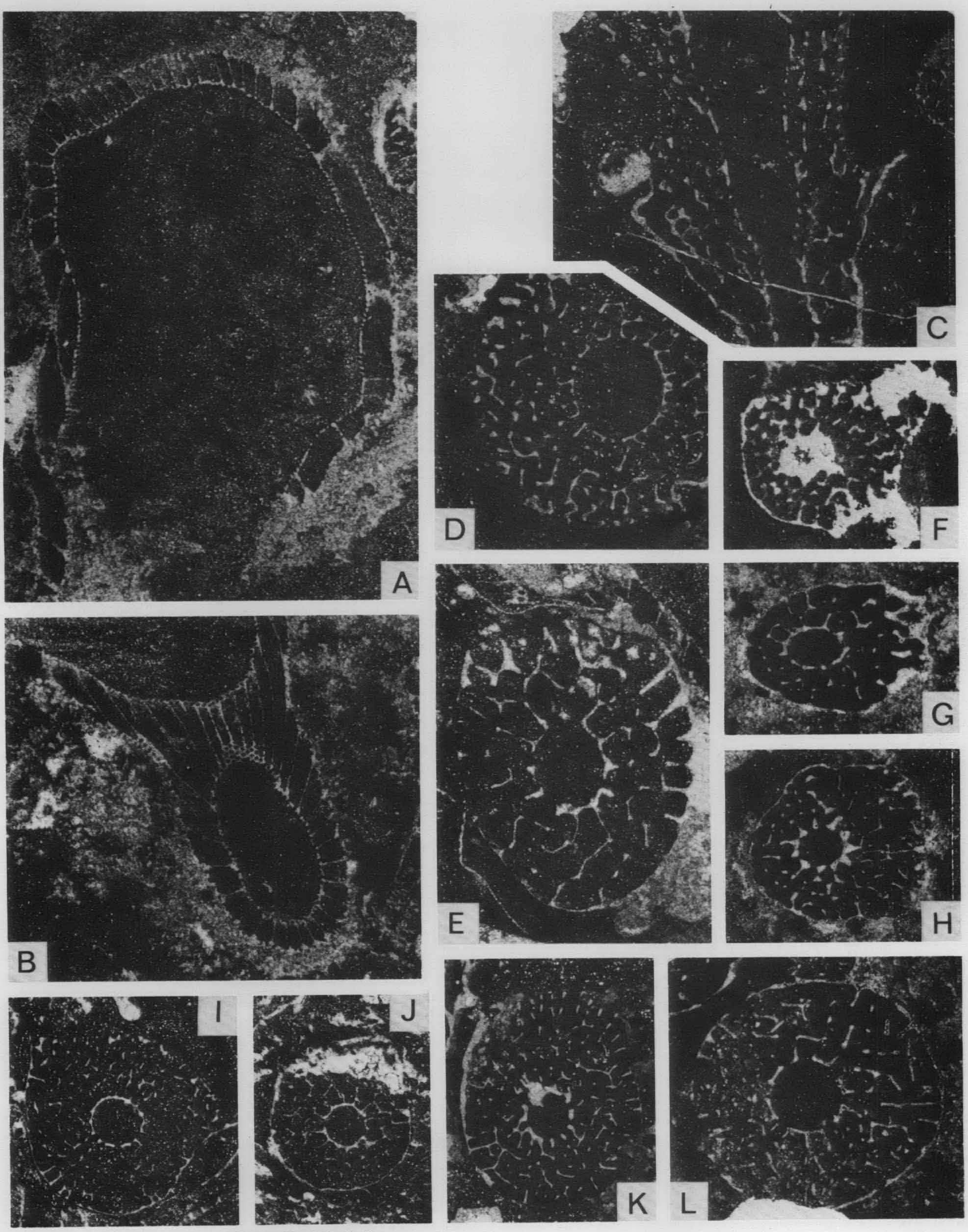

Figure 9. Coscinocyathus bilateralis (Taylor).
A-B. Specimen SUP 86274. A. Transverse section X4. B. Longitudinal section X4.
'Dictyocyathus'.
C-D specimen SUP 86291. C. Longitudinal section X4. D. Transverse section X4. E. Specimen SUP 87156, transverse section X4. F. Specimen SUP 87177, transverse section X4. G. Specimen SUP 87176, transverse section X4. H. Specimen SUP 87152, transverse section X4. I. Specimen SUP 87170, transverse section X4. J. Specimen SUP 87158, transverse section X4. K. Specimen SUP 87180, transverse section X4. L. Specimen SUP 87174, transverse section X4.

widely spaced rows of rounded pores (diameter 0.09 mm, lintels 0.11 mm); pores also form slightly arched horizontal files. Septal coefficient 3.7-6.3. Ratio of sides of interseptal loculi 1/1.4-1/2.2. Tabulae flat, widely and irregularly spaced in mature cups, with 3-5 radial rows of 5-7 pores each per loculus (diameter 0.10 mm, lintels 0.05 mm).

Remarks: Taylor's (1910) original description of *C. bilateralis* was based on fragments of large cups from the Ajax Mine, South Australia. The present collection illustrates the intervening growth stages between these ribbon-like forms and the small conical cups of this species figured by Ting (1937) as *C. fultus* Gordon.

Although *Coscinocyathus* is a genus of widespread occurrence, the two species of Taylor, *C. bilateralis* and *C. australis*, are distinctive in the wide spacing of their septal pore rows and in their remotely spaced tabulae. *C. australis* has a wider intervallum (up to 3.5 mm) than *C. bilateralis*.

	SUP 86274	*CPC 18355*	*SUP 86264*	*SUP 86288*	*SUP 86220*	*SUP 86287*
ϕ	12.9	10.0	8.1	7.9	7.6	7.0
w	1.0	1.1	0.8	1.0	1.1	1.0
loc	1/2.2	1/1.7	1/1.5	1/1.6	1/1.8	1/1.4
SC	3.9	4.0	6.3	3.7	3.9	4.3
GPC	0.8	1.2	1.2	1.1	1.1	0.8
Outer wall:						
n	2	3–4	2–3	3–4	2–4	4
ϕ	0.14	0.11	0.11	0.14	0.15	0.13
l	0.08	0.10	0.08	0.08	0.08	0.09
ϕ/l	1.8	1.1	1.4	1.8	1.9	1.4
t	0.12	0.1	0.1	0.1	0.09	0.11
Inner wall:						
n	2	2–3	2	2–3	2–3	2–3
ϕ	0.12	0.12	0.12	0.16	0.15	0.11
l	0.08	0.09	0.07	0.08	0.07	0.10
ϕ/l	1.5	1.3	1.7	2.0	2.1	1.1
t	0.10	0.1	0.1	0.1	0.10	0.10
Septa:						
n	5	4–5	4–5	4	3–5	4–5
ϕ	0.08	0.09	0.09	0.09	0.09	0.10
l	0.11	0.12	0.10	0.10	0.10	0.12
ϕ/l	0.7	0.8	0.9	0.9	0.9	0.8
t	0.05	0.05	0.06	0.04	0.05	0.04
Tabulae:						
r		4		3–5	3–4	
p	5–6	~6	5–7	~7	~7	~7
ϕ	0.11	0.10		0.11	0.09	0.09
l		0.05		0.06	0.05	0.05
ϕ/l		2.0		1.8	1.8	1.8
t	0.09	0.05	0.1	0.1	0.09	0.04

Class IRREGULARES Vologdin, 1937

Family DICTYOCYATHIDAE Taylor, 1910

Genus **'DICTYOCYATHUS'** Bornemann, 1891

Type species: Dictyocyathus tenerrimus Bornemann, 1891; M.

Diagnosis: Both walls 'simple' in mature stages, with one pore per 'intersept'; walls formed largely by elements of the intervallum; intervallum composed of radial, vertical and tangential rods forming an orthogonal framework.

Remarks: Bornemann's conception of the genus *Dictyocyathus* is insufficiently known—the original specimens were poorly figured and described, and the type material is no longer extant. The diagnosis given above corresponds to that in current usage (Debrenne, 1974).

'DICTYOCYATHUS' spp.

Fig. 9C-L

Material: 73 specimens: SUP86215, 86220, 86222, 86254, 86262-86263, 86289-86299, 87150-87180; F24099, 24104-24108, 24138, 24149, 24165, 24180, 24184, 24194-24207. Ross River, Fergusson Range (AS63), Phillipson Pound (AS203), Ooraminna Anticline, Mopunga Range (GEO656), Elyuah Range (GEO654, X8).

Description: Cup narrowly conical, diameter up to 12.5 mm, with intervallum 4.2 mm in width. Outer wall aporose in juvenile stages, becoming 'simple' when cup diameter reaches 6-11 mm. Outer wall is contracted inward at this point (Fig. 9C). Pores of both walls bounded by adjacent rods of the intervallar framework; inner wall pores are well defined, and elliptical in outline (diameter 0.3-0.7 mm, wall thickness 0.1-0.2 mm), and form vertical rows, one per 'intersept'. Intervallum composed of an orthogonal framework of rods (thickness 0.07-0.13 mm) ranging in length from 0.2 to 0.85 mm. Radial and vertical rods may give the appearance of constituting 'pseudosepta', with 'pores' defined by adjacent rods. These 'pores' are subquadrate in outline, arranged in near-vertical rows inclined steeply upward toward the outer wall.

Remarks: The Australian forms assigned to *'Dictyocyathus'*, including *'D.' irregularis* Taylor (1910) and *'D.' quadruplex* Bedford & Bedford (1936), have an aporose outer wall in the juvenile stage. An examination of *'Dictyocyathus'*-like forms in the collection of D. Gravestock (University of Adelaide) has established that such forms are the young stages of irregular archaeocyathan cups.

	SUP 87180		*SUP 87179*	*SUP 87156*	*SUP 87174*	*SUP 87158*
ϕ	12.5	7.4	10.5	9.4	8.7	6.1
w	4.2	2.6	3.9	3.0	2.8	2.2
rod length	0.59	0.45	0.58	0.85	0.61	0.54
rod t	0.10	0.09	0.11	0.11	0.10	0.07
Outer wall:						
ϕ	0.6					
t	0.2	0.05–0.2	0.05–0.1	0.05–0.15	0.1–0.2	0.1
Inner wall:						
ϕ	0.5	0.3	0.3	0.7	0.5	0.4
t	0.2	0.15–0.2	0.1–0.2	0.1	0.1	0.1

Family METACYATHIDAE Bedford & Bedford, 1934

Genus **ARUNTACYATHUS** Kruse gen. nov.

Name: After the Arunta aboriginal people.

Type species: A. toddi Kruse sp. nov.

Diagnosis: Outer and inner walls simple, becoming sheathed in very mature stages of ontogeny; rod-like buttresses ('arcs-boutants' of Debrenne, 1974) connect septal margins with both walls; septa completely porous; synapticulae present.

Remarks: Outer wall buttresses are also known in the genus *Spirillicyathus* Bedford & Bedford (1937). The inner wall of *Spirillicyathus* differs from that of *Aruntacyathus* in being simple throughout ontogeny, with one pore, or rarely two pores, per intersept.

ARUNTACYATHUS TODDI Kruse sp. nov.

Figs. 10, 11

1979 new genus of Metacyathidae; Walter & others, p. 308.

Name: After Sir Charles Todd (1826-1910) and the Todd River Dolomite.

Material: 134 specimens: holotype CPC18356; paratypes SUP87202, 87205, 87228, 87233, CPC18357; additional material SUP86279, 87173, 87181-87256, F24099, 24106, 24109-24119, 24124, 24154-24193.

Ross River, Fergusson Range (AS63), Phillipson Pound (AS203), Ooraminna Anticline, Mopunga Range (GEO656), Elyuah Range (GEO654, X8).

Diagnosis: Septal pores large, rounded. Buttresses subtend medium to high angle to wall. Synapticulae occur in clusters.

Description: Cup conical, bifurcating to become 'colonial' in maturity; cup diameter up to 20 mm, with intervallum up to 3.7 mm in width. Outer wall with 2-5 irregular rows of rounded to irregular pores per intersept (diameter 0.18 mm, lintels 0.11 mm, wall thickness 0.2 mm). Rod-like buttresses unite septal margins to the outer wall: in young cups buttresses of adjacent septa mutually intersect the wall at a mid-interseptal position, so delineating a pair of wall pores in each intersept. Additional pores or pore rows appear with maturity. In mature specimens, particularly on the inner wall, there is a tendency for adjacent buttresses to coalesce at a point slightly behind the wall, with a common rod attaching normally to the wall (Fig. 11A). Buttresses subtend moderate to high angle to wall, and are spaced about a half to two millimetres apart longitudinally. In cups of diameter above about 15 mm, the outer wall becomes sheathed; sheath consists of a proliferation of fine lintels forming 2-6 irregularly shaped micropores per framework pore (diameter 0.07-0.15 mm, lintels 0.07 mm). Inner wall with 2-5 irregular rows of rounded to irregular pores per intersept (diameter 0.19 mm, lintels 0.10 mm, wall thickness 0.2 mm). Buttresses of similar arrangement to those on the outer wall unite septal margins with the inner wall. Inner wall becomes sheathed almost simultaneously with the outer wall, with an equivalent arrangement of micropores. Septa straight, with 5-9 near-vertical rows of rounded to ovoid pores (diameter 0.26 mm, lintels 0.20 mm); pore size variable, ranging from 0.2 up to 0.5 mm. There are false stirrup pores at junctions with both walls. Septal coefficient 2.2-3.2. Ratio of sides of interseptal loculi 1/2.4-1/4.0. Synapticulae rare, but when present tend to be clustered (Fig. 10A).

Remarks: Buttresses are present in all observed stages of ontogeny (from cup diameter about 8 mm). Younger ontogenetic stages were not identified due to poor preservation.

	**CPC 18356*	*SUP 87228*	*SUP 87233*	*SUP 87205*	*SUP 87202*	*CPC 18357*
φ	15	20	19.4	13.8	12.5	9.6
w	2.0	3.3	2.7	3.1	3.7	2.4
loc	1/2.9	1/3.3	1/4.0	1/2.8	1/4.0	1/2.4
SC	3.0	2.2	3.2	2.2	2.2	2.3
GPC	1.1	1.3	0.9	1.2	0.9	1.3
Outer wall:						
n	2–4	3–5	3–4	3–4	3–4	2–4
φ	0.19	0.17	0.21	0.19	0.19	0.14
l	0.09	0.11	0.09	0.13	0.12	0.11
φ/l	2.1	1.5	2.3	1.5	1.6	1.3
t	0.2	0.2	0.2	0.2	0.2	0.2
Inner wall:						
n	3–5	3–4	2–4	2–3	2–3	2–3
φ	0.17	0.18	0.18	0.20	0.18	0.20
l	0.07	0.09	0.09	0.11	0.13	0.12
φ/l	2.4	2.0	2.0	1.8	1.4	1.7
t	0.2	0.2	0.1	0.2	0.2	0.2
Septa:						
n	6–7	6–8	7–9	~7	~8	5–6
φ	0.25	0.29	0.21	0.30	0.29	0.24
l	0.17	0.23	0.19	0.23	0.17	0.20
φ/l	1.5	1.3	1.1	1.3	1.7	1.2
t	0.09	0.11	0.08	0.10	0.10	0.11

?ARUNTACYATHUS ROSSI Kruse sp. nov.

Figs. 12, 13A-B

Name: After Mr John Ross (1817-1903) and Ross River.

Material: 54 specimens: holotype SUP87257, paratypes SUP87281, 87289, 87299, 88151, 88153, additional material SUP86221, 86292, 87189, 87258-87298, 88150-88157. Ross River.

Diagnosis: Septal pores large, rounded to elliptical, ovoid or irregular. Buttresses subtend low angle to wall. Synapticulae spaced evenly across intervallum.

Description: Cup conical, diameter up to 16.6 mm, with intervallum 3.1 mm in width. Outer wall with 2-4 irregular rows of rounded to irregular pores per intersept (diameter 0.15 mm, lintels 0.12 mm, wall thickness 0.1 mm). Rod-like buttresses unite septal margins with the outer wall: in young cups buttresses of adjacent septa mutually intersect the wall at a mid-interseptal position, so delineating a pair of wall pores in each intersept. Additional pores or pore rows appear with maturity. Buttresses subtend low angle to wall. Inner wall with 2-4 irregular rows of rounded to irregular pores per intersept (diameter 0.15 mm, lintels 0.11 mm, wall thickness 0.1 mm). Buttresses of similar arrangement to those on the outer wall unite septal margins with the inner wall. Septa straight or wavy, closely spaced, with 5-8 rows (?) of rounded to elliptical, ovoid or irregular pores per intersept (diameter 0.30 mm, lintels 0.15 mm); pore size variable, ranging from 0.2 up to 0.5 mm. There are false stirrup pores at junctions with both walls. Septal coefficient 2.9-5.5. Ratio of sides of interseptal loculi 1/3.5-1/5.3. Synapticulae abundant throughout ontogeny, and generally spaced evenly across intervallum.

Remarks: The species is only doubtfully included in the genus *Aruntacyathus*, as very mature specimens, in which a sheath might be expected to be present, are not available for study. The type species *A. toddi* can be distinguished from *?A. rossi* by the rounded shape of septal pores, the more prominent development of buttresses, and the occurrence of synapticulae in clusters.

	**SUP 87257*	*SUP 87281*	*SUP 88153*	*SUP 87289*	*SUP 88151*	*SUP 87299*
φ	13.1	16.6	11.3	10.8	10.4	8.9
w	2.5	3.1	2.8	2.5	2.4	2.8
loc	1/3.6	1/4.8	1/3.6	1/3.5	1/4.1	1/5.3
SC	3.4	4.2	2.9	3.3	5.5	3.9
GPC	1.4	1.2	0.9	1.2	1.3	0.9–1.2
Outer wall:						
n	2–3	2–3	2–3	2–3	2–3	2
φ	0.15	0.17	0.15	0.14	0.12	0.14
l	0.11	0.13	0.11	0.13	0.11	0.1
φ/l	1.4	1.3	1.4	1.1	1.1	1.0–1.4
t	0.1	0.1	0.1	0.1	0.1	0.10
Inner wall:						
n	2	2–3	2–3	2–3	2–3	2
φ	0.17	0.18	0.12	0.15	0.11	0.16
l	0.09	0.11	0.10	0.12	0.08	0.13
φ/l	1.9	1.6	1.2	1.3	1.4	1.2
t	0.10	0.1	0.1	0.1	0.1	0.1
Septa:						
n	~6	5–8	5–6	6–7	5–6	5–7
φ	0.29	0.29	0.34	0.28	0.28	0.31
l	0.15	0.15	0.15	0.12	0.14	0.18
φ/l	1.9	1.9	2.3	2.3	2.0	1.7
t	0.07	0.10	0.10	0.09	0.08	0.10

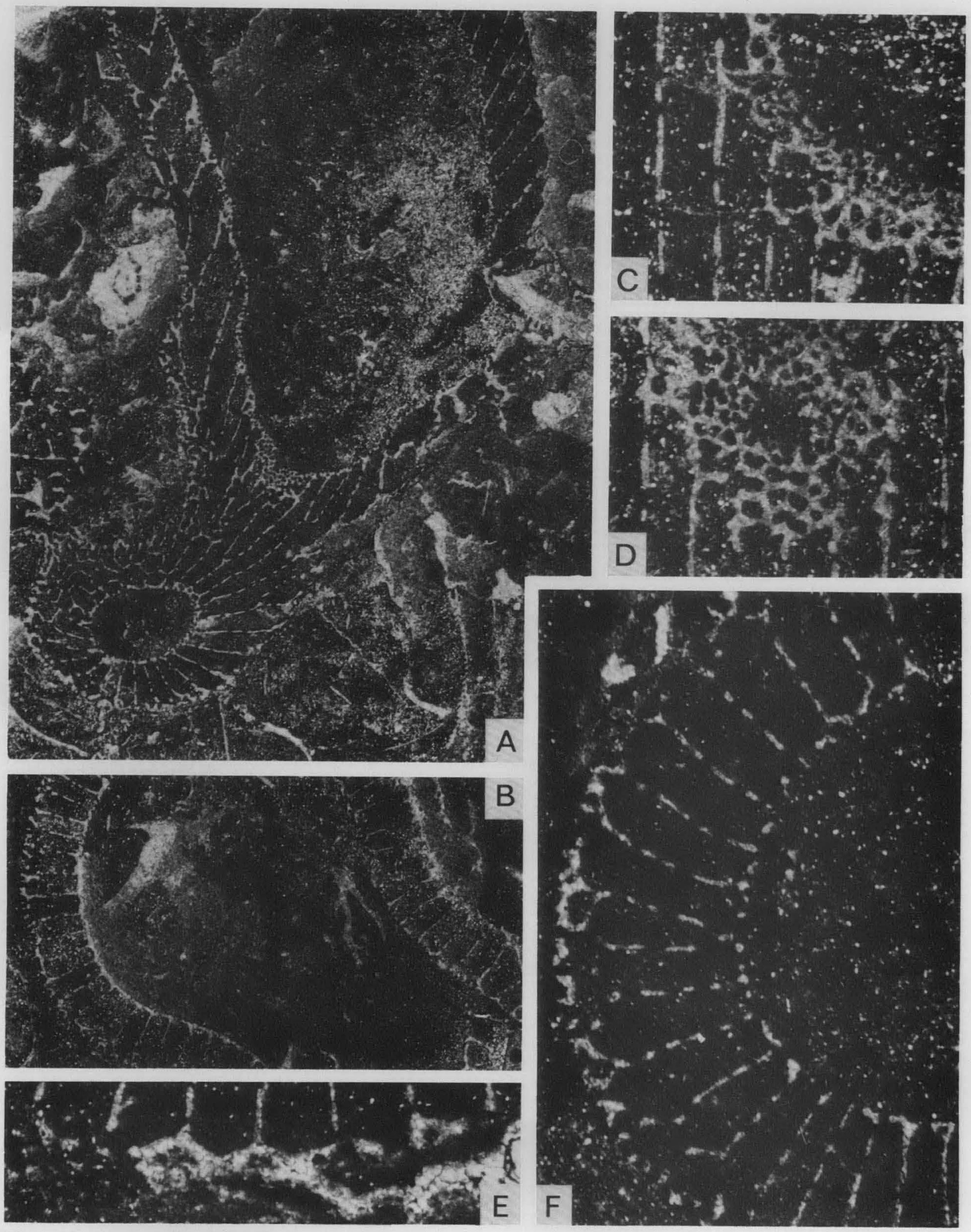

Figure 10. Aruntacyathus toddi Kruse gen. et sp. nov.
A-C. Holotype CPC 18356. A. Longitudinal section showing cluster of synapticulae at lower left X4. B. Transverse section showing bifurcating habit X4. C. Detail of inner wall in longitudinal section showing microporous sheath X12. D-E. Paratype SUP 87233. D. Detail of inner wall in longitudinal section showing microporous sheath X12. E. Detail of outer wall in transverse section showing buttresses X12. F. Specimen SUP 87244, detail of transverse section showing outer and inner wall buttresses X12.

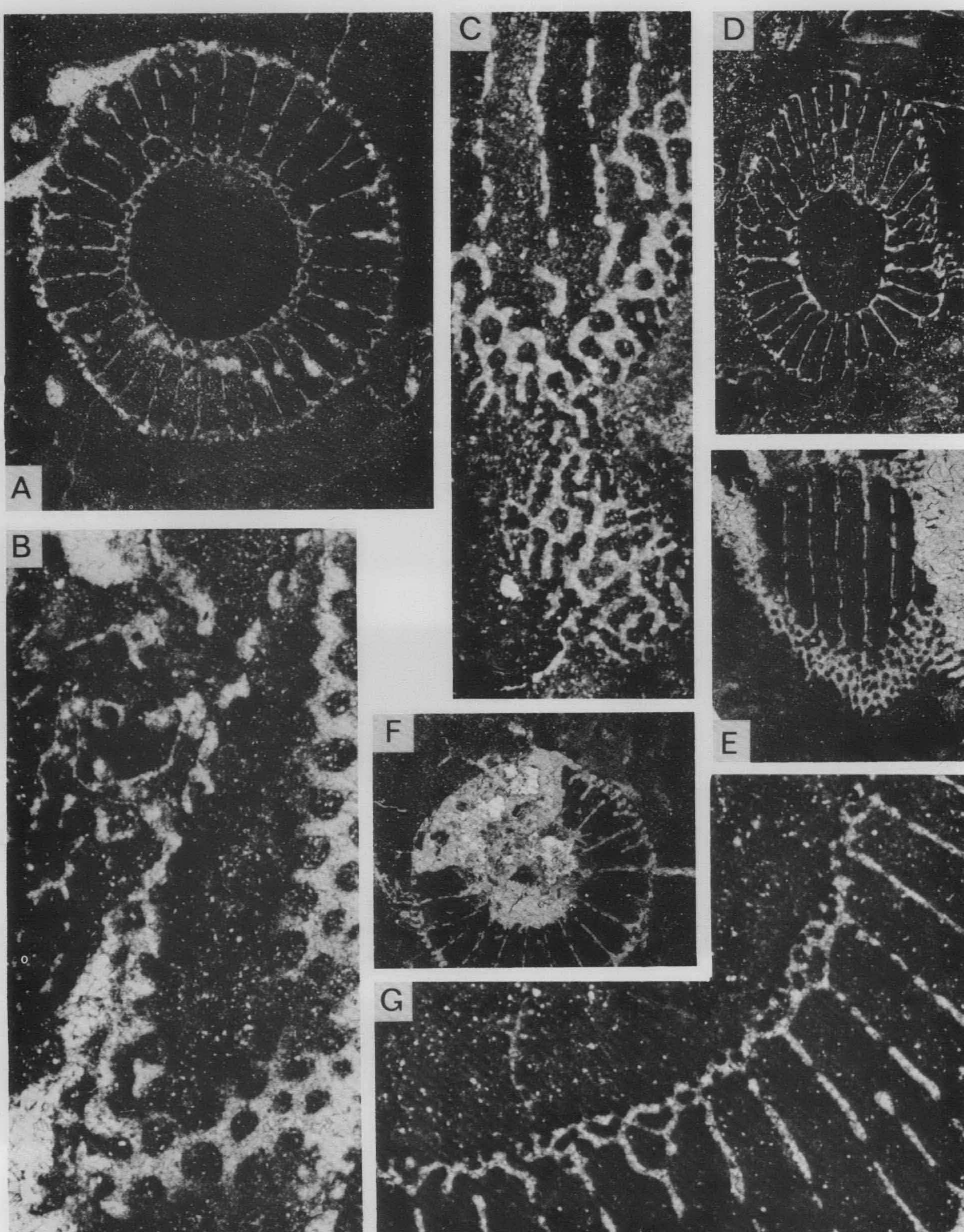

Figure 11. Aruntacyathus toddi Kruse gen. et sp. nov.
A. Paratype SUP 87205, transverse section X4. B. Specimen SUP 87225, detail of longitudinal section showing septal porosity X12. C. Holotype CPC 18356, detail of outer wall in longitudinal section showing microporous sheath X12. D. Specimen SUP 87237, transverse section X4. E. Specimen SUP 87227, longitudinal section showing outer wall prior to formation of microporous sheath X4. F. Paratype CPC 18357, transverse section X4. G. Specimen SUP 87244, detail of inner wall in transverse section showing buttresses X12.

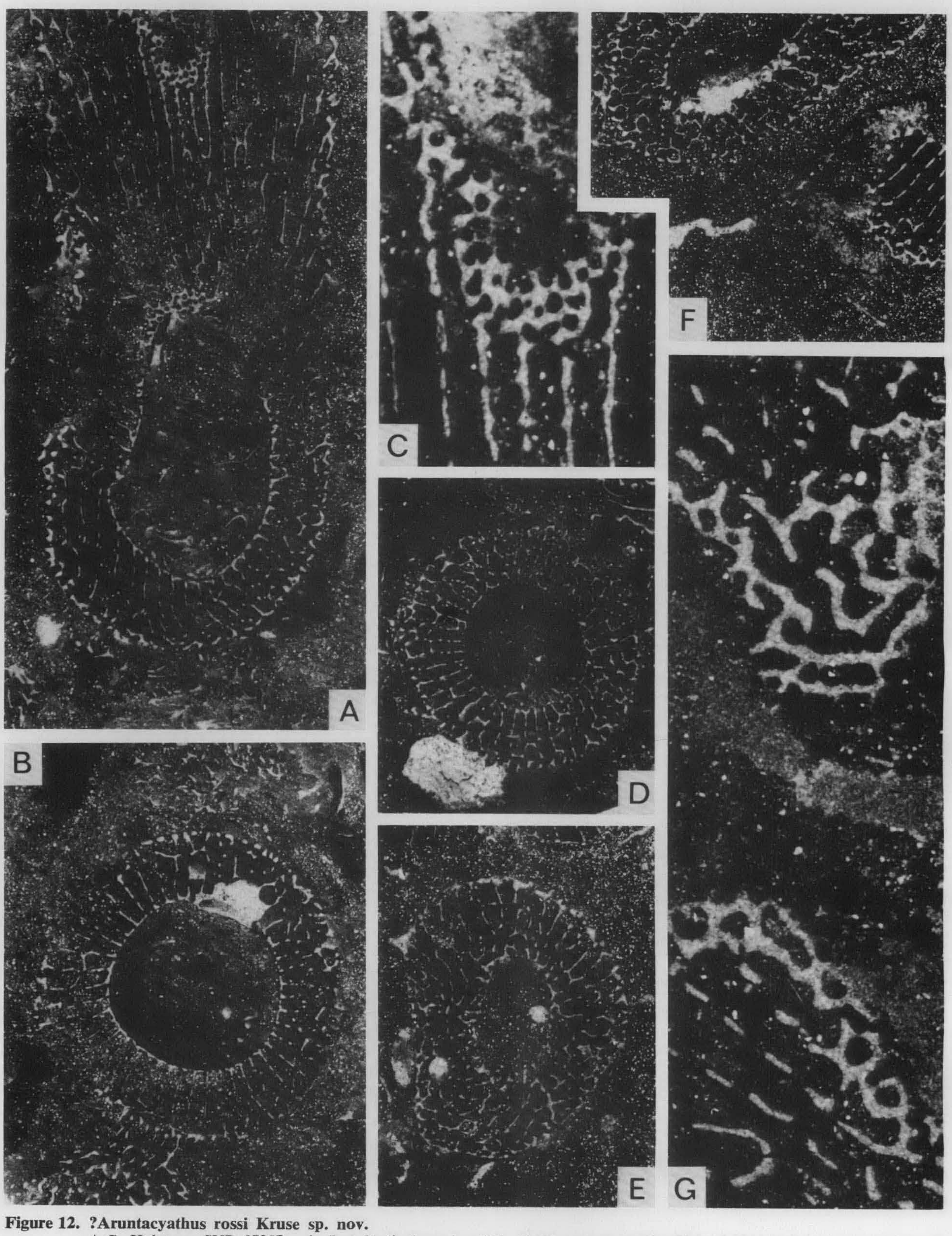

Figure 12. ?Aruntacyathus rossi Kruse sp. nov.
A-C. Holotype SUP 87257. A. Longitudinal section X4. B. Transverse section X4. C. Detail of inner wall in longitudinal section X12. D. Specimen SUP 87287, transverse section X4. E-F. Paratype SUP 87299. E. Oblique transverse section X4. F. Longitudinal section X4. G. Holotype SUP 87257, detail of outer wall in longitudinal section X12.

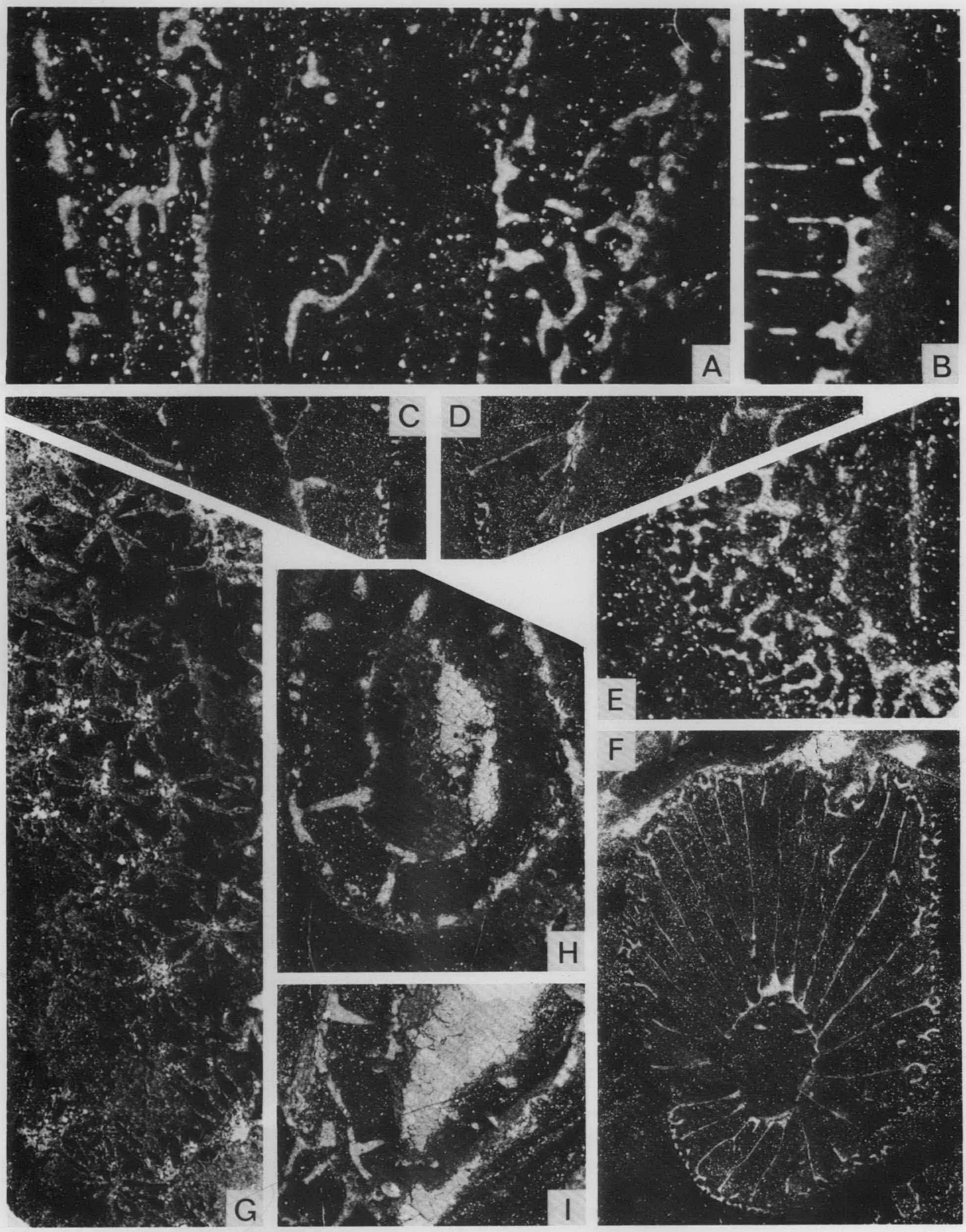

Figure 13. ?Aruntacyathus rossi Kruse sp. nov.
A. Paratype SUP 87289, detail of longitudinal section showing septal porosity X12. B. Holotype SUP 87257, detail of outer wall in transverse section showing buttresses X12.
Beltanacyathus sp.
C-F. Specimen SUP 88158. C. Longitudinal section showing septal porosity X4. D. Longitudinal section showing inner wall pore tubes X4. E. Detail of outer wall in longitudinal section showing microporous sheath X12. F. Transverse section X4.
Radiocyathus minor (Bedford & Bedford).
G. Specimen CPC 18685, detail of outer wall in longitudinal section showing asters X12. H-I. Specimen SUP 88159. H. Transverse section X4. I. Longitudinal section X4.

Family Beltanacyathidae Debrenne, 1970b

Genus **BELTANACYATHUS** Bedford & Bedford, 1936

Type species: Archaeocyathus wirrialpensis Taylor, 1910; SD Debrenne, 1974.

Diagnosis: Outer wall of pore canals protected by a microporous sheath; inner wall with one pore tube per intersept, opening upward into central cavity; intervallum with two types of septa: straight, radial, porous septa linking both walls, and short, incomplete 'quarter-septa' arising from the outer wall.

Remarks: B. ionicus Bedford & Bedford (1936) was originally proposed as type species of *Beltanacyathus*. Debrenne (1974) designated *A. wirrialpensis* as type when *ionicus* was found to be a junior synonym of that species.

BELTANACYATHUS sp.

Fig. 13C-F

Material: 1 specimen: SUP88158. Ross River.

Diagnosis: Septa with large, remotely spaced pores. Inner wall pore tubes steeply inclined upward into central cavity.

Description: Cup conical, diameter 11.9 mm, with intervallum 3.4 mm in width. Outer wall with 2-4 rows of rounded to elliptical pore canals per intersept (diameter 0.40 mm, lintels 0.14 mm, wall thickness 0.3 mm); pore canals angled slightly upward and outward. There are occasional false stirrup pore canals. Pore canals protected by a flat microporous sheath, consisting of 3-5 rounded to irregular micropores (diameter 0.14 mm, lintels 0.07 mm). Inner wall with 1 pore tube per intersept (diameter 0.55 mm, lintels 0.09 mm, wall thickness 0.04 mm), angled steeply upward into central cavity. Septa with 6-7 rows of rounded pores (diameter 0.24 mm, lintels 0.30 mm, septal thickness 0.09 mm). Septal coefficient 1.6. Ratio of sides of interseptal loculi 1/3-1/4. 'Quarter-septa', with a single row of pores close to the outer wall, are common.

Outer wall ø/l 2.9, inner wall ø/l 6.1, GPC 2.1.

Remarks: The type species *B. wirrialpensis* (Taylor, 1910) and its possible synonym *B. ionicus* Bedford & Bedford (1936; Debrenne, 1974) are known also from the Faunal Assemblage No. 2 interval in the Ajax Limestone of the Ajax Mine area, South Australia. *B. wirrialpensis* is known additionally from that interval in the nearby Mount Scott Range. Other, undescribed forms of *Beltanacyathus* are present within Faunal Assemblage No. 1 levels of the Wilkawillina Limestone at Wilkawillina Gorge, South Australia (D. Gravestock, pers. comm. 1979).

Phylum Incertae sedis

Class Radiocyatha Debrenne, Termier & Termier, 1970

Family Radiocyathidae Okulitch, 1955

Genus **RADIOCYATHUS** Okulitch, 1937

Type species: Heterocyathus minor Bedford & Bedford, 1934; OD.

Diagnosis: Two-walled conical cups in which asters form a continuous framework; each aster of one wall connects to a corresponding aster of the other wall via an intervallar rod.

Remarks: The genus name is the first proposed substitute for the preoccupied name *Heterocyathus* Bedford & Bedford (1934) *non* Edwards & Haime (1848). In proposing the substitute name *Radiocyathus*, Okulitch (1937) did not cite the type species *R. minor* (Bedford & Bedford). Consequently this entry does not appear in the synonymy list.

RADIOCYATHUS MINOR (Bedford & Bedford)

Fig. 13G-I

- *1934 *Heterocyathus minor* Bedford & Bedford, p. 7, pl. 6, fig. 32.
- .1934 *Heterocyathus major* Bedford & Bedford, p. 7, pl. 6, fig. 34.
- v?1936 *Dictyocyathus macdonnelli* Bedford & Bedford, p. 14, pl. 12, fig. 61.
- .1936 *Heterocyathus tertius* Bedford & Bedford, p. 22, pl. 21, fig. 90, pl. 22, fig. 91.
- 1936 *Heterocyathus minor* Bedford & Bedford; Bedford & Bedford, p. 22, pl. 22, fig. 92.
- 1955 *Radiocyathus minor* (Bedford & Bedford); Okulitch, p. E18, fig. 13,2.
- ?1964 *?Alphacyathus macdonnelli* (Bedford & Bedford); Zhuravleva & others, p. 91, text-fig. 55.
- 1965 *Radiocyathus minor* (Bedford & Bedford); Hill, p. 141, pl. 12, fig. 4.
- 1970 *Radiocyathus minor* (Bedford & Bedford); Debrenne, Termier & Termier, p. 121, pl. 4, figs. 1-3, pl. 5, fig. 1, pl. 6, figs. 1-2.
- .1970 *Radiocyathus major* (Bedford & Bedford); Debrenne, Termier & Termier, p. 121, pl. 4, fig. 4.
- .1970 *Radiocyathus tertius* (Bedford & Bedford); Debrenne, Termier & Termier, p. 122, pl. 4, figs. 5-6.
- 1972 *Radiocyathus minor* (Bedford & Bedford); Hill, p. E141.
- ?1974 *'Dictyocyathus' macdonnelli* Bedford & Bedford; Debrenne, p. 196, fig. 4.
- 1974b *Radiocyathus minor* (Bedford & Bedford); Zhuravleva, p. 58.
- 1979 *Radiocyathus minor* (Bedford & Bedford); Nitecki & Debrenne, p. 8, pl. 1, figs. 1-2, pl. 2, figs. 1-3, pl. 3, fig. 6.
- *1979* *Radiocyathus minor* (Bedford & Bedford); Walter & others, p. 308.

Material: 10 specimens: SUP88159-88166; CPC18685; F24208. Ross River, Mopunga Range (GEO656).

Diagnosis: Outer wall asters anastomosing on the inner surface, and interfingering on the outer surface of the wall; asters spaced 1-4 mm apart.

Description: Cup conical, diameter up to 33 mm, with intervallum 6.5 mm in width. Outer wall 0.3-0.6 mm in thickness, constructed of asters having 9-12 thickened rays (thickness 0.1-0.4 mm) on the inner surface and 12-21 thinner rays (thickness 0.1-0.3 mm) on the outer surface. Rays on the inner surface anastomose with those of neighbouring asters, forming angled junctions. Those on the outer surface do not anastomose, but interfinger with rays of adjoining asters. Asters spaced 1.1-3.3 mm apart. Inner wall 0.2-0.3 mm in thickness, not well preserved. Asters have 9-11 rays (thickness 0.1-0.2 mm) and are spaced 0.6-1.2 mm apart. Intervallum traversed by circularly cross-sectioned rods (thickness 0.2-0.7 mm) which link each outer wall aster with a corresponding aster on the inner wall.

Remarks: R. minor was originally described from the Ajax Limestone, Ajax Mine, South Australia (Bedford & Bedford, 1934). Nitecki & Debrenne (1979) have figured silicified specimens from the Todd River Dolomite at Ross River.

	CPC 18685	*SUP 88166*	*SUP 88163*	*SUP 88160*	*SUP 88165*	*SUP 88159*
ϕ	33	16.3	15.1	13	11.5	10.5
w	6.5	2.7	2.6	2.6	1.3	2.3
rod t	0.3	0.2	0.4	0.5	0.3	0.4
Outer wall:						
d	3.3	3.0	1.1	2.9	1.4	1.5
n	9–12/15–18	9–12/13–21	~9	12–15	9–10	
rt	0.2–0.4/0.1	0.1/0.2–0.3	0.1	0.3	0.1	
t	0.3	0.4	0.3	0.4	0.6	0.3
Inner wall:						
d	1.2			0.8	0.9	0.6
n	9–11			9		
rt	0.2			0.1		
t	0.2		0.2	0.2		0.3

d = distance between centres of asters
n = number of rays per aster (inner surface/outer surface)
rt = ray thickness (inner surface/outer surface)
rod t = rod thickness

Synthesis

A single archaeocyathan assemblage can be recognised within the Amadeus and Georgina Basins. Although of limited diversity, the assemblage provides a basis for regional and intercontinental correlation.

Regional correlations

Within the Amadeus and Georgina Basins, the discrete archaeocyathan assemblage described here is everywhere associated with Faunal Assemblage No. 2 of Daily (1956, 1972, 1974). The composite fauna provides an approximate correlation datum for the Early Cambrian of the central Australian region, linking the Todd River Dolomite of the Amadeus Basin with the Mount Baldwin Formation of the Georgina Basin. The archaeocyathan assemblage has recently been reported also from the Red Heart Dolomite on the HAY RIVER 1:250 000 map sheet (Walter & others, 1979).

Coscinocyathus bilateralis (Taylor), *Beltanacyathus* Bedford & Bedford and *Radiocyathus minor* (Bedford & Bedford) were originally described from the Ajax Mine area (Ajax Limestone) of the Flinders Ranges, South Australia. In the much more complete archaeocyathan succession of this region, in the Ajax and Wilkawillina Limestones, Faunal Assemblage No. 2 is commonly separated from younger Early Cambrian assemblages (Nos. 3-9) by a widespread disconformity (Daily, 1976b). The classic Ajax Mine locality (Ajax Limestone), from which Taylor (1910) and Bedford & Bedford (1934-1939) described many forms of Archaeocyatha, is an area of complex structure, but it appears that the majority of the described forms are from the interval stratigraphically above the disconformity (Daily, 1972). The remainder, particularly those from the nearby Paint Mine locality (Bedford & Bedford, 1937), and including *Beltanacyathus wirrialpensis* (Taylor), are from rocks bearing the Faunal Assemblage No. 2.

Although the full stratigraphic ranges of *Coscinocyathus bilateralis* and *Radiocyathus minor* are not yet established, a correlation of the Todd River Dolomite and Mount Baldwin Formation with at least the lower levels of the Ajax and Wilkawillina Limestones seems clear.

Intercontinental correlation

The best documented Early Cambrian successions are those of the Siberian region, at present divided into four stages named, from oldest to youngest, the Tommotian, Atdabanian, Lenian, and Elankian by Rozanov (1973) and Rozanov & Debrenne (1974). The Elankian and later part of the Lenian stages appear to be Middle Cambrian in the Australian sense (Öpik, 1976).

Of the central Australian archaeocyathan genera, only *Aldanocyathus* and *Coscinocyathus* are not endemic to the Australian region, and these are long-ranging forms of the Tommotian, Atdabanian, and Lenian stages. At present, a sounder basis for intercontinental correlation is to compare the more diverse faunas of the equivalent strata in the South Australian succession with those of Siberia.

The Ajax and Wilkawillina Limestones of South Australia are generally considered to represent part or all of the Atdabanian and early Lenian stages, with the archaeocyathan collections of Taylor (1910) and the Bedfords (1934-1939) being equivalent to the latest Atdabanian and earliest Lenian (Walter, 1967; Debrenne, 1969; Debrenne & others, 1971; Hill, 1972; Rozanov, 1973; Rozanov & Debrenne, 1974 Daily, 1976a; Debrenne & Rozanov *fide* Kirschvink, 1978). These conclusions are broadly based on the respective ranges of genera and higher taxonomic categories common to the two regions.

Thus Daily (1972, 1976a), on the evidence of his Faunal Assemblage No. 2, has considered the fossiliferous interval of the Todd River Dolomite to be Atdabanian. Certainly the archaeocyathan fauna exhibits no distinctively Lenian features, although *Coscinocyathus bilateralis* (Taylor) and *Radiocyathus minor* (Bedford & Bedford) may range into Lenian equivalent strata in the Flinders Ranges succession. An Atdabanian, possibly also early Lenian age, is suggested here for the archaeocyathan fauna of the Todd River Dolomite and Mount Baldwin Formation.

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Epeiric carbonate sedimentation of the Ninmaroo Formation (Upper Cambrian-Lower Ordovician), Georgina Basin

B. M. Radke

The Ninmaroo Formation (Upper Cambrian-Lower Ordovician) is one of several epeiric carbonate sequences in the Georgina Basin. It comprises ooid, peloid, flat-pebble conglomerate, skeletal and mixed carbonate lithofacies, terrigenous sandstones, and a late diagenetic crystalline dolostone lithofacies. Ninmaroo sedimentation took place in a broad, shallow epicontinental sea under normal marine, increasingly saline, and evaporitic conditions. A barrier complex of ooid, peloid and skeletal sands formed the seaward limit of these environments. Channels through this barrier extended weak tidal effects to the periphery of an extensive non-tidal complex of semi-emergent shoals in a patchwork pattern. Here, algal and nonskeletal carbonate sedimentation predominated because higher salinities restricted the fauna. Sedimentation was cyclic, probably due to repeated shoaling from storms. Sabkhas developed locally on emergent areas of shoals and landward where the complex was transitional with an emergent pavement. Where emergence was prolonged, microkarst resulted with both carbonate and sulphate dissolution. Lithofacies patterns indicate two regressive depositional sequences. An initial southeastern progradation of the barrier and epeiric environments was over a stable and extensive flat shelf. Subsequent instability increased shelf slope locally, and depositional environments along margins were condensed. With increased tidal circulation, skeletal carbonate production became dominant, producing a second offlap to the southeast.

Introduction

This paper presents an interpretation of carbonate cycles and lithofacies of the Ninmaroo Formation, and a regional synthesis of Ninmaroo sedimentation through time. It complements a detailed account of the Ninmaroo lithostratigraphy (Radke, in press).

The Ninmaroo Formation (Casey, 1959) is a thick sequence (up to 650 m) of epeiric carbonates and minor terrigenous rocks, with widespread distribution in the southeastern Georgina Basin across the Burke River Structural Belt, the central Smoky Anticline, and the Toko Syncline (Smith, 1972) (Figure 1).

The formation ranges from Payntonian (Late Cambrian) to early Arenigian (Early Ordovician) (Shergold & others, 1976) and has varying lateral stratigraphic relationships (Figure 2). During the Late Cambrian and Early Ordovician, Australia was a northerly segment of Gondwanaland, which straddled the equatorial belt (Embleton, 1973; Veevers, 1976). Part of the northerly margin of the Gondwanaland continent was flooded with vast shallow seas, which were the focus of carbonate and minor terrigenous sedimentation. Today, remnants of this event are represented by sequences in the Georgina, Amadeus, and Ngalia Basin (Webby, 1978). This epicontinental sea opened northwards over a continental shelf that was aligned east-west. The climate was most probably hot and arid, with high humidities immediately adjacent to and over this sea.

Models of clear-water carbonate sedimentation in such epeiric seas have been lucidly outlined by Shaw (1964), Irwin (1965), and Laporte (1969). Epeiric seas characteristically had extremely low shelf slopes and shallow-water conditions with apparent restricted water circulation. Tidal effects were probably diminished or non-existent, and higher salinities, and evaporitic and emergent conditions were common. Significant sediment transfer was presumably by less regular, seasonal storm events, with intermediate resorting and redeposition by prevailing lower-energy conditions to produce shoaling. Each of these features can be recognized in cyclic deposits, which are defined at base and top by erosional surfaces. Cycles or shallowing-upward sequences (James, 1979) each represent one sedimentation event. Shoaling and environmental conditions were interactive during prevailing conditions between storm events. Consequently, a variety of cycle types have resulted from varying local conditions. Sedimentation over a longer time period is therefore characterised by the patterns of superposition of different cycle types. Lithofacies, as discussed in this paper, are these larger scale patterns which can be defined by variations of the dominant rock types.

Expected environmental changes with shoaling

Changing environmental conditions with shoaling generally follow a pattern from normal marine through increasing salinities to evaporitic and emergent conditions. Recognition of these conditions is from faunal and sedimentary characteristics, which will be discussed prior to evaluating the Ninmaroo sequence.

Salinity

Increased salinity is indicated by a reduced diversity in fauna, the increased preservation of algal mats, the increased dominance of non-skeletal components in the sediment, extensive marine induration, flat-pebble conglomerates, and shrinkage cracks.

Reduced faunal diversity. Decreasing diversity of marine faunas has been attributed to the adverse conditions of abnormal salinities (Ginsburg, 1956; Logan, 1961; and Kendall & Skipwith, 1969). In a community, individual organisms have variable tolerances of salinity and subaerial exposure (Walker & Laporte, 1970) and of these, blue-green algae (cyanophytes) have the greatest tolerance to elevated salinities and desiccation, and hence have potentially the widest distribution in shallow-marine conditions. Of the Ordovician fauna, the apparent order of increasing salinity tolerance is conodonts, echinoderms, nautiloids, sponges, gastropods, trilobites, ribeirioids, monoplacophorans (chitons), brachiopods, infaunal suspension feeders, and ostracodes.

Consequently, in shallow-upward cycles, skeletal sediments from more diverse faunas would be prevalent

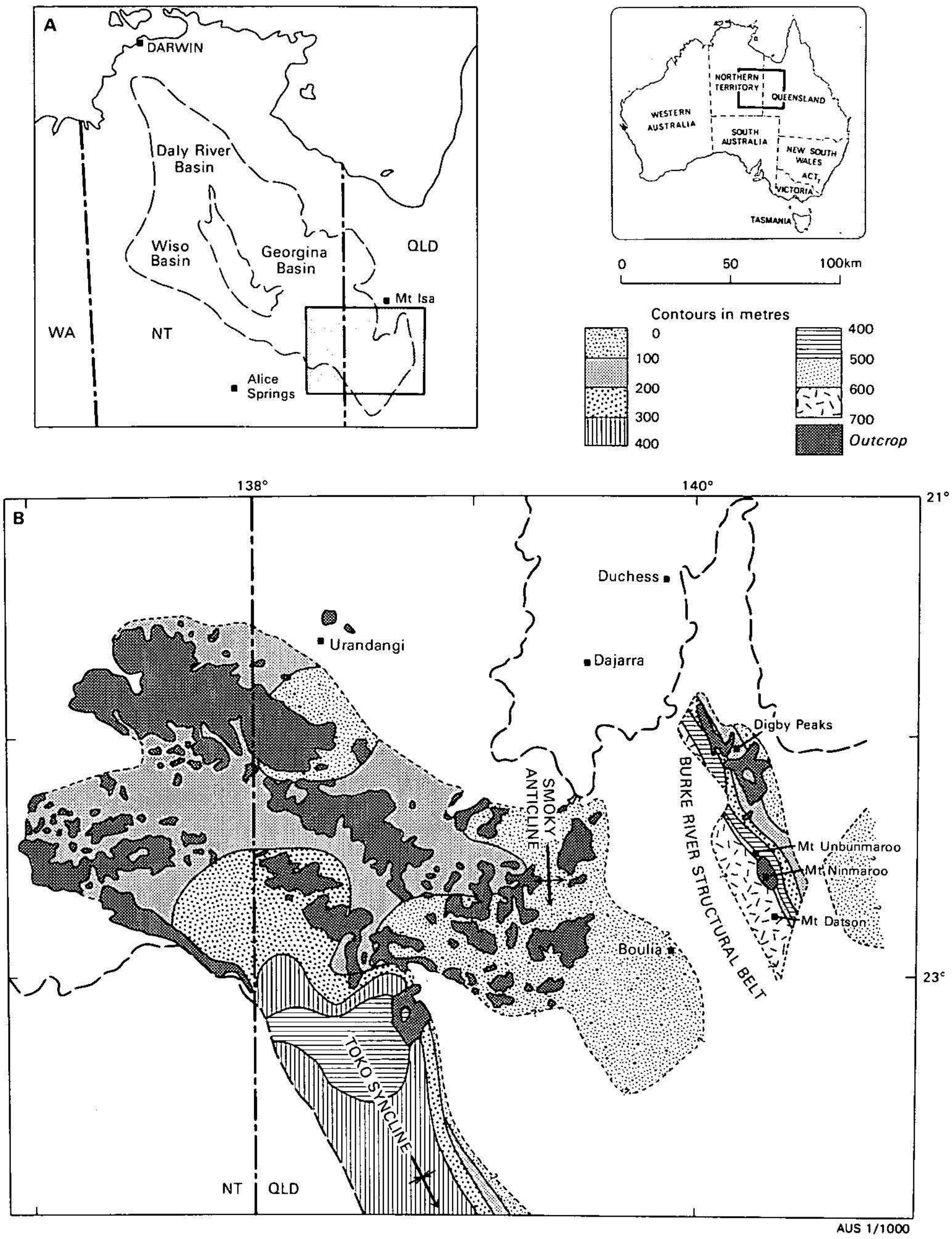
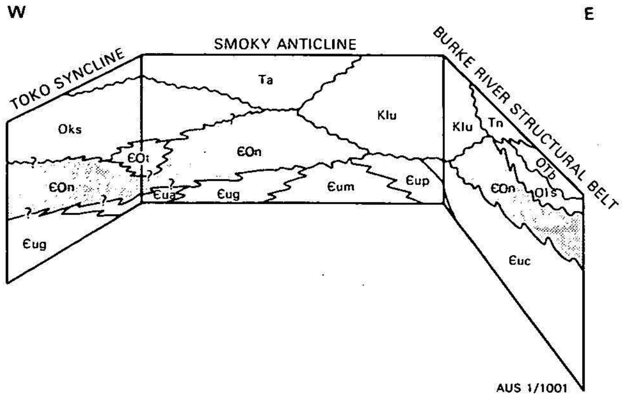


Figure 1. (a) Location of southeastern Georgina Basin.
(b) Geographic extent and thickness of the Ninmaroo Formation.

initially, with faunal diversity decreasing upward within the cycle.

Preservation of algal mats. Preservation of cryptalgal lamination is attributed, in part, to conditions of increased salinity and temperature, in which the contributing cyanophytes could flourish in seclusion, free from grazing organisms of lower salinity tolerance. This antipathetic relationship has been well documented (Curtis & others, 1963; Illing & others, 1965; Kendall & Skipwith, 1968, Garrett, 1970; Walker & Laporte, 1970; Friedman & others, 1973). Thrombolitic fabrics, which have poor to no lamination, tend to have the greatest inbound faunal diversity, comprising sessile suspension feeders, such as ribeirioids and brachiopods, grazing trilobites, ostracodes and gastropods, and ellesmeroceroid nautiloids. Such boundstones usually have a mottled fabric, commonly enhanced by later sulphate and dolomite overprints. There is a continuum from this fabric through to well-laminated stromatolites which are devoid of any recognisable fauna.

Dominance of non-skeletal carbonates. In marine waters with salinity exceeding 39‰ at 20°C, inorganic carbonate precipitation is possible (Logan, 1974; Lees. 1975). Above this threshold and up to salinities and temperatures where only cyanophytes can survive, carbonate is produced by both organic and inorganic sources. The controls influencing the production rates of skeletal and inorganic sources are complex, dependent on an interaction of many factors, including stability of substrate, water turbidity, light, nutrient supply, extremes of temperature and salinity. Parameters of salinity and temperature can be used to separate inorganic particle fields (Lees, 1975). Above 39‰ salinity at 20°C, pellets are preserved, and at higher temperatures and salinity, ooids, aggregate grains, and marine cements predominate. Purdy (1963a, b) estab-



TERTIARY		Ta Tn	Austral Downs Limestone Noranside Limestone
CRETACEOUS	Lower	Klu	Undifferentiated
	? to Lower	Otb Ols	Digby Peaks Breccia Swift Formation
ORDOVICIAN	Lower	Oks	Kelly Creek Formation
	Lower O to Upper €	€On €Ot	Ninmaroo Formation Tomahawk Beds
CAMBRIAN	Upper	€uc €up	Chatsworth Limestone Pomegranate Limestone
	Upper to Middle	€ua €ug €um	Arrinthrunga Formation Georgina Limestone Mungerebar Limestone

(After Smith, 1972; Druce & others, 1976; Shergold & others, 1976)

Figure 2. Stratigraphic relationships of the Ninmaroo Formation.

lished statistically an ooid-grapestone facies distinct from the occurrence of other carbonate facies. He showed it to be a result of increased salinity and temperature. Spherulites (Meijer, 1971) and ooids with dominant radial fabrics have both been associated with algal mat sedimentation under elevated salinities (Cayeux, 1935; Friedman & others, 1973).

Extensive marine induration. Although synsedimentary induration is common to many environments, it is best developed where higher salinity and temperature conditions prevailed in either prolonged periods (Logan, 1974) or intermittently in the tidal setting (Gavish & Friedman, 1969; Davies & Kinsey, 1973). Modern marine cements are aragonite and high-magnesium calcite, and both can give isopachous fabrics under phreatic conditions. High-magnesium calcite also occurs as micritic crusts and void fillings. Neomorphic equivalents of these are commonly difficult to distinguish from fresh-water calcite cement facies, both vadose and phreatic. Perhaps the best indication of early shallow-marine cementation is the development of crusts which show selective growth along stratification, erosion surfaces, and bioturbation, and which are disrupted by later boring or erosion.

Flat-pebble conglomerates. Flat pebbles are derived from indurated pavements or hardgrounds, which form in a variety of marine environments. Indurated pavements of Holocene age occur in the subtidal hypersaline waters of Hamelin Pool (Logan, 1974), and in peri-emergent (upper intertidal and supratidal) zones (Davies, 1970; Logan, 1974), where the pavements of pellet grainstone and packstone are littered with tabular clasts of coarse irregular and polygonal shapes. Logan (1961) considered flat-pebble conglomerates and stromatolites to be a common association in Holocene hypersaline conditions and in ancient sequences. In high intertidal and supratidal settings, gypsum can also be precipitated from hypersaline groundwaters and act as a crude cement in surface pavements (Logan, 1974).

Breakup of indurated pavements can be by a variety of processes. In the intermittently emergent setting, jointing and wedging can develop in the sediment by expansion during lithification (Assereto & Kendall. 1971) or by diurnal temperature fluctuations (Burri & others, 1973). Additionally, seasonal storms provide high-energy turbulent conditions sufficient for the breakup of clasts, abrasion, and transportation (Logan, 1974).

Edgewise fabrics in platy conglomerates have been documented as a typical littoral feature (Bluck, 1967; Sanderson & Donovan, 1974) that requires small but abrupt substrate relief to initiate the stacking. This fabric can only be produced by prevailing wave surge and swash. In contrast, where substrate relief is absent, the tabular clasts tend to be repeatedly moved and reoriented in wave surge until they are buried, producing well-sorted imbricate fabrics. If finer sediment is more abundant, the clasts tend to parallel stratification.

Shrinkage cracks. With high evaporation rates in shallow water, salinities may rise quickly and even exceed those of the interstitial pore fluids of the substrate. Synaeresis shrinkage cracks may result (Burst, 1965; Donovan & Foster. 1972). Such cracks are generally indistinguishable from subaerial desiccation cracks, although the latter may be better developed into characteristic polygonal patterns.

Evaporitic conditions

Above the calcium carbonate precipitation field, gypsum precipitates at about 130‰ salinity, and crystal growth is commonly within the host sediment. Less common but more conspicuous anhydrite nodules result from nucleation and growth on pre-existing gypsum crystals. Sulphate overprints are most common in fine-grained cryptalgal sediments with desiccation features. Because of the relative solubility of these minerals, they are invariably redissolved or replaced. Consequently, evidence for the former presence of evaporitic conditions is required. This includes: traces of relict sulphate crystals; pseudomorphs after gypsum crystals, anhydrite nodules, sulphate-laminates with buckle folding; sediment textures and shapes of carbonate particles that were modified by displacive/replacive sulphate crystal growth before induration; collapse breccias; and associated fine-grained dolomite and fluorite. Quartzine and lutecite, forms of length-slow chalcedony, are also considered indicative of former sulphates (Folk & Pittman, 1971).

Emergence

Horizons of emergence can be recognised by well-developed desiccation cracks, silica and calcrete crusts, solution and erosion features on indurated surfaces, and subsurface stratiform cavities.

Subaerial induration. Early induration of carbonate sediments has been demonstrated to occur in shallow-marine as well as subaerial environments (Friedman, 1964; Shinn, 1969; Davies & Kinsey, 1973). Consequently, these diagenetic environments need to be differentiated. Evidence for induration in the subaerial environment is the presence of calcrete (James, 1972; Read, 1974), vadose fabrics (Dunham, 1969), penecontemporaneous desiccated chert crusts (Radke, 1978), teepee structures and columnar stalagmitic cements in cavities (Asserto & Kendall, 1977).

Erosional surfaces. These can occur over firm or indurated substrates. Where the substrate is firm and plastic, but not lithified, eroded lumps are susceptible to being rounded and modified in shape during transportation (Braun & Friedman, 1969), deposited as round-pebble conglomerates, and later compacted following deposition.

Erosional surfaces over indurated substrates can be quite variable and complex. Three common kinds are (1) irregular, low relief surfaces covered with variable-sized intraclasts of similar lithology and irregularity of shape as the substrate; (2) a scalloped morphology on both planar and domed surfaces; and (3) smooth planar surfaces. Several processes have been proposed for the erosion of indurated surfaces: storm erosion (Logan, 1974), subaerial dissolution, bioerosion (Taylor & Way, 1976; Read & Grover, 1977), and submarine erosion under prevailing high-energy conditions (Klein, 1967). Frequently these processes are superimposed, and individual features cannot be attributed to any one process.

Erosion and burial of an indurated surface may be included in one event, as in storm deposition, or alternatively occur over an extensive period of time during which several processes may have been responsible. For example, with a transgression over an emergent pavement, the surface may be sequentially subjected to dissolution, bioerosion, and mechanical abrasion, with each process modifying or enhancing the pre-existing surface.

Non-tidal versus tidal sedimentation

Recognition of non-tidal shallow-marine sedimentation is limited to confirming the absence of tidal features. Most distinctive of tidal conditions are herringbone cross-lamination and erosional channel structures, even though they are not restricted solely to the intertidal belt (de Raaf & Boersma, 1971; Reineck & Singh, 1975). Additionally, cross-stratification in the tidal regime is characteristically bimodal (de Raaf & Boersma, 1971).

This negative evidence (the lack of characteristic sedimentary tidal features) is consistent with models of epeiric seas (Shaw, 1964; Irwin, 1965) that infer tidal effects cannot be persuasive because of frictional drag that would attenuate small amplitudes in the comparatively high frequency tidal cycles. This concept is incorporated in the regional sedimentation model proposed in this paper.

Ninmaroo Formation

Cycles

Cyclic sedimentation is recognised throughout most of the formation except the uppermost part, where little can be discerned through dolomitisation and silicification overprints. Thirty-eight cycles are recognised in the type section, consisting of three types that are named after the dominant component rock type; Type A—cryptalgal carbonate cycles, Type P—peloid carbonate cycles, and Type SO—skeletal-ooid carbonate cycles. The generalised structure of these cycles is described here, but variations from these idealised models are discussed in Radke (in press).

Type A—cryptalgal carbonate cycles

Three subtypes of cryptalgal cycles (Figure 3) are distinguished by the presence of different cryptalgal morphologies: Type A1—cryptalgal domes, Type A2—cryptalgal domes and laminites, and Type A3—cryptalgalaminites.

Type A1 cryptalgal carbonate cycle. This cycle contains in descending order:

4. cross-stratified intraclast-peloid grainstone and lightly bioturbated packstone grading down to;
3. edgewise flat-pebble conglomerate, adjacent to and overlying;
2. bioherms or biostromes of cryptalgal domes with a sparse fauna of nautiloids, trilobites, ribeirioids, and chitons;
1. imbricated flat-pebble conglomerate with an ooid, peloid, or skeletal matrix.

Cycle A1 forms sheets and probable lenses, 1 to 3 metres thick, underlain by an abrupt erosional surface, which is usually irregular to cuspate, developed on basal indurated grainstones and cryptalgal domes. The upper contact is also an irregular erosional surface.

Type A2 cryptalgal carbonate cycle contains in descending order:

5. homogeneous to laminated wackestone or packstone;
4. irregular collapse-breccia layers on top of the domes;
3. bioherms or biostromes of cryptalgal domes with adjacent lime mudstone;
2. laminated variegated muddy wackestone or packstone which may be a cryptalgalaminite, grading down to;
1. basal intraclast flat-pebble conglomerate and ooid-intraclast grainstone.

This cycle forms sheets, 0.5 metres thick, which are clearly defined by an erosional base and either an erosional or gradational upper contact.

Type A3 cryptalgal carbonate cycle. This cycle contains in descending order:

3. cryptalgalaminites comprising peloid limestone with fenestral fabrics, shrinkage cracks, chert nodules, and pseudomorphs after sulphate nodules and crystals;
2. ooid, peloid, and minor skeletal grainstone; gradational with
1. basal flat-pebble conglomerate.

The cycle forms sheets from 1 to 4 metres thick, with gradational or distinct basal erosional contacts that may not always be exposed. The upper contact is distinct and planar.

Type P—peloid carbonate cycle. Peloid carbonate cycles (Figure 3) contain in descending order:

4. lime mudstone with minor bioturbation and a homogeneous upper rind;
3. laminated and bioturbated peloid packstone and wackestone;
2. cross-stratified peloid and ooid grainstone with thinner sets towards the top, gradational with;
1. imbricated pebble conglomerate with intraclast and peloid matrix.

This cycle occurs as sheets and lenses, 0.1 to 0.6 metres thick, defined by distinct, irregular erosional

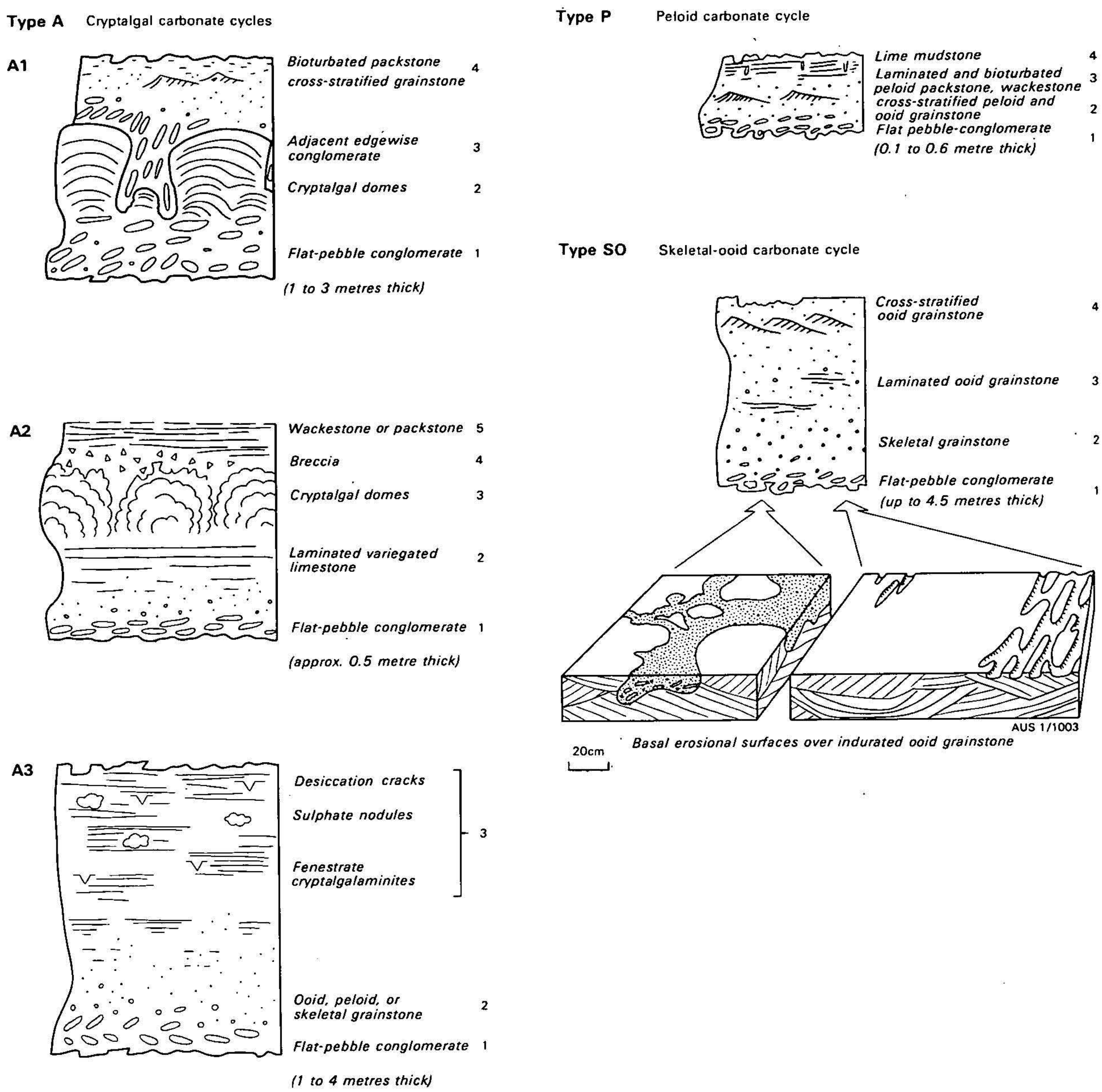


Figure 3. Type A, P and SO carbonate cycles.

surfaces at the base and top. The basal contact may overlie rocks interpreted to have been a firm ground or indurated substrate.

Type SO—skeletal-ooid carbonate cycle. This cycle (Figure 3) contains in descending order:

4. cross-stratified ooid grainstone;
3. planar-laminated ooid grainstone;
2. skeletal grainstone, grading down to;
1. flat-pebble conglomerate.

SO cycles form extensive sheets up to 4.5 metres thick, defined by distinct basal contacts that are planar or irregular with relief of up to 0.2 metres. Irregular depressions commonly have large blocks of underlying rock types. Lower relief, of about 5 centimetres, may be in the form of unidirectional anastomosing rills with smooth undercut sides. The upper contact is similar, though not always exposed.

Lithofacies

Accumulation of these cyclic deposits in varying order has produced, on a larger scale, subtle but simpler sequences which enable distinction of lithofacies by dominant rock types. The lithofacies recognised on this basis each have differing combinations and abundances of the component cycles (Fig. 4).

The lithofacies are:

Io	Ooid carbonate lithofacies;
II	Peloid carbonate lithofacies, consisting of two kinds;
IIp	Peloid carbonate dominant lithofacies;
IIps	Peloid and skeletal carbonate lithofacies;
IIIc	Flat-pebble conglomerate carbonate lithofacies;
IV	Skeletal carbonate lithofacies, consisting of two kinds;
IVs	Skeletal carbonate dominant lithofacies;
IVscp	Mixed carbonate lithofacies;
Vt	Terrigeneous lithofacies; and
VId	Crystalline dolostone lithofacies.

	Lithofacies	Diagnotic features	Lithologies (order of decreasing abundance)	Carbonate rock types	Sedimentary structures
Ic	Ooid carbonate	ooid grainstone, dominant lithology	limestone, dolostone calcareous sandstone	ooid grainstone peloid grainstone flat-pebble conglomerate echinoderm grainstone columnar thrombolitic bioherms	cross-stratification in grainstones (up to 1 m sets, trough-shaped bases, moderate angle stratification) see Fig. 5a, herringbone cross-lamination
IIp	Peloid carbonate dominant	peloid limestones dominant; 'two-tone' patterns	limestone, sandy and silty limestone, calcareous siltstone, sandstone, shale, dolostone	peloid grainstone (Fig. 5c), packstone, and wackestone; flat and round-pebble conglomerate intraclast and skeletal carbonates; cryptalgalaminites (planar biostromes (Fig. 5d, e), domed bioherms); lime mudstone	channel scours (Fig. 5f) (5 m wide, 0.5 m deep) (infilled with cross or planar stratified grainstones); stromatolites bioturbation
IIps	Peloid and skeletal carbonate	thin beds of alternating peloid limestone and skeletal grainstone. Banded cherts	limestone, calcareous siltstone, dolostone, chert	peloid grainstone packstone; coarse skeletal grainstone, minor cryptalgal grainstone	bioturbation tubes
IIIc	Flat-pebble conglomerate carbonate	flat-pebble conglomerates abundant	limestone, sandy limestone, fine-grained sandstone	flat-pebble conglomerate (Fig. 6a); peloid, ooid, skeletal grainstone packstone; cryptalgal limestone; lime mudstone	hardgrounds, bioturbation, domed biostromes; edgewise flat-pebble conglomerate
IVs	Skeletal carbonate dominant	coarse thick-bedded echinoderm grainstones; SO cycles	echinoderm carbonates sandy carbonates, calcareous sandstone	echinoderm grainstone (Fig. 6b); ooid, peloid, flat-pebble conglomerate, grainstone; cryptalgalaminites	cross-stratification in echinoderm and ooid grainstones, karstified hardgrounds, herringbone cross-lamination
IVscp	Mixed skeletal, pebble-conglomerate, peloid carbonate	no dominant lithology	carbonate; sandy and silty carbonate	skeletal grainstone, flat-pebble conglomerate, peloid grainstone, ooid grainstone, cryptalgalaminites	
Vt	Terrigenous	thin-bedded sandstones	sandstone (fine-very fine), calcareous siltstone		planar lamination, cross-lamination minor parting lineation
VId	Crystalline dolostone	crystalline dolostone	dolostone; minor sandstone		

Table 1. Ninmaroo lithofacies.

The crystalline dolostone lithofacies (VId) comprises dolostones which lack any primary textures and is distinguished for this reason. It is a late diagenetic modification of former carbonates and consequently will not be discussed further.

Characteristics of these lithofacies are summarised and compared in Table 1.

Interpretation

The interpretation of depositional environments is approached on two scales—micro and macroenvironments. Microenvironments are resolved from the cycles, and indicate localised conditions in a small area, on the order of kilometres, that were stable for a short period. Macroenvironments are interpreted from the lithofacies, and indicate the norm of conditions on a regional scale of hundreds to thousands of square kilometres over a longer period. As such, macroenvironments reflect the average effects of the shorter-lived transistory microenvironments.

Regional models of sedimentation can be synthesised from the distribution of macroenvironments at any one

Fauna (decreasing order of abundance)	*Cycles (Refer Figure 4)*	*Diagenetic overprints* early	late	*Comments*
echinoderms trilobites brachiopods rostroconch molluscs nautiloids conodonts	SO cycles poorly developed	anhydrite nodules (Figure 5b)	quartzine-rich cherts; dolomitisation; dedolomitisation (imparts yellowish-orange colouration); collapse breccias	Lithologies form prominent scarps
trilobites, ellesmeroceroid nautiloids, rostroconch molluscs, brachiopods, chitons, gastropods *(Ceratopea)* blastoids, echinoderms (undiff.), ostracodes, ichnofossils, calcareous sponges, calcareous algae *(Nuia)*	P cycles A1, A2, A3 cycles	anhydrite nodules gypsum crystals, chert nodules, dolomitisation (minor)	'two-tone' patterns from selective dolomitisation and dedolomitisation, bitumen, stratiform collapse breccias, cherts, dolomitisation	comparable abundance of cryptalgal sediments
trilobites, siliceous sponge spicules, brachiopods, bellerophon gastropods, hyolithids, calcareous algae, conodonts, minor nautiloids, bryozoans	P cycles	gypsum crystals	dolomitisation, silicification	thin bedded; may be gradational with lithofacies VId
cystoids, echinoderms (undiff.); trilobites ostracodes, brachiopods, gastropods; ellesmeroceroid nautiloids, rostroconch molluscs, calcareous algae	modified P cycles A1, A2, A3 cycles	indurated hardgrounds	dolomitisation; fluorite, bitumen; dedolomitisation	
echinoderms; minor brachipods ostracodes, trilobites, rostroconch molluscs, sponges, nautiloids	SO cycles dominant, A3 cycles	hardgrounds karstification (Figures 3, 6c)	dolomitisation, silicification, (as selective replacement of particles, or as nodules)	echinoderm limestones appear to be coarsely crystalline
echinoderms	A. P and minor SO cycles			mixed lithologies
		glauconite	mega-quartz cement; authigenic K-feldspar	generally recessive
		dolomitisation?	dolomitisation; some dedolomitisation; silicification	most primary structures obliterated

time. Extrapolation of these models through time has been used to outline the regional depositional history of the Ninmaroo Formation. The informal time zones used for this purpose have been based on biostratigraphic zones, ranging from Payntonian to Early Ordovician (01-06) (Jones & others, 1971; Pojeta & others. 1977; E. C. Druce & J. H. Shergold, pers. comm.).

Models for cyclicity

The cyclic deposits reflect a predictable repetition of shoaling and environmental response, which can be defined in terms of: prevailing wave or current energy conditions; water salinity and temperature; and time, with emergence expressed as a final stage in the evolution of the cycle.

Where net rates of sediment accumulation exceeded rates of relative sea-level rise, shoaling occurred. As the sediment surface approached sea level, offlapping progradation followed, producing extensive sedimentary sheets. In the Ninmaroo Formation, these are 5 to as much as 18 kilometres wide (Brown, 1961) and 4.5 metres thick. Variations in extent of progradation indicate shelf dimensions, slope, stability of the source environment, and fluctuations of relative sea level.

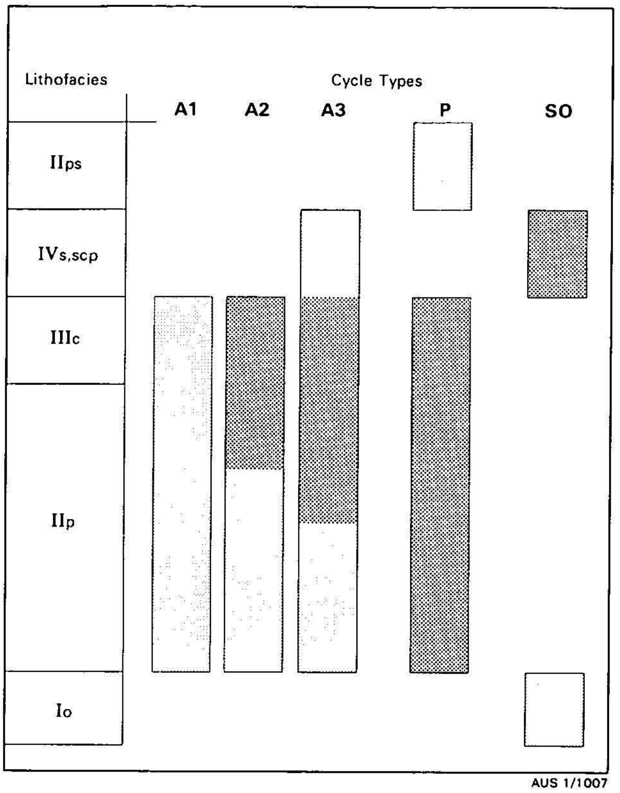


Figure 4. Distribution of cycles in the lithofacies, type section, Mount Unbunmaroo.

In comparable modern environments, localised sediment accumulation occurs at exceedingly high rates during intermittent storms, the dominant source of energy in the peri-emergent zones (Davies, 1970; Logan, 1974). Between storms, sedimentation is much slower under prevailing wind-generated currents and wave surge. Where water bodies are of sufficient size and fetch, effective wave-induced currents can be produced, even under non-tidal conditions (Friedman & Sanders, 1978). However, with shoaling, these effects are reduced by increased frictional drag on the sediment bottom.

Microenvironments of cyclic sedimentation

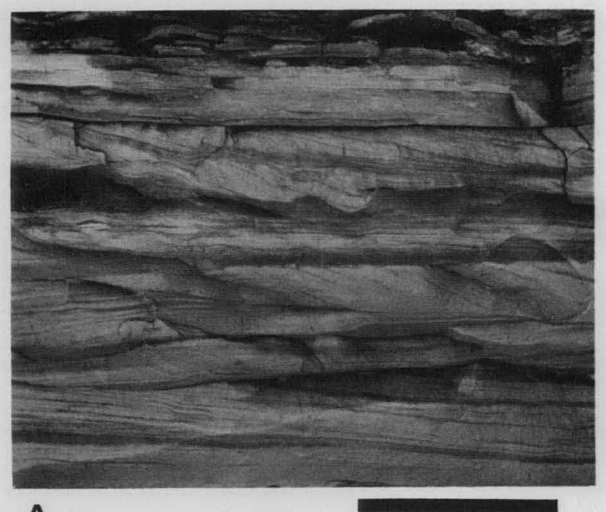
Type A1 cryptalgal carbonate cycle. This cycle is indicative of prevailing high energy wave-surge conditions over an indurated pavement covered in a flat-pebble lag deposit. Flat pebbles accumulated in edgewise fabric around domed stromatolitic bioherms, which acted as baffles, dissipating wave energy. Behind this zone, sand shoals accumulated to near-emergence with up to 3 metres relief, and eventually prograded over the zone of stromatolitic domes (Figure 7). Muddier sediments accumulated on the leeward sides of the shoals, where conditions were locally evaporitic, and gypsum precipitated within the veneer of packstone and underlying grainstones. Where metahaline salinities prevailed, the bioherms were populated with sessile ribeirioids and brachiopods, grazing trilobites, chitons, and nautiloids. This cycle reflects initially deeper, high-energy conditions established with rapid transgression or subsidence, followed by progradational shoaling and emergence as sediment accumulation exceeded relative sea-level rise.

Type A2 cryptalgal carbonate cycle. This cycle represents shallow-water sedimentation with higher salinities, temperatures, and lower wave energy than environments of cycle A1. The basal flat-pebble deposits and overlying veneer of sand, though not always present, indicate initially high-energy sedimentation that probably occurred during storms. These basal sands shoaled into algal-stabilised laminites, which evolved with sedimentation, by repeated desiccation and re-wetting of the mat, into patches of elevated crinkled mat domes in near-emergent conditions. In modern environments, pustular mats with crinkled morphology occur where there is periodic desiccation in the inter-tidal zone (Logan & others, 1974). There is a virtual absence of fauna associated with these stromatolites. Adjacent to this zone, under evaporitic conditions, gypsum precipitated as a crystal mush within the sediment. Subsequent subaerial leaching of the sulphates (Logan, 1974) produced irregular collapse breccias. Homogeneous lime muds, with only minor sulphate overprint, accumulated adjacent to the stromatolites. Similar lime muds with sharp conformable contacts coat subfossil 'stromatolites' in ephemeral evaporite lagoons (von der Borch & others, 1977). Early induration of the sediments was by both carbonate and sulphate cements.

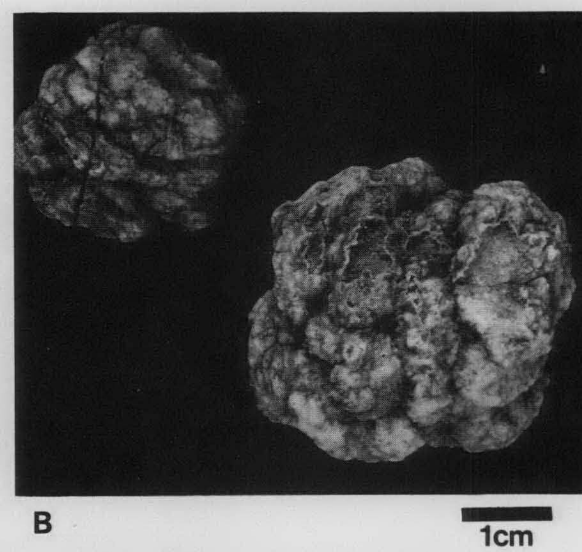
Type A3 cryptalgal carbonate cycle. Type A3 cycles represent depositional conditions similar to those of type A2 cycles; initially high-energy conditions that were probably storm-induced, followed by decreasing energy and increasing salinity, where algal mats could flourish. Under evaporitic conditions, gypsum precipitated within the sediment in existing fenestral and interparticle porosity (Figure 7). Subsequently, andhydrite nodules nucleated and grew over some of these clusters of gypsum crystals. Shrinkage polygons (Figure 5e), and indurated, fragmented laminites reflect emergence and desiccation of the algal mats. During sulphate precipitation and desiccation, chert precipitated as nodular concretions within the desiccation polygons. This unit formed as low-relief shoals in an offlap progradational situation, where brief evaporitic conditions culminated in emergence and subaerial erosion.

Type P—peloid carbonate cycle. These deposits are characteristic of moderate to high salinities with sedimentation initiated under erosional high-energy conditions during storms. Flat-pebble lag deposits accumulated over indurated pavements, while round-pebble conglomerates were produced over muddy firmground

Figure 5. (a) Thin sets of cross-stratified sandy ooid grainstone, typical of type SO cycles. Section GEO 202; 504 metres. (b) Pseudomorphs after anhydrite nodules. The compound spheroidal, or 'cauliflower' morphology has been preserved by chalcedonic replacement. 74712670. (c) Grainstone with peloids of varied shape and size. Peloids are probable micritisation products after grapestone, intraclasts and ooids as indicated by faint relief textures in some particles. Photomicrograph, plane-polarised light. 74712390. (d) Cryptalgalaminite horizon with continuous, platy thin beds. Section GEO 202; 126 metres. (e) Cryptalgalaminite with fenestrate laminae, shrinkage cracks (SC) and wavy lamination. Sediments are fine to medium-grained peloid grainstone, packstone, wackestone. 74712618. (f) Channel-scour structure with gently sloping banks cut into underlying cryptalgalaminites. The well-indurated lag deposits within the tidal channel contain a dominant flat-pebble component. Section GEO 202; 177 metres. Hammer for scale.



A



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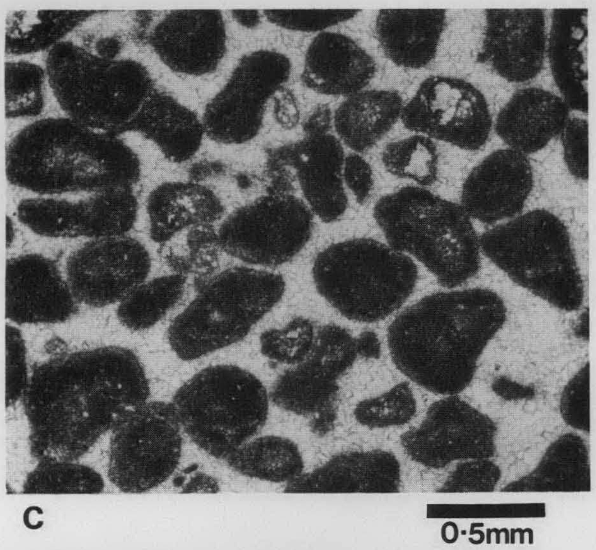

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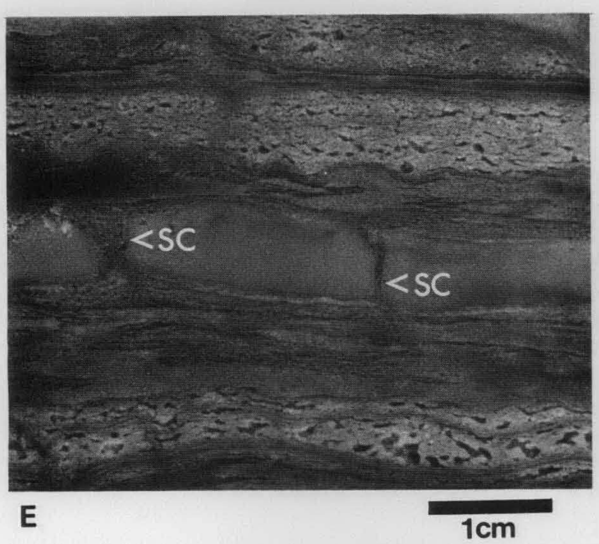

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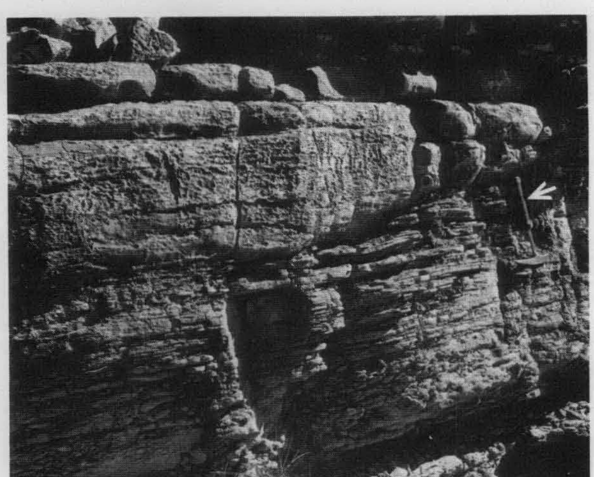

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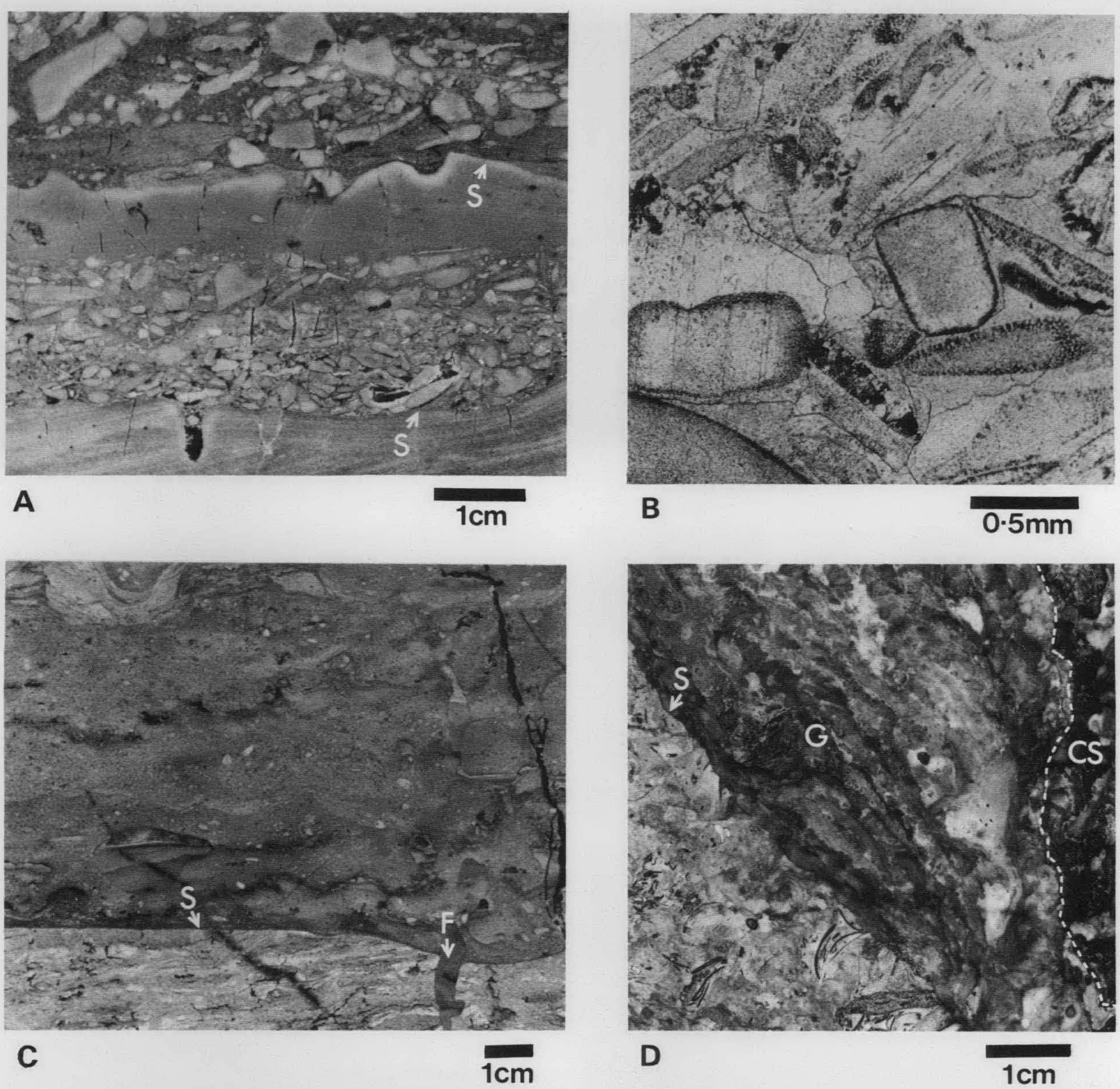


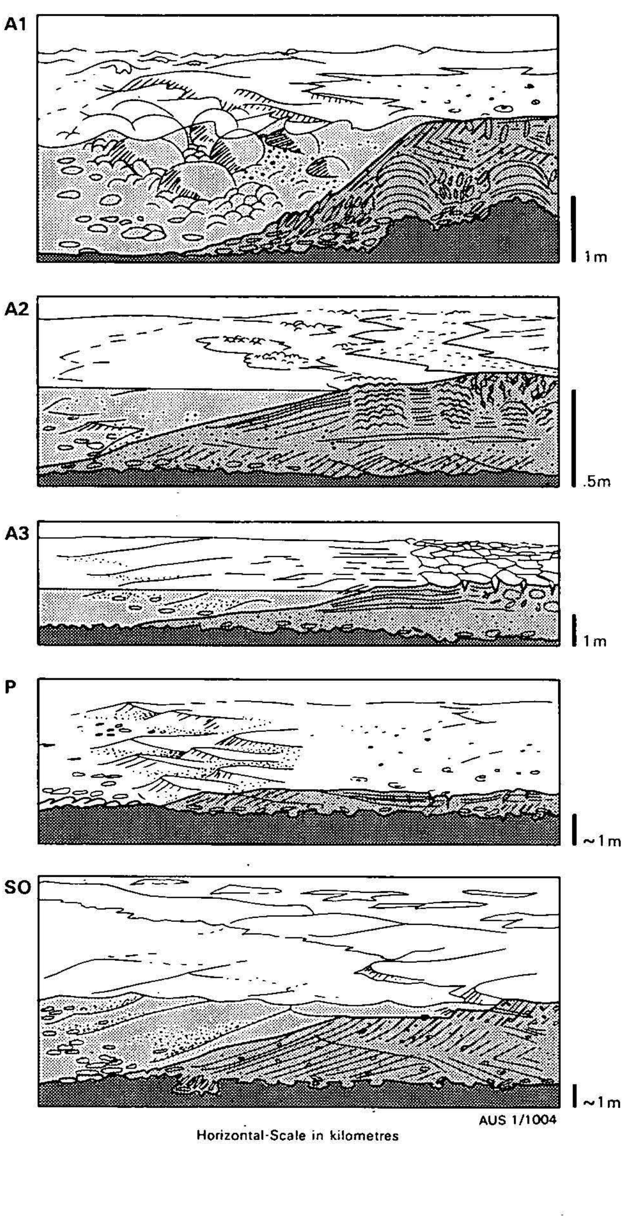
Figure 6. **(a) Repeated horizons of flat-pebble lag deposits overlying eroded indurated surfaces (S). Each conglomeratic bed fines up to another indurated surface. 74712303. (b) Echinoderm grainstone comprising platelets and columnals with well-developed syntaxial cement rims. Photomicrograph, plane-polarised light. 74712276. (c) A smoothed planar erosional surface (S) and solution-enlarged fracture (F) over an indurated cryptalgalaminite and separating a younger cryptalgal unit. Calcrete cements and geopetal sediments infill and occlude fenestrae and other solution-modified porosity. 74712328. (d) Erosional surfaces and recolonisation phases within a cryptalgal mound. A cuspate erosional surface (S) on a skeletal-rich thrombolitic boundstone is encrusted with dense irregular laminae of *Girvanella* (G). Open-crinkled stromatolites (CS) have grown over this encrustation. 74712645.**

substrates. As high-energy conditions waned, progressively finer peloid, ooid, and skeletal sediments accumulated with a final overlying veneer of lime mud that settled from suspension. The presence of either bioturbation or evaporitic overprints in these muddier sediments indicates the range of salinities that prevailed after the rapid depositional episode.

Type SO—skeletal-ooid carbonate cycle. Type SO cycles, like type A2 cycles, are characteristic of high-energy conditions that were initiated in a rapid flooding phase and persisted through sediment accumulation and progradation. These shoals of skeletal and ooid sediments indicate lower salinities, apparently near normal and within tidal influence as indicated by herringbone cross-lamination. Sedimentation was over indurated and karstic low-relief surfaces (Figure 3), with sparse or patchy pebble-lag deposits. The basal bedforms of the shoals are large, with low-angle cross-stratification, and comprise echinoderm sands with minor trilobite and brachiopod components. It is probable that the dominant echinoderm platelets were of larger surface area and lower density than other sediment particles and were consequently more readily mobilised. These sands only accumulated as subtidal sand bars, below the most active wave surge zone in up to 5 metres of water. Ooid sands accumulated over these extensive skeletal dunes, within the zone of active surge and tidal currents. The terrigeneous component of these sediments may have been either locally derived from land via tidal channels, or transported by longshore currents on the seaward side of the ooid shoal zone. In restricted areas between ooid shoals in the higher intertidal zone, elevated temperatures and salinities locally approached evaporitic conditions, where marine carbonate cementation was prolific and minor gypsum was precipitated. With subsequent exposure, the indurated shoals developed karst features, that were later modified in high-energy marine conditions of an ensuing reflooding event.

Sea level fluctuations

Small fluctuations in relative sea level are indicated by features of the cycles; recurring horizons of extensive cryptalgal mound development (Cycles of type A1, A2); alternations of subaerial erosional surfaces and recolonised bands within the larger cryptalgal bioherms (Cycle type A1); and repeated karstic surfaces within ooid and skeletal grainstones (Cycle type SO). Active biohermal development (Cycle type A1) is attributed to periods of rapid transgression (Irwin, 1965), when conditions were favourable and salinities sufficient to prevent excessive bioerosion, prior to stagnation with shoaling and the eventual burial within prograding sand bodies.



Type A1 cycles depict stromatolite growth over flat-pebble deposits and on eroded and indurated pavements. Where surface relief existed, algal growth was selective of elevated substrates, and there is repeated evidence of earlier, relict biohermal domes (Figure 6d). Where high-energy conditions prevailed and sedimentation rates were minimal, subaerial erosion alternated with algal recolonisation and growth in response to relative sea-level fluctuations. The cumulative effect on the biohermal mounds was an enhanced relief with each transgressional phase. Reversals of these cycles have not been recognised, which suggests that transgressions were erosional and rapid rather than depositional (Curray, 1964).

Macroenvironments—depositional environments of lithofacies

Ooid carbonate lithofacies. Sedimentation was in a shallow subtidal to intertidal shoal complex in a wave-dominant regime with fluctuating metahaline conditions. The repeated occurence of herringbone cross-lamination is evidence for tidal effects.

Ooid, minor peloid, and rare terrigenous sands accumulated in extensive shoals in water depths of up to 3 metres. Individual bedforms were up to 1 metre high, suggestive of strong currents that were probably localised in tidal passes where large columnar thrombolitic bioherms developed. These bioherm complexes are spaced at greater than 100 metres along depositional strike and possibly indicate the positions of tidal passes through the barrier shoals. Ranges in temperatures and

Figure 7. Depositional setting of cycles.

(a) Type A1 cycle
On indurated pavements with flat-pebble cover, high wave-energy conditions produced edgewise conglomerates around stromatolite mounds. Attenuation of wave energy by this baffle zone was sufficient for detrital sand accumulation and shoaling to occur to the leeward. Over and beyond the shoal crests, the shallow waters were of higher salinities and locally, evaporitic and emergent conditions prevailed.

(b) Type A2 cycle
Under shallow-water conditions with negligible wave energy, sand shoals accumulated on indurated pavements. Salinities and temperatures increased in the shallowing conditions, where algal mats proliferated. These were gradational with low-relief crenulated mounds in semi-emergent areas. Gypsum crystal mush developed within the sediment under evaporitic conditions in the vicinity of the mounds.

(c) Type A3 cycle
Shallow-water conditions of low energy and high salinity protected algal mat development which, near emergence, desiccated into shrinkage polygons. Gypsum crystals and anhydrite nodules precipitated within the sediment in this situation.

(d) Type P cycle
Periodic storm conditions over hypersaline shallow waters or emergent areas eroded both indurated pavements and firm grounds, producing storm-lag deposits. Following the storms, fining-upward sequences were deposited during the abating conditions. Under periods of quiescence, the resultant shoals were colonized by deposit and suspension feeders or, where conditions were more saline, induration resulted from sulphate precipitation.

(e) Type SO cycle
Submerged shoals of echinoderm detritus accumulated under normal to moderate salinities and high-tidal energy. Where these shoals were extensive, overlying waters became more saline and ooid sands accumulated to near-emergence. The shoals were subsequently indurated and eroded.

salinity within these passes during tidal cycles were probably of sufficient latitude to inhibit a destructive imbalance of algal grazers on these bioherms.

Evidence for moderately elevated salinities and temperatures in the environment is the preservation of bioherms from bioerosion, the active formation of ooids, and the formation of indurated crusts on some sediment surfaces.

Modern ooids most commonly form under slightly elevated temperatures and salinities (Newell & others, 1960; Purdy, 1963b; Lees, 1975), and in hypersaline conditions adjacent to active stromatolitic growth (Logan & others, 1974). The ooid shoals formed compact, laterally continuous belts comparable to the Y zone (Irwin, 1965) of an epeiric sea. The distinct basal contacts of this lithofacies at the base of the formation are compatible with well-defined seaward margins of an ooid shoal complex within a wave-dominant regime.

Peloid carbonate dominant lithofacies. The inferred depositional environment is shallow marine with metahaline to evaporitic conditions and limited emergence, over a platform of characteristically variable but subdued topography. Extensive shoals of low relief, with adjacent biostromes and scattered bioherms, formed a reticulate maze of elevated relief over indurated pavements and minor firm-grounds, with interspersed areas of terrigenous silt and sand sheets. A belt under weak tidal influence adjacent to the ooid shoal complex was gradational with an inner region of non-tidal conditions. In the tidal belt, rare meandering tidal channels were infilled by pebble-lag deposits (Figure 5f) and sand from migrating shoals.

Overlap of progradational shoals with time produced a cyclicity of sedimentation units which occur throughout both the tidal and non-tidal environments. Algal mat accumulations and bioherms produced shoaling, sometimes initiated under high-energy transgressions. Sedimentation was mainly by storm accumulations now preserved as type P cycles. Non-skeletal sediment was dominant, consisting mostly of peloids of variable origin (Figure 5c), faecal, algal degradation products (Logan & others, 1974), and abraded micritised particles.

Under metahaline conditions in close proximity to the tidal channels, algal bioherms were populated with sessile suspension feeders, such as ribeirioids and brachiopods, and inundated with grazing trilobites, chitons, ostracodes, gastropods, and nautiloids. Additionally, echinoderms, calcareous sponges and calcareous algae formed a sparse community over adjacent pavements. Detritus from this fauna accumulated in the tidal channels and as minor shoals. Where shoal configurations were more reticulate, and away from the tidal influence near channels, water movement was restricted and salinities were higher. Algal mats proliferated in these conditions that were adverse to grazing and bioturbating organisms.

On the periphery of emergent shoals, conditions were evaporitic with both extensive induration of sediments, and precipitation of gypsum as crystal mush with the sediment. Anhydrite nodules (Figure 5b) grew within sabkha flats that extended over the central emergent areas of the larger shoals.

Peloid and skeletal carbonate lithofacies. This lithofacies accumulated in very shallow non-tidal hypersaline conditions over flats that were restricted from normal marine tidal circulation by a barrier complex of the skeletal carbonate lithofacies (IVs). It comprises mainly skeletal detritus from a prolific fauna of sessile sponges, bryozoa, echinoderms, brachiopods, trilobites and nautiloids. Algal mats flourished on restricted shallow tidal flats.

Flat-pebble conglomerate lithofacies. Deposition was probably in hypersaline extremely shallow to emergent conditions. Extensive low-relief indurated pavements were partially covered with flat-pebble conglomerate shoals, and mixed terrigenous and peloid sands. During intermittent local transgressions, extensive domed biostromes developed over pavements of flat-pebble shoals under high-energy conditions.

This environment is similar to that of the peloid carbonate lithofacies, but had larger areas of emergence, rare tidal conditions, and dominantly conglomeratic sediments. Shoals of flat-pebble conglomerate were predominantly storm accumulations from erosion of indurated pavements (Figure 6a).

Periodic drops in salinity permitted sudden increases in the grazing fauna of trilobites and bellerophon gastropods. As salinities subsequently increased, the fauna died off and the skeletal debris accumulated as extensive laminar sheets over peloidal sediments of both faecal and algal origin. Drops in salinity were probably due to marine flooding during abnormal tides, or to seasonal runoff by continental floodwaters, which could have introduced silts and fine sand in traction and suspension. It is probable that both events occurred.

Skeletal carbonate dominant lithofacies. This lithofacies accumulated under fluctuating high-energy tidal to emergent conditions, and represents a shoal complex extending from shallow subtidal to supratidal. Salinities were mainly normal marine and only locally were there evaporitic and emergent conditions. Individual shoals (type SO cycles) comprised subtidal to intertidal accumulations of echinoderm detritus and overlying intertidal to supratidal ooid banks.

In the tidal setting, both flat-pebble conglomerates and other skeletal-peloidal sands were derived from a community that populated indurated pavements. This community was similar to those of the tidal peloid carbonate lithofacies setting. The source of the abundant echinoderm detritus is unresolved, because of a lack of knowledge of the contributing organisms. Sessile stalked pelmatozoa may have flourished in deeper normal marine or in sheltered conditions leeward of near-emergent shoals (Titus, 1979). However, the dominance of echinoderm platelets over stem ossicles in the sediment (Figure 6b) indicates only a minor contribution of these stalked forms. At this time, ophiocistoids were evolving (Ubaghs, 1966). These were mobile and armoured benthic echinozoa which would have been at an advantage to graze under normal metahaline conditions, and these may have dominated a niche previously occupied by other grazing organisms.

In the intertidal regime, mixed ooid, terrigenous, and peloidal sands accumulated in low-relief bedforms, and were mobilised in wave surge and tidal currents, as indicated by preserved herringbone cross-lamination. Locally, where intershoal areas became restricted, cryptalgalaminites (type A3 cycles) flourished in fluctuating hypersaline-evaporitic conditions. During periods of reduced salinities, these were intensely bioturbated by infauna. Adjacent, near-emergent ooid shoals were indurated under agitated hypersaline conditions. Where they were emergent, karstic dissolution modified these surfaces (Figure 6c), sulphates were leached and vadose calcretes developed in the resultant mouldic porosity.

Terrigenous lithofacies. Any inference of depositional environment from the poor exposures is speculative. The combination of interbedded sandstones and calcareous siltstones is consistent with marine shelf accumulation of sediments derived from both marine and continental sources. Component carbonate and glauconitic particles in the sandstones are indicative of a marine source. Small-scale cross-stratification, and the well-sorted mature components of the sandstones imply sublittoral deposition, with reworking and migration of the low bedforms by current activity. The absence of unstable lithic fragments is suggestive of a mature source, probably of older sandstones. This lithofacies occurs adjacent to emergent areas of uplift during Ninmaroo sedimentation.

Mixed skeletal-pebble conglomerate-peloid carbonate lithofacies. The depositional environment was one of variability from metahaline through evaporitic to emergent conditions in shallow non-tidal waters over a low but variable topography. Accordingly, diverse environmental domains were spatially adjacent and of apparently equal area, producing combined features of the peloid carbonate dominant lithofacies (IIp) and flat-pebble conglomerate carbonate lithofacies (IIIc) with fluctuating but gradual change to tidal influence and the establishment of subtidal to intertidal echinoderm shoals (lithofacies IVs).

Lithofacies distribution

The distribution of lithofacies is summarised in a west to east cross-section (Figure 8).

The ooid carbonate lithofacies forms an extensive unit that defines the base of the formation in both the Burke River Structural Belt and the Toko Syncline. It is gradational with the overlying peloid carbonate lithofacies, commonly with an increase of skeletal limestone content. Both the ooid carbonate and lower part of the peloid carbonate lithofacies form the Unbunmaroo Member of Druce & others (1976).

In the Smoky Anticline region, this lithofacies is completely dolomitised, but original fabrics are preserved in chert nodules. The stratigraphic position of the lithofacies in this region is not clear. Thinner bodies recur within the overlying peloid carbonate, flat-pebble conglomerate and skeletal carbonate lithofacies. In the Toko Syncline, such bodies overlie terrigenous rocks which are also enclosed within the peloid carbonate lithofacies.

The peloid carbonate dominant lithofacies, dominant in the lower part of the sequence, is gradational over the basal ooid carbonate lithofacies. In the Burke River Structural Belt it has variable thickness and the upper part has a well developed 'two-tone' appearance which has been mapped as the Jiggamore Member (Druce & others, 1976). In the Toko Syncline, this lithofacies may be as thick as 510 metres with enclosed bodies of ooid carbonate, skeletal carbonate and crystalline dolostone lithofacies. In the central Smoky Anticline region, type A1 cycles are common, forming prominent and extensive beds.

The peloid and skeletal carbonate lithofacies occurs only in the Burke River Structural Belt, where it has been mapped as the Datson Member (Druce & others, 1976). Locally it intertongues with the underlying skeletal carbonate lithofacies. A regolith of pre-Cretaceous age, the Swift Formation, overlies this lithofacies with unconformity.

The flat-pebble conglomerate carbonate lithofacies is recognised only in the Burke River Structural Belt as the Mort Member (Druce & others, 1976), and in the central Smoky Anticline region, where type A1 cycles are abundant. In the Burke River Structural Belt, the lithofacies is lens-shaped in north-south section, thickest at Mount Unbunmaroo, and thins towards Mount Datson in the south, and Digby Peaks in the north (Figure 8). In the Smoky Anticline region, only an eroded remnant is preserved in outcrop. This lithofacies overlies and interfingers with the peloid carbonate dominant lithofacies and grades laterally as well as upwards into the mixed lithofacies with an increasing abundance of skeletal carbonate, or into the skeletal carbonate lithofacies with an additional abrupt decrease of flat-pebble conglomerate. In the Mount Ninmaroo-Mount Unbunmaroo area, a thin lens of the ooid carbonate lithofacies is enclosed by the flat-pebble conglomerate carbonate lithofacies.

The skeletal carbonate dominant lithofacies occurs in the upper part of the formation in the Burke River Structural Belt, thickest at Mount Datson and thinning towards Mount Unbunmaroo (Figure 8). It has been mapped as the Corrie Member (Druce & others, 1976). The lithofacies interfingers with and overlies the flat-pebble conglomerate carbonate lithofacies, is laterally gradational into the mixed carbonate lithofacies, and grades up into the peloid-skeletal carbonate lithofacies. The ooid carbonate lithofacies forms a thick lens within this lithofacies at Mount Unbunmaroo.

Dolomitisation of the lithofacies is minimal at Mount Unbunmaroo, but becomes more extensive to the south, where it is gradational with the crystalline dolostone lithofacies at Mount Datson. In the Toko Syncline, only thin lenses of this lithofacies occur within thick units of ooid carbonate lithofacies.

The mixed carbonate lithofacies occurs in the Burke River Structural Belt at Mount Datson and at Digby Peaks, where it is truncated by an unconformity (Figure 8). In the Toko Syncline this lithofacies has a higher proportion of impure carbonates than elsewhere, and is overlain by sandstones of the Kelly Creek Formation. Lenses of the ooid carbonate lithofacies are enclosed in this lithofacies (Figure 8).

The terrigenous lithofacies crops out in the Toko Syncline, overlying the peloid carbonate lithofacies, and is overlain by the ooid carbonate lithofacies. In the Smoky Anticline region, this facies is not represented in the section (Figure 8), but significant occurrences have been reported south of this section line (Reynolds & Pritchard, 1964).

In the Burke River Structural Belt, the *crystalline dolostone lithofacies* cross-cuts and is gradational with other lithofacies. It is prevalent at the base of the formation at Mount Ninmaroo and Mount Datson adjacent to faulting, as well as the uppermost 130 metres of section at Mount Datson. Many areas have dolomitised beds, but commonly, sufficient features are preserved for identification of original limestone textures. Figure 8 shows the extent of this lithofacies and its cross-cutting relationships.

Regional model of sedimentation

Ninmaroo sedimentation occurred under peridital to non-tidal conditions over a stable shelf with extremely low slope. Shoaling produced local sabkha development and emergence over the centres of numerous shoals. There was a gradation from isolated sab-

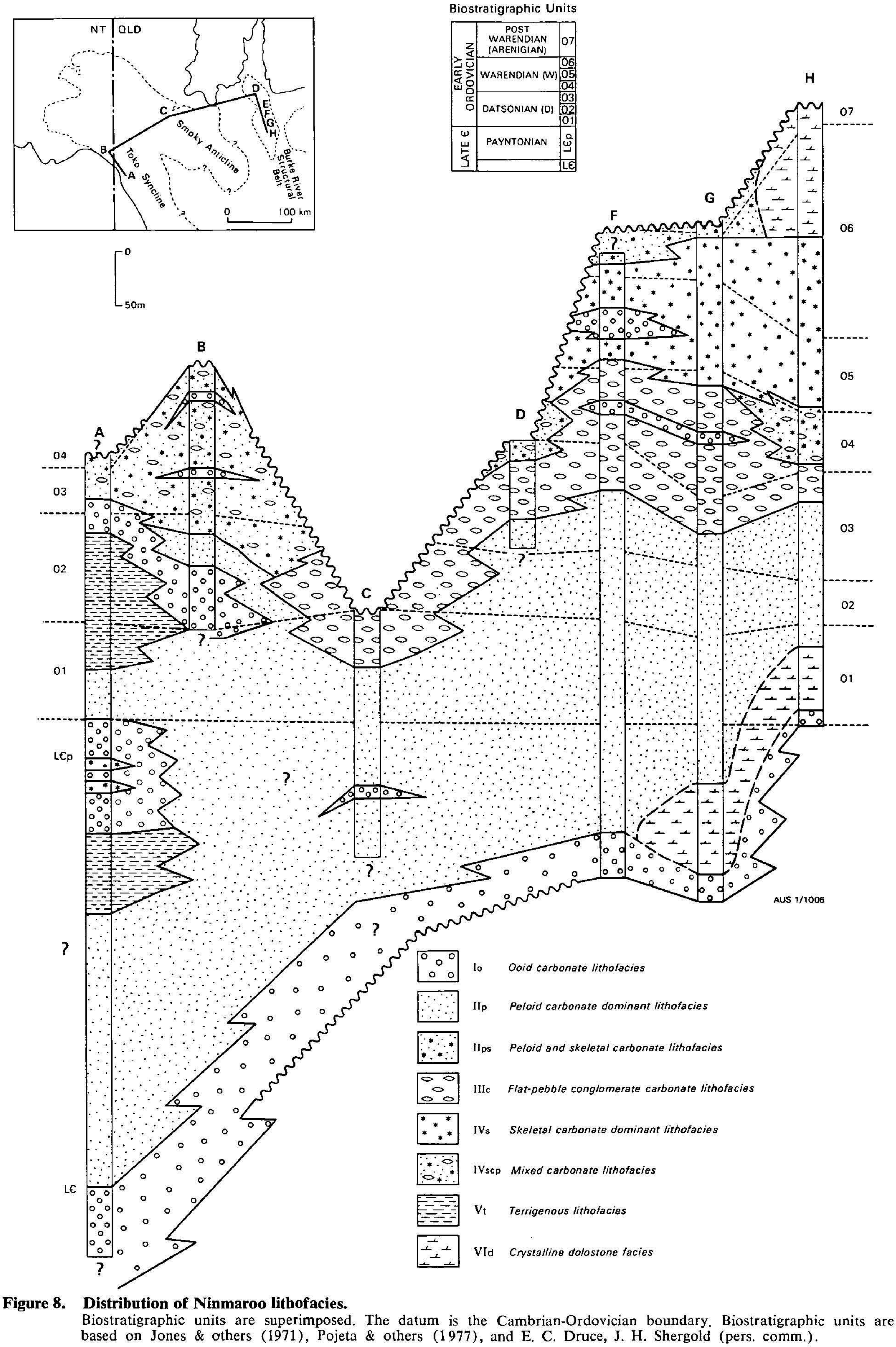


Figure 8. Distribution of Ninmaroo lithofacies.
Biostratigraphic units are superimposed. The datum is the Cambrian-Ordovician boundary. Biostratigraphic units are based on Jones & others (1971), Pojeta & others (1977), and E. C. Druce, J. H. Shergold (pers. comm.).

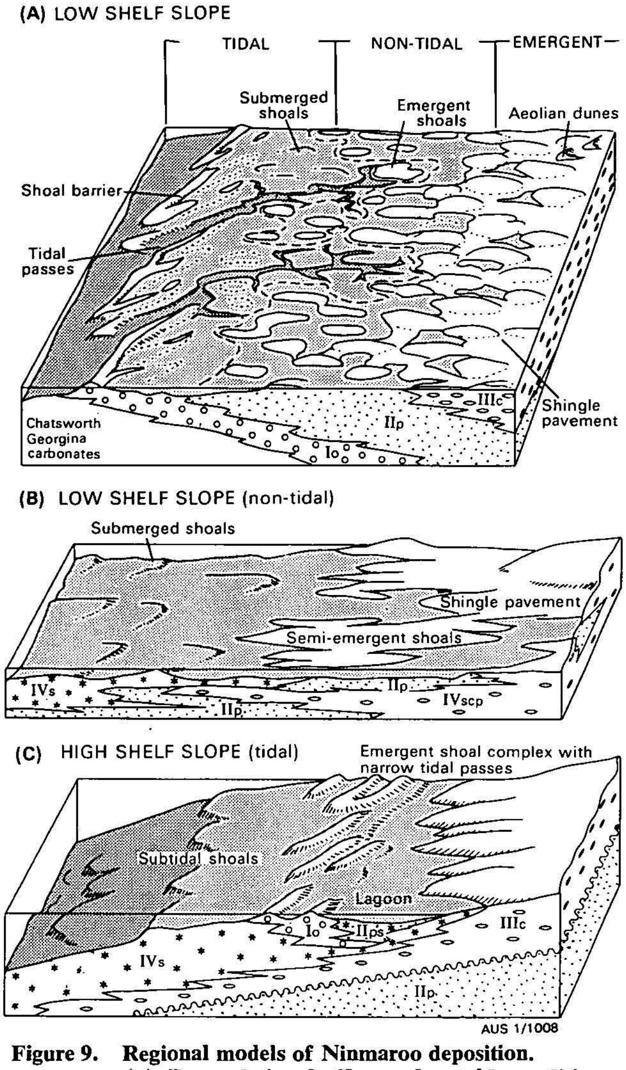


Figure 9. Regional models of Ninmaroo deposition.

(a) Progradational offlap under stable conditions
Ooid shoals (Lithofacies Io) formed an effective barrier to wave energy and restricted tidal influence into the depositional area of the peloid carbonate lithofacies (IIp), a shallow shelf with numerous shoals and mainly epeiric conditions. This region was gradational with a marginal area of more frequent emergence, the depositional site of the flat-pebble conglomerate carbonate lithofacies (IIIc).

(b and c) Sedimentation under variable tectonism
b. In regions of low shelf-slope, skeletal production waned with shoaling and increasing salinities. Consequent slower epeiric sedimentation produced skeletal - conglomerate - peloid lithofacies (IVscp) and flat-pebble conglomerate carbonate lithofacies (IIIc).
c. Where shelf slope increased with tectonism, the zones of sedimentation environments were condensed, becoming narrower and more continuous along depositional strike. Wave-resistant tidal shoals of ooid and skeletal sands barred a lagoon, depositional site of the peloid-skeletal-carbonate lithofacies (IIps), from normal marine conditions.

khas that surrounded shoals, to coalesced reticulate-patterned sabkhas, to emergent marginal areas.

Sedimentation was initiated as a progradational offlap during a relatively stable sea level. A subsequent rise in relative sea level induced a brief depositional transgression followed by a depositional regression. Throughout all phases, smaller-scale fluctuations in sea level were superimposed. Sedimentation patterns differed under both stable and rising relative sea level.

The initial stable conditions of subsidence and sedimentation over an epicontinental shelf with virtually no slope produced shoaling and offlapping of lithofacies (Figure 9a). A barrier zone (ooid carbonate lithofacies) up to 20 kilometres wide, consisted of a complex of mobile, semi-emergent ooid shoals, with a probable continuous bar and strand line on the seaward side. This barrier was punctuated by tidal passes in which large algal bioherms were able to develop. Weak tidal conditions extended behind this barrier, within and adjacent to small meandering tidal channels that were continuations of the tidal passes. Elsewhere on this restricted shelf, non-tidal conditions prevailed within a maze of shoals that probably formed a 'crazy quilt pattern' (Potter & Blakely, 1968) over an indurated pavement with algal biostromes and bioherms in locally deeper water. Over these shoals, environmental conditions ranged from hypersaline to evaporitic and emergent. The extent of shoal emergence increased landward to total emergence, where only local inundations occurred during small eustatic fluctuations on the scale of a few metres. During such inundation, algal mats re-established growth over a variety of indurated and conglomeratic substrates. Sheets of flat-pebble detritus were extensive and characterised the flat-pebble conglomerate carbonate lithofacies. Locally, small aeolian sand sheets migrated over this environment.

A relative rise of sea level restored submergence, lower salinity conditions and tidal circulation locally. Smaller short-term sea-level fluctuations were also superimposed on this trend. Prolific production of skeletal detritus from an echinoderm-dominated fauna resulted in low relief shoals of echinoderm sands. Where little or no shelf slope existed (Figure 9b), this produced progradational offlap, restricted circulation, and caused higher salinities and a return to non-tidal conditions (mixed carbonate lithofacies). This repetitive alternation of normal marine and non-tidal sedimentation was controlled by the location of faunal productivity and resultant rate of progradation of this zone with shoaling, as well as subsidence (Matti & McKee, 1976). Only where a shelf slope existed was a more distinct zonation of shoals comprising skeletal sands apparent (Figure 9c). Here, high-energy conditions produced an emergent prograding shoal barrier, which partially isolated a leeward lagoonal environment of higher salinities and restricted fauna (peloid-skeletal carbonate lithofacies). Emergence and erosion of the shoals as well as changing conditions in the lagoon resulted from smaller fluctuations of sea level.

Depositional history

Ninmaroo sedimentation (Figure 10) was initiated in the Late Cambrian with a general eastward and southeastward migration of the ooid carbonate lithofacies from the northwestern region. This basal lithofacies was conformable over and interfingered with contiguous rocks of the Georgina Limestone in the Toko Syncline and the Chatsworth Limestone in the Burke River Structural Belt, delineating a progradational offlap in these two areas. It is probable that this lithofacies was also the basal unit of a depositional onlap over the emergent Smoky Anticline region and the northern end of the Burke River Structural Belt, where the surface was locally karstified.

By early Datsonian time (01), the ooid carbonate lithofacies had prograded south, and sedimentation of the peloid carbonate dominate lithofacies was being established over the western region (Figure 10). The central Smoky Anticline area, that was emergent prior to Ninmaroo sedimentation, again became intermittently emergent during accumulation of the flat-pebble conglomerate carbonate lithofacies, and totally emergent again in 02 time. As the areal extent of emergence in the northern Smoky Anticline area increased, the flat-pebble conglomerate carbonate lithofacies extended east into the northern part of the Burke River Structural Belt and west into the Toko Syncline region, where sedimentation of the ooid carbonate, peloid carbonate and terrigenous lithofacies had prevailed earlier. By 03 time, a transgression in the Toko Syncline initiated deposition of the mixed carbonate lithofacies. By 04 time, a response in sedimentation to this now regional transgression also occurred in the Burke River Structural Belt, except in the Mount Ninmaroo-Mount Unbunmaroo area, where deposition of the flat-pebble conglomerate carbonate lithofacies continued under intermittent emergence. Ninmaroo sedimentation in the western Toko Syncline region at this time slowly receded south, in response to increasing terrigenous sedimentation of the Kelly Creek Formation to the north. By 05 time, Ninmaroo sedimentation was confined to the Burke River Structural Belt, where deposition of the skeletal carbonate lithofacies under productive normal marine conditions produced a progradational offlap. Deposition of the peloid-skeletal carbonate lithofacies began in the north of the Burke River

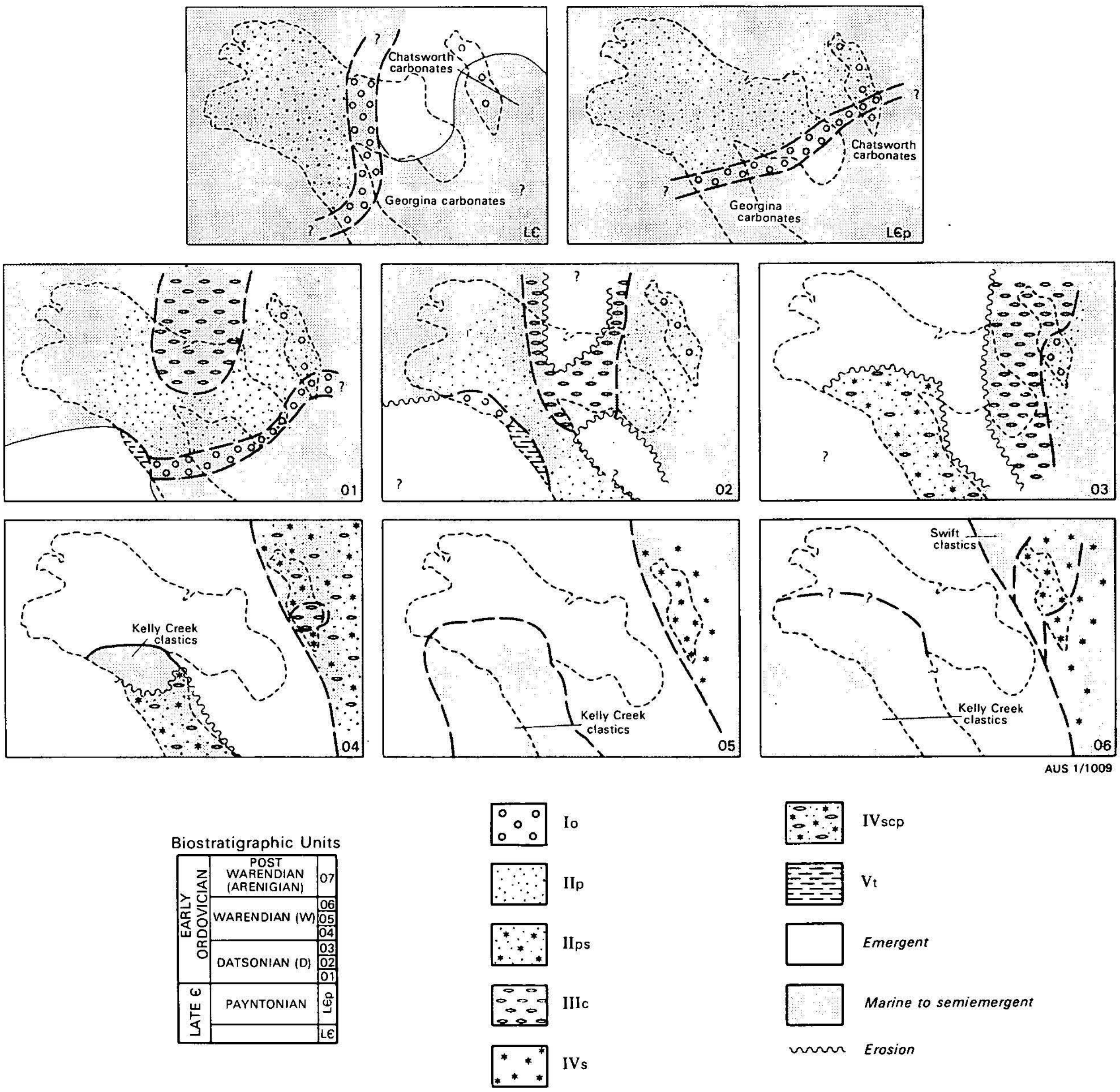


Figure 10. Ninmaroo sedimentation in time — Lithofacies distribution from early? Payntonian (Late Cambrian) to Warendian (Early Ordovician).

Io	Ooid carbonate lithofacies.
IIp	Peloid carbonate dominant lithofacies.
IIps	Peloid and skeletal carbonate lithofacies.
IIIc	Flat-pebble conglomerate carbonate lithofacies.
IVs	Skeletal carbonate dominant lithofacies.
IVscp	Mixed carbonate lithofacies.
Vt	Terrigenous lithofacies.

Structural Belt, prograded south over the skeletal carbonate lithofacies, and was followed by siltstones of the Swift Formation. By 06 time, this peloid-skeletal carbonate lithofacies dominated the waning Ninmaroo sedimentation, which continued into 07 time.

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The Toomba Fault and the western margin of the Toko Syncline, Georgina Basin, Queensland and Northern Territory

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The Toomba Fault is a major basement fault which extends for 200 km and forms part of the southwest margin of the Lower Palaeozoic Georgina Basin. Structural data from five detailed seismic and gravity profiles over the Toomba Fault establish that it is a high-angle reverse fault, with a dip varying between 40° and 70° and vertical displacement up to 6.5 km. The Palaeozoic strata to the northeast of the fault are steeply upturned, overturned, or folded into anticlines or monoclines. Associated faulting varies from small-throw faults to fracture zones 4 km wide, and reverse faulting.

These data are consistent with other geological evidence that the area of the Toko Syncline was under general northerly compression during Late Devonian or Early Carboniferous time, and that right-lateral wrenching occurred along the fault, with up to 4 km of horizontal displacement. The presence of compressional features in adjoining Palaeozoic sediments indicates oblique convergence of crustal blocks during the wrenching. The area immediately east of the fault has several types of potential hydrocarbon traps. Up to 10 km of Adelaidean strata underlie Palaeozoic sediments within the Toko Syncline and up to 3.5 km of these sediments are present west of the syncline. A near-surface low-velocity layer, up to 250 m thick, west of the Toomba Fault, and concealed by sand and alluvium, probably comprises Jurassic to Cretaceous strata.

Introduction

The Georgina Basin occupies about 325 000 sq km in the Northern Territory and Queensland (Fig. 1). It contains Upper Adelaidean to Lower Cambrian shallow marine and glacigene clastic sediments and dolostones; Middle Cambrian and Ordovician shallow-marine carbonate, sandstone and siltstone; and some Devonian fluvial sandstone and conglomerate. It is bounded on the west and east by Precambrian rocks of the Arunta and Mount Isa Blocks respectively. Much of the northern half of the basin contains less than 500 m of Palaeozoic section, but in the southeast the Toko Syncline contains the thickest section, up to 5000 m of Palaeozoic strata.

The stratigraphy of the Toko Syncline, summarised in Table 1, has been discussed by Smith (1972), Shergold & others (1976), Shergold & Druce (1979), and Draper (1976, 1977). Previous geophysical work in the Toko Syncline has been reviewed by Mathur & Bauer (1977), Vale (1978), and Harrison (1979).

The Toomba Fault is a major structure, about 200 km long, which separates Adelaidean sediments and basement of the Arunta Complex in the west from the Cambro-Ordovician Toko Syncline in the east (Fig. 2). Earlier studies had failed to define clearly the nature of the Toomba Fault, and in particular could not distinguish whether the fault displacement was normal or reversed. The nature of the fault and the structure of the adjoining sediments are important in understanding the evolution of the Toko Syncline and, thereby, in assessing its petroleum potential. These aspects are also important in understanding the regional structure and tectonics of central Australia.

Reynolds (1968a, 1968b) concluded that the Toomba Fault was a high-angle reverse fault because juxtaposed beds are overturned in several places. However, Smith (1972) considered that the fault was normal and that overturning was caused by hill-creep, collapse, slumping or cross-faulting.

The regional gravity field (Fig. 3) and the magnetic field shed little light on the nature of the fault or the structure of the adjoining sediments, but do indicate that the Toko Syncline is a deep depression plunging

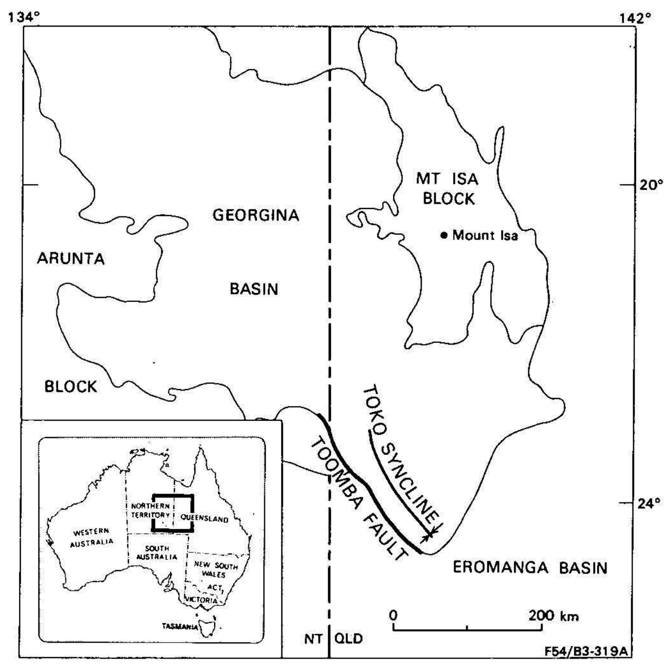

Figure 1. Regional setting of the Toko Syncline and Toomba Fault.

southeast beneath Mesozoic and Quaternary cover. Seismic surveys between 1960 and 1970 indicate that the Toko Syncline is an asymmetrical trough, with steep dips along its deeper, western side and gentler dips on its shallower eastern flank. The total sedimentary thickness was indicated to be 6000 m (5000 m of Palaeozoic, 1000 m of Cretaceous) and the presence of older (Adelaidean?) strata beneath the syncline was inferred from some discontinuous deep reflections in some areas. Seismic lines recorded across the Toomba Fault gave no clear indication as to its nature.

Recent geological mapping west of the Toomba Fault (Walter & others, 1978) indicated compressional features (Fig. 2) such as broad folds, notably the Field River Anticline and Desert Syncline, the latter contain-

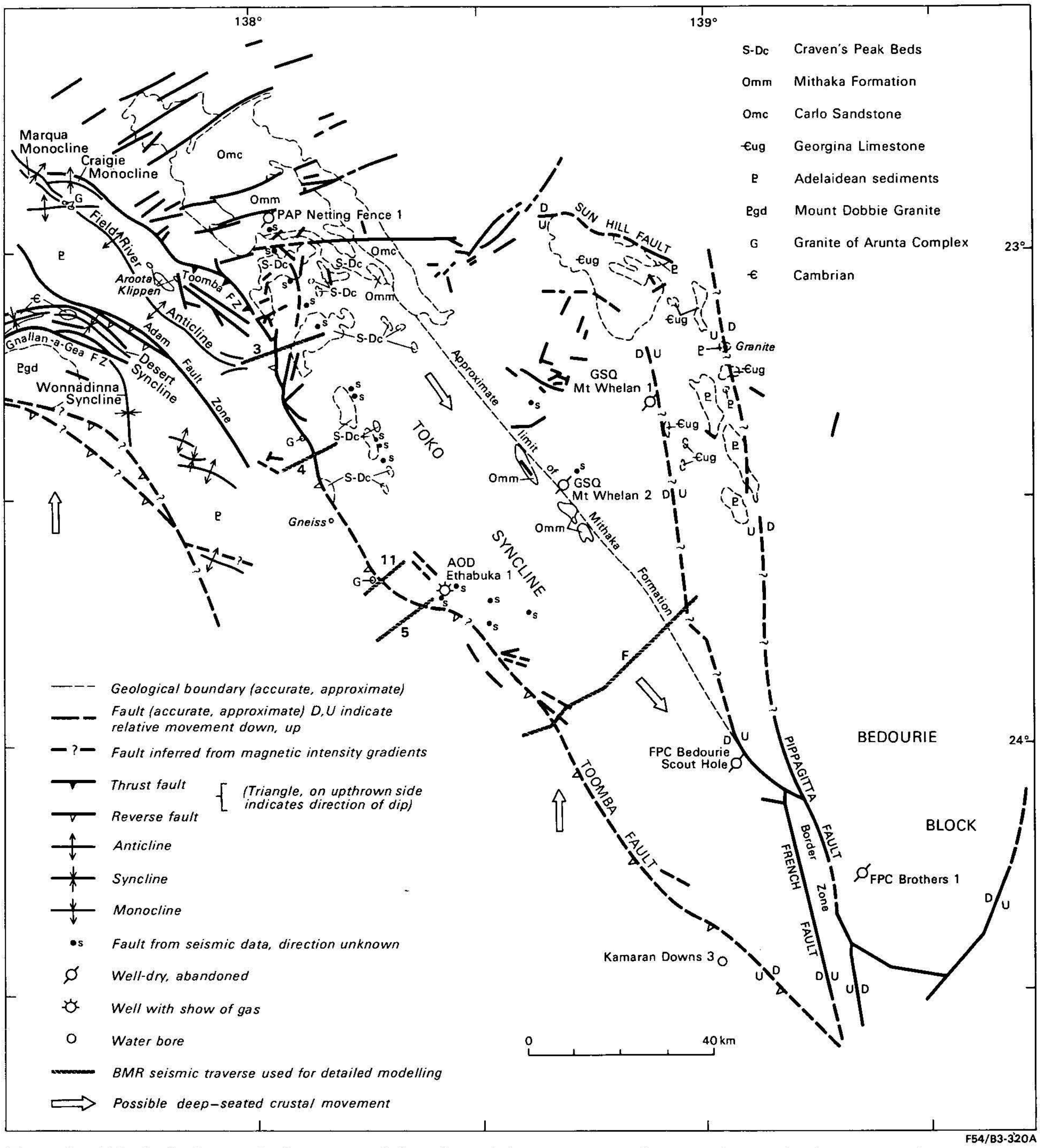

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Figure 2. Principal structural elements and location of traverses used for combined seismic and gravity modelling. Directions of possible deep-seated crustal movements during Alice Springs Orogeny are shown.

ing 400 m of Palaeozoic strata; and Klippen (Aroota Klippen) of Adelaidean strata.

The 1977 BMR seismic and gravity survey in the Toko Syncline aimed at investigating the nature and structure of the Toko Syncline, and particularly the nature of the Toomba Fault. The survey was tied to wells to identify recorded reflections, and included five traverses across the fault (Fig. 2). The survey used modern digital recording with mainly six- and twelve-fold CDP coverage and dynamite or geoflex sources (Harrison & Schmidt, 1978). The main results of the survey bearing on stratigraphy and petroleum prospects are given by Harrison (1979). The present paper interprets the combined seismic and gravity profiles which contribute to the interpretation of the Toomba Fault and the structure of the western margin of he Toko Syncline.

Method of study

Modelling of the sub-surface geology was made along five profiles crossing the Toomba Fault (Appendix, Figs. 5 to 10).

Reflections were identified by ties to PAP Netting Fence 1 and AOD Ethabuka 1 wells, and GSQ Mount Whelan 1 & 2 coreholes (Harrison, 1979).

Along each of the seismic profiles over the Toomba Fault, reflections were converted to depth using average velocities obtained from either the stacking or RMS velocities, derived from digital analyses or expanded spreads, respectively. Interval velocities for key inter-

Age	*Formation*	*Lithology*	*Maximum thickness (m)*	*Mean interval velocity (m/s)*	*Density used (t/m³)*	
EARLY CRETACEOUS	Hooray Sandstone	Sandstone	?	2000	2.1	
DEVONIAN	Cravens Peak Beds	Sandstone Conglomerate	280	3200	2.4–2.6	
MIDDLE ORDOVICIAN	Ethabuka Beds	Sandstone Conglomerate	1170+			R
MIDDLE ORDOVICIAN	Mithaka Formation	Siltstone Sandstone Shale	126	4050	2.4–2.6	R
? MIDDLE ORDOVICIAN	Carlo Sandstone	Sandstone	174			
EARLY ORDOVICIAN	Nora Formation	Sandstone Siltstone Limestone	231	4250	2.5–2.6	
EARLY ORDOVICIAN	Coolibah Formation	Limestone Marl	79			R
EARLY ORDOVICIAN	Kelly Creek	Sandstone Siltstone Dolomite Evaporite	182?			
EARLY ORDOVICIAN -LATE CAMBRIAN	Ninmaroo Formation	Limestone Dolomite Sandstone	488+	4900	2.75	R
LATE CAMBRIAN	Georgina Limestone	Limestone Dolomite Sandstone	601			
MIDDLE CAMBRIAN	Steamboat Sandstone	Calcareous sandstone Sandy limestone	221	5400	2.75	
MIDDLE CAMBRIAN	Marqua Beds	Limestone Dolomite Sandstone Shale	410			
MIDDLE CAMBRIAN	Thorntonia Limestone	Limestone Dolomite Chert	49			R
ADELAIDEAN-EARLY CAMBRIAN	Former Field River Beds	Arkose Tillite		5200	2.70	

R SEISMIC REFLECTION

Table 1. Stratigraphy, interval velocities, and densities.

vals shown in Table 1 were calculated from the foregoing seismic velocities, some well sonic logs and a well-shoot in GSQ Mount Whelan No. 2. These interval velocities were used to convert times to depths in some areas of complex structure near the Toomba Fault; they were used also to assist in defining structure.

Surface geology and shot-hole sample results were plotted onto each profile. The seismic depth information and the near-surface information were used together to derive an interpretation of the sub-surface geology along the profile. Air photos were used to check the surface position of the Toomba Fault (E. C. Druce, BMR pers. comm., 1978).

The thickness and velocity of shallow refractors, determined from first-breaks on normal reflection records, were also plotted on the profiles.

Estimates of the densities appropriate for the sediments and basement rocks were determined by examining earlier work. Few density measurements are available for rocks in the Georgina Basin, and most of them apply to Palaeozoic sediments, particularly carbonates (Gibb, 1967). There are some unpublished BMR core density measurements, which show similar mean densities for Adelaidean, and for Palaeozoic rocks (mainly Cambrian carbonates), taken over the whole basin. However, in five out of six wells which intersected both Adelaidean and Cambrian strata, the mean density of the latter rocks in the well exceeded that of the former. Interval velocities derived from seismic and well data were also used to study possible density changes within the sedimentary section (Table 1). Densities were assigned to intervals on the seismic depth models and the calculated gravity was compared to the observed profiles. Adjustments were made to the densities to obtain the best fit between the calculated and observed gravity.

The detailed gravity modelling across the Toomba Fault in the present paper used regional models by Tucker & others (1979), and Mathur (BMR pers. comm., 1979) as starting models.

The present study assumed a constant crustal thickness and constant basement density within the area of the Toko Syncline; this follows Tucker & others (1979), and Rumph (1978), who consider that the Toko Syn-

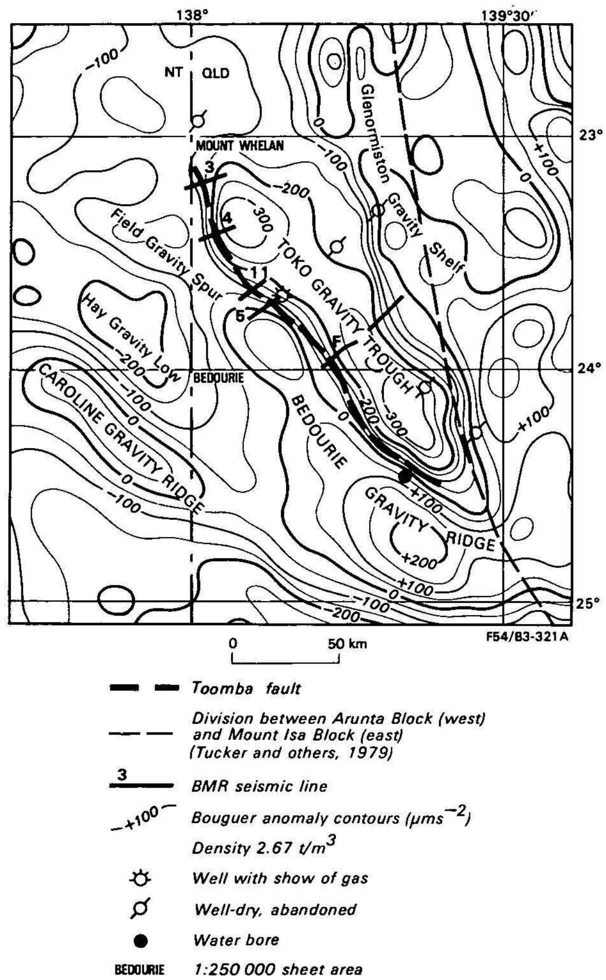

Figure 3. **Regional Bouguer anomaly contours and location of traverses used in modelling.**

cline area is underlain by a single domain, the Arunta Block, and who place the boundary between the Arunta Block and Mount Isa Block just east of the syncline (Fig. 3).

Discussion

The disposition of the Toomba Fault

The sub-surface models across the Toomba Fault (Appendix) indicate that it is a high-angle reverse fault that varies in direction and dip along its length. The subcrop of the fault and the westerly extent of Palaeozoic sediments beneath the fault plane are shown on Figure 4, with interpreted sections along the five seismic traverses (3, 4, 11, 5 and F) discussed in the Appendix. The varying dip of the fault plane is indicated (Fig. 4) by the varying horizontal distance that the fault plane overlies the sediments. On traverses 4, 5 and F the dip is 40°-50°, and the fault overlies Palaeozoic strata for 3.5 to 4 km. On traverse 11, however, the fault is steeper, about 70°, and the corresponding distance is only 700 m. On traverse 3, the dip is imprecisely known but is greater than 50°.

Some small magnetic anomalies on MOUNT WHELAN indicate shallow magnetic sources less than 400 m deep (D. Tucker, BMR, pers. comm., 1979) where Palaeozoic sediments are about 4 km thick. The anomalies form a line coincident with the interpreted Toomba Fault trace between 23°50′S and 24°S (Fig. 4). There is no evidence for intrusions within the Georgina Basin sediments, thus the anomalies support the interpretation of reverse faulting. An isolated circular anomaly near intersection of lines 12 and B (Fig. 4) may arise from a detached piece (Klippe) of overthrust basement.

Deformation of Palaeozoic strata east of the fault

The structure of the Palaeozoic strata east of the fault varies along its length. North of 23°30′S, where Palaeozoic rocks are exposed east of the fault, the strata have steep easterly dips (80° near traverse 3) and in several places are overturned (with westerly dips of 60°, north of traverse 4). South of 23°30′S the Palaeozoic sediments are concealed by Mesozoic or Quaternary cover; here the sub-surface structure has been inferred from geophysical data alone. There is a broad fold centred between traverses 11 and 5 called the Mirrica-Ethabuka Structure (Harrison, 1979). The structure is an asymmetrical anticline with a long easterly limb, but considerably shorter western limb. It has up to 1000 m vertical closure and is parallel to the Toomba Fault (Fig. 4). On traverse F, near 24°S, the strata dip monoclinally to the west.

The sediments east of the Toomba Fault have been fauted to varying degrees as indicated by breaks in reflection continuity, diffractions and zones of no reflection. On traverses 3 and 11 there are a few faults with small throws.

On traverses 4 and F there is a zone 4 to 5 km wide of poor to no reflections, with sudden loss of reflection continuity. These zones may consist of numerous faults with throws less than 50 m. On traverse 5 there is complex faulting with several faults with small throws (less than 50 m) and a high-angle reverse fault with about 500 m vertical displacement, dipping about 45° east (opposite to the Toomba Fault). The two reverse faults on this traverse may form a conjugate pair.

Structural development of the western margin of the Toko Syncline

The area of the Toko Syncline was uplifted, tilted to the south and eroded after the Middle Ordovician. This ended the almost continuous marine deposition that had taken place since Early Cambrian. The first recognized movement of the Toomba Fault in the Palaeozoic was in early Devonian, when the Craven's Peak Beds were deposited (Draper, 1976). High-angle reverse movement on the fault and deformation of the adjacent sediments occurred in post-Middle Ordovician time; it is likely that it was coincident with the Alice Springs Orogeny, of Late Devonian to Early Carboniferous age (Playford & others, 1976). It is however, possible that the deformation occurred at an earlier time, such as the Pertnjara Movement during Middle to Late Devonian time in the Amadeus Basin (Wells & others, 1970).

Fault displacement. There has been significant vertical movement on the fault: the minimum vertical displacement deduced from the maximum thickness of Palaeozoic sediments preserved next to the fault is 5 km. It is estimated that about 1.5 km of Palaeozoic strata were removed by erosion, hence the vertical displacement could have been up to 6.5 km. The amount of erosion was estimated by considering the projected thinning out of several Palaeozoic formations between AOD Ethabuka 1 and PAP Netting Fence 1, and between GSQ Mount Whelan 1 and 2.

There is independent geological evidence of significant strike-slip movement on the fault.

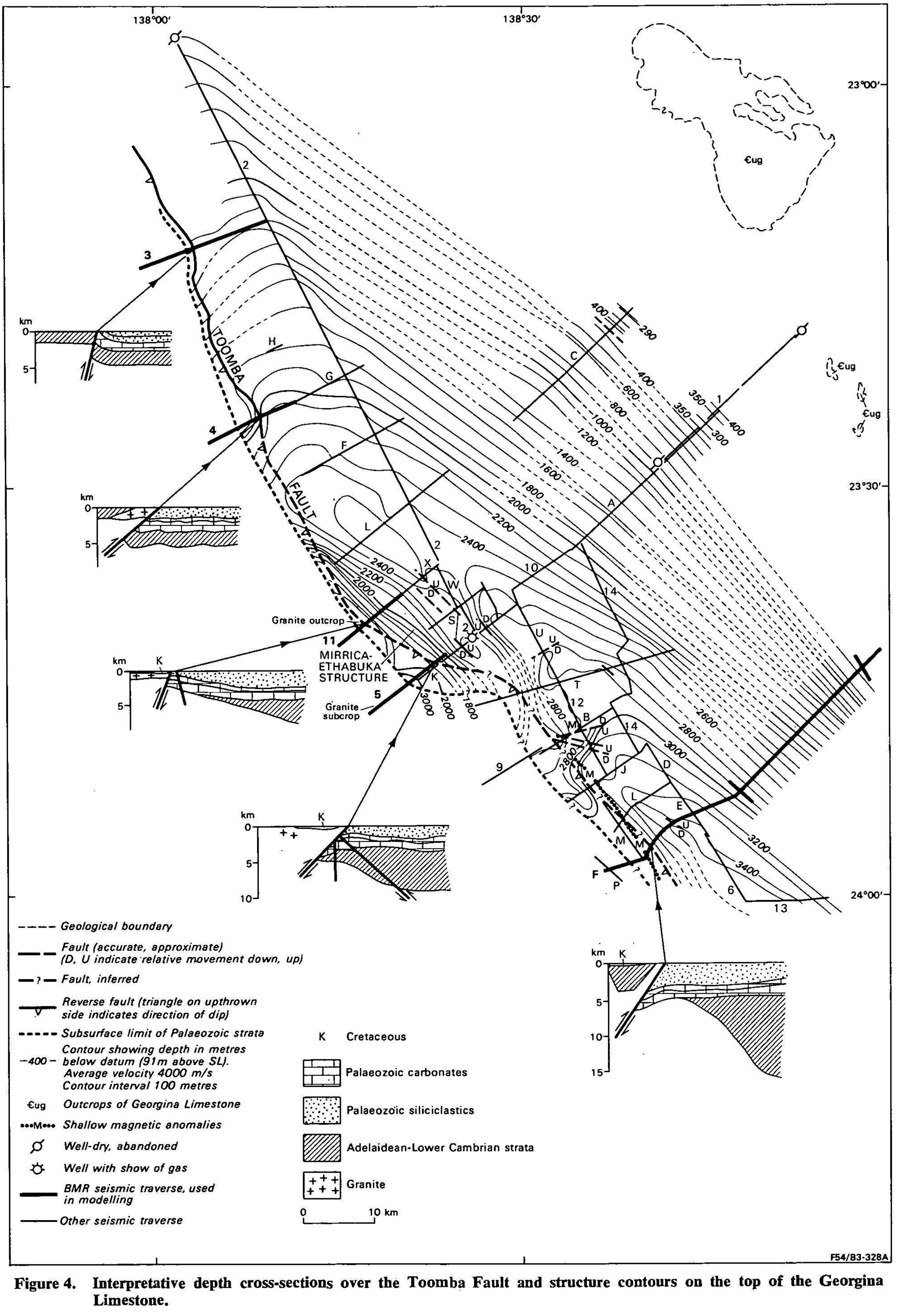

Figure 4. Interpretative depth cross-sections over the Toomba Fault and structure contours on the top of the Georgina Limestone.

Simpson and Walter (BMR, pers. comm., 1979) suggest that the area of the Toko Syncline was under northerly compression during the main (Alice Springs Orogeny) deformation. The evidence they cite comes from detailed geological mapping on the ADAM SPECIAL 1:100 000 sheet (Walter & others, 1978; see also Fig. 2). The circular outcrop of Proterozoic granite (Mount Dobbie Granite) west of the Toomba Fault has a folded syncline of Adelaidean and Palaeozoic sediments around its northern edge. The fact that the folding is greatest on the northern side and decreases on the easterly side indicates the principal compressive stress was northerly. They consider that the strike-slip component on the Toomba Fault (from sectional reconstructions) was about 4 km of right-lateral movement.

Fault mechanism. The variation in the style of deformation of the Palaeozoic sediments adjoining the fault, from steep folding to overturning in the north, to broad anticlinal folding in the central area to monoclinal folding in the south, make it difficult to explain the structural development in detail along a typical or average profile, as was done for example by Howard (1966) for the Williams Range Thrust in Colorado, USA. The difficulty was compounded by the distances between profiles (10-40 km) and the paucity of outcrops.

The geophysical studies have not provided direct evidence to confirm or disprove significant strike-slip movements on the fault. Naturally, with up to 6.5 km vertical movement, any Palaeozoic sediments west of the fault, which might have provided such evidence, have been eroded.

However, invoking significant wrenching makes it possible to explain most of the structures in the area of the Toko Syncline by one major phase of crustal movement. If wrenching is not invoked, the variation in structures adjoining the fault seems to require several periods of movement or re-alignment of stress patterns by basement irregularities.

The mechanics of wrenching and the structures associated with wrenching have been discussed by Wilcox & others (1973), and Harding (1974, 1976). They describe oblique, convergent wrenching as a type of wrenching in which crustal blocks move side-by-side and obliquely together, thereby emphasizing compression. As a result, reverse faulting often occurs, and en echelon folds often develop at a low angle to the wrench. The Whittier Fault along the northeast margin of the Los Angeles Basin (Harding, 1974, 1976) is an example of a typical oblique, convergent wrench. This fault is similar in several aspects to the Toomba Fault. It has right-lateral displacement of up to 4.8 km, vertical displacement up to 4250 m, is a reverse fault dipping between 65° and 75°, and folds have developed in the adjoining sediments on its downthrown side. There is also a strongly squeezed structural 'pucker' directly along the fault, with horizons on either side of the fault dipping steeply away from it in several places. One major half-anticline—the Whittier structure which includes the Whittier oilfield—lies parallel to the fault with vertical closure of about 1000 m. This structure is very similar to the Mirrica-Ethabuka Structure (Fig. 4) next to the Toomba Fault. Both structures occur where their associated faults have significant bends. The bends in the fault planes appear to have enhanced the compressive effect of the wrenching, presumably by increasing resistance to strike-slip movement. The result has been formation of large folds.

It is proposed that the Toomba Fault is an oblique convergent wrench with significant vertical and horizontal displacement. The deep-seated crustal movements believed responsible for the wrenching are indicated on Figure 2.

A major north-northwesterly to northerly-trending horst along the eastern edge of the Toko Syncline (Fig. 2) may also be explained by the oblique convergent wrenching. This horst corresponds with the Border Zone (FPC, 1965) in the south and a ridge of Adelaidean outcrops in the north. The feature coincides with the major crustal boundary between the Arunta and Mount Isa Blocks (Fig. 3). It is suggested that the horst formed along a line of crustal weakness as a reverse-faulted block during wrenching which moved the Toko Syncline in a southeast direction (Fig. 2) during the Alice Springs Orogeny.

Recognizing that the major deformation of the Toko Syncline sediments was by oblique convergent wrenching suggests a variety of potential hydrocarbon traps adjacent to the fault zone. These could comprise half-folds parallel to the fault, such as the Mirrica-Ethabuka structure; or en echelon folds at angles up to 45° to the fault, extending into the syncline, en echelon drag folds, homoclines and fault blocks formed by subsidiary reverse and normal faults.

Conclusions

The Toomba Fault on the western margin of the Toko Syncline is a high-angle reverse fault for 200 km. The fault plane dips between 40°W and 70°W and extends over Palaeozoic strata for from 4000 to 700 m. The adjoining Palaeozoic sediments in the north are steeply folded to overturned; in central MOUNT WHELAN they are folded in a broad asymmetrical anticline, and in the south they form a monocline. The strata are also faulted, varying from putative faults with throws less than 50 m, to fracture zones about 4 km wide; in one area there is a high-angle reverse fault opposite in direction to the Toomba Fault.

The deformation of the Palaeozoic strata in the Toko Syncline was post-depositional, and occurred in post-Middle Ordovician time, probably during the Late Devonian to Early Carboniferous Alice Springs Orogeny.

The deformation occurred during general northerly compression which resulted in oblique slip movement along the Toomba Fault, with up to 4 km right-lateral displacement and up to 6.5 km of vertical displacement. The presence of compressional features in the Palaeozoic sediments adjoining the fault indicates oblique convergence of crustal blocks during wrenching.

There are several types of potential hydrocarbon traps in Palaeozoic sediments immediately east of the fault.

Thick Adelaidean strata (up to 10 km) are indicated within the Toko Syncline and in places just west of the Toomba Fault, where up to 3.5 km may be present.

A near-surface low-velocity layer west of the Toomba Fault, up to 250 m thick, which is concealed by sand and alluvium, is probably Jurassic to Cretaceous strata seen in outcrop on HAY RIVER and southern MOUNT WHELAN. The layer is most important in explaining small-wavelength anomalies on the gravity profiles.

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Appendix

Geological and geophysical profiles across the Toomba Fault

The results of combined studies of outcrops, near-surface refractors, seismic and gravity data are discussed for each traverse over the Toomba Fault, from north to south.

Traverse 3 (Fig. 5)

Four reflections within the Toko Syncline were mapped in this traverse: top of Carlo Sandstone, top of Coolibah Formation, top of Georgina Limestone and base of Middle Cambrian. Good rock exposures along the traverse have enabled the Toomba Fault to be located, as Palaeozoic rocks are mapped east of the fault with easterly dip of 80° (Reynolds, 1968a). The seismic reflector at the top of Coolibah Formation is almost horizontal and about 800 m deep near SP 3870, but at SP 3860, just 830 m further west, it crops out with 80° easterly dip. The surface geology and seismic data therefore indicate steep upturning of the Palaeozoic section adjacent to the Toomba Fault.

West of the fault, weak, discontinuous reflections were recorded at 0.7 s, between SP 3810 to 3742, where Adelaidean Yardida Tillite and Black Stump Arkose crop out. The reflections are probably from within a sequence of Adelaidean sediments, which Walter (BMR pers. comm., 1979) estimates are up to 6000 m thick on HAY RIVER southwest of the traverse. The reflections suggest a gentle anticline at the western end of the traverse and this is consistent with observed folding of the Adelaidean rocks there (Reynolds, 1963).

The small gravity high in the centre of the profile is attributed to upturned Coolibah Formation and older formations which are mainly carbonates and are denser than both the overlying Palaeozoic siliciclastics and the Adelaidean arkoses and tillite west of the fault (see Table 1). The lower gravity values east of the fault have been successfully modelled by assuming that a similar thickness (about 2 km) of Adelaidean strata of lower density than the Arunta Complex extends east of the fault. There is some reflection evidence for the presence of these strata below the Middle Cambrian, indicated by reflections at about 1.3s east of the fault (Fig. 5) and on other traverses in the syncline. Also, GSQ Mount Whelan 1 intersected about 150 m of these rocks on the eastern flank of the syncline (P. Green, GSQ, pers. comm., 1978). A small gravity low centred near

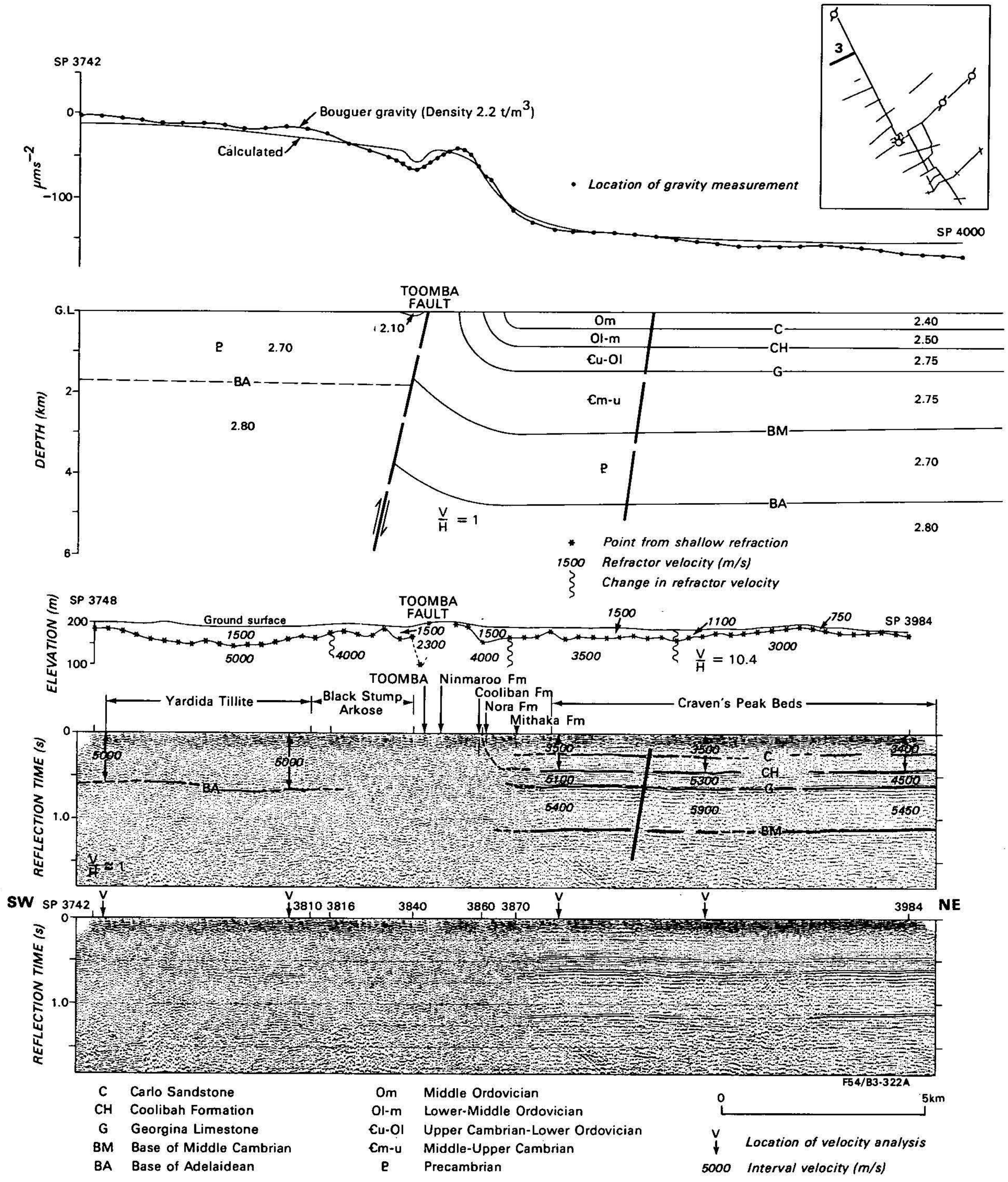


Figure 5. Traverse 3: Uninterpreted and interpreted seismic, shallow refraction model, seismic and gravity depth model, and observed and calculated gravity.

SP 3840 may be partly explained by shallow, low-density strata, evidence for which is shown by the small trough (2300 m/s) on the refractor depth section.

The angle of the Toomba Fault cannot be determined from the available data, although it is likely to be reverse, as on the other traverses. Here it lies between vertical and 50° west, the latter limit imposed by the continuity of reflections between SP 3742 to 3816. In the gravity modelling, the fault angle was varied between these limits, but made no appreciable difference to the calculated gravity effect.

Traverse 4 (Fig. 6)

The reflection quality on this traverse is generally poor, probably owing to faulting of the Palaeozoic strata east of the Toomba Fault. Three main reflections can be followed for a short distance on the eastern end of the traverse. They become very poor near SP 4958 and cannot be followed continuously further west. At about SP 4900 reflections are again recorded over a short distance, and three reflections are correlated by comparing their character with those in the east. The surface location of the Toomba Fault from aerial photographs is at SP 4916 and Adelaidean sediments and

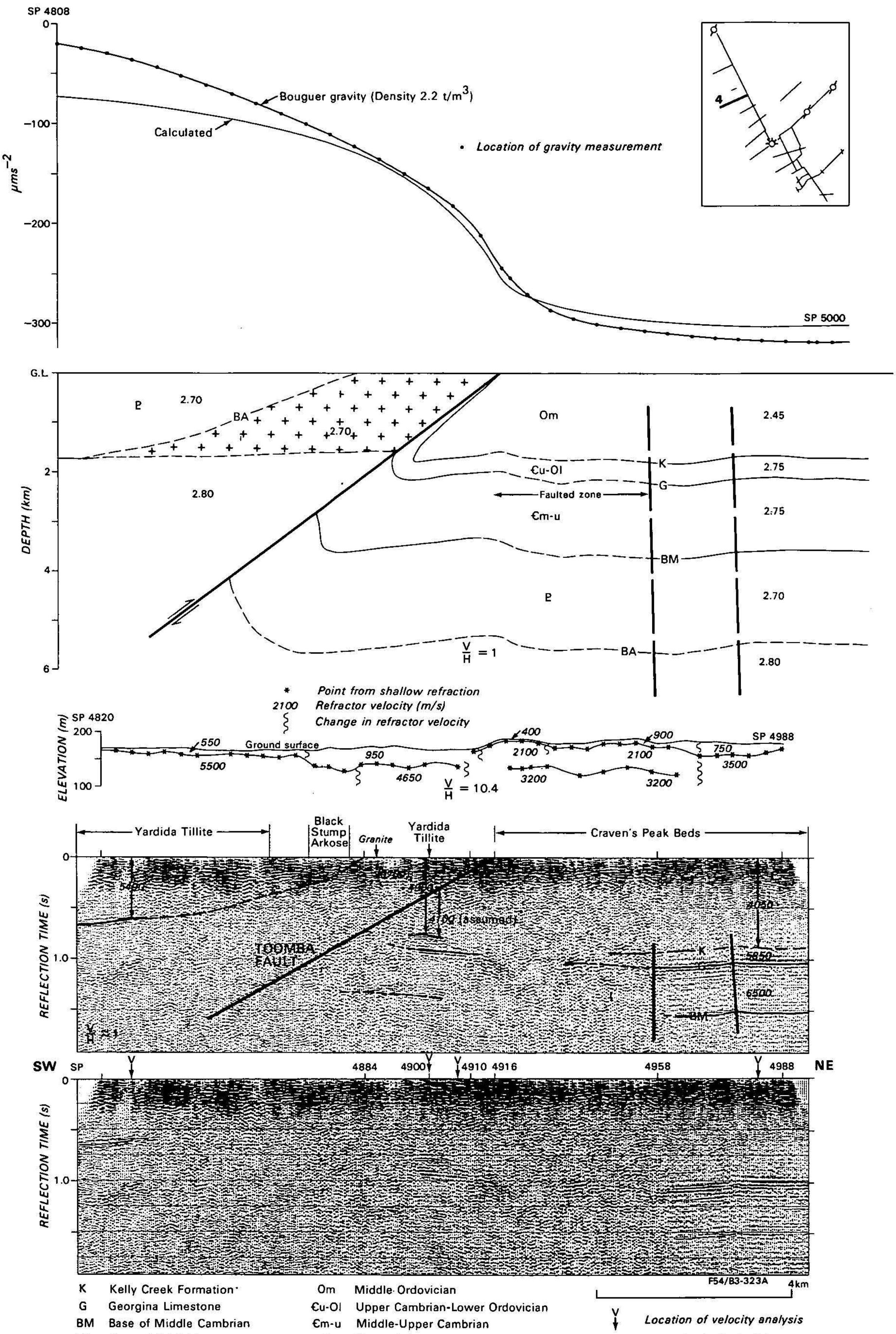
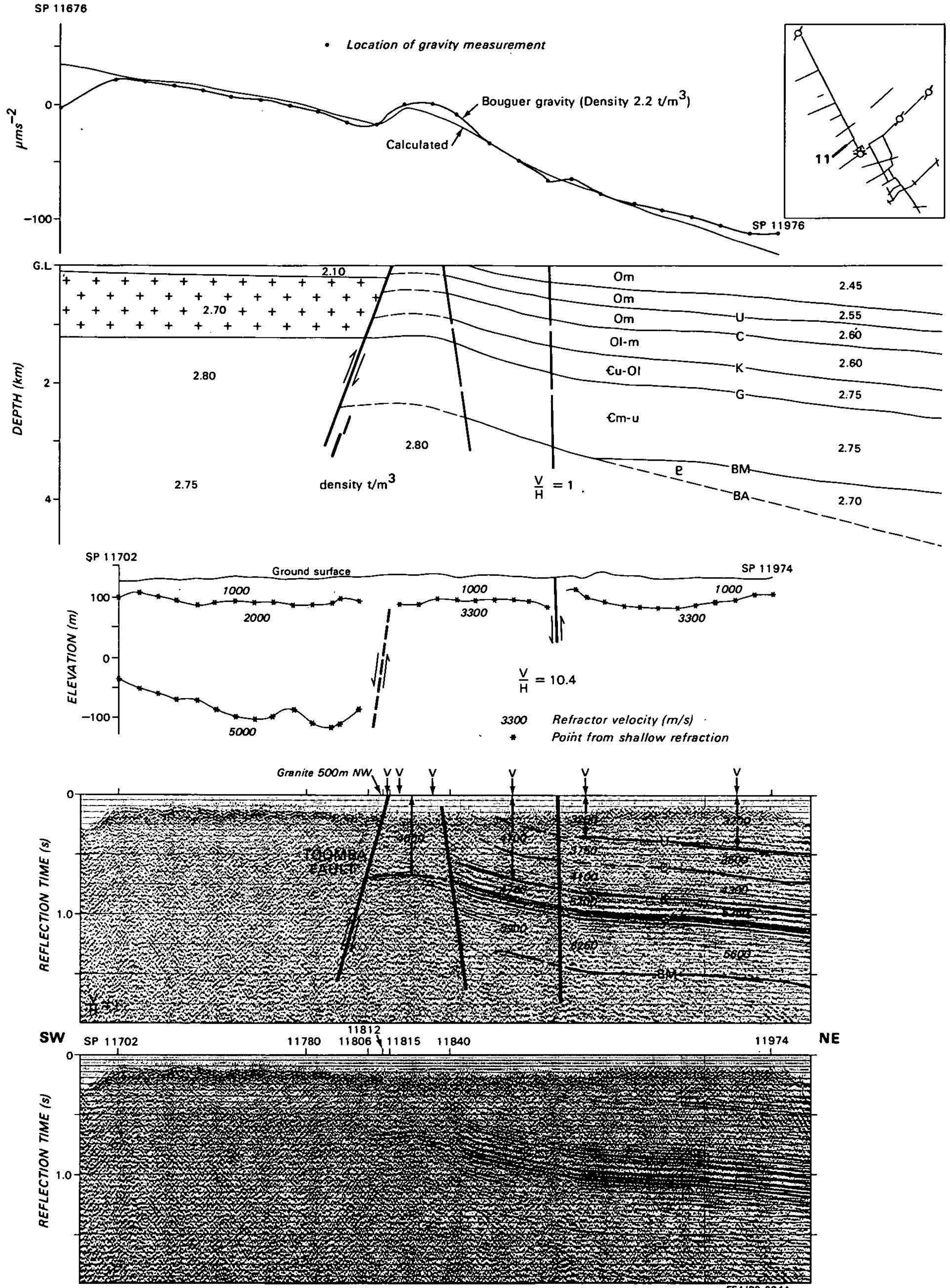


Figure 6. Traverse 4: Uninterpreted and interpreted seismic, shallow refraction model, seismic and gravity depth model, and observed and calculated gravity.



U	Unconformity within Ethabuka Beds	Om	Middle Ordovician	0 — 3 km
C	Carlo Sandstone	Ol-m	Lower-Middle Ordovician	V ↓ *Location of velocity analysis*
K	Kelly Creek Formation	Ꞓu-Ol	Upper Cambrian-Lower Ordovician	*5900 Interval velocity (m/s)*
G	Georgina Limestone	Ꞓm-u	Middle-Upper Cambrian	
BM	Base of Middle Cambrian	Ᵽ	Precambrian	
BA	Base of Adelaidean	+ +	Granite	

Figure 7. Traverse 11: Uninterpreted and interpreted seismic, shallow refraction model, seismic and gravity depth model, and observed and calculated gravity.

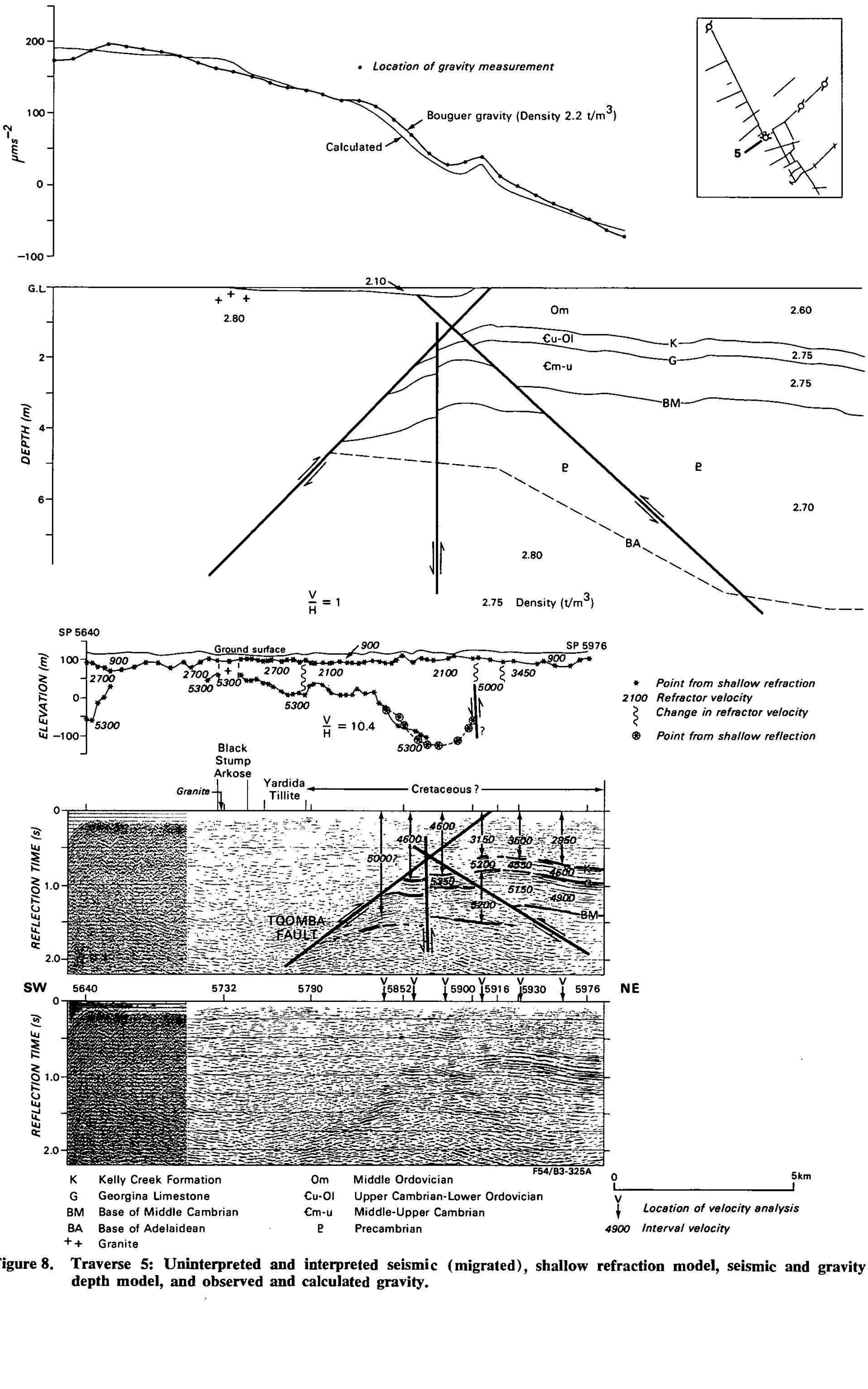


Figure 8. Traverse 5: Uninterpreted and interpreted seismic (migrated), shallow refraction model, seismic and gravity depth model, and observed and calculated gravity.

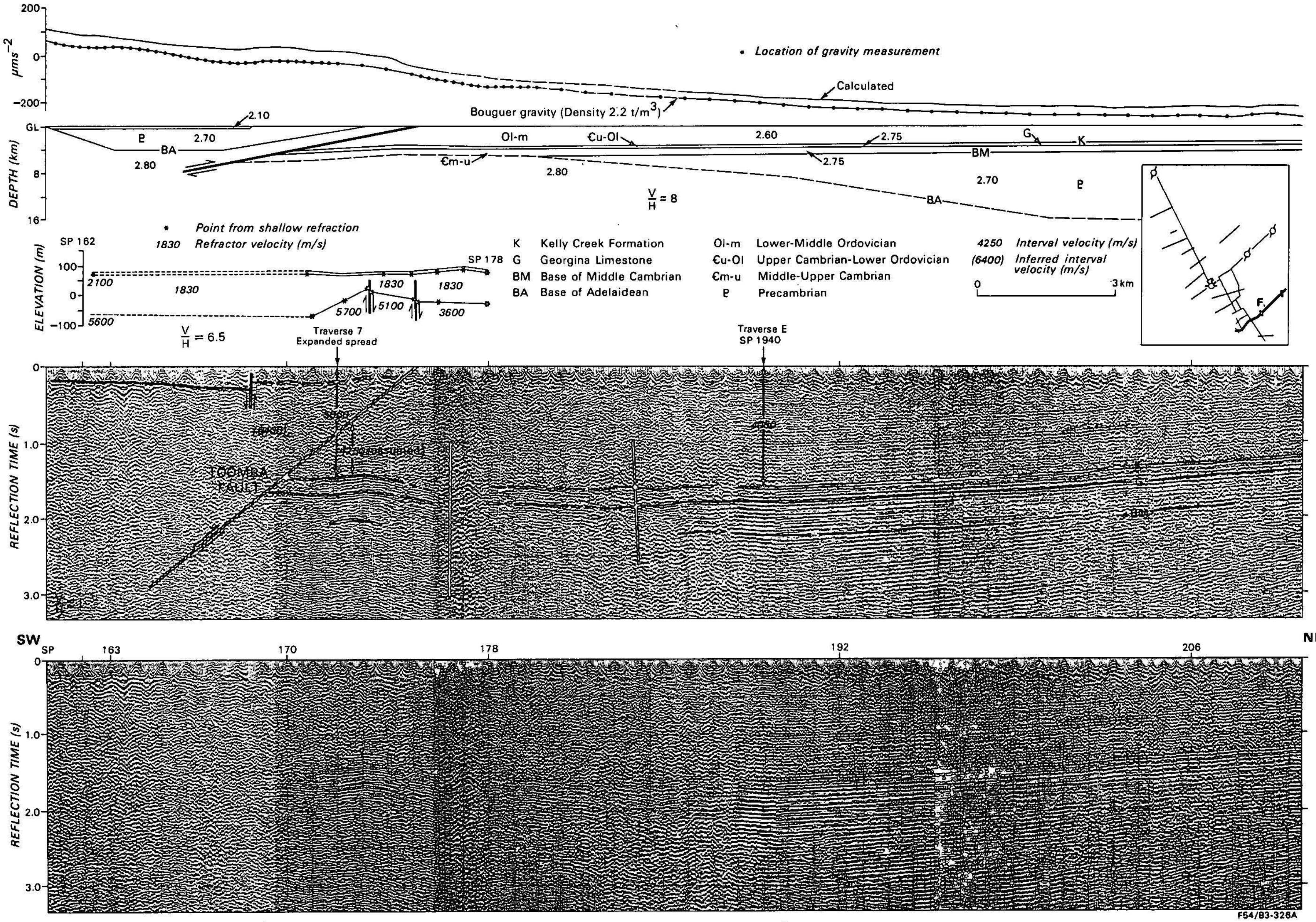


Figure 9. Traverse F (western part): Uninterpreted and interpreted seismic, shallow refraction model, seismic and gravity depth model, and observed and calculated gravity.

granite crop out above these reflections. It is, therefore, apparent that the fault overlies the Palaeozoic strata and is reverse. The average velocity to the top of the Kelly Creek Formation is significantly higher at SP 4900 (4900 m/s) than at 4982 (4050 m/s). Also, the reflections at SP 4900 are at smaller reflection times (by 0.15 s) than on the eastern end of the traverse. This is a velocity pull-up effect, caused by the overlying wedge of older, higher velocity rocks. When the appropriate interval velocities are used to convert reflection times to depth, the depth model (Fig. 6) shows only a slight anticline on the reflector. A short, high-amplitude reflection segment at about 0.65 s on the western end of the traverse is interpreted to be from within Adelaidean sediments. It has apparent westerly dip.

It was initially considered that the subsurface position of the Toomba Fault could be determined from the position of termination of the three reflections near SP 4900; the deeper reflections successively terminate further west. However, consideration of the surface geology just north of the traverse makes it more likely that the fault angle is shallower (about 38°) as shown in Figure 6; between 2.5 km and 10 km north of the traverse, beds are overturned next to the fault with dips of about 60° west. The beds narrow in outcrop towards the traverse and are absent on the traverse, suggesting that the beds are cut out by the fault. The gap between the three reflections and the proposed fault plane is explained by the beds being upturned sharply to angles beyond the limit of recording reflections. The fault angle is unlikely to dip much less than 38° because, otherwise the inferred interval velocity of basement rocks (5700 m/s on Fig. 6) would tend to become unrealistically high.

The near-surface refraction model indicates changes in the sub-weathering velocities which support the location of the Toomba Fault (velocity changes from 3200 m/s to 4650 m/s west of the fault) and indicate that the contact between granite and Adelaidean sediments is near SP 4884 (velocity changes from 4650 m/s to 5500 m/s at SP 4884).

As on traverse 3, the regional easterly decrease in Bouguer anomaly values can be explained by proposing that about 2 km of Adelaidean sediments of lower density than the Arunta Complex exist east of the fault. The inferred faulted zone between SP 4910 to 4958 does not appear to have any expression in the gravity.

To obtain a fit to the observed gravity it was necessary to propose that the granite exposed west of the fault has lower density (2.70 t/m³) than rocks of the Arunta Block (2.80 t/m³) and extends 1500 m deep.

Traverse 11 (Fig. 7)

This traverse is mostly over sand-dunes; the only surface control comes from an outcrop of granite about 500 m northwest of SP 11812. The position of the Toomba Fault plane is determined by three points—

(1) Its surface position is at SP11815 from a lineament on satellite photographs.
(2) It is defined to be about 200 m deep at SP 11812 by the easterly termination of a shallow reflection at 0.2 s, and also by a change in subweathering velocity from 5000 m/s to 3300 m/s associated with a shallow fault.
(3) It is defined in the subsurface at SP 11806 by the westerly termination of a reflection at 0.65 s.

From these three points, the fault plane dips at about 70°W. There is no evidence for steep upturning of beds against the fault as on traverse 4.

The reflection quality on the eastern part of the section is good as far west as SP 11840, where there is a sudden break in the reflections, probably caused by a fault. One reflection can then be followed for a short distance from near SP 11840 to 11806. There is difficulty in correlating this single reflection with a reflection east of the fault at SP 11840. Three velocity analyses were made between SP 11810 to 11840 to assist in the correlation. The results indicated a velocity of 4000 m/s to the reflection; this compares with velocities from 3900 to 4250 m/s between the surface and the top of the Georgina Limestone measured east of SP 11840. The single reflection is, therefore, correlated with the Georgina Limestone and thus the fault near SP 11840 has small throw, probably less than 50 m. The sub-weathering velocities are the same (3300 m/s) on both sides of the fault, which supports the interpretation that vertical displacement of the fault was small.

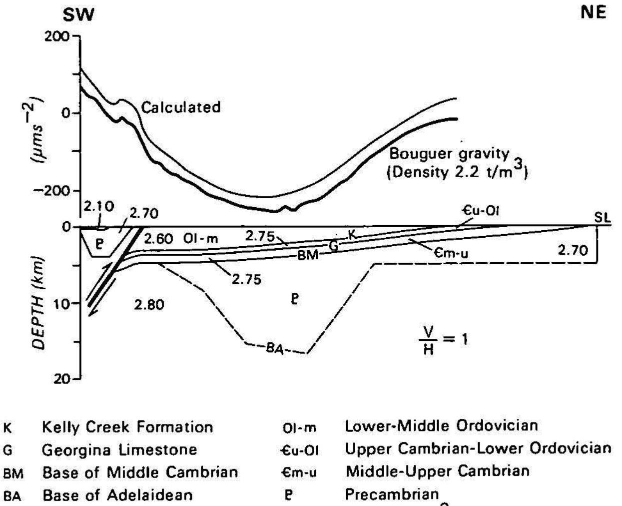
West of the Toomba Fault a shallow reflection is recorded which is at about 0.15 s at SP 11780 and becomes shallower slightly to the west. Diffractions are associated with the reflector, suggesting it is an eroded surface. The reflection appears to correspond to the base of a 200 m thick low-velocity layer (2000 m/s) west of the Toomba Fault. The presence of granite northwest of SP 11812, and the absence of deep reflections on the western end of the traverse, suggests that Adelaidean strata are absent in that area.

The observed gravity profile shows a small high superimposed on a gentle gradient with values increasing to the west. The gentle, eastern side of the high is explained by the shallowing of sedimentary layers whose density increases with depth. The steep, western side of the high can be caused by combined effects of two bodies: a thick low-velocity layer, assigned a density of 2.1 t/m³, and a granite to 1000 m depth with lower density than the Arunta Block.

Traverse 5 (Fig. 8)

This traverse shows complex structures at the western margin of the Toko Syncline. Three main reflectors can be followed on the eastern end of the traverse for a short distance; the deepest one to about SP 5930, and the shallower ones to about SP 5900. There is then a break in reflection continuity and on the rest of the traverse there is a confusion of short reflection segments, diffractions, reflected refractions and noise. Some of the structure is seen more clearly on the earlier single-coverage Alliance line K (AOD, 1970, which traverse 5 partly overlaps and extends further west. Migration after stacking (Fig. 8) helped to elucidate the structure. The three reflectors are affected by a high-angle reverse fault dipping about 40°E, east of the Toomba Fault.

The traverse is covered by sand dunes, obscuring the near-surface geology and position of the Toomba Fault. Shot-hole cuttings of arkose and tillite indicated the presence of Adelaidean strata sub-cropping between SP 5732 and 5790; chips of granite from a shot-hole at SP 5732 indicate shallow basement. The near-surface position of the Toomba Fault is estimated to be near SP 5916, because sub-weathering velocities change from 3450 m/s to 5000 m/s to the west at that location. In the sub-surface, the fault position is estimated by the abrupt termination of the Kelly Creek reflection at SP 5852 and by the westerly limit of deeper, folded beds (refer to migrated section, Fig. 8). The fault thus dips at 45°W.



K	Kelly Creek Formation	Ol-m	Lower-Middle Ordovician
G	Georgina Limestone	€u-Ol	Upper Cambrian-Lower Ordovician
BM	Base of Middle Cambrian	€m-u	Middle-Upper Cambrian
BA	Base of Adelaidean	P	Precambrian
		2.75	Density (t/m³)

F54/B3-327A

Figure 10. Traverse F: Seismic and gravity model northeast across Toko Syncline.

The proposed position of the fault is supported by higher stacking velocities to the Kelly Creek reflector (4600 m/s) west of SP 5916, compared to 3200 m/s east of that point. The higher velocities are attributed to older rocks overlying the Palaeozoic strata. The fault is unlikely to dip much less than 45° otherwise inferred basement velocities would tend to become unrealistically high (5500 m/s is inferred velocity at SP 5859).

Adelaidean strata are inferred to be very thin or absent west of the Toomba Fault at this locality, because of the presence of shallow granite at SP 5732 and absence of reflections.

The refraction depth profile indicates a low-velocity layer (2100 m/s) up to 220 m thick west of the fault. Shallow reflections correspond to the base of this layer, but they are clearer on Alliance line K (AOD, 1970). The presence of this shallow layer, given a density of 2.1 t/m^3, was essential in explaining the detailed shape of the observed gravity profile. To obtain a close fit to the observed gravity it was necessary to propose that up to 5500 m of Adelaidean strata are present east of the fault, confirming the basin-wide regional gravity modelling of Tucker & others (1979). There is, however, no seismic evidence on the traverse to support this proposal.

Traverse F (Jones & Robertson, 1967)
(see Figures 9 & 10)

In 1964 BMR recorded seismic and gravity data on traverse F across the syncline in a northeasterly direction (Fig. 2). Gravity was generally measured at 600 m intervals, but with 200 m spacing near the western margin of the syncline. The regional gravity field along the traverse was not interpreted by Jones & Robertson, but they explained a residual gravity high of about 5 mgals at the western edge of the syncline as reflecting a narrow wedge of basement rocks brought close to the surface by reverse faults. They also interpreted Palaeozoic Georgina Basin strata to extend some 8.5 km west of the wedge of basement rocks.

In the present study, a new attempt for a combined modelling of the seismic and gravity data was made using experience gained from the other traverses across the Toomba Fault. The new model derived also shows reverse faulting at the western margin, but with Palaeozoic strata limited to east of the Toomba Fault (Figs. 9 & 10).

The surface position of the Toomba Fault is defined by a change in sub-weathering velocity from 5100 m/s to 3600 m/s at SP 175. The subsurface position is taken to be the westerly termination of reflections at about 1.6 s. The fault plane, therefore, dips at about 40°W. The dip is unlikely to be much less than this, otherwise the inferred basement velocity (6400 m/s at SP 172) would be unrealistically high.

To explain the regional gravity it is necessary to assume a considerable thickness (up to 11 km) of Adelaidean strata below the Palaeozoic section (Fig. 10). There is some seismic evidence for this section, as shown by easterly-dipping reflections at about 3.5 s between SPs 192 and 206 (Jones & Robertson, 1967).

A 4-km thick block west of the Toomba Fault, of lower density (2.70 t/m^3) than the Arunta Block (2.80 t/m^3), is required to account for the gravity anomalies. This block may comprise Adelaidean strata or, alternatively, granite. A significant factor in explaining the residual gravity high mentioned above is the presence west of the Toomba Fault of a thick wedge (up to 250 m thick) of shallow, low-velocity strata. The wedge is defined by an 1830 m/s layer on the refraction profile between SPs 163-178 and from shallow reflections at 0.15 s to 0.3 s (Fig. 9). This layer, assigned a low density (2.10 t/m^3), can explain a small gravity low between SPs 163 and 170. The residual gravity high is then explained by the superimposed effects of the gravity low, and the westerly increase in gravity values across the Toomba Fault caused by the contrast between the less dense Palaeozoic strata to the east and the denser rocks to the west.

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The Quilalar and Surprise Creek Formations—new Proterozoic units from the Mount Isa Inlier: their regional sedimentology and application to regional correlation

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The Quilalar and Surprise Creek Formations are new Proterozoic units in the Western Succession of the Mount Isa Inlier; they replace the Surprise Creek Beds of earlier workers. They occur stratigraphically between the Haslingden Group and Mount Isa Group, and are themselves separated by a major regional unconformity, and, in places, by the Fiery Creek Volcanics.

The Quilalar Formation is a sandstone-dolomite-dolomitic siltstone sequence unconformable on basement Tewinga Group rocks and Kalkadoon Granite, but conformable or disconformable on Haslingden Group rocks. It is a regressive to ?transgressive shoreline deposit which contains possible dune, beach, lagoonal and offshore sandbar and carbonate shelf palaeoenvironments. The Surprise Creek Formation is a sequence fining upwards from conglomerate and sandstone to siltstone, the latter containing abundant load-casting and water-escape structures. Fluvial, lagoonal, near-shore and delta-slope or delta-front palaeoenvironments are indicated. Regionally the Surprise Creek Formation is host to numerous small copper deposits. Age of the Quilalar Formation is between 1780 and 1680 m.y., although it is probably older than 1740 m.y.; the Surprise Creek Formation is from 1680 to about 1670 m.y. old.

Definitive correlations are proposed between the Western and Eastern Succession: the Quilalar Formation west of, and Mary Kathleen Group east of, the Kalkadoon-Leichhardt basement block are correlated because of marked congruence of stratigraphy, lithology and photogeology after fault reconstruction. The Surprise Creek Formation similarly is correlated with the Mount Albert Group. All units were probably continuous across the basement block and formed a single depositional entity before folding and faulting. From these correlations we propose that Mount Isa Group equivalents are either absent from or have not yet been recognised in the Eastern Succession, and that the Pb-Zn deposit at Dugald River is older than the Mount Isa Pb-Zn deposit. At least two separate periods of major stratabound Pb-Zn accumulation are therefore present in the Mount Isa region; this may be of significance in regional exploration strategy.

Introduction

This paper redefines an old stratigraphic unit, the Surprise Creek Beds, as two new stratigraphic units, the *Quilalar Formation* and the *Surprise Creek Formation*. The publication of these definitions, the regional sedimentology of the units, and their application to the problems of correlation in the Mount Isa region result from detailed regional mapping by the Bureau of Mineral Resources (BMR) and Geological Survey of Queensland (GSQ) from 1969 to 1979. This investigation updated earlier studies by BMR and GSQ between 1950 and 1958 (Carter & others, 1961). A previous series of papers (for example, Derrick & others 1977, 1978) has revised stratigraphic nomenclature for most of the region.

Throughout this paper we have followed the principles of stratigraphic classification embodied in the International Stratigraphic Guide (Hedberg, 1976) wherever possible.

The Quilalar and Surprise Creek Formations occur in the Western Succession of the Mount Isa Inlier (Figs. 1, 2). They were mapped previously by Carter & others (1961) as the upper parts of the Myally Beds, the Surprise Creek Beds, and the lower parts of the Ploughed Mountain Beds; Derrick, Wilson, Hill, Glikson & Mitchell (1977) depicted the two units as Surprise Creek Beds in MARY KATHLEEN*, equivalent to the lower Mount Isa Group; in PROSPECTOR (Derrick, 1974; Wilson & others, 1977), they were also shown as Surprise Creek Beds, but were described as a sequence stratigraphically between the older Myally Subgroup and the younger Mount Isa Group.

Recent studies in ALSACE, MYALLY and MOUNT OXIDE, and revision of earlier work in PROSPECTOR and MARY KATHLEEN have established that much of the Surprise Creek Beds can be divided into a lower sedimentary unit, the **Quilalar Formation**, and an upper sedimentary unit, the **Surprise Creek Formation**, separated by a regional unconformity. In the north and northwest of the Mount Isa Inlier the two formations are separated by the Fiery Creek Volcanics (Cavaney, 1975), a sequence of basalt, rhyolite, trachybasalt, agglomerate and basal conglomerate and sandstone, bound top and bottom by major unconformities.

The Quilalar Formation contains a basal sandstone facies and an overlying carbonate-siltstone-sandstone facies, each regarded as unnamed members; similarly the Surprise Creek Formation contains a basal conglomerate-sandstone facies overlain by a fine sandstone-siltstone facies, also regarded as unnamed members. It is anticipated that both the Quilalar and Surprise Creek Formations could be elevated to Group rank if the major facies subdivisions above are more fully investigated and formally defined as formations.

Two other units which may attain member status are also recognised; a thin unnamed volcanic member consisting mainly of basalt and trachybasalt occurs in the basal Quilalar Formation near Alhambra, in MOUNT OXIDE, and an unnamed orthoquartzite member occurs in the upper Quilalar Formation west and south of the Ewen Block (Fig. 2).

A summary of old and revised stratigraphy is shown in Figure 2. A correlation is proposed between the Quilalar Formation in the west, and the Ballara Quart-

1. Geological Survey of Queensland, GPO Box 194, Brisbane, Queensland 4001.

*** 1:100 000 Sheet area names are shown in upper case.**

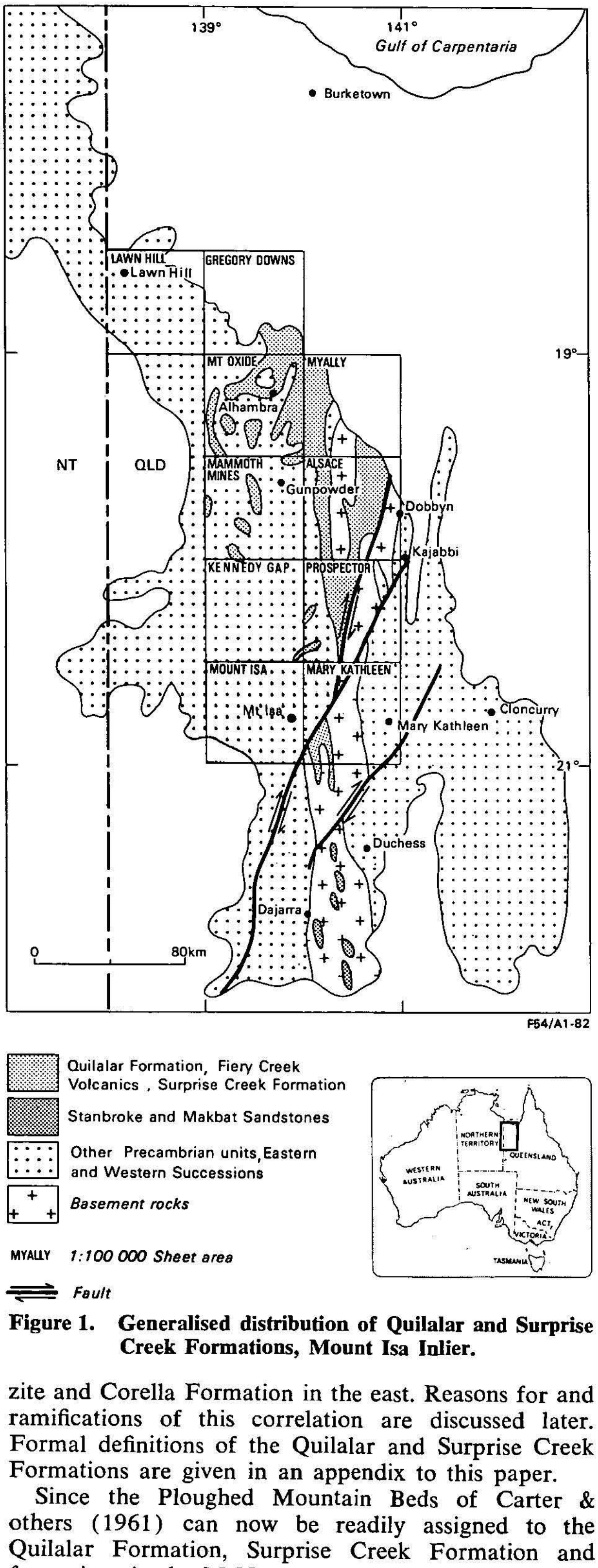

Figure 1. Generalised distribution of Quilalar and Surprise Creek Formations, Mount Isa Inlier.

zite and Corella Formation in the east. Reasons for and ramifications of this correlation are discussed later. Formal definitions of the Quilalar and Surprise Creek Formations are given in an appendix to this paper.

Since the Ploughed Mountain Beds of Carter & others (1961) can now be readily assigned to the Quilalar Formation, Surprise Creek Formation and formations in the McNamara Group (Cavaney, 1975), it is proposed that usage of the term 'Ploughed Mountain Beds' be discontinued.

Quilalar Formation: description and comments

The Quilalar Formation extends discontinuously for over 100 km from the faulted western edge of the Kalkadoon-Leichhardt Block west and northwest across the Ewen Block (Figs. 1, 4). Rocks mapped as Surprise Creek Beds by Derrick & others (1977) 15 to 25 km southeast of Mount Isa, and as Stanbroke Sandstone (Bultitude & others, 1978; Blake & others, 1978) and Makbat Sandstone (Carter & others, 1961) between Duchess and Dajarra are possibly equivalent to the Quilalar Formation.

It consists of a basal conglomerate-sandstone sheet (mainly bimodal feldspathic sandstone and some orthoquartzite) overlain by dolomite, dolomitic siltstone and sandstone, ferruginous sandstone and some orthoquartzite. A thin basalt to trachybasalt member is present in the basal sandstone near Alhambra, and fine-grained, green siliceous bands of rhyolitic tuff are widespread in the dolomitic upper unit in MOUNT OXIDE, MYALLY and ALSACE (Fig. 1).

Thickness variations are evident in the sandstone sheet where it overlies old basement highs in the Ewen Block. From Dobbyn west towards Gunpowder (Fig. 1) the basal sandstone thins from 600 m to only a few metres, but thickens northwards to 500 m near Alhambra. The dolomitic unit ranges from 100 m to about 500 m, and the orthoquartzite member from 30 m to 750 m thick.

Facies variations include an increase in dolomitic cement and thin stromatolite beds in the basal sandstone, from the Ewen Block towards Alhambra (Figs. 1, 4); an increase in the fine ferruginous sandstone content of the dolomitic unit from the Ewen Block towards Dobbyn; and an increase in dolomite and stromatolitic dolomite in the upper unit towards Gunpowder and Alhambra. The stromatolites are columnar-layered or form tabular bioherms and biostromes of small erect branching or non-branching columns; other biostromes are of linked bulbous domes up to 3 m thick, with at least 50 cm of growth relief (M. R. Walter, personal communication, 1978).

The orthoquartzite member is best developed along the western edge of the Ewen Block (Figs. 1, 4), where it overlies and interfingers with stromatolitic dolomite.

Sedimentary structures. Cross-bedding, planar bedding, ripple marks (including bevelled types) and rain-drop impressions occur in the basal sandstone; halite casts, flaser bedding, desiccation cracks, ripple-marks and micro-crossbedding are common in the upper dolomitic unit, in association with various stromatolite types. The orthoquartzite member commonly displays herring-bone-style cross-bedding.

Relations. The Quilalar Formation conformably or disconformably overlies the Myally Subgroup (Fig. 2), but onlaps unconformably across the Ewen and Kalkadoon-Leichhardt Blocks, where sheets and lenses of grit, arkose and cobble to boulder conglomerate separate the basal quartzite from the underlying Leichhardt Metamorphics, Argylla Formation and Kalkadoon Granite. It is overlain unconformably by the pebbly sandstone facies of the Fiery Creek Volcanics, or unconformably by conglomerate of the basal Surprise Creek Formation where the volcanics are absent (Fig. 2). The Weberra Granite intrudes Quilalar Formation dolomitic rocks near Alhambra (Fig. 1), and forms calc-silicate rocks in the aureole.

Age. The maximum age is 1780 m.y., the age of the underlying Argylla Formation; the minimum age is 1680 m.y., the age of the Carters Bore Rhyolite (Page, 1978), which is thought by us to be equivalent to the

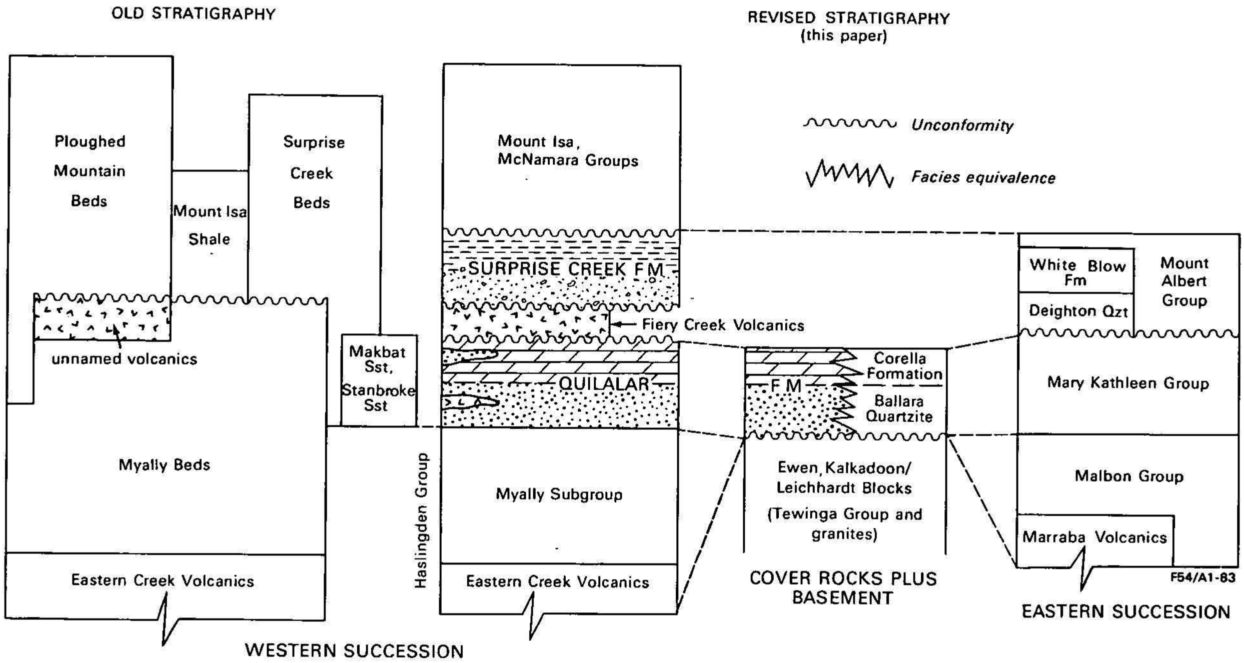

Figure 2. Old and revised stratigraphy and correlations, Mount Isa Inlier.

Fiery Creek Volcanics. Ages of between 1720 and 1740 m.y. for the Burstall and Wonga Granites, apparently intrusive into Corella Formation (Page, 1979), may also be minimum ages for the Quilalar Formation, if our correlations (Fig. 3) are correct; therefore the Quilalar Formation was possibly deposited sometime in the period 1780 to 1740 m.y.

Palaeogeography. Sedimentary structures outlined above, and the abundance of stromatolites all indicate shallow-water environments subject to intermittent subaerial exposure, particularly in the northwestern areas of Quilalar Formation. The basal sandstone overlies ?lagoonal dolomitic sediments of the Myally Subgroup, and grades upwards from festoon cross-bedded bimodal sandstone and, locally, lag and channel-fill sandstone deposits, to better sorted and more quartzose sandstone with cross and planar bedding—a vertical succession interpreted as a mainly regressive shoreface sand system (dune and beach environments). The rapid change from basal sands to uppermost dolomite and orthoquartzite is interpreted as a mainly transgressive sequence in an intertidal, shallow-water environment marginal to the shoreface sand system. Herringbone cross-bedding in the generally well-sorted orthoquartzite member, and its interfingering relations with dolomitic facies rocks, possibly indicate a tidal channel or barrier island complex.

The sandstone facies of the Quilalar Formation forms a linear sheet which extends for at least 160 km north-south (inferred to be the general depositional strike direction) and up to 100 km east-west; it has an average thickness of about 400 m. Similarly, the dolomitic facies with the orthoquartzite member parallels the sandy facies to the east and north and also has an average thickness of about 400 m. Such thicknesses are not common in other postulated regressive-transgressive coastal barrier sequences (Reinson, 1979), and we suggest that the accumulation of relatively thick shoreface dune and beach deposits, with thick intertidal lagoonal and off-shore barrier island deposits, requires the overall subsidence and transgression to be punctuated by periods of regression along the ancient strandline. The vast extent of the Quilalar Formation indicates broad regional controls on the migration of the strandline.

Surprise Creek Formation: description and comments

The Surprise Creek Formation mostly represents the middle and upper parts of the old Surprise Creek Beds of Carter & others (1961). Its distribution tends to parallel that of the Quilalar Formation, but extends further to the west and southwest in MOUNT OXIDE and MAMMOTH MINES (Fig. 1). It is a fining-upwards sequence grading from basal conglomerate and feldspathic sandstone to a sequence of fine sandstone, siltstone and shale; a thin fine to medium-grained sandstone member is generally present in the fine-grained units.

Characteristically the conglomerate contains clasts of various quartzite types, some red jasper, and only rare volcanic and plutonic debris. Associated sandstone (quartzite) is commonly clayey and/or feldspathic. The upward transition to finer-grained rocks is marked by the appearance of abundant detrital muscovite in grey-green thin-bedded to laminated fine-grained feldspathic sandstone and siltstone; interbeds of brick-red to cream laminated shale (carbonaceous at depth) are especially common towards the top of the formation. Ferruginous, ?gossanous sandstone and dolomitic siltstone marker beds are present west and northwest of the Ewen Block.

Stratabound copper mineralisation, mainly chalcocite with some chalcopyrite, is present in the fine-grained facies throughout the region, but deposits are currently uneconomic.

Pronounced thickness variations are characteristic of the basal conglomerate-sandstone facies especially east of the Ewen Block, near Dobbyn. It ranges between 400 m and 2000 m thick along 4 km of strike-length. Thickness variation reflects the sudden appearance of conglomeratic channel-fill deposits in the sequence. The siltstone-rich facies is commonly 500 m to more than

1000 m thick, and is thickest in the western areas of MYALLY (Fig. 1). Regionally the Surprise Creek Formation thins towards the southwest and northwest regions of the Mount Isa Inlier, and is thin or absent across ridges of older basement rocks e.g. the Quilalar Arch along the eastern edge of the Ewen Block, and the Mount Gordon Arch between Mount Isa and Gunpowder (Fig. 4).

Sedimentary structures. Basal clastics display trough and planar cross-bedding (commonly in very large-scale bed forms 1 to 2 m thick), some interference and current ripple marks, and locally contain zones of shale-clast conglomerate. Finer sediments display flaser, graded and lenticular bedding, ripple marks, microcrossbedding and abundant load casting and convoluted bedding. Some Bouma cycles have been recorded (Derrick, 1974).

Relations. The Surprise Creek Formation overlies Fiery Creek Volcanics and Quilalar Formation with regional unconformity (Fig. 2). Northeast of Gunpowder it rests unconformably on Myally Subgroup. The basal contact is commonly disconformable, but angular discordances of up to 90° are present west of Alhambra, which indicate significant folding of Haslingden Group and Quilalar Formation prior to Surprise Creek deposition. It is overlain conformably and disconformably by Mount Isa and McNamara Groups; locally the contact is an angular unconformity.

Age. A U-Pb zircon age of 1680 m.y. for Carters Bore Rhyolite (Page, 1978) is taken as a maximum age of the Surprise Creek Formation, since the rhyolite is considered by us to be equivalent to the Fiery Creek Volcanics. A minimum U-Pb zircon age is 1670 ± 17 m.y., the age of tuff beds in the overlying Mount Isa Group (Page, in prep.).

Palaeogeography. Deposition of the Surprise Creek Formation followed a period of volcanicity and regional warping, and the basal conglomerate-sandstone facies is a mainly regressive unit derived by erosion of significantly uplifted crustal regions. Massive bed forms and variable cross-bed types, abundant boulder and cobble gravel deposits and rapid thickness variations are typical of the basal clastic sequences towards the east, near Dobbyn, and are interpreted as mainly proximal alluvial deposits, formed in braided streams, flood plains and fans. Unimodal current directions from the south and southwest are recorded from channel-fill deposits near Dobbyn, and from the Deighton Quartzite of the Mount Albert Group in the Eastern Succession near Mary Kathleen; Derrick & others (1977) considered the Deighton Quartzite to be mainly a fluvial deposit. In this paper the Deighton Quartzite is considered to be a direct correlative of the basal sand unit of the Surprise Creek Formation (Fig. 2).

A vertical and lateral transition from coarse clastics to well-sorted, sporadically pebbly sandstone with more sheet-like geometry, and the presence of cross-beds and ripple marks, is interpreted as a change to more distal alluvial and shallow-water ?marine environments; the latter could include coalescing deltaic sand deposits and more linear coastal sand deposits of the beach, shelf or barrier type. Sporadic shaly partings and shale-clast conglomerate in the sandstone are possibly thin overbank or levee deposits of mud in the distal alluvial environment.

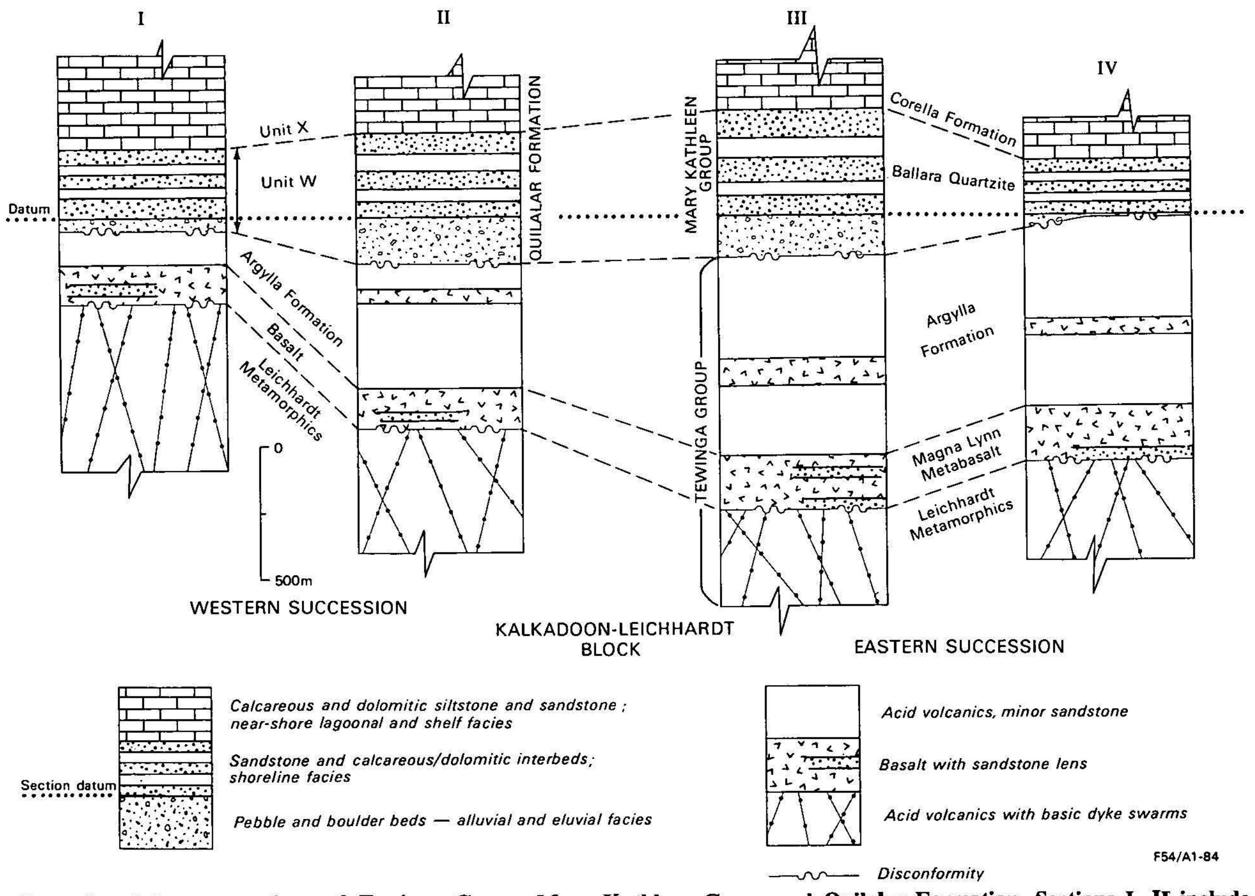

Figure 3. Columnar sections of Tewinga Group, Mary Kathleen Group and Quilalar Formation. Sections I, II include Quilalar Formation, Western Succession; sections III, IV include Mary Kathleen Group, Eastern Succession.

Deposition of finer grained sediments of the upper Surprise Creek Formation (mainly fine sandstone and coarse micaceous siltstone) with abundant flaser and micro-crossbedding, ripple marks, graded bedding, and ubiquitous convoluted bedding, is thought to have taken place in pro-delta slope and shallow shelf environments, marginal to the ?deltaic and coastal sand environments of the underlying clastic rocks. The finer grain size of the upper Surprise Creek Formation is attributed to more distal deposition relative to source areas, and gradual planation of source areas.

A paucity of carbonate rocks is attributed to a generally high rate of fine and coarse clastic sediment supply to the various depositional environments. Carbonaceous siltstone and shale, especially near the top of the Surprise Creek Formation, may reflect a decreased rate of sediment supply and preservation of muddy restricted lagoonal or delta-marsh environments.

Thickness variations listed earlier, and the range of environments postulated above, indicate the Surprise Creek Formation was deposited in a broad basin bounded by uplifted, possibly metamorphosed crust to the east and southeast (vicinity of Dobbyn/Cloncurry/Mary Kathleen), on which most ?fluvial deposition took place; uplifted crust of probably lower relief bounded the basin to the south, west and northwest (Duchess/Mount Isa/Lawn Hill), but the increased thickness of the fine-grained facies to the north (in MYALLY) suggests the basin was open in that direction.

Copper mineralisation in the Surprise Creek Formation is confined, in the model presented here, to the sand-silt transition in a near-shore muddy deltaic environment; the carbonaceous facies appears particularly favourable, especially in the vicinity of buried basement highs (e.g. near the Quilalar Arch, along the eastern margin of the Ewen Block).

Evidence for and significance of correlations across the Kalkadoon-Leichhardt Block

The post-depositional structural history of the Mount Isa Inlier is dominated by the development of large reverse faults subparallel to bedding strike, and by younger northeast-trending wrench faults which show large right-lateral displacements (Derrick & others, 1977; Plumb & others, 1980). Some of these younger faults are shown in Figures 1 & 4; right-lateral displacements of from 20 to 30 km along them can be estimated from the distribution of several rock types and other geological features, e.g. displacement of fault-bounded synclines of Mount Isa Group, displacement of the Kalkadoon-Leichhardt Block, displacement of the stromatolitic facies of the Quilalar Formation, and of the inferred depositional basin edge for Eastern Creek Volcanics of the Haslingden Group (Figs. 2 & 4). Narrow north-trending belts of high-grade metamorphic rocks passing east of Kajabbi, through Mary Kathleen and then to a belt 5 km west of Duchess, also appear to form a nearly continuous, collinear belt once right-lateral displacement is accounted for.

If such displacements are also applied to quartzite in the Quilalar Formation and the Ballara Quartzite in the Mary Kathleen Group (Fig. 4, sequences at I, II, III, IV) it is apparent that they too form a near-continuous north-trending belt, with sequences at location III providing a link across the Kalkadoon-Leichhardt Block. Details of columnar sections in each of areas near I, II, III and IV are shown in Figure 3.

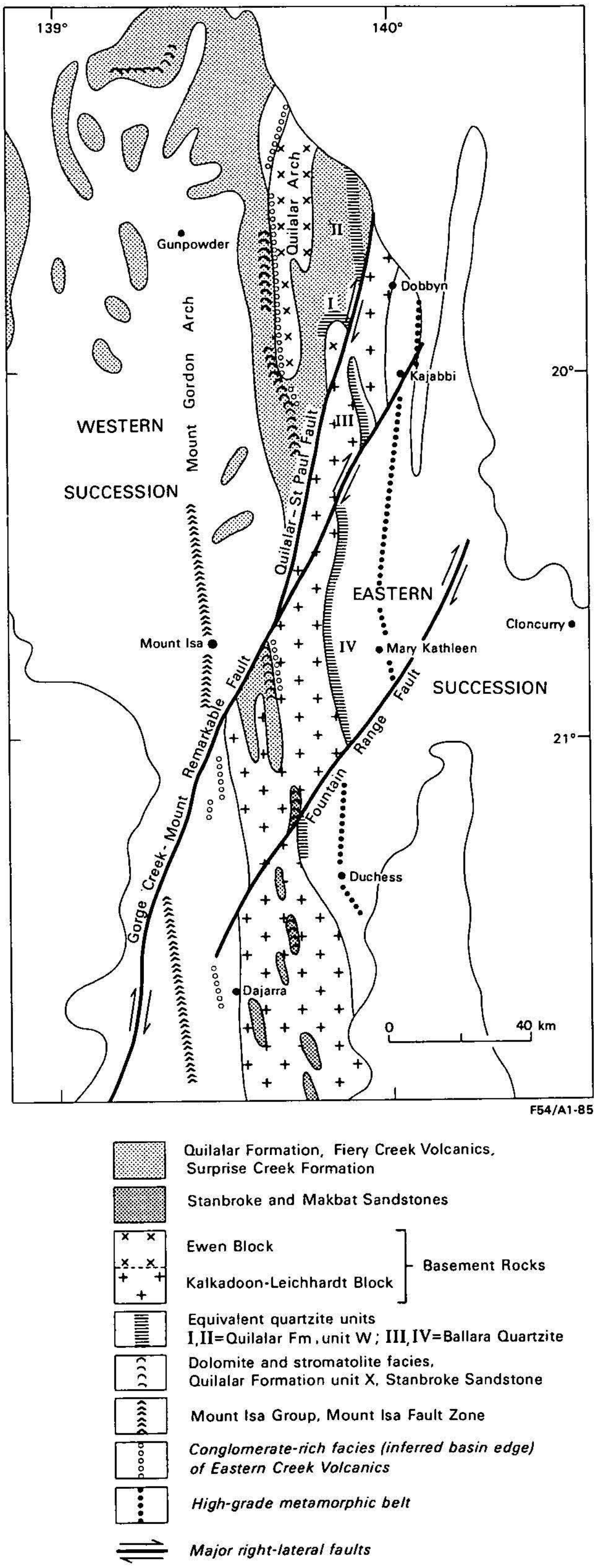

Figure 4. Distribution of rock type, palaeogeographic features and metamorphic belts, showing right-lateral displacement along major faults in the Mount Isa Inlier.

Note the relative position of Quilalar Formation section II, and Ballara Quartzite sections III and IV.

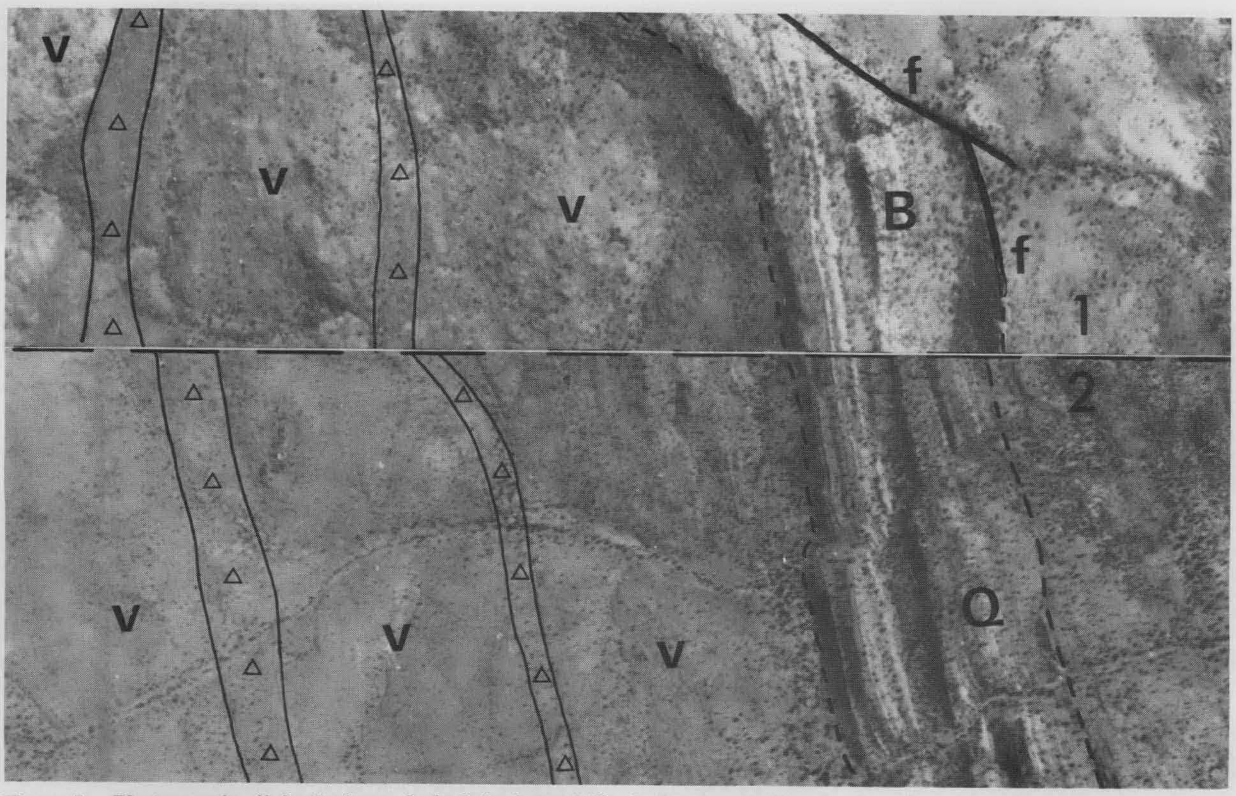

Figure 5. Photomosaic (joined along dashed horizontal line) showing similar stratigraphy within Tewinga Group at two widely separated localities, and markedly similar lithology and photopatterns for Ballara Quartzite (B) and quartzite of the Quilalar Formation (Q).
Acid volcanics = v, basic volcanics = open triangles; f = fault. Scene 1 is from MARY KATHLEEN Run 4, photo 0125 (Section IV, figures 3 and 4); scene 2 is from ALSACE Run 5, photo 032 (Section II, figures 3 and 4); the two scenes are 106 km apart, located east and west of the Kalkadoon-Leichhardt basement block, respectively.

A correlation between the Ballara Quartzite and basal quartzite in the Quilalar Formation was first suspected because of a remarkable similarity of photopatterns (Fig. 5). Columnar sections (Fig. 3) show an equally remarkable coincidence not only of Quilalar Formation and Mary Kathleen Group lithologies, but also units of the underlying Tewinga Group. Figures 3 & 4 show that, after reconstruction, the Ballara Quartzite and the basal quartzite of the Quilalar Formation, each with three distinctive sandstone bands, probably formed a sandmass continuous along the depositional strike for at least 200 km (Fig. 4, Dobbyn area to Duchess area), accompanied by fine-grained calcareous and dolomitic platform sediments of the Corella Formation and upper Quilalar Formation, respectively. If the Stanbroke and Makbat Sandstones are equivalent to Quilalar Formation (Fig. 2), this sandstone sheet extends for over 250 km along strike. The only significant but typical variations evident from Figure 3 are in the thickness of the basal alluvial facies below the shoreline sandstone facies.

The postulated equivalence of Quilalar Formation and the Mary Kathleen Group allows more definitive correlation of other units in the Western and Eastern Successions than was previously possible. For example, both the Quilalar Formation and Mary Kathleen Group overlie sequences characterised by thick sequences of basic volcanics—the Eastern Creek Volcanics and Marraba Volcanics respectively (Fig. 2), which therefore may be broadly coeval, as suggested on other grounds by Carter & others (1961).

The Mount Albert Group is the youngest middle Proterozoic sequence so far delineated in the Eastern Succession; from the correlation of Surprise Creek Formation with Mount Albert Group (Fig. 2) it follows that Mount Isa Group equivalents are probably not present, or perhaps have not yet been found, in the Eastern Succession. Certainly the Corella Formation, thought by some workers (e.g. Whitcher, 1975), to be equivalent to the Mount Isa Group, is considerably older (Fig. 2), and the Pb-Zn mineralisation in Corella Formation at Dugald River is therefore much older (possibly by about 70 m.y.) than the Mount Isa Pb-Zn orebodies. Thus, at least two separate periods of major stratabound base-metal accumulation are indicated in the Mount Isa Inlier, a fact of some significance for exploration strategy in the region.

Conclusions

- The term 'Surprise Creek Beds' should be discarded it is replaced by two newly defined units, the Quilalar Formation and Surprise Creek Formation. The term 'Ploughed Mountain Beds' should also be discarded.
- The Quilalar Formation is a sandstone-siltstone-carbonate unit which overlies the Myally Subgroup conformably or disconformably, and is overlain unconformably by the Fiery Creek Volcanics. It is between 1780 and 1680 m.y. old, but is probably older than 1740 m.y.
- Sandstone and siltstone of the Surprise Creek Formation overlie the Fiery Creek Volcanics unconformably, and locally rest unconformably on Quilalar Formation. The formation is overlain unconformably or disconformably by the Mount Isa Group, and is between 1680 and about 1670 m.y. old.

• Palaeoenvironments for the Quilalar Formation range from fluvial channels and pediments, periodically exposed shorelines with possible active beach, small-scale dune and offshore sandbar barrier zones, to lagoons and intertidal shelf regions with abundant stromatolites. Sandstones of the Surprise Creek Formation formed in alluvial regions (braided streams, flood plains and fans) and near-shore shallow-water regions; siltstones possibly formed in subtidal to inter-tidal lagoonal and delta-slope environments.

• After restoration of major right-lateral fault displacements, Quilalar Formation units appear to be nearly continuous with Mary Kathleen Group rocks across the Kalkadoon-Leichhardt basement block. Lithological sections along strike of the Tewinga Group, Mary Kathleen Group, and Quilalar Formation are nearly identical over a minimum strike length of 200 km.

• Definitive correlations are proposed across the Kalkadoon-Leichhardt basement block, thus relating Western Succession geology to Eastern Succession geology. The Quilalar Formation in the west correlates directly with the Ballara Quartzite and Corella Formation in the east; the Surprise Creek Formation in the west correlates directly with the Deighton Quartzite and White Blow Formation of the Mount Albert Group in the east. Most subunits are remarkably uniform north-south along the strike, but show significant facies and thickness variations east-west across the strike.

• No equivalents of Mount Isa Group rocks have yet been identified in the Eastern Succession.

• At least two separate ages of major stratiform Pb-Zn accumulation are present in the Mount Isa region, one 1740 m.y. or older at Dugald River in the east, the other about 1670 m.y. old at Mount Isa in the west, factors which may be of significance for regional exploration strategy.

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L. Hutton (Geological Survey of Queensland) contributed to regional studies of the Surprise Creek Formation in MOUNT OXIDE and MAMMOTH MINES. We thank R. Brunker and S. Needham for their constructive comments on a draft of this paper. I. H. Wilson publishes with the permission of the Under Secretary, Department of Mines, Queensland.

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Appendix

Definition of the Quilalar Formation

Derivation of name. Parish of Quilalar (pronounced 'Key-larla'), which surrounds Kajabbi Township, near lat., 20°2'S, long. 140°00'E, 6857-953845*. The Quilalar Fault truncates the Quilalar Formation near lat. 20°11'S, long. 139°50'E, 6857-710677.

Distribution. (Fig. 1): In open to moderately tight anticlines and synclines north, west and southwest of Alhambra (MOUNT OXIDE, GREGORY DOWNS**); in a tight to isoclinal 2 to 6 km-wide synclinal fold belt extending for about 80 km along the western edge of the Ewen Block; and in tight to moderately tight synclines separated by an anticline in a north-trending belt 10 to 15 km wide and 60 km long between the Ewen and Kalkadoon-Leichhardt basement blocks (MYALLY, ALSACE, PROSPECTOR). These two latter fold belts are faulted against one another south of the Ewen Block, and terminate against the Quilalar and Mount Remarkable Faults. Some

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* **Australian Map Grid Reference, Zone 54 (metric)**
** **1:100 000 Sheet area.**

Quilalar Formation is present in MARY KATHLEEN, where it is shown as Surprise Creek Beds south of the Gorge Creek-Mount Remarkable Fault, mainly 15 to 20 km southeast of Mount Isa. This belt also extends southwards onto DUCHESS.

Type section (holostratotype). In PROSPECTOR, about 55 km north-northeast of Mount Isa, and 5 km north-northwest of old Glenroy homestead, near the junction of Conglomerate Creek and the Leichhardt River. The base of the section is at lat. 20°17′25″S, long. 139°42′00″E (6857-644558); the top of the section is 2.5 km to the northeast, at lat. 20°16′35″S, long. 139°43′10″E (6857-664573). The holostratotype exposes, from top to base:

120 m of purple siltstone, friable fine-grained feldspathic sandstone, calcareous siltstone and laminated shale

500 m of orthoquartzite and massive medium-grained feldspathic quartzite, with minor siltstone partings—the unnamed orthoquartzite member

335 m of dolomitic siltstone and sandstone, dolomite, stromatolitic dolomite, brown feldspathic sandstone, purple shale and siltstone

360 m of massive brown to white feldspathic and clayey sandstone with pebbly beds and minor siltstone.

This section is overlain disconformably by pebbly beds of the Fiery Creek Volcanics, and underlain by ferruginous sandstone and siltstone of the Lochness Formation of the Myally Subgroup.

Reference sections (hypostratotypes) are necessary to illustrate the facies variations within the Quilalar Formation. In MOUNT OXIDE, a reference section is located 3 km west-southwest of Alhambra homestead overlying Myally Subgroup rocks. From the base at 6759-308798, 500 m of feldspathic quartzose and dolomitic sandstone are overlain to the north by at least 300 m of dolomite, dolomitic and ferruginous siltstone and sandstone with halite casts; this dolomitic sequence is capped by 50 m of orthoquartzite, the top of which ends the reference section at 6759-296819.

The basal sandstone contains a 50-m thick trachybasalt unit, the unnamed volcanic member of the Quilalar Formation; the orthoquartzite at the top of the section is probably equivalent to the unnamed orthoquartzite member in the type section.

A second reference section is located 17 km west-southwest of Dobbyn, in ALSACE, from 6858-807028 (base) northwest for 2 km to 6858-795042. Here, 600 m of feldspathic sandstone with basal arkose disconformably overlie acid volcanics of the Argylla Formation; the sandstone is overlain by 450 m of ferruginous sandstone and siltstone, and dolomitic siltstone with thin interbeds of rhyolitic tuff or ashstone. It is overlain unconformably by pebbly sandstone of the Fiery Creek Volcanics.

Lithology. The basal part of the formation consists of white, grey or buff, medium to coarse-grained feldspathic quartzite, orthoquartzite, fine-grained feldspathic sandstone, clayey sandstone and minor siltstone, shale, conglomerate and trachybasalt; in areas near the Ewen Block the basal rocks include arkose and grit, pyritic sandstone and minor acid tuff and basalt.

The upper part is mainly stromatolitic dolomite, brown dolomitic sandstone and siltstone, ferruginous sandstone and siltstone, purple-grey siltstone, siltstone with fine-grained sandstone lenses, orthoquartzite, shale-clast conglomerate and minor green to grey rhyolitic tuff or ashstone. Calc-silicate rocks occur in the predominantly dolomitic unit in the aureole of the Weberra Granite in MOUNT OXIDE.

Thickness. 500 to 1 500 m; the basal sandstone unit varies from almost no thickness along the eastern side of the Ewen Block, to 600 m; the dolomitic unit, exclusive of the orthoquartzite member, ranges from 100 to 520 m; the orthoquartzite member varies from 30 m in the northwest to 750 m near Julius Dam, in PROSPECTOR.

Relations and boundary criteria. The Quilalar Formation conformably overlies the Lochness Formation of the Myally Subgroup, and undivided Myally Subgroup; Wilson & others (1977) suggest this contact may also be disconformable since the underlying Lochness Formation is locally a massive, structureless and mottled siltstone, possibly a palaeosol.

The Quilalar Formation overlies basement rocks unconformably. In ALSACE, Quilalar Formation quartzite with basal arkosic grit and pebble conglomerate directly overlies ?Leichhardt Metamorphics at Hendersons Soak (6858-720946) and elsewhere along the eastern edge of the Ewen Block; in PROSPECTOR, Quilalar Formation arkose and quartzite overlie small inliers of ?Leichhardt Metamorphics unconformably at 6857-7209762, and also overlie Kalkadoon Granite unconformably at Sunday Gully (6857-730573), where cleaved conglomeratic siltstone is also present in the sequence.

In ALSACE, the formation rests disconformably on acid volcanics of the Argylla Formation, in a series of north-plunging anticlines 15 to 25 km southwest of Dobbyn, and along the eastern edge of the Ewen Block at Mistake Creek (6858-743316).

The Quilalar Formation is overlain unconformably by pale pink to purple conglomeratic sandstone of the Fiery Creek Volcanics; this contact is an angular unconformity in many areas of MOUNT OXIDE, west of and just east of Alhambra, but is a disconformity throughout ALSACE and PROSPECTOR. Where the Fiery Creek Volcanics are absent, basal conglomeratic quartzite of the Surprise Creek Formation overlies the silty and dolomitic sequence of the Quilalar Formation unconformably or disconformably.

Weberra Granite intrudes dolomitic rocks of Quilalar Formation in MOUNT OXIDE, a few kilometres west-northwest of Alhambra.

Age. Between 1780 m.y. (Argylla Formation) and 1680 m.y. (Carters Bore Rhyolite, a probable correlative of the Fiery Creek Volcanics) (Page, 1978).

Topography. Quartzite and sandstone in the Quilalar Formation form a distinctive series of about three close-spaced ridges; the silty, dolomitic and ferruginous upper part of the formation is recessive, forming low hills and valleys between the major quartzite units.

Correlation. Probably equivalent to the Ballara Quartzite and Corella Formation of the Mary Kathleen Group; possibly equivalent to Stanbroke Sandstone and Makbat Sandstone.

Definition of the Surprise Creek Formation

Derivation of name. Surprise Creek, a tributary of the Leichhardt River, which it joins 20 km west of Kajabbi, at lat. 20°01′35″S, long. 139°50′40″E (6857-793852). The name 'Surprise Creek Beds' was used by Carter & others (1961); it included rocks which are now mapped as Mount Isa Group, Myally Subgroup, and Surprise Creek and Quilalar Formations. However, a significant portion of the Surprise Creek Beds coincides with our proposed Surprise Creek Formation, hence we have retained the long-standing name 'Surprise Creek' in this validation.

Distribution. In north-trending complexly folded and faulted synclinal belts 2 to 20 km wide immediately east, west and south of the Ewen Block and north-northwest of Mount Isa; in tightly-folded basin-and-dome structures extending northwards from Gunpowder; in a narrow belt extending from north of Alhambra westwards and southwards around a broad dome of Weberra Granite, Myally Subgroup and Quilalar Formation; and as prominent quartzite inliers surrounded by McNamara Group rocks southwest of Gunpowder.

Type section and reference sections. The type section of the Surprise Creek Beds proposed by Carter & others (1961) is in PROSPECTOR, 42 km southwest of Kajabbi; it extends along Doughboy Creek westwards for 3 km to Glenroy homestead (6857-687533), then 2 km to the southwest. It was described by Carter & others as 'faulted and incomplete'.

Nearly all of this type section is now mapped by us as Quilalar Formation and sediments of the Fiery Creek Volcanics; the remainder of the type section of Carter & others includes rocks now mapped as Surprise Creek Formation, but extensive faulting makes this remaining section unsuitable for use as a type section for the proposed new unit, the Surprise Creek Formation.

We therefore propose that the type section (holostratotype; ISG, 1976) for the Surprise Creek Formation be as follows: in ALSACE, just south of the Kajabbi-Gunpowder road, 25 km west-northwest of Kajabbi and 6 km northwest of the junction of Surprise Creek with the Leichhardt River. The base of the section is at lat. 19°59'20"S, long. 139°48'20"E (6858-758885); the top of the section is 1.6 km west, at lat. 19°59'20"S, long. 139°47'40"E (6858-743886). The type section exposes from top to base:

300 m of cream, red-brown to buff-grey laminated siltstone, fine-grained sandstone and minor dolomitic sandstone

170 m of buff to white medium-grained feldspathic sandstone and intercalated grey, green and buff siltstone and fine sandstone

270 m of buff fine-grained feldspathic sandstone and siltstone, minor carbonaceous siltstone

230 m of massive white, medium to coarse-grained feldspathic sandstone and pebbly sandstone.

This section is overlain conformably or disconformably by basal quartzite of the Mount Isa Group, and is underlain disconformably by dolomitic sediments within the Fiery Creek Volcanics.

Reference sections (hypostratotypes) of the Surprise Creek Formation are located in ALSACE 16.5 km west of Dobbyn, where from the base at 810106, 1200 m of basal sandstone and conglomerate are overlain by 650 m of siltstone and fine sandstone, with the top at 798124; and in MYALLY along the old Dobbyn-Mount Oxide track, 19 km northeast of Gunpowder, where from the base at 523628, 800 m of sandstone are overlain to the east by at least 1400 m of siltstone; this section is terminated by faulting at 544631. The latter section mainly coincides with the reference section of Surprise Creek Beds nominated by Carter & others (1961), but includes a basal sandstone facies mapped by them as Myally Beds.

Lithology. White, pale pink and buff medium to coarse-grained feldspathic sandstone (quartzite) and white clayey feldspathic sandstone; pebbly feldspathic sandstone and conglomerate; brown and green-grey micaceous sandstone and siltstone, minor shale, carbonaceous siltstone and ferruginous and dolomitic sandstone and siltstone. In most areas four informal subdivisions have been mapped; unit A is the basal sandstone/conglomerate. Units B and D are mainly siltstone and fine sandstone units separated by unit C, which in addition to siltstone contains a lower white sandstone marker and an upper brown sandstone marker that can be traced over large areas. Copper staining is present in units B, C, and D, especially in D.

Thickness. The type section is 970 m thick; the reference sections are 1600 m and over 2000 m thick, respectively. Thickness ranges from 200 m to over 2000 m; most thickness variation occurs in the basal conglomerate and pebbly sandstones.

Relations and boundary criteria. The Surprise Creek Formation overlies the Fiery Creek Volcanics and in some areas the Quilalar Formation disconformably, or with slight angular unconformity. It is overlain disconformably by basal orthoquartzite (Warrina Park Quartzite) of the Mount Isa Group east of Gunpowder and by the Torpedo Creek Quartzite Member (Cavaney, 1975) of the McNamara Group west of Gunpowder. Southwest and northwest of Gunpowder the basal McNamara Group quartzite rests diconformably on massive basal sandstone of the Surprise Creek Formation, which indicates erosion or non-deposition (probably the former) of the upper siltstone facies.

Age. Between 1680 m.y. (Carters Bore Rhyolite: Fiery Creek Volcanics equivalent; Page, 1978) and about 1670 m.y., the age of tuff beds in the Mount Isa Group (Page, in prep.).

Topography. Basal sandstone and quartzite forms rugged, upstanding ridges and plateaux; sandstones of Unit C commonly form narrow ridges which contrast with the generally low hills and valleys developed over the siltstone fine sandstone facies.

Correlation. The Surprise Creek Formation sandstone facies and siltstone facies are correlated with the Deighton Quartzite and White Blow Formation of the Mount Albert Group, respectively, in the Eastern Succession across the Kalkadoon-Leichhardt Block to the east and southeast.

To the west the Surprise Creek Formation is a correlative of, and replaces, all except the upper part of the Mammoth formation (i.e. excluding the Torpedo Creek quartzite member) proposed by Cavaney (1975).

Remarks. The Surprise Creek Formation is of economic interest because of widespread traces of copper mineralisation (mainly as stratiform or stratabound chalcocite and malachite) in units B, C, and D; the nature of the mineralisation resembles Zambian copper-belt occurrences.

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Lord Howe Rise, Tasman Sea—preliminary geophysical results and petroleum prospects

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The Lord Howe Rise is a major submarine feature in the Tasman Sea; it extends northwest from the New Zealand continental margin and lies about 600 to 1200 km off the east coast of Australia. It is about 2000 km long and 300 km wide, and most of its crest lies in water ranging from 750 to 1200 m deep. It has a continental crustal structure. The general absence of rift-valley or pull-apart basins along the eastern seaboard of Australia has led some authors to speculate that when breakup took place in the Tasman Basin, the rift-valley was breached along its western boundary fault, and is now represented by a zone of horst and graben structures some 200 km in width underlying the western part of the Lord Howe Rise and possibly the Dampier Ridge. Any sedimentary basins associated with rifting would have remained wholly attached to the 'Lord Howe Plate'. Although survey data from the R.V. *Sonne* cruise show that sediment-filled basins, some of which are grabens, make up much of western Lord Howe Rise, the degree to which they are related to the pre-Tasman Basin rifting remains conjectural.

The basins on Lord Howe Rise are 20-40 km wide; some contain up to 4000 m of sediment. Sediments are also relatively thick on the eastern flank of the Middleton and Lord Howe Basins. The seismic profiles indicate that wave-base erosion was taking place on Lord Howe Rise in the Late Cretaceous, and imply that a shallow marine environment was present prior to seafloor spreading in the Tasman Basin. Shallow marine silts and clays penetrated in DSDP Site 207, and palaeogeographical reconstructions, which juxtapose central Lord Howe Rise and the Gippsland Basin, indicate that both marine and non-marine petroleum source rocks may be present. Petroleum traps appear to exist against the boundary faults of the grabens, as internal structures within basins, and in structures interpreted as reefs of Late Cretaceous and Paleocene age. A seal may be provided by pelagic oozes.

The eastern flank of Lord Howe Rise was probably the ancient (pre-Maestrichtian) continental margin of the 'Australian-Antarctic supercontinent'. A wedge of Late Cretaceous or older sediment, up to 2000 m thick, which was deposited across the margin, may also be prospective. The presence of potential source rocks, suitable traps, and indications of higher than normal heat flow, suggest that this deep water area, which is now just within range of oil drilling technology, should be considered prospective for petroleum at least in the long term.

Introduction

In 1970-73 the Bureau of Mineral Resources (BMR) conducted an extensive geophysical survey (CGG, 1975), which led to a better understanding of most of the Australian continental margin. During this survey two reconnaissance traverses were run across the central Lord Howe Rise, in the vicinity of Lord Howe Island (Fig. 1). They indicated distinctive changes in structure across the Rise, which may bear on the evolution of the Tasman Basin and on the petroleum potential of the region. In October 1978 the BMR co-operated with the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in exploring the western part of the Lord Howe Rise, with the R.V. *Sonne* (Cruise SO-7A; Hinz & others, 1979), to provide more detail on its structure and petroleum potential.

The Lord Howe Rise (Fig. 1) is the major feature in the eastern Tasman Sea, extending for almost 2000 km from the Coral Sea region to the Challenger Plateau off New Zealand. It lies about 600 to 1200 km east of the Australian continental shelf; Australia's claim to part of the region stems from the presence of Lord Howe Island, which is Australian territory.

The survey extended primarily over the western half of the Rise, between 25° and 37°S, but also included a single crossing of its eastern flank, the West Norfolk Ridge, and the southern New Caledonia Basin, en route from the starting point in Suva (Fiji). Lines also extended west of Lord Howe Rise crossing the Middleton Basin, the Lord Howe Basin, and the Dampier Ridge. Most of the 4000 line-km of 24-channel digital seismic, gravity, and magnetic data is being processed for detailed interpretation; however, the single-channel on-line seismic records are of sufficient quality to enable a preliminary assessment of the area.

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Previous knowledge

Surveys

Since the early 1950s, when the full extent and regional morphology of the Lord Howe Rise were first recognised, many traverses have been run across it; however, because of its size, only a sparse coverage has yet been achieved. Before the *Sonne* survey the few track crossings of sufficient quality to reveal the deep sedimentary structure came from four sources: United Geophysical Corporation (1970 Survey); the two BMR

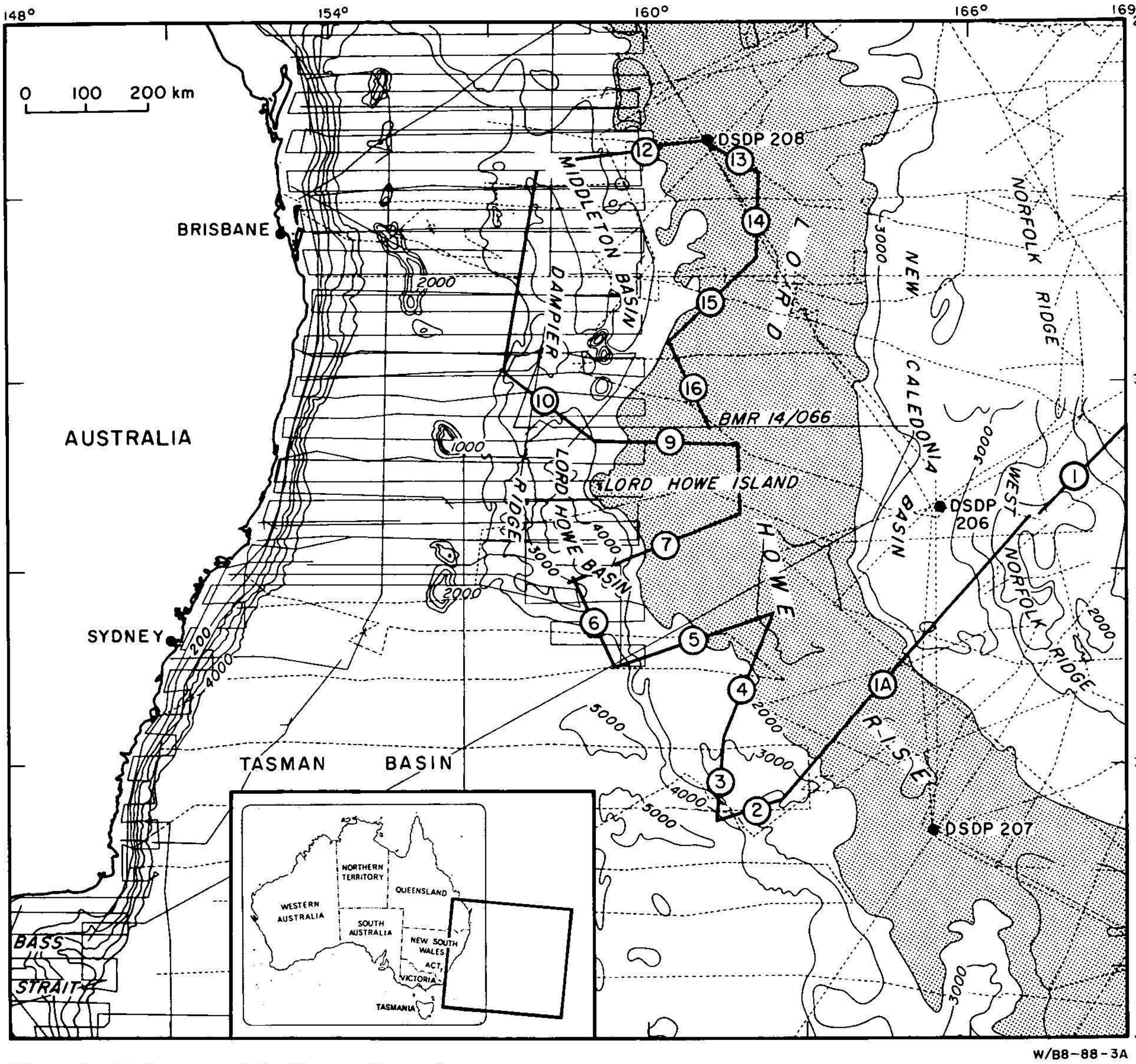


Figure 1. Bathymetry of the Tasman Sea region.
After Ringis (1972) with seismic reflection profiling tracks (BMR Continental Margin Survey lines solid; 'Sonne' SO-7 lines heavy solid, 1 = Line SO-7-001 etc.). Also shows location of DSDP Sites 206, 207 & 208, and BMR Line 14/066.

(1971 Survey) crossings of the central portion of the Rise around Lord Howe Island; Mobil Oil Corporation (1972 Survey); and Austradec 1/2 (1972/73 Survey) on the northern portion of the Rise. A summary giving details of all surveys was given by Jongsma (1976); the track distribution for all surveys is shown in Figure 1.

General structure

The Lord Howe Rise is most clearly outlined by the 2000 m isobath (Fig. 1); much of its crest lies in water ranging from 750 to 1200 m deep. To the east lies the New Caledonia Basin, which is flat-floored and at a depth of 3000 m. To the west, between 26° and 34°S, the smaller Middleton and Lord Howe Basins separate the Rise from the Dampier Ridge. Beyond this, the 4000-4500 m deep Tasman Basin extends to the narrow continental margin of eastern Australia.

The crustal structure of the Lord Howe Rise, as interpreted from seismic refraction measurements (Officer, 1955; Shor & others, 1971) and the gravity field (Dooley, 1963; Woodward & Hunt, 1971), indicates a continental origin, and a thickness of 26 km. Shor & others (1971) have shown that it is mostly composed of rocks with a P-wave velocity of 6.0 km/s, which is similar to values found for the Australian continent.

Mutter & Jongsma (1978) computed the gravity response associated with the refraction model of Shor & others (1971), and showed that it gave a marked gravity gradient, unlike the relatively flat field observed on the BMR profiles and on profiles presented by Woodward & Hunt (1971). Using the refractors obtained by Shor & others (1971) they presented a revised crustal model which satisfied the requirement of a flat gravity field. A sharp division, in the deep and the shallow crustal structure of the Lord Howe Rise, supports the concept of a rift-zone on the western side, with associated crustal thinning and alteration.

The two reconnaissance seismic profiles recorded by BMR show that the central part of Lord Howe Rise may be divided longitudinally into an eastern province, characterised by an elevated and planed-off basement surface, with thin sediment cover; and a western pro-

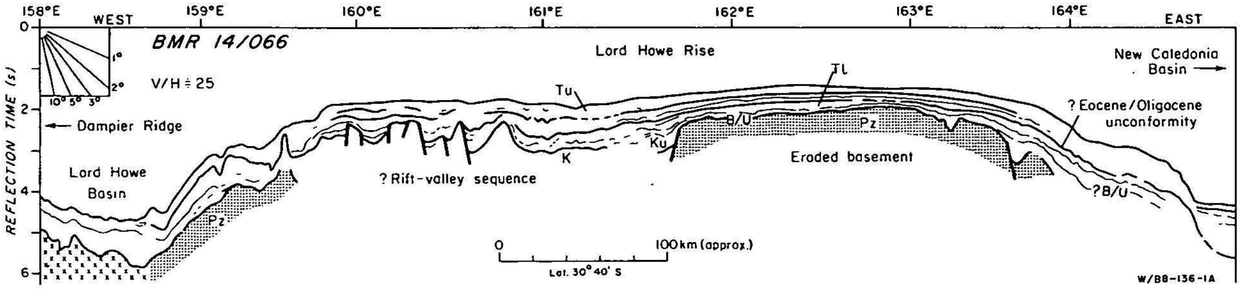


Figure 2. Structural profile across Lord Howe Rise.
Based on BMR Line 14/066 (after Willcox, in press). Location given in Figure 1. (Tu = Miocene-Recent, Tl = Paleocene-Oligocene, Ku = Late Cretaceous, Pz = Palaeozoic, B/U = breakup unconformity, crosses = crystalline basement of unknown origin.)

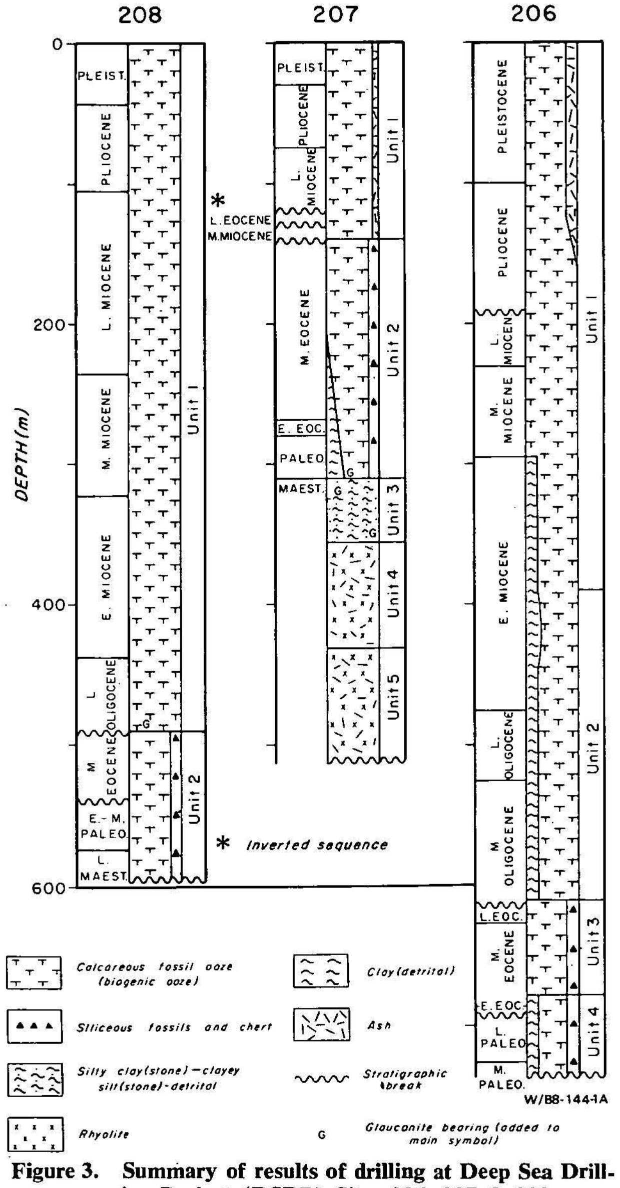


Figure 3. Summary of results of drilling at Deep Sea Drilling Project (DSDP) Sites 206, 207 & 208.
After Burns, Andrews, & others (1973). Locations given in Figure 1.

vince, characterised by horsts and grabens (Fig. 2) (Jongsma & Mutter, 1978). The greater depth of basement in the western province gives rise to a slightly quieter magnetic signature, and the horst and graben structures are reflected in the free-air anomaly profiles. This longitudinal division is less clear-cut, however, in the southern part of the Lord Howe Rise, on line drawings presented by Bentz (1974).

Sediment cover

Sediment thicknesses of up to 3000 m have been reported (Dubois & others, 1974) on the northern part of the Rise, and similar thicknesses are probably present within troughs in the central area (Jongsma & Mutter, 1978; Willcox, in press; Fig. 2). A regional unconformity of Middle Eocene to Late Oligocene age (Burns, Andrews & others, 1973) extends across the area, and is overlain by up to 400 m of Neogene oozes. The underlying sediments comprise Paleogene oozes, a Maestrichtian shallow marine unit (Fig. 3), and, speculatively, Late Cretaceous fluvial-deltaic deposits.

Known lithology

The only direct information about the nature of the rocks forming the Lord Howe Rise comes from outcrop on Lord Howe Island, the Deep Sea Drilling Project (DSDP), and dredging of one of the volcanic features shown in Bentz (1974) on the southeastern side of the rise.

Lord Howe Island and Ball's Pyramid are the only islands on Lord Howe Rise and thus, until the DSDP results, outcrop on them represented the only direct evidence of the types of rocks making up the Rise. Game (1970) described at least three major eruptive periods, which he considered to have begun as early as the mid-Tertiary and ended with an eruptive period that was isotopically dated as of Late Miocene age (7.7 m.y. B.P.).

There are three DSDP holes in the region that are directly relevant to the *Sonne* survey—Sites 206, 207, and 208 (Figs. 1 and 3). At Site 206, which lies on the floor of the New Caledonia Basin, a relatively uniform sequence of Early Paleocene to ?Late Pleistocene calcareous oozes was intersected. At Site 208 on the northern Lord Howe Rise the lithologic sequence consisted of Late Oligocene to Late Pleistocene calcareous ooze overlying Late Cretaceous to early Middle Eocene siliceous fossil-bearing chalk. Palaeontological evidence at these two sites indicates that bathyal conditions generally prevailed throughout the deposition of the sequences sampled.

At Site 207 in the southern Lord Howe Rise a somewhat different lithologic sequence was intersected. At the base of the drillhole Upper Cretaceous rhyolitic lapilli tuffs and vitrophyric rhyolite flows were encountered; van der Lingen (1973) has suggested that at least some of them may be of subaerial or very shallow marine origin. The rhyolites, which give a mean potassium-argon age of 94 m.y. B.P. (McDougall & van der

Lingen, 1974), are overlain by a sandy sequence containing reworked rhyolitic material, and then by a Maestrichtian glauconitic silty claystone. The rarity of planktonic fossils in the silty claystone led Burns, Andrews, & others (1973) to suggest that it was probably deposited in a shallow marine environment with restricted (non-oceanic) circulation. The rest of the rocks intersected at this site are mostly carbonate oozes of Paleocene to Pleistocene age which were deposited well above the carbonate compensation depth. Palaeontological evidence at this site indicates that there has been a rapid increase in the depth of sedimentation from relatively shallow water in the Maestrichtian to depths similar to the present day (1400 m) by the Early Eocene.

Using the DSDP results it is possible to make a very general reconstruction of the geological history of the region. The results of Site 206 indicate that the New Caledonia Basin existed as an oceanic basin at least as far back as the Early Paleocene. Reworked Late Cretaceous (Maestrichtian?) radiolarians near the base of the hole probably indicate an even older age for the Basin. On Lord Howe Rise the known geological record begins with the eruption of rhyolites, possibly at or near sea level, 96 m.y. B.P. (McDougall & van der Lingen, 1974). This activity may have been a forerunner to the development of oceanic crust in the Tasman Sea at 80 m.y. B.P. (Hayes & Ringis, 1973); or 76 m.y. B.P. using time scale of LaBrecque & others, 1977. During the Maestrichtian the silty claystone intersected at Site 207 was deposited in a shallow marine environment with restricted circulation. In the south, true oceanic conditions began in the middle Paleocene, the Rise continued to subside and reached its present upper bathyal depth by the Early Eocene. In the north, however, oceanic conditions prevailed in the Maestrichtian or earlier, and the Rise had reached upper bathyal depths by latest Cretaceous. The Lord Howe Rise appears to have been stable at about its present depth since Middle Eocene.

The other direct evidence that we have of the rocks forming Lord Howe Rise is from a dredging program carried out during the French Georstom III cruise in 1975 (Launay & others, 1977) on the flank of the volcanic feature (Lat. 35°37.2′S, Long. 165°46.8′E) shown on Mobil Oil Corporations seismic lines 109 and 112 (Bentz, 1974) across the southeastern margin of the Rise. At this site olivine basalts, gabbros, and a mixture of hyaloclastic breccias and biomicrites were obtained (Launay & others, 1977). The biomicrites contained coral debris and planktonic foraminifera, which are mid-Miocene or younger. Launay & others (1977) interpreted this to indicate that sometime during the Paleogene about 500 m of subsidence occurred, permitting coral growth on the top of the volcanic feature and planktonic foraminifera at its base. After the mid-Miocene there was further subsidence until Lord Howe Rise reached its present depth of about 1500 m. This interpretation differs from that based on the DSDP results, which indicate that the Rise had subsided to its present depth by the Middle Eocene.

Evolutionary models that have been proposed for the Tasman Sea and Lord Howe Rise

Hayes & Ringis (1973) identified linear west-northwest-trending magnetic anomalies 24-33 in the Tasman Basin, which are disposed about a buried basement ridge, thus indicating formation by seafloor-spreading processes, about 76 to 56 m.y. ago (La Brecque & others, 1977). In a reappraisal of the spreading pattern and age identification of the magnetic anomalies, Weissel & Hayes (1977), showed that the transform faults trend more northeasterly (Fig. 4A) than suggested by Ringis (1972) and that Ringis's proposed interval of subduction at the east Australian margin between anomaly 27 and 24 (about 62 to 56 m.y. B.P.; La Brecque & others, 1977) was no longer necessary. Weissel & Hayes (1977) supported the suggestion of Ringis (1972) that the oldest anomalies, 32 and 33, should be found within the Middleton and Lord Howe Basins and that a ridge jump had taken place after anomaly 32 time, probably leaving the Dampier Ridge as a stranded fragment of continental crust on the western side of the 'Lord Howe Plate'. A recent reconstruction of the Lord Howe Rise and eastern Australia is given by Shaw (1978), and implies that strike-slip motion in the northern Tasman Basin was concurrent with accretion in the southern Tasman Basin during the early stages of opening from anomalies 33 to 32.

An evolutionary model of the early rifting history of the Tasman Sea has been put forward by Jongsma & Mutter (1978), who suggest that the western half of Lord Howe Rise, and probably the whole of the Dampier Ridge, formed an entire Early Cretaceous rift-valley prior to seafloor spreading in the Tasman Sea (Fig 4A). When new oceanic crust broke through the rift-valley, it was not along its axis as in most idealised models of rifting (e.g., Falvey, 1974), but along its western boundary fault. They proposed such a model to account for a zone of apparent horst and graben structures along the western half of Lord Howe Rise (Fig. 2), and the narrow continental margin and lack of rift basins along the eastern seaboard of Australia. In a later paper (Mutter & Jongsma, 1978) they envisage the fragmentation as resulting from a 3-branch rift system in which the Gippsland Basin formed a failed arm (Fig. 4B). This implies that pre-breakup Gippsland Basin sediments of the Lower Cretaceous Strezlecki Group and lowermost Upper Cretaceous Latrobe Group (Threlfall & others, 1976) may have equivalents beneath Lord Howe Rise.

Several hypotheses have been advanced to explain the origin of the New Caledonia Basin and the Norfolk and West Norfolk Ridges beyond it. These include the evolution of a complex arc system (Geze, 1963; Dubois & others, 1974), arc migration, and the development of marginal basins (Karig, 1971; Packham & Falvey, 1971). Whether the Norfolk Ridge was at one time also part of the Australian continental margin remains uncertain. However, the results of the DSDP drilling program support the conclusion that the basins and ridges in the area were formed by the end of the Mesozoic (Burns, Andrews & others, 1973). The interpretation of the *Sonne* data sheds some light on the relative ages of the New Caledonia, Middleton, Lord Howe, and Tasman Basins.

Interpretation of 'Sonne' data

Seismic stratigraphic sequences

We have been able to identify six widespread seismic stratigraphic sequences (Mitchum & others, 1977) on reflection profiles across the Lord Howe Rise, each with distinct internal reflection and boundary characteristics (Fig. 5). Several of these have been tentatively traced westwards across the Lord Howe Basin and onto the Dampier Ridge, and eastwards into the New

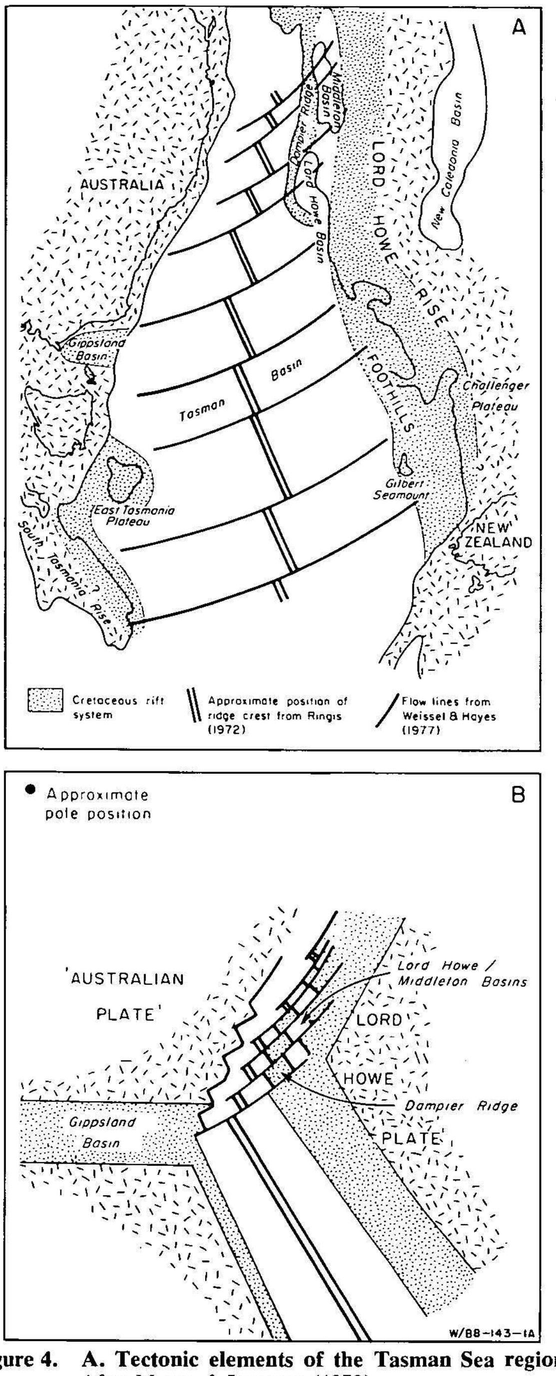


Figure 4. A. Tectonic elements of the Tasman Sea region. After Mutter & Jongsma (1978).
B. Schematic diagram showing tectonic pattern of the Tasman Sea. After Mutter & Jongsma (1978), reconstructed along the flow-lines of Weissel & Hayes (1977).

Caledonia Basin. However, continuous correlation of sequences from the Rise to the adjacent basins is hampered by abrupt changes in thickness and reflection character on the flanks of the Rise.

Figure 5 shows that the internal configuration of reflections within the upper five sequences (A to E) is consistent with the the environments of deposition and lithologies encountered in DSDP Sites 207 and 208. A good tie was achieved at Site 208 in the northern part of the survey area (Fig. 1), and an indirect tie was also made to Site 207 in the south, via profiles which were recorded by the New Zealand Department of Scientific and Industrial Research (DSIR), using a relatively low-power air-gun source. This second tie is much less reliable, mainly because of the location of the drill-site, which is on a small basement high overlain by an attenuated sedimentary column.

Seismic stratigraphic Sequence A exhibits parallel, low-amplitude reflectors; in places these reflections downlap onto the basal unconformity, which DSDP information suggests is of Mid-Miocene age. The sequence correlates with a deep-sea pelagic ooze penetrated in the drill-hole.

The underlying Sequence B is characterised by a chaotic internal reflection configuration, erosional truncation of its upper surface and, often, a concordant lower boundary. In the drill-holes it too is a pelagic ooze, mainly of Oligocene to Early Miocene age, which was probably deposited in turbulent bottom-water conditions. Such conditions are believed to have prevailed from the Eocene, following separation of Australia and Antarctica in the Paleocene (Weissel & Hayes, 1972), and probably also resulted in the formation of the widespread Eocene/Oligocene unconformity (Burns, Andrews & others, 1973).

Sequence C is composed of subparallel, high-amplitude events, and is in places discordant with the underlying sequence. The very prominent increase in amplitude which occurs at the B/C interface (Fig. 5) correlates at the drill sites with what is little more than a slight increase in the siliceous content of the pelagic oozes. The sequence is considered to be of Eocene age.

Sequence D shows a subparallel, high-amplitude internal configuration, general erosional truncation at its upper boundary, and onlap at its base. It correlates with a sequence of shallow-marine silts and clays of Paleocene to Maestrichtian age, intersected at the base of DSDP Site 207.

The internal configuration of Sequence E is subparallel, but its top shows marked erosional truncation, and at its base it onlaps basement. It forms the sediment-fill within grabens on the western part of the Lord Howe Rise, but is normally absent over the basement highs. The markedly erosional nature of the D/E unconformity indicates that there was probably considerable subaerial or wave-base erosion in the Late Cretaceous. Maestrichtian shallow marine sediments, as intersected at DSDP Site 207, were deposited on this erosion surface. We thus regard the D/E interface as a Maestrichtian breakup unconformity formed following the onset of seafloor spreading (anomaly 33 time, 76 m.y. B.P., LaBrecque & others, 1977), when Lord Howe Rise subsided below wave-base. Although correlatives of Sequence E have not been penetrated in either DSDP Sites 207 or 208 it seems likely that the sediments are of continental or shallow-marine origin, and of Cretaceous age or older.

The properties of Sequence F and of the E/F interface are variable: in places the sequence is characterised by incoherent reflectors and forms acoustic basement, but in parts of the Rise and the Dampier Ridge a clearly defined stratification, which indicates folds and faults, is evident. In many places, particularly along the faults which bound horst-blocks, the sequence includes intrusions. The range in refraction velocities apparently associated with Sequence F, and the variation in magnetic response, are more evidence of its complexity (Willcox & others, in preparation). We believe that this sequence is a composite of Palaeozoic metasediments, which are part of the Tasman Geosyncline of eastern Australia; of intrusives; and of

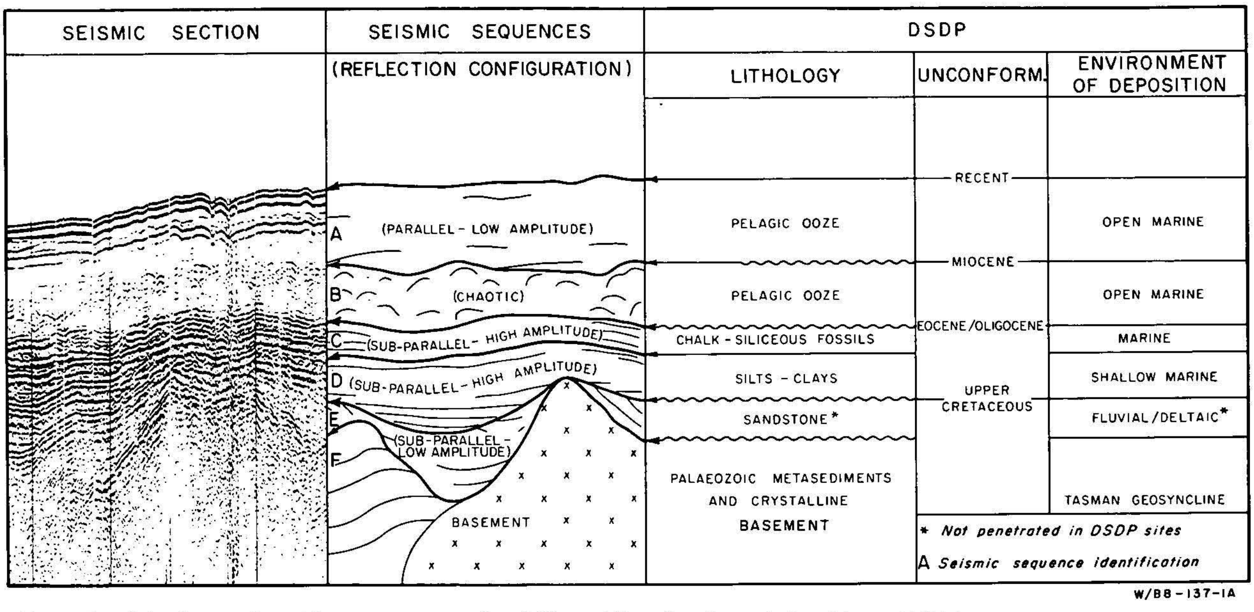


Figure 5. Seismic stratigraphic sequences on Lord Howe Rise showing relationship to DSDP data.

sediments of probable Permo-Triassic age, which may be related to those in the Sydney Basin. Although younger rift-fill sediments have not been identified within Sequence F, their possible presence cannot be dismissed—they may be revealed by processing of the seismic data.

From indirect seismic ties to DSDP Site 206, we have also been able to identify seismic stratigraphic sequences in the New Caledonian Basin, the upper four of which correspond almost precisely in age with Sequences A to D on the Lord Howe Rise. In general, however, the sequences within the New Caledonia Basin (Fig. 7A) are more stratified than those on the Rise. Direct correlation of Sequences A to D between the two areas is made difficult by the steep gradient and thin section along the eastern edge of the Rise. The lowermost sedimentary sequence has not been penetrated at the drill-site but has been correlated tentatively with Sequence E of Lord Howe Rise, with which it appears to tie.

Structure

The *Sonne* survey was planned principally to examine the western part of the Lord Howe Rise, between DSDP Sites 207 and 208, which may be underlain by a Late Cretaceous rift-valley (Jongsma & Mutter, 1978). Only the southernmost line, extending from the New Caledonia Basin to the Tasman Basin, provides a complete cross-section of the area.

Our seismic monitor data indicate that there is some justification for distinguishing an eastern province, characterised by relatively elevated and planed-off basement, and a western province, containing horst and graben structures (see Figs. 2, 6); however, this division is not as clear cut as indicated by previous interpretations (Jongsma & Mutter, 1978; Willcox, in press; Fig. 2). In the northern part of the survey area, near DSDP Site 208, company lines show that the planar basement area is quite narrow, and in places is also dissected by small grabens. Also, in the far south-east, on R. V. *Eltanin* Line 34 (Davey, 1977, fig. 3) an additional horst and graben province seems to be present on the New Caledonia Basin margin of the Lord Howe Rise (which in that area is referred to as the Challenger Plateau).

A cursory examination of the BGR seismic data, which have recently been re-displayed after initial processing, indicates that other problems may exist in interpreting the so-called western horst and graben province as a part of a Late Cretaceous rift-valley. Some horsts and grabens are still apparent on these records, but many of the structures now appear as half grabens or little more than basement depressions. The observation of Jongsma & Mutter (1978) that the western rift-valley province on Lord Howe Rise is associated with a more subdued magnetic field than the eastern province is not borne out either by our magnetic data or the profiles of Launay & others (1977, fig. 2), which show that a disturbed magnetic field occurs across the Rise, at least in the north.

Within the western province intrusions are quite prominent, particularly along the fault-planes bounding horsts. Very few faults extend beyond the Late Cretaceous unconformity, and many are confined to the basement itself. The structural trends in this province are difficult to determine, as few features can be correlated between lines; however, where closely-spaced lines are available, the trends seem to be north-northwest or possibly northwest, approximately parallel to the magnetic lineation in the Tasman Basin.

Fault-blocks of the type which occur on the western part of the Rise also appear to be present beneath the Middleton and Lord Howe Basins, and are certainly present on the Dampier Ridge (Fig. 6A). Apart from the obvious differences of water and basement depths, there are two other important differences between the western part of the Rise and the features further west: firstly, intrusions and crystalline rocks appear to make up a greater proportion of basement in the Middleton and Lord Howe Basins and Dampier Ridge; secondly, the occasional planed-off horst blocks which occur on the western part of the Rise are not apparent farther west. It thus seems probable that the Dampier Ridge is at least in part of continental origin (as originally suggested by Ringis, 1972), but that it has been extensively altered and possibly distended by intrusions.

The Maestrichtian horizon (D/E) generally lies less than 100 m above the planed basement surface on the

Rise, but is draped across the basins in many instances, with 2000 m or more of sediment beneath it. On the Rise itself, this horizon is an erosional unconformity which we interpret as a 'break-up unconformity' (Fig. 6) associated with the formation of the Tasman Basin. In the Middleton and Lord Howe Basins the horizon grades into a disconformity and is up to 1000 m above basement (Fig. 6A, B). The fact that the Maestrichtian break-up unconformity is not continuous with basement in the Middleton and Lord Howe Basins means either that they are oceanic basins which are older than the Tasman Basin, or that they are underlain by continental crust, albeit extensively altered by rifting.

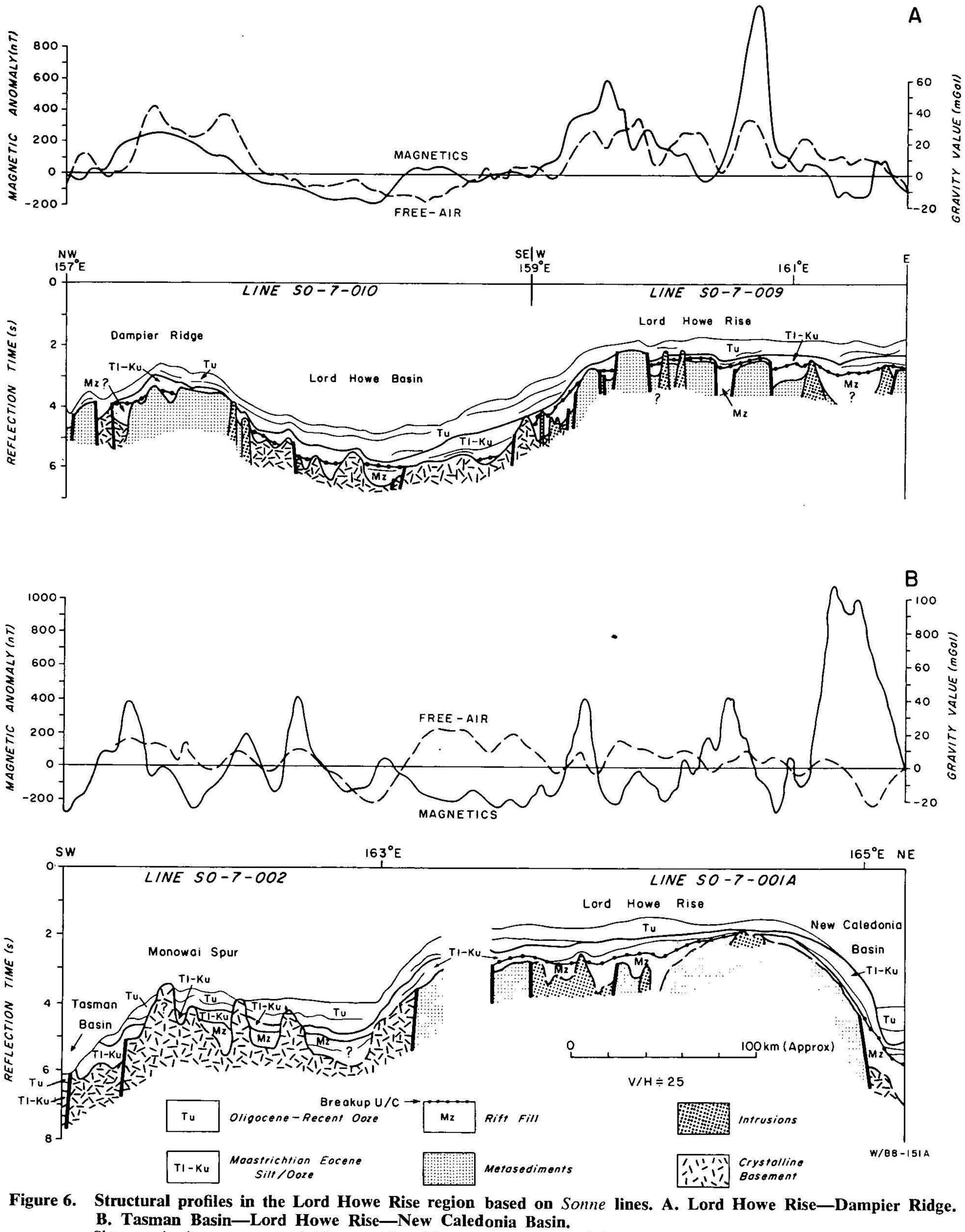
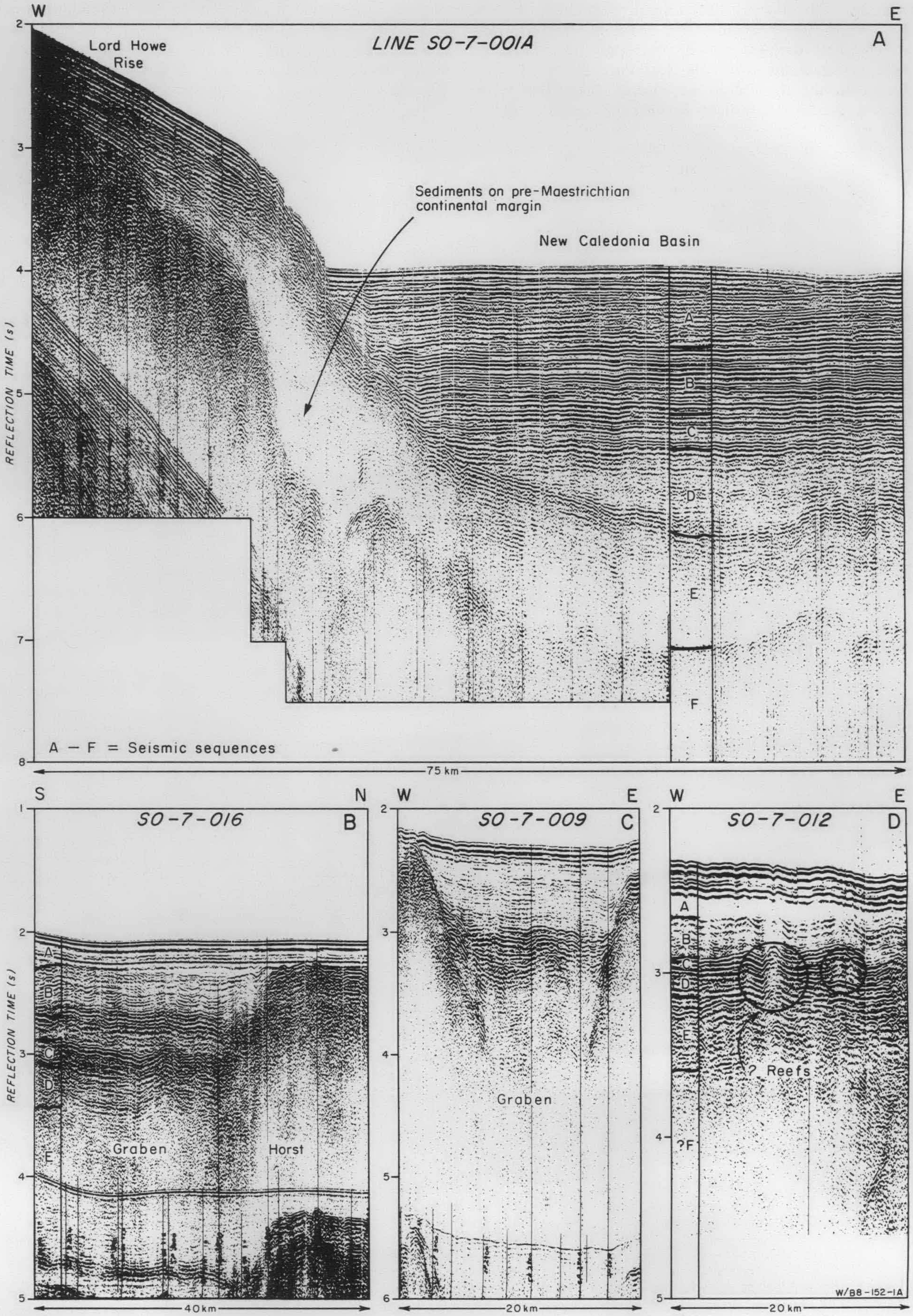


Figure 6. Structural profiles in the Lord Howe Rise region based on *Sonne* lines. A. Lord Howe Rise—Dampier Ridge. B. Tasman Basin—Lord Howe Rise—New Caledonia Basin.
Shows seismic sequences (A-F), unconformities, and apparent variation in basement type. Shows also free-air anomaly (FAA) and magnetic anomaly (MAG = total magnetic intensity minus IGRF). Locations given in Figure 1.


W
E
LINE SO-7-001A
A
Lord Howe Rise
Sediments on pre-Maestrichtian continental margin
New Caledonia Basin
REFLECTION TIME (s)
A
B
C
D
E
F
A – F = Seismic sequences
75 km
S
N
SO-7-016
B
Graben
Horst
40 km
SO-7-009
C
Graben
20 km
SO-7-012
D
?F
? Reefs
W/B8-152-1A
20 km

The present topographical configuration, consisting of a basin or trough between the Dampier Ridge and Lord Howe Rise, appears to have existed prior to formation of the Tasman Basin. This, with the areal extent of planed basement and the nature of the Maestrichtian unconformity, suggests that the Lord Howe Rise may have been a shallow, trough-bounded marginal plateau bordering the New Caledonia Basin. A modern-day analogy, although at a greater water depth, might be the Queensland Plateau off northeast Australia (Mutter, 1977; Willcox, in press, fig. 19), which is bordered by the Queensland and Townsville Troughs, each underlain by continental basement.

The eastern margin of Lord Howe Rise is steeply dipping; on the lines we have examined, it appears to be structured over a major basement fault, which separates continental basement on the Rise and oceanic basement in the New Caledonia Basin (Figs. 6B & 7A). Once again, the Maestrichtian break-up unconformity is not continuous with basement, and in most places lies 1000 m or more above it. Thus the New Caledonia Basin must be older than the Tasman Basin, and it seems reasonable to postulate that the eastern flank of Lord Howe Rise is the ancient (pre-Maestrichtian) continental margin of the 'Australian—Antarctic supercontinent'.

Sedimentary accumulations on western Lord Howe Rise

Within the survey area we have found no evidence of a single sediment-filled depression resulting from rifting or pull-apart tectonics, such as occurs on the 'Atlantic type' southern margin of Australia (Bremer, Great Australian Bight, and Otway Basins; e.g. Fraser & Tilbury, 1979). However, the Lord Howe Rise area does bear a superficial resemblance to other trough-bounded marginal plateaus around the Australian margin, such as the Exmouth Plateau (Exon & Willcox, 1978), although by comparison with the latter it has obviously been starved of sediment both before and after breakup. The numerous small basins and grabens contain sediment which in some of them has a thickness of 4000 m (Fig. 7B & 7C). The section underlying the Maestrichtian unconformity is frequently 2000 m thick, but the overlying section is nearly everywhere less than 1000 m thick.

In some areas reef-like structures occur on and near the Maestrichtian unconformity (D/E). Figure 7D shows two such features: one is on the unconformity, and the other within Sequence D, which onlaps the unconformity and is believed to be of shallow-water origin. Both features exhibit velocity pull-up and lateral facies variation, as would be expected of reefs.

The palaeogeographic considerations discussed above lead us to speculate that the pre-Maestrichtian sediments infilling the grabens are probably either continental or shallow-marine deposits, which are in turn overlain by shallow marine silts and clays of the type intersected at DSDP Site 207. Deeper marine environments may have existed within the embryonic Middleton and Lord Howe Basins. The blanket of younger sediment is probably entirely pelagic ooze, as intersected at all the DSDP sites (Fig. 3).

Sediment on the eastern flank of Lord Howe Rise

An acoustically semi-transparent sediment wedge extends across the boundary fault that separates the continental crust of Lord Howe Rise from oceanic crust beneath the New Caledonia Basin (Fig. 7A). Sediment thicknesses of at least 2000 m are probably present. In this area we envisage Sequence E as a wedge of clastic sediment, of Late Cretaceous and older age, deposited on the ancient continental margin of the Australian-Antarctic supercontinent. Some company profiles across this margin show progradation within the sequence, similar to that which occurs around the margin of present-day Australia. In places, folding and slump structures are also apparent.

The D/E unconformity surface within the New Caledonia Basin exhibits gentle undulation, and there is a well-defined onlap of Sequence E by Sequence D; this may indicate that the New Caledonia Basin has been affected by compressional force in or before the Late Cretaceous, and it may be related to the folding observed on the West Norfolk Ridge (Willcox & others, in preparation).

Petroleum prospectivity

This assessment of the petroleum prospectivity of the Lord Howe Rise region depends largely on our understanding of its palaeogeography, and the results of the DSDP drilling.

There are three distinct areas of thick sediment accumulation in the region: the basins on the western part of the Lord Howe Rise, the flanks of the Middleton and Lord Howe Basins, and the sediment wedge on the eastern margin of the Rise.

Western Lord Howe Rise

The distribution and orientation of the basins (grabens) is still not clear: in general they range in width from 20-40 km and probably extend at least over several tens of kilometres. In the central portion of the Rise (between about 25° and 37°S) the largest basin (graben) commonly lies adjacent to the area of planed basement. The sedimentary fill is very variable, but within grabens such as that shown in Fig. 7C it spans at least 2.8s of reflection time, equivalent to a total thickness of 3000 to 4000 m.

We have no direct indication of the depositional environments which prevailed within the basins in pre-Maestrichtian times. If these features formed as described by the classical models for Atlantic-type margin development, we would expect that the sediment fill is predominantly fluvio-lacustrine, and hence they may have contained a high proportion of terrestial (humic)

Figure 7. Seismic reflection details, recorded as single channel on-line monitors.
Locations given in Figure 1.
A. Profile across eastern flank of Lord Howe Rise and New Caledonia Basin.
Note marginal fault apparently separating continental and oceanic basement. Also breakup unconformity traced from Lord Howe Rise (D/E) appears to lie above oceanic basement in the New Caledonia Basin.
B. Profile showing horst and graben structures on western side of Lord Howe Rise.
C. Graben with boundary intrusion on western side of Lord Howe Rise.
It is about 15 km wide, and is probably filled by 2000+ m of pre-breakup sediment, overlain by 1000+ m of post-breakup marine sediment.
D. Profile showing possible pinnacle reefs built on or near the ?Late Cretaceous breakup unconformity.

kerogen, which is generally gas-prone. However, even terrestrial organic matter, when deposited under reducing conditions, can give rise to paraffinic oils and wet gas (Harwood, 1977). As already discussed, several of the horst blocks appear to have undergone wave-base erosion during the Late Cretaceous, implying that shallow-marine conditions occurred within the intervening grabens and basins. We believe that these features may have formed restricted basins in which anaerobic conditions prevailed. Deposition of aquatic (liptinitic) kerogen within the sedimentary fill of such basins would provide source beds with a capacity to generate oil. The DSDP results confirm that shallow-marine silts and clays were being deposited in the Maestrichtian, within an environment which had restricted (non-oceanic) circulation (Burns, Andrews & others, 1973) and they could therefore contain source material. If the reef-like structures within the Maestrichtian-Paleocene sequence are reefs, shallow-marine conditions must have prevailed during their growth. In summary, up to 3000 m of section containing potential petroleum source rocks may be present in the basins and grabens.

Similar thicknesses of source rocks may also be preserved on the flanks of the Middleton and Lord Howe Basins. If the Lord Howe Rise existed as a trough-bounded marginal plateau during the Late Cretaceous, shallow-marine and marine clastic sediment would probably have been shed into the trough throughout much of this time.

Possible reservoir rocks may include sandstones within the basins and grabens, and the Maestrichtian reefs. It is not known whether any induration of potential reservoir rocks has occurred as a result either of volcanism during the rifting process, or of intrusions along the fault planes. Eruptions and intrusions may be either of Cretaceous age, or related to the three eruptive periods spanning the mid-Tertiary to mid-Pliocene observed on Lord Howe Island (Game, 1970).

Any petroleum generated within the grabens (basins) would probably be trapped against the boundary faults, although further structural traps may have been created by the minor folding and faulting observed within the graben-fill (Fig. 7B, C). Petroleum could also have migrated upwards and been trapped in reef-structures, which are sealed by pelagic oozes.

In most places it is unlikely that source material within the Maestrichtian shallow-marine sequence (D) would have been buried deeply enough to have generated hydrocarbons. On Lord Howe Rise the sedimentary overburden ranges from a few hundred to about 1000 m and could not have provided a sufficient thermal blanket unless the heat-flow was abnormally high. Thus any mature source would probably have to be at greater depth within the basins. In contrast, on the eastern flank of the Lord Howe Basin, the sedimentary overburden is thick enough (up to 2000 m) to have matured any source material within the Maestrichtian sequence.

There are some indications that the Lord Howe Rise region may be associated with an anomalous thermal regime. The only heat-flow measurement (Grim, 1969) gave a value of about twice normal heat-flow. Also, the Tertiary volcanism in the region may be related to northward drift of the area over a mantle hot-spot (Vogt & Conolly, 1971). As little exploration activity has been undertaken in basins of the pull-apart type, their petroleum potential and the nature of any hydrocarbons are virtually unknown. Theoretically, as suggested by Klemme (1975), these basins may be expected to have had high geothermal gradients at the inception of seafloor spreading, and source rocks may well have matured with less overburden than would normally be required.

Our final consideration on the petroleum prospectivity of the western part of Lord Howe Rise relates to the reconstruction of the central area of the Rise against the Gippsland Basin (Jongsma & Mutter, 1978; Shaw, 1978; Fig. 4). The Gippsland Basin lies at the eastern end of Bass Strait and is the main oil and gas-producing province of Australia. It is thought to have formed within the failed-arm of a triple rift system (Burke & Dewey, 1973). There are two major sedimentary divisions of the Basin: the Lower Cretaceous Strzelecki Group, comprising non-marine greywackes, shales, and coals with poor reservoir characteristics; these are unconformably overlain by sands, silts, and minor shales of the Late Cretaceous to Late Eocene Latrobe Group. Threlfall & others (1976) consider that the primary source of the oil and gas has been the non-marine shales and coals within the uppermost Cretaceous and Paleocene Latrobe Group. Trapping generally occurs at the Eocene/Oligocene unconformity which lies at the top of the Latrobe Group.

The DSDP results and the Late Cretaceous or older wave-base erosion of many of the horst blocks on Lord Howe Rise indicate that subsidence, and thus the transition from predominantly continental to predominantly marine deposition, would have occurred earlier on the Lord Howe Rise than in the Gippsland Basin on the western margin of the Tasman Basin rift (Fig. 4). Thus non-marine shales and coals of similar type to those thought to source the hydrocarbons in the Gippsland Basin, but of somewhat greater age, may have been deposited deep within the basins on Lord Howe Rise. The development of successive shore-lines and palaeoslopes in the eastern part of the Gippsland Basin (Threlfall & others, 1976) suggests that parts of the Latrobe Group may have a laterally equivalent shallow marine sequence, perhaps containing aquatic kerogen, to the east on the western margin of the Tasman Basin rift. The Maestrichtian shallow marine, silty claystone at DSDP Site 207 on Lord Howe Rise may represent the uppermost part of a similar sequence on the eastern margin of the rift.

Eastern flank of Lord Howe Rise

We believe that the eastern flank of Lord Howe Rise was the ancient seaboard of the Australian-Antarctic supercontinent (Fig. 7A), and that a considerable thickness (about 2000 m) of clastic sediment was deposited across this margin during or before the Late Cretaceous. Most of this was probably derived from the planed basement block to the west. The overburden of pelagic sediments ranges from about 1000 m on the eastern edge of the Rise, to as much as 3000 m in the New Caledonia Basin. Depositional environments favourable for both the production of aquatic, petroleum-generating organic matter and its preservation in sediments may have occurred on this continental slope, as on many other continental slopes around the world (Dow, 1979).

Folding within the ?Late Cretaceous sediment wedge could provide traps for petroleum, and the progradation observed on some profiles may incorporate stratigraphic traps. Petroleum migrating updip could be trapped against the basement surface and sealed by the overlying pelagic oozes.

Conclusion

Our preliminary analysis of the *Sonne* data shows that numerous small basins, some of which may have formed within grabens, underlie the western part of the Lord Howe Rise. These probably trend north-northwest, range from 20-40 km wide, but are of uncertain length. The deepest basin contains in excess of 3000 m of sediment. Tensional features are also present on the Dampier Ridge and possibly within the Lord Howe and Middleton Basins. We conclude that the Dampier Ridge is at least in part of continental origin. We cannot presently support Jongsma & Mutters' (1978) contention that 'a zone of horst and graben basement structures some 200 km in width' underlies the western part of the Lord Howe Rise, and that it represents the whole of the pre-Tasman Basin rift valley. The degree to which basement structures on the Lord Howe Rise and the Dampier Ridge are related to Tasman Basin rifting remains conjectural.

Relatively thick prograded sediments occur on both the western and eastern flanks of the Rise. A Maestrichtian unconformity which overlies these sediments is markedly erosional on the Rise, and is believed to be a 'breakup unconformity' associated with formation of the Tasman Basin. Since the Maestrichtian unconformity is not continuous with basement in the Lord Howe and Middleton Basins to the west of the Rise, or in the New Caledonia Basin to its east, all three basins must be older than the Tasman Basin. We consider that the eastern (New Caledonia Basin) flank, upon which 2000-3000 m of pre-Maestrichtian sediment has been deposited, is the ancient continental slope of the Australian-Antarctic supercontinent. In the Late Cretaceous, it seems probable that the Lord Howe and Middleton Basins were troughs, and that the Lord Howe Rise was a trough-bounded marginal plateau. We envisage that the Queensland Trough and Queensland Plateau form a modern-day analogy of this situation.

The absence of major rift-basins of the type that underlie other Atlantic or 'pull-apart' margins (for example, the Ceduna Terrace and Northwest Shelf/ Exmouth Plateau regions) is disappointing for petroleum potential. However, structural and palaeogeographic considerations suggest that petroleum source rocks may have been deposited on the Lord Howe Rise in the Late Cretaceous, prior to formation of the Tasman Basin. A favourable restricted marine environment may have been associated with the small basins and grabens.

Petroleum traps appear to exist against the boundary faults, and as smaller structures within the basins. Structures interpreted at Late Cretaceous and Paleocene reefs are also possible targets. A seal may be provided by interbedded shales and pelagic oozes. The prograded sequences on the flanks of the Rise also warrant further examination.

Detailed assessment of the petroleum prospectivity of the Lord Howe Rise requires a greater understanding of the nature of the sediment, both within the small basins and grabens, and on its eastern flank. Our interpretation suggests that potential petroleum source rocks and suitable traps may exist and thus this deep-water area may provide a long-term petroleum prospect.

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Ninth BMR Symposium

BMR holds an annual symposium, at which results of relevance to industry are stressed. The Ninth Symposium was held in Canberra on 29 and 30 April 1980. Abstracts of the talks presented are given below.

Limitations and survey design parameters for time-domain EM methods in mineral exploration

B. R. Spies

The TEM method is being used increasingly for mineral exploration and geological mapping in Australia. The techniques include one-loop systems (SIROTEM and MPPO-1) and two-loop systems (PEM and EMP); these techniques show different responses over the conductive surface layers which cover much of Australia. The response of both one-loop and two-loop systems to a variable surface layer or host rock has been investigated with a scale-model facility using an interactive mini-computer, and numerical studies. For a homogeneous ground the response is relatively simple for a one-loop configuration, but becomes more complex when the transmitter and receiver loops are separated. For the two-loop configuration the response changes sign at a time which depends on the loop separation and ground conductivity. Variations in the conductivity of the overburden can cause complex anomaly shapes which are difficult to interpret intuitively. For both one-loop and two-loop configurations, anomaly sources within the overburden may be difficult to distinguish from anomalies caused by deeper, more conductive sources.

The limits of detection of TEM methods have been investigated from the modelled response of the Elura and Roxby Downs mineral deposits. The TEM response is determined for a variety of loop sizes, depths of burial, and conductivity contrasts between the deposit and host rock. It is shown that the optimum time range for detecting these types of deposits is usually between 1 and 50 ms, and that some conductors remain undetectable, irrespective of equipment sensitivity, time range, or loop size. By a parametric study of two-layer curves it is shown that the earliest sample time a body can be detected under a conductive layer is determined only by the conductivity of the layer and the sample time, and is not dependent on loop size.

The optimum loop size for detecting a body in a resistive environment is slightly larger than the size of the body in plan. If the body is contained in a conductive host rock, then a smaller loop will minimise coupling with the host rock and will enable detection of the body over a wider time range. However, the smaller loop emphasises lateral inhomogeneities in the overburden.

Techniques for discrimination of surficial and bedrock magnetic sources at Cobar, NSW

P. R. Gidley

The magnetic method is the main exploration tool used in the search for mineral deposits in the Cobar area of NSW; this is because most deposits discovered to date contain magnetic minerals. Unfortunately, widespread occurrences of near-surface laterite commonly produce anomalies which are difficult to distinguish from those reflecting bedrock sources. Work during 1978 and 1979 has confirmed that the near-surface response is caused by hematite/maghemite concentrations with a high magnetic susceptibility and remanence. These magnetic suites usually occur in surface layers up to 6 m thick and exhibit large lateral and vertical variations in magnetic properties over small distances.

To avoid anomaly aliasing, high sampling rates and close line spacing are important factors in the design of ground or airborne surveys. Such data collected, followed by relatively simple processing procedures, permit the depths of magnetic sources to be determined, thereby distinguishing bedrock from surface sources. In addition, the frequency content of the data allows the distribution and dimensions of magnetic cells which make up the sources of near-surface anomalies to be determined. Once these parameters are established band-pass filtering can be used to enhance the response from bedrock sources, therefore permitting discrimination between source types. Knowledge of the magnetic cell dimensions permits more accurate modelling, and investigation of discrimination techniques.

Gravity and electrical methods also enable the discrimination of shallow and bedrock sources. Case studies, including drill-hole and physical rock property information, are presented to demonstrate the ability to discriminate between different source types.

The influence of the geoelectric section on EM and IP surveys at Elura, NSW

I. G. Hone, B. R. Spies, & E. D. Tyne

The Bureau of Mineral Resources has investigated the geoelectric properties of fresh and weathered rocks at Elura through a program of downhole logging, Schlumberger soundings, and laboratory measurements on drill-core. The knowledge gained by such work has enabled BMR and the Geological Survey of New South Wales (GSNSW) to model the electromagnetic and electrical responses of the deposit.

Logging showed that resistivities of intensely weathered country rocks, comprising shales, sandstones and siltstones, are less than 30 ohm-m just below the water-table, in some instances being as low as 1 ohm-m. Resistivities gradually increase with depth as rocks become less weathered, and at 200 m resistivities of approximately 2000 ohm-m were recorded. A decrease in the resistivity of the country rocks in the vicinity of the deposit has been observed which may indicate a fracture halo or some other effect related to the deposit. Induced polarisation logging indicates that the chargeability of country rocks is approximately 10 mV/V just below the water-table and increases to approximately 20 mV/V at 200 m depth. Laboratory measurements and results of logging indicate that the mineralisation has a resistivity of about 0.2 ohm-m and very high chargeability.

Interpretation of Schlumberger depth soundings indicates that the top 5 m of section consists of a thin, resistive layer which is sometimes overlain by a thinner, more conductive layer. Below a depth of approximately 5 m the section has a low resistivity of approximately 10 ohm-m and a very low chargeability which probably represents very weathered rocks; this very weathered zone appears to be approximately 110 m thick. Below this zone rocks have higher resistivities and chargeabilities indicative of relatively less weathering. Detailed analyses of the sounding data over the deposit show that the top 50 m of section has a higher conductivity-thickness product than the section on either side. A zone with higher resistivity and chargeability is interpreted to lie above the deposit extending up to about 40 m from surface. This may reflect the presence of a siliceous gossan.

A. single-loop TEM line surveyed across the deposit gave results of the same form as obtained in model studies. Grid coverage using 50 m loops delineated at early sample times a near-surface conductive feature striking approximately north and located over the deposit. At late sample times three anomalous zones were defined; semi-quantitative interpretation of these anomalies using decay curves favourably highlights the anomaly over Elura as compared with the other two anomalies. A time-domain IP survey using a 100 m dipole-dipole array made over Elura in 1979 by GSNSW produced a much better defined anomaly over the deposit than a frequency domain IP survey using a similar array conducted in 1974 by BMR. The improvement in results demonstrates the advantages of using more technologically-advanced equipment which is now available.

Computer modelling of the IP and resistivity response of the deposit carried out by GSNSW has produced results consistent with field data. Modelling shows that inhomogeneities in the overburden, in particular a low resistivity zone over the deposit, obscure its resistivity response. A detectable anomaly appears unlikely to be observed should the deposit be insulated from the 110 m thick, conductive overburden.

Lachlan Fold Belt; geological associations with regional geophysics

B. W. Wyatt, A. N. Yeates, & D. H. Tucker

The Lachlan Fold Belt Regional Geophysical Project, started in April 1979, aims to investigate aspects of the geology controlling the geophysical characteristics of the region to provide a better understanding of the use of geophysics in geological mapping, mineral exploration and deeper crustal studies. The project team carried out regional field investigations involving geological observations, rock sampling, and geophysical measurements, to gain an appreciation of the geology, to directly investigate the causes of anomalies, and to compile a physical property data base. The project has so far been retsricted to NSW; 1000 locations have been investigated. These include representative outcrops of the major Palaeozoic rock groups and most outcropping sources of gravity and magnetic anomalies. The data base contains information on site location, topography, geology, structure, in situ magnetic susceptibility, 4-channel gamma-ray spectrometry, and laboratory density, porosity, and magnetic remanence measurements. The data base will be supplemented by petrological descriptions and some major and trace-element geochemistry. The density and susceptibility values will constrain future modelling studies of subsurface structures.

The regional magnetic and gravity data indicate four geophysical domains, each with different patterns of anomaly trend and amplitude and unique geological features, separated by disjunctive boundaries. Within the domains, a classification of magnetic anomalies by length, width, and amplitude appears capable of distinguishing between the various sources, thereby providing a useful mapping tool in regions with thin cover.

Radiometric readings from the data base suggest a relation between uranium and thorium concentrations and known tin and tungsten-bearing granites, and indicate other potentially prospective granites with no known mineralisation.

The Batten Trough: a structural problem in the McArthur Basin

K. A. Plumb

The fundamental concept in the palaeogeographic model of the McArthur Basin is that a thick sequence (up to 12 km) of sediments was deposited in a syndepositional graben 500 km long and 60 km wide, the Batten Trough, with much thinner sequences (up to 5 km) present on the adjacent stable shelves. Depositional thicknesses are postulated to have changed rapidly across major syndepositional fault zones. The graben has subsequently been deformed and uplifted, to form the Batten Fault Zone. The HYC lead-zinc deposit lies adjacent to one of these postulated boundary faults, so the palaeogeographic model may be a critical factor in exploration for further deposits of this type.

However, lack of outcrop in the critical areas makes it impossible to accurately define the original form of the Batten Trough from surface geology alone, and the possibility remains that the observed thickness changes may take place progressively over a considerable distance. Consequently, a geophysical investigation has been carried out across the southern McArthur Basin to attempt to resolve details of subsurface structure and stratigraphy, particularly in the critical zone immediately to the east of the Emu Fault. This symposium presents preliminary results of this survey; analysis is continuing.

McArthur Basin crustal seismic survey

C. D. N. Collins & J. Pinchin

During June and July 1979, a seismic refraction/reflection survey was carried out to determine the crustal structure across the Basin and, in particular, to investigate the crustal differences east and west of the Emu Fault. One long refraction line of 300 km, and one shorter line of 100 km were recorded on each side of the Fault. At each shot-point, seismic reflection recordings were made; two additional smaller shots were recorded by reflection spreads near Starvation Hill and at Batten Creek. Good reflection and refraction arrivals were recorded at all locations, except between Daly Waters and OT Downs, where deep weathering of Cretaceous rocks probably masked the deeper seismic reflections and refractions.

A preliminary interpretation of the refraction data shows the Moho at a fairly constant depth of 36 km on the western side of the Emu Fault. At Daly Waters, a surface layer about 4 km thick has a velocity of 4.6 km/s. This layer wedges out eastwards—there is no evidence for it east of OT Downs. The only other layers apparent on this side of the Emu Fault are surface layers with velocities of 5.9 km/s between HYC and OT Downs, which probably represent the thick carbonates of the McArthur Group, and 5.66 km/s between OT Downs and Daly Waters, which may represent the Roper Group.

On the eastern side of the Emu Fault, the Moho shallows from 37.5 km near the Fault to 34.0 km near the Murphy Inlier. Three other seismic velocities were measured within the crust: a 5.53 km/s near-surface arrival which probably correlates with the Tawallah Group; a 5.98 km/s refractor which marks the basement to the McArthur Basin succession; and a 6.39 km/s layer which represents a dipping layer within the basement rocks.

The seismic reflection sections have been digitally processed and reflections from the Moho were recorded at nearly all locations and correlate well with the refraction data. A characteristic wide band of reflections correlates with the 6.39 km/s intracrustal refractor to the east of the Emu Fault; a similar reflection band appears near the HYC Mine, to the west of the Fault. The vertical displacement within the basement rocks between these bands is 1.8 km upwards on the west side of the Fault. A tentative identification and correlation of basement across the Emu Fault gives a depth of 3.9 km near the HYC, to the west of the Fault, and 5.7 km at Starvation Hill, to the east. Because there is reasonable stratigraphic control of the McArthur Group to the west of the Fault it is implied that the Tawallah Group must thin towards the Emu Fault Zone.

Gravity evidence across the Batten Trough, McArthur Basin

W. Anfiloff

A detailed gravity survey was started across the Batten Fault Zone and the Bauhinia and Wearyan Shelves in 1978. Traverses with a combined length of 570 km have been measured, and 500 km of traverses are planned for 1980. The objective was to study the regional structural setting. Traverses have been positioned to cross the numerous topographic features in the area at sites where they are reasonably elongate; this makes it possible to process terrain effects automatically, and to obtain the continuous detailed and accurate coverage necessary to locate the short wavelength features which are essential for a thorough investigation.

The survey has detected a number of important short wavelength anomalies whose presence is not indicated by the existing helicopter reconnaissance coverage. Such features can be related directly to specific geological formations, and the repeated occurrence of some formations in outcrop along long traverses and on different traverses allow density contrasts to be evaluated. Small density contrasts are apparent at all depths in the basin sequence, but the greatest contrasts occur in the upper part. There is a good correlation between gravity and the geologically inferred basement shape across the Batten Fault Zone, and the basement appears to become very shallow in the Robinson River area. Near Borroloola, there is a small fault anomaly over a splay fault from the Emu Fault, but there is no fault anomaly where the main traverse crosses the Emu Fault farther south. However, at this site, there is a steep 3 mGal anomaly, which may represent a dense sulphide body near the surface.

The lack of a substantial fault anomaly across the Emu Fault would appear to rule out any sudden change in thickness of the critical McArthur Group dolomites, which are unlikely to have the same density as the underlying Tawallah Group sandstones. Mutually cancelling structures can be advocated deeper in the section, but the arrangement would be a fortuitous one. It is presently concluded from these results that the HYC mineralised zone occurs in an essentially undeformed part of the eastern platform; this is in disagreement with previous geological concepts.

A magneto-telluric approach to the structure of the Batten Trough, McArthur Basin

J. P. Cull

In 1978 seventeen MT sites were occupied in a 350 km traverse across the Wearyan Shelf and the eastern Batten Fault Zone. A preliminary examination of the resistivity plots at each site reveals marked differences across the Emu Fault, with diverging components of apparent resistivity. This feature is emphasised with data presented as 2D pseudo-sections. Isotropic data for the eastern sites were inverted in a 1D analysis, revealing a well defined basement of good contrast, with resistivity of about 95 kilohm-metres. This is covered by a layer 800 m thick with consistently low resistivity values of 70 ohm-m. Above this the resistivity increases with values in the range 600-900 ohm-m. However, there is about 10 m of overburden, with a very low resistivity of about 2.5 ohm-m. Consistent with surface geology the results indicate a depth to basement of about 2.8 km near the Calvert River, increasing to about 3.5 km near the Robinson River crossing. The 1D analysis demonstrates that MT responds to basement trends in the McArthur Basin; at shallower depth there are relatively conductive strata consistent with the sandstones of the Tawallah Group, but there are no distinct layers which can be attributed to the very thin, discontinuous outcrops of McArthur Group carbonates.

The non-isotropic data in the western part of the traverse have been analysed using inversion techniques to generate a 2D model, which shows a major discordance at the Emu Fault. Furthermore, this discordance persists to great depth, reflecting the concept that the major faults of the Batten Fault Zone had a significant history before the formation of the McArthur Basin.

In the area to the east of the Emu Fault, the statistical parameters of the 2D program generate different resistivities to the 1D results, but the main features remain: a clearly defined resistive basement overlain by a fairly simple conductive sequence; again, there is no layer which may be correlated with the carbonate rocks of the McArthur Group.

To the west of the Fault, there is a new block of highly resistive rocks, which may be directly correlated with the McArthur Group carbonates, which crop out in this area. Carbonate rocks typically have high resistivities, and the calculated depth of this block ($\sim$ 4.45 km) is very close to the thickness of McArthur Group predicted from surface geology. An underlying layer has a conductivity equivalent to the Tawallah Group, measured on the Wearyan Shelf, and is consistent with the predicted geological model.

The resistivities resolved in the 2D model can be related to the McArthur Group to the west of the Emu Fault, and the Tawallah Group to the east and west of the Fault. The distinctiveness of the McArthur Group to the west of the fault makes it impossible that an appreciable thickness of McArthur Group is present for any significant distance to the east of the fault. The results of the MT modelling across the Wearyan Shelf and eastern Batten Fault Zone, and the geological interpretation, support the currently preferred geological model that the Batten Trough was a syndepositional graben, with rapid changes in depositional thickness across boundary faults.

Some conclusions on the structure of the Batten Trough, McArthur Basin

K. A. Plumb

Seismic and MT results provide consistent constraints to the subsurface geology adjacent to the Emu Fault. Basement to the McArthur Basin succession is recorded on the Wearyan Shelf, at depth consistent with predicted geology. A crustal discontinuity appears to occur at the Emu Fault and, while thick McArthur Group carbonates are registered to the west of the Emu Fault, the Tawallah Group is identified as the main sequence present to the east of the Fault. The combined data make it seemingly impossible that any appreciable thickness of McArthur Group can be present for any significant distance to the east of the Emu Fault. The lack of a gravity anomaly across the Emu Fault implies that there is no significant present displacement, or sudden change in preserved (post-uplift and erosion) thickness of stratigraphic units at the Emu Fault. However, the use of the available seismic, MT, and geological constraints produces mutually compatible cross-sections which are also compatible with the gravity data; these sections constrain the palaeogeographic models which are possible. When these sections are restored to the situation which existed prior to uplift and erosion, it is implied that the McArthur Group thinned significantly at the Emu Fault.

The preliminary data analysis presently available favours the geologically predicted model for the nature of the Batten Trough.

Geochemical and palaeomagnetic limits on Precambrian Earth dimensions

A. Y. Glikson

It is shown that the early and middle Proterozoic crustal record cannot be explained by the present-day Earth surface dimensions, and consequently modern radius. With few exceptions, lithostratigraphic, geochemical and isotopic data for the 2.6-1.0 b.y. interval indicate ensialic environments—with little or no evidence for contemporaneous ocean crust and operation of accretion-subduction-partial melting cycles. Unlike Archaean crustal history, which was dominated by two-stage mantle-melting processes and a uni-directional sima-to-sial transformation, most Proterozoic cratonic and mobile-belt domains show evidence of granitic basement. Ophiolites are unknown and island-arc-type volcanic assemblages very rare in these terrains, Silicic igneous formations are dominated by high-K and LIL element abundances, high initial Sr^{87}/Sr^{86} ratios and negative Eu anomalies. Palaeomagnetic data indicate coincidence of apparent polar wander paths (APWP) of cratons within the Laurentian, African and Australian shields, disallowing relative plate movements within these shields. The joint APWP of each of these shields and of Greenland for the interval 2.3-1.6 b.y., has recently been shown to overlap if present-day angular relations between these continents are maintained. An integrity of the early and middle Proterozoic sialic crust is indicated by cross-Atlantic, cross-Pacific, and other fits, and by the parallel alignment of Archaean tectonic trends. These constraints raise an enigma for any model, involving the present-day Earth radius, for the following reasons: (1) models assuming global sial of continental thickness are ruled out on a volume basis, as sial can not be lost from the crust; (2) models assuming a global thin sial are ruled out by palaeomagnetic constraints; on a structural basis and from estimates of crustal palaeothicknesses; (3) models assuming the coexistence of sial and sima face such questions as the lack of ophiolites, scarcity of two-stage mantle melting products, and palaeomagnetic constraints on horizontal plate movements.

The combined evidence arising from the lack of simatic records during the period 2.6-1.0 b.y., the contiguity of the sialic crust during this time, and the maintenance of modern angular relations between these shields, are only amenable to interpretation with an Earth approximately 0.5-0.6 of the present-day radius. About 1.0 $\pm$ 0.2 b.y. ago, the apearance of ophiolites and two-stage mantle melting products in pan-African belts, and the divergence of the APWP, associated with major compression (thrusting) within the continents, signified the onset of expansion and related plate tectonic processes. The empirical geological evidence requires further attention from physicists to investigate potential mechanisms which could account for a growth in the Earth's dimensions.

Mining and associated research in China today

A. Renwick & I. R. McLeod

In October 1979 a delegation, led by the Acting Director of BMR and comprising three other BMR officers and seven representatives of mining companies, visited China at the invitation of the Government of the Peoples' Republic to study mineral deposits and mineral exploration methods. The delegation visited six mines (tungsten, lead-zinc, antimony, copper, iron, and magnesite), one prospect (uranium), a Geological College, and some six research institutes. Overall impressions were of markedly dated technology, being rapidly up-dated by great effort, enthusiastically applied. China, with its large domestic requirement and economic system, is able to develop many small and low-grade deposits, although it has both large and high-grade ones as well. Viability and economic extraction have different meanings in a socialist economy to those accepted elsewhere.

There is a significant contrast between facilities in Beijing and those in the Provinces, and a serious communication gap exists. This results in the very slow spread of new concepts and theories, and a localised pragmatic approach to exploration which is generally unrelated to ore genesis theory. Most deposits currently being worked are extensions of old small workings, many of which have been known for hundreds of years. With such a large population, labour-intensive methods are not, in the national sense, uneconomic; but the progressive upgrading of only parts of the total mining process leads to the uneconomic use of much equipment.

An outline of the organisation of the Ministry of Geology and its relationship to other Ministries is given, and some details of current research projects and of equipment are presented.

Australian mineral export forecasts to 2000

A. Driessen

Australia is an important world producer and exporter of a range of mineral commodities, in particular coal, iron ore, aluminium (whether as bauxite, alumina or metal), copper, lead, zinc, nickel, tin, manganese, ilmenite, rutile, and zircon; these 12 commodities account for about 90 percent of earnings from mineral exports. For 10 of these commodities Australia ranks in the first five as a world producer (coal and copper are the exceptions); in all of these ten commodities Australia exports more than 70 percent of its mine production. Forecast copper and coal exports for the year 2000 show the greatest quantitative increase, copper from 101 000 tonnes in 1978 to 600 000 tonnes in 2000, and coal from 37.5 million tonnes to 185 million tonnes in the same period. Despite the very large increase in the forecast quantity of aluminium metal exports, forecast exports in the year 2000 of combined aluminium metal and the aluminium equivalent of alumina and bauxite are only 2.6 times the quantity in 1978, an increase of similar magnitude to that for iron ore (2.5 times); nickel exports are forecast to increase by a factor of 2.2 and manganese ore by a factor of 2.7. Forecast exports of lead and zinc in the year 2000 are less than double those in 1978. The forecast declining level of exports for mineral sands, and the uncertainty about the level of tin exports in the 1980s, reflect some uncertainty about demonstrated economic resources of these minerals in the future. A shift towards exporting more minerals in processed form is expected because of Australia's abundant coal resources and its consequent energy cost advantage.

The uranium cycle and the development of vein-type deposits

John Ferguson

Development of quartz-pebble conglomerate uranium deposits was confined to the period 2800-2200 m.y. The first appearance of these deposits coincides with major igneous, sedimentary, biogenic and tectonic changes; it is suggested that all these factors contribute to the uniqueness of quartz-pebble conglomerate uranium deposits. Vein-type uranium deposits made their appearance in the post-2200 m.y. period. However, over 90 percent of vein-type uranium deposits are found in rocks dated between 2200 and 1400 m.y. This skewness is considered to be real. As continental crustal development after 2200 m.y. ago appears mainly to follow uniformitarian lines, the only variable which could explain the concentration of vein-type uranium in the 2200-1400 m.y. period appears to be a steadily evolving atmosphere. It is suggested that during these times the hydrosphere was sufficiently oxidising for uranyl transport, but that rapidly reducing conditions were met short distances into the lithosphere. Reduction resulted in precipitation of uranium as UO_2 from meteoric water into suitable structural traps, which were largely developed during periods of prolonged erosion. Rapid development of impermeable cover rocks preserved the uranium deposits.

BMR studies of vein-type uranium deposits in the Proterozoic have been confined mostly to those within the Lower Proterozoic sequence of the Pine Creek Geosyncline, Northern Territory. Using this area as the type-model, an attempt is made to account for the extensive development of vein-type uranium deposits originally formed within the time span 2200-1400 m.y.

Anatomy of a Proterozoic rift, Mount Isa

G. M. Derrick

The Leichhardt River Fault Trough near Mount Isa is a 550 km by 65 km ensialic rift formed from about 1800 m.y. to 1650 m.y. ago. Extensions in the 1800 m.y.-old acid volcanic-granite basement was followed by deposition of 10 km of epicontinental clastics, minor dolomite and redbeds and marginal fanglomerates, and 6 km of subaerial to shallow subaqueous basalt, at depositional rates of up to 500 m per m.y. Further volcanicity (1680 m.y.) accompanied deformation of the rift; younger intracontinental molasse, distal flysch and Pb-Zn-bearing restricted shale basin deposits 7 km thick blanketed earlier clastics, at depositional rates of 200 m per m.y. Igneous rocks from the Leichhardt River Fault Trough display compositional bimodality with time, typical of non-orogenic terrains; they range from basement rhyolite, to tholeiitic basalt, to granite and alkali granite, to rhyolite and trachybasalt, and finally to tholeiitic dyke swarms.

The Fault Trough formed by extension and sagging of continental crust. Mantle upwelling and subsequent deep rifting tapped basalt sources; magma withdrawal and basalt loading of the crust led to further sagging and epicontinental sedimentation. Heat from earlier mantle upwelling caused lower crustal fusion and subsequent granite intrusion of the rift pile. Genesis of major Cu and Pb-Zn deposits is partially controlled by early and reactivated growth faults, and by the movement of subsidiary crustal blocks within the Fault Trough.

Crustal structure of the Archaean of northwest Australia

B. J. Drummond

Two Archaean cratons are exposed in Western Australia; the Pilbara in the northwest and the Yilgarn in the southwest. They are separated by the Proterozoic Capricorn Orogenic Belt. In 1977, BMR conducted a seismic refraction and gravity survey in the Pilbara and northern Yilgarn regions. The aims of the survey were to study the crustal structure of the Pilbara and northern Yilgarn Cratons and the Capricorn Orogen. It was hoped to derive models which would be useful for studying crustal evolution in the area. Recordings were made along several traverses both across and parallel to the regional geological strike. Seismic recorder spacing was about 20 km, and the routine quarry blasts at the iron ore mines were used as seismic sources.

Excluding the rocks of the Hamersley Basin, the Pilbara Craton has a two-layered crust. A layer with a seismic velocity of about 6.0 km s^{-1} overlies a second layer (6.4 km s^{-1}) at about 13 km depth. The crust is 28 km thick in the north of the Pilbara Craton, and 33 km thick in the south, and the upper mantle velocity is 8.34 km s^{-1}. The crust in the northern Yilgarn Craton is 55 km thick. A layer with a seismic velocity of 6.2 km s^{-1} overlies a second layer of 6.4 km s^{-1} at 15 km. A third layer (7.0 km s^{-1}) is present below 32 km. The upper mantle velocity under the northern Yilgarn Craton is 8.1 km s^{-1}. The crust between the cratons has thicknesses intermediate between those of the cratons, and is characterised by zones of high velocity gradients in the lower crust. These zones indicate that the lower crust is denser than the lower crust of the cratons.

Synthetic seismogram modelling showed that the velocity increases slightly through the layers, and the boundaries are gradational. The velocity/depth functions suggest that the cratons are of overall acid to intermediate chemical composition, and that the velocity jumps are phase changes, probably owing to granulite facies at 13 to 15 km in both the Pilbara and Yilgarn Cratons, and to eclogite at 32 km in the Yilgarn Craton. The dense lower crust between the cratons is probably due to metamorphism and magma injection of the lower crust during intercratonic tectonics.

Structure and petroleum potential of the Lord Howe Rise

J. B. Willcox

The Lord Howe Rise is a major submarine feature in the Tasman Sea, which lies about 600 km off the east coast of Australia. It has a continental crustal structure. Two 1971 BMR reconnaissance seismic profiles indicated that the Rise is divided longitudinally into an eastern shallow basement province, and a western province characterised by horsts and grabens. The western province has been interpreted as a submerged 'rift-valley' formed prior to the Late Cretaceous breakup of the Tasman Sea. It has been suggested that the general lack of rift-valley or pull-apart basins along the eastern seaboard of Australia indicates that during breakup the rift-valley was breached along its western boundary fault, and that any associated basins remained wholly attached to the 'Lord Howe Plate'.

During October 1978 the Federal German Geological Survey (BGR) and the BMR conducted a co-operative geophysical survey of the central Lord Howe Rise area to examine its structure, geological evolution, and petroleum potential. A preliminary interpretation indicates that: (i) numerous small basins, which may have formed within grabens, underlie the western half of Lord Howe Rise. These probably trend NNW, range from 20-40 km wide; the deepest of them contains 3000-4000 m of sediment; (ii) a larger basin, about 50 km across, has been delineated 250 km NE of Lord Howe Island, in a water depth of 1700 m. It is possibly of Mesozoic age; (iii) a horst and graben province extends across the Middleton and Lord Howe Basins and onto the Dampier Ridge, which is considered to be at least partly of continental origin; (iv) relatively thick prograded sediments occur on both the western and eastern flanks of the Rise. On the eastern New Caledonia Basin flank, 2000-3000 m of pre-breakup sediment is observed, which was probably deposited on the ancient (pre-Late Cretaceous) seaboard of the Australian-Antarctic supercontinent.

The absence of major rift-basins of the type that underlie other Atlantic or pull-apart margins (for example, Ceduna Terrace and Northwest Shelf/ Exmouth Plateau regions) is disappointing in terms of petroleum potential. However, structural and palaeogeographic considerations suggest that petroleum source rocks may have been deposited on Lord Howe Rise, in the Late Cretaceous, prior to formation of the Tasman Basin. A favourable restricted marine environment was possibly associated with the small basins and grabens. Possible petroleum traps exist against the boundary faults and as pinchouts within the basins. Structures interpreted as Late Cretaceous and Paleocene reefs are also possible targets. A seal may be provided by interbedded shales or pelagic oozes. The prograded sequences on the flanks of the Rise also warrant further examination.

New information on the Denison Trough and its petroleum prospects from recent seismic surveys

J. A. Bauer

During 1978 and 1979 BMR conducted a seismic survey in the southern Denison Trough to study the structure of the Trough and to examine facies distributions. The study complements detailed work on the stratigraphy of the Trough being carried out by the Geological Survey of Queensland (GSQ). Although a large amount of seismic data has already been recorded in the Trough, mainly in the early 1960's, the quality of these data was sufficient to map only the strongest reflection horizons and generally little information was obtained from the deeper parts of the sequence. The new seismic data, recorded and processed digitally, are significantly better, and of sufficient quality to allow the thickness and distribution of most formations to be reliably interpreted along the seismic lines. It was not always possible, however, to obtain a reliable and consistent basal Permian reflection in areas with a very thick Early Permian sequence.

Three major phases of folding—Early Permian, Late Triassic, and Late or post-Jurassic—are identified. Minor phases of deformation which affected depositional patterns towards the end of the Early Permian are also identified. The extent of the Comet Platform has been better defined,' and the configuration and depth of the base of the Permian sequence are better, though still incompletely, known. Several previously undiscovered structural features have been identified which shed new light on the structural and depositional history of the Trough.

Considerable scope has been demonstrated for the existence of hydrocarbon traps, both (i) structural, particularly involving structures which formed earlier than the Triassic ones most commonly tested to date, and (ii) stratigraphic, particularly in the Early Permian sequence. The new BMR seismic data, together with GSQ regional facies analyses, joint BMR/CSIRO source rock evaluation, and renewed company seismic investigations, has led to a better understanding of the Denison Trough and its hydrocarbon potential.

Future prospects for liquid fuel supplies in Australia

D. J. Forman

Indigenous production of oil and condensate from known fields is expected to remain fairly steady at about 150 million barrels a year until 1987, and then to decline. Indigenous production currently provides about 68 percent of total crude oil input to Australian refineries, but estimates suggest that production from known oil fields will meet about 55 percent of demand in 1985, and about 35 percent of demand in 1990. Because of the lead time between discovery and development, it is unlikely that any new discoveries will have much effect on indigenous supply before 1985, but Australia's geological potential for further conventional oil discoveries, though modest, could well allow high levels of self sufficiency to be attained again for at least a few years in the late 1980's, possibly extending into the mid to late 1990s—but in nearly all projections falling to low levels shortly after the year 2000.

There are abundant resources, such as oil shale, coal and gas, from which alternative fuels may be developed, but the technology and/or economics of the various processes and the lead times involved in developing them are uncertain and there may be serious environmental constraints.

Geochemical evaluation of the petroleum prospects of the Galilee Basin

K. S. Jackson

The Galilee Basin in central Queensland is an extensive intracratonic basin covering some 234 000 km^2, containing up to 2800 m of Late Carboniferous to Middle Triassic strata. The sediments have been deposited under predominantly fluviatile conditions in two depocentres, the Koburra Trough and Lovelle Depression, separated by the Maneroo Platform. The forty-seven exploratory wells drilled to date have encountered only two significant hydrocarbon shows—oil in ENL Lake Galilee No. 1, and gas in FPN Koburra No. 1.

A systematic petroleum source rock study of sixty-one cores from wells in the northern Galilee Basin has been carried out. Generally, the results are disappointing. Source rock quality is poor, with only the Late Permian Bandanna Formation correlative and Colinka Sandstone correlative rocks showing fair source potential. The kerogens analysed prove to be sub-Type III (sub-humic) and hence gas prone, if source at all. Maturation levels within the basin are suitable for present-day oil generation in the Early Permian strata.

The oil recovered from the Late Carboniferous Lake Galilee Sandstone at ENL Lake Galilee No. 1 is encouraging. An attempt using carbon-isotope data is being made to correlate this oil with possible source rock; core material from Devonian strata (either Adavale or Drummond Basin) underlying the oil show have been included in this study. The available data do seem to rule out the Permo-Triassic strata as the oil source.

Groundwater in oceanic islands

G. Jacobson

Nearly all small oceanic islands have water supply problems, and the utilisation of groundwater is commonly the solution to these problems. The assessment of groundwater resources on an oceanic island requires consideration of geology, climate and the water balance. Generally there is a layer of freshwater overlying saltwater, and the measurement of the freshwater layer thickness can most readily be done by resistivity depth probing. Examples will be given of some recent BMR investigations of oceanic islands including the Cocos (Keeling) Islands—a coral atoll, and Niue Island—a raised atoll.

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