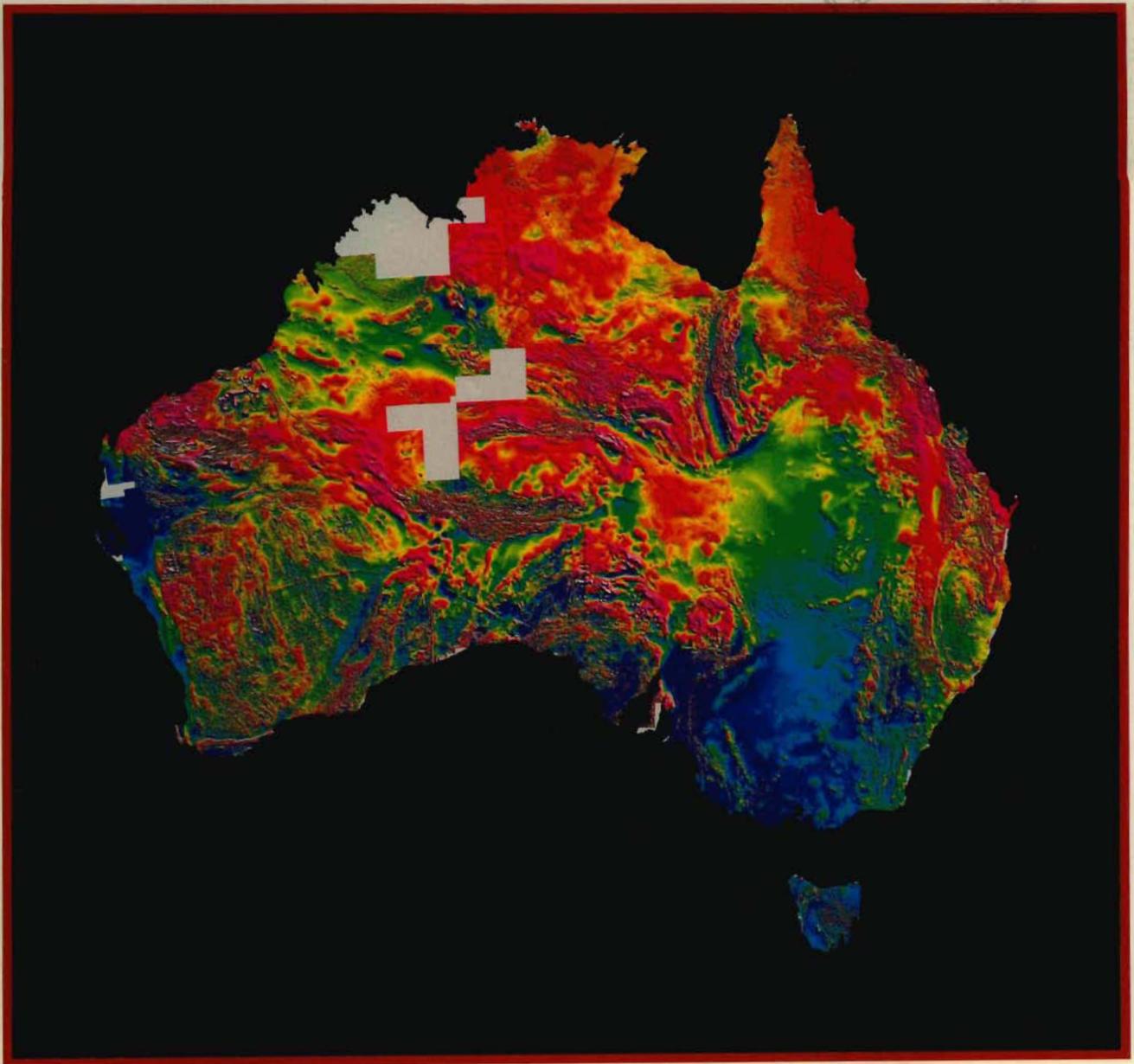
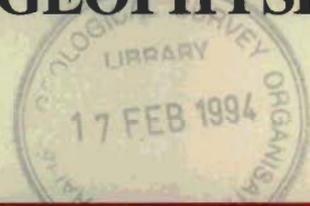




AGSO JOURNAL

OF AUSTRALIAN GEOLOGY & GEOPHYSICS

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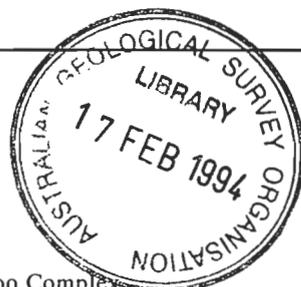
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Granite, gabbro, and migmatite field relationships in the Proterozoic Lamboo Complex of the East Kimberley region, Western Australia

D.H. Blake¹ & D.M. Hoatson¹

Intrusive contacts between granite plutons and adjacent gabbro in the Proterozoic Lamboo Complex are characterised by net-veined complexes in which pillow-like mafic bodies are enclosed in and veined by granitic rock. Pillow features, such as marginal chilling and cusped contacts with granitic rock, are diagnostic of magma mingling, and show that either the mafic and felsic components of the net-veined complexes were intruded as magmas together or, as is considered more likely, mafic magma was intruded into already emplaced granite which became partly melted and remobilised; i.e. granite plutons are older than adjacent

gabbro intrusions, not younger as previously proposed. Differences in age between granite and adjacent gabbro are probably not large, as the granite is presumed to have been hot, and perhaps not completely crystallised, at the time of gabbro intrusion, to account for the large volumes of remobilised granitic melt represented in the net-veined complexes. Migmatite spatially associated with the net-veined complexes may be attributed to partial melting during gabbro intrusion, rather than to an earlier regional metamorphism.

Introduction

The Lamboo Complex comprises the oldest rocks of the East Kimberley region in Western Australia (Fig. 1), ranging in age from about 1920 Ma (Bureau of Mineral Resources, 1992) to about 1850 Ma (Page & Hancock, 1988). The western part of this complex, west of the Halls Creek and Angelo Faults, is characterised by areally extensive granite and gabbro intrusions, and the more local development of migmatite. Although previous workers have regarded the granites as being younger than the gabbros, there is abundant field evidence to indicate that many gabbroic intrusions postdate adjacent granite plutons, rather than vice versa, and additionally that some migmatites previously attributed to an earlier high-grade regional metamorphism may instead be contact-metamorphic rocks related to the emplacement of both granite and gabbro.

The Lamboo Complex in the Gordon Downs and Dixon Range 1:250 000 Sheet areas (Fig. 1) is currently being investigated jointly by the Australian Geological Survey Organisation (AGSO, previously the Bureau of Mineral Resources or BMR) and the Geological Survey of Western Australia (GSWA) as part of the Kimberley-Arunta National Geoscience Mapping Accord (NGMA) project. The NGMA, endorsed by the Australian (now Australian and New Zealand) Minerals and Energy Council in August, 1990, is a joint Commonwealth/State/Territory initiative to produce over the next 20 years, using modern technology, a new generation of geoscientific maps, data sets, and other information of strategically important regions of Australia. The Kimberley-Arunta project commenced in 1990 and is due to be completed in 1995. Products will include 1:100 000 scale geological maps of well-exposed parts of the area and 2nd-Edition 1:250 000 maps of the Gordon Downs and Dixon Range Sheets. These will update previous reconnaissance geological mapping of the area by BMR and GSWA carried out more than 25 years ago (Dow & Gemuts, 1969).

Geological framework

The oldest rocks exposed in the Lamboo Complex, as defined by Griffin & Grey (1990), belong to the Halls Creek Group of Dow & Gemuts (1969) and, west of both

the Halls Creek and Angelo Faults (Fig. 1), the probably correlative Tickalara Metamorphics (Griffin & Tyler, 1992). These two units consist of sediments, including turbidites and carbonates, together with felsic, intermediate, and mafic volcanics, which were first folded and regionally metamorphosed during a deformation corresponding to the Barramundi Orogeny of Etheridge & others (1987). The metamorphism was of low pressure-high temperature type (e.g. Gemuts, 1971; Hancock & Rutland, 1984; Allen, in Plumb & others, 1985). The Tickalara Metamorphics, which range from greenschist to granulite facies and include migmatite, are intruded by granite and gabbro. The relationships between these granite and gabbro intrusions, and between them and migmatites of the Tickalara Metamorphics, mainly in the Halls Creek and McIntosh 1:100 000 Sheet areas (Fig. 1), are discussed in this paper.

The early deformation affecting the Tickalara Metamorphics took place between 1870 ± 4 Ma, the ion-microprobe U-Pb zircon age of folded felsic volcanics near the top of the Halls Creek Group (Page, personal communication, 1992), and 1850 ± 5 Ma, the age of the Whitewater Volcanics (Page & Hancock, 1988), which postdate the early deformation. A minimum age for the granite and gabbro intruding the Tickalara Metamorphics is given by the sill-forming Hart Dolerite. This dolerite was intruded at about 1800 Ma (U-Pb zircon age of granophyre differentiate; Page, personal communication, 1991) into unconformably overlying shallow-water clastic sediments and subordinate volcanics of the Kimberley Basin succession.

Deformation postdating 1800 Ma in this part of the East Kimberley is largely confined to the vicinity of major faults, such as the Halls Creek and Springvale Faults. It was not associated with major metamorphism here, as no units younger than the granite and gabbro of the Lamboo Complex are metamorphosed to more than lower greenschist facies. Movements along the Halls Creek Fault, mainly strike-slip, continued until at least the late Palaeozoic.

Granite intrusions

Granites of the Lamboo Complex form numerous plutons ranging from about 1 km to more than 10 km across. These intrude previously folded and regionally metamorphosed rocks of the Tickalara Metamorphics and, to the west, the Whitewater Volcanics. Some small irregular

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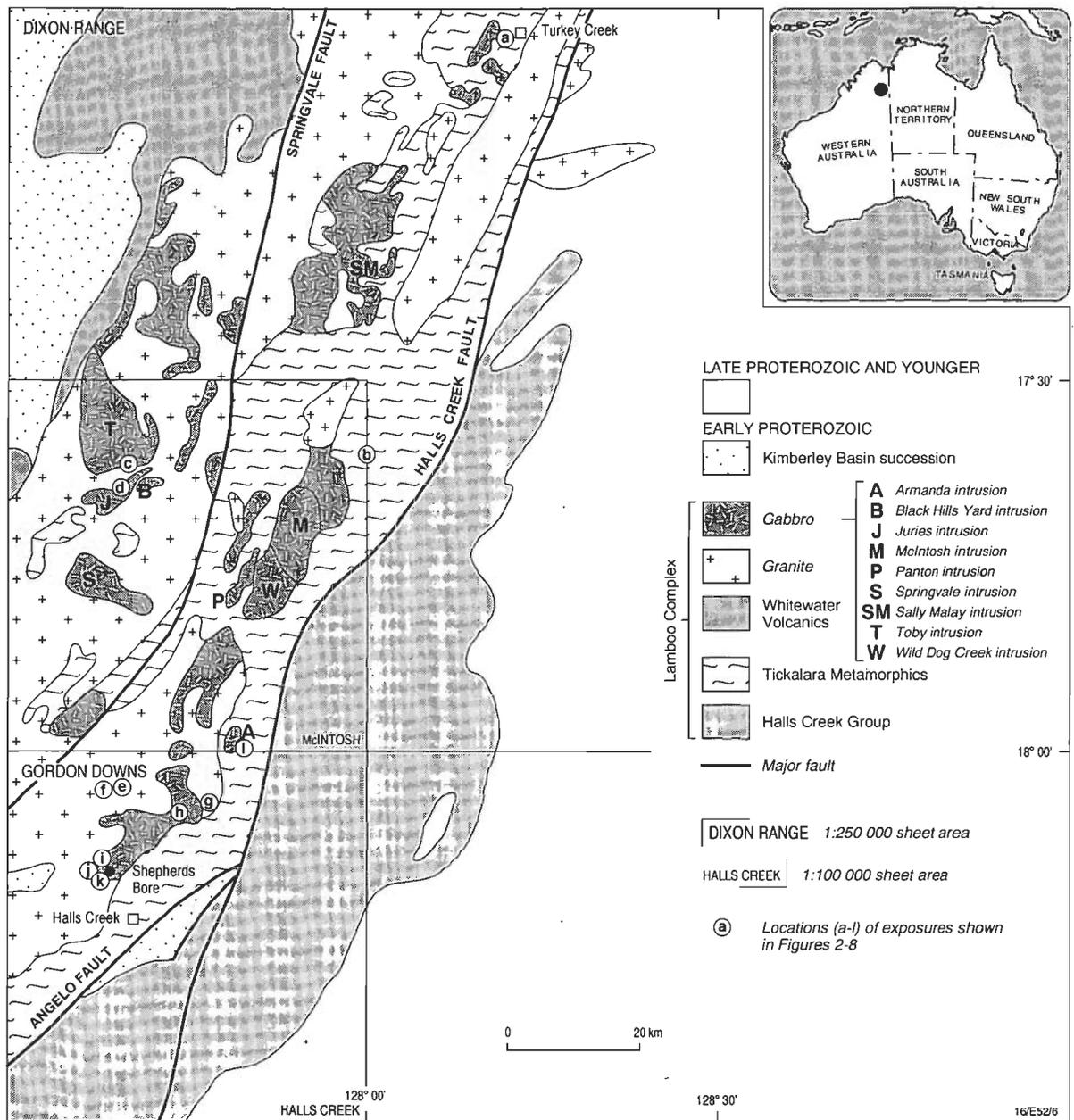


Figure 1. Geological setting of the East Kimberley showing locations described in the text.

granite intrusions also cut gabbro bodies. The plutons were mapped by Dow & Gemuts (1969) as either Bow River Granite or Mabel Downs Granodiorite. Field evidence and preliminary petrographic and chemical data indicate a range in composition from granite *sensu stricto* to tonalite and quartz diorite. Biotite granite with abundant feldspar phenocrysts around 2 cm long is probably the most common type. The distribution of the different granite types can be readily mapped using recently acquired airborne gamma-ray spectrometric data (line spacing of 400 m and flying height of 100 m). Contact aureoles, extending in places for several kilometres from exposed granite, are developed in adjacent Tickalara Metamorphics in the Halls Creek 1:100 000 Sheet area. Relatively late irregular intrusions, thin sheets, and cross-cutting veins typically consist of leucogranite or heterogeneous granite that are either even-grained or contain small and partly ovoid feldspar megacrysts.

Gabbro intrusions

In this paper, 'gabbro' and 'mafic' are used as general terms for dolerite, diorite, and ultramafic rocks, as well as various types of gabbro *sensu stricto*. As such, the gabbro of the Lamboo Complex corresponds to the McIntosh Gabbro and Alice Downs Ultrabasics of Dow & Gemuts (1969). The gabbro forms plug-like and funnel-shaped bodies, sills, and lopoliths up to 21 km across and 8 km thick intruding previously deformed Tickalara Metamorphics and, as documented here, Bow River Granite. Many of the intrusions show a cyclic layering of rock types indicative of open-system fractionation involving repeated injections of mafic magma (Mathison & Hamlyn, 1987; Hoatson & Tyler, 1993). Five main compositional and age groupings have been recognised (Hoatson, 1993); in ascending age these are typified by (1) the mafic-ultramafic Panton intrusion, (2) Wild Dog Creek intrusion, (3) McIntosh intrusion (the

most voluminous group), (4) troctolite plugs at Black Hills Yard, and (5) Ni-Cu sulphide-bearing Sally Malay intrusion (Fig. 1).

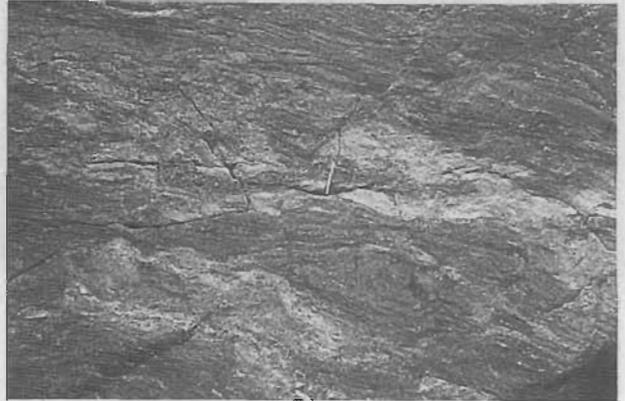
It has been suggested that both the Panton intrusion (Hamlyn, 1980) and McIntosh intrusion (Hancock & Rutland, 1984) crystallised at depth (8–9 kb) before being tectonically emplaced into the upper crust (4–6 kb). However, geobarometry by Mathison & Hamlyn (1987) shows that the McIntosh intrusion probably crystallised at less than 6 kb, like many other major layered mafic/ultramafic intrusions, such as the Munnii Munnii Complex, Western Australia (3.5–5 kb: Hoatson & others, 1992), the Bushveld Complex, Republic of South Africa (4–5 kb: Nell, 1985), and the Stillwater Complex, Montana, USA (3–4 kb: Labotka, 1985). Also, new field evidence indicates that the East Kimberley gabbro intrusions generally crystallised *in situ* rather than being tectonically transposed bodies (Hoatson & Tyler, 1993); this evidence includes the presence of chilled margins, contaminated contact rocks, narrow contact aureoles, comagmatic satellite intrusions, and net-veined complexes at contacts with granite (see below).

Migmatites

Migmatites are exposed in the immediate vicinity of some, but not all, juxtaposed granite and gabbro intrusions in the Halls Creek and McIntosh 1:100 000 Sheet areas, and have also been examined by the authors to the north, near Turkey Creek (locality a in Fig. 1). They consist predominantly of pelitic and quartzofeldspathic metasediments of the Tickalara Metamorphics, and show banding, which is commonly complexly folded, and sparse to abundant leucosomes indicative of partial melting (Fig. 2). With distance away from gabbro and granite intrusions near Halls Creek, migmatites merge into hornfelses (Fig. 2c), which in turn merge into regionally metamorphosed, greenschist facies Tickalara Metamorphics, supporting the suggestion of Gemuts (1971, p. 58) that some migmatite formed during contact metamorphism.

Granite-gabbro field relationships

A characteristic feature of many contact zones between gabbro intrusions, especially those of Group 3, and granite plutons are net-veined complexes ranging from a few metres to more than 100 m in width. In these complexes, inclusions of gabbroic and finer-grained mafic rocks of all sizes up to several metres across are enclosed in variably heterogeneous granite, and are cut, together with the main gabbro bodies, by veins of generally fine-grained leucogranite emanating from the adjacent granite plutons (Figs 3 to 5). At first sight, these features may seem to indicate that the granite plutons are younger than, and contains xenoliths of, the adjacent gabbro bodies. However, the following evidence shows that this is generally not the case.



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b



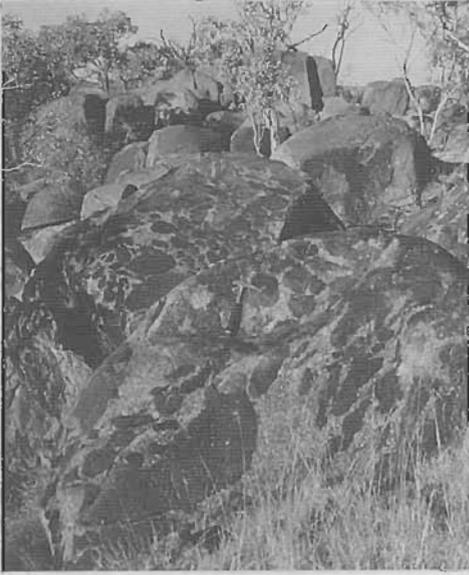
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Figure 2. Migmatite and hornfels of the Tickalara Metamorphics.

(a) Migmatite 2 km west of Turkey Creek (locality a in Fig. 1), consisting mainly of pelitic and quartzofeldspathic metasediments. Most of the pale material represents leucosomes indicative of partial melting.

(b) Similar migmatite a few metres from granite and gabbro 15.5 km north of Shepherds Bore (23 km NNW of Halls Creek), with irregularly folded leucosomes (locality f in Fig. 1).

(c) High-grade metasedimentary hornfels, almost migmatitic, about 100 m from exposed granite and gabbro 12 km north-northeast of Halls Creek (locality g in Fig. 1).



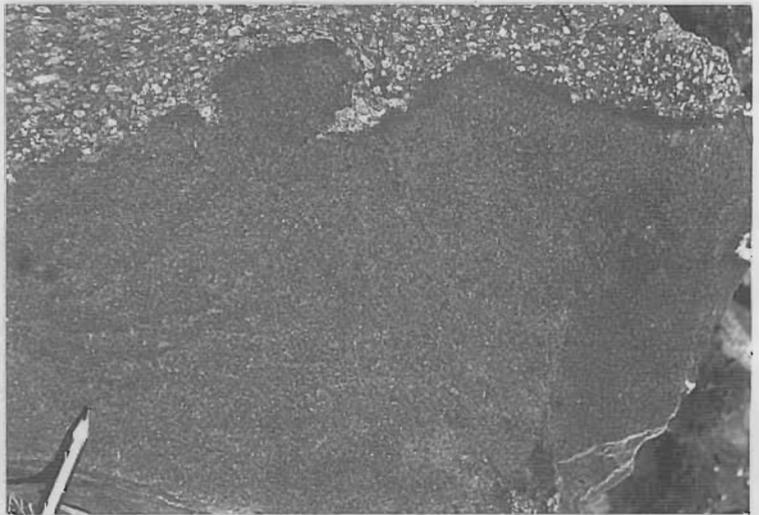
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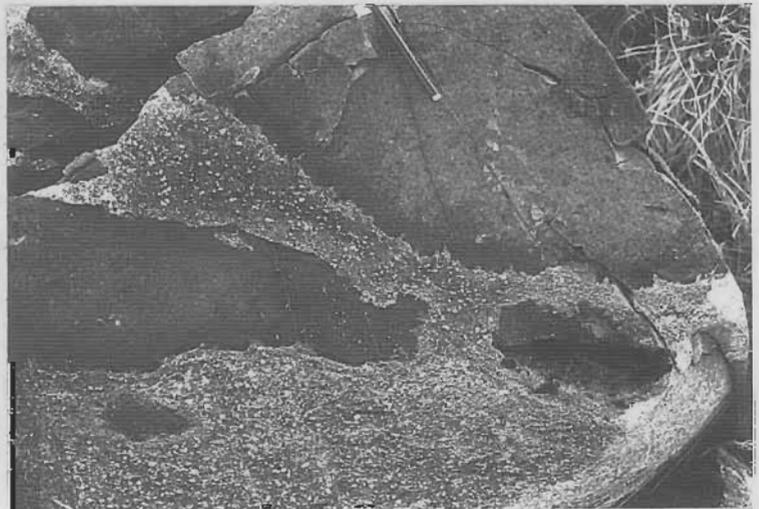
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- In the net-veined complexes of the Lamboo Complex that have been examined by the authors at least some of the mafic inclusions are ellipsoidal rather than blocky in general shape, and resemble pillows in pillow lavas except that their contacts with adjacent granite, though generally sharp, are irregularly cusped in detail: rounded protuberances of the mafic rock alternate with pointed embayments of more felsic rock, like contacts between liquids of contrasting viscosities and compositions. The pillows have normal igneous textures, in some cases partly obliterated by subsequent recrystallisation. Their cusped margins are typically finer-grained than their interiors, indicating marginal chilling, and also darker due to an increase in modal biotite or amphibole (inferred to be due to *in situ* contamination). The pillows are commonly cut by granitic veins, and all stages can be recognised from pillows with no veins, through pillows that are fragmented by networks of veins, to isolated fragments of dismembered pillows with parts of the cusped margins attached (Figs 3 to 5). Many other mafic fragments in the net-veined complexes may be derived from the interiors of completely dismembered pillows. Pillows of several different types of dolerite, including both porphyritic and non-porphyritic varieties, and also of heterogeneous dioritic hybrid rocks, are present in many of the net-veined complexes.
- The granitic rock enclosing the mafic pillows and pillow fragments in the net-veined complexes ranges from leucogranite to biotite granite, biotite tonalite, and diorite, and is commonly heterogeneously blotchy, due to the presence of what appear to be partly digested or assimilated inclusions. Feldspar phenocrysts, if present, are typically smaller and less well-shaped than those in granite nearby, and some have corroded outlines and sieved interiors — features suggestive of resorption and partial melting (Fig. 6).

Discussion

Mafic pillows with cusped contacts and chilled margins have been described from many plutonic net-veined complexes world-wide and also from extrusions and high-level dykes and sills, and are nowadays considered diagnostic of mafic magma mingling with, and chilling against, cooler more felsic magma or melt, i.e. a liquid-liquid relationship (e.g. Wager & Bailey, 1953; Blake & others, 1965; Wiebe, 1974; Frost & Mahood, 1987; Vernon & others, 1988; Didier & Barbarin, 1991; Blundy & Sparks, 1992). The process of magma mingling can readily account for the fragmentation of mafic pillows and development of hybrid rocks in net-veined complexes, as discussed, for example, by Blundy & Sparks (1992). Precambrian net-veined complexes attributed to magma mingling have been described in Australia from the Proterozoic Mount Isa Inlier (Blake, 1981, 1987) and Arunta Block (e.g. Blake, 1993) and from the Archaean Pilbara Block (Hoatson & others, 1992).

Where mingling of mafic magma and felsic magma has

taken place, the mafic and felsic components are either of essentially the same age and were emplaced together, as is probably the case in small dykes and sheets, where only small volumes of magma may be involved (e.g. Fig. 7), or the felsic component is the older and had largely or completely crystallised before being intruded and subsequently partially melted by the mafic magma. In the Lamboo net-veined complexes, the presence of pillow-like mafic inclusions several metres across and isolated in granite indicates that the mafic magma was probably intruded into already emplaced and at least partly solidified granite. Otherwise the large mafic pillows, being relatively dense, would have settled to the base of the felsic magma body. The presence of several types of mafic rock-forming pillows in many of the net-veined complexes, each type representing a separate pulse of mafic magma, is a further indication that granite emplacement probably preceded intrusions of mafic magma.

Liquidus temperatures of mafic magmas that form layered gabbro intrusions are generally in the range of 1050–1300°C (e.g. Mathison & Hamlyn, 1989; Hoatson & others, 1992). A large body of such magma can partly melt granite that it intrudes, and the resulting felsic melt can mingle with the mafic magma to form net-veined complexes like those of the Lamboo Complex. However, magmas of granitic composition have crystallisation temperatures of 750–950°C (e.g. Sparks & others, 1977), and are not able to melt and mobilise pre-existing mafic rock.

Granitic melt formed as a result of gabbro intrusion into granite will not begin to solidify until it cools to its liquidus temperature, by which time the gabbro magma will have long since completely crystallised. The granitic melt, therefore, is able to vein and disrupt mafic pillows and react with and assimilate material of more mafic composition to form the heterogeneous hybrid rocks characteristic of many net-veined complexes (e.g. Blundy & Sparks, 1992). It can also form back-veins cutting the main gabbro intrusion that caused the melting, and may be sufficiently voluminous in places to form isolated larger bodies injected into nearby gabbro, granite, and Tickalara Metamorphics. The last part of the felsic melt to crystallise may be represented by late cross-cutting veins of leucogranite, aplite, and pegmatite.

For melting of crystallised granite to take place on the scale evident from the extent of net-veined complexes in the Lamboo Complex, the granite would have to have been sufficiently hot at the time to be easily melted and remobilised by mafic magma. If this was not the case, net-veined complexes and hybrid rocks would be much less widespread. Consequently, the gabbro bodies are unlikely to be much younger than the granite plutons they intrude.

Examples of magma mingling

Some of the features of the Lamboo net-veined complexes are illustrated in Figures 3 to 5; localities are shown in Figure 1. Clusters of mafic pillows in granite at localities

Figure 3. Features of Lamboo net-veined complexes in the Halls Creek and McIntosh 1:100 000 Sheet areas.

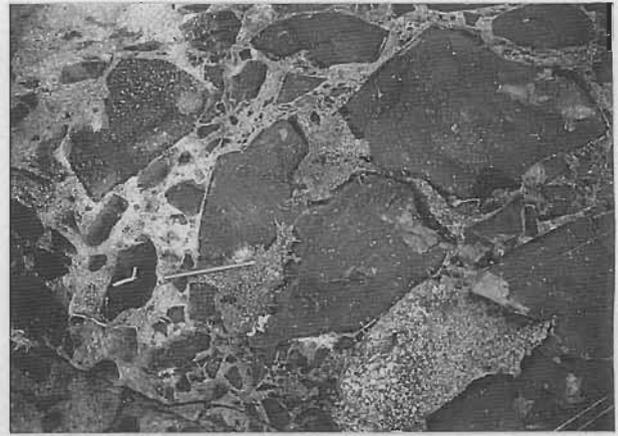
- Closely spaced mafic pillows in porphyritic granite 1.5 km northwest of Shepherds Bore (locality i in Fig. 1).
- Concentration of small pillows and pillow fragments in a net-veined complex at the contact between the mafic Toby intrusion and porphyritic Bow River Granite (locality c in Fig. 1).
- Elongate or discoid mafic pillow with cusped margins in porphyritic granite 16 km northwest of Shepherds Bore (locality e in Fig. 1).
- Typical cusped contact between a mafic pillow with a darker and finer-grained (chilled) margin and porphyritic granite 13 km north-northeast of Halls Creek (locality h in Fig. 1).
- Cusped contacts between mafic pillows with darker and finer-grained (chilled) margins and heterogeneous porphyritic granite showing a flow-type foliation. Net-veined complex 1.5 km southwest of Shepherds Bore (locality k in Fig. 1).

A and C (Figs 3a and 3b) and a single mafic pillow with an irregular cusped contact with enclosing porphyritic granite (Fig. 3c) are typical products of mafic magma

that was intruded into, and partly melted, previously emplaced granite. Figures 3d, 3e, 4a, and 4b show details of liquid-liquid type contacts between mafic pillows and



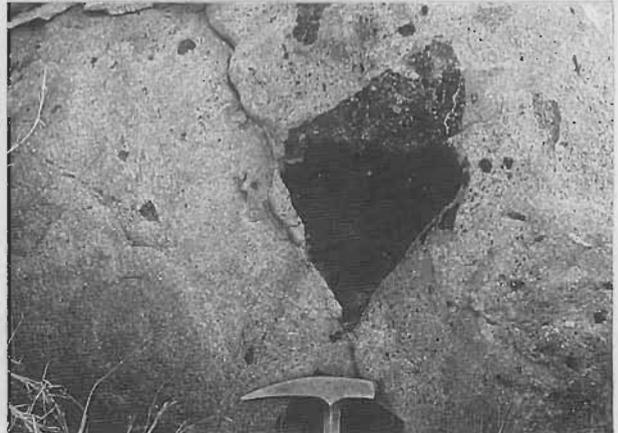
a



c



b



d



e

Figure 4. Features of Lamboo net-veined complexes in the Halls Creek and McIntosh 1:100 000 Sheet areas.

- (a) Net-veined complex in the contact zone of the mafic Juries intrusion with Bow River Granite (locality d in Fig. 1). Ellipsoidal mafic pillows, similar in size and shape to pillows of typical pillow lavas, are enclosed by partly hybridised, heterogeneous granite.
- (b) Close-up of top left part of (a), showing details of highly irregular liquid-liquid-type contacts between mafic pillows with chilled margins and granite.
- (c) Fragments of mafic pillows, mainly porphyritic dolerite, in a heterogeneous host ranging in composition from leucogranite to probably diorite. Net-veined complex 1.5 km west of Shepherds Bore (locality j in Fig. 1).
- (d) Leucogranite containing small mafic inclusions and a larger composite inclusion comprising a fragment of a mafic pillow in contact with hybrid-type diorite. Same locality as c.
- (e) Thin band of leucogranite separating two large mafic pillows in a net-veined complex at locality k in Fig. 1.

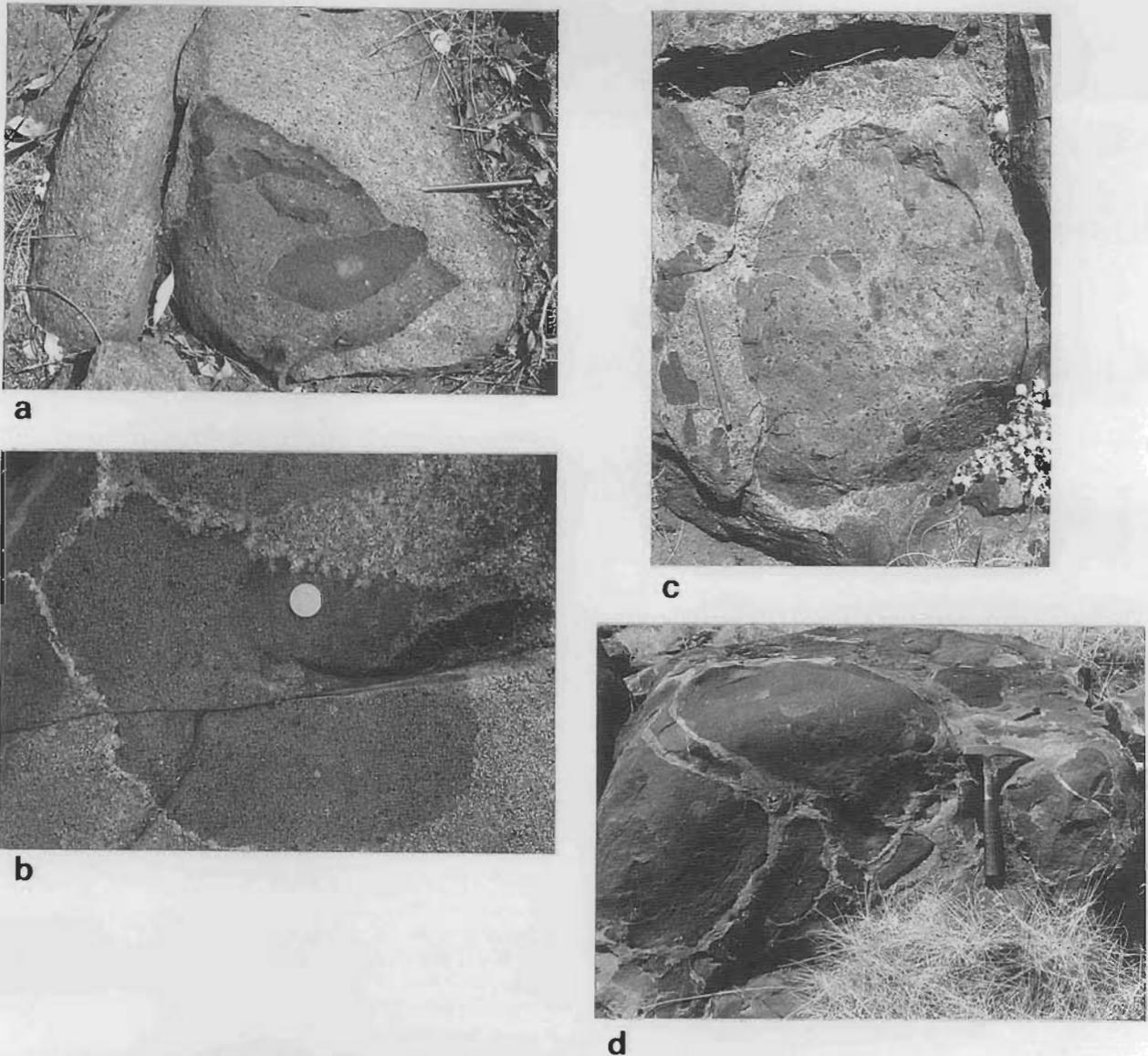


Figure 5. Pillows in net-veined complexes in McIntosh 1:100 000 Sheet area.

(a) Angular composite inclusion in leucogranite of hybrid-type diorite containing pillows of more-mafic rock. The composite inclusion is a fragment of a net-veined complex that predates crystallisation of the leucogranite. Net-veined complex at the southern contact of the mafic Toby intrusion with Bow River Granite (locality c in Fig. 1).

(b) Diorite pillow, with a highly irregular crenulate to cusped margin partly rimmed by a thin zone of leucogranite. Such zones may represent partial melts of the adjacent granite (e.g. Blundy & Sparks, 1992; locality c in Fig. 1).

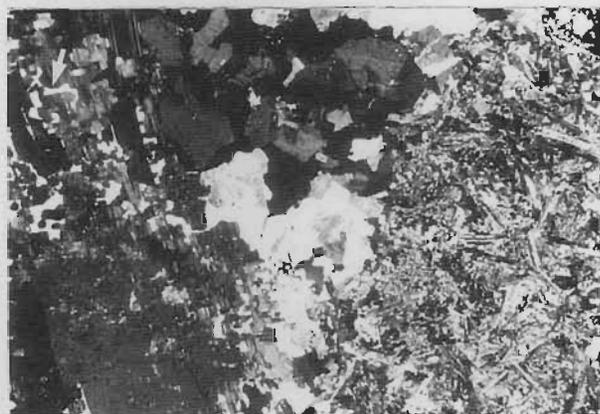
(c) Pillow-like inclusion of hybrid diorite containing small pillow-like inclusions of more-mafic rock. Same locality as a and b.

(d) Mafic pillows in fine-grained leucogranite in a net-veined complex on the east side of the Armanda intrusion (locality 1 in Fig. 1). The leucogranite here represents melted rhyolite (see text).

adjacent granite, and marginal chilling of the pillows. The dark pillow margins are due partly to finer grain-size resulting from chilling and partly to an increase in biotite content attributable to chemical diffusion between the pillow and enclosing felsic component (e.g. Blundy & Sparks, 1992).

At the net-veined complex shown in Figure 4c, only a few of the contacts between the mafic inclusions (mainly formed of microgabbro or dolerite with small feldspar phenocrysts), and the felsic host are of highly irregular (liquid-liquid) type, e.g. near the pencil point. The felsic host is heterogeneous, ranging from leucogranite to possibly diorite, and has the appearance of a typical hybrid rock. The interpretation proposed for this exposure is that the dolerite inclusions are fragments of pillows

formed when mafic magma came into contact with felsic melt, and that subsequent physical mixing of magma, melt, and partially to completely crystallised rock resulted in the fragmentation of the pillows and hybridisation of the enclosing granitic material (cf. Frost & Mahood, 1987; Blundy & Sparks, 1992). In the same net-veined complex, a few metres away, leucogranite containing many small mafic inclusions encloses a larger composite fragment in which a mafic pillow segment has a crenulate contact with adjacent dioritic hybrid rock (Fig. 4d). A likely explanation is that the larger fragment is a remnant of an earlier net-veined complex that became broken and dispersed during a subsequent phase of mafic magma injection and melting of granite. Other composite inclusions of probably similar origin are present in a net-veined complex at the contact between Bow River Granite and



a



b

Figure 6. Photomicrographs of Bow River Granite in contact with a mafic pillow (locality i, Fig. 1.), showing irregular outline and sieved interior of a partially melted sodic plagioclase phenocryst in the granite, under crossed polarisers.

(a) Contact between granite (left) with plagioclase phenocryst (far left) and fine-grained mafic rock containing plagioclase microliths; field of view 8 mm across.

(b) Detail of sieved plagioclase phenocryst; field of view 3 mm across. The phenocryst now consists of slightly displaced segments (showing fine lamella twinning) enclosing irregular patches of quartz (white) which are in crystallographic continuity with one another. Arrows in (a) and (b) point to the same patch of quartz.

the southern margin of the mafic Toby intrusion (Fig. 5a). In this net-veined complex, there are also pillows of hybrid-type diorite (Fig. 5b) and of hybrid diorite with small more-mafic pillow-like inclusions (Fig. 5c) — a

'pillows-in-pillow' situation. The common occurrence of more than one rock type forming pillows in a net-veined complex implies that several pulses of mafic magma were intruded into, and partially melted, the granitic host, and indicates that the granitic host may have remained relatively hot for a considerable time.

Part of a net-veined complex on the east-side of the mafic Armanda intrusion is shown in Figure 5d. Here the fine-grained leucogranite hosting the mafic pillows merges to the east, over a distance of 10 to 20 m, into massive, inclusion-free, metarhyolite of the Tickalara Metamorphics. To the west, veins of the leucogranite penetrate many metres into the main gabbro body. There seems to be little doubt here that the leucogranite was formed by melting of rhyolite, rather than granite, during emplacement of the Armanda intrusion.

Examples where mafic magma and granitic melt (or magma) were probably emplaced together are exposed in a creek pavement near White Rock Bore (locality b in Fig. 1), where dykes consisting of mafic pillows in a leucogranite host intrude previously deformed Tickalara Metamorphics—amphibolite facies mafic pillow lavas and thin-bedded sediments (Fig. 7). There are also some younger cross-cutting dykes here, formed of mafic rock apparently similar to that forming the pillows, and hence possibly only slightly younger than the dykes with pillows.

Implications for migmatite formation

If it is accepted that mafic magma intruded and partially melted hot granite to form the Lamboo net-veined complexes, as suggested here (rather than the mafic and felsic components being intruded simultaneously), it follows that there is a high probability that mafic magma also caused partial melting in nearby Tickalara pelitic and quartzofeldspathic country rocks. While partially melted, the country rocks would be particularly susceptible to deformation. Hence, swirly and irregularly folded migmatites like those shown in Figure 2 could result from relatively minor tectonism associated with magma intrusion. Evidence in favour of such an origin for at least some migmatite in the Lamboo Complex includes the following:

- Presence of migmatitic contact aureoles in Tickalara Metamorphics adjacent to some granite plutons (Gemuts, 1971; Griffin & Tyler, 1992) and gabbro intrusions (Hoatson & Tyler, 1993).
- Local, rather than regional, development of migmatite near Halls Creek, with marked changes in metamorphic grade, from greenschist to upper amphibolite or granulite facies, commonly taking place over short distances (in some cases less than 1 km) — a feature more typical of contact than regional metamorphism.
- Spatial association in the Halls Creek and McIntosh 1:100 000 Sheets of migmatites with granite and gabbro intrusions and especially with net-veined complexes in which there is abundant evidence for commingling of mafic and felsic magmas.
- Melting and remobilisation of metarhyolite by the Armanda mafic intrusion, and its subsequent recrystallisation as fine-grained leucogranite in a net-veined complex and in back-veins cutting the main gabbro body.

- Presence in migmatite near Turkey Creek (locality a in Fig. 1) of mafic dykes showing features such as necking along their length, back-veining by leucogranite, dismemberment into trains of pillows with cusped margins of liquid-liquid type, and hornfels/

recrystallisation textures: all features typical of syn-plutonic dykes (Pitcher, 1991) intruding granite, or partially melted rock, which had not completely solidified (e.g. Fig. 8).

- Ashworth & Chinner (1978) have described migmatites comparable to those of the Lamboo Complex from contact aureoles associated with granitic and mafic intrusions in the Scottish Caledonides. They estimated that these migmatites formed at 4–6 kb, which is similar to the emplacement depth of the McIntosh intrusion estimated by Mathison & Hamlyn (1987), and at temperatures of 700–800°C, well below the crystallisation temperature of mafic magma at such pressures.

Inclusions of mafic granulite in migmatite, as described, for example, by Gemuts (1971), may be the result of multiple pulses of mafic magma intruding the migmatite. Early mafic intrusions and older mafic metamorphics could have been subjected to several episodes of contact metamorphism, and the pelitic and quartzofeldspathic country rocks to varying amounts of partial melting, if successive pulses of mafic magma were intruded into, and thus reheated, the migmatite.

Further work is needed to determine how much Lamboo migmatite can be attributed to contact metamorphism related to granite and gabbro emplacement, and how much to an earlier regional metamorphic event.

Interpreted sequence of events

The following scenario is suggested, following Blake (1991), to account for the development of the net-veined complexes and at least some of the migmatites in the Lamboo Complex west of the Halls Creek Fault.

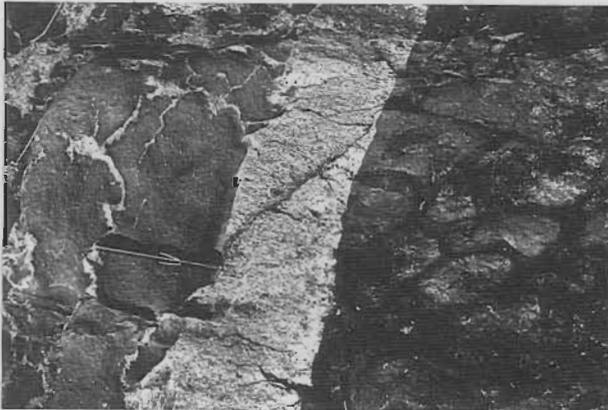
After the folding and regional metamorphism (mainly greenschist facies?) of the Halls Creek Group and correlative Tickalara Metamorphics during the Barramundi Orogeny, at around 1860 Ma, numerous granite plutons were emplaced in the western part of the Lamboo Complex (west of the present day Halls Creek and Angelo Faults). This plutonism was accompanied by widespread heating and contact metamorphism of the Tickalara country rocks. Gabbro emplacement followed shortly afterwards, while much of the granite and adjacent hornfels were still hot, and the granite perhaps not completely crystallised. The intrusions of much hotter mafic magma raised the temperature of adjacent granite, and pelitic and quartzofeldspathic hornfels, to well above the normal melting temperatures of felsic rocks. The mafic magma chilled against the resulting felsic melt, mafic pillows were formed, back-veining by felsic melt took place, and physical mixing and chemical diffusion led to the forma-

Figure 7. Composite dykes cutting previously deformed Tickalara Metamorphics exposed in a creek pavement 700 m east of White Rock Bore, eastern edge of McIntosh 1:100 000 Sheet area (locality b in Fig. 1).

(a) Basaltic pillow lava (right) intruded (to left) by a composite dyke consisting of leucogranite and pillowed mafic rock with typical liquid-liquid-type contacts.

(b) Thin composite dyke, formed of leucogranite enclosing mafic pillows, and thin leucogranite vein, both cutting foliated mafic metavolcanics.

(c) Thinly bedded metasediments and two cross-cutting dykes. The older dyke, running from left to right, is a composite intrusion of leucogranite and pillowed mafic rock, and the younger dyke consists of mafic rock that appears to be similar in composition to the mafic component of the older dyke.



a



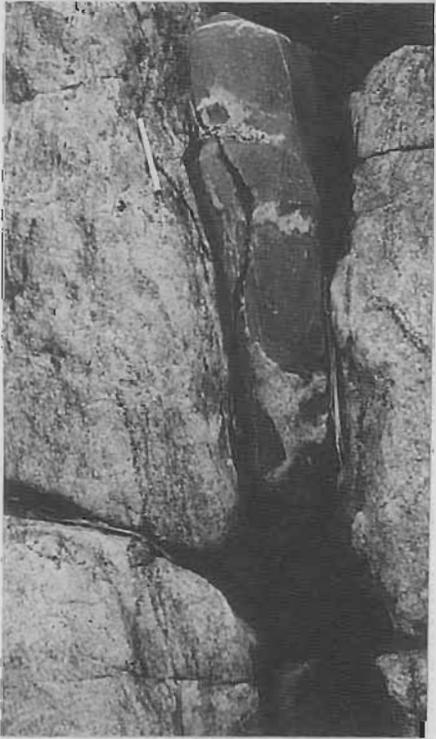
b



c



a



b



c



d



e

tion of hybrid rocks. This resulted in the development of the net-veined complexes and at least some of the migmatites of the Lamboo Complex.

Conclusions

- Granite plutons in the Lamboo Complex west of the Halls Creek Fault are generally older than adjacent intrusions of gabbro, in contrast to previous interpretations.
- Net-veined complexes with mafic pillows formed where previously emplaced and partly or completely crystallised granite was intruded, and partially melted, by mafic magma.
- Migmatites were formed where Tickalara Metamorphics, already contact-metamorphosed by granite, were further heated, and partially melted, by gabbro intrusions. One of the authors (DHB) considers that this may be the origin of many of the Lamboo migmatites previously ascribed to regional metamorphism predating granite emplacement.

Acknowledgements

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Figure 8. Synplutonic-type mafic intrusions in migmatitic Tickalara Metamorphics 2 km west of Turkey Creek (locality a in Fig. 1).

- Thin mafic dyke parallel to the general foliation in adjacent migmatite. Necking of this dyke is evident about 1 m above the pencil in the centre of the photograph.
- Mafic dyke back-veined by leucosome from the adjacent migmatite.
- Irregular mafic dyke cutting migmatite with mafic blocks representing dismembered earlier dykes.
- Dismembered mafic dyke, comprising irregular pillow-like blocks with partly cusped margins, in swirly migmatite.
- Irregular mafic dykes cutting migmatite. The apparent folding of the dykes is attributed to emplacement before the migmatite host had completely solidified.

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Editorial comment. Magma mingling and migmatite formation have always been controversial, and undoubtedly many geologists will have alternative interpretations for the features described above.

The editor would welcome discussions for publication in the *AGSO Journal of Australian Geology and Geophysics*.

The ages of Proterozoic granites in the Georgetown Inlier of northeastern Australia, and their relevance to the dating of tectonothermal events

L.P. Black¹ & I.W. Withnall²

U-Pb zircon SHRIMP ion-microprobe ages are presented for five Proterozoic igneous rocks from the Georgetown Province of northeastern Queensland. Four of these are interpreted as the igneous crystallisation ages of the Croydon Volcanic Group (1548±18 Ma), Lighthouse Granite (1561±10 Ma), Digger Creek Granite (1554±10 Ma), and Mount Hogan Granite (1549±25 Ma). Most of the zircon within the Forest Home Trondhjemite is apparently xenocrystic, being rounded cores that crystallised at 1650±17 Ma; the time of emplacement is not known with certainty, but is thought to be better represented by a 1553±46 Ma Rb-Sr

isochron age.

The U-Pb zircon emplacement ages are internally consistent in constraining the age of a prograde, intense tectonothermal event (D₂) in the province to 1554±10 Ma. This is about 80 Ma older than a previous estimate for the age of this event, based on the correlation of Rb-Sr whole-rock isochron ages and the development of a penetrative (S₂) fabric. The use of that particular Rb-Sr technique in terranes of this type should therefore be treated with considerable caution.

Introduction

It is often difficult to obtain reliable isotopic ages for tectonothermal events. One aspect of the problem is the ease with which some isotopic systems are reset, and the consequent chance of a partially reset age, with no direct relevance to the geological history of the analysed rock. The second part of the problem is to assign any meaningful age to the appropriate event in the rock's history.

The isotopic techniques used to date tectonothermal events within complex metamorphic terranes have evolved progressively in line with technological advances. Initially, the relatively easily reset K-Ar and Rb-Sr mineral systems were utilised (e.g. Gilletti & others, 1961; Goldich & others, 1961). Subsequently, Rb-Sr isochron studies (e.g. Peterman, 1966; Heier & Compston, 1969), conventional U-Pb multi-grain zircon analyses (e.g. Pidgeon & Bowes, 1972; Pidgeon & Aftalion, 1972), and Pb-Pb total-rock studies (e.g. Black & others, 1973) gained popularity.

In recent years there has been a trend to more sophisticated procedures. Of particular relevance are the techniques which directly date minerals that grew during, or are diagnostic of, a particular metamorphic event. The best example is garnet, which has been dated using Rb-Sr (Christensen & others, 1989), U-Pb (Mezger & others, 1989), and Sm-Nd (Vance & O'Nions, 1990) isotopes.

There have also been attempts to date tectonothermal events indirectly, most notably by determining the crystallisation ages of intrusives that were emplaced before or after such events (e.g. Van Breeman & others, 1971; 1974; Black & others, 1992).

This study presents SHRIMP (Sensitive High Resolution Ion Micro Probe) U-Pb zircon data that indirectly, but unequivocally, constrain the minimum age of a major tectonothermal event (D₂) which affected the Georgetown Province of northeastern Australia in the Middle Proterozoic. This constraining age conflicts with that obtained in a previous attempt (Black & others, 1979) to date D₂ directly using the Rb-Sr whole-rock technique. The results of the latter study were internally consistent in demon-

strating a correlation between Rb-Sr whole-rock isochron ages and the last penetrative fabric to have been developed on the scale of sampling. The technique has been subsequently applied, apparently successfully, to the dating of superposed tectonothermal events in other regions. But now the new U-Pb data, from the region in which the technique was first developed, show that it cannot be universally applied. Therefore, if used, it should be accompanied by substantial supporting data from another isotopic system.

Geological background

The Precambrian (probably Proterozoic) Georgetown Inlier occupies 100 000 km² of northeastern Australia (Fig. 1). It is bounded to the east by the Palaeozoic Tasman Orogen, which extends virtually the entire length of the continent. To the west, the inlier is separated from other outcrops of Precambrian rocks by Mesozoic sediments of the Great Artesian Basin.

Metasedimentary rocks of the Etheridge Group make up most of the inlier, with few, if any, interbedded felsic volcanics. Consequently, it has proven very difficult to assess the depositional age of the succession directly — it is probably Late Palaeoproterozoic or Early Mesoproterozoic. The metasediments were deformed during five tectonothermal events (Black & others, 1979; Withnall & others, 1980, 1988). The first two of these (D₁ and D₂) formed tight to isoclinal folds during prograde metamorphisms, which ranged in grade from greenschist facies in the west to granulite facies in the east (Black & others, 1979). The above authors had concluded from Rb-Sr whole-rock isochron data that D₁ and D₂ occurred at 1570±20 Ma and 1470±20 Ma, respectively, but the present study shows that the latter age is too young (see below). The retrograde D₃ event, dated by the same technique at 970±30 Ma, was less intense. The D₄ and D₅ events were not sufficiently intense to have produced penetrative fabrics. They were assigned ages of about 400 Ma and 300 Ma, respectively, mainly on the basis of K-Ar and Rb-Sr mineral isotopic data, and regional structural correlations.

About half of the Georgetown Inlier (and the immediately adjacent Palaeozoic orogen) consists of felsic igneous rocks. These are of three distinct ages: Proterozoic, Silurian–Devonian and Carboniferous–Permian [the latter belonging to the Coastal Ranges Igneous Province, as

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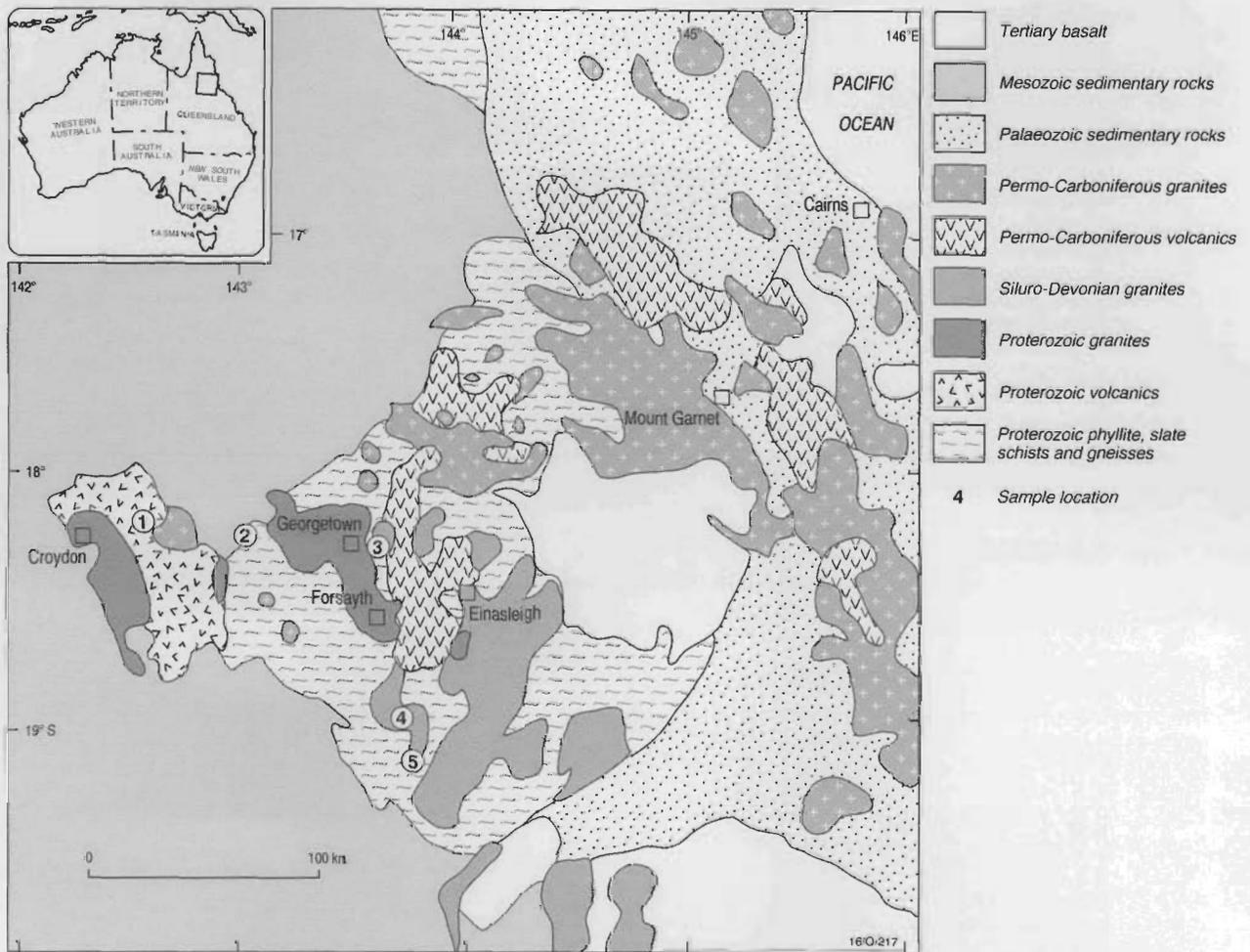


Figure 1. Summary geology of the Georgetown Inlier and adjacent regions. Sample locations are, 1. Croydon Volcanic Group (sample 77303064), 2. Forest Home Trondhjemite (sample 81303069), 3. Lighthouse Granite (sample 81303067), 4. Digger Creek Granite (sample 75303012), 5. Mount Hogan Granite (sample 82303010).

defined by Stephenson & Griffin (1976) and Henderson (1980)], each of which broadly coincides with the tectonothermal events identified above.

Volcanic and plutonic rocks of Carboniferous to Permian age are about equally abundant in outcrop. Granite and granodioritic compositions dominate, though rocks as mafic as basalt and gabbro are also present. The volcanics occur mostly in huge volcano-tectonic structures (Oversby & others, 1980), and to a lesser extent with intrusive components in ring complexes. Some of the high-level granites intrude contemporaneous volcanics. Most of the Permo-Carboniferous igneous rocks are of I type (Chappell & White, 1974), and therefore probably derived by the melting of predominantly igneous rocks. However, Champion & Heinemann (1993) also document the presence of some A-type igneous rocks, particularly within volcanic units.

A notable feature of the Siluro-Devonian igneous activity in the Georgetown Inlier is that only plutonic rocks have been preserved. These rocks crop out in the southeastern quadrant of the inlier and beyond its margin. Although they are dominantly granodiorites and granites, compositions as mafic as quartz diorite and olivine gabbro are also present. All rocks are of I-type.

The extensive Proterozoic igneous rocks (Fig. 1) form the subject of this study. There is only one significant felsic volcanic unit of this age, the Croydon Volcanic Group, which crops out over 3000 km² in the far west of the province. This unit consists mainly of densely welded, recrystallised rhyolitic and rhyodacitic ignimbrite and less common dacitic ignimbrite and peripheral rhyolite flows (Withnall & others, 1980, 1988; Mackenzie & others, 1986). Field data indicate that this unit post-dates D₂. These volcanics are of S-type (Chappell & White, 1974), and are therefore probably derived by the partial melting of a meta-sedimentary source, in common with the vast majority of the Proterozoic granites in the province. The Croydon Volcanic Group is intruded by the Esmeralda Granite, a comagmatic and coeval intrusive. Graphitic enclaves are common to both units.

Proterozoic granites in the central part of the Georgetown Inlier form the 700 km² Forsyth Batholith. They have been subdivided into nine named units, and several smaller unnamed bodies of pegmatite and leucogranite (Withnall & others, 1980; Bain & others, 1985). All are S-types. The Lighthouse Granite, one of the oldest members of the batholith (based on field relationships), has been dated in this study. This gneissic, characteristically inclusion-rich leucogranite commonly contains both biotite and

muscovite. As it has D_2 folds and an S_2 foliation, the granite was emplaced either during or prior to that deformation.

Three other granites have also been dated. The Digger Creek Granite forms small, but widespread bodies throughout the higher-grade parts (sillimanite zone and higher) of the Etheridge Group, in particular the pelitic to psammo-pelitic Robertson River Subgroup. These bodies consist of aplitic to pegmatitic muscovite granite. Locally they contain D_2 folds, but elsewhere occupy D_2 foliation planes. Hence, the Digger Creek Granite was emplaced either before or during the D_2 tectonothermal event. Dykes and veins of muscovite granite and pegmatite, which intruded the Forsyth Batholith late in its evolution, might be related to the Digger Creek Granite.

The S-type, biotite-bearing Mount Hogan Granite forms an isolated 6 by 10 km pluton. Hydrothermally altered zones within the granite are host to gold and minor uranium and fluorite mineralisation. This granite clearly truncates D_2 folds outlined by metadolerite sills in surrounding metamorphic rocks.

The Forest Home Trondhjemite is an unusual representative of the Proterozoic magmatism in the Georgetown Province. In contrast to the other Proterozoic granites, the small, biotite-bearing intrusions of this unit to the west of the Forsyth Batholith were derived dominantly from the partial melting of an I-type protolith(s). The trondhjemite was emplaced after D_1 (for which it provides a minimum age), but its relationship to D_2 is not clear.

The major objective of this study was, through precise U-Pb SHRIMP dating of the zircons in these Proterozoic igneous rocks, to define as precisely as possible age constraints for the D_1 and D_2 tectonothermal events, and to compare these ages with those previously obtained using Rb-Sr whole-rock isochrons (Black & others, 1979). In another isotopic study, Black & McCulloch (1990) attempted to determine the emplacement ages for some of these units (Croydon Volcanic Group, Forest Home Trondhjemite, and Lighthouse Granite) using conventional multi-grain U-Pb zircon techniques. However, due largely to the presence of inherited zircon components, only the Croydon Volcanic Group was successfully dated. The present SHRIMP study was instigated to overcome this difficulty.

Methodology

The U-Pb zircon analyses were determined using the SHRIMP ion-microprobe at the Research School of Earth Sciences, ANU; according to the procedures described in Compston & others (1984) and Williams & others (1984). Values for Pb/U were normalised to a mean $^{206}\text{Pb}/^{238}\text{U}$ value of 0.0928 (corresponding to an age of 572 Ma) for a standard zircon fragment (SL13). Systematic inter-element fractionation was corrected by means of a Power Law relationship between Pb^+/U^+ and UO^+/U^+ . The relatively precise ^{208}Pb method was used for common Pb correction for most of the samples, because the analyses of these were affected by the atypical presence of extraneous counts at mass 204. There was no evidence of open-system behaviour in the Th-U-Pb systematics of those zircons. In contrast, the ^{204}Pb method was used to correct for common Pb in the Forest Home Trondhjemite zircons, because these grains exhibited disturbed Th-U-Pb systematics, but were not affected by excess counts at

mass 204. Non-radiogenic Pb in all samples is indistinguishable from contemporaneous common Pb (Cumming & Richards, 1975). Each of the reported ages and their errors are derived from the weighted means of the $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. The precision of all isotopic ratios (in Table 1 and on the figures) and that of the ages in Table 1 are given at the 1σ level. Elsewhere (i.e. in the text and on the figures) age uncertainties are reported at the 95% confidence level (1σ).

Isotopic ages of the Proterozoic igneous rocks

Croydon Volcanic Group (sample number 77303064)

The analysed sample is from the Idalia Rhyolite, the uppermost and most extensive (300 km²) unit of the Croydon Volcanic Group. This unit is up to 400 m thick and consists of grey, moderately crystal-rich, rhyolitic to rhyodacitic ignimbrite.

The Croydon Volcanic Group was originally presumed by Branch (1966) to be Carboniferous because of similarities in lithology and outcrop style to more easterly exposures of Carboniferous volcanics. On the basis of Rb-Sr whole-rock data, the age of this group was subsequently revised to 1430 Ma using two data points (Richards & others, 1966) and then to 1400±75 Ma after the deletion of four out of eleven data points (Webb, in Black, 1973).

Conventional multigrain U-Pb zircon data (Black & McCulloch, 1990) yielded an age of 1552±2 Ma for this unit from a perfectly fitted regression. Only one analysis had been omitted from the regression, its exclusion being justified on the grounds that it was the only separate ?to contain obvious cores. The occurrence of this analysis to the right of the discordia was consistent with this observation.

Cores were not observed in any of the zircons from the Idalia Rhyolite. Except for a few anhedral examples, these grains are more euhedral than those in any of the granitic rocks of this study. Although primary crystal faces dominate, secondary prismatic and pyramidal faces are also present. All grains are elongate; extreme examples have length:breadth ratios up to 10:1. Maximum length is 600 µm; widths rarely exceed 100 µm. Average grain size is about 300x100 µm. Most grains are clear, and no zoning was observed. Long, clear, rod-like inclusions are common; smaller silicate inclusions are also present.

The zircons have the relatively low U and Th contents typical of felsic volcanics. Except for analyses 1.2, 11.2 and 14.2, all isotopic data plot close together, near concordia (Fig. 2). Although the total spread of $^{207}\text{Pb}/^{206}\text{Pb}$ is slightly outside experimental precision, it is not significantly reduced by the omission of any particular grains. An emplacement age for the Croydon Volcanic Group of 1548±18 Ma is therefore derived from all of the analyses. This is 150 Ma older than the Rb-Sr whole-rock age.

The Lighthouse Granite (sample number 81303067)

This is described by Withnall & others (1976, 1980) as a gneissic muscovite-biotite leucogranite (locally with

Table 1. U-Th-Pb isotopic compositions of zircons from Proterozoic igneous rocks from the Georgetown Inlier.

Grain area	U $\mu(g/g)$	Th	Th/U	$^{206}Pb/^{204}Pb$	f206	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Age (Ma)
							$\pm 1\text{ error}$		
<i>CROYDON VOLCANIC GROUP (sample 77303064)</i>									
1.1	135	207	1.526	1348	0.0178	0.2661±.0037	3.19±.15	0.0868±.0037	1357±84
1.2	106	149	1.406	1023	0.0257	0.2479±.0038	2.89±.13	0.0845±.0034	1305±81
2.1	69	73	1.053	471	0.0214	0.2716±.0040	3.42±.15	0.0913±.0037	1454±80
3.1	136	50	0.366	936	0.0055	0.2688±.0036	3.53±.09	0.0952±.0018	1532±36
3.2	145	58	0.403	1898	0.0058	0.2591±.0038	3.44±.08	0.0961±.0014	1551±28
4.1	191	85	0.446	1854	0.0064	0.2648±.0034	3.36±.08	0.0920±.0016	1467±33
4.2	218	99	0.456	3387	0.0071	0.2592±.0037	3.38±.07	0.0944±.0012	1517±23
5.1	147	161	1.093	1354	0.0097	0.2624±.0035	3.33±.12	0.0921±.0028	1470±58
5.2	180	147	0.817	3320	0.0089	0.2593±.0037	3.30±.08	0.0922±.0018	1472±37
6.1	209	84	0.402	1896	0.0052	0.2693±.0035	3.58±.08	0.0963±.0015	1554±30
7.1	105	104	0.993	1116	0.0124	0.2628±.0036	3.30±.12	0.0912±.0029	1450±63
7.2	143	112	0.783	2442	0.0137	0.2553±.0037	3.18±.09	0.0903±.0019	1433±40
8.1	153	61	0.400	1988	0.0060	0.2657±.0035	3.49±.08	0.0952±.0018	1531±35
9.1	412	112	0.272	3750	0.0008	0.2814±.0035	3.85±.07	0.0991±.0010	1608±19
10.1	300	139	0.465	2136	0.0050	0.2785±.0035	3.72±.08	0.0968±.0014	1563±28
10.2	162	74	0.456	1110	0.0060	0.2645±.0034	3.58±.09	0.0981±.0018	1589±34
11.1	84	116	1.381	697	0.0062	0.2734±.0039	3.62±.16	0.0961±.0039	1549±79
11.2	57	73	1.272	616	0.0087	0.2317±.0035	3.01±.16	0.0942±.0047	1513±96
12.1	333	113	0.340	565	0.0258	0.2693±.0034	3.59±.07	0.0966±.0013	1559±25
13.1	122	36	0.294	1368	0.0048	0.2747±.0037	3.77±.09	0.0995±.0019	1614±36
13.2	146	52	0.356	2801	0.0071	0.2569±.0037	3.39±.07	0.0956±.0012	1541±25
13.3	161	56	0.345	1445	0.0127	0.2571±.0037	3.33±.07	0.0940±.0012	1508±24
14.1	260	87	0.333	2114	0.0037	0.2869±.0037	3.97±.08	0.1003±.0014	1629±25
14.2	259	126	0.486	2987	0.0052	0.2264±.0032	2.99±.06	0.0958±.0013	1544±25
15.1	118	134	1.133	851	0.0115	0.2640±.0036	3.35±.13	0.0920±.0031	1468±65
16.1	302	97	0.321	2754	0.0030	0.2738±.0034	3.59±.07	0.0952±.0012	1532±25
17.1	776	193	0.248	2401	0.0042	0.2629±.0032	3.54±.05	0.0977±.0007	1581±14
19.1	386	122	0.317	2769	0.0018	0.2769±.0035	3.67±.07	0.0962±.0011	1551±22
20.1	154	42	0.274	601	0.0213	0.2730±.0036	3.55±.09	0.0943±.0017	1514±35
21.1	163	69	0.423	1239	0.0078	0.2693±.0035	3.58±.09	0.0964±.0018	1556±35
30.1	146	40	0.271	1694	0.0060	0.2575±.0038	3.50±.07	0.0987±.0011	1599±22
31.1	82	67	0.816	1590	0.0135	0.2628±.0041	3.31±.11	0.0913±.0024	1453±52
32.1	56	67	1.199	1191	0.0186	0.2550±.0042	3.30±.15	0.0938±.0037	1505±77
33.1	94	44	0.470	1047	0.0079	0.2651±.0041	3.52±.09	0.0964±.0017	1555±34
<i>LIGHTHOUSE GRANITE (sample 81303067)</i>									
1.1	156	59	0.377	124	0.1242	0.2843±.0059	3.90±.11	0.0996±.0017	1616±32
2.1	771	328	0.425	6939	0.0038	0.2774±.0056	3.65±.08	0.0953±.0004	1534±9
3.1	2163	165	0.076	50400	0.0009	0.2855±.0057	3.80±.08	0.0965±.0002	1557±3
4.1#	2411	145	0.060	678	0.0229	0.2856±.0057	3.79±.08	0.0964±.0002	1555±4
5.1*	514	107	0.208	181	0.0846	0.2437±.0049	3.22±.07	0.0958±.0007	1544±15
6.1*	196	138	0.705	15210	0.0042	0.2871±.0059	3.94±.10	0.0995±.0011	1615±21
7.1*	183	143	0.780	5416	0.0048	0.3750±.0077	6.62±.16	0.1280±.0011	2071±16
8.1*	903	264	0.293	476	0.0318	0.3233±.0065	4.87±.10	0.1092±.0004	1786±7
9.1*	630	61	0.096	9111	0.0044	0.3251±.0066	4.88±.10	0.1089±.0004	1782±7
10.1*	134	56	0.416	6102	0.0031	0.4741±.0099	10.68±.24	0.1634±.0010	2491±10
11.1*	89	45	0.507	3377	0.0064	0.2757±.0058	3.89±.11	0.1023±.0015	1666±27
12.1*	155	76	0.492	17170	0.0018	0.4344±.0090	9.27±.21	0.1547±.0010	2399±11
13.1*	287	87	0.303	14620	0.0027	0.4726±.0096	10.78±.23	0.1654±.0006	2512±6
14.1*	260	202	0.777	23950	0.0073	0.6432±.0131	21.96±.47	0.2476±.0009	3169±6
15.1	1137	212	0.187	429	0.0382	0.2695±.0054	3.59±.08	0.0967±.0004	1561±7
15.2	629	79	0.126	6909	0.0026	0.2642±.0053	3.54±.07	0.0971±.0004	1568±7
16.1	815	84	0.103	35260	0.0012	0.2795±.0056	3.78±.08	0.0981±.0003	1587±6
17.1	387	38	0.099	14160	0.0008	0.2733±.0055	3.66±.08	0.0970±.0004	1568±8
18.1	373	23	0.062	9961	0.0016	0.2760±.0056	3.69±.08	0.0970±.0004	1568±9
19.1*	259	104	0.403	93	0.1689	0.2938±.0060	3.70±.11	0.0913±.0016	1454±33
20.1*	171	85	0.497	5684	0.0023	0.3618±.0075	6.33±.15	0.1268±.0010	2054±14
20.2*	295	82	0.279	22920	0.0018	0.3674±.0075	6.06±.13	0.1196±.0006	1949±9
21.1*	42	32	0.777	2122	0.0080	0.4011±.0090	7.61±.23	0.1376±.0024	2198±31
21.2*	42	33	0.790	1882	0.0076	0.4082±.0092	7.68±.23	0.1364±.0025	2182±32
21.3*	42	31	0.746	2164	0.0094	0.3960±.0090	7.54±.23	0.1381±.0025	2204±31
22.1*	913	485	0.531	2615	0.0084	0.3001±.0060	4.20±.09	0.1014±.0005	1650±9
23.1*	102	68	0.666	5404	0.0033	0.5336±.0113	13.87±.32	0.1885±.0014	2729±12

Grain area	U μ(g/g)	Th	Th/U	²⁰⁶ Pb/ ²⁰⁴ Pb	f ₂₀₆	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb	Age (Ma)
						±1σ error			
<i>DIGGER CREEK GRANITE (75303012)</i>									
18.1	3094	30	0.010	4000	0.0038	0.2784±.0034	3.68±.05	0.0959±.0003	1545±7
18.2	2346	21	0.009	45310	0.0003	0.2800±.0038	3.72±.05	0.0964±.0002	1555±4
22.1	6745	33	0.005	3788	0.0044	0.1822±.0024	2.40±.03	0.0956±.0001	1540±3
22.2	6606	30	0.005	4609	0.0042	0.2378±.0032	3.14±.04	0.0956±.0001	1540±3
23.1	1562	31	0.020	190	0.0923	0.1777±.0024	2.23±.03	0.0911±.0004	1449±9
24.1	5423	30	0.006	979	0.0199	0.1051±.0014	1.22±.02	0.0842±.0002	1297±4
25.1	3943	35	0.009	4995	0.0025	0.2563±.0034	3.39±.05	0.0959±.0001	1547±3
25.2	3414	20	0.006	3484	0.0045	0.2817±.0038	3.75±.05	0.0965±.0002	1557±3
25.3	3090	24	0.008	2370	0.0067	0.2678±.0036	3.58±.05	0.0969±.0002	1565±3
26.1	3098	78	0.025	2486	0.0044	0.2615±.0035	3.53±.5	0.0978±.0002	1583±4
26.2	1698	24	0.014	2777	0.0041	0.2661±.0036	3.57±.5	0.0974±.0002	1574±5
27.1	2090	17	0.008	13380	0.0010	0.2736±.0037	3.66±.5	0.0969±.0002	1566±4
28.1	6823	55	0.008	329	0.0516	0.0233±.0003	0.19±.1	0.0601±.0005	607±17
29.1	7843	57	0.007	3277	0.0094	0.4641±.0062	5.91±.08	0.0923±.0001	1473±2
<i>MOUNT HOGAN GRANITE (sample 82303010)</i>									
1.1	1132	365	0.322	11120	0.0008	0.2448±.0025	3.28±.04	0.0973±.0005	1573±9
2.1	488	791	1.622	15580	0.0084	0.2665±.0028	3.34±.08	0.0910±.0017	1446±36
3.1	250	367	1.470	20460	0.0066	0.2681±.0030	3.46±.09	0.0936±.0021	1501±44
4.1	1578	2285	1.448	70820	0.0057	0.2825±.0029	3.57±.05	0.0917±.0008	1462±17
5.1	256	321	1.255	122400	0.0106	0.2582±.0028	3.22±.08	0.0904±.0019	1434±40
6.1	433	457	1.056	69490	0.0017	0.2758±.0029	3.64±.06	0.0958±.0012	1543±24
7.1	534	683	1.278	8926	0.0154	0.2605±.0027	3.00±.06	0.0835±.0013	1280±31
8.1	526	691	1.313	58110	0.0048	0.2731±.0029	3.50±.07	0.0929±.0013	1487±27
9.1	453	451	0.995	20040	0.0111	0.2348±.0025	2.84±.05	0.0879±.0013	1379±28
10.1	1347	530	0.394	364000	0.0003	0.2578±.0026	3.46±.04	0.0973±.0004	1573±8
11.1	1417	828	0.584	30710	0.0042	0.2698±.0027	3.48±.04	0.0936±.0005	1500±10
12.1	513	103	0.201	18450	0.0005	0.2765±.0029	3.69±.05	0.0968±.0006	1564±11
13.1	956	390	0.407	11730	0.0040	0.2296±.0023	2.98±.04	0.0943±.0006	1514±11
14.1	1318	380	0.288	39530	0.0000	0.2717±.0028	3.71±.04	0.0989±.0004	1604±7
15.1	838	318	0.379	311000	0.0013	0.2668±.0027	3.53±.04	0.0959±.0005	1545±10
16.1	1140	650	0.571	8570	0.0000	0.2015±.0020	3.60±.04	0.1296±.0005	2092±7
17.1	1085	1175	1.083	59800	0.0028	0.2782±.0028	3.61±.05	0.0941±.0008	1509±16
18.1	313	382	1.220	8397	0.0081	0.2582±.0028	3.24±.07	0.0911±.0017	1449±36
<i>FOREST HOME TRONDHJEMITE (sample 81303069)</i>									
1.1*	479	440	0.918	1450	0.0108	0.2378±.0036	3.24±.06	0.0987±.0010	1601±18
1.2*	292	399	1.364	11020	0.0014	0.3066±.0047	4.31±.08	0.1019±.0007	1658±13
2.1*	260	274	1.053	22060	0.0007	0.3014±.0046	4.29±.08	0.1033±.0007	1685±13
3.1*	498	317	0.636	634	0.0235	0.3494±.0053	5.87±.11	0.1218±.0012	1982±18
3.2*	280	194	0.692	3962	0.0038	0.3927±.0060	6.95±.12	0.1283±.0008	2075±11
4.1#	431	119	0.276	6607	0.0024	0.2700±.0041	3.75±.07	0.1007±.0006	1637±12
5.1*	559	428	0.767	655	0.0215	0.4477±.0068	10.20±.18	0.1653±.0010	2511±10
5.2#	1461	450	0.308	41	0.3879	0.0890±.0015	1.00±.08	0.0814±.0062	1232±157
6.1*	335	336	1.003	5395	0.0029	0.2971±.0045	4.12±.07	0.1006±.0008	1636±14
7.1*	320	171	0.534	13150	0.0012	0.3058±.0047	4.35±.08	0.1031±.0006	1681±11
8.1*	103	71	0.690	6412	0.0025	0.2786±.0044	3.94±.09	0.1026±.0015	1671±27
9.1*	454	249	0.548	530	0.0296	0.2697±.0041	3.87±.09	0.1042±.0016	1700±28
10.1*	213	253	1.188	142	0.1106	0.3176±.0051	4.25±.19	0.0970±.0039	1568±77
11.1*	291	222	0.765	69000	0.0002	0.3013±.0046	4.19±.07	0.1007±.0005	1638±10
12.1*	36	52	1.427	6975	0.0022	0.3287±.0059	4.95±.16	0.1092±.0028	1786±48
13.1*	262	319	1.215	53500	0.0003	0.2824±.0044	3.91±.07	0.1003±.0008	1630±15
14.1*	143	137	0.962	71800	0.0002	0.3114±.0049	4.48±.09	0.1043±.0011	1703±19
14.2#	367	255	0.695	137	0.1186	0.2489±.0039	3.08±.14	0.0898±.0036	1422±78
15.1*	606	35	0.058	2301	0.0061	0.4926±.0075	11.06±.18	0.1628±.0006	2485±6
16.1*	227	222	0.976	5614	0.0028	0.2716±.0042	3.70±.07	0.0986±.0010	1599±19
17.1*	457	388	0.847	130	0.1212	0.2156±.0034	2.95±.12	0.0994±.0034	1612±65
18.1*	243	339	1.397	217	0.0725	0.2802±.0044	3.95±.15	0.1023±.0034	1667±62
19.1*	273	172	0.631	46020	0.0003	0.3432±.0053	5.44±.09	0.1149±.0006	1878±10
20.1*	286	312	1.090	18210	0.0009	0.2981±.0046	4.09±.07	0.0995±.0007	1614±13
21.1*	102	87	0.850	660	0.0238	0.2980±.0049	4.23±.16	0.1028±.0032	1676±59
22.1*	765	1264	1.653	155	0.1015	0.2625±.0040	3.45±.10	0.0953±.0022	1534±44
23.1*	574	238	0.415	450	0.0349	0.3084±.0047	4.27±.09	0.1004±.0014	1632±27
24.1*	554	388	0.700	2596	0.0061	0.3175±.0048	4.59±.08	0.1049±.0007	1713±13

* Core. # Rim. f₂₀₆ is the proportion of common to total Pb in terms of ²⁰⁶Pb. Grid references for the analysed samples are Croydon Volcanic Group-649679834; Forest Home Trondhjemite-717479665; Lighthouse Granite-772879743; Digger Creek Granite-791678952; Mount Hogan Granite-794578765.

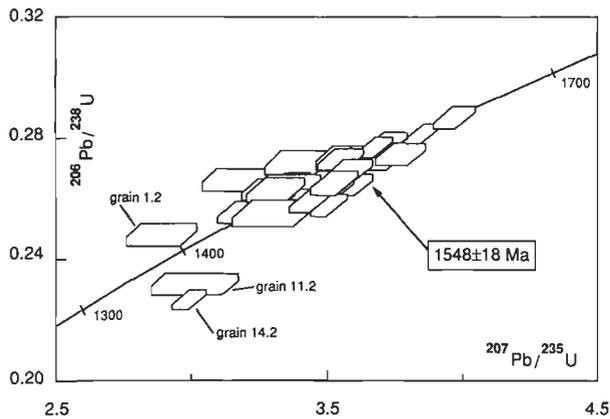


Figure 2. $^{207}\text{Pb}/^{235}\text{U}$ – $^{206}\text{Pb}/^{238}\text{U}$ concordia plot for zircons from the Idalia Rhyolite (sample 77303064), Croydon Volcanic Group. The crystallisation age of 1548 ± 18 Ma is derived from the average $^{207}\text{Pb}/^{206}\text{Pb}$ of all analyses.

garnet) from the northern part of the Forsayth Batholith. It has a wide range of grain size and mafic mineral content, and commonly contains bands and enclaves of biotite schist and gneiss, and grey gneissic biotite granite, as well as biotite xenocrysts.

Seven whole-rock analyses from a 1 m^3 sample site yielded an Rb–Sr age of 1503 ± 33 Ma (initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7095\pm 0.0007$) for the Lighthouse Granite (Black & Holmes, in press) which, because of the strong S_2 foliation at this location, was thought to be the age of the D_2 deformation, and approximately the age of magma emplacement. Muscovite and biotite Rb–Sr ages of 1410 Ma and 580 Ma, respectively, have been partially reset by later events.

Conventional multigrain U–Pb zircon data for the Lighthouse Granite are highly scattered (MSWD is 235) and therefore inadequate for the derivation of a precise emplacement age (Black & McCulloch, 1990). Displacement of the analyses to the right of data for other, broadly contemporaneous, representatives of the Forsayth Batholith, is assumed to reflect the presence of inherited zircon cores/grains.

Most Lighthouse Granite zircons display distinct cores and rims, with about equal volumetric development of each phase. There is a bimodality in overall grain size. The larger grains measure about $300\times 150\ \mu\text{m}$ and the smaller about $150\times 50\ \mu\text{m}$, although this feature does not correlate with the observed wide range of ages (Fig. 3). There is, however, a correlation between SHRIMP ages and morphology. Thus, with one exception, all analyses of rims or of single-phase grains (e.g. grains 1, 2 and 17, which may be either zoned or homogeneous, but have euhedral igneous shapes) yield ages between 1500 Ma and 1600 Ma (Fig. 4).

The exception is analysis 5.1, which was located on a euhedral, elongate core surrounded by an atypically thin rim. None of the other cores make up such a large volumetric proportion of their constituent grains. Neither are they euhedral nor particularly elongate. It is surmised that, in common with most of the contemporaneous grains, the core of grain 5 crystallised from the Lighthouse Granite magma, and that its thin rim is of subsequent metamorphic derivation. Although not all of the $^{207}\text{Pb}/^{206}\text{Pb}$ values for the syn-magmatic zircons are within

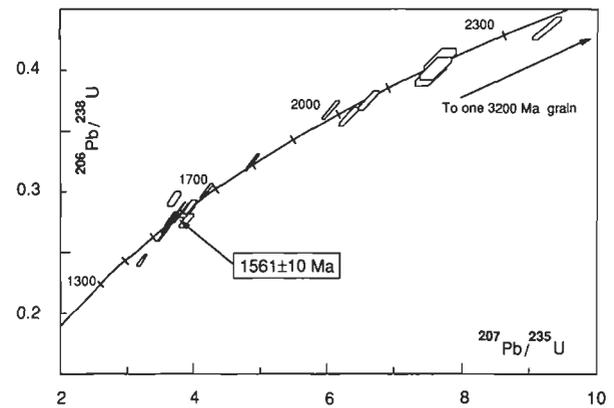


Figure 3. $^{207}\text{Pb}/^{235}\text{U}$ – $^{206}\text{Pb}/^{238}\text{U}$ concordia plot for zircons from the Lighthouse Granite (sample 81303067). The indicated crystallisation age of 1561 ± 10 Ma is derived from the average $^{207}\text{Pb}/^{206}\text{Pb}$ values of ten analyses.

error of each other, they nevertheless form a reasonably tight isotopic grouping with a mean age of 1561 ± 10 Ma, which defines the age of granite crystallisation. This is about 60 Ma older than the Rb–Sr whole-rock age.

The rounded cores have a large range of relatively evenly spread ages, extending from close to that of the granite to more than 3100 Ma. The most obvious explanation for this array is that the local metasedimentary rocks were derived from many different provenances. An alternative explanation would be that a smaller number of provenances were involved, and that the age-spread partially reflects incomplete isotopic resetting, primarily during the life of the Lighthouse Granite magma.

The Digger Creek Granite (sample 75303012)

This unit has extremely variable texture, which ranges from aplitic to pegmatitic. Black & others (1979) derived a Rb–Sr whole-rock isochron age of 1460 ± 40 Ma from a pink, garnetiferous, muscovite-bearing pegmatite; a sample from the same outcrop was dated by SHRIMP in the present study.

Zircons in the Digger Creek Granite are of relatively uniform grain size (approximately $300\times 100\ \mu\text{m}$). The grains are elongate and euhedral, with simple prismatic and pyramidal faces. Zoning is ubiquitous. Most grains

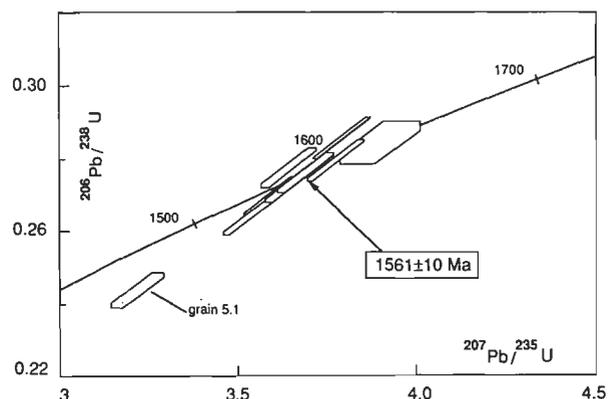


Figure 4. $^{207}\text{Pb}/^{235}\text{U}$ – $^{206}\text{Pb}/^{238}\text{U}$ concordia plot for zircons which crystallised at 1561 ± 10 Ma from the Lighthouse Granite (sample 81303067).

are extensively fractured and have many minute dark inclusions. Dark brown, highly metamict areas are common, particularly in the centres of grains. Such areas were not analysed, as they would be expected to contain extremely high levels of common Pb, and to be very discordant due to their exceptionally high U contents. Table 1 shows that even the relatively clear exterior parts of the grains have very high U contents, ranging from about 1500 µg/g to nearly 8000 µg/g. In contrast, Th contents are remarkably low (less than 100 µg/g). The high U contents would have originally produced high ²⁰⁶Pb/²⁰⁴Pb (and low *f*₂₀₆— see Table 1) values. However, these would have been substantially modified by the subsequent addition of common Pb into the radiation-damaged zircon lattice, presumably in combination with some accumulated radiogenic Pb being lost, in Phanerozoic times [the most normally discordant analysis (28.1) has a ²⁰⁶Pb/²³⁸U age of about 150 Ma].

No zircon cores were optically identified, nor is there any isotopic evidence of their presence. The isotopic data (Fig. 5) display an unusual, and marked range of discordance, from about 90% normally discordant (analysis 28.1) to about 70% reversely discordant (analysis 29.1). Analyses with the highest U contents are most displaced from their original concordant composition, except for analysis 23.1 (with 1562 µg/g of U). A ²⁰⁷Pb/²⁰⁶Pb age of 1554±10 Ma is obtained after deletion of the most isotopically aberrant grains (23.1, 24.1, 28.1 and 29.1), although there is still significant scatter about the isochron. The validity of this age depends on the absence of a significant correlation between ²⁰⁷Pb/²⁰⁶Pb and degree of discordance of the selected analyses. Potential bias from such a correlation can be assessed by constructing a line of best fit through the analyses. Ages indistinguishable from that given above are produced irrespective of whether all analyses are included (1537±27 Ma) in the regression, or only those ten analyses averaged above (1560±7 Ma). The Digger Creek Granite therefore crystallised at 1554±10 Ma, about 100 Ma earlier than its Rb-Sr whole-rock age would indicate.

The Mount Hogan Granite (sample 82303010)

The analysed sample is a pink, medium to coarse-grained biotite granite. It had previously yielded a scattered array of Rb-Sr whole-rock analyses with an insufficient range

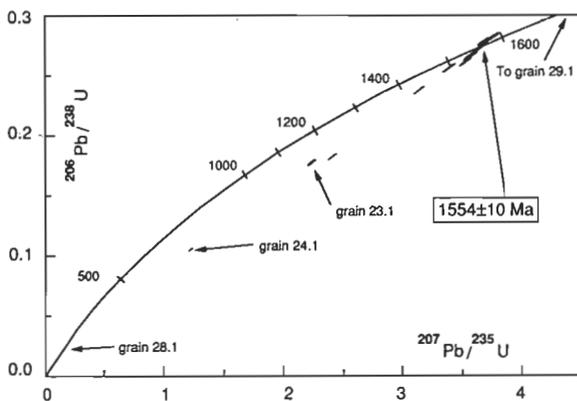


Figure 5. ²⁰⁷Pb/²³⁵U–²⁰⁶Pb/²³⁸U concordia plot for zircons from the Digger Creek Granite (sample 75303012). Analyses 23.1, 24.1, 28.1 and 29.1 have been excluded from the calculation of the average ²⁰⁷Pb/²⁰⁶Pb age of 1554±10 Ma, which is that of igneous crystallisation.

of Rb/Sr to provide useful age information (Black & Holmes, in press). There was, however, a suggestion from those data that emplacement might have been roughly coincident with the plutons of the Forsyth Batholith.

Zircons in this granite are dark brown and commonly cracked. They have a restricted range of grain sizes, averaging about 300x120 µm. Most of the characteristically euhedral grains have simple pyramidal and prismatic faces, and sharp terminations. The majority of grains are strongly zoned, but low-U grains (e.g. grains 3 and 5) are optically homogeneous. Although present in some grains, rounded cores (grains 9 and 12) are not chronologically distinctive.

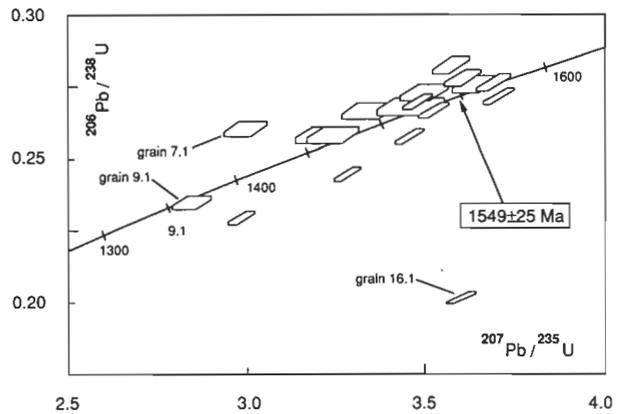


Figure 6. ²⁰⁷Pb/²³⁵U–²⁰⁶Pb/²³⁸U concordia plot for zircons from the Mount Hogan Granite (sample 82303010). After deletion of analyses 7.1, 9.1 and 16.1, an average ²⁰⁷Pb/²⁰⁶Pb age of 1549±25 Ma is obtained for the crystallisation of this granite.

Analyses 7.1, 9.1, and 16.1 have been discarded from the age calculation. Grain 16, in particular, plots off the trend of the other analyses (Fig. 6). Although the data-spread is still about four times that expected for a simple population, there are no obvious remaining outliers. The resultant ²⁰⁷Pb/²⁰⁶Pb age of 1549±25 Ma dates the emplacement of the granite.

The Forest Home Trondhjemite (sample number 81303069)

This is a light grey, fine to medium-grained equigranular biotite-bearing trondhjemite characterised geochemically by low K₂O, CaO, MgO, Rb, total FeO, and high Na₂O, Sr, Ba, and by very sodic plagioclase (An₁₀₋₂₅ — Black & Holmes, in press). The twelve individual plutons have sharp contacts with the enclosing country rocks, and metamorphic aureoles up to 200 m wide.

Biotite from this unit yielded K-Ar and Rb-Sr ages of 1229 Ma (Richards & others, 1966) and 1238 Ma (Black & Holmes, in press), respectively. We believe that the similarity of these ages merely reflects the similar, fairly low, blocking temperatures of the two isotopic systems (Dodson & McClelland-Brown, 1985), and does not define the emplacement age of the trondhjemite. A Rb-Sr whole-rock age of 1553±46 Ma was subsequently derived from seven undeformed samples from several of the plutons (Black & Holmes, in press). The low attendant ⁸⁷Sr/⁸⁶Sr initial ratio of 0.7028±.0003 is indistinguishable from that of an unfractionated mantle reservoir at that time.

Black & McCulloch (1990) were unable to derive a meaningful U-Pb zircon age for the Forest Home Trondhjemite because of the presence of inherited cores in the multigrain concentrates. Nominal intersections of the highly discordant data with concordia were at about 400 and 2000 Ma, but the upper intersection clearly does not define the age of emplacement.

Zircons in the Forest Home Trondhjemite are mostly dark brown, elongate, and quite small (about $180 \times 70 \mu\text{m}$). They are morphologically complex; all of the grains consist of thin overgrowths surrounding distinct, volumetrically dominant, cores (which commonly contain abundant rods of silicate inclusions). The U-Pb isotopic data do not define the age of this rock because most analyses (25 out of 28) on Figure 7 represent rounded cores ranging in age from about 2500 to 1600 Ma. Nineteen of those cores have a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1650 ± 17 Ma from an analytical array that is about twice as dispersed as would be expected from analytical imprecision alone. The rounded character of these cores indicates they did not crystallise from their host magma. Their relative volumetric dominance might suggest they were inherited from a major source component from which the trondhjemite was partially melted. As this was an I-type magma (i.e. dominantly derived from the melting of igneous source components), these conclusions could be interpreted to indicate that 1650 ± 17 Ma igneous rocks underlie this area (if these represent underplated magma, the sedimentary sequence in the Georgetown Inlier would be older than that age). An alternative explanation, consistent with the low total abundance of zircon in the trondhjemite, is that the zircon cores were derived from a minor metasedimentary (rather than igneous) component. In this scenario, these cores would define a maximum age for sedimentation. This model is supported by the observation that at least one of the analysed cores (analysis 11.1), with an age of 1638 ± 20 Ma, appears to contain the type of external pitting characteristic of detrital zircons.

Only three rims were sufficiently broad to be analysed. Of these, analysis 5.2 is too discordant to provide a meaningful age. The age (1420 ± 160 Ma) of rim 14.2, although imprecise, is apparently younger than the 1700 ± 40 Ma core it encloses, as would be expected. The

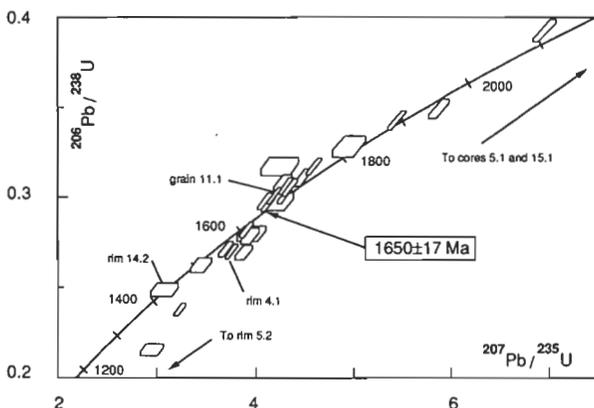


Figure 7. $^{207}\text{Pb}/^{235}\text{U}$ – $^{206}\text{Pb}/^{238}\text{U}$ concordia plot for zircons from the Forest Home Trondhjemite (sample 81303069). All of the zircon grains in this rock consist of rims and cores. Nineteen of the latter yield a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1650 ± 17 Ma, which does not represent the crystallisation age of this rock. This is probably given by a Rb-Sr whole-rock isochron age of 1553 ± 6 Ma.

analysis indicates this rim grew no earlier than about 1580 Ma. Based on the deduced age of the trondhjemite (see above) this rim could have either crystallised directly from the trondhjemitic magma, or have grown during subsequent high-grade metamorphism. An important feature of the third rim (4.1) is that it is itself overgrown by a very thin rim. The inner rim yields an age (1637 ± 24 Ma) indistinguishable from the majority of cores; the outer rim (undated) is possibly contemporaneous with the analysed 14.2 rim.

Discussion

Unlike some previous studies, the new U-Pb zircon SHRIMP data provide accurate emplacement ages for several Proterozoic granites in the Georgetown Province of northeast Queensland. The SHRIMP data for the Croydon Volcanic Group (1548 ± 18 Ma) confirm that the precise conventional zircon age (1552 ± 2 Ma — Black & McCulloch, 1990) is also an accurate assessment of the emplacement age, not having been biased by the incorporation into the magma of older zircon grains. However, the Rb-Sr whole-rock isochron age of 1400 ± 75 Ma is clearly younger than the time of crystallisation. Based on the arguments presented below, the 1400 ± 75 Ma age probably has no direct geological meaning.

In contrast, the conventional multigrain zircon analyses for the Forest Home Trondhjemite clearly yield an erroneously old upper intercept age of about 2000 Ma, which is shown by the SHRIMP data to have been caused by the presence of zircons almost entirely of inherited origin. This is the only example where the SHRIMP data apparently do not provide an accurate crystallisation age, and it is the Rb-Sr whole-rock isochron age of 1553 ± 46 Ma (Black & Holmes, in press) which probably defines the time of emplacement. This argument is supported by the undeformed nature of this trondhjemite (as opposed to the deformed fabrics of the other dated granites), which indicates that post-crystallisation conditions would not have been particularly conducive to isotopic resetting. In addition, any significant updating should have raised initial $^{87}\text{Sr}/^{86}\text{Sr}$ noticeably above unfractionated mantle values, and this has not occurred.

Black & McCulloch (1990) were unable to derive an emplacement age for the Lighthouse Granite by means of conventional multigrain U-Pb analyses, which show considerable scatter. SHRIMP data indicate this granite crystallised at 1561 ± 10 Ma, and confirm that the scatter of the conventional analyses results from the common presence of inherited zircon cores (with a 1500 Ma age range). The Rb-Sr whole-rock isochron age of 1503 ± 33 Ma (Black & Holmes, in press) is younger than the time of igneous crystallisation.

Conventional U-Pb zircon ages are not available for the Mount Hogan and Digger Creek granites. SHRIMP U-Pb zircon analyses yield an emplacement age of 1549 ± 25 Ma for the former, and 1554 ± 10 Ma for the latter. This technique detected only one inherited grain (16.1 in the Mount Hogan Granite) in either of these granites; however, the central parts of Digger Creek Granite zircons were too metamict to warrant analysis. The 1460 ± 40 Ma Rb-Sr whole-rock isochron age (Black & others, 1979) for the Digger Creek Granite is clearly younger than that of igneous crystallisation.

The new isotopic data show that much (and possibly all)

Table 2. Crystallisation ages and structural relationships of the Proterozoic igneous rocks.

<i>Unit</i>	<i>Crystallisation age</i>	<i>Structural relationship</i>
Croydon Volcanic Group	1548±18 Ma 1552±2 Ma*	Postdates D ₂
Lighthouse Granite	1561±10 Ma	Predates or synchronous with D ₂
Digger Creek Granite	1554±10 Ma	Predates or synchronous with D ₂
Mount Hogan Granite	1549±25 Ma	Postdates D ₂
Forest Home Trondhjemitic	1553±46 Ma#	Postdates D ₁

Ages derived from SHRIMP ion-microprobe analysis, except

* Conventional multigrain U-Pb zircon age.

Rb-Sr whole-rock isochron age.

of the Proterozoic igneous activity in the Georgetown Province, including both plutonism and volcanism, was confined to a relatively restricted time interval around 1550 Ma. As discussed above, these ages also provide constraints on the timing of certain events involved in the structural evolution of the province, in particular that of the widespread D₂ event (see Table 2). Previously, Rb-Sr whole-rock isochron ages had been used to derive ages of 1470±20 and 1570±20 Ma for D₂ and D₁, respectively. Apart from the consistency between the Rb-Sr ages and the last penetrative fabric to be developed on the scale of the sampling (1 m³), there was also support for those ages from two different isotopic systems. Thus, zircon concentrates from one of the gneisses with a penetrative S₁ (but no penetrative S₂) fabric, and which yielded a D₁ "age" of 1569±33 Ma, gave an indistinguishable U-Pb concordia intersection age of 1558±7 Ma (L.P. Black, unpublished analyses). Support for the D₂ "age" was provided by a ⁴⁰Ar/³⁹Ar age of 1461 Ma for hornblende which grew during D₂ in a mafic granulite from Turpentine Hill, near Einasleigh (McNaughton, 1979), and ⁴⁰Ar/³⁹Ar muscovite ages of 1456 Ma and 1478 Ma for schists from the Robertson River Subgroup (Black & others, 1979).

Despite this evidence to the contrary, the SHRIMP U-Pb zircon ages reported above demonstrate that the 1470±20 Ma age, previously ascribed to D₂, cannot be correct. Based on the observed field relationships for the Croydon Volcanic Group, Lighthouse Granite, and Mount Hogan Granite (Table 2), that event must have occurred about 80 Ma earlier, within 20 Ma of 1550 Ma. The age of D₂ can be further refined to 1554±10 Ma from the data for the syn-tectonic Digger Creek Granite. The concurrence of the four Rb-Sr whole-rock isochron ages (1440±70, 1488±35, 1477±142, and 1460±40 Ma) at 1470±20 Ma must be coincidental, probably being caused by relatively constant degrees of partial isotopic resetting by subsequent, retrogressive tectonothermal events (D₃, D₄ and/or D₅ of Black & others, 1979).

The new data do not precisely constrain the age of D₁. The inherited grains in the Forest Home Trondhjemitic indicate it is younger than 1650±17 Ma, and the lower limit of the post-D₁ Lighthouse Granite age demonstrate that it is at least as old as 1551 Ma. The 1558±7 Ma conventional U-Pb zircon age reported above for an upper amphibolite-facies paragneiss profoundly affected by D₁ (but not D₂) suggests this event occurred only shortly before D₂.

Conclusions

The results of this study have important ramifications for the isotopic dating of geologically complex regions, especially those affected by superposed tectonothermal events. It is now clear that the use of Rb-Sr whole-rock isochrons to directly date tectonothermal events in such terranes should be treated with considerable caution. Relatively minor mineralogical and structural changes during some retrogressive events can apparently lead to subtle, but distinct isotopic resetting or partial resetting, and the production of anomalous ages. Moreover, there is no guarantee that a concordance of ages derived from different isotopic systems (e.g. Rb-Sr whole-rock isochrons and ⁴⁰Ar/³⁹Ar ratios of hornblendes) in rocks with common structural and mineralogical characteristics has any geological significance. Wherever possible, isotopic systems which are relatively resistant to subsequent geological processes should be used. U-Pb zircon dating is a prime example of such a system, but it is not always possible to relate zircon growth to particular tectonothermal events. The present study shows that in the absence of syn-orogenic zircon, it should be possible to indirectly constrain the ages of tectonothermal events by the U-Pb zircon dating of felsic igneous rocks which crystallised before and after such events. The advantage of SHRIMP is that it eliminates errors arising from the inadvertent analysis of mixed zircon populations, whether these be present as discrete grains or as parts of individual grains.

The new U-Pb zircon isotopic data also significantly increase our knowledge of the evolution of the Georgetown Inlier. It is now clear that most, and possibly all, of the Proterozoic igneous rocks crystallised during a short time interval about 1550 Ma ago. Contrary to previous conclusions based on Rb-Sr dating, the oldest (D₁ and D₂) tectonothermal events that are recognised in the region probably occurred within a few million years of each other and the widespread ~1550 Ma igneous activity.

Acknowledgements

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Potential from enhanced oil recovery applications in Australia

D. Wright¹, S. le Poidevin¹, G. Morrison² & R. Thomas³

As a result of a Society of Petroleum Engineers/National Energy Research Demonstration and Development Council (NERDDC) meeting in Adelaide in April 1986 between Australian oil industry representatives, researchers and government, it was decided to propose a NERDDC project on the potential from Enhanced Oil Recovery (EOR) applications in Australia. The aim was to highlight to government, industry and the public the scope for EOR, and to provide assistance in planning EOR projects and policies. The specific project objectives were to identify the most likely field prospects for EOR applications and to assess the additional oil which may be recovered under various recovery techniques at selected oil prices.

Oilfield data from 177 significant reservoirs were compiled, checked for consistency, and subjected to technical screening,

reservoir simulation and preliminary economic evaluation.

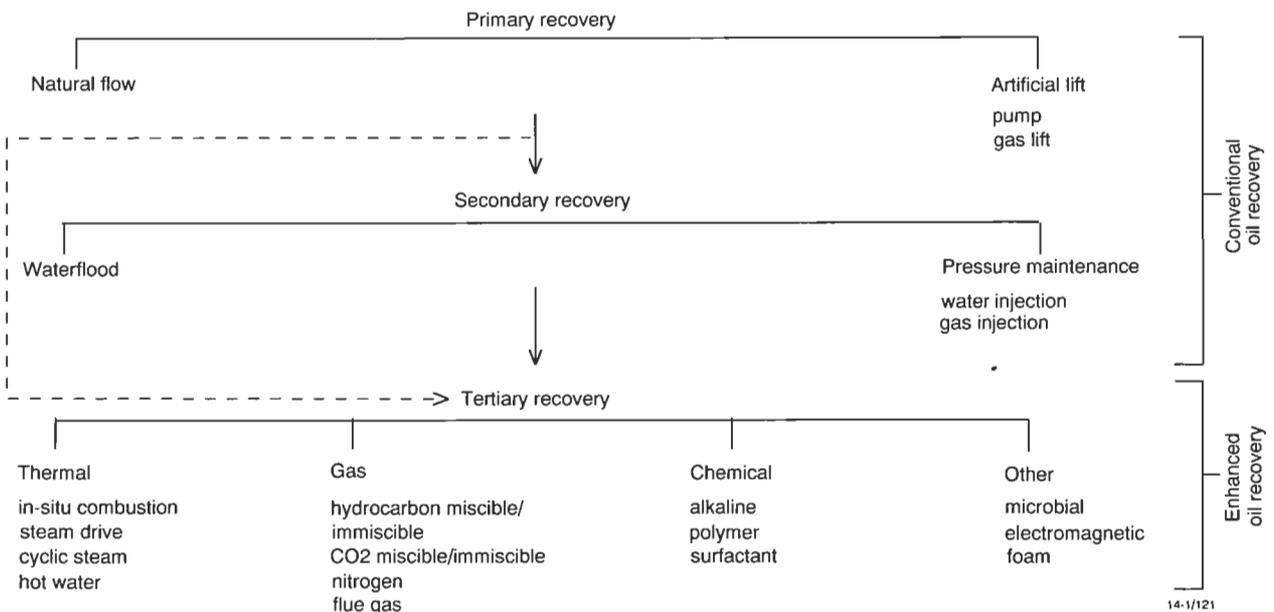
For Australia's reservoirs discovered before June 1988, the "target" for EOR (i.e. oil-in place minus reserves) is estimated as 3914 million barrels. Of this, 2346 million barrels is offshore where miscible or immiscible processes appear to be most promising. 1568 million barrels is onshore, where miscible/immiscible gas flooding is applicable and where, in the event of technical or economic improvements, waterflooding with polymers may be applicable. A preliminary and optimistic estimate of economically recoverable oil at current prices is 709 million barrels. Results for individual fields have been given to the operating companies concerned.

A major issue of concern is premature abandonment of existing wells and facilities, which can preclude future EOR opportunities.

Introduction

Enhanced oil recovery (EOR) refers to the additional oil which can be produced from a reservoir above the primary and secondary recovery. Primary recovery refers to the use of natural energy (expansion, gravity, gas or water drive) to produce oil. Secondary recovery refers to the use of additional energy (injection of water or gas) to increase production. Table 1 shows the types of technology used in EOR.

Table 1. Enhanced oil recovery technologies.



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Since the early 1980s, interest in enhanced oil recovery has increased as the potential for this technology was recognised. In April 1986, at the initiative of Mr John White, then Assistant Director of the Petroleum Branch

It was decided to attempt a comprehensive study of all oil fields which would cover the subject better than a selective, detailed study of a few major, or typical fields. Following this decision, the sheets setting out available data were sent to oil companies and/or State governments throughout Australia, for correction and updating of the basic data.

It was anticipated that the study would:

- Screen all known Australian petroleum accumulations to identify those fields that have potential for improving

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recovery through EOR.

- Describe such selected fields in terms of physical characteristics pertinent to EOR studies.
- Determine the best EOR process(es) applicable to the selected fields.
- Estimate additional oil recoverable through such process(es) at various pricing levels.
- Consolidate data derived as above to enable an estimate to be made of potential, at different oil price levels, of EOR processes.

The study paralleled the US National Petroleum Council's (NPC) 1976 and 1984 studies of EOR potential in the US. This was to ensure consistency and to make fullest use of the enormous amount of expertise involved in the NPC study. Details of the study are given in Wright & others (1990).

Data compilation

Compilation of data was the most time-consuming and the most valuable part of the project. Data were received directly from State mines' departments or oil companies, or compiled by BMR personnel from State or BMR sources. In a few cases, up-to-date data from oil companies were already available. No data were included for discoveries after June 1988, for a few small fields for which insufficient data were available, and some secondary reservoirs in major fields. The result of the compilation is the most comprehensive collection of reservoir data to date for Australian oil fields.

Data included were the minimum necessary to define the fields in the broadest sense, for input to the screening and evaluation models. For example, permeability variations, faulting, and fracturing data could not be included. The data requested is shown in Table 2.

Table 2. Example of technical data input sheet.

Accumulation	Oil type
Producing status	Wax content
Basin	Bubble point pressure
Formation	Gravity
Elevation	• Pour point
Closure area	Viscosity
Depth (top)	Water salinity
Depth (gas oil contact)	Water resistivity
Depth (oil water contact)	Drive mechanism
Thickness (gross)	Gas cap (yes/no)
Thickness (net)	Formation volume factor
Porosity	Gas oil ratio
Permeability	Oil initially in place
Water saturation	Initial recoverable reserves
Formation pressure	Cumulative production
Temperature	

The data are not exact; that is, in many cases values of average formation net thickness have to be altered to achieve a match with oil in place. The data are complete in the sense that all fields have an assigned value for each parameter even when fluid data, or other properties, have to be interpolated from data from similar or nearby fields in the same formation. *Average* oil saturation after waterflooding was back-calculated from reserves and

oil-in-place data.

The compiled results are summarised in Figures 1 to 7 and in Table 3, which shows median values for Australian reservoirs.

Table 3. Australian reservoir median parameters.

Depth	4950 feet
Area	500 acres
Thickness (gross)	33 feet
Thickness (net)	17 feet
Porosity	17.5%
Permeability	16 millidarcys
Water saturation	40%
Pressure	2300 psia
Temperature	195°F
Oil gravity	44.5°API
Viscosity	0.85 centipoise
Recovery factor	15%

Technical evaluation

Current EOR field applications

A full list of EOR technologies is given in Table 1, which includes exotic processes in the research stage. A technical breakthrough in any of these technologies cannot be ruled out (Carroll & Linville, 1986). However, this study is focused on the currently applied technologies (called the "implemented technology" case), with an "advanced technology" case (with hypothetical future technology improvements) also being considered. These corresponded to the NPC "implemented" and "advanced" cases.

The only Australian field application of EOR as a commercial process is in the Cooper Basin by SANTOS — the very successful ethane flooding of the Tirrawarra and Moorari fields which increased reserves by 18 million barrels (Williams, 1989; Rodda & Paspaliaris, 1989; Petroleum Resources Branch, BRS, 1993). A possible EOR project in the Jackson field in the Eromanga Basin is also under investigation. Cyclic LPG storage by Esso in the Barracouta M-1 oil reservoir in the Gippsland Basin undertaken for logistic reasons has incidentally resulted in improved recovery efficiency by reducing the residual oil saturation (Williams, 1986). Investigations into EOR in the Flounder field have also been conducted (Younes, 1987). Field trials of microbial EOR were undertaken by TMOC in the Alton field in February 1989 (Sheehy, 1990).

In contrast, overseas applications of EOR are now numerous. In the USA over 2000 EOR projects were active in the period 1980–1992. As at 1 January 1992, EOR contributed 761 000 barrels per day (b/d) of crude (or 10%) of US oil production from 248 projects. This is an increase from just over 300 000 b/d in 1980. Other projects are active in Venezuela (35 000 b/d), Canada (153 000 b/d of which hydrocarbon miscible projects contribute 127 000 b/d), and other countries shown in Table 4. Other countries not listed, including Japan, Denmark and Norway, either have active projects or pilot studies in progress.

Most of the EOR production in the US is contributed by thermal EOR, particularly in California where heavier crudes are common (the Shell Oil Belbridge project

produces 101 000 b/d alone). Carbon dioxide miscible flooding predominates in the Permian Basin of Texas.

It is significant that a wide variety of process types are in operation worldwide, reflecting the wide variations of reservoir and fluid types, and the availability of flooding agents.

Table 4. Some worldwide active EOR projects, 1990.

Country	Types
Austria	Caustic, steam
Canada	Alkaline, CO ₂ miscible, caustic, hot water, <i>in situ</i> combustion, foam, hydrocarbon miscible, polymer, steam
Columbia	Steam
Congo	Steam
England	Micellar-polymer
France	Polymer, steam
Hungary	CO ₂ , <i>in situ</i> combustion
Indonesia	Micellar-polymer, steam
Libya	Hydrocarbon miscible
Trinidad	CO ₂ immiscible, CO ₂ cyclic, steam
USA	Steam, <i>in situ</i> combustion, hot water, micellar-polymer, polymer, caustic/alkaline, hydrocarbon miscible, hydrocarbon immiscible, CO ₂ miscible, CO ₂ immiscible, nitrogen, flue gas, carbonated waterflood
Venezuela	Gas, steam
West Germany	Hot water, polymer, steam

Source: International Petroleum Encyclopedia, 1991

Screening criteria

The screening criteria considered were obtained from the following references:

- (1) National Petroleum Council, 1976;
- (2) Brashear & Kuuskraa, 1978;
- (3) National Petroleum Council, 1984 — Implemented Technology Case;
- (4) National Petroleum Council, 1984 — Advanced Technology Case; and
- (5) Carbon dioxide miscibility criteria — 11 published criteria (see Wright & others, 1990).

It was decided to use criteria (3) and (5), with (4) (a hypothetical case with future research advances) as a sensitivity.

Thermal recovery

The potential for thermal recovery exists for heavy crude oils which cannot be produced at the original reservoir pressure and temperature. The viscosity of the oil can be dramatically decreased by raising the reservoir temperature, thereby enabling the oil to flow more readily towards the producing well. The heat is provided by steam or hot water injection, or by burning some of the oil in place

(*in situ* combustion). Steam injection is the predominant form of thermal recovery.

Steam flooding

The reservoir is usually steam-stimulated (by alternately injecting and producing steam in the same well) to increase injectivity before a steam-drive commences. The steam drive itself consists of continuous injection into one well and production from surrounding wells. Very high recovery factors can be achieved because of the creation of a light solvent bank by the steam. However, close well spacings (five acres/well) are required to ensure effective heating of a large portion of the inter-well volume.

***In situ* combustion**

If air is injected into an oil reservoir, the oil near the wellbore can ignite (or be ignited) and burn. As more air is injected, the burning zone moves through the reservoir away from the well, distilling the oil ahead of it. The burning oil forms combustion gases and vaporises water in the reservoir to form steam. The burnt portion of the oil is mainly coke — the rest being distilled by the heat. In order to control the burning process, water injection is combined or alternated with air injection.

Applicability

In general, thermal processes are most applicable to those reservoirs which contain heavy oil. A typical criterion is an API gravity between 10° and 35°. As almost all Australian crude oils are lighter than this (Fig. 1), the process would not seem to be applicable to Australian crudes. The pay zone thickness minimum (20 feet) is also a major limitation (Fig. 2), as is the porosity (minimum 20%) (Fig. 3). However, the possibility of *in situ* combustion of light oils has recently been proposed as an effective EOR method for remote areas, where the cost of importing chemicals could be prohibitive.

One advantage of thermal methods is that the cost of heating is tied to the cost of oil, so that when the price of oil decreases the cost of heating also decreases.

Chemical methods

Chemical EOR (including polymer flooding, surfactant flooding, and alkaline flooding) is used to lower the viscosity or interfacial tension of oil, or to increase the

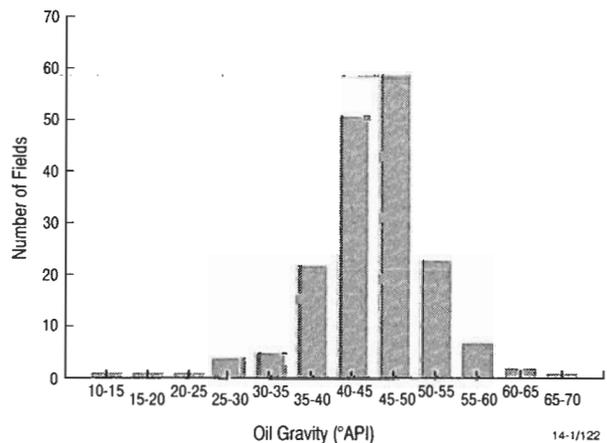


Figure 1. Oil gravity.

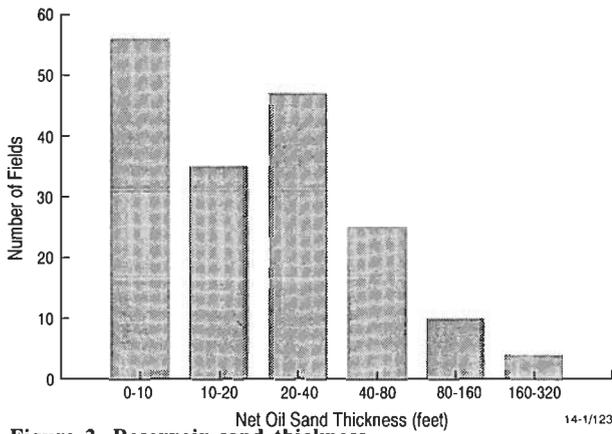


Figure 2. Reservoir sand thickness.

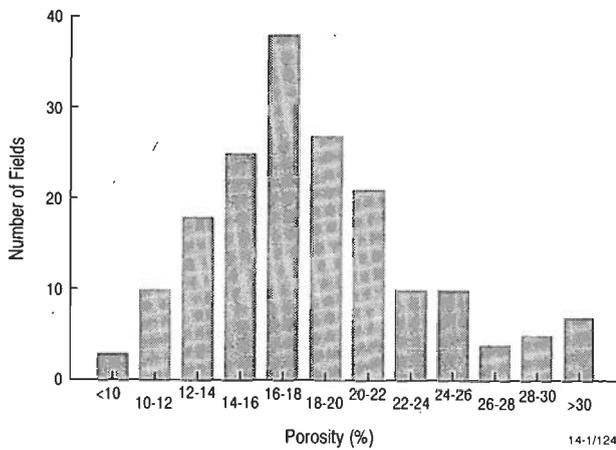


Figure 3. Reservoir porosity.

swept volume of the reservoir. In general, chemical costs can increase independently of the price of oil, so the process' economics need to be carefully scrutinised.

Polymer flooding

The objective of polymer flooding is to increase the viscosity of injected water to increase the sweep efficiency during the displacement of oil by water. Water-soluble polymers, either synthetic or biologically produced, are mixed with injection water. The polymer may also have the effect of reducing the permeability of the formation to water, which also improves the sweep efficiency.

Alkaline flooding

The objective of alkaline flooding is to create a reaction between injected alkaline chemicals and crude oil. The reaction forms surfactants which can reduce interfacial tension, alter the formation wettability, and result in emulsification of oil.

Surfactant flooding

The objective of surfactant flooding is to reduce the interfacial tension between oil and water, although the formation of emulsions is also important. Surfactants, such as sulphates and sulphonates, are mixed with polymers and the surfactant slug is injected into the reservoir followed by drive water.

Applicability

Alkaline flooding requires a highly acidic crude. The acid number, measuring the surface active material content of oil, is related to the crude gravity. This must be less than 30° API in order to have an acid number high enough to ensure effective alkaline flooding performance. As nearly all Australian crudes are lighter than 30° API (Fig. 1), the apparent possibility of using alkaline floods is limited.

In general, the polymer flooding process is limited by conditions which tend to destroy the polymer, or decrease its effectiveness. Salinity reduces the mobility improvement resulting from polyacrylamide flooding. Temperature combined with divalent cations can reduce the stability of both polysaccharides and polyacrylamides. Although most Australian formation waters are very fresh, the temperature maximum of 200° F limits the applicability of the process (Fig. 4). Polymer flooding is ideally suited to reservoirs where the waterflood sweep efficiency is low. It does not decrease the residual oil saturation in the swept volume.

Surfactant flooding is also limited to fields with temperatures less than 200° F, as the polymers used with the surfactant are not stable above this temperature.

Research since the time of the study has increased the polymer temperature maximum, bringing the advanced technology case closer to reality.

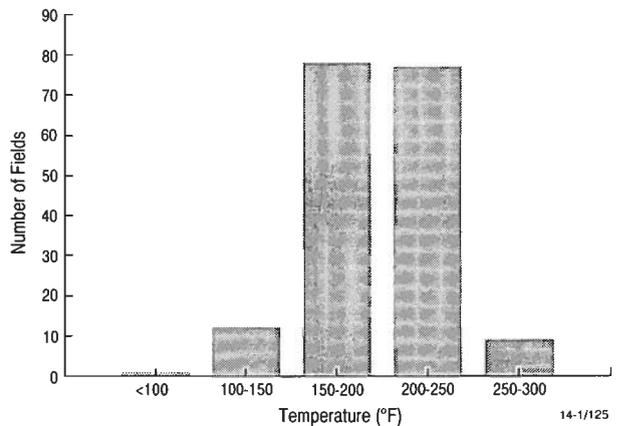


Figure 4. Reservoir temperature.

Miscible and immiscible flooding

In miscible flooding, a fluid such as LPG or carbon dioxide is injected into a reservoir. The miscible fluid is either directly miscible with the oil in the reservoir, or extracts components from the oil which forms a bank of liquid miscible with both the reservoir and the injected gas-carbon dioxide, hydrocarbon gases, LPG or nitrogen (for deep, high-pressure reservoirs). Immiscible flooding with carbon dioxide is also used, as even without miscibility the carbon dioxide swells the oil and reduces its viscosity. Miscible floods are often alternated with water floods to improve the sweep efficiency of the process, as the miscible fluid is generally less viscous than the oil and tends to "finger" through the oil, giving a sweep efficiency much less than 100%.

Applicability

Carbon dioxide miscible flooding depends on the availability of a large volume carbon dioxide source: either a carbon dioxide reservoir, or from flue gas or separator gas. In addition, for miscible flooding, the reservoir temperature, pressure and oil composition must be such that the oil can be miscibly displaced. High pressures and light oils promote miscibility. Shallow reservoirs with low initial reservoir pressure may require rich hydrocarbon gas mixtures to achieve miscibility. Higher-pressure reservoirs may allow miscibility with mixtures of carbon dioxide and nitrogen, as in flue gas, or with nitrogen alone (Fig. 5).

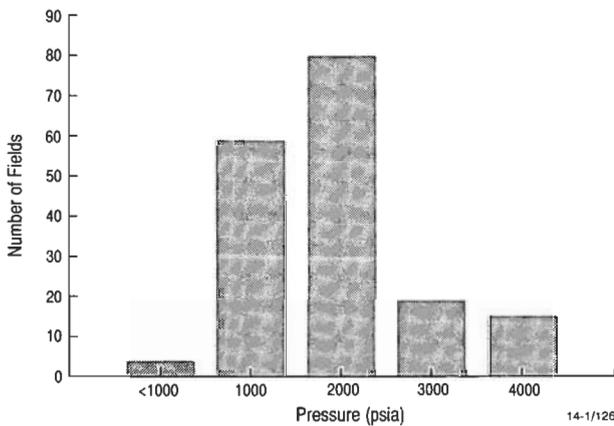


Figure 5. Reservoir pressure.

Screening for miscible methods

Considerable research effort has been put into determining the conditions for miscibility of carbon dioxide and other fluids with oil. These conditions are normally in the form of "minimum miscibility pressures" as a function of fluid composition and reservoir temperature. As a general comment, it appears that other factors than temperature, pressure and fluid composition may play an important role in determining whether lowering of the residual oil saturation throughout the reservoir can be achieved; the rate of diffusion of the flooding agent through the water phase also seems to be important. All the reservoirs in the database were screened using eight of the most readily applicable of the eleven correlations considered. A "majority vote" from the correlations for miscibility was used

as the criterion for the suitability of miscible flooding. For further information and details of the references, see Wright & others (1990).

Other miscible gases and immiscible floods were not explicitly considered in this screening process. However, ethane, or ethane enriched with LPG, is a possible and available flooding agent in many parts of Australia. It was assumed the oils miscible with carbon dioxide would also be miscible with appropriately enriched ethane.

Comments on technical screening

The results of screening runs for each field are available only to operating oil companies or to the State Mines Department which supplied the data. Because of confidentiality requirements the data are not available to any other parties.

Table 5 shows the "target" oil-in-place for each process using the 1984 NPC "implemented technology" screening criteria. The "target" is the total oil-in-place remaining, after extraction of primary and secondary reserves, in reservoirs for which a given process appears applicable. Only a fraction of the "target" oil-in-place can be recovered because of the limited sweep efficiency for each process and, in the case of polymer flooding, the inability of the process to reduce residual oil saturation. Table 6 shows the same data for the 1984 NPC "advanced technology" case.

In Tables 5 and 6, in addition to the screening parameters listed, reservoirs were excluded (see Fig. 6):

- from the miscible flooding total, if a large gas cap existed (some exceptions were made in specific cases); and
- from the polymer, surfactant and alkaline total, if strong or moderate water drive existed.

Miscible gas processes

Miscible processes apply to the largest "target" oil-in-place of any process. Some Australian crudes cannot achieve miscibility with carbon dioxide at reservoir temperature and pressure. However, because of the difficulty in reliably determining miscibility criteria theoretically, laboratory tests should be used to confirm or exclude miscibility. The results of this study refer to miscibility with carbon dioxide only. Miscibility with other flooding agents (such as ethane) have not been checked.

Table 5. Target oil for implemented^a technology case.

Process and number of applicable reservoirs	Original oil-in-place in applicable reservoirs	Primary/secondary reserves in applicable reservoirs	"Target" oil-in-place
			(million stock tank barrels)
Miscible gas flooding ^b (78)	5904	3602	2302
Surfactant flooding (35)	277	358	219
Polymer flooding (39)	292	61	231
Alkaline flooding (2)	3	1	2
Steam flooding (2)	9	4	5
<i>In situ</i> combustion (2)	9	4	5
Cumulative total target oil (single process per reservoir):			
Miscible gas flooding (78)	5904	3602	2302
Polymer flooding (23)	151	12	139
Others (0)	—	—	—
No process applicable (76)	2059	586	1471
Total Australian oil-in-place	8114	4201	3913

^a Current technology limits

^b Assumes carbon dioxide or equivalent miscibility

Table 6. Target oil for advanced^a technology case.

Process and number of applicable reservoirs	Original oil-in-place in applicable reservoirs	Primary/secondary reserves in applicable reservoirs	"Target" oil-in-place
		(million stock tank barrels)	
Miscible gas flooding ^b (78)	5904	3602	2302
Surfactant flooding (74)	560	106	454
Polymer flooding (74)	560	106	454
Alkaline flooding (2)	3	1	2
Steam flooding (25)	291	117	174
<i>In situ</i> combustion (44)	6165	3675	2490

^a Hypothetical future technology advances

^b Assumes carbon dioxide or equivalent miscibility

Immiscible gas floods are also common in the United States. No estimate of the recovery from these processes, which may have considerable potential, is made in this study.

Chemical flood processes

Note that polymer and surfactant flooding have approximately the same "target" oil-in-place, because of similar screen criteria. The temperature limitations result in the process being inapplicable to most offshore reservoirs, so the "target" oil-in-place is smaller than for miscible flooding.

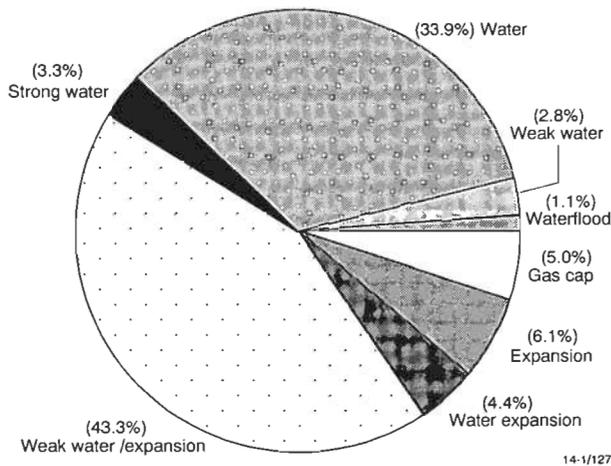


Figure 6. Reservoir drive types.

Alkaline flooding is unsuitable, based on API gravity correlations, for most Australian crudes, resulting in a low "target" oil-in-place. However, specific tests of crudes have not been carried out to check this assertion.

Thermal processes

The "target" oil-in-place for both steam and *in situ* combustion applies only to a very small group of relatively heavy oil reservoirs. However, as mentioned above, thermal EOR may not necessarily be unsuitable for light oils. It may be appropriate in the future for remote applications where other flooding agents are difficult to import.

General comments

Note that most Australian reservoirs have moderate permeabilities (Fig. 7) but also have very low *in situ* oil

viscosities (Table 3). Most of the oil-in-place is, however, concentrated in a few very high-permeability offshore reservoirs, with strong water-drive. The median recovery factor is very low (15%) compared to the oil-in-place weighted average (51.8%). The reason appears to be that the drive mechanisms (Fig. 6) in many fields are insufficient in spite of the low crude viscosity to achieve high recovery factors. As a result, additional secondary recovery (waterflooding or gas injection) combined with infill drilling may have some economic benefits. Secondary recovery is still relatively rare in Australia.

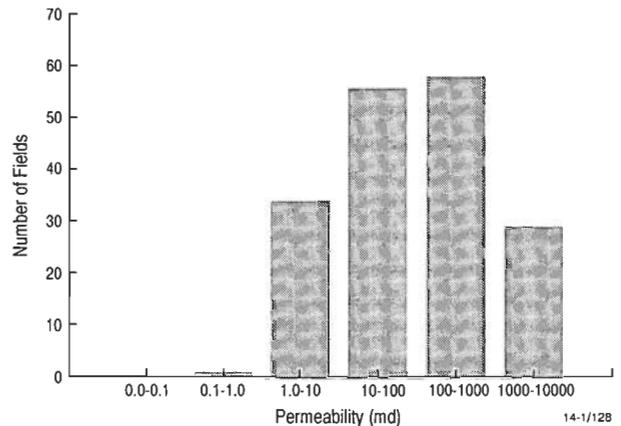


Figure 7. Reservoir permeability.

Reservoir simulation and economic evaluation

Technical/economic models used

The second objective of the study is to assess the additional oil which may be recovered under various improved recovery techniques at selected oil pricing levels. For this purpose, five predictive models were made available to BMR. These models were developed by Scientific Software-Intercomp for the US Department of Energy, and were used in the NPC's 1984 survey of US EOR potential. These models are listed below (US Department of Energy, 1986a-e):

- the Carbon Dioxide Miscible Flood Predictive Model,
- the Chemical Flood Predictive Model,
- the Polymer Flood Predictive Model,
- the Steamflood Predictive Model, and

- the *In situ* Combustion Predictive Model.

In each of the models, an oil rate-versus-time function for a single pattern is computed using theoretical simulation techniques. The results are passed to the economic calculations. To estimate the effect of multi-pattern project behaviour on cash-flow a pattern development schedule is required.

Details of the models, which are rather complex, are given in the referenced reports (US Department of Energy, 1986a-e).

Technical and economic data input

The technical data were supplied from the spreadsheet (see Data Gathering) build up based on the input data sheets used for the technical screening runs. Macros were written to transfer the data from the spreadsheet to the input file for the evaluation models.

The economic data were supplied using the macros provided by Thomas Petroleum Consultants. Because there is no established carbon dioxide supply system or other EOR infrastructure in Australia, major assumptions had to be made about the logistics, processes, and prices based on available information. It must be stressed that these assumptions make the economic results very subjective.

Oil price

Oil prices of US\$12/barrel, US\$20/barrel (base case), and US\$50/barrel were assumed with an exchange rate of US\$0.80 = A\$1.00.

Well-spacing

It was assumed that, given the existing well-spacing in each field, adequate EOR could be achieved without additional drilling. Drilling of even a small number of extra wells to reduce the well-spacing was found in some trial field cases to have a major adverse effect on process economics. The need for infill drilling and its benefits and costs in Australian conditions, were impossible to check in a broad study of this kind. The individual fields were not all checked to optimise well-spacing. Conversion costs (for producers converted to injectors) were not included. It was also generally assumed that half the wells in the field would become injectors, and the pattern area was based on a five-spot.

Offshore EOR is even more affected by the impact of infill drilling as additional platforms might be required. As a result, it was again assumed that conversion of existing wells, rather than new drilling, would provide injection facilities. This appears to be the most likely technique for offshore EOR in its early development.

Transportation

In a general study of this kind, it is assumed that oil transportation costs are similar to those of a line owner.

Miscible gas

It is assumed that the miscible gas is supplied from either a local cheap source of carbon dioxide, or local sources of ethane. Costs were calculated for carbon dioxide from a gas treatment plant and from flue gases. The higher price of flue-gas derived CO₂ virtually eliminates carbon

dioxide (required at approximately 10 kscf/barrels produced oil) from consideration for an oil price of US\$20/barrel. The alternative is to assume a local source of suitably enriched ethane and assume that most of the ethane can be recovered from the reservoir during or after oil depletion. Two sensitivities for gas price were used.

Results

Some of the critical factors in the economic analysis are crude price, infill drilling assumptions, and availability of flooding agents.

Carbon dioxide miscible flooding

Most of the fields with reasonably large oil-in-place (more than 5 million barrels) which met the miscibility criteria, were economic at a discount rate of 15%. Because the infrastructure cost is a larger burden for small fields (less than 5 million barrels), such fields were generally very uneconomic. Grouping of small fields with common facilities is an obvious solution, but was not checked in this study, although some sharing of pipeline costs was included. For offshore fields, most of which met the miscibility criteria, economics were generally attractive. However, the availability of sufficient flood gases for large offshore reservoirs is an important issue. It should be emphasised, however, that in stratified reservoirs unit-by-unit flooding should be possible. For all reservoirs recycling of produced miscible gas will be possible. The major issue for large, unstratified offshore reservoirs is the supply of enough gas to saturate the entire reservoir. Probably in the long term the availability of gas from coal-fired power stations or undedicated ethane production may assist in these cases. The low residual oil saturation of many offshore reservoirs is counteracted by their excellent permeability which is favourable to efficient EOR.

Figure 8 shows the results. At US\$12/barrel, 581 million barrels incremental recovery is possible. This increases to about 709 million barrels at US\$20/barrel and 750 million barrels at US\$50/barrel. A doubling in gas price decreased the reserves at \$20/barrel to 570 million barrels. The relative lack of sensitivity to oil price arises from the field size distribution, and the technical restrictions on EOR, which result in several fields not being candidates at any oil price. By contrast, in the US NPC study

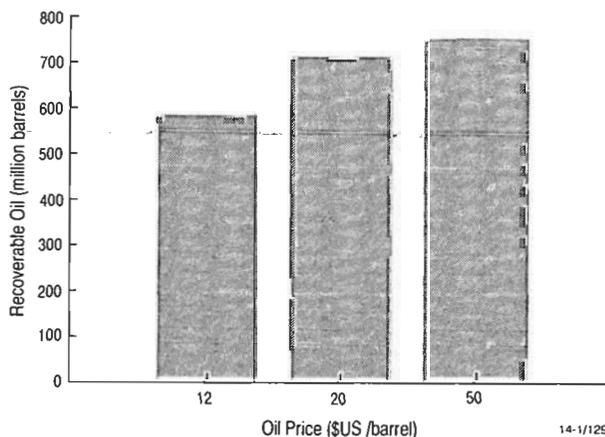


Figure 8. Recoverable oil by enhanced oil recovery versus oil price.

(National Petroleum Council, 1984), the number of candidate fields increases more uniformly with oil price. When the price of the miscible flooding agent doubled, the incremental recovery for the US\$20/barrel case reduced to 570 million barrels.

Polymer/surfactant flooding

The polymer flooding model used gave incremental economic results which were negative for the reservoirs selected as being technically suitable for existing polymers (i.e. in the correct temperature and salinity range). These results were also observed in the example run referred to by the US Department of Energy (1986b). In other words, it was found to be preferable to enlarge or develop other waterfloods rather than add polymer to an existing waterflood, because the additional oil recovery did not justify the polymer cost.

However, the economics of polymer flooding (*versus* doing nothing) were also investigated. It was assumed that no wells were drilled, and that the reservoirs were suitable for waterflooding. At US\$20/barrel, about 55 million barrels was recovered economically (secondary plus EOR recovery).

Other flooding agents

No simulations or detailed economics for alkaline, steam and *in situ* combustion were calculated. For the reasons given previously, these processes appear to be generally inapplicable in Australia.

Main findings and conclusions

The study of EOR applications requires detailed knowledge of reservoir heterogeneity and detailed *in situ* behaviour of hydrocarbons. Only overall conclusions can be made with the limited general information available on each field in this study, the scarcity of Australian field trials, and the early stage of research into EOR.

The "residual" or "target" oil-in-place (million barrels) for EOR in discovered Australian fields is:

	Initial oil-in-place	Initial reserves	"Residual" oil-in-place
Onshore	2085	517	1568
Offshore	6030	3684	2346
Total	8114	4201	3914

Primary and secondary recovery is thus expected to produce only 51.8% of the total oil-in-place in discovered reservoirs. Onshore, only 24.8% will be produced. This leaves 3914 million barrels of oil-in-place or about 20 years' production at Australia's total oil production rate.

The major perceived scope for EOR in discovered oil fields in Australia lies in miscible gas processes. It is estimated on a very preliminary basis that about 709 million barrels of reserves could be recovered using this process at an oil price of US\$20/barrel. However, these results will depend heavily on the availability and cost of miscible gases. Ethane and carbon dioxide are the most readily available; flue gas or nitrogen may be suitable for some deeper reservoirs.

Polymer and surfactant floods may have applications in

some fields where reservoir conditions result in significant bypassing of oil and where waterflood operations are already in progress. Temperature limitations prevent their application in most large Australian fields, and economics also hinder applications in the reservoirs in this study. However recent improvements in the temperature stability of polymers are promising.

Because of Australian crude properties, it is unlikely that alkaline flooding or steam flooding will be of major interest in the hitherto discovered oil fields. *In situ* combustion of light oils may have applications in remote areas where miscible gases are unavailable.

Microbiological, electrical, and other EOR processes are in their infancy. As research progresses, they may find widespread applications. However, no assessment of their future promise can be made based on current limited field trials.

A key factor in the economics of EOR for depleted fields is the existence of infrastructure and wellbores to allow continued production with favourable economics. Thus, a major issue of concern for EOR in Australia is the life of production wells and facilities. As most oil is offshore, platform abandonment may lead to the loss of EOR potential, and the EOR issue should therefore be taken into account by industry as part of the platform abandonment process.

Acknowledgements

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A preliminary overview of groundwater quality in the Northern Territory¹

J.S. Childs² & P.S. McDonald³

Approximately 25 000 water bores are registered under the Northern Territory Water Act. Entry of bore data (including water quality data) into a computer data set has been proceeding for several years. Sufficient entered data for meaningful statistical output is only available for the arid (southern) zone. Preliminary

examination of the status of arid zone bores indicates that, while failure to obtain adequate yield is the major reason for unsuccessful drilling, unsuitable water quality has resulted in the rejection of 26% of bores obtaining an otherwise sufficient supply for community water supply purposes.

Introduction

The Water Resources Division of the Northern Territory Power and Water Authority has been involved in all stages of groundwater exploration, assessment, development and management in the NT over several decades. Water samples for a variety of both public and private purposes, including statutory surveillance, community water supply, industrial and agricultural purposes, are processed by, or through, the Division.

Since 1986, an experienced technical officer has been assigned to enter water analysis results into a computer data set. All known water chemistry data have been entered, together with a portion of bacteriological data.

Data extraction has, however, been extremely limited. A recent decision to move to commercial data management software (HYDSYS water quality software) has enabled limited database access to the data for checking and preparation purposes. The summaries and statistics below come from that initial view of data. In due course, when the new software has been installed and the data converted, the Northern Territory's data set will be available in a range of common computer formats.

This paper aims to present:

- a brief overview of the water quality data holdings; and
- some preliminary results of the arid zone subset of the data, which is in a more advanced stage of data entry than that of the northern region.

Water quality data in the Northern Territory

The computerised data set contains physical, chemical, and bacteriological results for both surface water and groundwater sampling locations. The data currently resides on a VAX/VMS platform as a hierarchical indexed file with variable length records. Data input is through a purpose-written Pascal program.

Data extraction was performed using the VAX/Datatrieve database language operating both on the hierarchical file and on a flattened version of the data file. The contents of the data set may be summarised as follows:

Sample type	Number of samples analysed	Comment
Overall program	75 000	Average of 13 parameters per analysis
Groundwater	50 000	11 000 locations
Surface water	25 000	1500 locations, including sewage
Bacteriological	15 000	7000 surface water 8000 groundwater

Data have been collected since the 1950's, with a more systematic collection program developed in the 1960's. A time distribution of groundwater analyses (excluding bacteriological) is shown in Figure 1. Sample collection and processing peaked in the period 1981-1985, with a decrease in activity since that time due to both reduced levels of overall drilling activity, and financial constraints on sample collection and analysis (which have had the effect of prompting better targeting of sample collection programs).

Some seventy-three different parameters have been measured, but only around twenty have been monitored routinely. Table 1 lists these parameters together with the number of sample analyses. For some parameters, values (and hence units) are not presented, as it was found that more than one unit has been used to record analyses, and corrections to reach uniformity are incomplete.

Both overall and exclusively arid zone data are shown. Average values are also included where these were able to be calculated from the number of samples shown, but as checking is incomplete, are considered to be indicative only. More rigorous statistical examination would be premature.

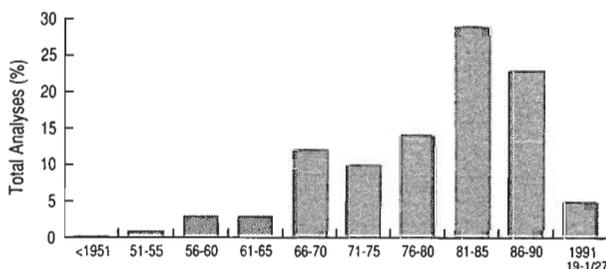


Figure 1. Time distribution of Northern Territory groundwater chemistry analyses.

¹ Paper presented at the conference on "Aquifer at Risk: Towards a natural groundwater quality perspective", Canberra, ACT, February 1993.

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Table 1. Parameter types, and selected average values for all Northern Territory registered water bores.

Parameter	Number of samples		Average value (mg/L except as indicated)	
	All NT	Arid zone	All NT	Arid zone *
Acidity (field, pH units)	2495	128	8.4	7.0
Acidity (laboratory, pH units)	33516	13580	8.1	7.6
Alkalinity (total)	31092	12847	235	286
Aluminium	483			
Ammonia	611	51	33.9	1.32
Arsenic	1199	49		
Barium	1		0.02	
Bicarbonate	28972	14234	344	351
Bicarbonate alkalinity	3767		170	
Biochemical oxygen demand	34	25		
Boron	46	24	0.22	0.34
Bromide	38		0.02	
Cadmium	2446	20		
Calcium	31112	12953	73.8	102
Carbonate	65	3	35.7	2.0
Carbonate alkalinity	3385		0.15	
Chloride	33361	14429	513	857
Chloride (as NaCl)	20206	9466	870	1413
Chromium	429			
Cobalt	1285			
Colour (Hazen Units)	82	31		
Conductivity	2225	673		
Conductivity (lab, μ S/cm)	32141	12508	2346	3549
Copper	6386	40		
Cyanide	37			
Dieldrin	1			
Dissolved oxygen	18	9	3.7	4.6
<i>E. Coli</i>	2871	231		
Faecal streptococci	3630	631		
Faecal coliforms	3936	2102		
Fluoride	26538	12791	0.9	1.3
Hardness (carbonate)	2172	92	149	31.5
Hardness (non-carbonate)	1998	77		
Hardness total (calculated)	1492	179.67		
Hardness (total)	30665	14258	531	741
Hydroxide alkalinity	2440		0.19	
Iron	25578	9803		
Lead	5171	61		
Magnesium	31037	12945	108	96.6
Manganese	7557	53		
Mercury	27			
Nickel	1601	20		
Nitrate (as Nitrate)	27952	12449	19.8	39.1
Nitrate/Nitrite	1816			
Nitrite	885			
Nitrogen (organic)	29	21		
Non-filterable residue	41			
Oils and grease	1		20	
Orthophosphate	1410	122	0.96	3.91
Phosphorus (total)	324	5	0.15	1.25
Plate Count	1250	238		
Potassium	29519	12789	19.3	34.7
Radium 226	3981	71		
Redox potential	567			
Residue (filterable)	1200		232.53	
Residue (volatile)		25		10.8
Selenium	615	6		
Settleable matter	8		0.18	
Silica	23445	10581	37	46
Silver	23			
Sodium	29700	12871	226	400
Sulphate	31018	13033	428	351
Suspended solids	403	269	566	675
Total dissolved solids	8217	1433	995	1940
TDS (by evaporation at 180°C)	17839	11454	1523	1907
Temperature	5566	1653		
Total coliforms	6691	2246		
Turbidity field	7			
Turbidity laboratory	983	49		
Uranium	4426			
Volatile residue	38			
Zinc	6495	38		

* See text for definition of arid zone.

Status of bores in the arid zone of the Northern Territory

Under Northern Territory water legislation, drillers are required to submit a summary of drilling and construction details for each water bore drilled to enable registration of the bore, and to provide a sample of any water struck during drilling for analysis. Registration provides a unique

identifier (registration number) for each bore entered into the system. Although a computerised data set of the 25 000 water bores registered exists for the whole of the Northern Territory, this data set currently only includes the purpose/use/success-failure/yield data for the southern administrative region. This region roughly coincides with the arid zone of the Northern Territory (Fig. 2).

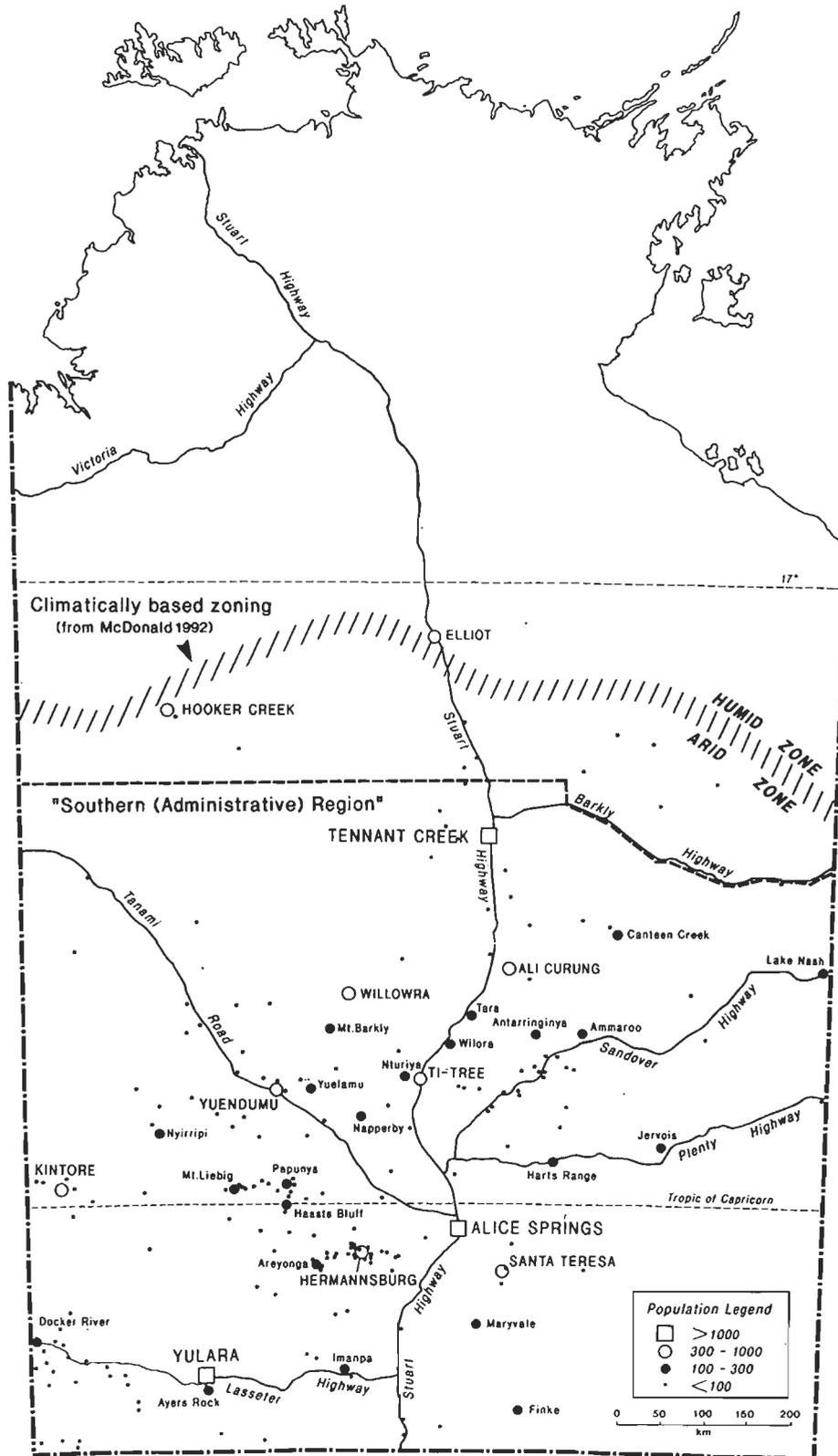


Figure 2. Arid zone definition of the Northern Territory.

Each of the approximately 10 000 bores in the southern region has been classified as to its:

- intended primary purpose, summarised in Table 2; and
- status, in terms of its success in meeting the intended purpose (Table 3).

Table 3 shows details of the 57% (5753 bores) where status criteria can be applied. Success/failure status can only be conferred where this information is known or relevant. It is worth noting that while supplies may be rejected on the basis of unacceptable quality in the water samples obtained during drilling, experience has shown that these samples are not always representative of long-term pumping supply.

Excluded from Table 3 are bores comprising 43% of the data set, which are:

- for investigation/monitoring, and mineral purposes (29% of total); and
- of unknown purpose or status (14% of total).

Spatial variability of Northern Territory groundwater chemistry

Sufficient location data now exists in the data set to fix the position of most registered water bores in the Northern Territory with reasonable precision. In the Northern Territory's southern region, key groundwater chemistry parameters (measured in milligrams per litre) lie in the ranges:

• Total dissolved solids	45	to	79 500
• Nitrate (as NO ₃)	0	to	955
• Fluoride	0	to	50

By grouping bores by 1:250 000 scale map sheet and averaging the most recently measured salinity value for each bore, the broad spatial distribution of salinity shown in Figure 2 was derived. The three areas of elevated TDS are:

- that part of the Barkly Tableland which overlies evaporite sequences in Cambrian limestone aquifers;
- part of the Precambrian Arunta Block characterised by internal drainage to salt lake and playa systems; and

Table 2. Primary purpose of registered water bores in the southern region of the Northern Territory.

Purpose of drilling	Number of bores	Percentage of total	Number of salinity determinations recorded ¹		
			≥1	≥5	≥10
Stock	4103	40%	2321	140	10
Investigation ²	2548	25%	1170	167	20
Community supply	936	9%	547	207	83
Domestic	862	8%	438	50	4
Mining ³	453	5%	141	2	0
Construction ⁴	432	4%	213	7	0
Irrigation	157	2%	104	21	4
Purpose unknown	716	7%	266	8	1
TOTAL	10207	100%	5210	602	122

¹ Number of bores within the purpose class for which the stated range of salinity determinations (measured as total dissolved solids) are recorded.

² Predominantly investigations for community water supplies or for regional baseline assessment. Includes monitoring bores.

³ Drilled for mineral exploration and registered as a water bore when groundwater data available.

⁴ Primarily drilled for road construction and maintenance.

Table 3. Drilling success rates, southern region of the Northern Territory.

Purpose of drilling	Number (where status known)	Successful % ¹	Unsuccessful (insufficient yield) %	Unsuccessful (poor quality) %	Unsuccessful quality ² (% of yielding bores)
Stock	3681	64	23	8	12
Community supply ³	871	44	41	15	26
Domestic supply ⁴	676	65	29	6	9
Construction ⁵	407	52	48	0	0
Irrigation ⁶	118	75	25	0	0
TOTAL	5753	60	32	8	12

¹ Deemed successful if used for that purpose.

² As "unsuccessful due to insufficient yield" takes precedence in determining status, a more useful statistic is the percentage of bores which, after yielding sufficient water were unsuccessful due to poor quality.

³ The success rates for community supplies are lower than the average because more exacting yield and quality criteria (NH&MRC, 1980, 1987) are used in determining acceptability. In the 1970's, the criteria (WHO, 1971) were applied inflexibly. Many bores drilled then, which were backfilled and abandoned, would today be accepted with the knowledge that better alternatives are unlikely to be found.

⁴ Supplies used for domestic purposes often lie well outside accepted criteria for potable water. In such cases, the supply is used regardless or supplemented with rainwater. They are deemed successful, however, if used for domestic purposes.

⁵ Primarily for road construction and maintenance. The requirement here is for high yield, with quality generally irrelevant.

⁶ The success rate for irrigation supplies is high, with no failures due to poor quality, as irrigation development proceeds usually only after previous work has identified suitable water resources.

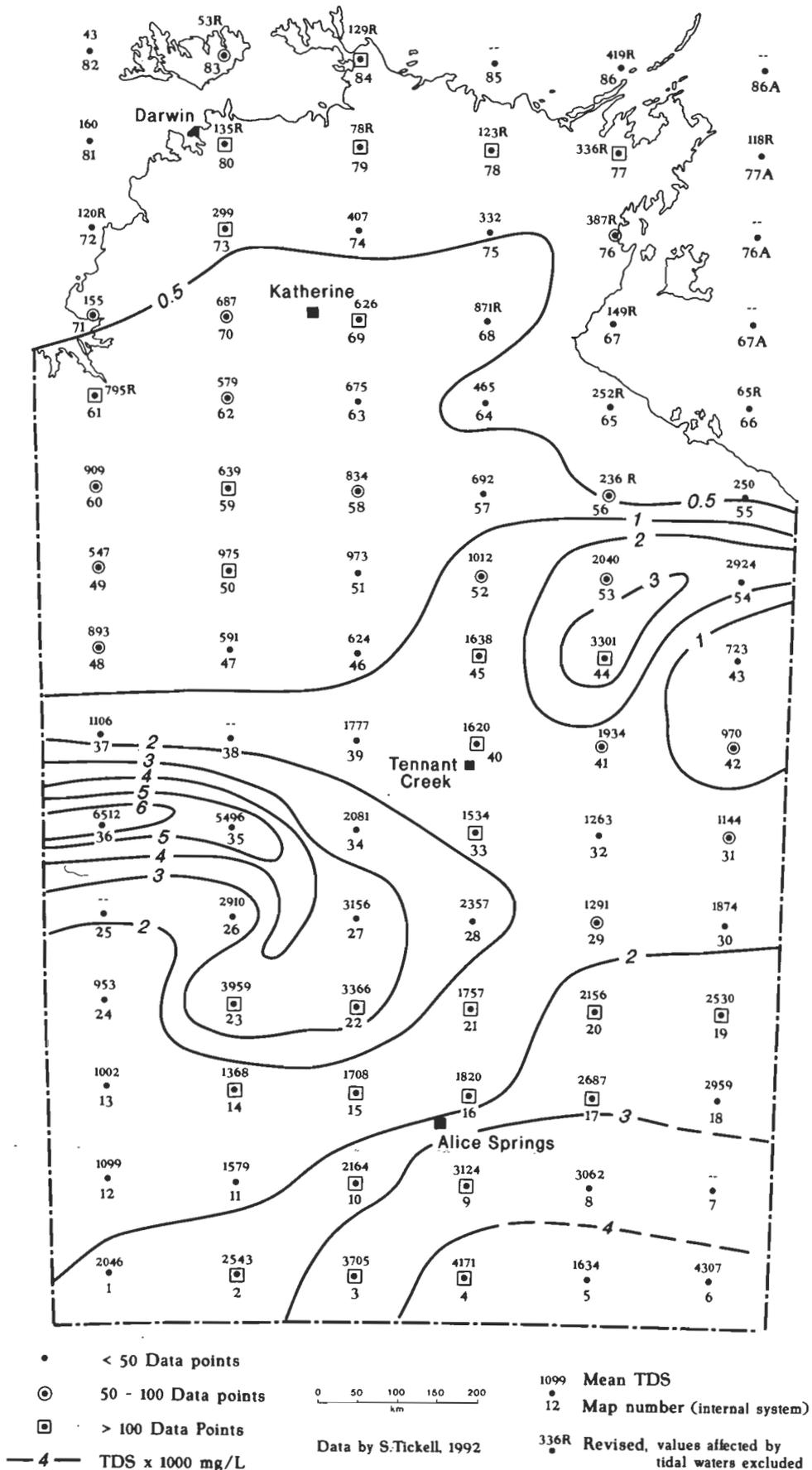


Figure 3. Mean groundwater salinity, Northern Territory (as determined from available bore data for each 1:250 000 map sheet).

- that part of the Great Artesian Basin occurring in the Northern Territory, underlying the Simpson Desert.

Further examination of the data, and the reasons for this pattern of overall salinity, is within the subject of a current study by the Northern Territory Power and Water Authority (Tickell, in preparation). More detailed hydrogeological maps of the Northern Territory have been published for selected areas at a scale of 1:250 000, and are cited in the references.

The AWRC review of **nitrate**-rich groundwaters of Australia (Lawrence, 1983 p. 26) suggested that in view of the natural origin of soil nitrogen in the arid zone, nitrate-rich groundwaters here may not be confined to shallow depth as observed in areas where the nitrogen accession is related to cultivation on improved pasture. As an initial test of this hypothesis, the average nitrate value was calculated for ten-meter depth intervals and is displayed in Figure 4.

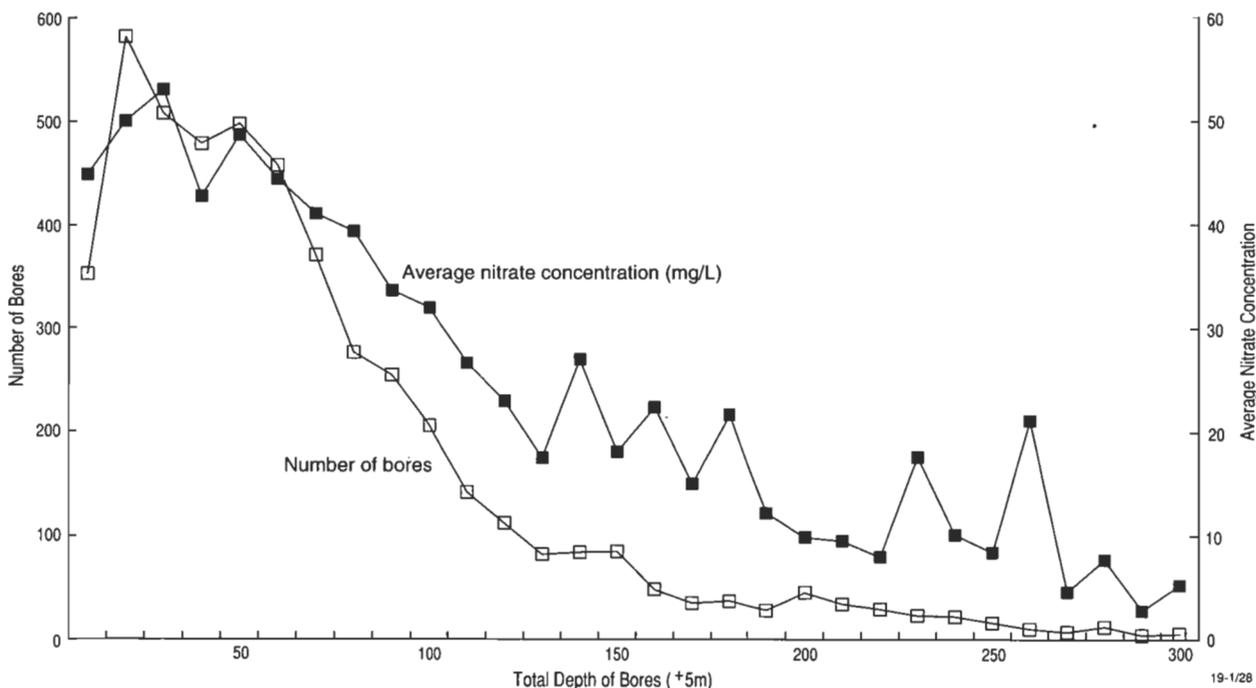


Figure 4. Average nitrate concentration versus bore depth, Northern Territory and zone.

A clear decrease in groundwater nitrate concentration with increasing bore depth is evident, supporting the conclusions of more recent investigations into the natural groundwater nitrate phenomena in the Australian arid zone (Barnes & others, 1992), which attributed a near-surface biological origin to the nitrate. However, total drilled depth is not a reliable estimator for aquifer depth. A project has recently commenced to enter further detailed groundwater data, including the aquifer-depth-yield description supplied by the driller. This will eventually permit far more rigorous data analysis.

High levels of **fluoride** in groundwater is a widespread feature of the arid zone; Table 1 shows an average value of 1.3 mg/L here. Isolated areas of above average values also occur in the Barkly Tableland and Victoria River

region. A study of stock waters in Northern Australia (McCosker & Winks, 1993) presents high fluoride occurrence in some detail.

Conclusions

The groundwater quality data held by the Water Resources Division of the Northern Territory Power and Water Authority is now approaching the position where it can be readily supplied to both internal and external users for overview and specific area assessments.

The importance of groundwater quality as a constraint on settlement of the arid zone is confirmed by examination of drilling success rates, and overview of salinity and health-related parameters. Nitrate and fluoride levels in particular have often exceeded drinking water criteria.

Changing water quality standards can result in changed drilling success rates, with impact on community viability,

and the capacity of related funding arrangements to match water-supply development programs. Application of the new draft criteria (NH&MRC, 1993) with the relaxed guideline for nitrate is likely to increase the success rate of community water-supply drilling in the arid zone.

Acknowledgments

That this preliminary overview is now possible is due to the perseverance of Water Resources Division staff who have been involved in the entry of data to computer over a period of years. In particular the dedication of Ron Blackmore in the Darwin office, and Col Garner in Alice Springs, deserves recognition. We also thank Steve Tickell for his contribution on salinity, and Avis Wiegeler for preparation of Figures 2 and 3.

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Gradational benthic marine communities in the Early Carboniferous *Rhipidomella fortimuscula* Zone (late Visean), New South Wales

Ian H. Lavering¹

Four benthic marine fossil communities are recognised in faunas of the *Rhipidomella fortimuscula* brachiopod Zone of late Visean (Early Carboniferous) age using multivariate (cluster) analysis of bulk samples extracted from available fossiliferous horizons. As a consequence of their occurrence over a wide geographic area, the communities are considered to be representative collections of *in situ* invertebrates (largely brachiopods). The number of species and genera in each community varies according to the favourability of water column and substrate conditions for habitation by such invertebrate filter-feeders. Elements of the *Balanoconcha elliptica* community were present in marine shelf waters with high suspended-sediment concentrations in the water column, such conditions excluded all but a few species well adapted to them. The *Rhipidomella fortimuscula* community was present in turbulent nearshore conditions, but could also tolerate calmer conditions below wave-base. The *Tylothyris planimedia* and *Marginicintus reticulatus* communities inhabited quiet-water conditions, one closer to shore than the other, but differ in the number and variety of species present. The *Marginicintus reticulatus* community is the most widespread and has the highest species diversity.

Sampling by bulk collection allows the communities to be identified by the distribution and abundance of all species. Clusters formed by multivariate analysis identify the recurrent species associations or communities. Examination of the com-

munities show that several species are numerically important in more than one community. It is suggested from this evidence that the communities do not contain mutually exclusive species associations, but are abstractions from a continuum. As such the communities intergrade and are distinguishable on the basis of their total faunal content. Several species comprise the most abundant forms in more than one community: *Balanoconcha elliptica*, *Rhipidomella fortimuscula*, *Marginicintus reticulatus*, and *Tylothyris planimedia*. The community assemblages are gradational (Whittaker community concept) rather than forming fixed associations inhabiting specific depth zones (Petersen community concept).

Compared to the 'time averaged' nature of fossil communities, surveys of modern benthic communities are an 'instantaneous' view of biota and less likely to identify the long-term impact of periodic perturbations. Major periodic fluctuations in environmental parameters are more likely to be reflected over time in the fossil record where the populations of more than one generation are preserved. The inherently patchy nature of both fossil and modern benthic species populations is also a feature readily evident in the fossil record, but more difficult to detect in modern surveys. Marine benthic communities of the *Rhipidomella fortimuscula* Zone provide an illustration of the cumulative effects of gradational faunal boundaries and the inherent patchiness of species populations.

Introduction

The Early Carboniferous brachiopod-dominated faunas of eastern Australia have been sufficiently well documented to provide regional correlations as well as intercontinental comparisons of age, tectono-stratigraphic setting, and a time-stratigraphic framework for detailed palaeogeographic reconstructions (Roberts, 1975; Jones & Roberts, 1976; Roberts & Engel, 1980; Roberts, 1981). The diversity and distribution of the faunas within various marine sequences in both New South Wales and Queensland have been used as a basis for regional correlation charts of the Carboniferous system in Australia (Jones & others, 1973; Jones & Roberts, 1976). A schematic representation of the stratigraphy discussed in detail by Roberts & Engel (1987) is shown in Figure 1.

One of the most important features of the Early Carboniferous faunal succession in eastern Australia is the disappearance of large numbers of genera and species at the end of each zonal assemblage (Roberts, 1975; Roberts & others, 1976). The 'punctuated' nature of zonal assemblages is evidently controlled by oscillations in sea level and a gradually colder climate (Roberts, 1981). It is the Visean benthic community types of the *Rhipidomella fortimuscula* Zone on which this study is focussed. Faunas of this zone are present in the southern New England region in the Isismurra and Chichester Formations, shown in Figure 1. The faunas of the Visean *Rhipidomella fortimuscula* (*Rf*) brachiopod Zone are the last of the warm-water cosmopolitan assemblages in the Early Carboniferous succession and they were followed by Late

Visean and Early Namurian low-diversity, cold-water temperature assemblages (Roberts, 1981).

Detailed regional mapping of the Carboniferous sequence in the Southern New England region by Roberts & others (1991) is the basis for a wide-ranging set of stratigraphic and biostratigraphic correlations in a complexly faulted terrane of marine and non-marine sequences (Roberts, 1975; Jones & Roberts, 1976; Roberts & Engel, 1980, 1987). The brachiopod-dominated faunas of the *Rhipidomella fortimuscula* Zone are present in several major stratigraphic reference sections of the region between Carrow Brook and Dungog described by Lavering (1974, 1978), Roberts (1975) and Roberts & others (1991). The stratigraphy of each reference section and the palaeogeographic development of the sequence present in each section was outlined by Roberts (1975) and refined by Roberts & Engel (1980, 1987) and Roberts & others (1991).

A major feature of the fossiliferous horizons assigned to the *Rhipidomella fortimuscula* Zone, and examined by Roberts (1981) and Lavering (1978), is that depth-limited communities (species assemblages) of the type noted in the Early Palaeozoic by Ziegler (1965) and Brett & others (1993) are not evident. The brachiopod-dominated faunas of eastern Australia, and in particular the *Rhipidomella fortimuscula* Zone, have a complex and variable control mechanism not related to water depth alone. This study attempts to outline the nature of the community groups present in the *Rhipidomella fortimuscula* Zone, and the individualistic distribution patterns which the various species populations exhibit.

A wide variety of techniques are used for identifying the major features of both fossil and living benthic marine

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species assemblages. The approach used here is similar to those employed by Field & others (1982), Gray & others (1988), Rainer (1981), and Zenetos (1990) in their respective examinations of modern benthic marine assem-

blages. Rainer (1981) undertook a periodic (quantitative) assessment of a modern estuarine fauna. He concluded that there was greater stability in species composition, but low species diversity in the shallow-water areas, in

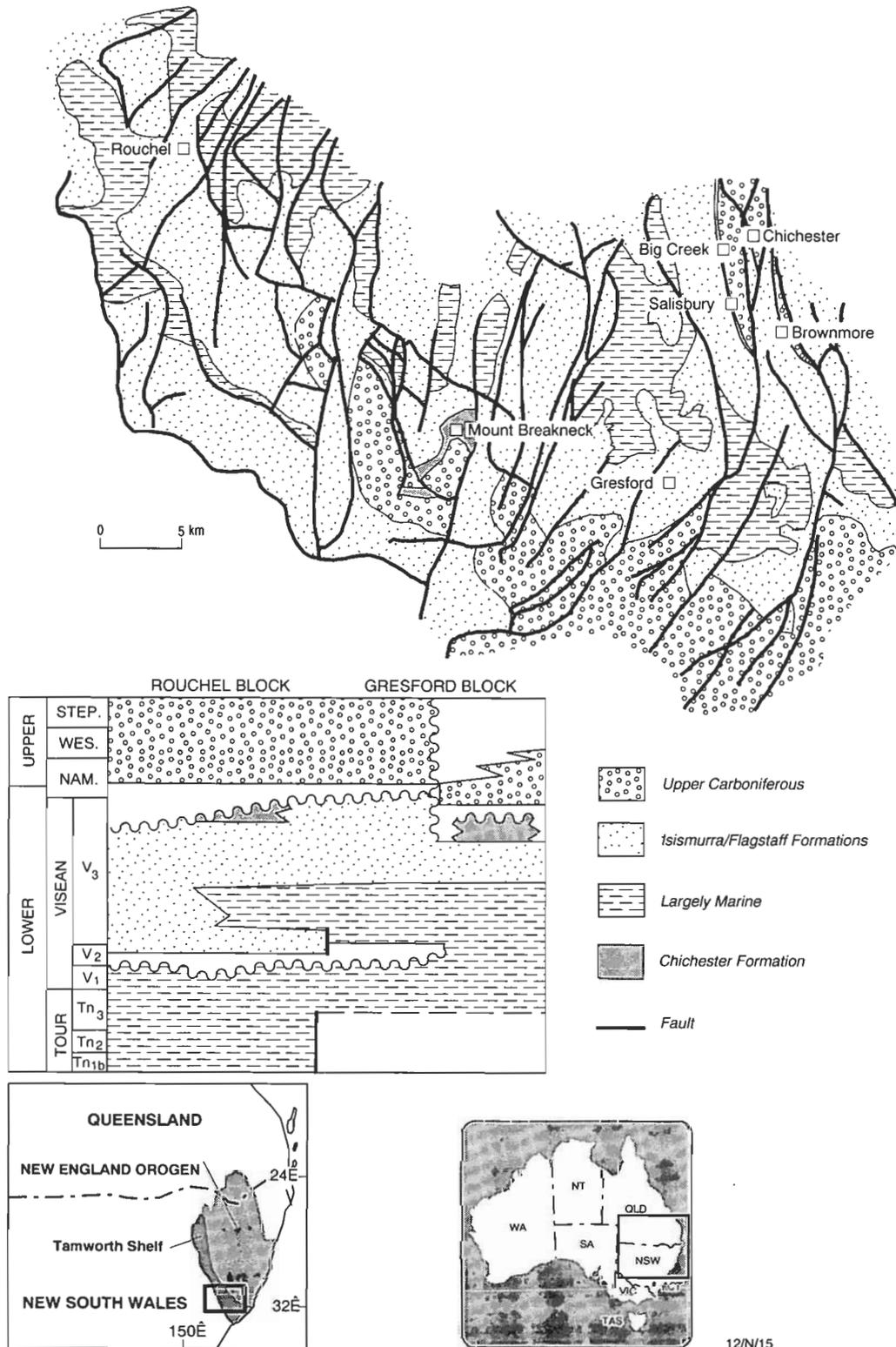


Figure 1. Location and regional geology of the Carboniferous sequence in the southern New England region. The Chichester Formation is mainly marine siltstone and sandstone. The largely marine part of the sequence includes the Dangarfield, Waverley, Ararat, Bingleburra and Woolooma Formations. The Isismurra/Flagstaff Formations are dominantly non-marine except for the Isismurra sequence near Mount Breakneck and the lower part of the Flagstaff which is marine. The Upper Carboniferous is mainly non-marine and comprises the Mt Johnstone Formation, Paterson Volcanics, and Seaham Formation. Schematic stratigraphy after Roberts & Engel (1987).

contrast to the more diverse and stable substrates offshore. Such results provide a comparison with the present quantitative study.

Stratigraphic setting

The Carboniferous sequence of eastern Australia has been mapped by the New South Wales and Queensland Geological Surveys, Universities, and Bureau of Mineral Resources (Roberts & Oversby, 1974; Roberts & Engel, 1987; Roberts & others, 1991, 1993). For the southern New England region a detailed set of geological maps as well as stratigraphic reference sections, biostratigraphic zonations and palaeogeographic reconstructions are available as a result (Roberts, 1975; Jones & Roberts, 1976; Roberts & Engel, 1980, 1987; Roberts & others, 1991). Nine biostratigraphic zones, based on brachiopod ranges, have been recognised in major reference sections within the sequence (Roberts, 1975; Roberts & others, 1976; Roberts & others, 1993). All of the zonal assemblages, except the youngest (*Levispustula levis* Zone—Late Carboniferous), are present in the Early to Mid Carboniferous rocks of the New England Region. The *Rhipidomella fortimuscula* Zone is the sixth of eight brachiopod assemblage zones and is present in a thin (>30 m thick) marine sequence within the Isismurra Formation at Mount Breakneck (Lavering, 1974, 1978), as well as thicker sequences of the Chichester Formation in the Salisbury, Rawdon Vale and Barrington districts (Lavering, 1974 & 1978; Roberts & Engel, 1980, 1987; Campbell & McKelvey, 1972; Peou & Engel, 1979).

Some of the more subtle structural controls of sedimentation in the New England region have become evident recently — well after initial regional mapping, biostratigraphic studies, and palaeoecological analysis were undertaken. As well, new dating of volcanic units and biostratigraphic work have revised the age of some sequences and clarified the ages of others (Roberts & Engel, 1987; Roberts & others, 1991, 1993). The detailed stratigraphic and sedimentological results of Lindley (1981, 1984), Roberts & Engel (1987), and Roberts & others (1991, 1993) have provided insight into structural controls of sedimentation and provide a better framework for the earlier palaeoecological results of Lavering (1978, 1983).

Other advances in the understanding of structural evolution and controls on stratigraphic development have occurred. Roberts & Engel (1987) identified two major fault-bounded terranes ('blocks') in the Carboniferous (late Viséan) sequence within which the faunas of the *Rhipidomella fortimuscula* Zone are present — the Gresford and Rouchel Blocks (Fig. 1). Differences in the stratigraphic succession within these and other terranes have been identified as being due in part to movement along the major bounding faults during periods of active sedimentation (Roberts & Engel, 1987) and different source areas for volcanic and related non-marine sediments.

The faunas of the *Rhipidomella fortimuscula* Zone examined in this study are present in marine shelf sediments of the Chichester Formation (Roberts & Engel, 1987) and a thin marine tongue within the upper part of the Isismurra Formation. According to Roberts & others (1991), these sequences were deposited following early to middle Viséan marine transgression, which initially inundated the Gresford Block (Chichester Formation) and eventually the eastern part of the Rouchel Block (marine Isismurra

Formation). The extent of the latter sequence has been mapped by Lavering (1974, 1978) on the upper slopes of Mount Breakneck, immediately east of Glennies Creek Dam. Late Viséan regression and associated uplift terminated deposition of the marine Isismurra and Chichester Formations. A colder climate in the late Viséan resulted in the disappearance of a number of genera and species from the faunal succession (Roberts, 1981). It is within this somewhat complex stratigraphic framework that the following analysis of the *Rhipidomella fortimuscula* Zone faunal communities is undertaken.

Palaeogeographic setting

At the time of deposition of the Martins Creek Ignimbrite Member, which preceded the marine sediments containing the faunas of the *Rhipidomella fortimuscula* Zone, the entire southern New England region was emergent. This land surface was covered with ash-fall tuffs (ignimbrites) or non-marine volcanogenic sediments of the Isismurra Formation (Roberts & Engel, 1980, fig. 8). A marine transgression, during the time period represented by the *Rhipidomella fortimuscula* Zone assemblage, deposited rippled shallow-water sandstone, siltstone and mudstone at Mount Breakneck (Isismurra Formation), and thicker sequences of siltstone and mudstone at Chichester (MacDonald, 1972; Roberts & Engel, 1980).

The marine transgression associated with the marine part of the Isismurra Formation (and Chichester Formation) did not extend more than 2 km west of Mount Breakneck, where there is wave-rippled shallow-water sandstone. This passes laterally into siltstone and bioturbated mudstone deposited below wave-base (Lavering, 1978). A major regression terminated marine shelf sedimentation of the Isismurra and Chichester Formations — depositing deltaic and alluvial fan material (Roberts & Engel, 1980, fig. 9).

Sampling method

To identify benthic community types of the *Rhipidomella fortimuscula* Zone assemblage, preserved within the marine Isismurra Formation and Chichester Formation, material was collected from known major fossiliferous horizons. A total of 38 horizons were analysed from the six stratigraphic sections described in detail by Roberts (1975) and Roberts & others (1993). Additional descriptions of the regional geology in which the sections are located are given by MacDonald (1972) (sections in the Salisbury to Chichester regions) and Lavering (1974 & 1978) (Mount Breakneck section). A total of 26 fossiliferous horizons present in the Isismurra Formation at Mount Breakneck were sampled. The sequence of the Chichester Formation at Brownmore, Salisbury and Big Creek, as described by Roberts (1975), contains eight fossiliferous horizons. Additional fossiliferous horizons along strike, and northwards of the Brownmore and Salisbury reference sections, identified by MacDonald (1972), were sampled as part of the study (Lavering, 1974, 1978).

The fossiliferous material is lodged in the collection of the Department of Applied Geology, University of New South Wales. Samples numbered 1 to 22 were collected at Mount Breakneck (Lavering, 1978); the remaining samples are from locations in major stratigraphic sections identified by Roberts (1975) and other locations along strike from those sections identified by MacDonald (1972). The letters A, B and C refer to horizons at the same

location which were sampled in ascending order; 115-23A is location 23 in section 115 identified by MacDonald, A is the first horizon collected, 115-23B immediately overlies it, and so on.

Samples were collected by removing fossiliferous layers from exposed bedding planes using a variety of commonly available masonry hammers and chisels. A total volume of up to 50 litres was collected at each site by using standard cylindrical containers. Samples of this size were also the physical limit which the author found possible to carry, as access to most collection sites was only possible on foot. Transportation of full cylinders from each site was facilitated by adaptation of a carrying harness available from the Australian Defence Force disposal stock designed for carrying heavy-duty field radio and communication equipment (Laving, 1978; fig. 59). This physically demanding bulk-sampling approach is not generally recommended for reasons of occupational health and safety.

Where necessary, samples were further disaggregated in the laboratory so that all fossiliferous remains preserved in the material could be identified and counted. Identification was undertaken as far as possible using available systematic descriptions. Where fragments were present which could not be identified, these were omitted from the statistical analysis. In most cases, less than 5% of fossil remains was discarded. In some instances, heat treatment and quenching was used to aid desegregation of strata, but this did not reveal any additional species or genera.

An accurate sampling method, including the bulk-sampling approach used here, should yield consistent estimates of the true number of specimens preserved. The amount of material required to sample a representative collection of species in each horizon will depend on the number of species preserved and their distribution. Ager (1963) noted that as more of a representative sample is examined, an asymptotic limit to the number of species will be evident. Also, new species will appear at a decreasing rate as more material is examined. Hence, the minimum amount of material necessary to obtain a representative collection depends both on the density of specimens and total number of species present (diversity). Chang (1967) and Dennison & Hay (1967) use the area of substrate as a guide to the required minimum sample size. Alternative and more practical approaches outlined by Tipper (1976a & b) suggest that the ideal sample must be at least 500 times the size of the largest species being examined, a criterion which the bulk-sampling approach used in this analysis readily satisfies.

Results

The degree of post-mortem transportation and selective preservation of species in the samples appears to be low. Many of the finer details of shell morphology are evident, such as external spines of some brachiopod forms and few shells are disarticulated. Soft-bodied deposit-feeding organisms could not be identified in any way apart from their feeding and dwelling traces. The samples appear to reflect the results reported by Johnson (1964), MacDonald (1969a & b), Warne (1969, 1971), and Petersen (1972, 1975) that, apart from the time-averaged nature of fossil faunas, there is little difference in abundance and diversity compared with equivalent living assemblages. The expected difference between living faunas and preserved

shelly fossils is the lack of preservation of soft-bodied organisms and disturbance by post-mortem transportation (Johnson, 1964; MacDonald, 1969 a, b, 1975; Petersen, 1975; Warne 1969, 1971; Warne & others, 1976).

Ekdale (1974) and Reineck & Singh (1973) suggest, along with other authors noted immediately above, that most post-mortem changes to shelly faunas are generally restricted to areas of major tidal currents or wave action. In many instances, the species examined in the course of this study were preserved in their inferred living orientations.

The samples contain a high proportion of brachiopods (90% of specimens counted) preserved in their inferred living orientations. Remaining specimens include pelecypod, gastropod, coral, bryozoan, trilobite, echinoid, and crinoid material. The brachiopods are largely spiriferid and strophomenid forms (productid and chonetid) with terebratulid, orthid and rhychonellid forms represented by one or two species. Other analytical results, such as the number of species per sample and other composition information, are listed by Laving (1978) and are being collated for further publication(s) which outline species diversity and population density patterns for the *Rhipidomella fortimuscula* Zone and the preceding *Delepinea aspinosa* Zone. Results of multivariate (cluster) analysis of the *Rhipidomella fortimuscula* Zone fossil horizons are outlined next.

Multivariate (cluster) analysis

The large number of species (up to 60) and samples (38) make subjective grouping of recurrent species associations difficult. It was evident, however, that several species were the most numerous in a number of samples from different horizons. A multivariate (cluster) analysis computer program was used to determine the underlying pattern of recurrent species associations. This method groups samples into clusters reflecting the degree of similarity between them, based on the presence and abundance of each species, and facilitates statistical measurement of recurrent species associations.

The cluster analysis approach used here was derived from the computer program listed by Davis (1973). The program standardises data and groups samples into clusters using the Euclidean distance coefficient. The greater the degree of similarity between samples, the smaller the Euclidean distance coefficient. The most similar samples are clustered initially and additional clusters are formed thereafter until all samples are aggregated into a dendrograph, shown in Figure 2, using a weighted pair grouping method outlined by Davies (1973). This method is, depending on the nature of the available data, recommended by Eades (1965), Jago (1969), Gower (1970), Hazel (1970), Blackith & Reyment (1971), Boratynski & Davies (1971), Davis (1973), Valentine (1973), and Keen (1977) specifically because the similarity of samples from unrelated clusters remains unchanged by the clustering process. Additional information on the program used for this analysis has been outlined by Thompson (1978), who used it to determine the numerical similarity of a number of Australian Carboniferous brachiopod forms.

The 38 samples generate four unique clusters, but four samples remain unclustered (Fig. 2). The first cluster in the dendrograph contains three samples (103-4, 20B & 3) and the levels of clustering (similarity) is high to

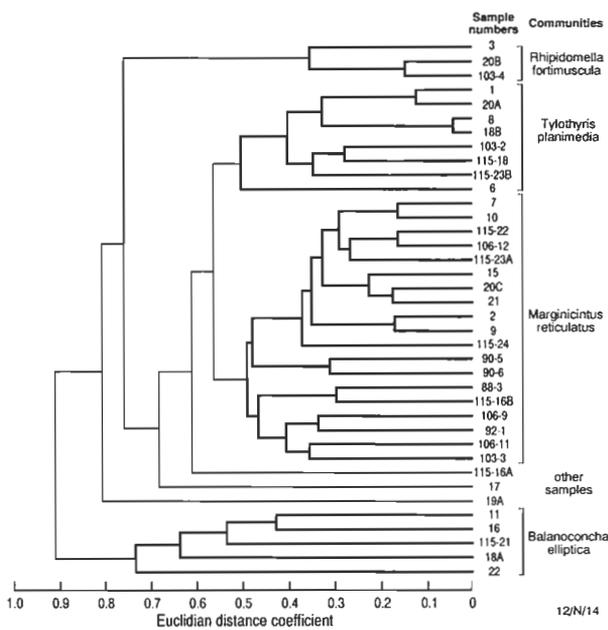


Figure 2. Multivariate cluster analysis of the *Rhipidomella fortimuscula* Zone faunas using the standardised, weighted pair group method of Davis (1973). All but three samples from the Isismurra and Chichester Formations cluster in one of four communities (cluster groups).

moderate — the samples cluster at levels of 0.1 to 0.4. The second cluster group contains eight samples with high to moderate similarity (0.05 to 0.58), and likewise the third and largest cluster group of 19 samples have high to moderate similarity. The fourth cluster of five samples have moderate to poor similarity (0.45 to 0.85).

The common species in most samples of the cluster groups are: *Marginicintus reticulatus*, *Balanoconcha elliptica*, *Rhipidomella fortimuscula*, *Orthotetes australis*, *Eomarginifera megalotis*. One difference between the samples in each cluster is the relative abundance of each of these common species. The clusters (communities) thus appear to represent abstractions from a continuum of overlapping species populations, each species is not necessarily limited to a single cluster, but can be present as a significant component of more than one. These clusters (communities), are a marked contrast to the Early Palaeozoic communities outlined by Ziegler (1965) and Brett & others (1993), which are a series of depth-limited, species assemblages. In those assemblages, few species are present in more than one depth-limited community (Anderson, 1971; Brett & others, 1993).

The contrast with such depth-limited zonation of species ranges highlights one of the significant results identified by this study — the apparently intergrading nature of the species assemblages (communities) identified by clustering. The interpretation placed on these results is that the Early Carboniferous benthic species populations overlap and do not appear to have coincident geographic or depth-limited boundaries.

The most widespread species, *Marginicintus reticulatus*, *Balanoconcha elliptica*, *Rhipidomella fortimuscula*, *Orthotetes australis*, and *Eomarginifera megalotis*, are the most common forms in the samples of each of the cluster groups. In samples comprising the first cluster group, the most common species (in order) are *R. fortimuscula*, *M.*

reticulatus, *O. australis*, *E. megalotis*, and *B. elliptica*, and they comprise 75% of all individuals present. Four of these species (except *B. elliptica*) are also the most common in samples of the second cluster group, three (*M. reticulatus*, *O. australis*, and *B. elliptica*) are the most common species in the third cluster and similarly in the fourth cluster (*M. reticulatus*, *R. fortimuscula*, and *B. elliptica*).

While a multivariate (cluster) analysis method is used by Keen (1977) to defined benthic communities, in his study the composition of each cluster group is unique and very little if any overlap between species is evident. In the present study, the recurrence of several major species in each cluster group is a major point of interest. The four benthic communities identified by cluster analysis are outlined next.

Benthic communities

Rhipidomella fortimuscula community (Table 1)

The four samples in the first cluster (*Rhipidomella fortimuscula* community) in Figure 2 contain a total of 364 specimens of 24 different species. The four most common species are identified as a trophic nucleus in the sense of Duff (1975). These species are *R. fortimuscula*, *M. reticulatus*, *O. australis*, *E. megalotis*, and *B. elliptica* and they comprise 75% of all individuals present in the community. The community is preserved in sandstone and siltstone, deposited near wave-base, in the marine part of the Isismurra Formation at Mount Breakneck (sample 3 & 20B) and Salisbury (103–4). The community is dominated by the numerically abundant *R. fortimuscula* (40% of all specimens), a species suited to turbulent conditions near wave-base. A robust but modest-sized shell and prominent shell muscle system make this species well suited to such a physically demanding environment. The *R. fortimuscula* community intergrades with the *T. planimedia* and *M. reticulatus* communities (clusters 2 and 3 in Fig. 2) in the calmer conditions below wave-base, but lacks their level of species diversity and with a modest average population of 15 individuals per species.

Table 1. *Rhipidomella fortimuscula* community.

Total of 24 species and 364 specimens counted		
Rank	Species	Specimens
1	<i>Rhipidomella fortimuscula</i>	143
2	<i>Orthotetes australis</i>	40
3	<i>Marginicintus reticulatus</i>	39
4	<i>Eomarginifera megalotis</i>	33
5	<i>Balanoconcha elliptica</i>	17
6	<i>Podtsheremia australis</i>	16
7	<i>Ectochoeristites watsi</i>	16
8	<i>Tylothyrus planimedia</i>	11
9	<i>Cleiothyridina segmentata</i>	11
10	<i>Spinulipica spinulosa</i>	9
11	<i>Stegacanthia larga</i>	6
12	<i>Spirifer lirellus</i>	5
13	<i>Brachythyris pseudovalis</i>	3
14	<i>Eumetria mona</i>	3
15	<i>Unispirifer striatoconvolutus</i>	3
16	? <i>Myonia</i> sp.	1
17	<i>Pecten</i> sp.	1
18	<i>Krotovia procidua</i>	1
19	<i>Punctospirifer ambyls</i>	1
20	<i>Pleuropugnoides</i> sp. B	1
21	<i>Rugosochonetes gloucesterensis</i>	1
22	<i>Productina macdonaldi</i>	1
23	<i>Planikeenia pristina</i>	1
24	<i>Schuchertella</i> sp. C	1

Tylothyris planimedia community (Table 2)

The eight samples of this community (cluster 2 in Fig. 2) contain 34 species represented by a total of 1004 individuals. The community is present in siltstone and mudstone deposited below wave-base at Mount Breakneck (Isismurra Formation) where it is replaced, towards the shoreline, by the *R. fortimuscula* community. The *T. planimedia* community extends into offshore areas (Chichester Formation) where it intergrades with the more diverse and widespread *Marginicintus reticulatus* community. The *T. planimedia* community has greater species diversity than the *R. fortimuscula* community, as the calmer conditions below wave-base did not require robust shell forms and living conditions were apparently more favourable. The *T. planimedia* community population sizes are larger than those of *R. fortimuscula* community with an average of 30 individuals per species.

Table 2. *Tylothyris planimedia* community.

Total of 34 species and 1004 specimens counted		
Rank	Species	Specimens
1	<i>Marginicintus reticulatus</i>	279
2	<i>Balanoconcha elliptica</i>	172
3	<i>Rhipidomella fortimuscula</i>	132
4	<i>Orthotetes australis</i>	121
5	<i>Tylothyris planimedia</i>	59
6	<i>Palaeacis</i> sp.	45
7	<i>Rhynchopora punctata</i>	30
8	<i>Spirifer osbornei</i>	23
9	<i>Palaeoneilo</i> sp.	20
10	<i>Rugosochonetes gloucesterensis</i>	18
11	<i>Stutchburia</i> sp.	15
12	<i>Krotovia prociua</i>	11
13	<i>Stegacanthia larga</i>	11
14	<i>Cleiothyridina segmentata</i>	11
15	<i>Spirifer lirellus</i>	9
16	<i>Podtsheremia australis</i>	6
17	<i>Loxonema lamellosus</i>	6
18	<i>Pleuropugnoides</i> sp. B	5
19	<i>Kitakamithyris triseptata</i>	5
20	<i>Eumetria mona</i>	5
21	<i>Leptagonia analoga</i>	2
22	<i>Schizophoria verulamensis</i>	2
23	<i>Brachythyris</i> sp.	2
24	<i>Didontopteria</i> sp.	2
25	<i>Coledium laevis</i>	2
26	<i>Pecten</i> sp.	2
27	<i>Starapollus davidi</i>	1
28	<i>Archaeocidarius</i>	1
29	<i>Limipecten</i> sp.	1
30	<i>Schizodus</i> sp.	1
31	<i>Eomarginifera megalotis</i>	1
32	<i>Nuculana etheridgei</i>	1
33	<i>Spirifer</i> sp.	1
34	<i>Scolococoncha geniculata</i>	1

Marginicintus reticulatus community (Table 3)

This is the most widespread and diverse of the four communities identified in Figure 2. It is present throughout the Salisbury region (Chichester Formation) and part of the Isismurra Formation sequence at Mount Breakneck. The *M. reticulatus* community contains 54 species represented by a total of 2673 individuals: an average population size of 49 individuals per species. Species with the largest population sizes are a mixture of spiny productid, orthid and flat-lying spiriferid forms: *Marginicintus reticulatus*, *Orthotetes australis*, *Balanoconcha elliptica*, and *Stegacanthia larga* comprise the trophic nucleus. The robust form *R. fortimuscula* ranks as one

Table 3. *Marginicintus reticulatus* community.

Total of 55 species and 2673 specimens counted		
Rank	Species	Specimens
1	<i>Marginicintus reticulatus</i>	701
2	<i>Orthotetes australis</i>	287
3	<i>Balanoconcha elliptica</i>	233
4	<i>Stegacanthia larga</i>	152
5	<i>Eomarginifera megalotis</i>	131
6	<i>Spirifer lirellus</i>	101
7	<i>Podtsheremia australis</i>	100
8	<i>Tylothyris planimedia</i>	81
9	<i>Brachythyris pseudovalis</i>	69
10	<i>Productina macdonaldi</i>	61
11	<i>Cleiothyridina segmentata</i>	58
12	<i>Ectochoiritites wattsi</i>	53
13	<i>Echinoconchus gradatus</i>	53
14	<i>Pleuropugnoides</i> sp.	50
15	<i>Fluctuaria campbelli</i>	44
16	<i>Eumetria mona</i>	43
17	<i>Palaeoneilo</i> sp.	43
18	<i>Kitakamithyris implicata</i>	40
19	<i>Rotaia subtrigonia</i>	29
20	<i>Schizophoria verulamensis</i>	27
21	<i>Rhynchopora punctata</i>	27
22	<i>Rugosochonetes gloucesterensis</i>	26
23	? <i>Pecten</i> sp.	22
24	<i>Leptagonia analoga</i>	22
25	<i>Schuchertella</i> sp.	20
26	<i>Planikeenia pristina</i>	20
27	<i>Stutchburia</i> sp.	15
28	<i>Starapollus davidi</i>	14
29	<i>Brachythyris</i> sp.	14
30	<i>Scolococoncha geniculata</i>	14
31	<i>Krotovia prociua</i>	12
32	<i>Unispirifer striatoconvolutus</i>	12
33	<i>Cleiothyridina</i> sp.	11
34	<i>Nuculana etheridgei</i>	10
35	<i>Spathella</i> sp.	8
36	<i>Syringothyris</i> sp.	7
37	<i>Loxonema lamellosus</i>	7
38	<i>Rhipidomella fortimuscula</i>	7
39	<i>Kitakamithyris triseptata</i>	7
40	<i>Didontopteria</i> sp.	6
41	<i>Kitakamithyris</i> sp.	5
42	<i>Cypricardella</i> sp.	4
43	<i>Spirifer</i> sp.	4
44	<i>Pernopecten</i> sp.	2
45	<i>Voiseyella anterosa</i>	2
46	<i>Stegacanthia abbotti</i>	2
47	<i>Pernopecten trevallynensis</i>	2
48	<i>Athyris lamina</i>	1
49	<i>Schuchertella</i> sp. C	1
50	<i>Myonia</i> sp.	1
51	<i>Stutchburia</i> sp.	1
52	<i>Copelandia acuta</i>	1
53	<i>Peruvispira kuttungensis</i>	1
54	<i>Bellerophon</i> sp.	1
55	<i>Mourlonia</i> sp.	1

of the less-common species, indicating that it could also populate calm conditions below wave-base.

Balanoconcha elliptica community (Table 4)

This community (cluster 3 in Fig. 2) has a limited number of species (24), which are preserved in siltstone and silty sandstone with a significant concentration of fine volcanic material (ash) which has been diagenetically altered into zeolite minerals. The community is mainly preserved in the marine part of the Isismurra Formation at Mt Breakneck, but was also present in offshore areas as indicated by one horizon in the Chichester Formation (Sample 115–21). Forms apparently tolerant of silt-sized volcanic ash, such as *Marginicintus reticulatus*, *Rhipidomella fortimuscula*, and *Balanoconcha elliptica*, comprise 75%

Table 4. *Balanoconcha elliptica* community.

Total of 24 species and 437 specimens counted		
Rank	Species	Specimens
1	<i>Marginicintus reticulatus</i>	34
2	<i>Rhipidomella fortimuscula</i>	93
3	<i>Balanoconcha elliptica</i>	83
4	<i>Leptagonia analoga</i>	26
5	<i>Rugosochonetes gloucesterensis</i>	24
6	<i>Spirifer lirellus</i>	20
7	<i>Eomarginifera megalotis</i>	15
8	<i>Schuchertella</i> sp. C	7
9	<i>Orthotetes australis</i>	5
10	<i>Stegacanthia larga</i>	5
11	<i>Palaeoneilo</i> sp.	4
12	<i>Podtsheremia australis</i>	4
13	<i>Cleiothyridina segmentata</i>	3
14	<i>Pecten</i> sp.	2
15	<i>Loxonema lamellosus</i>	2
16	<i>Krotovia procidua</i>	2
17	<i>Trichoconetes perpendicularis</i>	1
18	<i>Syringothyris</i> sp. A	1
19	<i>Pleuropugnoides</i> sp. B	1
20	<i>Ectochoeristites wattsi</i>	1
21	<i>Schuchertella</i> sp.	1
22	<i>Stutchburia</i> sp.	1
23	<i>Eumetria mona</i>	1
24	<i>Peruvispira kuttungensis</i>	1

of the individuals present in the community. The average population of the community is approximately 18 individuals.

Discussion

The analysis and clustering of samples collected from faunas of the *Rhipidomella fortimuscula* Zone (Isismurra and Chichester Formations) indicates that the communities are gradational (i.e. not fixed associations), and did not inhabit a specific depth zone (the Petersen community concept of fixed depth-limited species associations; Petersen, 1913). As such, the communities reflect overlap in a wide variety of species populations. The most numerous species are present in samples of all communities and are not limited to either a particular area, substrate type, or water-depth range. These results and the pattern of all species in the *Rhipidomella fortimuscula* Zone are such that the communities are gradational in composition and geographic extent. As such, they accord with the Whittaker (1967, 1970) community concept of a series of intergrading species assemblages.

The contrasting concept of depth-limited benthic communities has been given wide application in reference to the fossil record and in many instances the community concept of Petersen (1913) is implied. Such communities are characterised by a specific association of sedimentary conditions and species (Watkins & others, 1973). In contrast with the modern faunas examined by Petersen (1913), shelly invertebrate faunas preserved in the fossil record are also 'time averaged' and contain specimens from more than one generation. The approach used by Walker & Bambach (1974) to overcome 'time averaging' in the fossil record is that fossil communities should be defined by comparing the distributions of all species rather than the content of a single sample or horizon. The method suggested by Walker & Bambach (1974) is basic to the approach employed here.

In contrast, surveys of present-day marine invertebrates do not suffer from the problem of preservation inherent in fossil (*R. fortimuscula* Zone) communities. Modern communities can be identified *in situ* (Bloom & others, 1972; Boesch, 1973; Jones, 1969; Mills, 1969; Parker, 1956, 1975; Sanders, 1960, 1968; Stanton & Evans, 1972; Young & Rhoads, 1971). Modern communities can, however, like some studies of the fossil record (Ziegler, 1965; Anderson, 1971; Brett & others, 1993), readily lead to benthic community models based on a single census rather than an aggregated or time-averaged analysis. The concept of a community of fixed composition is also encouraged by the emphasis it places on the interactions between species in determining the composition, diversity, structure and distribution of the community (Speden, 1965). Such models which highlight the fixity of species populations and fixed-composition (Whittaker, 1967, 1970; Mills, 1969) omit the inherent cyclicality community patterns may reflect as a result of annual and long-term variations, as well as the overlapping nature of species populations. In this regard, they lack the time-averaged nature of fossil communities.

Modern marine benthic environments on broad continental shelves are likely to be characterised by subtle changes in physical parameters (Sanders, 1968), and a gradational change from one species assemblage to another. Surveys of intergrading faunas can, however, produce clusters of inherently dissimilar samples of the type identical to the Petersen classification approach if only limited sampling is undertaken (Springer & Bambach, 1985). The more samples of modern faunas that are collected and analysed, the more the intergrading nature of the species assemblages is likely to become evident. Lavering (1993), Poore & Rainer (1979), and Stephenson & others (1976) found marked changes from one group of species to another in response to subtle changes in environmental gradients, in present-day Australian temperate and tropical marine shelf environments. An implication of their results is that the Petersen (1913) approach to rigid description of species associations with respect to a particular depth range is not applicable, but it is possible to identify groups where there is numerical dominance of, one or more, species.

In contrast, however, floral community studies show that species associations are composed of populations distributed independently according to individual tolerances (Whittaker, 1970). Such results emphasise the intergrading nature of communities — where environmental conditions change gradually, so do the composition of communities. Johnson (1972) suggests that present-day marine invertebrates form highly variable communities due to the patchy nature of population distributions and gradational changes in environmental parameters. Modern faunal assemblages have been shown to be characterised by diffuse boundaries, which reflect the 'individualistic' tolerances of each species and their patchy distribution (Johnson, 1972). Faunal assemblages are, as such, abstractions from a continuum of overlapping species ranges with gradational geographic boundaries (Pielou, 1975; Whittaker, 1970). Such patterns, if they are developed in the fossil record, will only be evident if a high-density sampling approach is used.

The present study has attained a high sample density; every known horizon in major reference sections was included; samples were obtained from a wide geographic area; samples were collected from different substrate types

(micro-environments); the study was unlikely to suffer from sample size effects in that additional sampling of each site did not significantly increase the number of species identified. Studies using a similar high sampling density, including those of Springer & Bambach (1985) and Keen (1977), have been able to infer that environmental gradients control and influence the nature and pattern of intergrading benthic communities.

The environmental factors which controlled the *Rhipidomella fortimuscula* Zone benthic communities have been inferred by reference to the fossil samples and the immediate sequence surrounding each site (Laving, 1978), as well as by other relevant information from other parts of the sequence described by Roberts (1975 & 1981) and Roberts & Engel (1980 & 1987). These factors are discussed in the next section.

Interpretation

The four different benthic marine fossil communities recognised in faunas of the *Rhipidomella fortimuscula* brachiopod Zone are considered to be representative ecological collections of living invertebrates (largely brachiopods) because of their wide geographic occurrence and repeated representation. Elements of the *Balanoconcha elliptica* community are present in sequences which had a high suspended-sediment concentration in the water column. In contrast, only a few species in the *R. fortimuscula* Zone faunas were well adapted to such conditions. The *Rhipidomella fortimuscula* community is present in turbulent nearshore conditions, but could also tolerate calmer conditions below wave-base.

The *Tylothyris planimedia* and *Marginicintus reticulatus* communities inhabited quiet-water conditions, but they differ in the number and variety of species present. The *Marginicintus reticulatus* community is the most widespread and diverse. It is possible that the *M. reticulatus* community is the dominant species assemblage in the marine shelf sequence inhabited by faunas of the *R. fortimuscula* Zone. If so, it is possible that the *Balanoconcha elliptica*, *Tylothyris planimedia*, and *Marginicintus reticulatus* communities are derived from the *M. reticulatus* community. As such, the *B. elliptica*, *T. planimedia*, and *R. fortimuscula* communities comprise those species of the *M. reticulatus* community which could also tolerate either shallow-water conditions near (*R. fortimuscula*) or below wave-base (*T. planimedia*), or conditions of muddy substrates (*B. elliptica*).

The most common species are numerically significant in more than one community: *Balanoconcha elliptica*, *Rhipidomella fortimuscula*, *Marginicintus reticulatus*, and *Tylothyris planimedia*. The communities can be said to 'intergrade' in that they are abstractions from a continuum, in the sense of Whittaker (1970). They are gradational (Whittaker community concept) rather than forming associations inhabiting specific depth zones (Petersen community concept).

Surveys of modern benthic communities are an 'instantaneous' view of biota, and less likely to identify the long-term impact of periodic perturbations which are incorporated into fossil communities by their 'time-averaged' nature. Major periodic fluctuations in environmental parameters are more likely to be evident in the fossil record where the populations of more than generation are preserved. The inherently patchy nature of benthic species

populations is also evident in these fossilised samples, but is unlikely to be revealed by the 'snapshot' view which a survey of present-day benthic communities represent. The patchy distribution of species populations identified here appears to reflect the original pattern of dispersal, rather than any degree of geographic isolation between individual specimens.

Conclusions

A high-density sampling and cluster analysis of available faunas of the late Visian (Early Carboniferous) *Rhipidomella fortimuscula* Zone in the southern New England region of New South Wales indicates that the presence of gradational benthic communities. A few widespread species are numerically dominant in more than one community. The absence of specific-habitat or depth-related assemblages indicates that the communities intergrade and are abstractions from a continuum formed by overlap of species populations.

Multivariate cluster analysis identifies a total of four communities which intergrade with one another. The *Balanoconcha elliptica* community is present in marine shelf waters with high suspended-sediment concentrations which excluded all but a few species. The *Rhipidomella fortimuscula* community is present in turbulent nearshore conditions, but could also tolerate calmer conditions below wave-base. The *Tylothyris planimedia* and *Marginicintus reticulatus* communities inhabited quiet-water conditions, one closer to shore than the other, but differ in the number and variety of species present. The *Marginicintus reticulatus* community is the most widespread and diverse.

It is possible that the *M. reticulatus* community is the dominant community of the *R. fortimuscula* Zone and that the other three are derived from it. The *B. elliptica*, *T. planimedia* and *R. fortimuscula* communities may comprise those species of the *M. reticulatus* community which could also tolerate either shallow-water conditions near (*R. fortimuscula*) or below wave-base (*T. planimedia*), or substrates overlain by a water column with a high proportion of suspended sediment (*B. elliptica*).

Major periodic fluctuations in environmental parameters are more likely to be reflected in the fossil record where the populations of more than a single generation are preserved. The inherently patchy nature of both fossil and modern benthic species populations is also a feature readily evident in the fossil record, but more difficult to detect in modern surveys. Marine benthic communities of the *Rhipidomella fortimuscula* Zone provide an illustration of the cumulative effects of gradational faunal boundaries and the inherent patchiness of species populations.

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Palynostratigraphy of the Bookpurnong Beds and related Late Miocene–Early Pliocene facies in the central west Murray Basin, part 1: dinoflagellates

M.K. Macphail¹ & J.R. Kellett²

Dinoflagellates offer a reliable method for distinguishing the Late Miocene–Early Pliocene Bookpurnong beds from lithologically similar marginal marine sediments, such as the Winnambool Formation deposited during Oligocene–Middle Miocene transgressions. Species largely or wholly restricted to the Bookpurnong beds and correlatives in the central west Murray Basin include

Melitasphaeridium aequabile, *M. choanophorum*, *Tectatodinium psilatatum*, and (frequent) *Tuberculodinium vancampoeae*. Species diagnostic of the older Murray Group correlatives, such as the Geera Clay and Winnambool Formation, include *Apteodinium australiense* and *Pentadinium laticinctum*.

Introduction

Major fluctuations in global sealevel during the Tertiary resulted in the Murray Basin being partially flooded by shallow epicontinental seas on at least three separate occasions: in the Late Eocene to Early Oligocene, Late Oligocene to Middle Miocene, and Late Miocene to Early Pliocene. Sediments deposited over this period contain several regional aquifer systems, which allow a billion dollar agricultural industry to thrive in what is now a semi-arid region. Of particular importance are the fine-grained shallow to marginal marine facies acting as low permeability barriers and/or confining beds for groundwater flow, and as sources of salt also influence regional groundwater quality. These marine facies are: Winnambool Formation (map symbol = Tmw), and Geera Clay (map symbol = Tmg) deposited during the Oligocene–Middle Miocene, and the Bookpurnong beds (map symbol = Tpb), deposited during the Late Miocene–Early Pliocene (Fig. 1). Lateral, mostly non-marine correlatives, occur landwards in the Middle Renmark Group, Middle–Upper Renmark Group, and Loxton–Parilla Sands, respectively.

In many places, the Bookpurnong beds not only disconformably overlie, but also share many common lithological characteristics with the Winnambool Formation and Geera Clay, and this presents difficulties in identifying the boundaries of the formations in the field when the characteristic *Pecten* macrofauna (Brown & Stephenson, 1991, pp. 152–153) is absent from the Bookpurnong Beds. For example, units logged as “Bookpurnong beds” in the central east of the Basin have been found to preserve marine dinoflagellates that became extinct during the Middle Miocene, such as *Apteodinium australiense* (Deflandre & Cookson), *Williamsia*, *Pentadinium laticinctum* Gerlach, and *Systematophora placacantha* (Deflandre & Cookson) Davey & others emend. (Macphail & others, 1993; Macphail & Kellett, unpubl. data). Microfaunas provide a method for distinguishing the marine formations, but are inapplicable in non-marine facies.

This paper is the first of two that develop alternative (palynological) criteria for dating and correlating Late Miocene–Early Pliocene sediments in the central west of the Murray Basin. Our aim here is to identify species or assemblages of dinoflagellates diagnostic of Late Mio-

cene–Early Pliocene marine facies, based on species preserved in cores of Bookpurnong beds close to the type locality of this formation at Loxton (Noora 1, Taldra 1). These criteria are tested using dinoflagellates recovered from strata logged as Bookpurnong beds in boreholes farther to the east (Cal Lal, Talgarry, Piangil West 2) and north (Scotia 1) of the basin (Fig. 2). Where possible, samples from the underlying Geera Clay and/or Winnambool Formation were included in the analysis. The second paper develops spore–pollen criteria for identifying non-marine correlatives of the Bookpurnong beds (Macphail & Truswell, this issue).

Our approach is pragmatic to the extent that we have not attempted to fully document all dinoflagellate species present, although unusual or rare types are illustrated (Plates 1–3). Rather we have focussed on taxa easily identified even when poorly preserved or unfavourably orientated and which have well-documented ranges, providing additional biostratigraphic control on the age limits of the Bookpurnong beds. *Protoellipsodinium* Davey & Verdier is used to accommodate a distinctive group of dinoflagellates having subspherical to elongate ellipsoidal cysts characterized by a single wall layer, precingular archeopyle, and simple processes. Undescribed cysts characterized by a double-layered wall, precingular archeopyle and processes with bifurcating tips are referred to *Operculodinium* Wall.

Lithostratigraphy

The Bookpurnong beds mainly consist of poorly consolidated to plastic, brown to greenish-grey calcareous clays, silts and minor sands. Quartz sand and silty facies are locally important. Glauconitic, micaceous and carbonaceous facies may also be present locally. The formation is separated from the underlying Geera Clay and Winnambool Formation by a regional disconformity (the Mologa Surface), and like these formations was deposited in a low-energy environment across the central western depocentre of the basin (Fig. 3). It differs from the Geera Clay mainly in silt and carbonate content (higher) and colour (lighter), and from the Winnambool Formation in having a higher content of terrigenous clastics, but formation boundaries can be difficult to identify with precision (Brown & Stephenson, 1991 p. 53).

Previous studies

To date, the only palynostratigraphic studies of Tertiary dinoflagellates preserved in the Murray Basin are by

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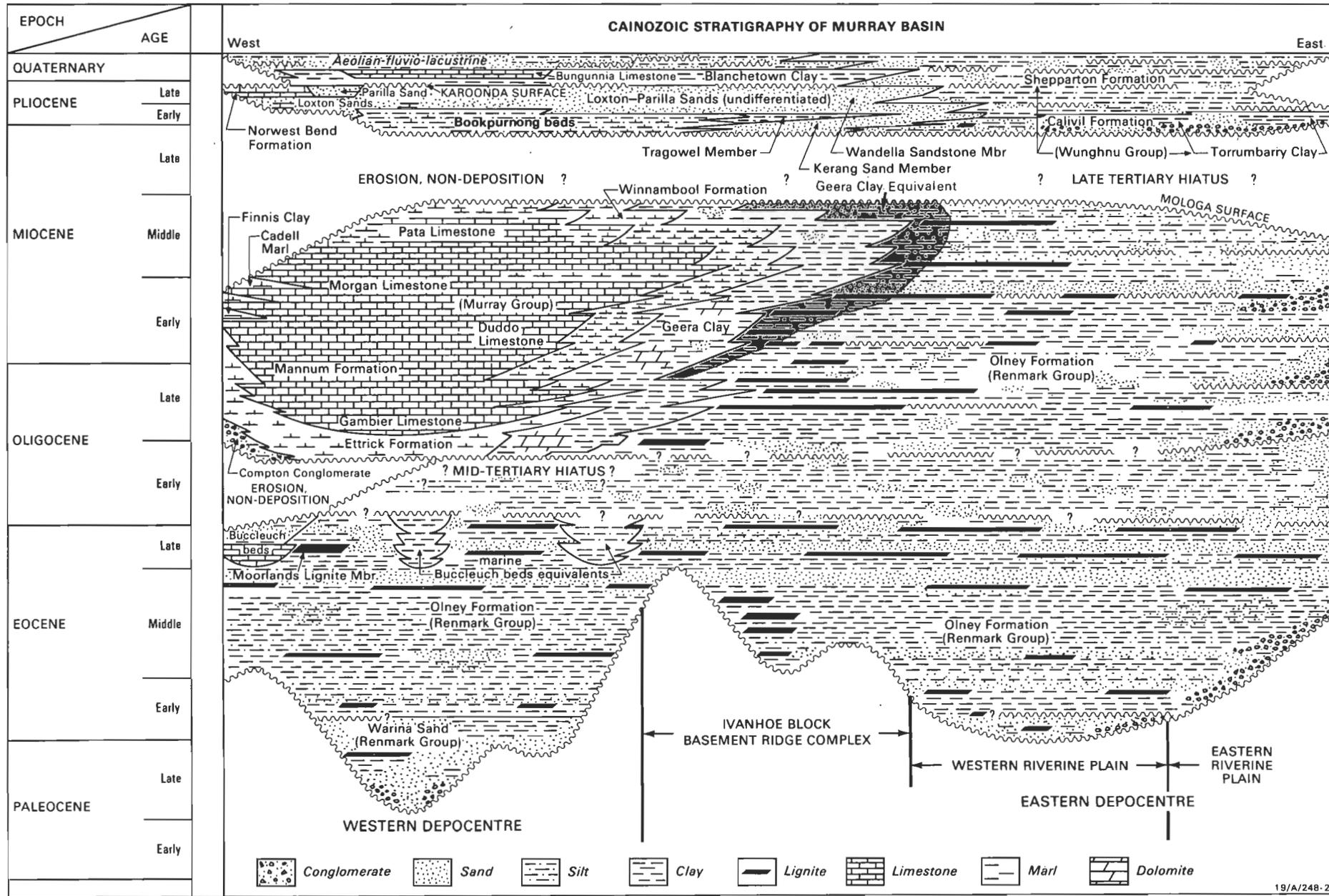


Fig 1. Tertiary stratigraphy of the Murray Basin.

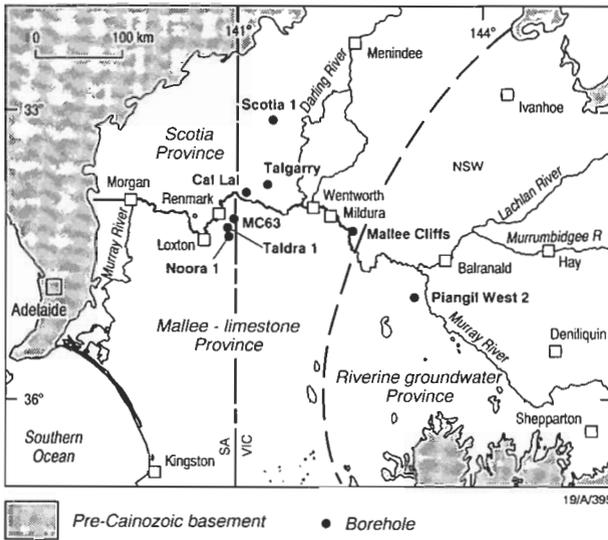


Figure 2. Locality map of boreholes used in this study.

Martin (1991) based on the South Australian Department of Mines and Energy (SADME) bore MC63, and Martin (1993) on the N.S.W. Department of Water Resources Mallee Cliffs bore 36465.

Dinoflagellates are extremely sparse in the two samples of Bookpurnong beds analysed, but diverse assemblages were recovered from the underlying Oligocene–Middle Miocene platform carbonates and marls of the Murray Group limestones and Ettrick Formation. Bookpurnong beds facies are not recorded in the Mallee Cliffs bore, although long-ranging dinoflagellates are present at the base of the Loxton–Parilla Sands. Dinoflagellate successions in Pliocene to Holocene carbonates in the Gippsland Basin have been studied by McMinn (1992a). Independent age control is provided by planktonic foraminifera at all three sites.

Borehole sequences

Except for Scotia 1, the boreholes analysed here are aligned along a gradient extending southeast from the central west depocentre (Mallee–Limestone aquifer prov-

ince of Evans & Kellett, 1989) into the Riverine Plain depocentre (Riverine aquifer province). All are located close to the Murray River and therefore within reach of salt-water incursions along palaeodrainage lines during the Late Tertiary (Stephenson & Brown, 1989). Scotia 1, occurs in the northwest of the basin, within the Scotia aquifer province.

Noora 1, Piangil West 2, Scotia 1, and Taldra 1 boreholes were conventionally cored, whilst cuttings samples only were available for Cal Lal and Talgarry. The latter were fully flushed between collection and all cuttings are considered to be a reliable sample of sediments over the depth indicated. Palynological strew mounts were prepared using (a) filtered, unoxidized and (b) oxidized residues by Laola Pty. Ltd., Midland, Western Australia — a technique which minimises loss of fragile dinocysts whilst providing acceptable spore–pollen concentrations. All mounts were examined for fossil dinoflagellates, spores and pollen using a Zeiss Photomicroscope fitted with Planapo and Neofluar objectives.

Only the Neogene marine section of each borehole is discussed here. Distributions of selected dinoflagellates and the ratio of marine dinocysts to spores and pollen (providing a crude estimate of the strength of the marine influence) are given in Figures 4a to 4f. Open squares indicate possible reworked or caved specimens (see below).

(A) MALLEE-LIMESTONE PROVINCE

(1) Noora 1

Figure 4a

Noora 1 (486300E, 6191750N) is located 26 km east-northeast of Loxton, a major irrigation centre on the Murray River in South Australia. Borelog data indicate the following Late Cenozoic units are present:

- 1.5–3.5 m Yamba Formation
- 3.5–29.5 m Loxton Sands
- 29.5–55.2 m Bookpurnong beds
- 55.2–72.9 m Winnambool Formation

Fourteen core samples representing the interval 33.04–53.72 m within the Bookpurnong beds, and one sample from a bioturbated silty clay bed in the Winnambool

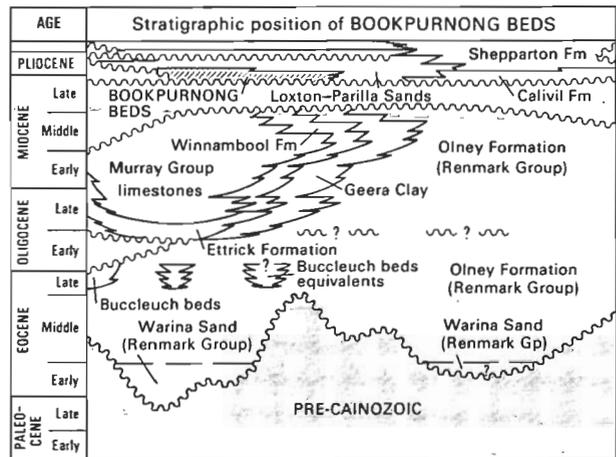
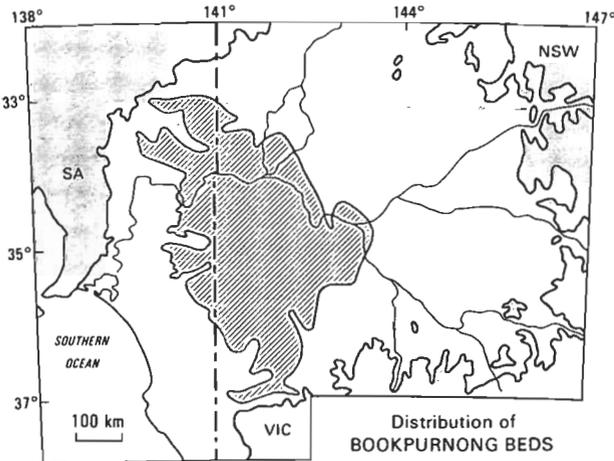
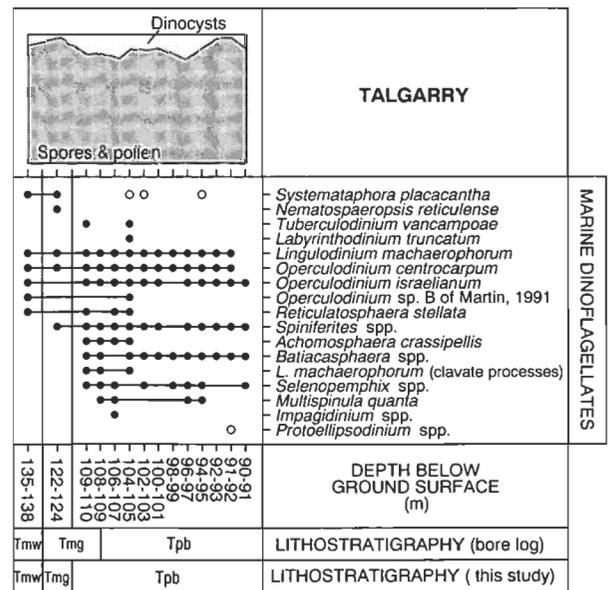
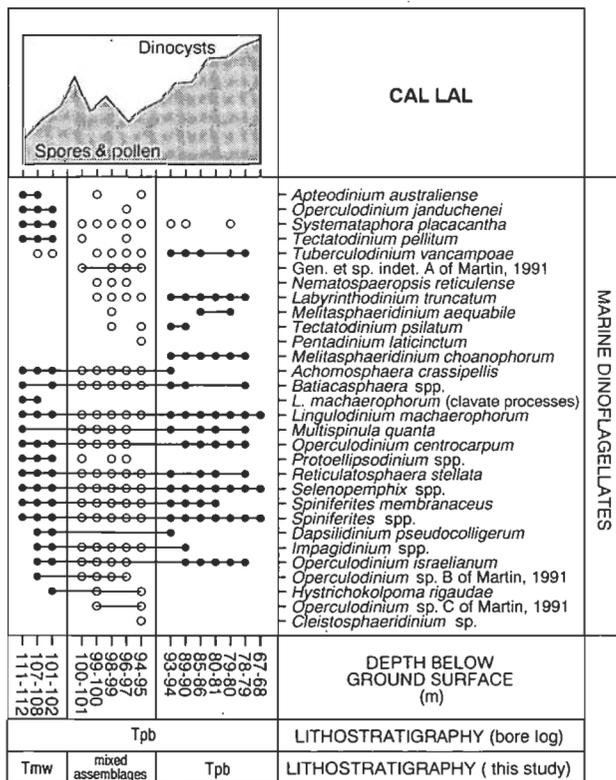
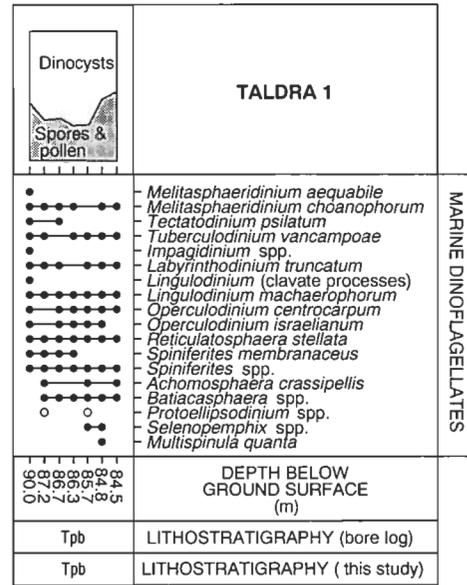
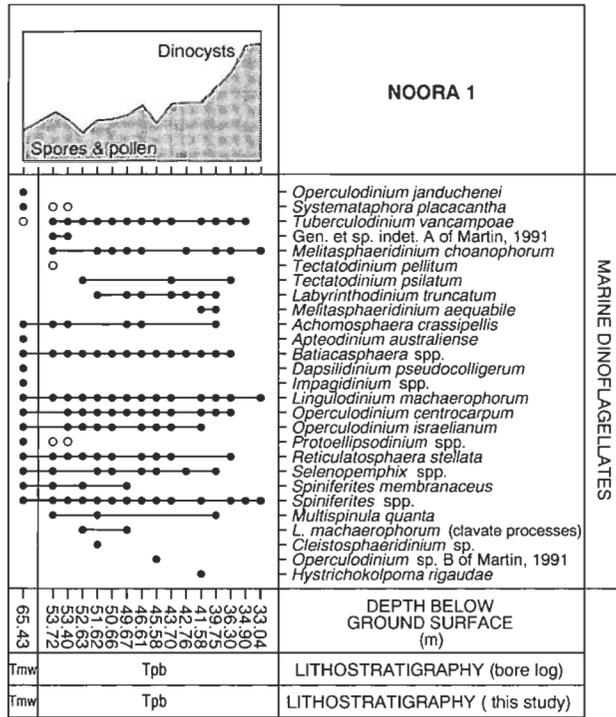


Figure 3. Distribution and stratigraphic position of the Bookpurnong beds.

Formation (65.43–65.45 m) were made available for palynological analysis. The Bookpurnong beds comprise a basal carbonate sand approximately 2.4 m thick, overlain by an alternating but overall coarsening upwards sequence of weakly cemented, glauconitic claystones, sandy claystones and clay-rich sandstones.

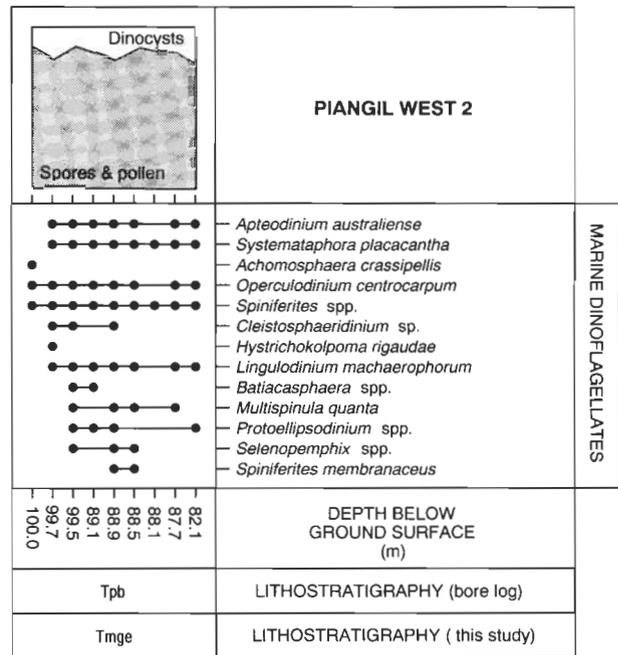
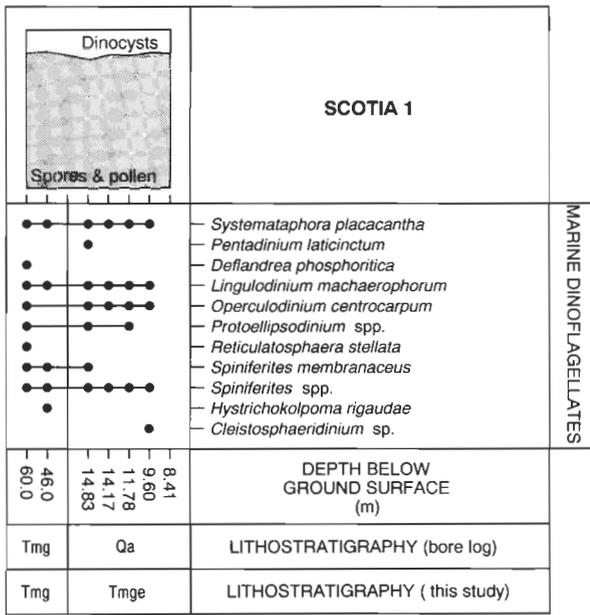
Winnambool Formation 65.42–65.45 m

The palynoflora is dominated by marine dinoflagellates, in particular *Apteodinium australiense*, *Batiacasphaera* spp., *Protoellipsodinium* spp., *Spiniferites* spp., and *Systematophora placacantha*. Uncommon species include *Dapsilidinium pseudocolligerum* (Stover) Bujak et al., *Impagidinium* spp., *Operculodinium janduchenei* Head et



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Figure 4. Stratigraphic distributions of selected dinoflagellates in (a) Noora 1, (b) Taldra 1, (c) Cal Lal, (d) Talgarry, (e) Scotia 1 and (f) Piangle West 2. Tmw = Winnambool Formation; Tmg = Geera Clay; Tmge = Geera Clay equivalent; Tpb = Bookpurnong beds; Qa = undifferentiated Quaternary sediments.



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al., *Spiniferites membranaceus* (Rossignol) Sarjeant, *Selenopemphix* spp., and *Tuberculodinium vancampoeae* (Rossignol) Wall. *Pentadinium laticinctum* was not recorded. *Botryococcus* (common), Desmidiaceae, and *Azolla* indicate an influx of brackish to fresh water.

Bookpurnong beds 33.04–53.72 m

Samples within this interval yielded variable amounts of marine dinoflagellates, and only in the top 2 m are numbers exceeded by spores and pollen. Species frequent to abundant in most samples include *Batiacasphaera* spp., *Lingulodinium machaerophorum* (Deflandre & Cookson) Wall, *Operculodinium* spp., *Reticulatosphaera stellata* Matsuoka, and *Spiniferites* spp. including *S. membranaceus*. *Tuberculodinium vancampoeae* is present in most samples. *Multispinula quanta* Bradford and *Selenopemphix* spp., including *S. nephroides* Benedek, occur in samples from the muddier facies.

Dinoflagellates present in the Bookpurnong beds samples, but not in the underlying Winnambool Formation sample at 65.42–65.45 m, include Gen. et sp. indet. A of Martin (1991), *Labyrinthodinium truncatum* Piasecki, *Melitasphaeridium aequabile* Matsuoka, *M. choanophorum* (Deflandre & Cookson) Harland & Hill, and *Tectatodinium psilatium* Wall et al. Fragments of *Systematophora placacantha* at 53.4–53.70 m and *Tectatodinium pellitum* Wall at 53.70 m are considered to be reworked from the underlying Winnambool Formation.

(2) Taldra 1 (Gordon 46) Figure 4b

Taldra 1 (485000E, 6201800N) is 10 km north-northwest of Noora 1 and 18 km southeast of Renmark. Borelog data indicate the following Late Cenozoic units are present:

- 0–15 m Parilla Sands
- 74–86 m Bookpurnong beds
- 86–120 m Winnambool Formation

Seven samples representing the interval 84.5–90.0 m were made available for palynological analysis. Dinoflagellates (this study) and lithology (moderately dark, silty, calcareous clays) indicate that the top 4 m of the interval assigned to Winnambool Formation are actually Bookpurnong beds. The ratio of dinoflagellates to spore–pollen decreases upsection, consistent with a diminishing marine influence.

Bookpurnong beds 84.5–90.0 m

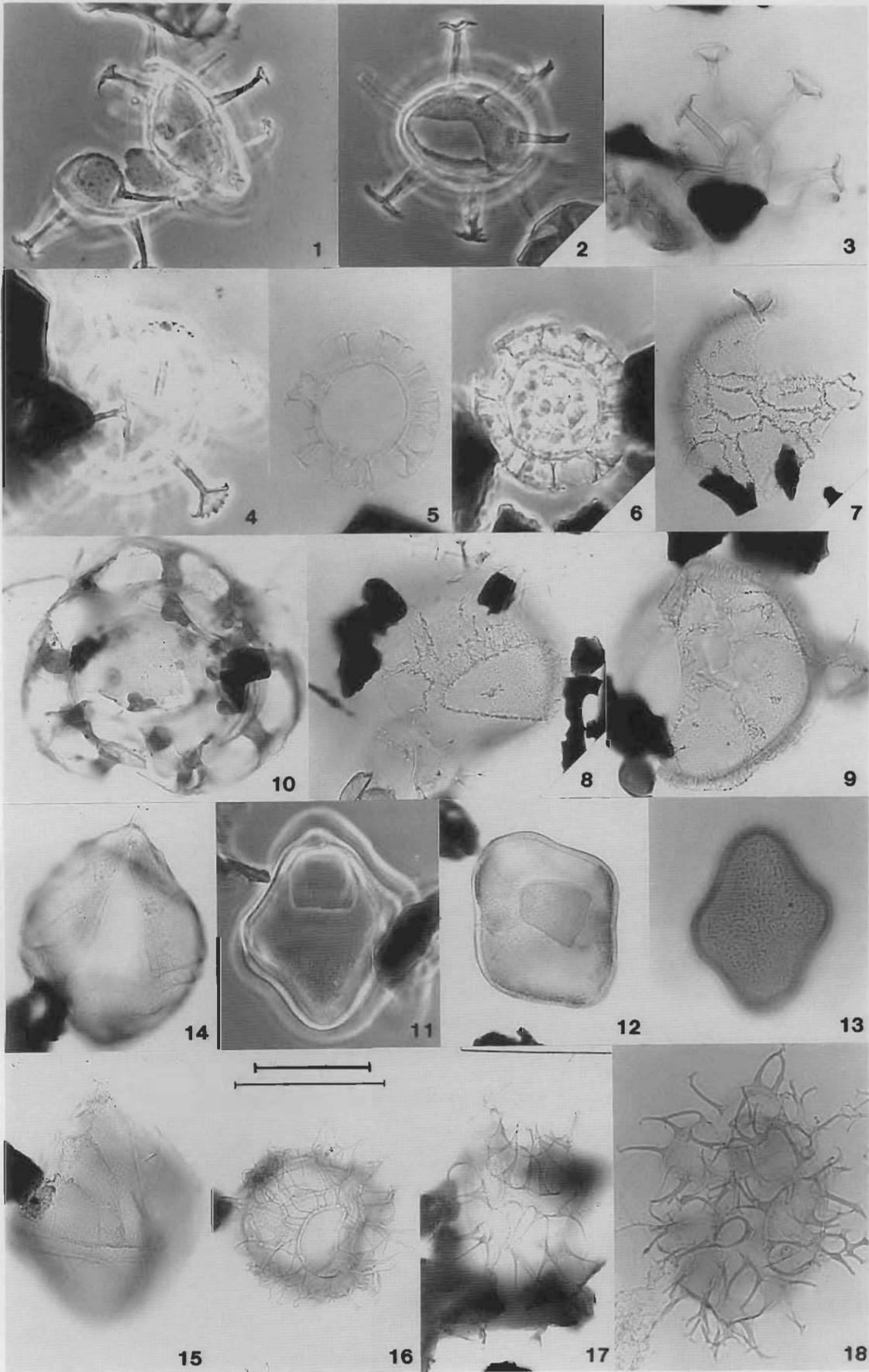
Dinoflagellates in this interval are dominated by *Spiniferites* spp. and *Operculodinium* spp. *Lingulodinium machaerophorum* and *Reticulatosphaera stellata* are frequent to common in individual samples. *Batiacasphaera* spp., *Labyrinthodinium truncatum*, *Melitasphaeridium choanophorum*, *Spiniferites membranaceus*, and *Tuberculodinium vancampoeae* are present in the majority of samples. *Selenopemphix* spp. occur mostly towards the top, and *Melitasphaeridium aequabile* and *Tectatodinium psilatium* towards the base of the unit. *Apteodinium australiense*, *Pentadinium laticinctum*, and *Systematophora placacantha* were not recorded.

(3) Cal Lal (DWR 36783) Figure 4c

The borehole (512130E, 6241450N) is located on the intersection of the Wentworth–Renmark Road and the Regunyah Road on the northern side of the Murray River, virtually at the tri-State junction. Borelog data indicate the following Late Cenozoic units are present:

- 0–19 m Undifferentiated Quaternary alluvium
- 19–79 m Loxton–Parilla Sands
- 79–112 m Bookpurnong beds
- 112–134 m Winnambool Formation?

Fifteen samples were available for palynological analysis. The interval logged as Bookpurnong beds consists of dark greenish-grey glauconitic and pyritic clayey silts, and silty clays which coarsen upwards into clayey fine sands between 67–79 m at the base of the Pliocene Sands.



Dinoflagellates (this paper) indicate that three palynologically distinct marine units are present between 67–112 m, interpreted as Bookpurnong beds (67–94 m) and Winnambool Formation (101–112 m), separated by a bioturbated interval.

Winnambool Formation 101–112 m

Palynofloras within this interval are characterised by frequent to abundant *Operculodinium* spp., *Protoellipsodinium* spp., *Spiniferites* spp., including *S. membranaceus*, and *Systematophora placacantha*. Less frequent taxa include *Apteodinium australiense*, *Batiacasphaera* spp., *Dapsilodinium pseudocolligerum*, *Hystrichokolpoma rigaudae* Deflandre & Cookson, *Impagidinium* spp., *Lingulodinium machaerophorum*, *Multispinula quanta*, *Selenopemphix* spp., *Operculodinium janduchenei*, *Reticulatosphaera stellata*, and *Tectatodinium pellitum*. *Tuberculodinium vancampoe* occurs near the top of the interval.

Bookpurnong beds 67–94 m

Dinoflagellates present in this interval, but not recorded between 101–112 m, include Gen. et sp. indet. A of Martin (1991), *Labyrinthodinium truncatum*, *Melitasphaeridium aequabile*, *M. choanophorum* and *Tectatodinium psilatam*. All are sporadically distributed. *Batiacasphaera* spp., *Reticulatosphaera stellata*, and *Tuberculodinium vancampoe* occur in the majority of samples. Fragments of *Systematophora placacantha* at 78–79 m, 89–90 m and 93–94 m are considered to be reworked.

“Mixed assemblage” Zone 94–101 m

This interval, which corresponds to an apparent expansion of dinoflagellates relative to spore and pollen, includes species typical of both the Winnambool Formation (e.g. *Apteodinium australiense*, *Operculodinium janduchenei*, *Pentadinium laticinctum*, *Protoellipsodinium*, *Tectatodinium pellitum*), and Bookpurnong beds (e.g. *Labyrinthodinium truncatum*, *Melitasphaeridium aequabile*, *Tectatodinium psilatam*). *Nematosphaeropsis reticulense* (Pastels) Sarjeant is restricted to this interval.

(4) Talgarry (DWR 36851) Figure 4d

Talgarry (537270E, 6246540N) is located 26 km east-northeast of Cal Lal on the northeastern side of Lake Victoria. Borelog data indicate the following Late Cenozoic units are present:

0–6	m	Woorinen Formation
6–26	m	Blanchetown Clay
26–90	m	Loxton–Parilla Sands
90–110	m	Bookpurnong beds
110–135	m	Geera Clay
135–166	m	Winnambool Formation

Fourteen cuttings samples were available for palynological analysis. Those at 135–138 m (Winnambool Formation) and 122–124 m (Geera Clay) are over-oxidized, resulting in the loss of some dinoflagellates. The abundance of dinoflagellates relative to spores and pollen in the Bookpurnong beds interval is very low compared to Noora 1, Taldra 1 and Cal Lal, with values decreasing to negligible levels at 91–92 m. Samples at 76–81 m and 60–61 m in the Loxton–Parilla Sands are non-marine.

The Bookpurnong beds consist of very dark-grey to black, carbonaceous, clayey fine sands grading to black carbonaceous sandy clay at depth. Pale grey weakly cemented siltstone and pyritic sandstone bands incorporating broken shell fragments occur between 103–109 m.

Winnambool Formation 135–138 m

This sample yielded moderate numbers of dinoflagellates, including *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* (Deflandre & Cookson) Wall, *O. israelianum* (Rossignol) Wall, *O. sp. B* of Martin, *Protoellipsodinium* spp., *Reticulatosphaera stellata*, *Spiniferites* spp., and *Systematophora placacantha*.

Geera Clay 122–124 m

The dinoflagellate flora at 122–124 m closely resembles that at 135–138 m, except that *Systematophora placacantha* is the most common dinoflagellate recorded and *Nematosphaeropsis reticulense* is present in low numbers.

Bookpurnong beds 91–110 m

Dominance is variable, with *Spiniferites* spp. being the most common taxon. *Lingulodinium machaerophorum* and *Selenopemphix* spp. are frequent to common in some samples. Dinoflagellates typical of the Bookpurnong beds in Noora 1, Taldra 1 and Cal Lal are absent except for *Labyrinthodinium truncatum*. The interval is provisionally correlated with the Bookpurnong beds, based on the persistent presence of Late Miocene–Early Pliocene spore and pollen indicators (see Macphail & Truswell, this issue).

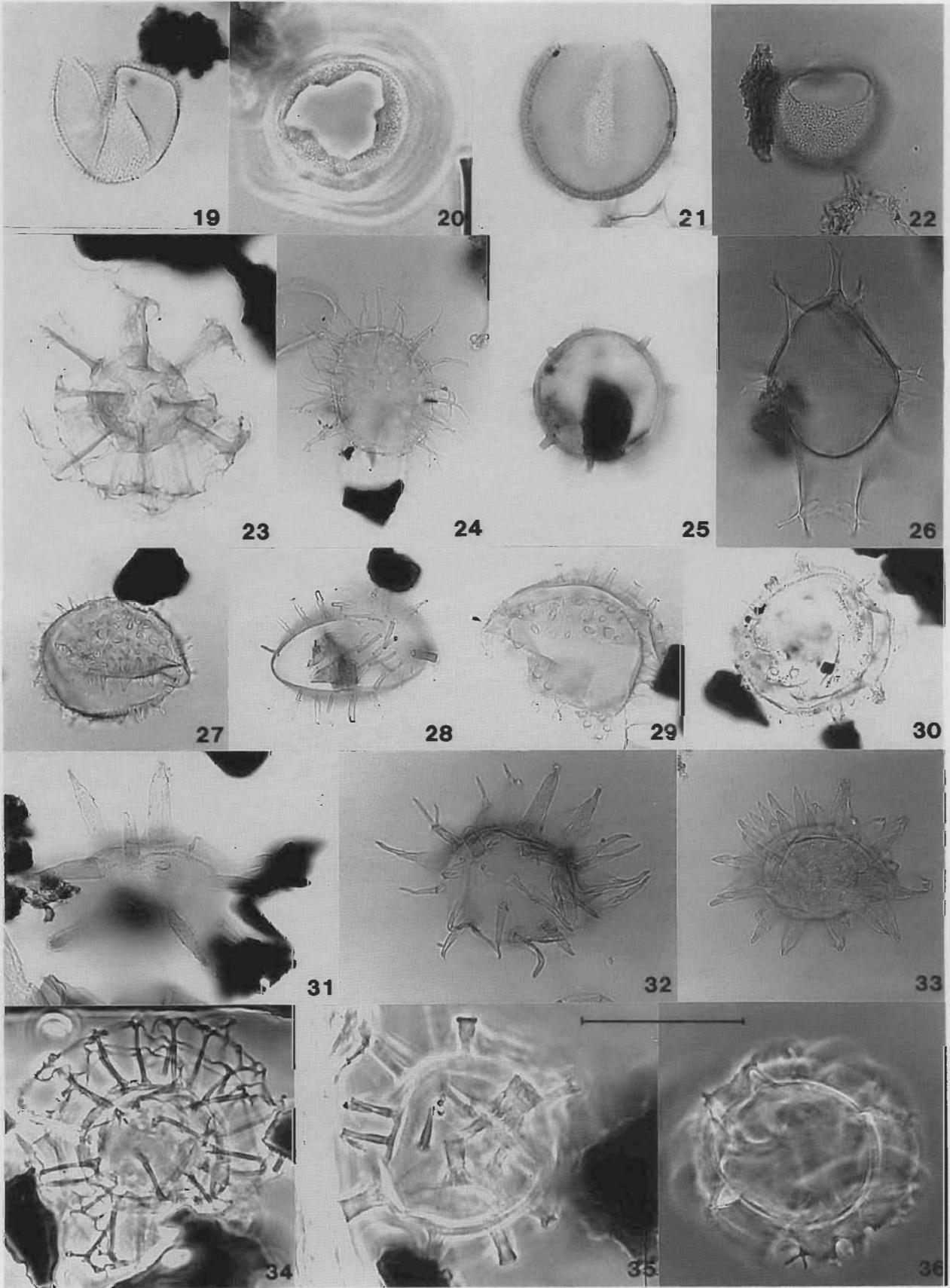
(B) SCOTIA PROVINCE

(1) Scotia 1 Figure 4e

Scotia 1 (533580E, 6334690N) is located on the Scotia Lakes, west of the Darling River Anabranch in New South Wales. Drilling has established that the Parilla Sand is about 8 m thick below the salt lake and overlies a clay. This was initially identified as Pleistocene because of the shallow depth, but has been reinterpreted as Geera Clay equivalent (Macphail & others, 1993). Microfossil distributions may have been disturbed during the development and lateral spread of a brine pool in the Parilla Sand, although there is no evidence that saline water has penetrated through the underlying clays.

Plate 1.

Fig. 1. *Melitasphaeridium aequabile*, Noora 1, 33.04–33.06m, phase contrast x1250. Fig. 2. *Melitasphaeridium* sp. cf. *M. aequabile*, Noora 1, 39.75–39.78m, phase contrast x1250. Fig. 3. *Melitasphaeridium choanophorum*, Taldra 1, 86.3–86.4m, x 1250. Fig. 4. *Melitasphaeridium choanophorum*, Noora 1, 45.58–44.61m, phase contrast x 1250. Fig. 5. *Labyrinthodinium truncatum*, Noora 1, 49.67–49.69m, x 1250. Fig. 6. *Labyrinthodinium truncatum*, Taldra 1, 86.7–86.8m, phase contrast x 1250. Fig. 7. Gen. et sp. indet. A of Martin 1991, Noora 1, 53.4m, x 400. Fig. 8. Gen. et sp. indet. A of Martin 1991, Noora 1, 53.4m, x 788. Fig. 9. Gen. et sp. indet. A of Martin 1991, Cal Lal, 94–95m, x 788. Fig. 10. *Tuberculodinium truncatum*, Noora 1, 39.75–39.78m, x 788. Fig. 11. *Tectatodinium psilatam*, Taldra 1, 90.0m, phase contrast x 1250. Fig. 12. *Tectatodinium psilatam*, Noora 1, 52.63–52.65m, x 1250 [detached operculum inside cyst]. Fig. 13. *Tectatodinium psilatam*, Taldra 1, 86.7–86.8m, x 1250 [verrucate ornamentation]. Fig. 14. *Apteodinium australiense*, Piangil West 2, 87.7–87.9m, x 788. Fig. 15. *Apteodinium australiense*, Piangil West 2, 87.7–87.9m, x 788. Fig. 16. *Systematophora placacantha*, Piangil West 2, 88.1m, x 788. Fig. 17. *Systematophora placacantha*, Piangil West 2, 99.7m, x 788. Fig. 18. *Systematophora placacantha*, Cal Lal, 96–97m, x 788.



Geera Clay 46.0–60.0 m

The two samples in this interval are dominated by spores and pollen. *Spiniferites* and *Systematophora placacantha* are the only dinoflagellates present in significant numbers. Rare taxa include *Deflandrea phosphoritica* Eisenack and *Reticulosphaera stellata* at 60.0 m, and *Hystrichokolpoma rigaudae* and *Lingulodinium machaerophorum* at 46.0 m.

Geera Clay equivalent 8.41–14.83 m

Samples within this interval closely resemble those at 46.0 m and 60.0 m, except that dinoflagellates are more abundant and the spores and pollen component is more diverse. *Systematophora placacantha* is usually frequent. *Pentadinium laticinctum* occurs at 14.83 m. Dinoflagellates characteristic of the Bookpurnong beds in Noora 1 and Taldra 1 are absent, although one assemblage, at 11.78 m, includes a pollen type that first appears in the Late Miocene, *Rhoipites ampereaformis* Macphail & Truswell.

**(C) RIVERINE DEPOCENTRE
(RIVERINE PROVINCE)****(1) Piangil West 2****Figure 4f**

The Piangil West 2 borehole (702500E, 6118300N) is located 8 km west of Piangil, in the Swan Hill district of northern Victoria. Detailed analyses of lithofacies and spore–pollen in the Geera Clay are given in Brown & Radke (1989) and Macphail & Truswell (1989). Late Cenozoic units penetrated by the bore are:

0–9	m	Yamba Formation
9–81.5	m	Loxton–Parilla Sands
81.5–102	m	Bookpurnong beds
102–232	m	Geera Clay

Nine samples were available for palynological analysis. The interval logged as Bookpurnong beds consists of bioturbated, interbedded, dark olive-grey sand, mud and sandy silts which grade upsection into mottled grey and olive-black, pebbly, sandy clays and muds. Dinoflagellates (Macphail & others, 1993; this study) indicate that the unit is a regressive facies (Geera Clay equivalent) overlying the Geera Clay.

Geera Clay equivalent 82.1–100.0 m

Samples within this interval yielded variable but mostly low numbers of dinoflagellates. *Systematophora placacantha* is frequent in most samples, and *Apteodinium australiense* and species of *Cleistosphaeridium*, *Operculodinium* and *Spiniferites* frequent in occasional samples. Uncommon taxa include *Batiacasphaera* spp., *Lingu-*

lodinium machaerophorum, *Multispinula quanta*, *Protoleipsodinium* spp., *Selenopemphix* spp., and *Spiniferites membranaceus*. *Tuberculodinium vancampoae* and other species characteristic of the Bookpurnong beds in Noora 1 and Taldra 1 are not recorded.

Comparison with SADME MC63 borehole

The SADME MC63 borehole (494400E, 6214000N) lies 15 km northeast of Taldra 1. Late Cenozoic units intersected in the borehole are:

0–86	m	Loxton–Parilla Sands
86–100	m	Bookpurnong beds
100–250	m	Murray Group limestone

Data presented by Martin (1991) indicate *Melitasphaeridium aequabile* ranges from the Murray Group limestone into the Bookpurnong beds interval; *M. choanophorum* occurs at the top of the limestone and (caved?) in one sample (312–314 m) near the base of the underlying Oligocene–late Early Miocene Ettrick Formation. *Labyrinthodinium truncatum* and Gen. et sp. indet. A are restricted to the limestone sequence and *Apteodinium australiense*, *Batiacasphaera* spp., *Lingulodinium machaerophorum*, *Operculodinium* spp., including *O. janduchenei*, *Reticulosphaera stellata*, *Systematophora placacantha*, and *Tectatodinium pellitum* range no higher than this formation. *Tectatodinium psilatatum* was not recorded.

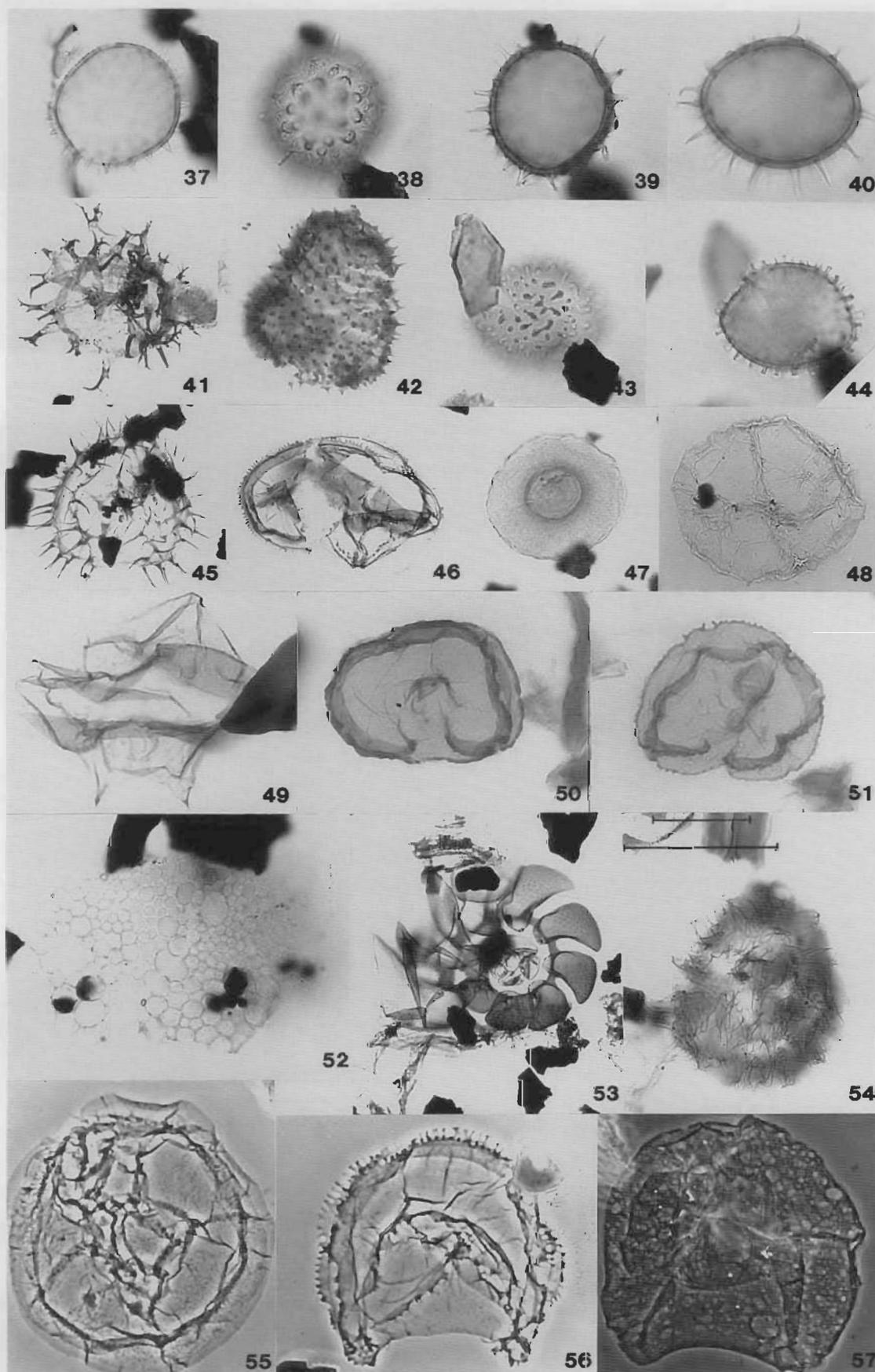
The Mallee Cliffs borehole 36465 (628100E, 6219800N) is located on the northern banks of the Murray River 25 km southeast of Mildura. Late Cenozoic units intersected in the bore are:

0–66	m	Loxton–Parilla Sands
66–169	m	Geera Clay (upper unit)
169–244	m	Duddo Limestone

Data presented by Martin (1993) indicate *Melitasphaeridium choanophorum*, *Hystrichokolpoma rigaudae*, *Pentadinium laticinctum*, and *Reticulosphaera stellata* occur in cuttings dated as Oligocene–late Early Miocene, close to the base of the Geera Clay. *Tuberculodinium vancampoae* occurs in cuttings of the same age at the base of the Geera Clay and close to the top of the Duddo Limestone. *Apteodinium australiense*, *Lingulodinium machaerophorum*, and *Systematophora placacantha* occur in late Early–Middle Miocene and Oligocene–late Early Miocene sections of the Geera Clay; *Operculodinium janduchenei* and *Tectatodinium pellitum* range no higher than the Duddo Limestone. Gen. et sp. indet. A, *Labyrinthodinium truncatum* and *Tectatodinium psilatatum* were not recorded.

Plate 2.

Fig. 19. *Batiacasphaera* sp. cf. *B. hirsuta*, Noora 1, 52.63–52.65m, x 1250. **Fig. 20.** cf. *Bitectatodinium tepikiense*, Noora 1, 45.58–45.61m phase contrast x 1250 [archaeopyle]. **Fig. 21.** cf. *Bitectatodinium tepikiense*, Noora 1, 45.58–45.61m, x 1250. **Fig. 22.** *Tectatodinium* sp., Talgarry, 100–101m, x 788. **Fig. 23.** *Reticulosphaera stellata*, Taldra 1, 85.7–85.9m, x 1250. **Fig. 24.** *Lingulodinium* sp. cf. *L. machaerophorum*, Noora 1, 39.75–39.78m, x 788 [narrow acuminate processes]. **Fig. 25.** *Lingulodinium*?, Taldra 1, 86.7–86.8m, x 788. **Fig. 26.** *Spiniferites membranaceus*, Scotia 1, 14.83m, x 788. **Fig. 27.** *Lingulodinium* sp. cf. *L. machaerophorum*, Noora 1, 43.7m, x 788 [short acuminate processes]. **Fig. 28.** *Lingulodinium* sp. cf. *L. machaerophorum*, Piangil West 2, 99.7m, x 788 [narrow blunt processes]. **Fig. 29.** *Lingulodinium* sp. cf. *L. machaerophorum*, Noora 1, 49.67–49.69m, x 788 [short blunt processes]. **Fig. 30.** *Lingulodinium* sp. cf. *L. machaerophorum*, Noora 1, 49.67–49.69m, x 788 [club-like processes]. **Fig. 31.** *Lingulodinium machaerophorum* var., Taldra 1, 87.2–87.3m, x 788. **Fig. 32.** *Lingulodinium machaerophorum* var., Taldra 1, 87.2–87.3m, x 788. **Fig. 33.** *Lingulodinium machaerophorum* var., Talgarry, 104–105m, x 788. **Fig. 34.** *Nematosphaeropsis* sp. cf. *N. labyrinthina*, Noora 1, 49.67–49.69m, phase contrast x 1250. **Fig. 35.** cf. *Homotryblium*, Noora 1, 52.63m, phase contrast x 1250. **Fig. 36.** *Spiniferites*?, Cal Lal, 96–97m, phase contrast x 1250.



Age limits of the Bookpurnong beds

Several of the dinoflagellates recorded in the Bookpurnong beds have well-established international (chiefly northern hemisphere) time distributions: *Melitasphaeridium choanophorum* which ranges from the late Early Oligocene (nanofossil Zone NP23) to the Early Pliocene (nanofossil Zone NN12); *Tuberculodinium vancampoeae* ranging from the Late Oligocene (nanofossil Zone NP24) to the Present; and *Labyrinthodinium truncatum* ranging from the Middle to early Late Miocene (nanofossil Zones NN5–NN10) (Williams & Bujak, 1985; Powell, 1992). *Hystrichokolpoma rigaudae* ranges no higher than nanofossil Zone NN14 (Early Pliocene).

Melitasphaeridium choanophorum and *Tuberculodinium vancampoeae* have similar last appearance times in the offshore Gippsland Basin (McMinn, 1992a). *Labyrinthodinium truncatum* and *Hystrichokolpoma rigaudae* are absent. *Systematophora placacantha* occurs in carbonates independently dated as Early Pliocene and (in one sample) basal Late Pliocene age, although it is possible that all specimens are reworked (*ibid.*, p. 154).

The precision with which the time distribution of these species can be used to date sediments in the land-locked Murray Basin is unclear. For example, based on its international range, *Labyrinthodinium truncatum* indicates that the Bookpurnong beds in Taldra 1 are no younger than early Late Miocene. This age limit is inconsistent with the microfaunal evidence (see Brown & Stephenson, 1991 p. 153) and a more realistic explanation is *L. truncatum* has an extended range within the Murray Basin. Similar evidence of ecologic provincialism of dinoflagellate species is provided by the extreme rarity of *Tuberculodinium vancampoeae* and, except for the Mallee Cliffs and SADME MC63 bores, the absence of *Melitasphaeridium choanophorum* in Oligocene–Middle Miocene sediments. Both species are ubiquitous in the Bookpurnong beds.

At present, we prefer to rely on microfaunal age limits, but note that records of *M. choanophorum* and *Hystrichokolpoma rigaudae* are consistent with a minimum age of Early Pliocene for the Bookpurnong beds. To date, the most reliable dinoflagellate evidence that the Bookpurnong beds are no older than Late Miocene is negative — the absence of *Apteodinium australiense* and *Pentadinium laticinctum*. Records of *Systematophora placacantha* in the Bookpurnong beds are presumed to be reworked until more compelling evidence is available that the species ranges into the Early Pliocene (compare Head & others, 1989).

Depositional environment

Faunas in the Bookpurnong beds are typical of low-energy shelf conditions, leading Brown & Stephenson (1991) to

interpret the formation as a shallow-marine to lower shore-face facies which grades north and east into the upper shore-face and littoral facies of the basal Loxton–Parilla Sands. The transgression is considered to have occurred rapidly, followed by a gradual regression resulting in progradation of sands over the muddy, quieter-water sediments.

Relative abundances of marine dinoflagellates (Figs. 4a to 4d) strongly supports both conclusions given that marine dinoflagellates ratios are (a) highest in the bore closest to central western depocentre (Noora 1) and lowest in the most landward bore (Talgarry) and (b) show an overall decrease upsection, markedly so in the case of Noora 1 and Cal Lal. Based on studies of Neogene to Recent populations of dinoflagellates in eastern Australian waters (McMinn, 1992b), *Protooperidinium (Selenopemphix)* and *Operculodinium israelianum* indicate normal seawater salinities, whilst the latter species and *Tuberculodinium vancampoeae* indicate warm water.

Two lines of evidence, however, indicate a persistent fresh-water influence, although it is unclear whether the influx was high enough to affect local salinity levels:

- The occurrence in many samples of the buoyant microspore bodies (massulae) produced by the free-floating, fresh-brackish water fern *Azolla*. Fresh to brackish water algae, such as *Botryococcus*, Desmidiaceae and *Pediastrum*, are present but rare compared to numbers recovered from the Geera Clay.
- The sporadic (but then frequent) occurrence of a dinoflagellate believed to be restricted to fresh or brackish water, *Tectatodinium psilatum* (Plate 1). This variable species was first described by Wall & others (1973) from Holocene sediments in the Black Sea, where it is associated with a distinctive variant of *Lingulodinium machaerophorum* in which the usual blade-like processes are replaced by club-like spines. The same morphotype is present in dinoflagellate assemblages recovered from the Geera Clay, Winnambool Formation, and Bookpurnong beds (Plate 2).

Discussion and conclusions

Two conditions need to be fulfilled before a sedimentary unit can be shown to be characterized by a particular fossil species or assemblage of species: (1) the samples analysed are accurate representatives of that unit, and (2) the fossils are *in situ*.

Neither condition is fully satisfied in this study due to: (a) uncertainties in the position of the formation boundaries, (b) possible downhole caving of younger material (cuttings samples), (c) drilling mud-contamination of weakly lithified sediments (some core samples), and (d) reworking of older palynofloras (ubiquitous in the Murray Basin). All may have contributed to blurring of palynos-

Plate 3.

Fig. 37. *Operculodinium* sp. cf. *O. janduchenei*, Noora 1, 65.43–65.45m, x 788. **Fig. 38–39.** *Operculodinium* sp. cf. *O. israelianum*, Cal Lal, 96–97m, x 788. **Fig. 40.** *Operculodinium* sp. cf. *O. longispinigerum*, Cal Lal, 94–95m, x 788. **Fig. 41.** *Xandarodinium?*, Noora 1, 51.62–51.64m, x 788. **Fig. 42.** *Cleistosphaeridium?*, Noora 1, 51.62–51.64m, x 1250. **Fig. 43.** *Protoellipsodinium* sp., Talgarry, 104–105m, x 788. **Fig. 44.** *Protoellipsodinium* sp., Talgarry, 104–105m, x 788. **Fig. 45.** *Multispinula quanta*, Noora 1, 53.70–53.72m, x 400. **Fig. 46.** *Selenopemphix brevispinosa* subsp. *conspicua*, Noora 1, 51.62–51.64m, x 788. **Fig. 47.** ?*Pterospermella* sp. of Martin 1993, Piangil West 2, 99.5m, x 788. **Fig. 48.** Unidentified taxon, Cal Lal, 101–101m, x 788. **Fig. 49.** *Lejeunecysta* sp., Talgarry, 96–97m, x 788. **Fig. 50.** *Selenopemphix* sp. cf. *S. nephroides*, Talgarry, 90–91m x 788. **Fig. 51.** *Selenopemphix* sp. cf. *S. brevispinosa*, Taldra 1, 84.5m, phase contrast x 1250. **Fig. 52.** Fragment of vacuolate massulae of *Azolla*, Noora 1, 43.7m, x 788. **Fig. 53.** Foraminiferal trochospiral liner, Cal Lal, 100–101m, x 400. **Fig. 54.** *Cleistosphaeridium* sp., Piangil West 2, 88.9m, x 788. **Fig. 55.** Unidentified taxon, Piangil West 2, 88.5m, phase contrast x 1250. **Fig. 56.** *Selenopemphix brevispinosa*, Talgarry, 96–97m, x 788. **Fig. 57.** Unidentified taxon, Cal Lal, 98–99m, phase contrast x 1250.

stratigraphic differences between the Bookpurnong beds and underlying strata.

As a working hypothesis — based on the analysis of upward of one hundred Oligo–Miocene palynofloras from the Murray Basin (Macphail & Kellett, unpubl. data) — we regard: (a) specimens of *Labyrinthodinium truncatum*, *Melitasphaeridium aequabile*, and *M. choanophorum* in the Geera Clay, Murray Group limestone and Ettrick Formation as either caved, or reflecting ecological factors that did not exist in lower-energy depositional environments to the north and east; and (b) specimens of *Pentadinium laticinctum* and *Systematophora placacantha* (mostly fragmented) in the Bookpurnong beds as reworked.

If correct, then two mutually exclusive groups of dinoflagellates can be identified:

- Bookpurnong beds — *Melitasphaeridium aequabile*, *M. choanophorum*, *Tectatodinium psilatatum*, and frequent *Tuberculodinium vancampoae*. We note that specimens of *Nematosphaeropsis reticulense* and Gen. et sp. indet. A of Martin (1991) tend to occur only near the base of this unit.
- Geera Clay, Winnambool Formation and platform carbonate correlatives — *Apteodinium australiense*, *Operculodinium janduchenei*, *Pentadinium laticinctum*; and (frequent) *Impagidinium*, *Protoellipsodinium* spp., and *Systematophora placacantha*.

The finding that the Cal Lal borehole includes both groups separated by a zone of mixed dinoflagellate (and spore-pollen) assemblages in an interval less than 8 m thick is good evidence that dinoflagellate assemblages can be used to separate the two marine transgressions even though some uncertainty exists about the ranges of individual species.

We emphasize that the limits of the Bookpurnong beds are not the limits of Late Miocene–Early Pliocene transgression in the basin, since marine faunas and dinoflagellates also occur in the basal Loxton–Parilla Sands. A similar situation exists in the Renmark Group where some sediments, identical in lithology to the fluvio-lacustrine Olney Formation, are found to preserve marine dinoflagellates (Macphail & Truswell, 1989; Macphail & other, 1993). These demonstrate that a marine influence extended along palaeo-rivers up to about 100 km upstream from the maximum limits of Eocene–Middle Miocene shorelines, and it is likely that analogous saltwater ‘wedges’ extended upstream during the Late Miocene–Early Pliocene transgression. Whether the dinoflagellates associated with such saltwater incursions included diagnostic species, such as *Melitasphaeridium choanophorum*, is unknown.

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Palynostratigraphy of the Bookpurnong Beds and related Late Miocene–Early Pliocene facies in the central west Murray Basin, part 2: spores and pollens

M.K. Macphail¹ & E.M. Truswell²

Fossil spores and pollen preserved in the Late Miocene–Early Pliocene Bookpurnong beds and correlatives of the central west Murray Basin allow a new palynological zone to be recognized: the *Monotocidites galeatus* Zone. In vertical succession, the zone overlies the late Early–Late Miocene *Triporopollenites bellus* Zone and underlies as yet unzoned Late Pliocene–Pleistocene

palynosequences.

Species described as new herein include: *Densoisporites implexus*, *D. simplex*, *Rhoipites ampereaformis*, *R. cissus*, *R. muehlenbeckiaformis*, *R. risus*, *Myrtacidites lipsis*, *Proteacidites punctiporus*, *Malvacipollis regataensis*, *Monotocidites galeatus*, and *Acaciapollenites weissii*.

Introduction

Palynological zones developed for the Gippsland Basin (Stover & Evans, 1973; Stover & Partridge, 1973) are widely used as a biostratigraphic framework elsewhere in southern Australia, including the Murray Basin (see Martin, 1984; Truswell & others, 1985; Macphail & Truswell, 1989).

Zones common to both the Gippsland and Murray Basin extend from the Middle Eocene, Lower *Nothofagidites asperus* Zone to the late Early–Late Miocene, *Triporopollenites bellus* Zone (Fig. 1). It is uncertain whether palynological events defining the upper boundary of the *T. bellus* Zone in the Gippsland Basin, i.e. the first appearance of *Haloragacidites amolus* and/or a marked decrease in the relative abundance of *Nothofagus* pollen, are reliable outside that basin. No palynological zones have hitherto been published for the Late Neogene and Quaternary, except for ‘phases’ defined by changes in the relative abundance of one or more of Casuarinaceae, Myrtaceae, *Nothofagus*, and gymnosperm pollen (see Martin, 1973, 1987).

In this paper, we erect a new palynostratigraphic zone, the *Monotocidites galeatus* Zone, based on fossil spores and pollen preserved in the Late Miocene–Early Pliocene Bookpurnong beds. This marginal marine unit unconformably overlies the Geera Clay/Winnambool Formation, deposited during an earlier, Oligocene–Middle Miocene (*Proteacidites tuberculatus*–*Triporopollenites bellus* Zone) marine transgression in the central west of the basin.

Unlike the scheme proposed by Martin (1987), the zone is defined by the presence or absence of widely dispersed species. Boundaries defined in this way may be less affected by local ecologic factors than zones defined by changes in the relative abundance of selected common pollen types, such as the Casuarinaceae and Myrtaceae.

Geological setting

The geological setting of the Bookpurnong beds and the location and lithostratigraphic details of the four boreholes analysed in this study — i.e. Noora 1 and Taldra 1 (eastern South Australia near Renmark), and Cal Lal, and Talgarry

(southwest N.S.W., close to the tri-State junction) — are given in Macphail & Kellett (this issue).

Palynostratigraphy

Figure 2 gives the time distributions of selected spores, pollen and dinocysts. Filled in squares represent specimens which we propose are *in situ*; open squares represent specimens which we suggest have been caved (downwards) or reworked (upwards) into the Bookpurnong beds. Figure 3 gives the relative abundance of the more common tree, shrub and herb species, expressed as percentages of the total identifiable spore and pollen count (minimum of 200 counts), and the ratio of dinocysts to spores + pollen. Formal descriptions of all new species are given in Appendix 1.

We note that *Triporopollenites bellus*, the nominate species of the late Early to Late Miocene *T. bellus* Zone of Stover & Partridge (1973), has been transferred to *Canthiumidites* by Mildenhall & Pocknall (1989). The original name is retained for the zone in this paper. Map symbols Tpb, Tmg and Tmw refer to the Bookpurnong beds, Geera Clay, and Winnambool Formation, respectively.

Distribution data from the four boreholes presented in Figures 2a–d, allow a new zone, the *Monotocidites galeatus* Zone, to be defined using the presence/absence of selected species including *Densoisporites implexus*, *D. simplex*, *Monotocidites galeatus*, *Myrtacidites lipsis*, and *Rhoipites ampereaformis*. Age control is provided by dinocysts (Macphail & Kellett, this issue) and by macro- and microfaunal remains preserved in the Bookpurnong beds in other bores (Brown & Stephenson, 1991).

Monotocidites galeatus Zone Zone nov.

Diagnostic features. The lower boundary of the zone is defined by the earliest appearance of *Monotocidites galeatus* and/or consistent occurrences of *Densoisporites implexus/simplex*, *Myrtacidites lipsis*, and *Rhoipites ampereaformis*. The upper boundary is defined by the first consistent appearance of *Tubulifloridites pleistocenicus*.

Occurrence. The zone is widespread in the central west Murray Basin where it unconformably overlies the *T. bellus* Zone. Based on data presented by Bint (1981), sediments of *M. galeatus* Zone age are also present in the southwest of Western Australia.

Age: An age range of Late Miocene–Early Pliocene is considered likely, based on the late Middle Miocene

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ERA	SUB-ERA	PERIOD	EPOCH	SUB-EPOCH	AGE (Ma)	PLANKTONIC FORAM ZONES	GIPPSLAND BASIN SPORE-POLLEN ZONES (Stover & Partridge, 1973)	
CENOZOIC	QUATERNARY	NEOGENE	HOLOCENE				<i>T. pleistocenicus</i> ^A	
			PLEISTOCENE	Late	0.01			
				Middle	0.127			
				Early	0.79			
			PLIOCENE	Late	1.64	N21		
				Early	3.4	N19-N20		
	MIOCENE	Late	5.2		N18	<i>T. bellus</i>		
			10.4	N17				
		Middle		N16				
				N15				
				N12-N14				
				N11				
		Early	16.3	N8-N10				
				N7				
	OLIGOCENE	Late	23.3	N5-N6	Upper <i>P. tuberculatus</i>			
				N4				
			Early	29.3	P21-P22	Middle <i>P. tuberculatus</i>		
					P20			
				35.4	P19	Lower <i>P. tuberculatus</i>		
					P18			
		P17			Upper <i>N. asperus</i>			
		P16						
		Middle	38.6	P15	Middle <i>N. asperus</i>			
				P14				
			50.0	P11-P13	Lower <i>N. asperus</i>			
				P10				
	P9			<i>P. asperopolus</i>				
	P8			Upper <i>M. diversus</i>				
	PALEOCENE	(THANETIAN)	56.5	P7	Middle <i>M. diversus</i>			
				P6	Lower <i>M. diversus</i>			
		(DANIAN)	60.5	P5	Upper <i>L. balmei</i>			
				P3-P4				
65.0			P2	Middle <i>L. balmei</i>				
			P1					

20-9/33

A After Partridge & Macphail (in preparation)

B Macphail & Truswell (this paper)

Correlation of spore and pollen zone against planktonic foraminifera zones based on A.D. Partridge (8 May 1993 unpublished)

Figure 1. Correlation of spore and pollen zones in the Gippsland Basin and Murray Basin against the Cenozoic time scale of Harland & others (1990).

extinction of *Apteodinium australiense* and *Systematophora placacantha* (Table 1 in Macphail & others, 1993) and Early Pliocene extinction of *Melitasphaeridium choanophorum* (Williams & Bujak, 1985; Powell, 1992).

Correlatives. Martin's (1973, 1987) lower Myrtaceae-Casuarinaceae, *Nothofagus*, and Gymnosperm phases in the Lachlan River valley of New South Wales are probable correlatives.

Comment. On the data available, the upper boundary appears to predate the first occurrence of frequent to common (ca. 10-20%) Asteraceae pollen in the central west Murray Basin. A number of typically Early Tertiary species may become extinct in the zone. These include *Aglaoreidia qualumis*, *Banksieaeidites arcuatus*, *Cyatheacidites annulatus*, *Malvacearumpollis* sp. cf. *M. mannanensis*, *Proteacidites pachypolus*, *P. sinulatus*, and *Verrucosiporites kopukuensis*. To date, *Proteacidites punctiporus* has only been recorded in this zone.

The upper age limit of Early Pliocene for the zone is consistent with the absence of *Tubulifloridites pleistocenicus*, a species which first appears in the Early to Late Pliocene in the Gippsland Basin (Macphail & Partridge, unpublished). As knowledge of time distributions in the central west Murray Basin improve, it may be possible to use the first appearance of fossil members of the Loranthaceae (*Amylothea pliocenicica*), Asteraceae: Liguliflorae (*Fenestrites*), and Thymeleaceae (*Thymelaepollis* [*Pimelea*] sp.) to subdivide the *M. galeatus* Zone.

(1) Noora 1

Figure 2a

Noora 1 (486300E, 6191750N) is 26 km east-northeast of Loxton, a major irrigation centre on the Murray River in South Australia. Neogene marine strata penetrated by this bore are:

29.5–55.2 m	Bookpurnong beds
55.2–72.9 m	Winnambool Formation

One sample from a bioturbated silty clay unit within the Winnambool Formation and fourteen samples from within the Bookpurnong beds were available for palynological analysis.

Triporopollenites bellus Zone 65.42–65.45 m [Tmw]

The palynoflora is dominated by marine dinocysts and Araucariaceae: *Nothofagus* (*Brassospora*) spp. are uncommon.

The age determination is based on the association of *Canthiumidites bellus*, *Rugulatisporites cowrensis*, *Apteodinium australiense*, and *Systematophora placacantha*. Rare species include *Dilwynites granulatus*, *Phyllocladidites mawsonii*, *Gothanipollis* sp. cf. *gothanii*, and *Reevesiapollis reticulatus*. *Densoisporites implexus*, *Monotocidites galeatus*, and *Rhoipites ampereaformis* are absent.

Monotocidites galeatus Zone nov. 33.04–53.72 m [Tpb]

Samples from the Bookpurnong beds yielded variable amounts of marine dinocysts, but only in the top 2 m are numbers exceeded by spores and pollen.

Dinocysts present in this interval, but not recorded at 65.42–65.45 m, include Gen. et sp. indet. A of Martin 1991, *Labyrinthodinium truncatum*, *Melitasphaeridium aequabile*, *M. choanophorum*, and *Tectatodinium psilatium*. Fragments of *Systematophora placacantha* at 53.4–53.7 m and *Tectatodinium pelitium* at 53.7 m are considered to be reworked from the underlying Winnambool Formation.

Pollen dominance is variable with Araucariaceae, Casuarinaceae, Myrtaceae, Cyperaceae, and Restionaceae being frequent to abundant in most samples. Except for the basal samples (53.4–53.7 m), *Nothofagus* (*Brassospora*) is rare to absent. Rare species present in most samples include *Densoisporites implexus*, *Monotocidites galeatus*, *Myrtaceidites lipsis*, and *Rhoipites ampereaformis*.

Acaciapollenites miocenicus, *Aglaoreidia qualumis*, *Densoisporites simplex*, *Hypolepis spinyspora*, *Myrtaceidites* (*Leptospermum*) sp., *Poluspissusites ramus*, *Polyporina granulata*, and *Rhoipites* sp. cf. *R. isoreticulatus* are restricted to the lower half of the interval; *Acaciapollenites weissii*, *Amylothea pliocenicica*, *Fenestrites*, *Hakeidites* (*Grevillea*) sp., *Malvacipollis regattaensis*, *Polyporina reticulata*, *Thymelaepollis* (*Pimelea*) sp. are restricted to the upper part of the interval. A number of long-ranging types, including index species of the *P. tuberculatus* Zone (*Cyatheacidites annulatus*) and *T. bellus* Zone (*Canthiumidites bellus*, *Symplocoipollenites austellus*), were recorded only in the same interval.

Isolated specimens of *Perisyncolporites pokorny* at 52.63 m and *Phyllocladidites mawsonii* and *Tricolporites leuros* at 39.75 m may be reworked.

(2) Taldra 1 (Gordon 46)

Figure 2b

Taldra 1 (485000E; 6201800N) is 10 km north-northwest of Noora 1 and 18 km southeast of Renmark. Neogene marine strata penetrated by this bore are:

74–86 m	Bookpurnong beds
86–120 m	Winnambool Formation

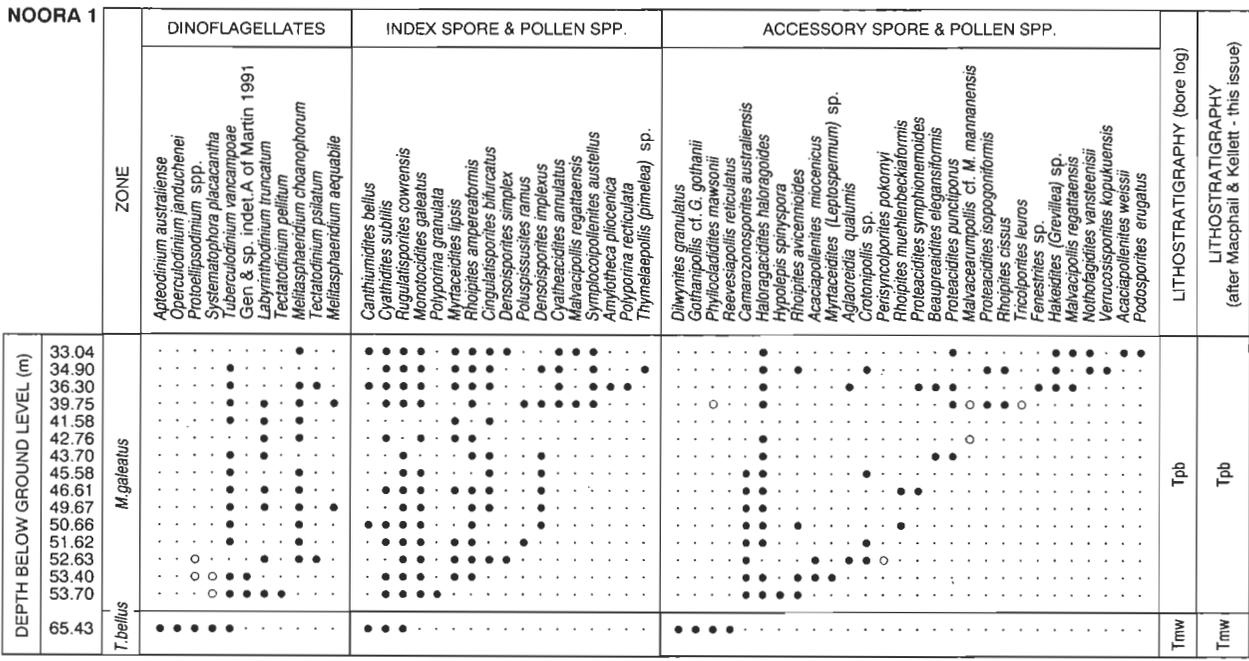
Dinocysts and lithology indicate that all samples are part of a marine unit that is transitional between the Winnambool Formation and the Bookpurnong beds (see Macphail & Kellett, this issue). The ratio of dinocysts to spores and pollen decreases upsection, consistent with a waning marine influence. Seven samples were available for palynological analysis.

Monotocidites galeatus Zone nov. 84.5–90.0 m [Tpb]

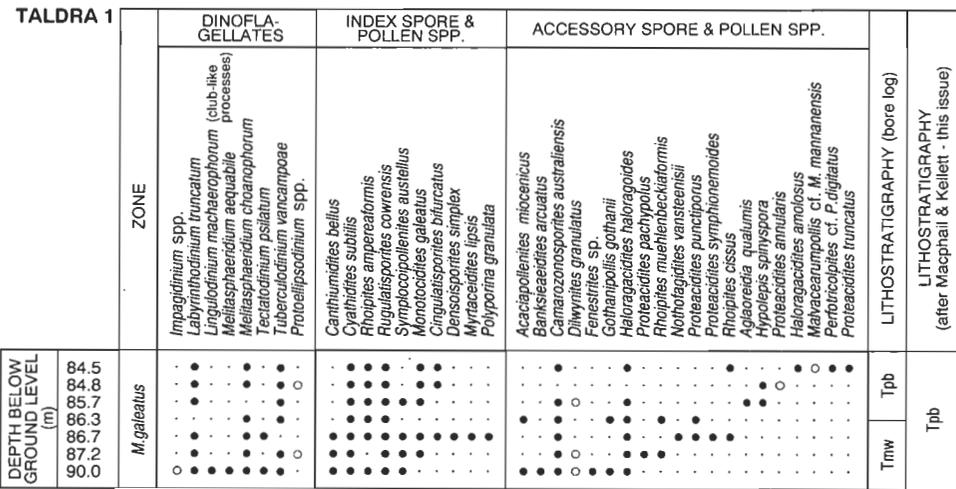
All palynofloras recovered from the Bookpurnong beds are dominated by Araucariaceae and Casuarinaceae, with variable amounts of Myrtaceae and *Nothofagus* (*Brassospora*) spp.

Dinocysts present in the majority of samples include *Labyrinthodinium truncatum*, *Melitasphaeridium choanophorum*, and *Tuberculodinium vancampoae*. *Melitasphaeridium aequabile* and *Tectatodinium psilatium* occur towards the base of the interval. *Apteodinium australiense* and *Systematophora placacantha* were not recorded.

Canthiumidites bellus, *Monotocidites galeatus*, *Rugulatisporites cowrensis*, and *Symplocoipollenites austellus* occur in the majority of samples; *Densoisporites simplex*,



- Possible caved (downward) or reworked (upward) specimens
- Specimens presumed to be in situ



- Possible caved (downward) or reworked (upward) specimens
- Specimens presumed to be in situ

20-93/4 (1 of 2)

Figure 2. Range charts showing stratigraphically significant spore, pollen and dinocyst species in Noora 1 (Fig 2a), Taldra 1 (Fig 2b), Cal Lal (Fig 2c) and Talgarry (Fig 2d).

Myrtaceidites lipsis, and *Polyporina granulata* occur at 86.7 m. *Aglaoreidia qualumis* occurs at 85.7 m. Specimens of *Dilwynites granulatus* and *Proteacidites annularis* may be reworked.

(3) Cal Lal (DWR 36783) Figure 2c

Cal Lal (512130E, 6241450N) is located on the intersection of the Wentworth–Renmark Road and the Regunyah Road on the northern side of the Murray River, virtually at the tri-State junction. Fifteen cuttings samples were available for palynological analysis.

Dinocysts (Macphail & Kellett, this issue) indicate that three palynologically distinct marine units are present

between 67–112 m. These are interpreted as Bookpurnong beds (67–94 m) and Winnambool Formation (101–112 m), separated by a bioturbated interval containing “mixed age” palynofloras.

Triporopollenites bellus Zone 101–112 m [Tmw]

Palynofloras in this interval are dominated by marine dinocysts, including *Systematophora placacantha*, *Apteodinium australiense*, *Operculodinium janduchenei*, and *Tectatodinium pellitum*. Two samples yielded *Tuberculodinium vancamppae*. The age determination is based on *Rugulatisporites cowrensis*, *Symplocoipollenites austellus*, *Nothofagidites flemingii*, *Apteodinium australiense*, and *Systematophora placacantha*.

CAL LAL		DINOFLAGELLATES	INDEX SPORE & POLLEN SPP.	ACCESSORY SPORE & POLLEN SPP.					
DEPTH BELOW GROUND LEVEL (m)	67-68	M. galeatus	Zone Agacipollinium australe Utriculoledinium machaerophorum (club-like processes) Oncolidinium landuchenei Proteolissodinium spp. Systematophora placacantha Tectatodinium pellicum Tuberculodinium spp. Tuberculodinium vancampoeae Gen. et sp. indet. A of Martin 1991 Adnastiphaeridium reticulense Labyrinthodinium truncatum Melitaspheeridium aequabile Tectatodinium psilatum Melitaspheeridium choanophorum Pentadinium laticinctum	Rhoipites ampereaformis Rugulatisporites cowrensis Cyathoidites subtilis Symplocoipollenites australis Monotocidites galeatus Poussipustites ramus Canthiumidites bellus Cyathaeacidites annulatus Densosporites simplex Crigulatisporites bifurcatus Polyporina reticulata Myrtaceidites lipsis Anylothea plicatica Tubulirodites pleistocenicus	Agacipollis qualumis Periporipollenites demarcatus Perisynopollenites pokornyii Proteacidites annularis Reevesiapollis reticulatus Tricolpites sinatus Acaciapollenites miocenicus Camarozonosporites australiensis Gothanipollis gothanii Haloragacidites haloragoides Notholagidites flemingii Proteacidites sinulatus Rhoipites avicernoides Liliacidites bainii Rhoipites muhlenbeckii Crotonipollis sp. Hakeidites (Grevillea) sp. Ilexpollenites anguloclavatus Proteacidites truncatus Proteacidites tripartitus Gothanipollis perplexus Santalumidites carozocicus Fenestrites sp. Proteacidites symphonomoides Alangiopollis sp. Proteacidites latrobensis Banksiaeacidites arcuatus Massariaacidites vanaadshooverii Crassireticulites vanaadshooverii Phyllocladites mawsonii Proteacidites pachypolus Rhoipites cissus Proteacidites sp. A of Macphail and Truswell 1989 Acaciapollenites weissii				
	94-95					indet.			Tpb
	101-102					T. bellus			Tmw

- Possible caved (downward) or reworked (upward) specimens
- Specimens presumed to be in situ

TALGARRY		DINOFLAGELLATES	INDEX SPORE & POLLEN SPP.	ACCESSORY SPORE & POLLEN SPP.			
DEPTH BELOW GROUND LEVEL (m)	90-91	M. galeatus	Zone Systematophora placacantha (club-like processes) Utriculoledinium machaerophorum Tuberculodinium vancampoeae Impagidinium spp. Labyrinthodinium truncatum Proteolissodinium spp. Canthiumidites bellus Cyathaeacidites annulatus Cyathoidites subtilis Rugulatisporites cowrensis Symplocoipollenites australis Rhoipites ampereaformis Anylothea plicatica Crigulatisporites bifurcatus Monotocidites galeatus Myrtaceidites lipsis Polyporina reticulata Densosporites simplex Crassireticulites vanaadshooverii Gothanipollis cf. G. gothanii Haloragacidites haloragoides Polycopropollenites esobalteus Reevesiapollis reticulatus Crotonipollis sp. Dihymnetes granulatus Perisynopollenites pokornyii Phyllocladites mawsonii Proteacidites pachypolus Proteacidites reikuscabratus Proteacidites sp. A of Macphail and Truswell 1989 Rhoipites cissus Banksiaeacidites arcuatus Haloragacidites myrtilloides Hypolepis spinispora Proteacidites sinulatus Camarozonosporites australiensis Fenestrites sp. Notholagidites vansteenisii Tricolpites pelargonoides Psilodiporites (Alyxia) sp. Acaciapollenites miocenicus Alangiopollis sp. Makacearumpollis cf. M. mannanensis Notholagidites flemingii Periporipollenites demarcatus Proteacidites annularis Proteacidites truncatus Rhoipites muhlenbeckii Verucosporites kopukensis Acaciapollenites weissii Ilexpollenites anguloclavatus Agacipollis qualumis Notholagidites goniatius Tubulirodites pleistocenicus Proteacidites kopensis Gothanipollis perplexus Proteacidites confragosus Proteacidites dinterimipollis Proteacidites latrobensis Proteacidites nasus Tricolpites rarus Tricolpites leuros	Agacipollis qualumis Periporipollenites demarcatus Perisynopollenites pokornyii Proteacidites annularis Reevesiapollis reticulatus Tricolpites sinatus Acaciapollenites miocenicus Camarozonosporites australiensis Gothanipollis gothanii Haloragacidites haloragoides Notholagidites flemingii Proteacidites sinulatus Rhoipites avicernoides Liliacidites bainii Rhoipites muhlenbeckii Crotonipollis sp. Hakeidites (Grevillea) sp. Ilexpollenites anguloclavatus Proteacidites truncatus Proteacidites tripartitus Gothanipollis perplexus Santalumidites carozocicus Fenestrites sp. Proteacidites symphonomoides Alangiopollis sp. Proteacidites latrobensis Banksiaeacidites arcuatus Massariaacidites vanaadshooverii Crassireticulites vanaadshooverii Phyllocladites mawsonii Proteacidites pachypolus Rhoipites cissus Proteacidites sp. A of Macphail and Truswell 1989 Acaciapollenites weissii			
	102-103						Tpb
	122-124				T. bellus		

- Possible caved (downward) or reworked (upward) specimens
- Specimens presumed to be in situ

Specimens of *R. sp. cf. R. isoreticulatus* at 107–108 m and *Rhoipites ampereaformis* at 111–112 m and 101–102 m are assumed to be caved.

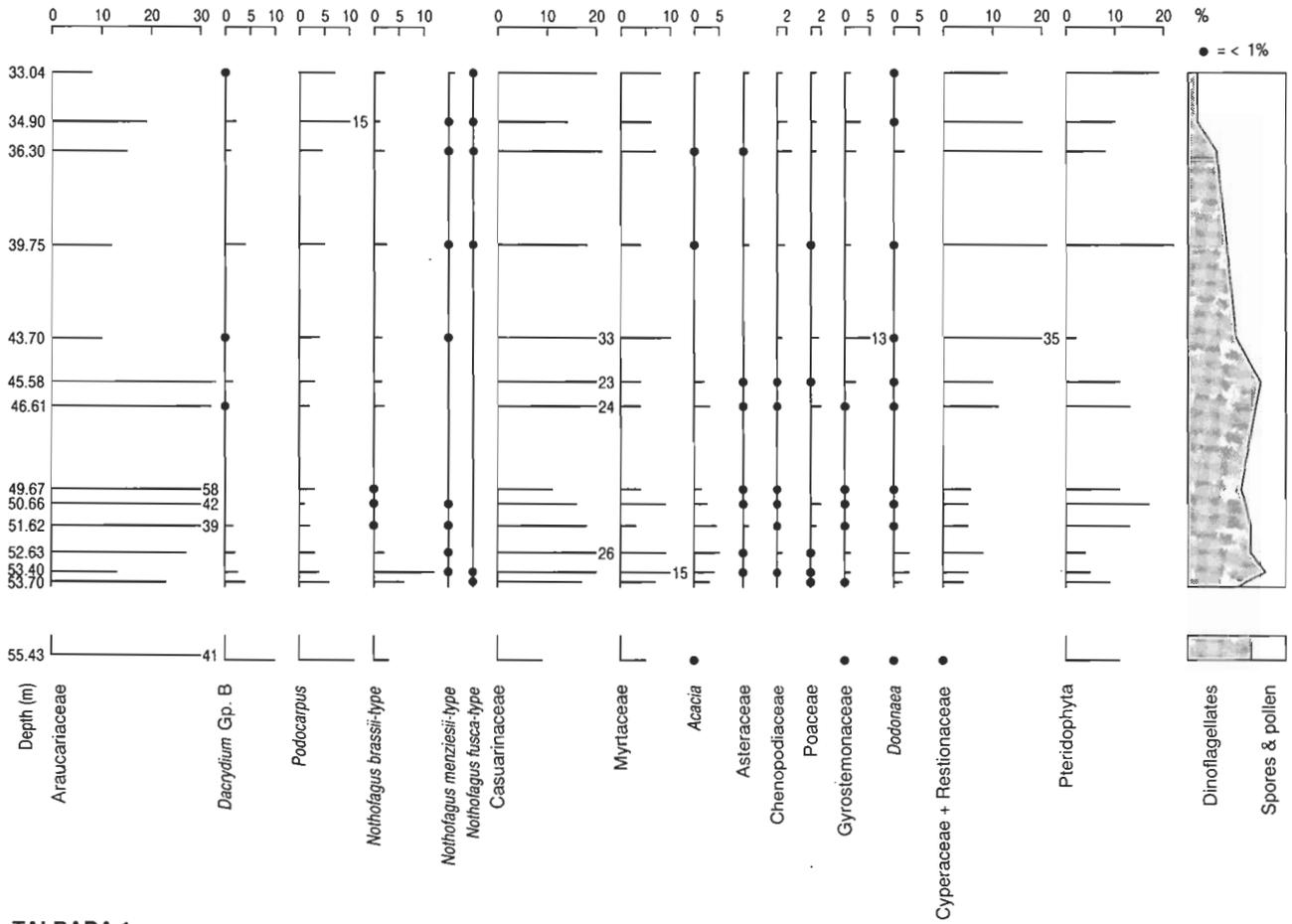
Monotocidites galeatus Zone nov. 67–94 m [Tpb]

Dinocysts present in this interval, but not recorded in the Winnambool Formation, include Gen. et sp. indet. A of Martin 1991, *Labyrinthodinium truncatum*, *Melitaspheeridium aequabile*, *M. choanophorum*, and *Tectatodinium psilatum*. *Tuberculodinium vancampoeae* occurs in the majority of samples. Fragments of *Systematophora*

placacantha at 89–90 m and 93–94 m are considered to be reworked.

Pollen and spores in most samples are *Canthiumidites bellus*, *Monotocidites galeatus*, *Rhoipites ampereaformis*, *Rugulatisporites cowrensis*, and *Symplocoipollenites australis*. *Amylothea plicatica*, *Densosporites simplex*, *Myrtaceidites lipsis*, and *Polyporina reticulata* occur in occasional samples. Other rare species include *Cyathaeacidites annulatus*, *Gothanipollis perplexus*, *Hakeidites (Grevillea) sp.*, *Fenestrites sp.*, *Alangiopollis sp.*, *Psilodiporites (Alyxia) sp.*, and *Acaciapollenites weissii*.

NOORA 1



TALDARA 1

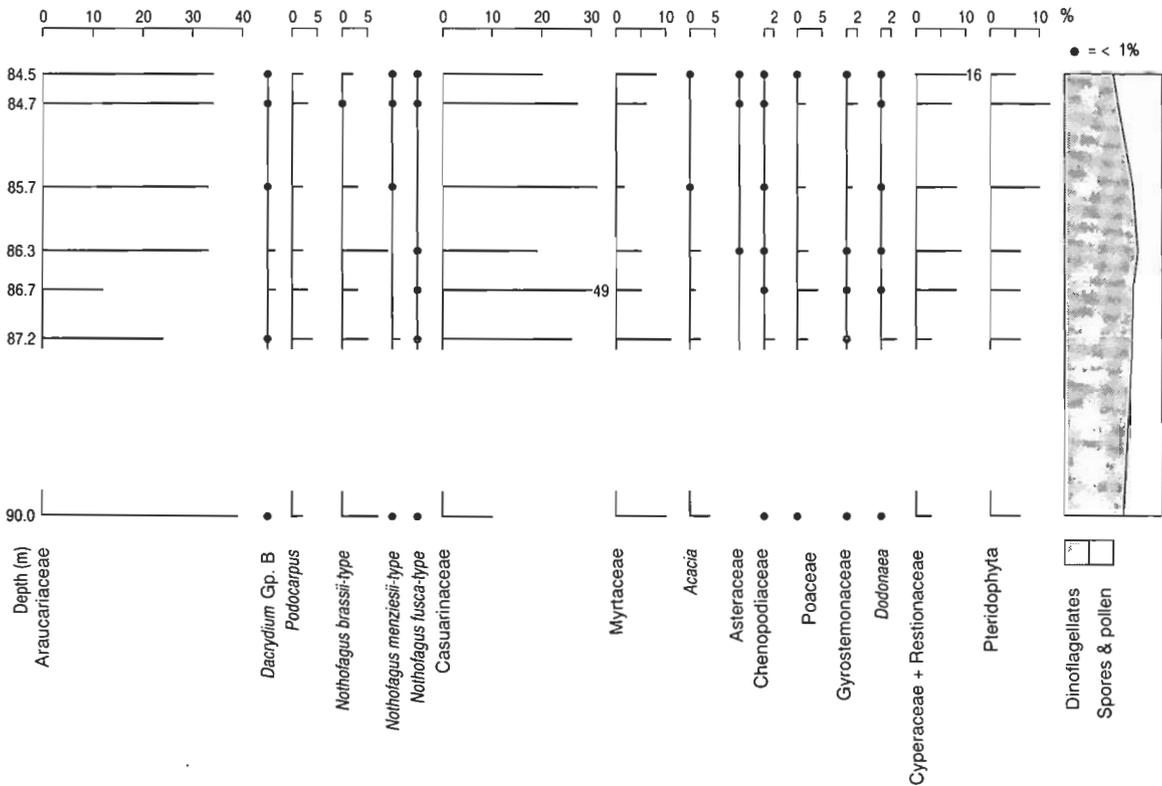
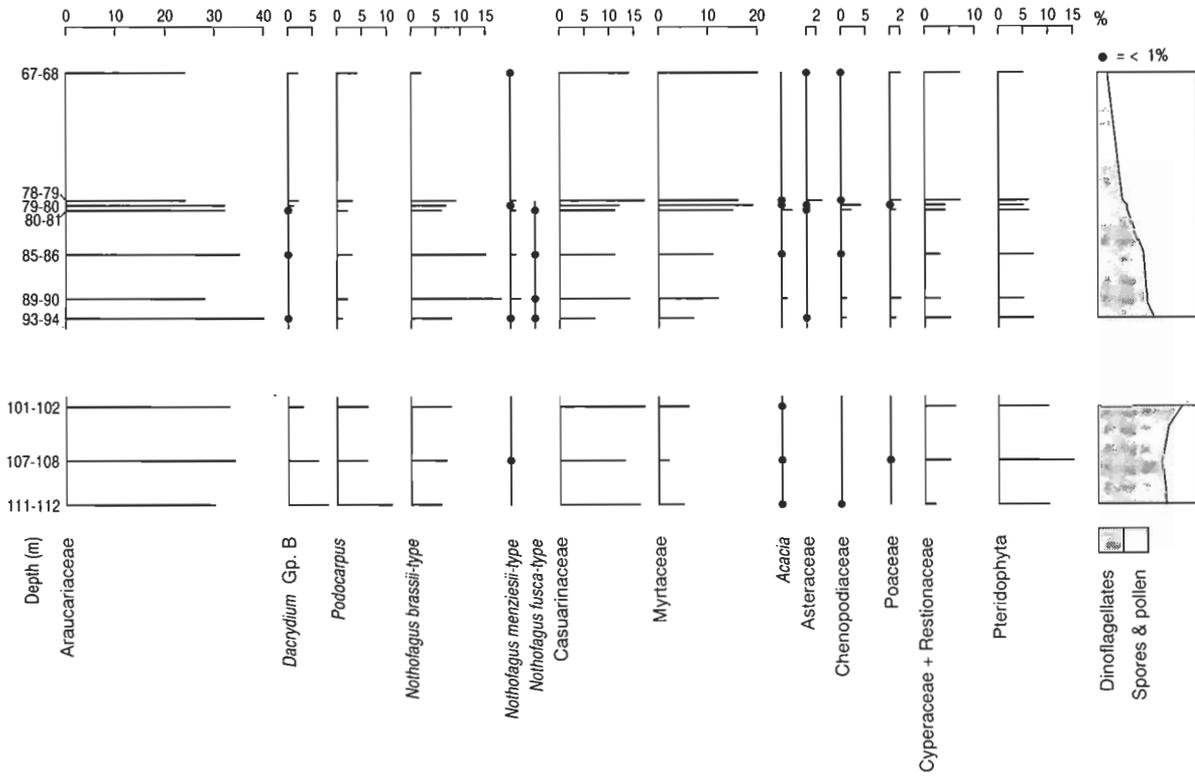
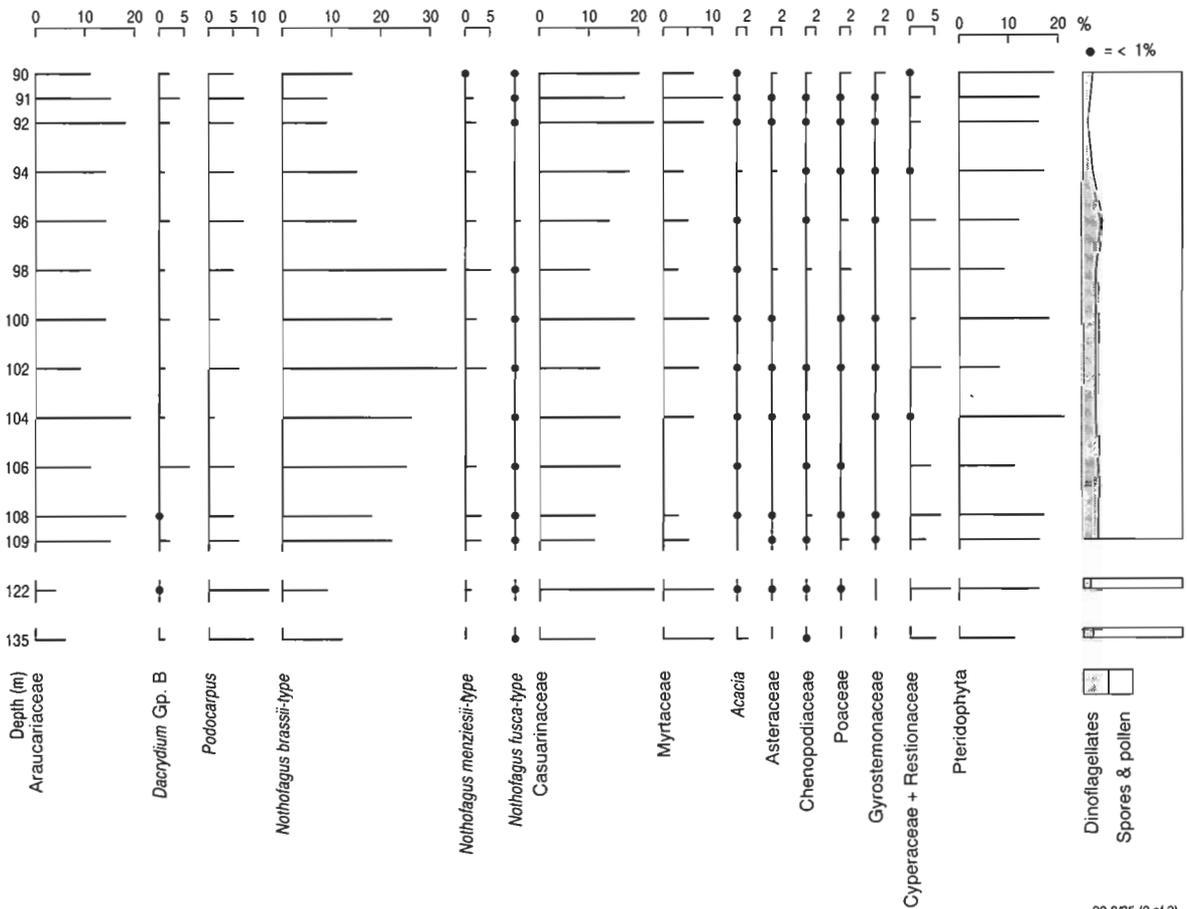


Figure 3. Frequencies of most common pollen taxa in the boreholes. Ratios of dinocysts to spores and pollen is indicated.

CAL LAL (DWR 36783)



TALGARRY (DWR 36851)



Specimens of *Ilexpollenites anguloclavatus*, *Phyllocladidites mawsonii*, *Proteacidites annularis*, and *P. latrobensis* may be reworked. The one grain of *Tubulifloridites pleistocenicus* recorded at 80–81 m almost certainly is caved.

“Mixed assemblage” interval 94–101 m

This interval, which corresponds to an apparent temporary expansion of dinocysts relative to spores and pollen, includes species characteristic of both the Winnambool Formation (*Aptodinium australiense*, *Operculodinium janduchenei*, *Tectatodinium pellitum*), and Bookpurnong beds (*Labyrinthodinium truncatum*, *Melitasphaeridium aequabile*, *Tectatodinium psilatium*). One dinoflagellate, *Nematosphaeropsis reticulense*, is restricted to the interval. *Pentadinium laticinctum* almost certainly is reworked.

The same mixing is evident in the association of *Monotocidites galeatus*, *Rhoipites ampereaformis*, *Poluspisusites ramus*, *Perisyncolporites pokorny*, *Proteacidites tripartitus*, and *Santalumidites cainozoicus*.

(4) Talgarry (DWR 36851) Figure 2d

Talgarry (537270E, 6246540N) is located 26 km east-northeast of Cal Lal on the northeastern side of Lake Victoria. Neogene marine strata penetrated by this bore are:

90–110	m	Bookpurnong beds equivalents
110–135	m	Geera Clay
135–166	m	Winnambool Formation

The abundance of dinocysts relative to spores and pollen in the Bookpurnong beds equivalent interval is very low compared to Noora 1, Taldra 1, and Cal Lal. Values increase then decrease upsection to negligible levels at 91–92 m. Samples at 76–81 m and 60–61 m in the Loxton–Parilla Sands are non-marine. Fourteen cuttings samples were available for palynological analysis. Only strongly oxidized residues were available for samples at 135–138 m (Winnambool Formation) and 122–124 m (Geera Clay), almost certainly resulting in the loss of the more fragile palynomorphs.

Tripolipollenites bellus Zone 122–138 m [Tmw–Tmg]

The interval includes one palynoflora each from the Winnambool Formation and Geera Clay. It is dated as *T. bellus* Zone based on records of *Systematophora placacantha*, *Symplocoipollenites austellus*, and *Canthiumidites bellus* at 135–138 m and 122–124 m. Isolated specimens of *Rhoipites ampereaformis* are assumed to be caved.

The Winnambool Formation palynoflora (135–138 m) is dominated by Myrtaceae (38%), Casuarinaceae (11%), and *Nothofagus* (*Brassospora*) spp. (12%). Dinocysts are present in moderate numbers. Rare species include *Cyatheacidites annulatus*, *Polycolporipollenites esobalteus*, and *Reevesiapollis reticulatus*.

The Geera Clay palynoflora (122–124 m) closely resembles that at 135–138 m except that Casuarinaceae are more abundant than Myrtaceae. The dinoflagellate component includes rare specimens of *Nematosphaeropsis reticulense*. Rare pollen species include *Crotonipollis* sp.,

Dilwynites granulatus, *Perisyncolporites pokorny*, *Phyllocladidites mawsonii*, and *Rhoipites cissus*.

Monotocidites galeatus Zone nov. 104–110 m [Tpb]

Palynofloras within this interval are dominated by Araucariaceae, Casuarinaceae, and *Nothofagus* (*Brassospora*) spp. Values of *Nothofagus* show an overall decrease and Casuarinaceae an overall increase upsection. Myrtaceae values are lower than in the *T. bellus* Zone palynofloras.

Dinocysts typical of the Bookpurnong beds elsewhere are absent except for *Labyrinthodinium truncatum* at 104–105 m and *Tuberculodinium vancampoe* in this and one other sample at 109–110 m.

The age determination is based on *Monotocidites galeatus* and *Rhoipites ampereaformis*, present in the majority of samples, and *Amylothea pliocenica*, *Densoisporites simplex*, *Myrtacidites lipsis*, and *Polyporina reticulata*, in occasional samples. *Rhoipites muehlenbeckiaformis* occurs at 90–91 m.

These are associated with sporadic occurrences of species that are more consistent with a Middle Miocene or older age for the interval, e.g. *Aglaoreidia qualumis*, *Ilexpollenites anguloclavatus*, *Nothofagidites flemingii*, *N. goniatus*, *Perisyncolporites pokorny*, *Polycolporipollenites esobalteus*, *Proteacidites confragrosus*, *P. differentipolis*, *P. latrobensis*, *P. nasus*, *Reevesiapollis reticulatus*, and *Tricolporites leuros*. Our preferred explanation, that these species have been reworked from the underlying Geera Clay or Winnambool Formation, is supported by the concentration of anomalous species in two samples: 91–92 m and 104–105 m. *Systematophora placacantha* is assumed to be reworked.

Comparison with the zonation proposed by Martin (1973, 1987)

Martin (1973, 1987) used high relative abundance values of long-ranging, palynologically prominent pollen taxa to erect a series of “phases” useful in correlating post *T. bellus* Zone ‘Pliocene’ sediments in the Lachlan River region. These are (oldest to youngest): the Lower Myrtaceae phase defined by Myrtaceae values in excess of 30–40%; the *Nothofagus* phase defined by values (ca 10–30%) of the *fusca* (= *Fuscospora*) and *menziesii* (= *Lophozonia*) types, the Gymnosperm phase defined by Podocarpaceae and/or Cupressaceae values in excess of 20%; and the Upper Myrtaceae phase in which Myrtaceae values again exceed 30%. All are distinguished from the *T. bellus* Zone by very low values of *Nothofagus brassii* (= *Brassospora*) species.

No such clearcut pattern is evident in the boreholes analysed here (Figs 3a to d):

- *Nothofagus* (*Brassospora*) values show a marked decline to low or negligible values near the base of the Bookpurnong beds in Noora 1, near the top of this formation in Cal Lal and Taldra 1. The taxon is common to dominant throughout the Talgarry sequence.
- Araucariaceae, not Podocarpaceae or Cupressaceae, is the most prominent gymnosperm present. Although values decline upsection, overall it is the dominant pollen type in Cal Lal, Noora 1, and Taldra 1.

- Casuarinaceae and Myrtaceae values are most abundant near the base of the Bookpurnong beds in Noora 1 and Taldra 1, and show an overall irregular decline upsection. The reverse is true in Talgarry and Cal Lal, where values show little overall change or (Cal Lal) a sustained increase upsection.

Discussion and conclusions

Murray Basin bores are difficult to correlate precisely due to the lack of any well-defined geological or geo-physical marker horizon, and biostratigraphic events have been used as approximate time planes across the basin, e.g. the first appearance of zone index species such as *Canthiumidites* (*Triporopollenites*) *bellus* (see Macphail & Truswell, 1989). As such it is difficult to avoid some degree of circular reasoning when comparing palynosequences from widely spaced boreholes. The problem is compounded, as here, by blurring of the zone boundaries by reworking and downhole caving of fossil palynomorphs.

As defined above, the *Monotocidites galeatus* Zone is a concurrent-range zone and, if it is to be useful, depends on the index species having either evolved/migrated or become extinct over a wide area at approximately the same time across the basin. Whilst some plants do display this stratigraphically useful behaviour in the Gippsland Basin, it is reasonable to assume most species were more irregularly distributed across the Murray Basin due to its large size and strong environmental contrasts between the (marginal marine) southwest and (fluvio-lacustrine) northeast.

For this reason, we propose the following accessory species may be useful in identifying the *M. galeatus* Zone when the index species are absent: *Amylotheca pliocenica*, *Densoisporites implexus*, *D. simplex*, *Fenestrites* sp., *Malvacipollis regattaensis*, *Polyporina granulata*, *P. reticulata*, *Poluspissusites ramus*, *Rhoipites muehlenbeckiaformis*, and *Thymelaepollis* (*Pimelea*).

Whether it will be possible to use the extinction of species to define the *M. galeatus*/*T. bellus* Zone boundary is less clear due to possible bioturbation and/or reworking, such as in Cal Lal and Talgarry. On the data available:

- It seems unlikely that any of the species which first appear in the *T. bellus* Zone or *M. galeatus* Zone become extinct in the latter zone. Most are part of the modern flora in southeastern Australia, e.g. (modern taxa in parentheses): *Cingulatisporites bifurcatus* (*Anthocerotae*), *Densoisporites implexus/simplex* (*Selaginella uliginosa*), *Monotocidites galeatus* (*Monotoca*), *Rhoipites ampereaformis* (*Amperea*), *Rugulatisporites cowrensis* (*Culcita*), and *Tubulifloridites pleistocenicus* (*Calomeria/Cassinia arcuata*). *Canthiumidites bellus* and *Symplocoipollenites austellus* are present in Pliocene sediments in the Lachlan River valley (Martin, 1987) and the latter species, *Malvacipollis regattaensis* and *Gothanipollis* spp. are present in Early–Middle Pleistocene deposits in western Tasmania (Macphail & others, in press).
- It is possible that a number of long-ranging species did not survive into *M. galeatus* Zone time in the central west of the basin. Based on the rarity of occurrences within the Bookpurnong beds, these include: *Dilwynites granulatus*, *Ilexpollenites anguloclavatus*, *Nothofagidites deminutus-vansteenisii*, *N. flemingii*, *N. goniatius*, *Periporopollenites demarcatus*,

Perisyncolporites pokorny, *Phyllocladidites mawsonii*, *Polycolporopollenites esobalteus*, *Proteacidites annularis*, *Reevesiapollis reticulatus*, *Tricolpites simatus*, and *Tricolporites leuros*.

- It is premature to use marked changes in the relative abundance of *Nothofagus brassii*-type pollen as a means for dating or correlating sediments across the basin. We do not see criteria proposed by Martin (1973, 1987) as being reliable in the central west Murray Basin and suggest that shifts in the relative abundance of Araucariaceae, Casuarinaceae, and Myrtaceae may well reflect local shifts in depositional environment.
- A number of minor species become consistent (<1%) to frequent (1–5%) for the first time during the *M. galeatus* Zone; for example *Acaciapollenites myriosporites*, *A. weissii*, *Crotonipollis*, *Haloragacidites haloragoides*, *Dodonaea sphaerica*, *Gyropollis psilatus*, *Myrtaceidites eucalyptoides*, and *Proteacidites truncatus*. It may be possible to use changes in relative abundance of those taxa as accessory (quantitative) criteria for recognizing the zone.

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Appendix 1. Taxonomy

M.K. Macphail, A.D. Partridge¹ & E.M. Truswell

Many of the fossil pollen and spores present in Late Miocene and Pliocene sediments in southeastern Australia cannot be distinguished, using light-microscopy, from pollen produced by living plants in the same region.

Although we do not doubt that the phylogenetic relationships are real, we have chosen to erect form names for the fossil representatives for several reasons:

- No definitive collection exists of pollen and spore types produced by the Australasian floras and it is probable that unidentified sources exist for many of the fossil types, e.g. *Tubulifloridites pleistocenicus* (see Macphail & Martin, 1991).
- The use of modern taxa to incorporate Late Miocene or Pliocene pollen morphotypes implies that no evolution has occurred in the 5 or 6 million years that have elapsed since then. It is highly unlikely that all characters have remained stable in that interval so that usage of form species provides an appropriately cautious approach to establishing affinities for the fossils.
- It is uncertain whether the fossil species had the same ecological preferences as their living counterparts. This almost certainly is not the case with Tertiary populations of *Myrtacidites lipsis* n.sp. in southeastern Australia, given the restriction of its modern homologue *Eucalyptus spathulata* to semi-arid situations in southwest Western Australia (see below).

Where possible, holotypes have been selected from Murray Basin specimens. If this was not possible due to poor preservation or orientation, holotypes have been selected from elsewhere and paratypes nominated or specimens illustrated from Murray Basin material.

All types have been ringed using a diamond scribe and England Finder co-ordinates provided (slide label of str_gw mounts on right-hand side of microscope stage) in the formal diagnoses. Except where specified, photomicrographs were taken at x1250 magnification using a Zeiss Photomicroscope II fitted with Neofluar and Planapo objectives.

A selection of zone accessory species and a selection of other distinctive types are illustrated in Plates 6–8.

Trilete spores

Genus *Densoisporites* Weyland & Krieger 1953, emend. Dettmann, 1963

Type species *Densoisporites velatus* Weyland & Krieger, 1953

Densoisporites implexus n. sp.

Pl. 1, Figs 1–9.

Holotype: Slide P 194410/CPC 31500, England Finder co-ordinates J44/0. Proximal face uppermost; 61 μ (perine); 43 μ inner diameter. Possibly swollen due to acetolysis.

Type locality: Esso–BHP well Hapuku 1, offshore Gippsland Basin at 655.3 m, Late Pliocene.

Derivation of name:

From the Latin *implexus* “plaited into”, referring to the plicate folding of the perine on the distal surface of the spore.

Description: Monad, heteropolar, radiosymmetric, trilete, laesurae straight, extending to periphery; amb subcircular–subtriangular; spore wall two layered, cavate, consisting of a homogeneous inner layer (exine) and a loosely enveloping, possibly proximally attached, outer layer (perine); exine smooth ca. 1 μ thick, often collapsed along laesurae; perine ca. 1.5 μ thick, proximal surface scabrate with three straight folds approximately following the lines of the laesurae, ornamentation on distal surface variable but usually consisting of long sinuous folds around the equator, the folds becoming tighter and interspersed with verrucae to form a rugulate–verrucate ornamentation across the pole; ca. 36 μ .

Paratypes: Slide CPC 31501, 31502, Hollands Landing (onshore Gippsland Basin) at 33.5 m, Pliocene–Pleistocene, England Finder co-ordinates W34/4.

Botanical affinity:

Selaginella uliginosa (Labill.) Spring Selaginellaceae (Pl. 1, Figs 15–17).

Known distribution:

Otway Basin–Pleistocene; Central-west Murray Basin–Late Miocene to Pliocene; Gippsland Basin–Early Pliocene to Present; Tasmania–Late? Pliocene to Present; N.S.W.–Holocene.

Discussion: *Densoisporites implexus* closely resembles spores of *Selaginella uliginosa*, a fern ally which is widely distributed on wet peaty soils in coastal heathland and around

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swamps and streams in forested areas inland.

scured at one margin: perine diameter 27 μ , inner diameter 21 μ .

Spores of *Selaginella kraussiana* (Kunze) A. Br., a native of tropical and southern Africa and of the Azores but now widely naturalized in temperate regions, are distinguished by prominent echini (cf. Figs 50–51 in Large & Braggins, 1991).

Type locality: Regatta Point, Strahan, west coast Tasmania, silt unit exposed on western side of Lowana Rd., Early–Middle Pleistocene.

Densoisporites simplex n. sp.

Derivation of name:

From the Latin *simplex*, “simple or plain”, referring to the non-plicate nature of the perine on the distal surface of the spore.

Pl. 1, Figs 10–14.

Description: Monad, heteropolar, radiosymmetric, trilete, laesurae straight, extending to periphery; amb subcircular–subtriangular;

Holotype: Slide CPC 31504, England Finder co-ordinates E42/3. Distal face uppermost, ob-

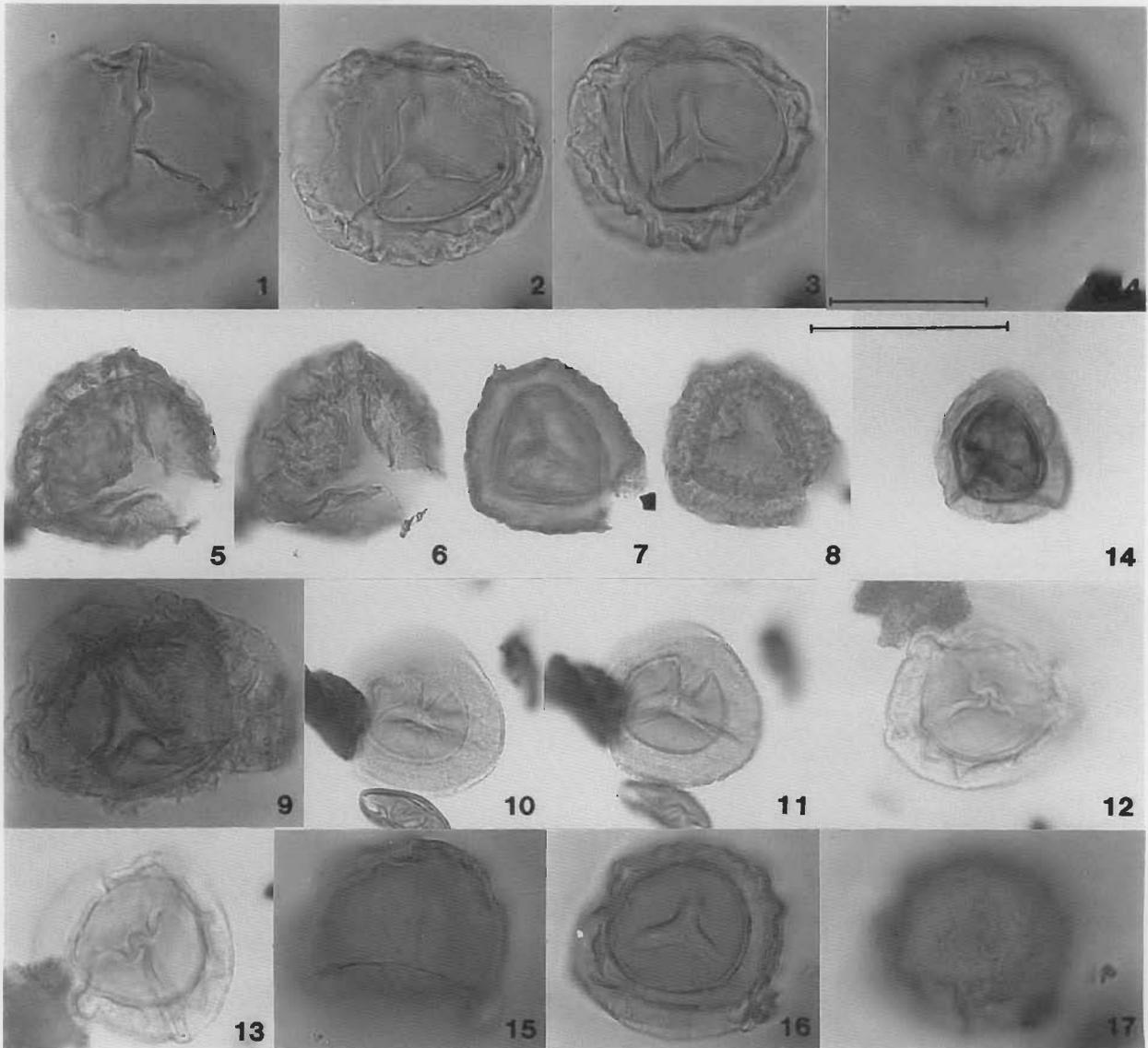


Plate 1.

Densoisporites implexus n. sp.

Figs 1–4. Holotype x 788. CPC 31500. Hapuku 1, 635.3 m, Late Pliocene. Figs 5–8. Paratypes x 788. CPC 31501, 31502. Hollands Landing, 33.5 m, Plio-Pleistocene. Fig. 9. Corroded specimen x 788. CPC 31503. Wendi (DWR 36840) 78–80 m, caved into *Triporopollenites bellus* Zone?

Densoisporites simplex n. sp.

Figs 10–11. Holotype x 788. CPC 31504. Silt unit on western side of Lowana Rd., Regatta Point, west coast Tasmania, Early–Middle Pleistocene. Figs 12–13. Paratype x 1250. CPC 31505. Hollands Landing, 135.3 m, Plio-Pleistocene. Fig. 14. Small specimen x 1250. CPC 31506. Taldra 1, 86.7–86.8 m, *Monotocidites galeatus* Zone. Figs 15–17. Microspores of *Selaginella uliginosa* (Labill.) Spring x 788. Ex Rodway Herbarium, Tasmanian Museum, Hobart.

spore wall two layered, cavate, consisting of a homogeneous inner layer (exine) and a loosely enveloping, possibly proximally attached, outer layer (perine); exine smooth ca. 1 μ thick, often collapsed along laesurae; perine ca. 1.5 μ thick, proximal surface with three straight folds approximately following the lines of the laesurae, otherwise both surfaces are unfolded, scabrate to weakly verrucate; perine diameter ca. 27–41 μ .

Paratype: Slide CPC 31505, Hollands Landing (on-shore Gippsland Basin) at 135.3 m, Pliocene, England Finder coordinates J66/2.

Botanical affinity: Selaginellaceae — immature miospores of *Selaginella uliginosa* (Labill.) Spring.

Known distribution: Otway Basin–Pleistocene; Central-west Murray Basin–Late Miocene to Pliocene; Gippsland Basin–Early Pliocene to Present; Tasmania–Quaternary; N.S.W.–Holocene.

Discussion: *Densoisporites simplex* closely resembles *Densoisporites implexus* but lacks the strongly plicate–rugulate perine of the latter species.

Genus *Leptolepidites* Couper 1953

Type species: *Leptolepidites verrucatus* Couper, 1953

Leptolepidites sp. cf. *L. verrucatus* Couper, 1953

Pl. 2, Figs 15–20.

Reference specimens: Slides CPC 31506, 31507, England Finder co-ordinates Y34/0; CPC 31528, England Finder co-ordinates E52/3 (on same strew mount as paratype of *Acaciapollenites weissii* (see below).

Localities: Noora 1 at 45.58–45.61 m (Late Miocene–Early Pliocene) and 65.43–65.45 m (late Early–Middle Miocene); Cal-Lal at 78–79 m (Late Miocene–Early Pliocene); Talgarry at 100–101 m, Late Miocene–Pliocene.

Description: Monad; heteropolar; radiosymmetric; amb subtriangular; trilete, laesurae sinuous, reaching periphery, raised with marked marginal ridges, ridges 2–3 μ wide, occasionally bifurcating near equator; exine non-cavate, of uneven thickness, less than 1 μ thick excluding ornamentation; verrucate on distal and outer 1/3rd of proximal surface, verrucae variable, usually subcircular less than 2.5 μ high, 1.5–4 μ across, some coalesced into low ridges up to 8 μ in longest dimension, remainder of proximal surface psilate to pitted; equatorial diameter 23–28 μ .

Botanical affinity:

Pteridophyte, possibly Grammitidaceae or Polypodiaceae.

Discussion: The species is provisionally referred to *Leptolepidites*, a form genus erected by Couper (1953) to accommodate trilete spores with large verrucae developed on both the distal and proximal faces. The lack of gemmae precludes assigning the species to genera such as *Gemmatriletes* Pierce 1961 (see Mildenhall & Pocknall, 1989) and *Uvaesporites* Doring 1965.

Leptolepidites cf. *L. verrucatus* differs from *Gemmatriletes multiglobus* Mildenhall & Pocknall, 1989 in that the distal surface is ornamented with broad, shallow verrucae, not gemmae, whilst the inner two thirds of the proximal surface and along the ridges bordering the laesurae are psilate. The verrucae on the Cretaceous species *Leptolepidites verrucatus* are usually larger and the laesurae are straight (see Dettmann, 1963) but otherwise the species is very similar.

Tricolpate pollen

Stylidiaceae

Pl. 2, Figs 21–22.

Reference specimen: Slide CPC 31509, England Finder co-ordinates G43/0.

Localities: Scotia 1 (Murray Basin) at 60.0 m, Late Oligocene–Early Miocene; Hapuku 1 (Gippsland Basin) at 2810 m, Early? Oligocene.

Description: Monad, isopolar, radiosymmetric, stephanocolpate, apertures 3, reaching close to poles, gaping with ragged margins, subprolate–prolate, distorted; amb subcircular; exine 1 μ at equator increasing up to 1.5 μ at pole, nexine markedly thicker than sexine, thickening across poles, intactate, apiculate, apiculae short and narrow, 0.5 μ high, scattered at regular intervals, ca. 1 μ apart.

Dimensions: Scotia 1 at 60.0 m: polar diameter 31 μ ; equatorial diameter ca. 22 μ . Other Murray Basin specimens are obliquely orientated.

Botanical affinity:

Stylidiaceae.

Known distribution:

Central-west Murray Basin–Oligocene to Late Miocene; Gippsland Basin–earliest Oligocene to terminal Pliocene; Tasmania–Early Oligocene to Present.

Discussion: This pollen type will be formally described elsewhere as *Tricolpites stylidioides* (Macphail & Hill, in press).

The type closely resembles pollen of the Stylidiaceae, in particular *Forstera* Linn. f., a very small genus of perennial

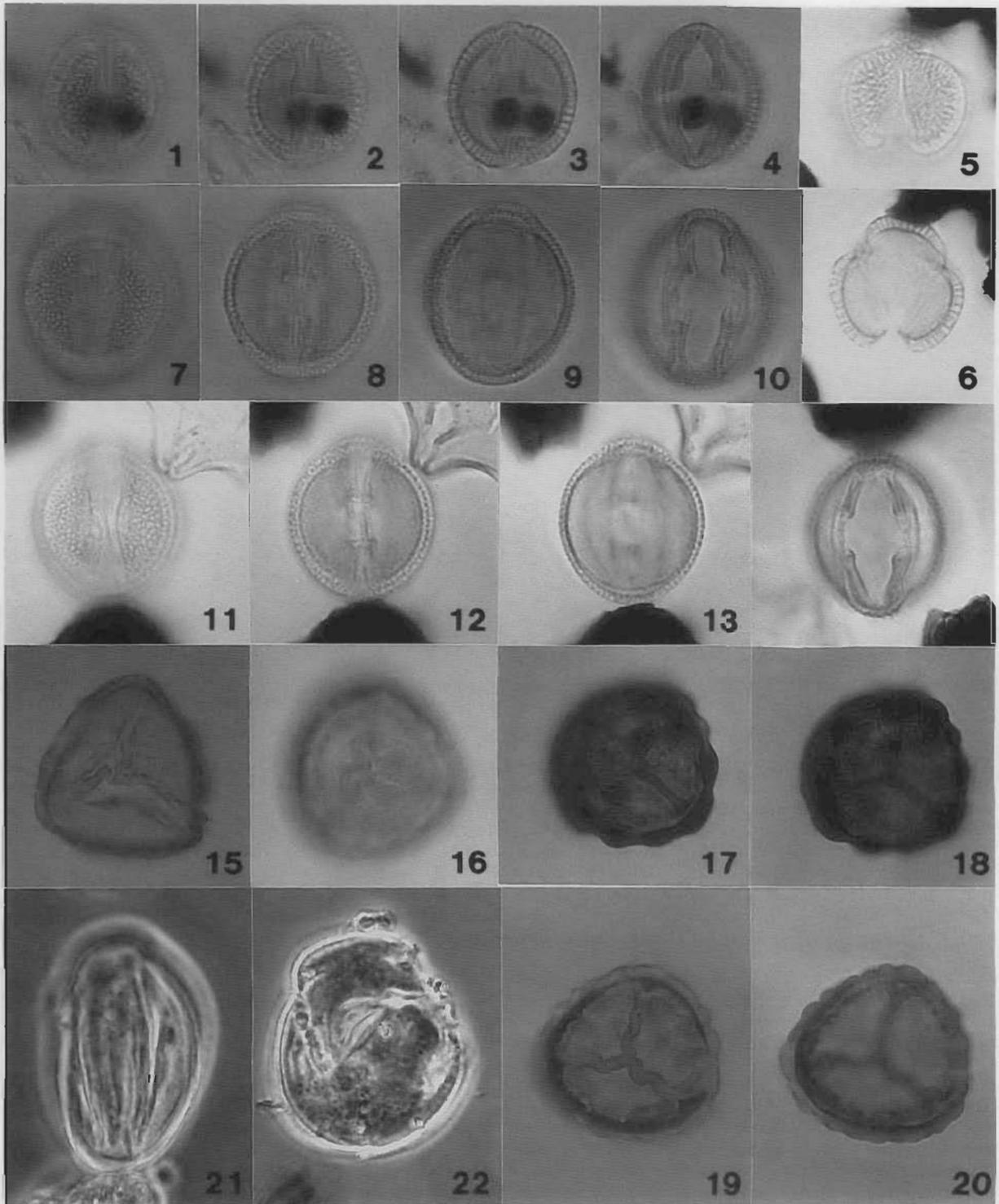


Plate 2.

Rhoipites ampereaformis n. sp.

Figs 1-4. Holotype x 1250. CPC 31511. Noora 1, 50.66-50.68 m, *Monotocidites galeatus* Zone. **Figs 5-6.** Paratype x 1250. CPC 31512. Noora 1, 50.66-50.68 m, *Monotocidites galeatus* Zone.

Rhoipites sp. cf. *R. isoreticulatus* Kemp & Harris 1977.

Figs 7-10. x 1250. CPC 31513. Noora 1, 53.4 m, *Monotocidites galeatus* Zone. **Figs 11-14.** x 1250. CPC 31514. Noora 1, 53.4 m, *Monotocidites galeatus* Zone.

Leptolepidites sp. cf. *L. verrucatus* Couper 1953

Figs 15, 19-20. Specimen with distal face uppermost x 1250. CPC 31506A. Noora 1, 65.43-65.45 m, *Triporopollenites bellus* Zone. **Fig. 16.** x 1250. CPC 31507. Noora 1, 45.58-45.61 m, *Monotocidites galeatus* Zone. **Figs 17-18.** Specimen showing puncto-reticulate sculpturing on proximal face (corrosion?) x 1250. CPC 31508. Cal Lal 78-79 m, *Monotocidites galeatus* Zone.

Stylidiaceae

Fig. 21. Corroded, strongly prolate specimen x 1250 phase contrast. CPC 31509. Scotia 1, 60.0 m, *Triporopollenites bellus* Zone.

Fig. 22. Crushed subprolate specimen x 1250 phase contrast. CPC 31510. Hapuku 1, 9218 ft. *Proteacidites tuberculatus* Zone.

herbs now confined to montane-subalpine habitats in Tasmania, New Zealand, and Fuegia. Tetracolpate, suboblate specimens approximate to the type produced by *Phyllachne* J.R. et G. Forst. The only widespread lowland member of the family in Australia, *Stylidium graminifolium* Swartz, produces strongly oblate pollen characterized by 5–6 gaping colpi with rounded apices, a type not recorded earlier than Late Pliocene sediments in Tasmania.

Specimens from southeastern Australia are the oldest fossil pollen record of the family to date.

Tricolporate pollen

Genus *Rhoipites* Wodehouse, 1933

Type species: *Rhoipites bradleyi* Wodehouse, 1933

Comment: The type species of *Rhoipites*, *R. bradleyi* (Wodehouse, 1933), has "rather finely reticulate-pitted" exine. Accordingly, the genus accommodates species in which the perforations in the tectum are less than 1 μ (puncto-reticulate) as well as types in which the diameter of the pits exceeds 1 μ (reticulate *sensu* Faegri & Iversen, 1964, p. 26), e.g. *Tricolporites microreticulatus* Harris 1965 and *R. rimulatus* Pocknall 1982.

Rhoipites amperaformis n. sp.

Pl. 2, Figs 1–6.

Holotype: Slide CPC 31511, England Finder co-ordinates O39/2. Grain in equatorial view; polar diameter 19 μ ; equatorial diameter 16 μ .

Type locality: E.W. & S (South Australia) borehole Noora 1 at 50.66–50.68 m, Loxton area, southeast South Australia, Late Miocene–Early Pliocene

Derivation of name: From the presumed botanical affinity with *Amperea* A. Juss. (Euphorbiaceae, subfamily Stenolobeae).

Description: Monad; isopolar; radiosymmetric; tricolporate, each colpus a recessed slit extending to near the poles and bordered by costae, endocolpi broad, lalongate with ends obscured by the sculpturing; sphaeroidal-subprolate, flattened at poles; amb inter-hexagonal; exine 1.5 μ at equator widening to 2.5 μ near poles, nexine thin but thickening strongly to ca. 1 μ near the endocolpi, tectate-reticulate, columellae distinct, irregularly heterobrochate with lumina increasing in size away from colpi; 20–21 x 18 μ .

Paratypes: Slide CPC 31512, Noora 1 at 50.66–50.68 m, England Finder co-ordinates H36/0 and Q28/4.

Botanical affinity: The type corresponds well with pollen produced by *Amperea*, a small genus of

low shrubs most of which are endemic to Western Australia. The pollen type is widely dispersed and grains identical to those produced by the one species with a pan Australian distribution (*A. xiphoclada*) are recorded in Holocene sediments in New Zealand (Macphail, 1979).

Known distribution:

Central-west Murray Basin–Late Miocene to Present; Gippsland Basin–Late Miocene to Present; Tasmania–Late? Pliocene to Present.

Discussion:

Rhoipites amperaformis is distinct from other Euphorbiaceae pollen in southeast Australia. Obliquely orientated/weakly developed specimens can resemble modern and fossil pollen of *Avicennia* (Verbenaceae (compare Mildenhall & Brown, 1987) but is more angular and has lalongate, elliptical rather than oval-subcircular endocolpi: the lumina are less regular in outline than in *R. sp. cf. R. isoreticulatus* (see below).

Rhoipites sp. cf. R. isoreticulatus Kemp & Harris 1977

Pl. 2, Figs 7–14.

Reference specimens:

Slide CPC 31513. Noora 1 53.40 m. England Finder co-ordinates G53/0, F58/0 and Q43/1.

Locality:

E.W. & S (South Australia) borehole Noora 1 (4836300E, 6191750N) at 53.4 m, Loxton area, southeast South Australia, Late Miocene–Early Pliocene.

Description:

Monad; isopolar; radiosymmetric; tricolporate, colpi narrow but flaring towards poles, inserted at base of a broad depression, endopores irregularly circular ca. 5–7 μ diameter; sphaeroidal-subprolate; amb inter semi-lobate; exine ca. 1.5 μ thick, nexine much thinner than sexine but thickening around and possibly protruding through endopori; tectate-reticulate, columellae distinct, homobrochate, lumina wider than muri, polygonal, less than 1 μ diameter; 21–24 μ x 24 μ .

Known distribution:

Central-west Murray Basin–Late Miocene–Early Pliocene. *R. isoreticulatus* occurs in probable Late Oligocene sediments at DSDP Site 254 at the southern extremity of Ninetyeast Ridge in the Indian Ocean.

Discussion:

The species closely resembles and may prove to be conspecific with *R. isoreticulatus*. Like the latter species (Kemp & Harris, 1977, p. 38–39), *R. sp. cf. R. isoreticulatus* closely resembles modern and Quaternary fossil (Mildenhall & Brown, 1987) *Avicennia* pollen.

Rhoipites cissus n. sp.

Pl. 3, Figs 8–15.

Holotype: Slide CPC 31515, England Finder co-ordinates S37/3. Grain in equatorial orientation, showing slight oblique compression; polar diameter 34 μ ; equatorial diameter 23 μ .

Type locality: Talgarry (DWR 36851) borehole at 91–92 m, southwestern N.S.W., Late Miocene–Pliocene.

Derivation of name:
From the presumed botanical affinity with *Cissus* L. (Vitaceae).

Description: Monad; isopolar; radiosymmetric; tricolporate, colpi narrow within a broad depression accentuated by the collapse of grain, endocolpi weakly annulate, lalongate–oval ca. 6 x 3 μ ; prolate, amb subcircular; exine ca. 1.5 μ at equator thickening to 2.5 μ across poles, tectate–reticulate, collumellae distinct, heterobrochate, lumina variable, mostly ovoid–polygonal, decreasing in size towards the poles and longitudinal colpi, less than 0.5 μ wide adjacent to colpi; 32–40 x 23–32 μ .

Paratypes: Slide CPC 31517, Scotia 1, 11.78 m (Murray Basin), Early–Late Miocene, England Finder co-ordinates R48/0; slide CPC 31516, Talgarry (Murray Basin) 91–92 m.

Botanical affinity:
The type closely resembles pollen of *Cissus*, a large genus of warm temperate to tropical lianes, which in Australia are restricted to the east coast of the mainland. Related genera occur in coastal areas in western Australia and the Northern Territory (Jackes, 1983).

Known distribution:
Central-west Murray Basin–Late Eocene to Early Pliocene; Otway Basin–Late Eocene; Gippsland Basin–late Early Miocene to ?Present; Tasmania–Miocene.

Discussion: Although no comparable pollen type appears to have been described, the worldwide distribution of Vitaceae indicates that the fossil pollen type could be widespread. Pollen of some modern Araliaceae and Sterculiaceae pollen, e.g. *Heriteria* (*Argyodendron*), resemble *R. cissus* but are distinguished by lalongate endocolpi that extend well beyond the depression containing the longitudinal colpi.

Rhoipites muehlenbeckiaformis n. sp.

Pl. 3, Figs 1–4.

Holotype: Slide CPC 31518, England Finder co-ordinates R34/3. Grain in equatorial view, one pole obscured; polar diameter 20 μ ; equatorial diameter 18 μ .

Type locality: Talgarry (DWR 36851) borehole at 91–92 m, southwestern New South Wales; Late Miocene–Pliocene.

Derivation of name:
From the presumed botanical affinity with *Muehlenbeckia* Meissner (Polygonaceae).

Description: Monad; isopolar; radiosymmetric; tricolporate, each colpus a recessed slit extending to near the poles, not bordered by costae, endocolpi lalongate diamond shaped, ca. 5 x 3 μ ; prolate-subprolate; amb circular; exine 1–1.5 μ , nexine thickened near the endocolpi, tectate–perforate, columellae distinct, pits crowded, subcircular or coalesced into fossula; diameter <1 μ , approximately equal to or wider than the intervening muri; 20–22 x 16–18 μ .

Botanical affinity:
The type corresponds well with pollen produced by *Muehlenbeckia*, a small genus of climbers and creeping plants with wiry stems, occurring throughout Australia and New Zealand from sea-level into the alpine zone, and in South America.

Known distribution:
Central-west Murray Basin–Late Miocene to Present; Gippsland Basin–Late Pliocene; Tasmania–Early Pleistocene to Present; New Zealand–Early? Miocene to Present (Mildenhall, 1980).

Discussion: Other puncto–reticulate *Rhoipites* species described from the Australasian region are *R. scabratus* Harris, 1965 and *R. rimulatus* Pocknall 1982. The former differs from *R. muehlenbeckiaformis* in shape and a much finer ornamentation; the latter in that the exine increases in thickness across the poles and the nexine splits between the apertures to form a lalongate endocrack around the equator of the grain.

Pollen of living *Muehlenbeckia* species in Australia vary considerably in size but all specimens examined possess puncto–reticulate sculpturing and lalongate, diamond-shaped endocolpi. The same combination of characters distinguishes *R. muehlenbeckiaformis* from other Tertiary *Rhoipites* spp. in Australia: several allied types occur in Late Eocene–Miocene sediments in the Murray Basin (see below).

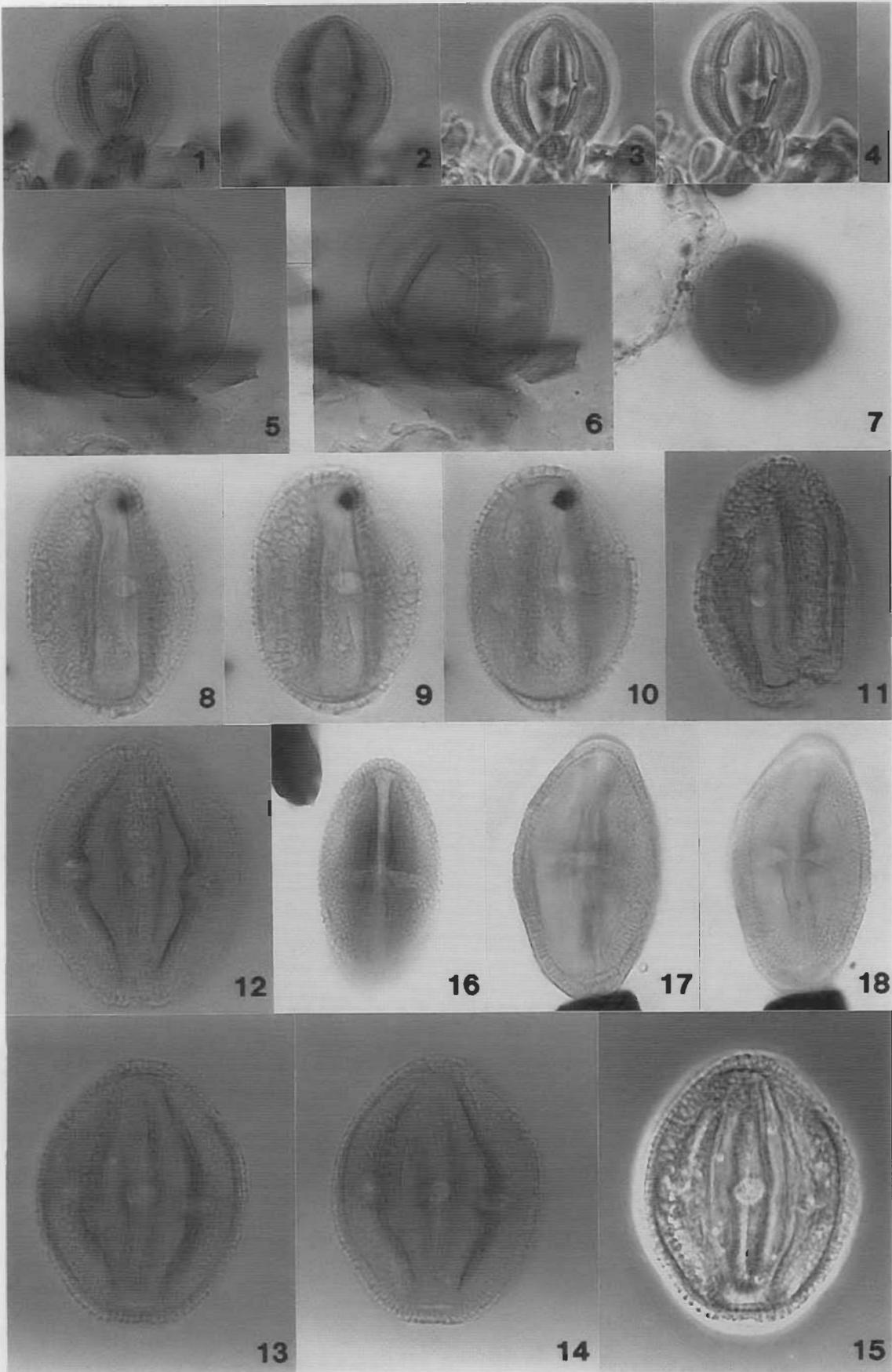
Rhoipites sp. cf. *Tricolporites microreticulatus* Harris 1965

Pl. 3, Figs 16–18.

Reference specimen:
Slide CPC 31519, England Finder co-ordinates V40/2.

Locality: Pomona (Murray Basin) at 250–251 m, Late Oligocene–Early Miocene.

Description: Monad; isopolar; radiosymmetric; tricolporate, each colpus a recessed slit extending



to near the poles, endocolpi lalongate, ca. 5 x 2.5 μ ; prolate; amb circular; exine <1.5 μ at equator widening to 2.5 μ across poles, nexine thickened near the endocolpi, tectate-reticulate, columellae distinct, homobrochate, lumina decreasing gradually in size towards the poles; 27–34 x ca. 24 μ .

Botanical affinity:
Unidentified angiosperm.

Known distribution:
Otway Basin—late Early to Late Eocene; Central-west Murray Basin—Late Eocene to Pliocene; Gippsland Basin—late Early Eocene to Early Oligocene?

Discussion: The illustration of *Tricolporites microreticulatus* provided by Harris (1965: Pl. 27, fig. 17) appears to be of *T. scabratus* Harris 1965 and vice versa (Pl. 26, figs 18–19). Both *T. microreticulatus* and *T. scabratus* fall within our concept of *Rhoipites* Wodehouse 1933.

The pollen type combines the amb shape and sexinous features of *Tricolporites microreticulatus* with the puncto-reticulate sculpture of *Tricolporites scabratus*. Additional specimens are required to establish whether the morphotype is a variant of *T. microreticulatus* or warrants species status.

Rhoipites risus n. sp.

Pl. 3, Figs 5–7.

Holotype: Slide CPC 31521, England Finder co-ordinates K61/1. Grain in equatorial view, showing oblique equatorial compression. Polar diameter 27 μ ; equatorial diameter 27 μ .

Type locality: Hydro-Electric Commission of Tasmania borehole 5825, Lemonthyme Creek, northern Tasmania at 42.9 m, Early Oligocene.

Derivation of name:
From the Latin *risus*, in reference to the clown's mouth outline of the endocolpus.

Description: Monad; isopolar; radiosymmetric; tricolporate, each colpus a narrow slit extending to near the poles, not bordered by costae, endocolpi lalongate diamond shaped, ca. 9 x 3 μ ; subprolate; amb circular-semiangular; exine ca. 1.5 μ , nexine very thin but thickening near the endocolpi, tectate-

perforate, columellae distinct, pits much less than 1 μ across but approximately equal in dimensions to the muri; ca. 30 x 28 μ .

Paratype: Slide CPC 31522, Booligal 1 (Murray Basin) at 224–225 m, England Finder co-ordinates K45/0.

Botanical affinity:
Polygonaceae.

Known distribution:
Central west Murray Basin—Late Oligocene to Early Miocene; Gippsland Basin—late Early to Late Miocene; Tasmania—Early Oligocene to ?Pliocene.

Discussion: *Rhoipites risus* is broadly similar to pollen of modern *Polygonum aviculare* L. but has a very fine, puncto-reticulate sculpture and a sphaeroidal rather than equatorially constricted prolate outline (compare Pl. 46, figs c,d in Moore & others, 1991).

Syncolporate pollen

Genus *Myrtacidites* Cookson & Pike, 1954 ex Potonie, 1960

Type species *Myrtacidites mesonesus* Cookson & Pike ex Potonie 1960

Myrtacidites lipsis n. sp.

Pl. 4, Figs 1–5, 8.

1981 *Myrtacidites* sp. C, Bint: 284, fig. 12

1988 *Eucalyptus spathulata*, Martin & Gadek, 319–322, fig. 10C-G.

Holotype: Slide CPC 31523, England Finder co-ordinates D51/4. Grain in polar view; equatorial diameter 21 μ ; rugulae projecting 2–3 μ at apices.

Type locality: E.W. & S (South Australia) borehole Noora 1 at 34.90–34.92 m,

Derivation of name:
Named after the heavily thickened, lip-like margins of the colpi.

Description: Monad; isopolar; radiosymmetric; parasyncolporate; colpi 5–10 μ long with heavily thickened margins (margo colpae), endopores elliptical transverse opening into

Plate 3.

Rhoipites muehlenbeckiaformis n. sp.

Figs 1–4. Holotype x 1250. CPC 31518. Talgarry 1, 91–92 m, *Monotocidites galeatus* Zone.

Rhoipites risus n. sp.

Figs 5–6. Holotype x 1250. CPC 31521. Lemonthyme Creek (northern Tasmania) DH 5825 43 m, *Proteacidites tuberculatus* Zone.

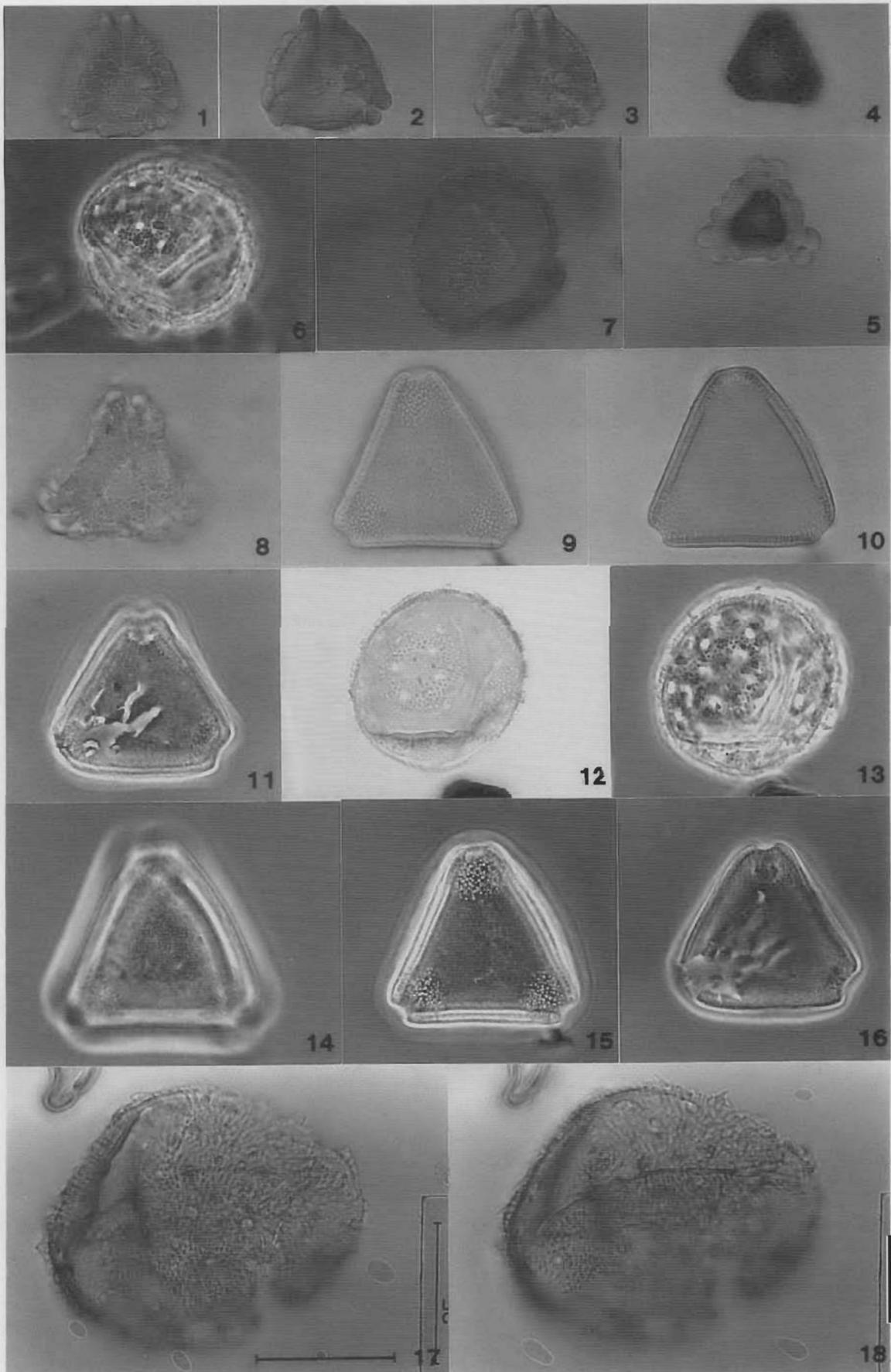
Fig. 7. Paratype x 1250. CPC 31522. Booligal (DWR 36803) 224–225 m, *Proteacidites tuberculatus* Zone.

Rhoipites cissus n. sp.

Figs 8–10. Holotype x 1250. CPC 31515. Talgarry, 91–92 m, *Monotocidites galeatus* Zone. Fig. 11. Paratype x 1250. CPC 31516. Talgarry, 91–92 m, *Monotocidites galeatus* Zone. Figs 12–15. Paratype x 1250. CPC 31517. Scotia 1, 11.78 m, *Triporopollenites bellus* Zone.

Rhoipites sp. cf. *Tricolporites reticulatus* Harris 1965

Fig. 16. x 1250. CPC 31519. Pomona (DWR 36784) 250–251 m, *Proteacidites tuberculatus* Zone. Figs 17–18. x 1250. CPC 31520. Deloraine (northern Tasmania) outcrop, Early Eocene.



vestibulae; oblate; amb triangular-subtriangular; exine ca. 0.8–1.5 μ , thickened into bulbous swellings ca. 2–3 μ across at the apertures which extend back along the colpi as rugulae; tectate, columellae obscure, tectum breaking down to form irregular verrucae bordering the mesocolpia, reduced to scabrae across poles and within the mesocolpia, verrucae up to 4 μ across; equatorial diameter 16–23 μ .

Paratypes: Slide CPC 31524, Halibut 1 (Gippsland Basin) at 151.6 m, England Finder co-ordinates J54/0, R33/3

Botanical affinity:

The type corresponds well to pollen of *Eucalyptus spathulata* Hook (see Martin & Gadek, 1988), a small tree (mallee) now restricted to southwestern Australia (Chippendale & Wolf, 1981).

Known distribution:

Southwest Western Australia–Pliocene to Present; southern South Australia–Late Oligocene to ? Pliocene; central-west Murray Basin–Late Miocene to Pliocene; Gippsland Basin–Late Miocene to earliest Pleistocene; Tasmania–Late? Pliocene to Middle? Pleistocene.

Discussion: *Myrtacidites lipsis* is superficially similar to *M. oceanicus* Kemp & Harris (1977), a verrucate species only recorded to date from Late Oligocene sediments from Ninetyeast Ridge in the Indian Ocean, but is readily distinguished by its more triangular shaped apocolpia, boxing glove appearance of the sexinous swellings around the apertures (obscuring the vestibula) and presence of rugulae along the adjacent colpi. On present indications, *Myrtacidites oceanicus* is an highly ornamented end-member of the same rhodomirtalean (Myrtaceae: subfamily Myrtoideae) lineage as *M. verrucosus* Stover & Partridge, 1973.

Eucalyptus spathulata may have been widely planted as a street tree in southeastern Australia (and its pollen may be widely dispersed) based on modern grains contaminating fossil preparations and some honey samples from the Canberra district.

Triporate pollen

Genus *Proteacidites* Cookson, 1950 ex Couper, 1953

Type species: *Proteacidites adenanthoides* Cookson,

1950 (subsequent designation by Couper, 1953).

Proteacidites punctiporus n. sp.

Pl. 4, Figs 9–11, 14–16.

1981 *Proteacidites* sp. A: Bint 286, fig. 39

Holotype: Slide CPC 31527, England Finder co-ordinates L33/3. Grain in polar view; equatorial diameter 30 μ .

Type locality: E.W. & S (South Australia) borehole Noora 1 at 33.04–33.06 m, Loxton area, southeast South Australia, Late Miocene–Early Pliocene.

Derivation of name:

From the puncto-reticulate ornamentation of the sexine surrounding the apertures.

Description: Monad; weakly heteropolar (plano-convex); radiosymmetric; amb triangular with straight sides, apices rounded; triporate, pores circular with smooth margins, 5–7.5 μ in diameter; exine ca. 1.5–2.5 μ thick, collumellae distinct, nexine approximately as thick as sexine in interradial area, thinning and becoming perforate-striate (grooved) near the apertures, nexinous membrane across apertures concave; tectate, tectum appearing etched or corroded in a complex scrobiculate–foveolate pattern in a zone ca. 7 μ wide around pores, psilate to minutely pitted across poles. Equatorial diameter 30–33 μ .

Paratypes: Slide CPC 31528, Noora 1 at 46.61–46.64 m, England Finder co-ordinates J32/2, Q44/4 and U40/0.

Botanical affinity:

Proteaceae aff. *Conospermum*

Known distribution:

Central-west Murray Basin–Late Miocene–Pliocene; southwest Western Australia–Pliocene.

Discussion: Most Tertiary fossil species of *Proteacidites* with puncto-reticulate to reticulate exine show some change in the diameter of the pits across the grain. The restriction of scrobiculate–foveolate sculpturing to the apertural regions, combined with ‘grooving’ of the underlying nexine, appears to be unique to this species.

Plate 4.

Myrtacidites lipsis n. sp.

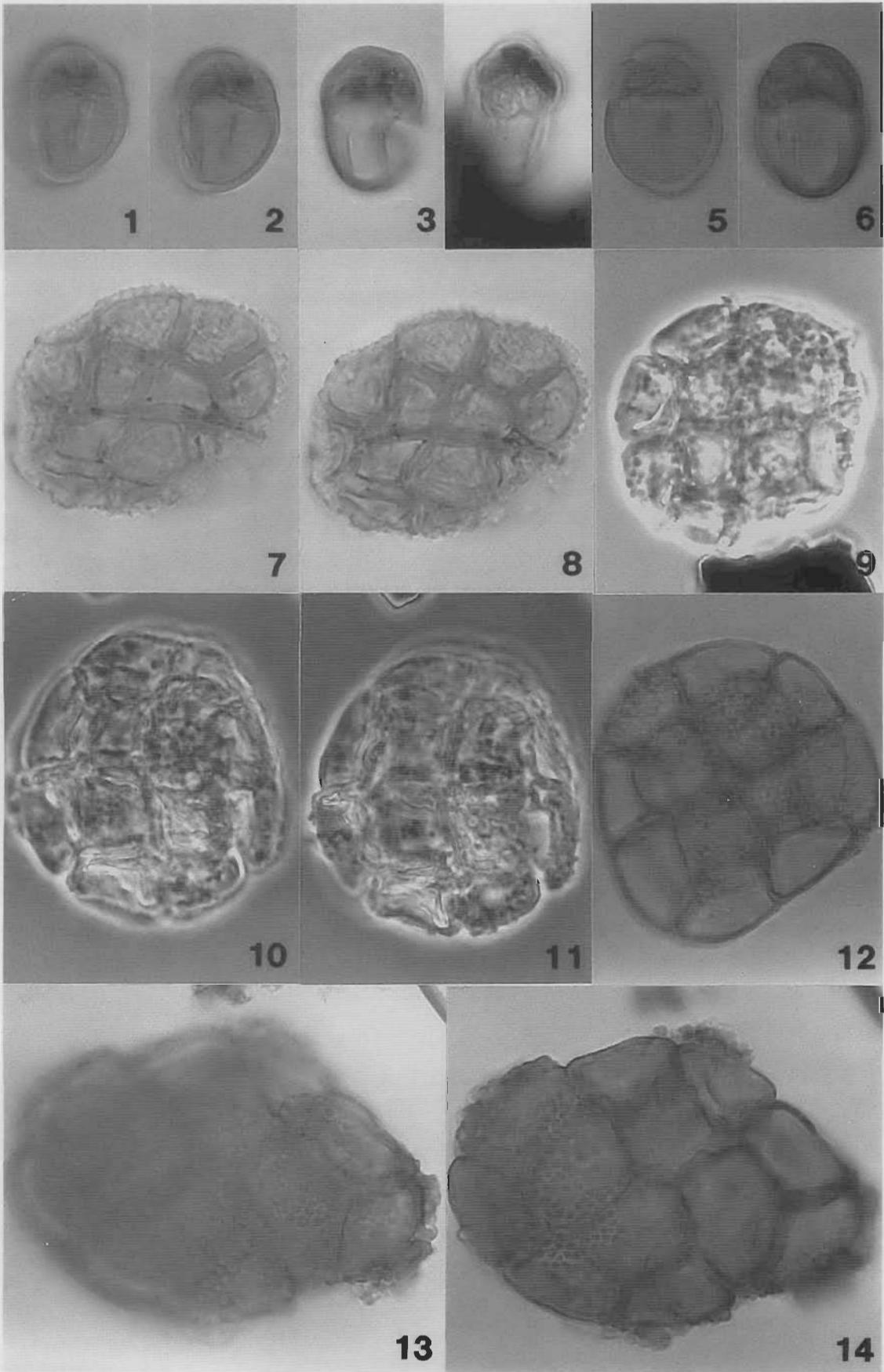
Fig. 1–3. Holotype x 1250. CPC 31523. Noora 1, 34.90–34.92 m, *Monotocidites galeatus* Zone. **Fig. 4.** x 1250. CPC 31526. Cal Lal, 67–68 m, *Monotocidites galeatus* Zone. **Fig. 5.** x 1250. CPC 31525. Noora 1, 36.3 m, *Monotocidites galeatus* Zone. **Fig. 8.** Paratype x 1250 (specimen swollen by acetolysis). CPC 31524. Halibut PFH, 497 ft.

Proteacidites punctiporus n. sp.

Figs 9, 10, 14, 15. Holotype x 1250. CPC 31527. Noora 1, 33.04–33.06 m, *Monotocidites galeatus* Zone. **Figs 11, 16.** Paratype x 1250. CPC 31528. Noora 1, 46.61–46.64 m, *Monotocidites galeatus* Zone.

Malvacipollis regattaensis n. sp.

Fig. 6. x 1250. CPC 31531. Noora 1, 39.75–39.78 m, *Monotocidites galeatus* Zone. **Fig. 7.** x 1250. CPC 31532. Transported mudstone clast, Regatta Point (west coast, Tasmania) Early–Middle Pleistocene. **Figs 12–13.** Holotype x 1250. CPC31529. Noora 1, 33.04–33.06 m, *Monotocidites galeatus* Zone. **Figs 17–18.** Paratype x 1250 (specimen swollen by acetolysis). CPC 31530. Hapuku 1, 1326 m, Early Pliocene.



Periporate pollenGenus *Malvacipollis* Harris 1965Type species: *Malvacipollis diversus* Harris, 1965*Malvacipollis regattaensis* n. sp.

Pl. 4, Figs 6–7, 12–13, 17–18.

Holotype: Slide CPC 31529, England Finder co-ordinates C34/0.

Type locality: E.W. & S (South Australia) borehole Noora 1 at 33.04–33.06 m, Loxton area, southeast South Australia, Late Miocene–Early Pliocene.

Derivation of name:

Named after the Early–Middle Pleistocene site at which this species was first recorded: Regatta Point at Strahan on the west coast of Tasmania.

Description: Monad, apolar, radiosymmetric, periporate, pores circular–subcircular, 1.5–2.5 μ diameter, ca. 24 in number, sphaeroidal; exine ca. 1.5–4 μ thick, tectate, columellae distinct, columellate pedestals absent, tectum removed in corroded grains to expose stout columellae, echinate, echini thorn-shaped, ca. 1.5–2.5 μ high and 1.5–2.5 μ across at base, regularly scattered; 30–38 μ .

Paratypes: Slide P 194460/CPC 31530, Hapuku 1 (offshore Gippsland Basin) at 1326 m, Early Pliocene, T56/0.

Botanical affinity: Malvaceae

Known distribution:

Central-west Murray Basin–Late Miocene–Early Pliocene; Gippsland Basin–Early to basal Late Pliocene; Tasmania–Early Pleistocene.

Discussion: The holotype of *Malvacipollis regattaensis* is located on the same strew mount as the holotype of *Proteacidites punctiporus* (above). The species resembles *Malvacipollis spinyspora* (Martin) Mildenhall & Pocknall, 1989 in being periporate with exine ornamentation consisting of spinae but differs from the latter in that the pores lack annuli, the nexine is thin (<1 μ vs 2–2.5 μ), the echini are more widely spaced (ca. 4 μ vs <3 μ) and as broad at the base as high. The ornamentation in *M. spinyspora* consists of coni that are3.5–4 μ high and ca. 1 μ across at the base. *M. regattaensis* differs from all *Malvacearumpollis* species in that there is no obvious swelling of the sexine below the echini. In both taxa, the columellae are clearly visible through the thin tectum, giving the pollen a pseudo–scabrate ornamentation.**Pollen in tetrads**Genus *Monotocidites* n. gen.Type Species *Monotocidites galeatus* n. sp.

Derivation of name:

From the presumed botanical affinity with *Monotoca* R. Br. (Epacridaceae, tribe Styphelieae).

Diagnosis: Modified tetrad (pseudomonad) characterized by one fully developed and three aborted but persistent miospores; heteropolar; radiosymmetric; prolate; tricolporate; psilate–scabrate.

Comment: No comparable fossil pollen type is known to have been described. The type is widespread in Quaternary palynofloras across Australia.

Monotocidites galeatus n. sp.

Pl. 5, Figs 1–6.

1981 Gen. et sp. nov. B, Bint: 286, figs. 23–24.

Holotype: Slide CPC 31533, England Finder co-ordinates O64/0. Grain in equatorial view; polar diameter 19 μ ; equatorial diameter 13 μ , aborted miospores 5 μ .

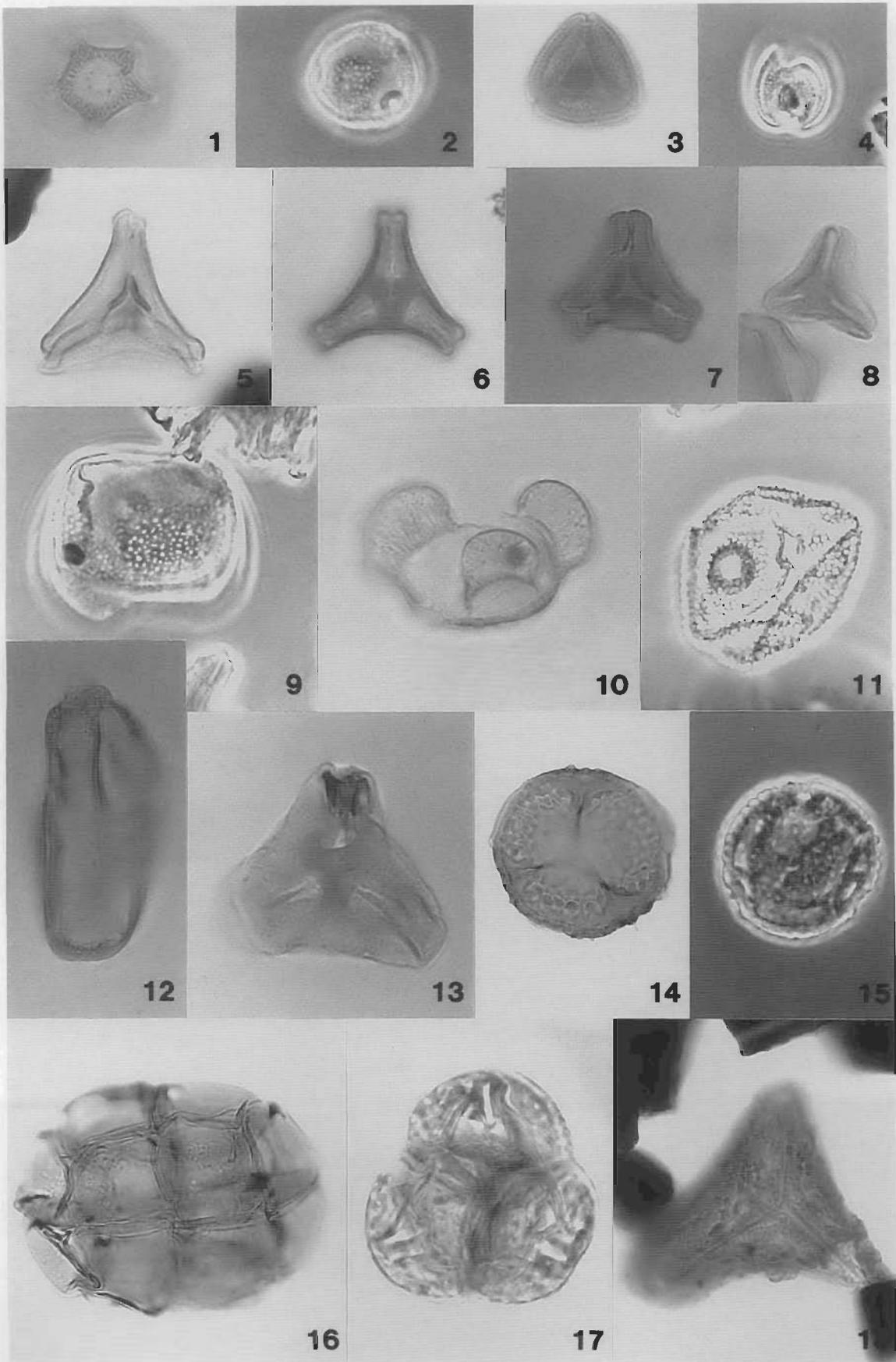
Type locality: Talgarry (DWR 36851) at 92–93 m, at the northern end of Lake Victoria, southwest New South Wales; Late Miocene–Early Pliocene.

Derivation of name:

From the Latin *galeatus*, in reference to the helmeted appearance conferred by the appearance and positioning of the aborted miospores.

Description: Pseudomonad with one fully developed and three aborted but persistent miospores; heteropolar; radiosymmetric; tricolporate, colpi long with weakly developed costae, endocolpi lalongate, adjacent to and often obscured by capping of aborted miospores; prolate; amb more or less circular; exine

Plate 5.*Monotocidites galeatus* n. sp.Figs 1–2. Holotype x 1250. CPC 31533. Talgarry, 92–93 m, *Monotocidites galeatus* Zone. Fig. 3. Paratype x 1250. CPC 31534. Talgarry, 92–93 m, *Monotocidites galeatus* Zone. Fig. 4. Paratype x 1250. CPC 31535. Talgarry, 92–93 m, *Monotocidites galeatus* Zone. Figs 5–6. x 1250. CPC 31536. Noora 1, 34.90–34.92 m, *Monotocidites galeatus* Zone.*Acaciapollenites weisii* n. sp.Figs 7–8. Holotype x 1250. CPC 31537. Benjeroop 73, 104–107 m, *Proteacidites tuberculatus* Zone. Fig. 9. Paratype x 1250, phase contrast. CPC 31538. Talgarry, 101–102 m, *Monotocidites galeatus* Zone. Figs 10–11. x 1250, phase contrast. CPC 31539. Talgarry, 91–92 m, *Monotocidites galeatus* Zone. Fig. 12. Partially stripped specimen x 1250. CPC 31540. Boga-17 47–50 *Monotocidites galeatus* Zone. Figs 13–14. *Polyadopollenites* sp. cf *Anadenanthera* x 1250. AM 6469. Lachlan Formation Bore 14747 281–287 ft, *Monotocidites galeatus* Zone.



- 1–1.5 μ thick, sexine thinner than nexine, tectate, columellae difficult to distinguish, tectum psilate to faintly scabrate; 17–20 x 12–16 μ .
- Paratypes: Slides CPC 31534, 31535, Talgarry at 92–93 m, England Finder co-ordinates at N33/0 and R39/4.
- Botanical affinity: The type is identical to pollen produced by *Monotoca*, an endemic genus of low to tall shrubs (some marginal to rainforest) found in all Australian states except the Northern Territory.
- Known distribution: Southwest Western Australia–Pliocene; Central-west Murray Basin–latest? Miocene to Present; Gippsland Basin–Late Miocene to Present; Tasmania–Late? Pliocene to Present.
- Discussion: Epacridaceae genera producing pollen tetrads in which abortion/absorption of 1–3 miospores creates functional monads, include *Astroloma*, *Brachyloma* and *Leucopogon* as well as *Monotoca* (see Franks & Watson, 1963; McGlone, 1978). The former (“A-type” of Smith-White, 1959) differ from *Monotoca* in that the remains of all three aborted miospores are wholly absorbed or do not form a radiosymmetric capping across one pole. The only non-Australian species known to produce pollen that are broadly similar to *Monotoca* is the New Zealand endemic *Cyathodes fasciculata* (Forst. f.) Allan.
- Holotype: Slide CPC 31537, England Finder co-ordinates O41/4. Polyad in equatorial view; 34 μ x 25 μ ; monads 8–10 μ .
- Type locality: Rural Water Commission of Victoria borehole Benjeroop 79 (eastern Murray Basin) at 104–107 m, late Early to Late Miocene.
- Derivation of name: Named after K. Weiss, whose innovative processing techniques have greatly improved the recovery of Tertiary spores, pollen and dinocysts from sediments in the Murray Basin.
- Description: Obligate polyad; ?inaperturate; flattened with circular to elliptical outline; individual miospores 16 — usually symmetrically arranged; anisopolar, central cells quadrangular, peripheral cells more elongate with a convex distal side; exine ca. 1–1.5 μ thick on distal surface, thinner along contact faces, collumellae not visible, tectate, tectum deciduous, bearing closely spaced verrucae and gemmae ca. 0.5–1.5 μ in diameter; 30–37 μ .
- Paratype: Slide CPC 31538, Talgarry (DWR 36851) at 101–102 m, England Finder co-ordinates L34/2.
- Botanical affinity: Mimosaceae
- Known distribution: Murray Basin–Late Oligocene to Pliocene; Sydney Basin–Early Miocene.
- Discussion: The only fossil species described to date that approaches *A. weissii* in size and ornamentation is an Early Miocene *Polyadipollenites* sp. from South America. The latter — referred to the modern genus *Anadenanthera* (aff. *A. macrocarpa*) by Barreda & Caccavari (1992) — is distinguished by the lower number of cells forming the polyad (12) and the broad, shallow nature of the verrucae. The same *Anadenanthera* species may be present in the Murray Basin (Pl. 5 Figs 13–14) although the size range is larger (37–60 μ).

Pollen in polyads

Genus *Acaciapollenites* Mildenhall, 1972

Type Species *Acaciapollenites myriosporites* (Cookson) Mildenhall, 1972

Acaciapollenites weissii n. sp.

Pl. 5, Figs 7–12.

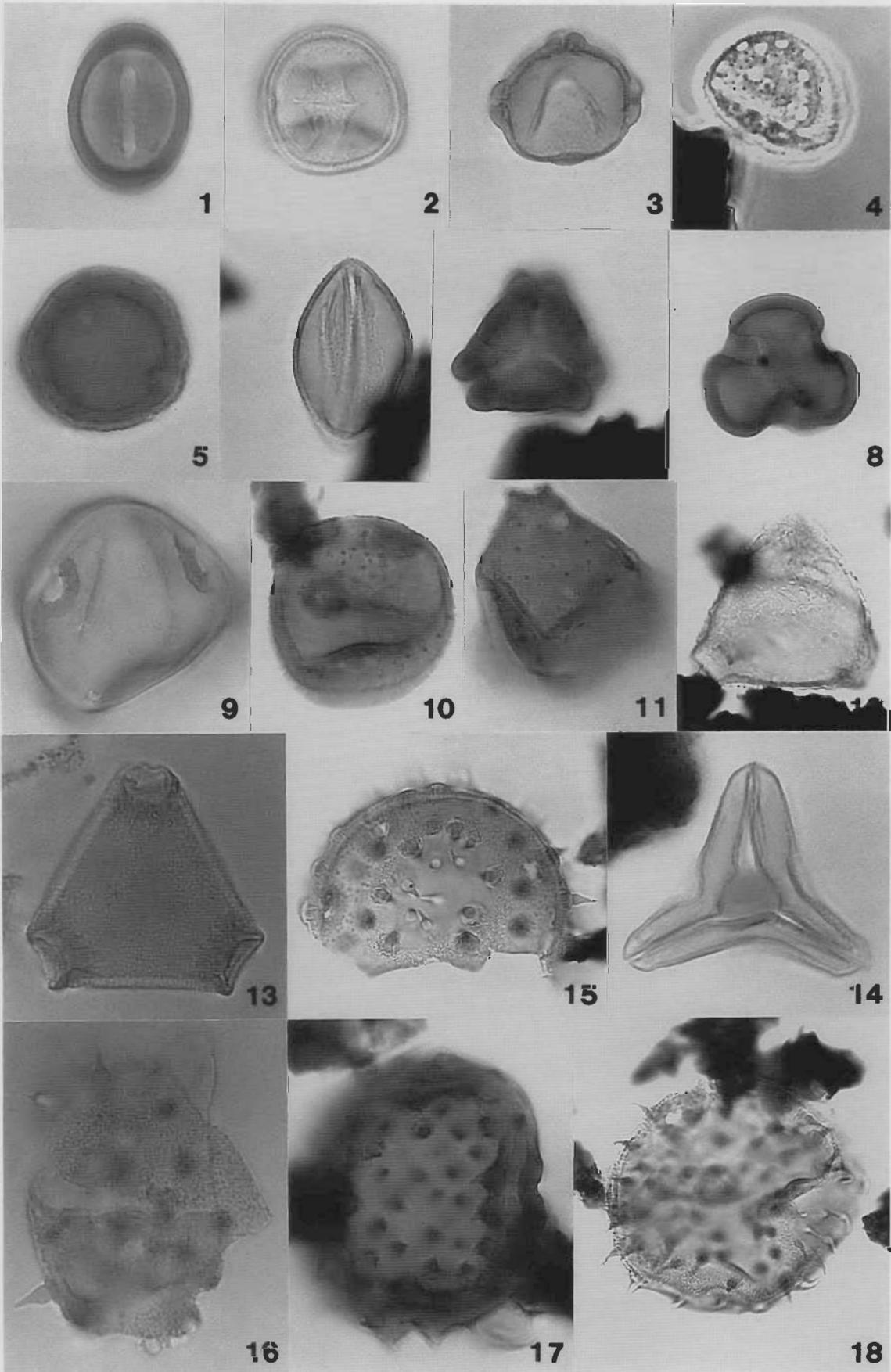
1989 *Acacia*, Knight & Martin: 287, fig. 61

non *Polyadipollenites* sp. (= *Anadenanthera* aff. *macrocarpa*) of Barreda & Caccavari (1992).

The presence of a regularly spaced rather than coalescing verrucae–gemmae distin-

Plate 6.

Fig. 1. Chenopodiaceae (*Hemichroa* type). CPC 31555. Noora 1, 43.7 m. x 1250. Fig. 2. var. of *Canthiumidites bellus* (Stover & Partridge). Mildenhall & Pocknall 1989 (puncto-reticulate). CPC 31549. Talgarry, 96–97 m. x 1250. Fig. 3. *Cupanieidites* sp. cf. *C. insularis* Mildenhall & Pocknall, 1989. CPC 31551. Talgarry, 96–97 m. x 1250. Fig. 4. *Dicolpopollis* sp. (Cunoniaceae). CPC 31553. Piangil West 2, 99.7 m. x 1250. Fig. 5. *Gothanipollis* sp. cf. *G. perplexus* Pocknall & Mildenhall 1984. CPC 31559. Piangil West 2, 99.5 m. x 1250. Fig. 6. *Gothanipollis* sp. cf. *G. gothanii* Krutzsch 1959. CPC 31557. Piangil West 2, 99.5 m. x 1250. Fig. 7. *Gothanipollis* sp. aff. *G. gothanii* Krutzsch 1959. CPC 31558. Talgarry, 100–101 m. x 1250. Fig. 8. *Gothanipollis bassensis* Stover & Partridge 1973. CPC 31556. Talgarry, 104–105 m. x 1250. Fig. 9. *Dicolpopollis* sp. (Arecaceae?). CPC 31552. Talgarry, 106–107 m, phase contrast. x 1250. Fig. 10. *Podosporites erugatus* Mildenhall 1978. CPC 31544. Noora 1, 33.04–33.06 m. x 1250. Fig. 11. *Aglaoreidia qualumis* Stover & Partridge 1973. CPC 31546. Noora 1, 52.63–52.65 m, phase contrast x 1250. Fig. 12. *Banksiaeidites* sp. (*Banksia serrata*-type). CPC 31548. Talgarry, 104–105 m. x 1250. Fig. 13. *Amylothea pliocenica* Cookson 1957. CPC 31547. Talgarry, 104–105 m. x 1250. Fig. 14. *Cingulatisporites bifurcatus* (Couper) Martin 1973. CPC 31542. Talgarry, 91–92 m, x788. Fig. 15. var. of *Canthiumidites bellus* (Stover & Partridge) Mildenhall & Pocknall 1989 (coarse reticulate) CPC 31550. Talgarry, 92–93 m. x 1250. Fig. 16. *Acaciapollenites miocenicus* Mildenhall & Pocknall 1989. CPC 31545. Talgarry, 104–105 m, x 788. Fig. 17. *Ericipites* sp. characterized by rugulate-verrucate sculpture (*Epacris*-type), CPC 31554. Talgarry, 96–97 m, phase contrast. x 1250. Fig. 18. *Cyatheacidites* sp. (*Cyathia medullaris* type). CPC 31543. Taldra 1, 86.7–86.8 m. x 1250.



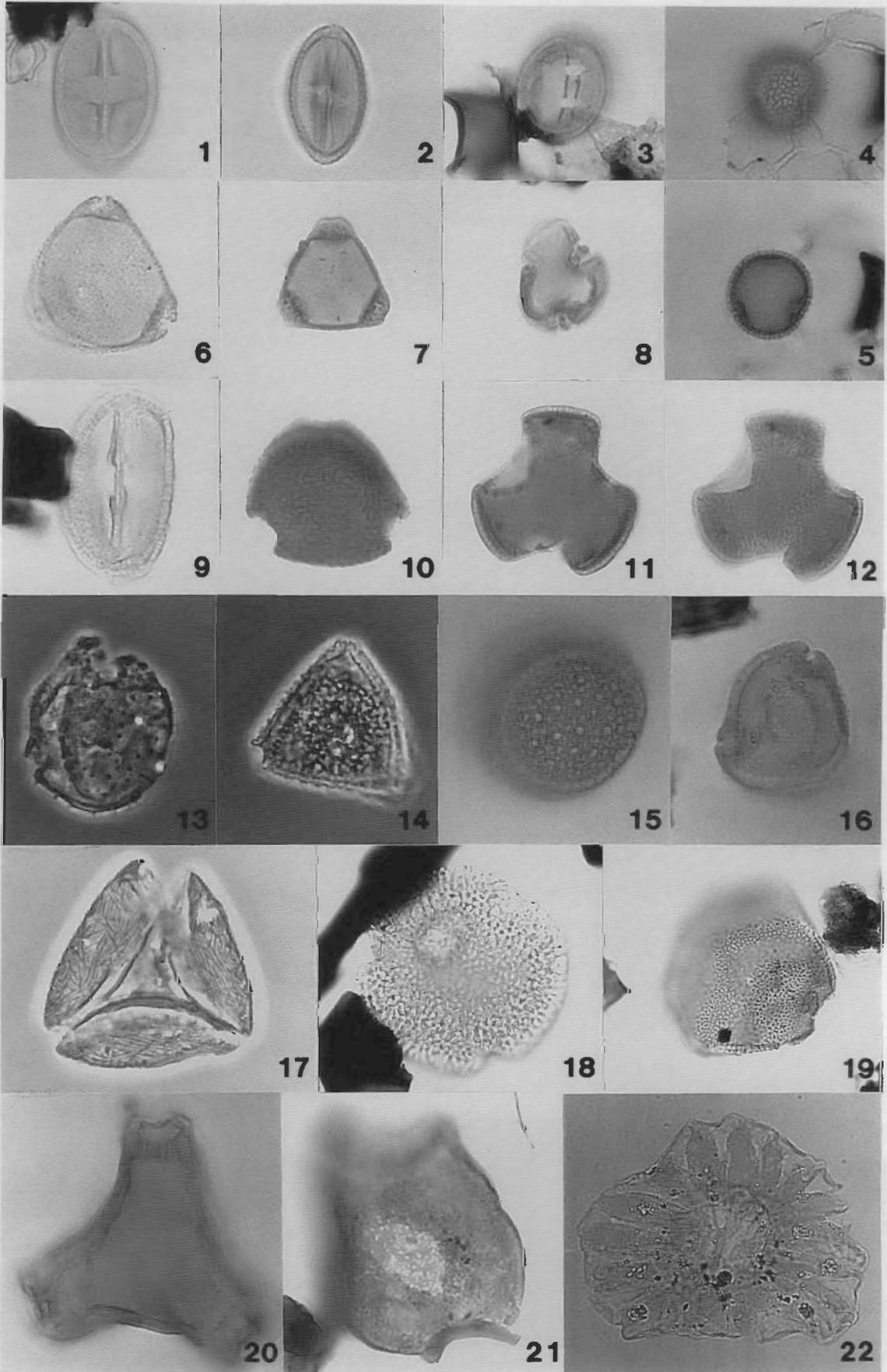
guishes *Acaciapollenites weissii* from the other two fossil Mimosaceae pollen recorded in Australia: *A. myriosporites* (Cookson) Mildenhall, 1972 and *A. miocenicus* Mildenhall & Pocknall, 1989. The African Late Tertiary species *Polyadopollenites granulatus* Sah 1967 has a coarse granulate sculpture but is substantially larger (110 μ) than *A. weissii*.

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Plate 7.

Fig. 1. *Gyropollis psilatus* Mildenhall & Pocknall 1989 (equatorial view). CPC 31562. Noora 1, 33.04–33.06 m. x 1250. Fig. 2. *Palaeocoprosmadites zelandiae* Pocknall 1982. CPC 31575. Noora 1, 52.63–52.65 m. x 1250. Fig. 3. *Haloragacidites* sp. cf. *H. myriophylloides* Cookson & Pike 1954 (*Myriophyllum*-type). CPC 31563. Piangil West 2, 99.5 m x 1250. Fig. 4. *Malvacipollis* sp. cf. *M. spinyspora* (Martin) Mildenhall & Pocknall 1989. CPC 31571. Noora 1, 53.4 m x 1250. Fig. 5. *Perisyncolporites pokornyi* Germeraad et al. 1968. CPC 31577. Talgarry, 104–105 m x 1250. Fig. 6. *Nupharipollis?* sp. (monosulcate, apiculate). CPC 31574. Noora 1, 53.4 m, x 788. Fig. 7. *Myrtaceidites eucalyptoides* Cookson & Pike 1954 (*Eucalyptus gummifera*-type). CPC 31573. Taldra 1, 86.786.8 m x 1250. Fig. 8. *Gyropollis psilatus* Mildenhall & Pocknall 1989 (polar view). CPC 31561. Noora 1, 41.58–41.61 m x 1250. Fig. 9. *Parsonsidites* sp. CPC 31576. Noora 1, 33.04–33.06 m. x 1250. Fig. 10. *Malvacipollis* sp. aff. *M. gracilis* Truswell & Owen 1988. CPC 31570. Talgarry, 94–95 m x 1250. Fig. 11. *Hakeidites (Grevillea)* sp. CPC 31564. Talgarry, 104–105 m x 1250. Fig. 12. *Hakeidites?* sp. CPC 31566. Noora 1, 52.62–52.65 m x 788. Fig. 13. *Hakeidites?* sp. CPC 31565. Talgarry, 104–105 m x 1250. Fig. 14. *Gothanipollis* sp. CPC 31560. Talgarry, 91–92 m x 1250. Fig. 15. *Malvacearumpollis* sp. CPC 31567. Talgarry, 104–105 m x 788. Fig. 16. *Malvacearumpollis* sp. CPC 31569. Talgarry, 100–101 m x 1250. Fig. 17. *Malvacipollis* sp. A (*Campostemon*-type). CPC 31572. Talgarry, 90–91 m x 1250. Fig. 18. *Malvacearumpollis* sp. CPC 31568. Talgarry, 96–97 m x 788.



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Plate 8.

- Fig. 1.** cf. *Zonocostites*. CPC 31596. Noora-1, 53.4 m x 1250. **Fig. 2.** *Tricolporopollenites cooksonii* Martin 1973. CPC 31593. Noora 1, 52.63–52.65 m x 1250. **Fig. 3.** cf. *Myoporum* (type characterised by two well-defined endopores on each longitudinal colpus. CPC 31595. Noora 1, 53.70–53.72 m x 1250.
- Figs 4, 5.** *Tripoporopollenites* sp.cf. *Canthiumidites bellus* (Stover & Partridge) Mildenhall & Pocknall 1989 (Menispermaceae?). CPC31594. Taldra 1, 87.2–87.3 m. **Fig. 6.** *Symplocoipollenites austellus* Stover & Partridge 1973. CPC 31588. Noora 1, 34.90–34.92 m x 1250. **Fig. 7.** *Proteacidites* sp. cf. *P. beddoesii* Stover & Partridge 1973. CPC 31580. Talgarry, 96–97 m x 1250. **Fig. 8.** *Schizocolpus* sp. CPC 31586. Piangil West 2, 99.5 m. x 1250. **Fig. 9.** *Poluspissusites ramus* Pocknall 1982. CPC 31578. Noora 1, 51.62–51.64 m x 1250. **Fig. 10.** *Proteacidites* sp. aff. *P. recavus* Stover & Partridge 1973. CPC 31584. Talgarry, 108–109 m, x 788. **Figs 11, 12.** *Tricolpites trioblatus* Mildenhall & Pocknall 1989. CPC 31591. Talgarry, 106–107 m x 1250. **Fig. 13.** *Tricolporites* sp. (apiculate). CPC 31592. Noora 1, 53.4 m, phase contrast x 1250. **Fig. 14.** *Proteacidites symphyonemoides* Cookson 1950. CPC 31582. Talgarry, 104–105 m, phase contrast. x 1250. **Fig. 15.** *Polyporina reticulata* Martin 1973. CPC 31579. Talgarry, 104–105 m x 1250. **Fig. 16.** *Symplocoipollenites austellus* Stover & Partridge 1973 (robust variant). CPC 31589. Talgarry, 91–92 m x 1250. **Fig. 17.** *Striasyncolpites* sp. (*Nymphoides/Villarsia*-type). CPC 31587. Taldra 1, 85.7–85.9 m, phase contrast. x 1250. **Fig. 18.** *Tricolpites pelargonoides* Martin 1973. CPC 31590. Talgarry, 100–101 m, x 788. **Fig. 19.** *Proteacidites isopogiformis* Couper 1960. CPC 31581. Piangil West 2, 88.1 m, x 788. **Fig. 20.** *Proteacidites* sp. cf. *P. annularis* Cookson 1950. CPC 31583. Noora 1; 36.3 m x 1250. **Fig. 21.** *Psilodisporites* sp. (*Alyxia*-type). CPC 31585. Talgarry, 96–97 m x 1250. **Fig. 22.** *Incertae sedis* of Truswell and others (1985). CPC 31597. Talgarry, 100–101 m x 788.

Cretaceous ammonites from south-central Papua New Guinea

Tatsuro Matsumoto¹ & Stanislaw K. Skwarko²

Eleven ammonite species, including one new taxon, are described from eleven localities in the south-central Papua New Guinea. One of them, *Fauriella boissieri* (Pictet), is a member of the Berriasian Tethyan fauna extended to peri-Gondwana. Three large, but fragmentary, ammonites are identified as *Puzosia* aff. *mayoriana* (d'Orbigny) and *Pachydesmoceras* sp. B and C, suggesting a Cenomanian age. *Acanthoceras rhotomagense* (Brongniart), *Calycoceras (Newboldiceras) asiaticum* (Jimbo), and *Cunningtoniceras cunningtoni* (Sharpe) indicate more dis-

tinctly the Cenomanian age. *C. cunningtoni* is associated with *Desmoceras (Pseudouhligella)* aff. *eozanum* Matsumoto, both occurring in generally the same area as the type locality of *Chimbuities sinuosocostatus* (Casey & Glaessner). From another locality a new species, *Chimbuities giganteus* is described. *Chimbuities* is regarded as an offshoot of *Eopachydiscus*, and therefore a member of Pachydiscidae rather than Hoplitidae. A well-preserved specimen of *Romaniceras deverianum* (d'Orbigny) indicates a Turonian age.

Introduction

Eleven taxa of Cretaceous ammonites are described from south-central Papua New Guinea. The specimens were collected during a number of geological reconnaissances conducted by the Australian Petroleum Company (A.P.C.) between 1954 and 1969. They were collected at eleven localities scattered between 6° 0' and 7° 30' and between 143° 0' and 145° 30' in the Central Highlands and the adjacent foothills in the south. This same general area has previously yielded other Cretaceous fossils (Erni, 1944; Glaessner, 1958), but there is little duplication of species between the present and the previously described faunas.

Stratigraphy

The source area of the ammonites described below (Fig. 1) is large, and its geology complicated. The detailed locality records are presented individually in the systematic descriptions and are limited to the actual collecting sites (Fig. 2). The numbers in Figures 1 and 2 were originally the actual specimen numbers, but on the transfer of the collection to the Bureau of Mineral Resources, they were allotted the Commonwealth Palaeontological Collection (C.P.C.) numbers, and consequently the original specimen numbers are herewith used as those marking the collecting sites.

The problem that we have encountered is the inconsistency in the terminology and definition of stratigraphic units between old ones supplied to us from the A. P. C. (1961) and those of later papers. Even in the latter there is some discrepancy between authors. In the current paper, we depend much on the terminology in the Kutubu Sheet area explained in tabular form by Brown & Robinson (1982) and we also cite the newer scheme proposed by Welsh (1990). The stratigraphic results of the present study are discussed under the headings of the international stages below.

1. **Berriasian.** A well-preserved ammonite *Fauriella boissieri* (Pictet) from the "Tubu Shale" (i.e. Maril Shale in the current usage) in the Kereru Range suggests strongly a Berriasian age that corresponds to the upper part of the Sequence J/K of Welsh (1990). *F. boissieri*, under the genus *Subthurmannia*,

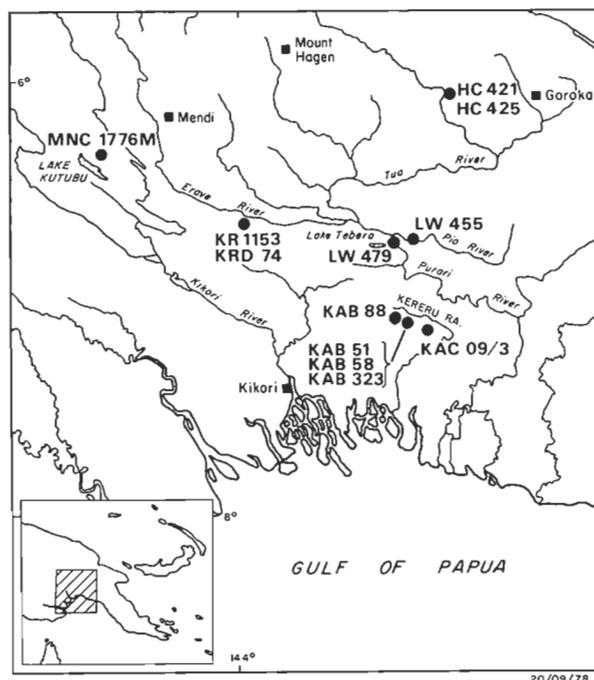


Figure 1. General map of south-central Papua New Guinea, showing localities of described ammonites.

has been reported previously from the Kereru Range (Spath, 1952, p. 23). Moreover, *Haplophylloceras strigile* (Blanford) and *?Parandiceras* sp. were identified and dated as basal Cretaceous (Berriasian) or transitional Jurassic by Glaessner (A.P.C., 1961, without description).

2. **Valanginian-Barremian.** No ammonites indicating this time span are to be found among the currently discussed material. The absence of well-dated faunas of this age may be due to the lack of suitable facies rather than to a depositional hiatus (Glaessner, 1958, p. 200). A record of *Heteroceras* cf. *astieri* d'Orbigny from the Pio Gorge (A.P.C., 1961, p. 30) suggests a Barremian age, but it is unwise — particularly with heteromorph ammonites — to accept unquestionably an identification devoid of an adequate description and illustration.
3. **Aptian and Albian.** No ammonite of an undoubted Aptian age has been ever reported from Papua New

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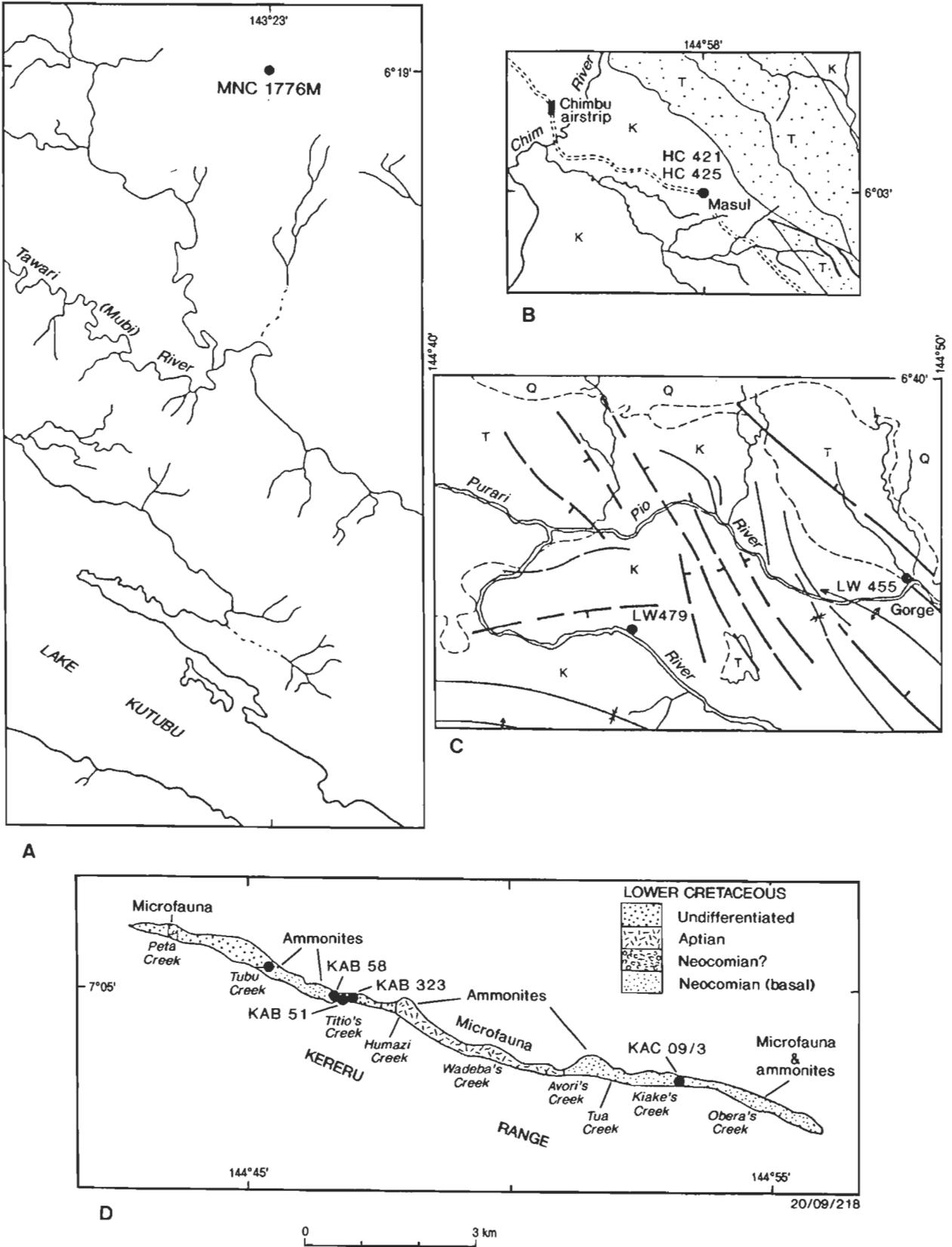


Figure 2. Individual fossil-collecting sites, with geographical data and, where available, geological information. (A) Northeast of Lake Kutubu. (B) Masul, southeast of Chimbu airstrip; K Cretaceous, T Tertiary. (C) Junction of the Purari and Pio Rivers; K, T as for Fig. B; Q Quarternary; thick line fault; moderate line with parting or facing arrows anticline or syncline. (D) Kereru Range. Information provided by courtesy of Australian Petroleum Company.

Guinea. Furthermore, neither the bivalve *Maccoyella* nor the belemnite *Peratobelus* — several species of which are both abundant and widespread in the Aptian strata in Australia — have been found in Papua New Guinea.

The Albian stage, however, is well represented by several species of heteromorph ammonites *Myloceras* and *Labe-ceras* from the Lake Toba area and from the middle Purari Valley, as well as by other molluscs — all described and illustrated by Glaessner (1958), who recognised the close faunal affinities with the Australian Albian. The above ammonites are absent from the collection described below which, however, includes *Puzosia* aff. *mayoriana* (d'Orbigny) and *Pachydesmoceras* spp. regarded as probably Cenomanian but possibly late Albian in age. It should be noted that there were in one of the A.P.C. collections several ammonites referable to *Mortoniceras* (*Durno-varites*) sp., *Spathiceras* sp. and *Bhimaites* (?) sp., which together suggest a late Albian age. Regrettably, these ammonites could not be made available for this study, but their photographs remain in a copied plate with a caption in which the CPC numbers are left blank. They were all collected at locality KRE 527M which is not shown on the maps in Figures 1 and 2, but inferred as somewhere on the Erave River in the Kutubu Trough.

There is a lack of data on the Albian–Cenomanian stratigraphy for the area under discussion. Glaessner (1958) noted that his Albian and Cenomanian fossils came from a greensand and calcareous shale which were probably an eastward extension of the Feing Group in the Upper Fly River area. The Feing Group consists of the latest Jurassic to earliest Cretaceous Toro Sandstone and Early to Late Cretaceous Ieru Formation in the northwest Papua New Guinea. Eleven Late Cretaceous ammonites have been recently described from the Ieru Formation (Matsumoto & Skwarko, 1991).

4. **Cenomanian.** Undoubted Cenomanian ammonites in the collection at hand are the *Acanthoceras rhotomagense* (Brongniart) from locality KR D 74 on the Erave River, and *Calycoceras* (*Newboldiceras*) *asiaticum* (Jimbo) from the same locality (KR 1153 = KR D 74), and from locality LW 479 on the Purari River. They are recorded as float shed from the Kerabi Formation, an assumption supported by the greenish–dark grey silty sandstone matrix. In the Kutubu Trough, the upper Mesozoic strata are placed in the Wahgi Group, which consists of the Middle to Late Jurassic Maril Shale, the mainly Early to Late Cretaceous Kerabi Formation (siltstone–sandstone) and the Late Cretaceous Chim Formation (shale) (Brown & Robinson, 1982). As *A. rhotomagense* and *C. (N.) asiaticum* are limited to the Middle Cenomanian strata in many parts of the world, the occurrence of these ammonites from the Kerabi Formation is quite natural.

Farther north in the Central Highlands there occurs another Middle Cenomanian guide fossil, *Cunningtoniceras cunningtoni* (Sharpe). It is represented in the collection under discussion by several specimens from locality F2148, Mingenda Dome, Chimbu–Mt. Hagen area, as well as by a specimen described previously as *C. holtkeri*, a synonym of *C. cunningtoni*, by Erni (1944, p. 470, pl. 11 figs A–C). Erni's specimen came from the Wahgi Valley between Hagen and Bismarck Mountains. The type locality of *Chimbuities sinuosocostatus* Casey & Glaessner is in the

same area — if not the same collecting site — as that of *C. cunningtoni*, and was collected from shale or mudstone which should be referred to the Chim Formation of the Wahgi Group. The boundary between Kerabi and Chim Formations is thus diachronous within the basin of sedimentation. In other words, the Chim Formation is at least partly a distal equivalent of the Kerabi Formation.

The zonal allocation of *Chimbuities sinuosocostatus* has yet to be worked out. It is, however, probably Middle Cenomanian in age, as the closely allied *Ch. mirindowensis* Wright occurs in Bathurst Island Middle Cenomanian with *C. cunningtoni* and *C. lonsdalei* (Adkins) (Wright, 1963).

A new species, *Chimbuities giganteus*, was collected at locality LW 455 at the Pio Gorge. The occurrence is somewhat isolated. It consists of a well-bedded calcareous sandstone with a bivalve-rich layer which may be referable to the Kerabi Formation. Future study of the associated fossils may indicate whether *Ch. giganteus* is also of Middle Cenomanian age.

Farther south in the Kereru Range fragmentary whorls of large *Puzosia* aff. *mayoriana* (d'Orbigny) and *Pachydes-moceras* sp. B and C have been found as floats shedding possibly from the "Tubu Shale". They are regarded as Cenomanian on evidence from allied species (see systematic descriptions below). Further detailed field studies are needed to ascertain whether they came from the shaly part of the Ieru–Chim Formations, or Welsh's units K4–K5.

5. **Turonian.** There is little information available on the Cenomanian–Turonian transitional part in the local sequence. Among the ammonites in the collection there are no indicators of the Late Cenomanian (in the recently revised sense: Cobban, 1984; Kennedy, 1984; 1986, etc.) or Early Turonian. *Romaniceras deverianum* (d'Orbigny) is an undoubted Turonian representative. It was collected from a coquina limestone bed in a siltstone formation at locality MNC 1776M in the Kutubu Trough. The bed was said to belong to the Kerabi Formation, but the ammonite is a good Middle Turonian species. Whether the Kerabi Formation extends up into the Middle Turonian, or whether the ammonite bed represented is part of the Chim Formation can only be determined with more detailed work in the area. In addition to *Romaniceras deverianum*, several specimens referable to *Ammonites bravaisianus* d'Orbigny were obtained at locality MNC 1763 in the Mubi Anticline, and at localities KRE 521 and KRE 1311 in the Erave Valley. *Am. bravaisianus* was referred to *Subprionocyclus* by some authors and even considered as synonymous with *S. neptuni* (Geinitz). It is, however, regarded as a distinct species of *Collignoniceras* by Futakami (1990, p. 238) on a large number of fairly well preserved specimens from the late Middle and early Upper Turonian strata in Japan. The specimens from the Papua New Guinea collections, which can be called *C. cf. bravaisianum*, have not been located in the C.P.C. collections, but their photographs remain in a copy of an unpublished plate. Their collecting sites are not marked on any map at our disposal. Although their stratigraphic data are not very precise this record may be useful in future studies on Turonian ammonites.

The age-span Coniacian–Maastrichtian is not represented by the ammonites on hand.

Systematic descriptions

Morphological terms and abbreviations used below follow those in a recent paper by Matsumoto & Skwarko (1991; see also Table 1 below). The suture terminology is the same as that used by Wright & Kennedy (1984, p. 17).

Superfamily **Perispinctacea** Steinmann 1890

Family **Neocomitidae** Salfeld 1921

Subfamily **Berriasellinae** Spath 1939

Genus **Fauriella** Nikolov 1966

Type species: *Berriasella gallica* Mazenot 1939 (by original designation).

Remarks. For the generic diagnosis see Le Hégarat, 1973, p. 146.

Fauriella boissieri (Pictet 1867)

(Figs 3, 4; Fig. 19 A–D)

1867 *Ammonites Boissieri* Pictet, p. 79, pl. 15 figs 1–3

1910 *Hoplites (Thurmannia) Boissieri* (Pictet); Uhlig, p. 233, pl. 80, figs 1a, b

1939 *Berriasella Boissieri* (Pictet); Mazenot, p. 106, pl. 15, figs 2a, b; pl. 16 figs 1a, b, 3, 4a, b

1939 *Subthurmannia boissieri* (Pictet); Spath, p. 51, pl. 9, figs 4a, b

1973 *Fauriella boissieri* (Pictet); Le Hégarat, p. 149, pl. 21 figs 1–3; pl. 48 fig. 1 (with synonyms)

Material and locality. A single fairly well preserved specimen, CPC 16088, from Tubu Shale collected at locality KAB 88 in the Kereru Range during the 1955 Abede Survey.

Description. The shell is fairly large. Assuming the body chamber of a little over half a whorl, the diameter of the original shell would have been nearly 200 mm. The whorl expands with a low ratio and is rather evolute, showing a degree of overlap between 1/3 and 1/4; the umbilicus is hence fairly wide ($U/D = 0.38$ to 0.40). The whorl is somewhat higher than broad and suboval or rounded oblong in cross-section. The body chamber has an arched venter, gently convex flank, tightly rounded umbilical edges, and steeply inclined umbilical walls. The septate whorl has flat siphonal zone on the arched venter, almost flat flanks, subangular umbilical edges and low but nearly vertical umbilical walls.

The ornament consists of numerous ribs of moderate intensity, and bullate tubercles at the umbilical edge on some ribs. The ribs are more or less gently sigmoidal on the main part of the flank, becoming more uniformly curved forward on the ventrolateral part. On the venter of the phragmocone, the ribs terminate on either side of the flat siphonal zone with or without tubercle-like thickening. On the venter of the body chamber, some ribs have feeble remnants of tubercle-like thickening on either

side of the mid-ventral zone, which is crossed, however, by weak ribs; other ribs do not show such remnants and run across the venter with a forward convexity. The ribs

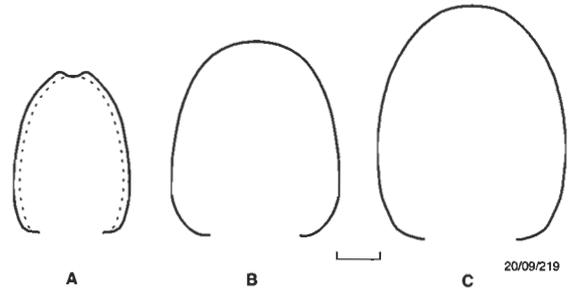


Figure 3. *Subthurmannia boissieri* (Pictet). Whorl-section of CPC 16088 at the beginning of outer whorl (A), site of last septum (B) and midst of body chamber (C); x 3/5. Scale-bar 10 mm.

of the former kind occur frequently in the earlier part of the body chamber, where the generally arched venter looks rather flat at its top.

On the phragmocone, ribs are crowded — some arising in pairs from the umbilical bullae of moderate intensity and others occurring singly with or without weak umbilical bullae. Bifurcation may occur farther at about the mid-flank and/or still farther out on the ventrolateral part. In the last part of the septate whorl, intercalated shorter ribs occasionally appear instead of bifurcated ones.

On the body chamber, the bifurcation tends to become irregular, with some of the long ribs arising in pairs from the umbilical bullae, and single long ribs with or almost without narrow umbilical bullae occurring frequently. Many, if not all, shorter ribs are of unequal length and intercalated between longer ribs; some of them arise slightly outside the umbilical edge on the inner flank, some others at about the mid-flank, and a few others on the ventrolateral part of the flank.

The suture is fairly deeply and finely ramified. L is deeper than E and trifid, but its stem is not much narrowed; E/L saddle is broad and bifid; L/U2 saddle narrow and asymmetrically bifid.

The rib in front of the last suture is strongly convex at about the mid-flank. It may be a remnant trace of the basal part of a lappet.

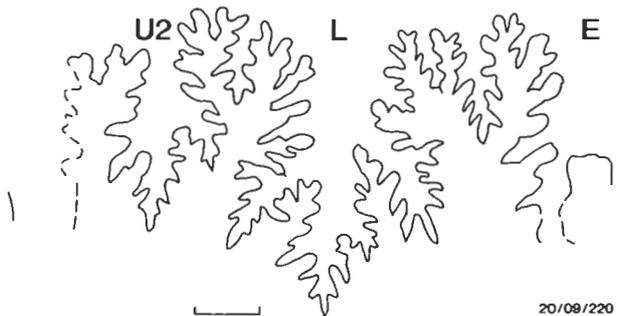


Figure 4. *Subthurmannia boissieri* (Pictet). Last suture of CPC 16088; x 3/5. Scale-bar 10 mm.

Table 1. Measurements of *Fauriella boissieri*.

Specimen and position	D	U	U/D	H	H/D	B	B/D	B/H	H/h	R (180°)
CPC 16088 LS	123	47	.38	43	.35	35	.28	.81	1.28	21/54
CPC 16088 LS+45°	134	53	.40	48	.36	40	.30	.84	—	—
CPC 16088 LS+180°	175	73	.42	—	—	—	—	—	—	—
LT(Mazenot, 1939)	150	58	.38	53	.35	39	.26	.73	—	—
Uhlig, 1910	224	89	.40	82	.37	66	.29	.80	—	19/56

D diameter, U umbilicus, H whorl-height, B whorl-breadth, h whorl-height at the point a half whorl adapical from H, R(180°) number of primary ribs/ that of all ribs in a half whorl, Inv involution. Position means the measured point, where LS at last septum, LS+90° at a point a quarter whorl adoral from LS, E preserved end, E-90° at a point a quarter whorl adapical from E, (c) costal, (ic) intercostal. HT holotype, LT lectotype. Linear dimension is measured in mm.

Dimensions. See Table 1.

Comparison and discussion. The specimen described above resembles the lectotype (see Mazenot, 1939, pl. 46 figs 4a, b) and other figured specimens of *Fauriella boissieri* from Europe, the Salt Range, and the Himalayas. Some of the French specimens are much compressed, but this compression may be partly secondary.

The body chamber of our specimen is generally similar to that of the one from the Himalayas described by Uhlig (1910, pl. 80 figs 1a, b). The difference between the two is seen in the earlier and more frequent irregularity in bifurcated ribbing in our specimen.

In the four specimens from France illustrated by Mazenot (1939) and Le Hégarat (1973), the characters mentioned above vary considerably. In the lectotype, the break-up of bifurcation to intercalation occur fairly frequently on the preserved outer whorl. Even in our specimen an intercalated short rib on one side extends to a long rib on the other side. On the unillustrated left side of the body chamber in our specimen, bifurcation of the ribs at or somewhat outside the umbilical bullae occurs more frequently than those on the right side.

In the immature stage, we see no significant difference between the specimens from the three separate provinces (for the Salt Range, see Spath, 1939, pl. 9 figs 4a, b).

Occurrence. See “Material and locality” above. In southeastern France *F. boissieri* is the late Berriasian zonal index (Le Hégarat, 1973).

Superfamily **Desmocerataceae** Zittel 1895

Family **Puzosiidae** Spath 1922

Genus ***Puzosia*** Bayle 1878

Type species. *Ammonites planulatus* Sowerby 1827 (non Schlotheim 1820) = *Ammonites mayorianus* d’Orbigny 1841 (see Wright & Kennedy, 1984, p. 54).

Remarks. See Matsumoto (1988, p. 8) for the generic diagnosis, relation with other genera, and occurrence.

Puzosia* aff. *mayoriana (d’Orbigny 1841)

(Fig. 5; Fig. 16 A–D)

Material and locality. A single specimen, CPC 16089, slightly more than a quarter of a whorl of a huge ammonite, septate throughout; collected as a float shed from the

“Tubu Shale” at locality KAB 323 during the 1955 Abede Survey.

Description. Although only a fragment of a whorl, the specimen is wholly septate; it is 120 mm high at the preserved end. The original shell must have been huge, at least 60 cm in diameter, probably evolute and with a wide umbilicus.

The whorl is somewhat higher than broad, with B/H from 0.80 to 0.85 adorally, suboval in cross-section, with a moderately arched venter, very gently convex converging flanks, well-rounded umbilical margin, and nearly vertical or even overhanging umbilical wall. It is broadest slightly outside the umbilical shoulders, i.e. considerably below the mid-height.

The surface looks almost smooth when an inner shell-layer alone is preserved as well as on the internal mould. On a part of the right side, where the outer shell-layer is preserved, faint ribs are discernible on the outer flank and venter, showing a moderately forward curve. Some of them may extend to, but fade away on, the inner flank. Periodic constrictions are shallow and broad running outward nearly radially or with a slight flexuosity on the inner flank and curving gradually forward on the outer flank in parallel with the ribs. They may be moderately frequent, as at least two are discernible on this fragmentary quarter whorl, but equally they may fade away in later growth-stages as they are already very shallow and the associated flares very weak.

The suture is typical of *Puzosia*: finely and deeply incised, with asymmetrically tripartite large L and retracted suspensive lobes.

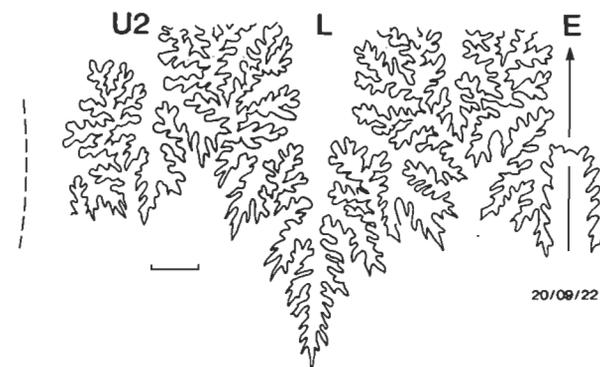


Figure 5. *Puzosia* aff. *mayoriana* (d’Orbigny). Suture of CPC 16089 at whorl-height about 105 (± 5) mm; x 3/5. Scale-bar 10 mm.

Dimensions. See Table 2.

Comparison and discussion. This specimen, although a fragment, resembles southern Indian *Puzosia planulata* var. *odiensis* Kossmat (1898, p. 112, pl. 16 figs 4, 5; pl. 18 fig. 1), which is a synonym of *Puzosia mayoriana* (d'Orbigny 1841) (see Wright & Kennedy, 1984, p. 55). The only difference is the apparently evolute, broadly curved shape which encircles a wide umbilicus. Whether this is an original character or an effect of a secondary deformation is difficult to judge. The Papua New Guinea specimen shows a probable trace of the umbilical seam of an outer whorl, which indicates 0.37 involution — a ratio close to that of Kossmat's medium-sized figured specimen.

Past literature contains little data on large examples of *P. mayoriana*. However, Kossmat (1899, p. 115) reported large specimens of "*P. planulata* var. *odiensis*", among which one of the fragmentary whorls measured by Kossmat shows $B/H=152/170=0.89$, which reasonably compares with the Papua New Guinea specimen, if the gradual increase of the ratio from 0.80 to 0.85 with growth in the outer whorl is considered.

It is not certain whether the huge *Ammonites planulatus* from southern India illustrated by Stoliczka (1865, pl. 68), can be referred to *P. mayoriana*. The specimen is indeed peculiar in having an unusually fat main part of the body chamber and a thick flare in front of a concave constriction at its peristome. Its entire shell diameter is 832 mm and its dimension at the thickened part, about a quarter whorl apically from the aperture, are shown in Table 2 below. Its specific identification is uncertain as it is recorded from the Trichinopoly Group at Anapadyr, but its septate part is not much different from, if not identical with, *P. mayoriana*. Many of the smaller specimens of *P. mayoriana* illustrated by Wright & Kennedy (1984) show geniculated ribs, suggesting basal traces of previous lappets. They are probably microconchs. Undoubted macroconchs should be described to define clearly *P. mayoriana*.

Jacob's (1908, pl. 6 fig. 2) large specimen is not the named species but a *Hyperpuzosia* (see Matsumoto, 1988, p. 27).

In summary, the specimen from Papua New Guinea is best tentatively referred to as *Puzosia* aff. *mayoriana*.

Occurrence. In Europe *P. mayoriana* occurs in the Cenomanian, although its true stratigraphic range has yet to be resolved.

Genus *Pachydesmoceras* Spath 1922

Type species. *Ammonites denisonianus* Stoliczka 1865 (by original designation).

Remarks. As discussed by Matsumoto (1988, pp. 22, 23), *Pachydesmoceras* is represented not only by a group of typical species, such as *P. denisonianum* (redefined by Matsumoto, 1987, p. 5), *P. kossmati* Matsumoto 1987, *P. linderi* (de Grossouvre 1894) and *P. pachydiscoides* Matsumoto 1954, but also by the atypical ones, such as the Cenomanian *P. rarecostatum* Collignon 1961, Turonian *P. hourcqui* Collignon 1961, etc. Some of the latter species appear similar in lateral view to *Parapuzosia* Nowak 1913 (with type species *Sonneratia daubreei* de Grossouvre 1894), but because of their thick whorls are hardly phylogenetically linked with any known species of *P. (Parapuzosia)* or *P. (Austiniceras)* Spath 1922.

Pachydesmoceras sp. nov., described by Matsumoto & Skwarko (1991, p. 246, pl. 1 fig. 4; text fig. 2) from the Cenomanian of western Papua New Guinea, is an example of an atypical(?) subgroup. For the sake of convenience it is called here *Pachydesmoceras* sp. A. The two incomplete specimens described below as *Pachydesmoceras* sp. B and *Pachydesmoceras* sp. C are referred to the same subgroup.

Pachydesmoceras ranges stratigraphically from Upper Albian to Santonian, and *Parapuzosia* — including the two subgenera — from Lower Cenomanian to Upper Campanian.

Pachydesmoceras sp. B

(Fig. 6; Fig. 16, E, F)

Material and locality. Specimen CPC 18119, a fragment of a whorl collected at locality KAB 58, Kereru Range, during the 1955 Abede Survey; it is a float probably derived from the "Tubu Shale".

Description. The fragment of a whorl — part of the body chamber — is about 250 mm long along the mid-ventral curve, and from 75 to 105 mm in height between both ends. The whorl section is thickly cordate, with a moderately arched venter, convex flanks, well-rounded umbilical shoulders, and steep umbilical walls. The whorl is broadest between the inner flanks at about one third of its height. H is slightly greater than B in the intercostal part, and nearly equidimensional in the costal section (see Table 3). The involution is slight and the umbilicus seems wide.

The ornament consists of primary and secondary ribs. The primary ribs are regularly spaced on the main part of the flank; they are strong and nearly rectiradial, with bullate tubercle-like elevations at the umbilical and the ventrolateral shoulders. The primary ribs give rise to two or three secondary ribs at about the ventrolateral shoulder. In addition there are four or three secondary ribs on each interspace of the outer extensions of primaries. The secondary ribs are thus 6 times as numerous as the

Table 2. Measurements of *Puzosia* aff. *mayoriana* (above) and allied species (below).

Specimen and position	D	U	U/D	H	B	B/H	Inv
CPC 16089 E	—	—	—	120	102	.85	—
CPC 16089 E-100°	—	—	—	97	78	.80	—
CPC 16089 restored	650	325	.50	190	—	—	.37
Kossmat, 1898, p. 115, fragmentary whorl	—	—	—	170	152	.89	—
Kossmat, pl. 16, fig. 5	116	38	.33	48	40	.83	.39
Stoliczka, 1865 E-90°	690	225	.33	260	255	.98	—

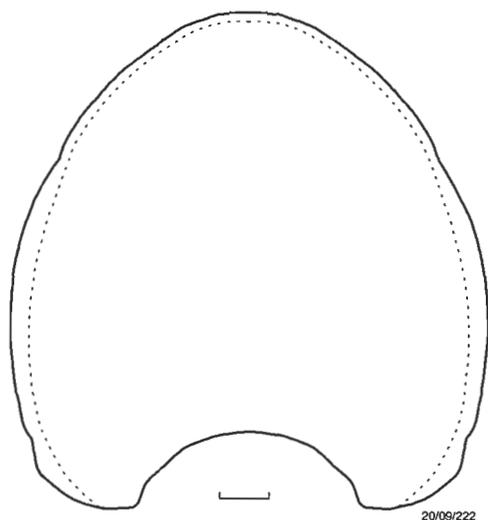


Figure 6. *Pachydesmoeras* sp. B

Diagrammatic cross-section of CPC 18119 at about the middle of the fragmentary body whorl, where $H = 98.0$ mm, $B(c) = 92.5$ mm; $x 2/3$. Scale-bar 10 mm.

primaries. They are somewhat prorsiradiate on the ventrolateral part, crossing the venter with a moderate convexity. Where shell layers are preserved on the venter, they are crowded and of moderate intensity. The secondaries are thus developed mainly on the outer part of the whorl, but some of them may extend inward to the middle part of the flank.

Comparison and discussion. The ornament of the Papua New Guinea specimen is similar to that of the lectotype (designated by Matsumoto, 1988, p. 19) of *Parapuzosia daubreei* (de Grossourve, 1894, p. 154, pl. 28), from the Santonian of France, although the primary ribs are more widely interspaced in the Papua New Guinea specimen. The large lectotype is somewhat compressed secondarily, but is never as thick-whorled as the Papua New Guinea specimen. This and other specimens of *P. daubreei* in Paris (e.g. the one shown by Matsumoto, 1966, p. 284, pl. 31 fig. 2) indeed do have the generally compressed whorl and tightly bent or nearly subangular umbilical edge.

The Papua New Guinea specimen has no affinity with any of other well-defined species of *Parapuzosia*. On the other hand, it is most closely allied to CPC 18126, here called *Pachydesmoceras* sp. A (an unnamed n. sp. by Matsumoto & Skwarko, 1991, p. 246, pl. 1 fig. 4; text-fig. 2) from locality 187, Cenomanian part of the Ieru

Table 3. Measurements of *Pachydesmoceras* spp.

Specimen and position	H	B	B/H
CPC 18119 at 5th rib (c)	98	92	0.94
CPC 18119 behind 5th rib (ic)	95	81	0.85
CPC 18120 at 3rd rib (c)	92	84	0.90
CPC 18120 adapical end (ic)	88	76	0.86

For comparison see Matsumoto & Skwarko, 1991, table 1.

Formation. The latter is somewhat larger and has thicker and more widely interspaced primary ribs and less numerous and coarser secondaries — differences which could merely represent changes with growth or variations of one and the same species.

Occurrence. As for “Material and locality” above. The above-mentioned similarity to CPC 18126 suggests Cenomanian age of CPC 18119.

Pachydesmoceras sp. C

(Fig. 7; Fig. 16G)

Material and locality. A large but incomplete specimen CPC 18120 collected during the 1957 Kereru–Purari Survey at locality KAC 09/3, Kereru Range. It is a float thought to have been shed from the “Tubu Shale”.

Description. This specimen consists of a quarter of an outer whorl, which represents a part of the body chamber and the next inner whorl with earlier whorls obscured by matrix. It must have been originally over 30 cm in diameter. It is secondarily compressed, with its right side severely squashed.

The whorl section, restored from the less deformed left half, is subrounded–trapezoid, with a broadly rounded venter, very gently convex flanks, rounded umbilical shoulder, and nearly vertical umbilical walls. Its maximum breadth is slightly outside the umbilical shoulder. The whorl height is a little greater than the whorl breadth, but B/H may have been originally somewhat larger as the left half itself has been secondarily flattened: the original whorl section was probably more rounded. The involution is slight and the umbilicus seems to be fairly wide.

The ornament consists of primary and secondary ribs somewhat irregularly disposed. On the outer whorl there are numerous long ribs, but some of them are weaker and less elevated than the undoubted major primaries. They are gently prorsiradiate, some gently flexuous. At about the ventrolateral shoulder, most become bipartite and occasionally tripartite. There are also two or three secondary ribs on each interspace. Some of the secondaries are fairly long, extending inward to or beyond the mid-flank and a few close to the umbilical edge. The long ribs are indistinctly bullate at the umbilical edge. On the venter, numerous secondary ribs are disposed regularly, showing a gently forward convex curve. They seem to weaken on the mid-ventral zone, but this may be due to abrasion.

On the flank of the next somewhat weathered inner whorl, there are also ribs of unequal length and strength. Long and strong primaries occur at frequent but irregular intervals and indistinctly tuberculate at the umbilical edge. On the interspaces there are secondaries of unequal length. All ribs are slightly prorsiradiate, and some gently concave.

Where discernible on the inner whorl, the sutures are of *Puzosia* type.

Comparison and discussion. This specimen probably represents a species which is distinct from the preceding one, because of the dissimilar outline of the whorl section and difference in ornament as described above. Both are,

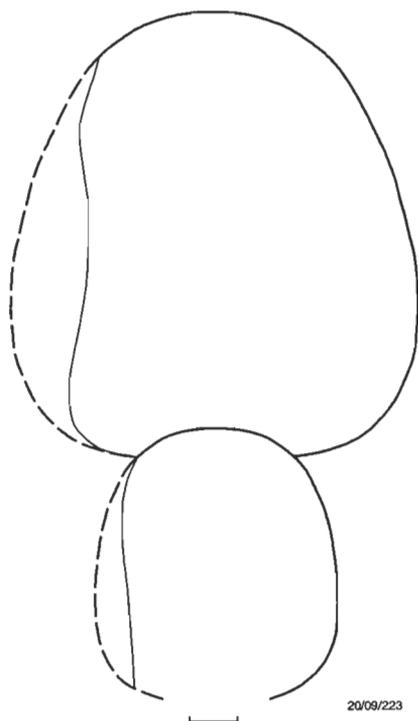


Figure 7. *Pachydesmoceras* sp. C.
Cross-section of CPC 18120 on its adapical side; thick broken line restored outline; $\times 2/3$. Scale-bar 10 mm.

however, referable to the same subgroup of *Pachydesmoceras*, because of broad whorls and *Parapuzosia*-like ribbing in the late growth stage. The ornament of the next inner whorl resembles that of the middle-aged whorls of the typical species of *Pachydesmoceras*, e.g. *P. denisonianum* described by Matsumoto & others (in Matsumoto, 1988, pp. 109–116, figs 48, 49).

Occurrence. Locality KAC 09/3 of CPC 18120 is separate from locality KAB 58 of CPC 18119, but the two specimens occur in nodules of similar lithology collected as float shed from a formation containing shale in the Kereru Range. A Cenomanian age may be suggested by this fact, but the true age of this species has yet to be worked out.

Family *Desmoceratidae* Zittel 1895

Genus *Desmoceras* Zittel 1884

Subgenus *Desmoceras (Pseudouhligella)* Matsumoto 1938

Type species. *Desmoceras (Pseudouhligella) japonicum* Yabe 1904 (by original designation).

Remarks. This subgenus was established in an English palaeontological note included as an appendix to a paper written mainly in Japanese (Matsumoto, 1938, pp. 1–46, of which pp. 13–24, pl. 1, 2, tables 2–6 are in English).

Desmoceras (Pseudouhligella) aff. *ezoanum* Matsumoto 1941

(Fig. 20A)

1941 *Desmoceras (Pseudouhligella) ezoana (sic)* Matsumoto, p. 26, fig. 4d

1942 *Desmoceras (Pseudouhligella) ezoana (sic)* Matsumoto; Matsumoto, p. 26, fig. 1b

1954 *Desmoceras (Pseudouhligella) ezoanum* Matsumoto; Matsumoto, p. 260, pl. 3 (19) figs 1–6

Material and locality. CPC 16084, an incomplete specimen consisting of the body chamber for half a whorl with destroyed last part and the last portion of the phragmocone, from locality 79, Mingenda Dome, Chimbu-Mt.Hagen area.

Remarks. *D. (P.) ezoanum* was established in a short paper (Matsumoto, 1941; repeated in 1942 in English), with a concise but clear diagnosis and distinction from other species. The species was based on a number of specimens, which are syntypes. More detailed description was given later when specimen GT. I-3030 [= UMUT. MM 6705] was chosen as the holotype (Matsumoto, 1954, p. 26, pl. 3 [19], fig. 1a–c); this specimen should now be considered as the lectotype.

Description and comparison. The specimen may be referable to *D. (P.) ezoanum* in its fairly compressed whorl ($B/H-32/42 = 0.76$) with very gently convex — instead of flat and parallel — flanks, frequent constrictions which are gently flexiradiate in the main part of flank and markedly projected on venter, and the suture with a number of regularly aligned lobes and saddles whose stems are rather narrow.

The lectotype from Japan is mainly a phragmocone with few constrictions. On the body chamber, the constrictions are numerous as seen in the specimens from a subsequent collection. Very faint subcostae or lirae are discernible in some well-preserved specimens from Japan; they generally parallel the constrictions, except for the portion near the apertural margin. Similar lirae are observable on some part of CPC 16084.

As the Papua New Guinea specimen has a somewhat wider umbilicus than *D. (P.) ezoanum*, and because of the absence of additional material, it is referred to *D. (P.) ezoanum* with a qualification. It is Cenomanian because it is associated with *Cunningtoniceras cunningtoni* (Sharpe).

Family *Pachydiscidae* Spath 1922

Genus *Chimbuites* Casey & Glaessner 1958

Type species. *C. sinuosocostatus* Casey & Glaessner 1958 (in Glaessner, 1958) (by original designation).

Diagnosis. Shell medium-sized to large, fairly involute and rather narrowly umbilicate in typical forms. Whorls in middle to late growth stages higher than broad, suboval or subelliptical or subtrapezoid in section, with steep umbilical walls, subrounded umbilical edges, very gently convex flanks, and narrowly or broadly arched venter which may be flat-topped in some cases.

Distant major ribs on inner half of flank with bullate tubercles at umbilical edge, lowered and broadened outward. Minor ribs superimposed on major ribs in addition to those on interspaces: sinuous, and some of them branch

from major ribs. On ventrolateral part ribs all curved forward, crossing (typically) venter with projection, but rarely fading away toward mid-venter. Some interspaces between minor ribs deeper than others and look like incomplete constrictions. In late growth-stage major ribs become less sinuous, and at the end of shell ornament tends to weaken.

Suture of general desmoceratacean type, with tripartite L and U2, bipartite E/L, L/U2 saddles and gently descending auxiliaries. In late growth stages, major elements (E, L, U2; E/L, L/U2) broadened and minutely fringed.

Affinities. Casey & Glaessner (in Glaessner, 1958) ascribed *Chimbuites* to the family Hoplitidae in a broad sense. However, on the general shell-form, the ornament, and in particular the sutural pattern, as well as its stratigraphic and biogeographic occurrences, this genus is best regarded as a descendant of *Eopachydiscus* Wright 1955 (p. 570) — a pachydiscid — which is represented by *E. marcianus* (Shumard 1854), a senior synonym of *Pachydiscus laevicaniculus* (ex Roemer MS) Lasswitz (1904, p. 236 [16], pl. 27 [3] fig. 2; text-fig. 3) (see Wright, 1955; Kennedy & others, 1983).

As Kennedy & others (1983) have demonstrated, in certain immature stages of *E. marcianus*, the major ribs have distinct umbilical bullae and cross the venter with a marked forward sinus; also in some immature stages minor ribs appear on the interspaces, showing a forward sweep on the ventrolateral part; occasionally some ribs branch from the umbilical bulla. These features seem to imply a high potential to give rise to the diagnostic ornament of *Chimbuites*. The only distinction is the sinuosity of the ribs on the flanks of *Chimbuites* in the early to middle growth stage. The absence of complete constrictions in the latter may be another difference.

The suture of *Chimbuites sinuosocostatus* on an immature shell is shown by Casey & Glaessner (in Glaessner, 1958, pl. 25, fig. 1), and that on a mature shell below (Fig. 8). They are similar to those of *Eopachydiscus* and *Lewesiceras* (see Kennedy & others, 1983, text-fig. 1B, C, D). The suture of a large new species (*C. giganteus*) described below (Fig. 10) is precisely like that of a similarly large specimen of "*Pachydiscus laevicaniculus*" of Lasswitz (1904, pl. 27 [3] fig. 2).

Lewesiceras Spath 1939 from the Cenomanian and Turonian is closely allied to *Eopachydiscus* from the Upper Albian, with retention of tuberculate ribs into later growth stages. It is regarded as linking the ancestral *Eopachydiscus* with later developments of the Pachydiscidae (Kennedy & others, 1983). *Chimbuites*, which has some peculiar features of its own, is not on this main evolutionary stock but probably an offshoot from *Eopachydiscus*.

Whether this offshoot died out or evolved into another group is not known, but some surprising similarity in the

suture pattern between *Chimbuites* species and such species of *Tragodesmoceras* as *T. carlilense* Cobban (1971, pp. 8–10, pls. 3–5; text-figs 6–8) might be significant. In the latter, however, the venter is fastigiate and the ribs form chevrons and may be tuberculate at their top. The bullae at the umbilical margin of the long ribs are very faint in *T. carlilense*, but they are fairly distinct in another *Tragodesmoceras* species, *T. ashlandicum* (Anderson 1902) (described under *Pachydiscus* by Anderson, 1958, p. 221, pl. 27 figs 3, 4) (see Matsumoto, 1959, pp. 26–29, pl. 5 fig. 1; text-figs 8–10). The suture of *T. ashlandicum* is more finely and deeply incised. In any case, *T. carlilense* and *T. ashlandicum* occur in the Middle Turonian. There is so far no species which could link *Chimbuites* successively with *Tragodesmoceras* either morphologically or stratigraphically.

Wright (in litt., 4 March 1992) seems right in thinking that *Eopachydiscus* is derived from *Uhligella* Jacob 1908, and presumably from one of the coarsely ribbed species such as *U. balmensis* (Jacob 1908). The numerous sigmoidal ribs in young to middle-aged *Chimbuites* may be a hereditary character from that desmoceratid member.

Chimbuites sinuosocostatus Casey & Glaessner 1958

(Fig. 8; Fig. 17 A, B)

1953 *Deshayesites* n. sp. Edward & Glaessner, p. 98

1958 *Chimbuites sinuosocostatus* Casey & Glaessner, in Glaessner, p. 214, pl. 24 figs 3a, 3b; pl. 25 figs 1a, b, 2; text-fig. 4

Material and locality. Specimen CPC 16081 and two other specimens of different size from locality HC 421 [= HC 425] regarded as the type locality, near Masul Village, about 4.5 km ESE of Chimbu Airstrip, Karimui 1:250 000 Sheet area; obtained from the local people during the Central Highlands Reconnaissance Survey. The locality is in the area of the Middle Cenomanian shale and mudstone 1980 m thick in the Wahgi Group.

Dimensions. See Table 4.

Descriptive remarks. Only one specimen, CPC 16081, out of three is available. It is nearly as large as one of the paratypes (Casey & Glaessner, in Glaessner, 1958, pl. 25 fig. 2), which shows similar measurement ratios and similar ornament in lateral view.

This specimen has suboval to subelliptical whorl sections, once the squashed left side of the phragmocone is restored. The venter on the body chamber is more broadly rounded than that on the phragmocone, although the roundness of the specimen is not quite identical with that of the paratype illustrated by Casey & Glaessner (op. cit., text-fig. 4). The character must vary with growth and also individually.

The ornament is quite similar to that of the holotype and

Table 4. Measurements of *Chimbuites sinuosocostatus*.

Specimen and position	D	U	U/D	H	H/D	B	B/D	B/H	H/h	Inv	R (180°)
CPC 16081 E (ic)	126	28	.22	57	.45	45	.36	.79	1.39	2/3	6/24
HT*	87	17.5	.20	43	.49	36.5	.41	.85	—	—	6/30
PT*	130	23	.17	60	.46	46	.35	.77	1.34	—	—

* Cited from Casey & Glaessner (1958, p. 215) for comparison.

the larger paratype. Its primary ribs arise from the bullate umbilical tubercles and are more or less prorsiradial on the inner flank, becoming sinuous and broadening outward on the main part of the flank. They show the same frequency (12 per whorl) as those of the types. The secondaries are numerous but of unequal length and superimposed on the outward-broadening primaries, some in a branched fashion from the primaries and others intercalated. On the outer part of the phragmocone, they are of moderate intensity and equally curved forward, crossing the venter with projection. Incomplete constrictions may run along some of the primary ribs.

On the body chamber, the ornament becomes weaker or blunter. Some ribs and shallow constrictions extend across the venter with a forward convexity, but other ribs seem to terminate with or without slight thickening on either side of the mid-venter. Such details are not recorded in the original description and are in fact partly obscured in the present specimen by surface abrasion.

Sutures are clearly exposed on the flank of the early part of the preserved outer whorl (with $H = 30$ to 35 mm). Their pattern is fundamentally similar to that shown on a smaller paratype (op. cit., pl. 25, figs 1a, 1b), but the stems of E/L, L and L/U2 are broader in the former. The difference is attributed to change with growth.

Comparison and discussion. *Chimbuities mirindowensis* Wright (1963, p. 603, pl. 82 figs 1, 2), from the Cenomanian of Bathurst Island, northern Australia, is closely allied to this species and distinguished mainly by its much-lesser differentiation between primary and secondary ribs.

C. aff. mirindowensis of Matsumoto & Skwarko (1991, p. 348, pl. 1 figs 1, 2), from the Cenomanian part of the Ieru Formation, is larger and more evolute.

Occurrence. See "Material and locality" above. As Wright (1963, p. 604) suggested, this species is probably Cenomanian in age.

Chimbuities giganteus sp. nov.

(Figs. 9, 10; Fig. 17 C-F)

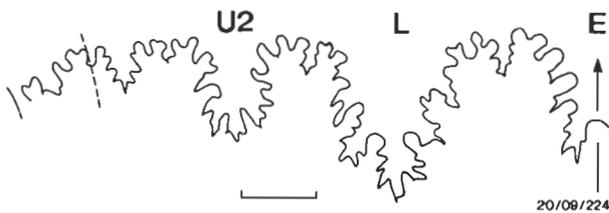


Figure 8. *Chimbuities sinuosocostatus* Casey & Glaessner. Suture of CPC 16081, slightly over a quarter whorl adapical from the last suture; x 4/5. Scale-bar 10 mm.

Material and locality. A single specimen, holotype CPC 16082, from locality LW 455 at Pio Gorge, 6.5 km east from the junction with the Purari River, in a well-bedded calcareous sandstone containing a bivalve-rich layer. Collected during the 1954 Pio-Purari Survey.

Description. The shell is very large, its original diameter being estimated at about 320 mm, if the incomplete ventral part of the outer whorl is restored. Whorls are fairly higher than broad, with $B/H = 0.65$ in a measurable part of the middle-aged whorl, and compressed suboval in cross-section; broadest at about the umbilical shoulder, with gently convex and outward converging flanks which show blunt ventrolateral shoulders passing to a subrounded venter. There is a narrow and nearly flat zone at the top of venter in the middle-aged whorl.

The whorl is fairly involute, overlapping nearly two-thirds in height of the preceding inner whorl. The umbilicus is fairly narrow, showing $U/D = 0.17$ in the middle growth-stage. The umbilical wall inclines steeply from the subangular (costal) or subrounded (intercostal) umbilical edge.

Primary ribs are widely separated, numbering six in half-whorl of the middle stage; each rib arising from a bullate tubercle at the umbilical edge, prorsiradial in an inner third of the flank with gradual broadening and obscure branching, curving backwards at about the mid-flank and again swinging forward at the ventrolateral shoulder. Secondary ribs of irregular length and strength are superimposed on the broadened outer part of the primary ribs. Some are extended from the branched primaries. Four or five secondaries are present for each primary rib. Ribs are all projected on the outer part of the flank. The interspaces between the primary ribs are gently concave and may form constriction-like grooves on the outer part of the flank. The nearly flat and narrow zone at the mid-venter of the middle-aged whorl is scarcely crossed by the secondaries.

On the outer whorl, which consists of the last part of the phragmocone and the body chamber, the primary ribs are coarser, arising from more or less thick and strong tubercles at the umbilical edge, and are nearly rectiradial or slightly prorsiradial with outward-broadening and lowering. The secondaries become faint and finally disappear, for the preserved longest primary (the fifth from the beginning of the body chamber shown on the right side) has no secondaries on its broad and low outer part.

The sutures exposed on the middle-aged whorl, have tripartite L and U2, bipartite E/L and L/U2, and nearly straightly aligned auxiliaries. E/L, L/U2 and L itself are broadly stemmed and minutely fringed.

Dimensions. See Table 5.

Table 5. Measurements of *Chimbuities giganteus*.

Specimen and position	D	U	U/D	H	H/D	B	B/D	B/H	H/h	Inv	R (60°)
CPC 16082 Em (c)	157	27	.17	78	.50	51	.32	.65	1.37	2/3	2/10
CPC 16082 Em-180° (ic)	102	17	.17	53	.52	32	.31	.60	—	2/3	—
CPC 16082 Em+180° (c)	235	47	.20	106	.45	80	.34	.75	—	—	—

Em: preserved end of middle-aged whorl; CPC 16082 Em+180° are based on a tentative restoration as shown by Fig. 9

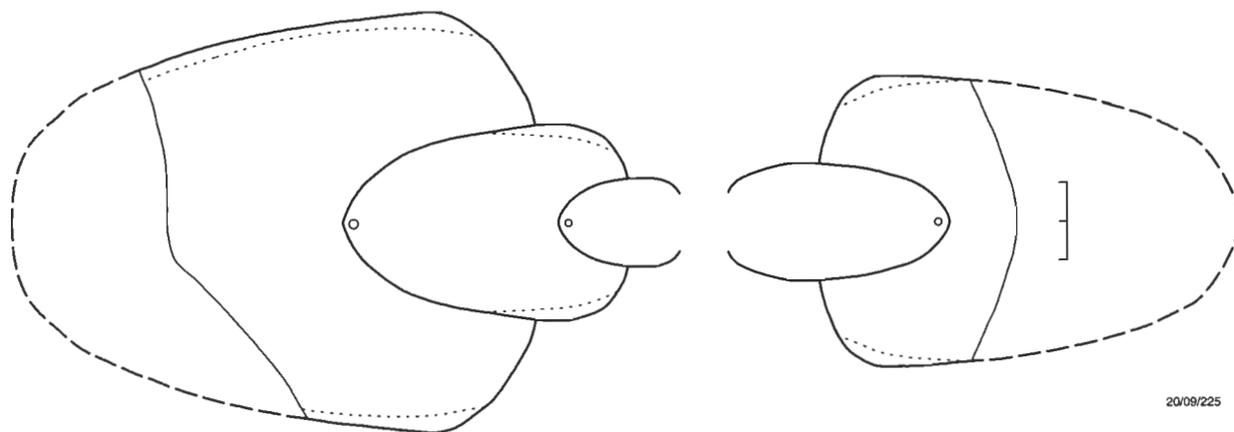


Figure 9. *Chimbuites giganteus* sp. nov. Diagrammatic cross-section of CPC 16082; thick broken line restored outline; x 8/15. Scale-bar 20 mm.

Comparison and discussion. With respect to the ornament and sutural pattern of the middle-aged shell, the holotype of this species is fundamentally similar to the holotype and paratypes of *C. sinuosocostatum*, but it has more compressed whorls with narrower venter in its young to middle-aged stages. Its adult shell is much larger and has coarser primary ribs with stronger umbilical tubercles, while the secondaries fading away.



Figure 10. *Chimbuites giganteus* sp. nov. Suture of CPC 16082 at H = 77 mm; x 1. Scale-bar 10 mm.

Although only a single somewhat incomplete specimen is available, it certainly does represent a distinct species of *Chimbuites*.

Occurrence. As for “Material and locality” above. The suggested age is Cenomanian, with confirmation to be sought among the associated fossils.

Superfamily *Acanthocerataceae* de Grossouvre 1894

Family *Acanthoceratidae* de Grossouvre 1894

Genus *Acanthoceras* Neumayr 1875

Type species. *Ammonites rhotomagensis* Brongniart 1822 (by subsequent designation of de Grossouvre, 1894)

Table 6. Measurements of *Acanthoceras rhotomagense*.

Specimen and position	D	U	U/D	H	H/D	B	B/D	B/H	H/h	Inv	R (360°)
CPC 16085 near E (c)	113	32	.28	48	.42	51	.45	1.06	1.45	.50	12/22
CPC 16085 near E (ic)	106	31	.29	44	.42	47	.44	1.07	1.42	.45	—
CPC 16085 E-180° (c)	71	20	.28	32	.45	35	.49	1.09	1.52	—	9/17

For comparison see Matsumoto & Skwarko, 1991, table 8.

Acanthoceras rhotomagense (Brongniart 1822)

(Fig. 11; Fig. 18 B–D)

Synonymy. See Wright & Kennedy, 1987, pp. 156–158.

Material and locality. A single specimen, CPC 16085, a float shed from the Kerabi Formation, obtained at locality KR D 74, some 3 km north of Kerabi Village and south of the Erave Valley, Karimui 1:250 000 Sheet area. Collected during the 1955 Erave Survey.

Description. The specimen is medium sized. The body chamber which begins at D = 95 mm (see Fig. 18C) is incomplete, but when restored the shell would be about 150 mm in diameter.

The whorl expands moderately, overlapping considerably the previous inner whorl. The umbilical ratio (U/D) is slightly less than 30%. The whorl is a little broader than high and subquadrate in cross-section, with sloping ventrolateral shoulders.

The ribs are mostly rectiradial, separated by broader interspaces, and alternately long and short on the septate whorls, with the longer ones becoming predominant on the body chamber. The long primary ribs have strong tubercles which are sharply pointed at the umbilical edge, and bullate inward and also outward. The short secondary ribs arise from some point on the inner flank. On the early part of the body chamber, some of the intercalated ribs become long but free from umbilical tubercles. All the ribs have inner and outer ventrolateral tubercles; the former are conical to obliquely clavate and the latter distinctly and sharply clavate. The siphonal tubercles are clavate but weak, becoming fainter or almost obsolete in the mature shell.

The suture is of *Acanthoceras* pattern, with deep and

roughly rectangular E, massive and bipartite E/L saddle, L and L/U2 saddle of moderate breadth and depth or height, and small U2.

Dimensions. See Table 6.

Comparison and discussion. This specimen is identified with *A. rhotomagense*, which shows a high morphological variability as demonstrated by Wright & Kennedy (1987). It is, however, noted that the hitherto described specimens from Papua New Guinea and adjacent areas (Wright, 1963; Matsumoto & Skwarko, 1991; the current paper) are commonly characterized by prominent outer ventrolateral clavi and much weakening siphonal ones. If populations from this province commonly showed these

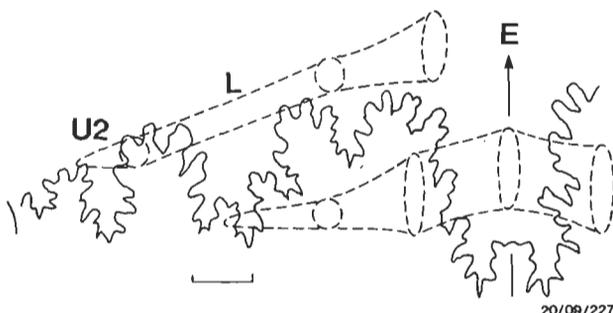


Figure 11. *Acanthoceras rhotomagense* (Brongniart). Suture of CPC 16085 at H = 34 mm; x 1. Scale-bar 5 mm.

characters, they would result in the naming of a subspecies, such as *Acanthoceras rhotomagense mirialampiense* Wright 1963. Further careful comparison is, however, needed in view of certain species from South Africa, the Gulf Coast, and Western Interior of North America which appear similar to but are not identified with *A. rhotomagense* (see Wright & Kennedy 1987, pp. 189–190).

Occurrence. As for “Material” above. In Europe and other regions *A. rhotomagense* occurs abundantly in the Middle Cenomanian.

Genus *Cunningtoniceras* Collignon 1937

Type species. *Ammonites cunningtoni* Sharpe 1855 (by absolute tautonymy).

Remarks. Cobban (1987, p. 19) and Krikland & Cobban (1986, p. 2) give the generic diagnosis of *Cunningtoniceras* and its distinction from *Euomphaloceras* Spath 1923. The phylogenetic origin of this genus is probably in *Acanthoceras* as discussed by Wright & Kennedy (1987, p. 193). Well-known species have a world-wide distribution in the Middle Cenomanian; but some species occur in the Late Cenomanian. There is a single record from the Turonian of Japan (Matsumoto & others, 1987, p. 37), but this may be either a relict or a derived fossil.

Cunningtoniceras cunningtoni (Sharpe 1855)

(Fig. 20 B–J)

Synonymy. See Wright & Kennedy (1987, p. 196).

Material and locality. Two adult specimens, CPC 16079 and CPC 16080, and one juvenile, CPC 16075, from loc. 79 (F2148), Mingenda Dome, Chimbu–MT. Hagen area, Central Highlands.

Description. The specimens from the Mingenda Dome, both mature and juvenile, are characterised by a depressed squarish whorl-section, widely separated primary ribs with prominent umbilical and ventrolateral tubercles, and numerous secondary riblets with smaller tubercles on the venter. The umbilicus is fairly deep and of medium width. The involution is slight; the outer whorl overlaps the ventral part of the inner one whose inner ventrolateral tubercles stretch along the umbilical wall of the former.

The umbilical tubercles are prominent at some distance outward from the umbilical edge and bullate on the umbilical wall. On the septate whorl, the inner ventrolateral tubercles are rather clavate; the ribs are normally divided at the outer ventrolateral tubercles, and there are often additional intercalated riblets which may or may not be looped at the base of the inner ventrolateral tubercles. Some of the riblets are associated with constriction-like grooves which may be extended onto the flank as somewhat deeper interspaces without forming distinct constrictions. Ventral riblets mostly run perpendicular to the siphonal line, but some of them are curved gently forward or form obtuse chevrons.

On the adult body chamber, the primary ribs are widely interspaced and strengthened; the inner and outer ventrolateral tubercles are united into prominent horns stretching upwards and sideways. The summit of each horn is obscurely doubled with a remnant of the outer ventrolateral tubercle on the siphonal side. The mid-ventral zone is concave between the paired horns. Short riblets remain on that concave part, and long and blunt ones are traced on the broad venter of the interspaces of horned ribs, whereas siphonal tubercles become obsolete and disappear.

The suture is of typical *Acanthoceras* type as seen clearly in CPC 16079.

Dimensions. See Table 7.

Comparison and discussion. On the basis of the characters described above, the three specimens from the Central Highlands of Papua New Guinea are certainly identifiable with *Cunningtoniceras cunningtoni* (Sharpe) as re-defined recently by Wright & Kennedy (1987), who pointed out the great variability of the species, and the difficulty in separating taxa of subspecific category under previously proposed names.

Our above described specimens share characters most similar, among others, to those in *Acanthoceras cunningtoni* var. *cornuta* Kossmat (1897, p. 18, pl. 5 figs 1a–c). This also holds true for another specimen from the Wahgi Valley described as *C. höltkeri* Erni 1944 (p. 470, pl. 11 figs A–C), and also probably to the one from Bathurst Island, Northern Territory of Australia, described as “*Euomphaloceras cunningtoni*” by Wright (1963, p. 607, pl. 88 fig. 2). Kossmat’s (1897) specimen came from southern India which in mid Cretaceous times was intimately palaeogeographically related with both northern Australia and Papua New Guinea. This may suggest that *cornutum* could be used as a geographical subspecies of *cunningtoni*, but further study of various forms from different areas is desirable before a definite conclusion

Table 7. Measurements of *Cunningtoniceras cunningtoni*.

Specimen and position	D	U	U/D	H	H/D	B	B/D	B/H	H/h	R (180°)
CPC 16075 near E (ic)	56	17	30	25	.45	32	.57	1.28	1.38	7/17
CPC 16079 near E (ic)	108	38	35	44	.41	60	.55	1.36	1.35	6/20
CPC 16080 near E (ic)	129	41	32	57	.44	—	—	—	—	7/21
CPC 16080 E-70° (c)	—	35	—	58	—	75	—	1.29	—	—

is to be reached. In any case, Wright (1963, p. 196) was correct in regarding *C. hoeltkeri* Erni 1944 as a synonym of *C. cunningtoni* (Sharpe, 1855).

Occurrence. See "Material and locality". *C. cunningtoni* occurs in various parts of the world, and where well-dated it is Middle Cenomanian in age (Wright & Kennedy, 1987, p. 205).

Genus *Calycoceras* Hyatt 1900

Type species. *Ammonites navicularis* Mantell 1822 (by designation under the Plenary Powers, ICZN Opinion No. 557).

Subgenus *Calycoceras* (*Newboldiceras*) Thomel 1972

Type species. *Acanthoceras newboldi* Kossmat 1897 (by original designation of Thomel, 1972, p. 105), which is a junior synonym of *Acanthoceras rhotomagense* var. *asiatica* Jimbo 1894, as pointed out by Wright & Kennedy (1990, p. 238).

Calycoceras (*Newboldiceras*) *asiaticum* (Jimbo 1894)

(Figs 12, 13; Fig. 18 A, E, F)

Synonymy. See Wright & Kennedy (1990, pp. 239–240) under *Calycoceras* (*Newboldiceras*) *asiaticum asiaticum* (Jimbo 1894).

1991 *Calycoceras* (*Newboldiceras*) *newboldi* (Kossmat 1897); Matsumoto & Skwarko, 1991, p. 252, pl. 4 fig. 4

Material and locality. Two specimens, CPC 16074, fairly large and wholly septate shell, from loc. LW 479, Gurimatu on the Purari River, downstream from its junction with the Pio River, collected during the Pio–Purari Survey of 1954; and CPC 18121, nearly as large as CPC 16074, float from loc. KR 1153 collected in the Erave Valley during Erave–Kutubu Survey conducted by R.C. Herrera and A.L. Findley. The rock matrix of the specimens consists of dark grey sandstone. Karimui 1: 250 000 Sheet area.

Description. Both specimens are about 200 mm in diameter. If the preserved end is assumed to be the last septum, and the body chamber as half a whorl, the entire shell diameter would be about 320 mm. The whorl expands with a moderate ratio ($H/h = 1.4$ to 1.5), overlapping about $1/3H$ of the preceding inner whorl. The umbilicus is of moderate width, with U/D from 28 to 33% in measured parts.

The whorl is somewhat broader than high, and broadest between inner flanks. Its intercostal section is subrounded, with abruptly rounded umbilical shoulders and a more or less broadly arched venter; the flanks are nearly flat in early growth stages and gently convex later. In the costal

section, the ventral zone between a pair of outer ventrolateral tubercles is nearly flat, whereas the zone between the rows of outer and inner ventrolateral forms a sloping facet.

Ribs are rather crowded and as a rule alternately long and short. The long or primary ribs arise from the umbilical seam and are slightly rurusradiate on the wall and at the umbilical shoulder provided with prominent tubercles which are bullate inward and outward. Secondaries arise on the inner flank, in some cases from the point close to the umbilical shoulder, and may approach the umbilical tubercle of the preceding primary rib.

On the main part of the flank ribs are mostly rectiradiate in CPC 16074. Gently flexuous ribs occur rarely in CPC 16074 but more frequently in CPC 18121. In both specimens some ribs are slightly elevated but not tuberculate at about the mid-flank. The inner ventrolateral tubercles are conical, whereas the outer ventrolaterals are clavate. Between them the ribs broaden gradually and are lowered and weakly projected; on the ventral zone the ribs are broad but low, running across the venter at right angles with the siphonal line. The siphonal clavi on the outer whorl are faint, becoming almost obsolete later.

In CPC 16074, a long rib with umbilical tubercle on one side of the outer whorl extends to a short rib on the other

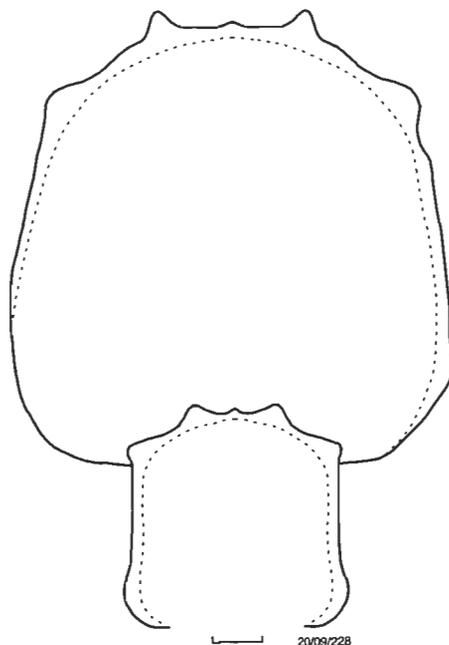


Figure 12. *Calycoceras* (*Newboldiceras*) *asiaticum* (Jimbo) Whorl-section of CPC 16074 near the preserved end at $H(c) = 83$ mm; $\times 2/3$. Scale-bar 10 mm.

Table 8. Measurements of *Calycoceras (Newboldiceras) asiaticum*.

Specimen and position	D	U	U/D	H	H/D	B	B/D	B/H	H/h	Inv	R (60°)
CPC 16074 E (c)	206	69	.33	83	.40	95	.46	1.14	1.48	.32	17/36
CPC 16074 E-90° (ic)	160	51	.32	65	.40	72	.45	1.11	1.44	—	16/33
CPC 18121 near E (c)	199	64	.32	82	.41	88	.44	1.07	1.49	.33	19/36
CPC 18121 E-120° (c)*	151	43	.28	64	.42	64	.42	1.0 *	1.42	—	15/30

* May be secondarily compressed.

For comparison see Matsumoto & Skwarko, 1991, table 4.

side. Such a feature is not seen in CPC 18121

The suture is of typical *Acanthoceras* pattern.

Dimensions. See Table 8.

Comparison and discussion. *Calycoceras (Newboldiceras) asiaticum* (Jimbo 1894) has been recently redefined by Wright & Kennedy (1991, p. 239) to include *C. (N.) newboldi* (Kossmat 1897) of previous authors as a synonym. Whether to rank *Acanthoceras newboldi* var. *spinosa* Kossmat 1897 as a subspecies of *C. (N.) asiaticum* or an independent (but closely allied) species is a problem still to be resolved.

The holotype from the Mikasa Formation in Hokkaido, and a number of specimens from the type and contiguous localities as well as from the correlatable zone in other parts of Japan, are now under investigation by Matsumoto and his colleagues. It has been already observed that the *newboldi*-type shell-form with rather flat and subparallel

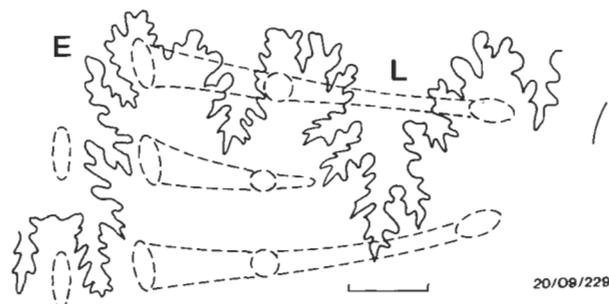


Figure 13. *Calycoceras (Newboldiceras) asiaticum* (Jimbo). Suture of CPC 16074 at H = 45 mm in the early part of the preserved outer whorl; x 1. Scale-bar 10 mm.

flanks occurs frequently in early to middle growth-stages, whereas fairly to very large outer whorls of late growth-stages show subrounded inter-costal sections with the maximum breadth between the inner parts of flanks or between the umbilical tubercles in costal section. In some cases, the *newboldi*-type form may persist to a late growth-stage, and as a matter of course there are gradations between the above two forms ontogenetically and also individually.

There is also some variation in ornament; the weakness of siphomal clavi can be attributed to such variation.

In summary, the Papua New Guinea specimens described above are identified as *C. (N.) asiaticum*. Another specimen, CPC 16073, from the Ieru Formation, western Papua New Guinea, earlier described as *C. (N.) newboldi*

(Matsumoto & Skwarko, 1991, p. 252, pl. 4 fig. 4) is now also identified as *C. (N.) asiaticum*.

Occurrence. See "Material and locality" above. From its occurrence in Japan, southern India and Europe *C. (N.) asiaticum* indicates the Middle Cenomanian age.

Genus *Romaniceras* Spath 1923

Type species. *Ammonites deverianus* d'Orbigny 1841 (by original designation).

Romaniceras deverianum (d'Orbigny 1841)

(Figs 14, 15: Fig. 19 E, F)

1841 *Ammonites deverianus* d'Orbigny, p. 346, pl. 110 figs 1-2

1980 *Romaniceras (Romaniceras) deverianum* (d'Orbigny); Kennedy & others, p. 332, pl. 39 figs 7-10; pl. 41 figs 1-6; pl. 42 figs 1-7; text-figs 1, 3D, 4, 5 (with full synonymy, except for those discussed below).

Material and locality. Specimen CPC 16086, which shows fine detail on the right side and the major part of the venter but is much abraded on the left side; collected from locality MNC 1776M, northwest end of the core of Mubi anticline, where up to 214 m of the Late Cretaceous Chim(?) Formation (siltstone with occasional coquina limestone) is exposed. This ammonite was taken from one of these limestones, a 90 cm thick band, 22 m below the top of the formation. Lake Kutubu 1:250 000 Sheet area.

Description. The specimen is fairly large, with diameter 175 mm at the last septum and probably about 250 mm when body-chamber was complete. Its outer whorl consists of the late part of the phragmocone and the body-chamber on halves. A restored whorl is nearly as high as broad at about the beginning of the body chamber, and shows a subrounded intercostal section.

The whorl expands with a fairly high ratio, overlapping one third of the previous inner whorl. The umbilicus is of moderate width, showing the umbilical ratio (U/D) of nearly 30%.

On the outer whorl ribs are all long; on the previous inner whorl long ribs predominate but occasionally short ribs are branched or intercalated. The ribs are nearly rectiradial and rather crowded on the inner whorl, but on the outer whorl they are prorsiradial or gently concave, broadening outward, but somewhat widely interspaced. The long ribs number 12 per half whorl.

Tubercles are in nine rows; those at the umbilical edge are small and bullate; the laterals are somewhat thick and bullate at the base and fairly prominent on the summit; the inner ventrolaterals are conical and the strongest; the outer ventrolaterals subconical to obliquely clavate and of moderate intensity; the siphonal ones clavate and distinct. The distance between the umbilical and lateral tubercles is slightly shorter than that between the lateral and inner ventrolateral ones.

Suture is of *Acanthoceras* type, showing broad and bipartite saddles of E/L and L/U2. The illustrated last suture is somewhat reduced in the depth of lobes and minor incisions.

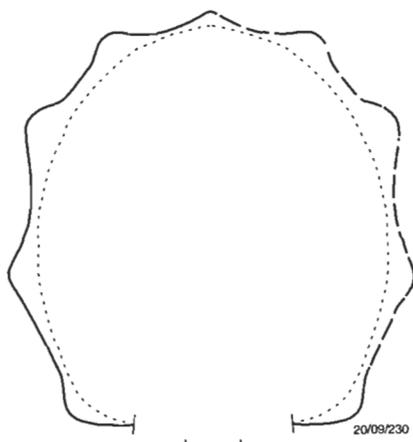


Figure 14. *Romaniceras deverianum* (d'Orbigny). Whorl-section of CPC 16086 at the last septum; x 2/3. Scale-bar 10 mm.

Dimensions. See Table 9.

Comparison and discussion. Kennedy & others (1980) have revised *Romaniceras deverianum* (d'Orbigny), showing a great extent of variation in its shell form and ornament. It is difficult to decide whether to regard *R. pseudodeverianum* (Jimbo 1894) as a synonymy of *R. deverianum* (see Matsumoto & others, 1985, pp. 165–167; pl. 8, fig. 3).

The described specimen from Papua New Guinea is somewhat peculiar in having equally long ribs on the outer whorl, whilst on the inner-whorl a few of the long ribs are nodeless at the umbilical margin and branched or intercalated shorter ribs do occur, though infrequently.

In the figured examples of *R. deverianum* (in the sense of Kennedy & others, 1980) from Europe, the frequency of intercalated secondaries seems to vary with growth and between individuals. In the holotype of *R. uchauxiense*

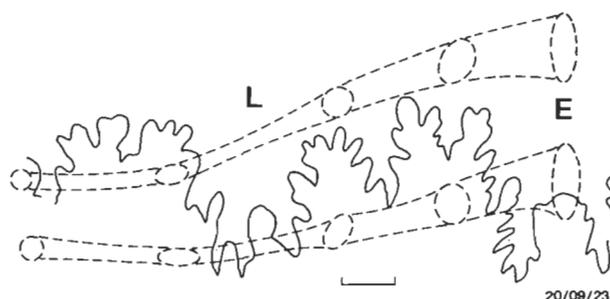


Figure 15. *Romaniceras deverianum* (d'Orbigny). Last suture of CPC 16086; x 2/3. Scale-bar 10 mm.

Collignon (1939, p. 38) (= Roman & Mazeran, 1913, pl. 3, figs 1, 1a), synonym of *R. deverianum* as Kennedy & others stated, the primaries are predominant over secondaries on its wholly septate whorl.

The lectotype of *Ammonites medicottianus* Stoliczka (1864, pl. 43 figs 1, 1a, 1b), GSI 181, is nearly as large as the present specimen (see Table 8) and has a similar mode of ribbing and tuberculation. In view of the great variability in the European material (Kennedy & others 1980), these minor differences can be attributed to intraspecific variation.

The specimen from Papua New Guinea is thus referred to *R. deverianum* despite some individual peculiarities.

A specimen illustrated by Noda (1969, pl. 3) as *Romaniceras* sp., from the middle part of the Zone of *Inoceramus hobetsensis* in Kyushu, is a distorted internal mould. It is very similar to the Papua New Guinea specimen in size, the presence of equally long and gently concave ribs on the outer whorl, and the configuration of tubercles. It is now identified with *R. deverianum*.

Occurrence. See "Material and locality" above. *R. deverianum* is widespread and limited to occurrence to the upper part of Middle Turonian wherever it is found.

Conclusions

Among the Papua New Guinea ammonites described in this paper: one is a member of the Berriasian-Tethyan fauna extended to peri-Gondwana; those of Albian age suggest a palaeogeographic connection with the Australian fauna; others, of Cenomanian age, are well-represented both by well-known widespread species and by *Chimbuites*

Table 9. Measurements of *Romaniceras deverianum*.

Specimen and position	D	U	U/D	H	H/D	B	B/D	B/H	H/h	Inv	R (180°)
CPC 16086 LS+85° (ic)	206	61	.30	91	.44	75	.36	82	1.62	—	12/12
CPC 16086 LS+80° (c)	208	61	.29	93	.45	90	.43	97	1.63	—	12/12
CPC 16086 LS (c)	173	52	.30	78	.45	79	.46	1.01	—	.33	12/13
GSI 181* LS+130° (c)	210	67	.32	87	.41	95	.45	1.09	1.50	.31	9/11

* Measured by T. M. (at the preserved last 3rd rib). For comparison see Kennedy & others, 1980, p. 336.

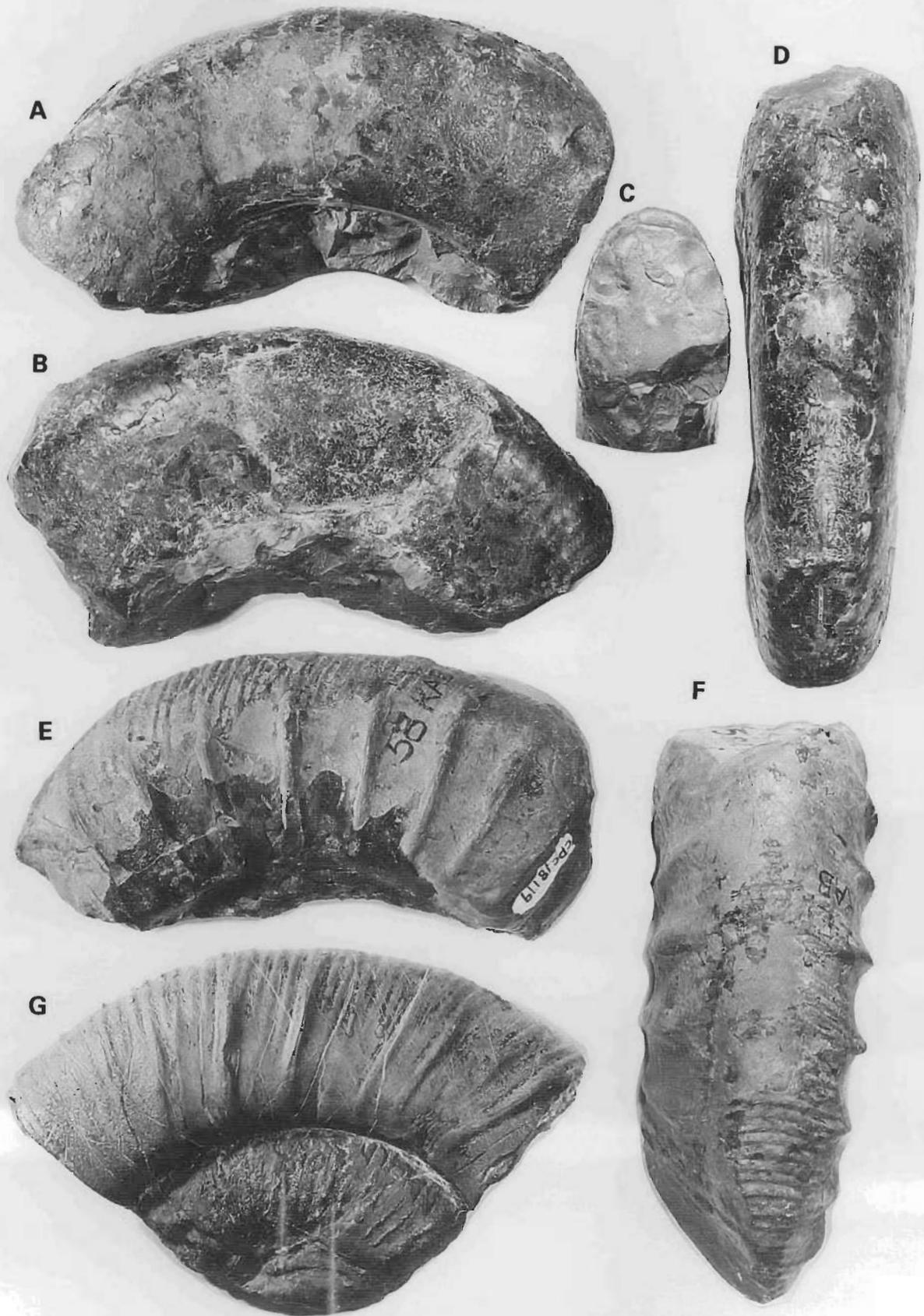


Figure 16. A–D. *Puzosia* aff. *mayoriana* (d’Orbigny 1841). CPC 16089; locality KAB 323, Kereru Range, Cenomanian (?). Left and right lateral views, adapical section, and ventral view; x 1/3. E, F. *Pachydesmoceras* sp. B. CPC 18119; locality KAB 58, Kereru Range, Cenomanian. Lateral and ventral views; x 2/5. G. *Pachydesmoceras* sp. C. CPC 18120; locality KAC 09/3, Kereru Range, Cenomanian; lateral view; x 1/3.

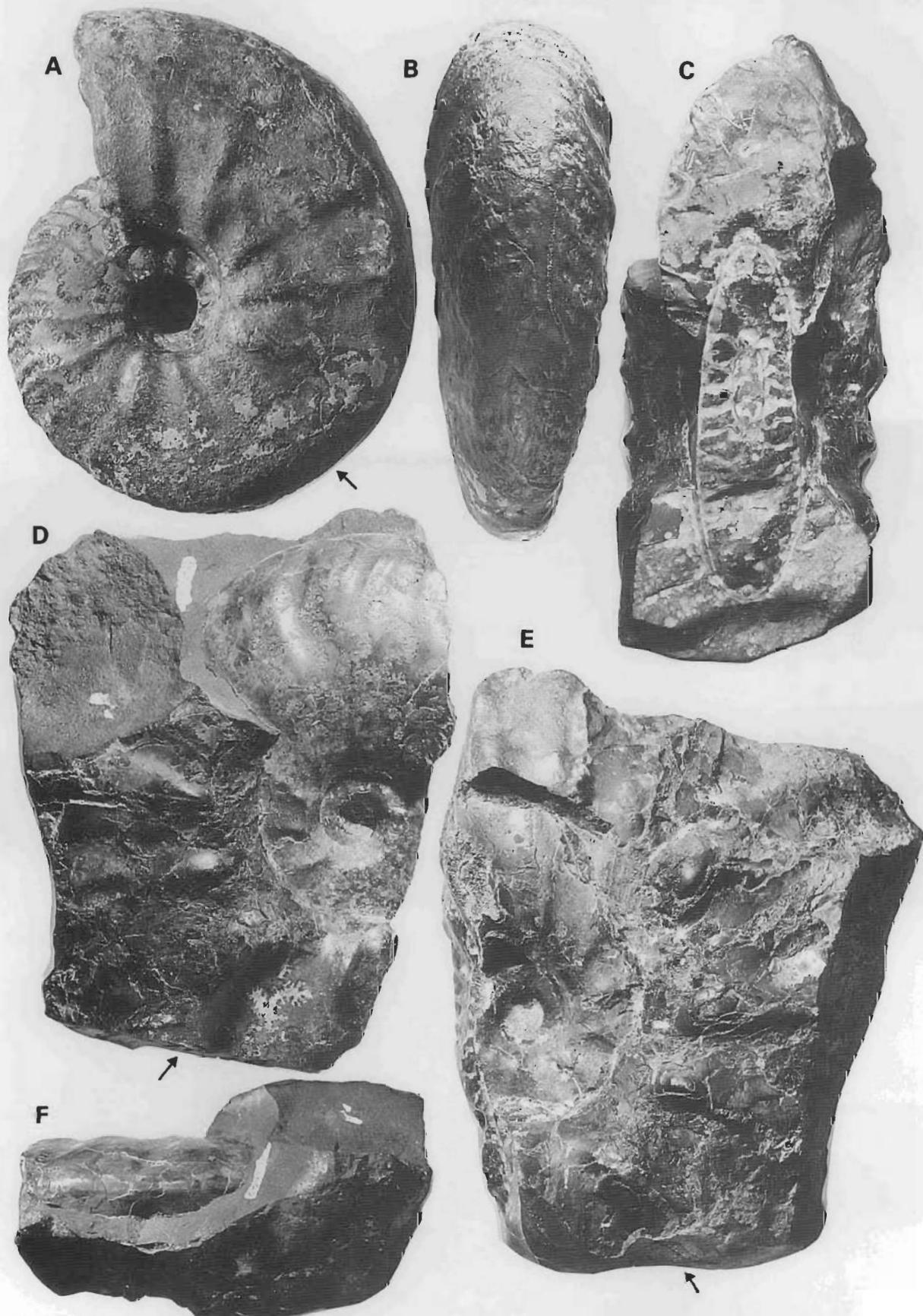
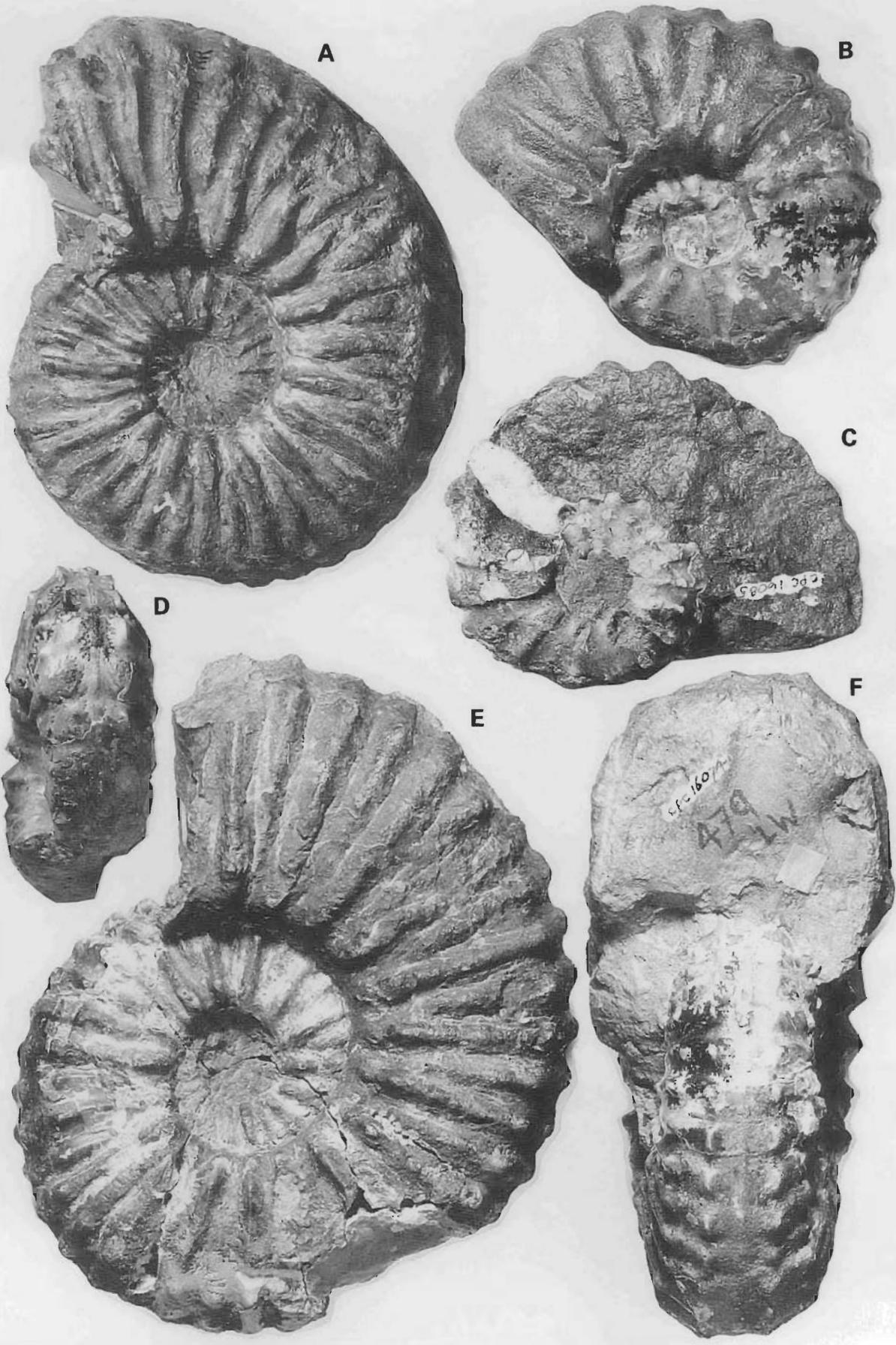


Figure 17. A,B. *Chimbuities sinuosocostatus* Casey & Glaessner 1958.
 CPC 16081; locality HC 425, 4.5 km ESE of Chimbu Airstrip in the Central Highlands, Cenomanian. Lateral and ventral views; x 7/10.
 C-F. *Chimbuities giganteus* sp. nov.
 CPC 16082; locality LW 455 at Pio Gorge, Central Highlands, Cenomanian. Natural section, left and right lateral views, ventral view of inner whorl cropping out through the broken part of the body chamber; x 3/5. Arrow: beginning of body chamber.



— now regarded as an offshoot of *Eopachydiscus* which is in turn ancestral to main members of Pachydiscidae — which so far seem endemic to Papua New Guinea and the northern Australian margin; *Romaniceras* is a cosmopolitan representative of the ammonites of Turonian age.

It is worthy of note that no Valanginian–Aptian ammonites are present in the collection; that in contrast to the extensive retreat of the sea from the main part of Australia, Papua New Guinea was well inundated during at least part of Cenomanian and Turonian times; and that the age-span Coniacian–Maastrichtian is not clearly indicated by the ammonites studied.

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Figure 18. A, E, F. *Calyoceras (Newboldiceras) asiaticum* (Jimbo 1894). (A) CPC 18121; locality KR 1153, Erave Valley, Cenomanian; lateral view; x 1/2. E, F. CPC 16074; locality LW 479, Guimatu on the Purari River, Cenomanian; lateral and frontal views; x 4/7.

B–D. *Acanthoceras rhotomagense* (Brongniart 1822).

CPC 16085; locality KRD 74, Erave Valley, Cenomanian; right and left lateral and rear views; x 2/3. The preserved last half whorl in Fig. C exhibits a natural longitudinal section in which the last 6 septa at dotted positions and posterior half of the body chamber are observable.

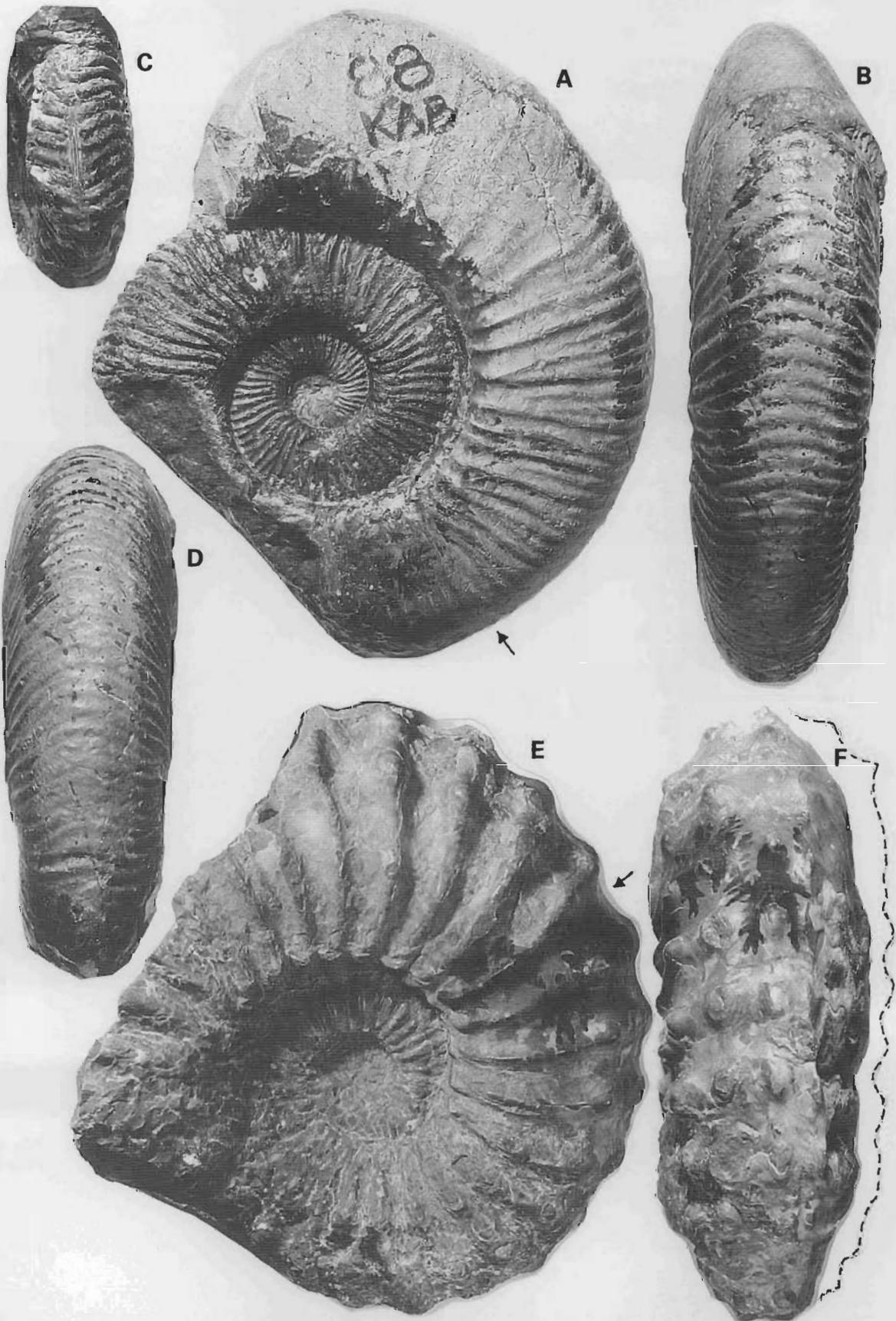


Figure 19. A–D. *Fauriella boissieri* (Pictet 1867). CPC 16088; locality KAB 88, Kereru Range, Berriasian. Lateral and three ventral views; x 7/10. Fig. C shows the venter of the early part of the outer whorl. E, F. *Romaniceras deverianum* (d’Orbigny 1841). CPC 16080; locality MCN 1776 M, about 8 km northeast from the northeastern coast of Lake Kutubu; Turonian. Lateral and ventral views; x 1/2.

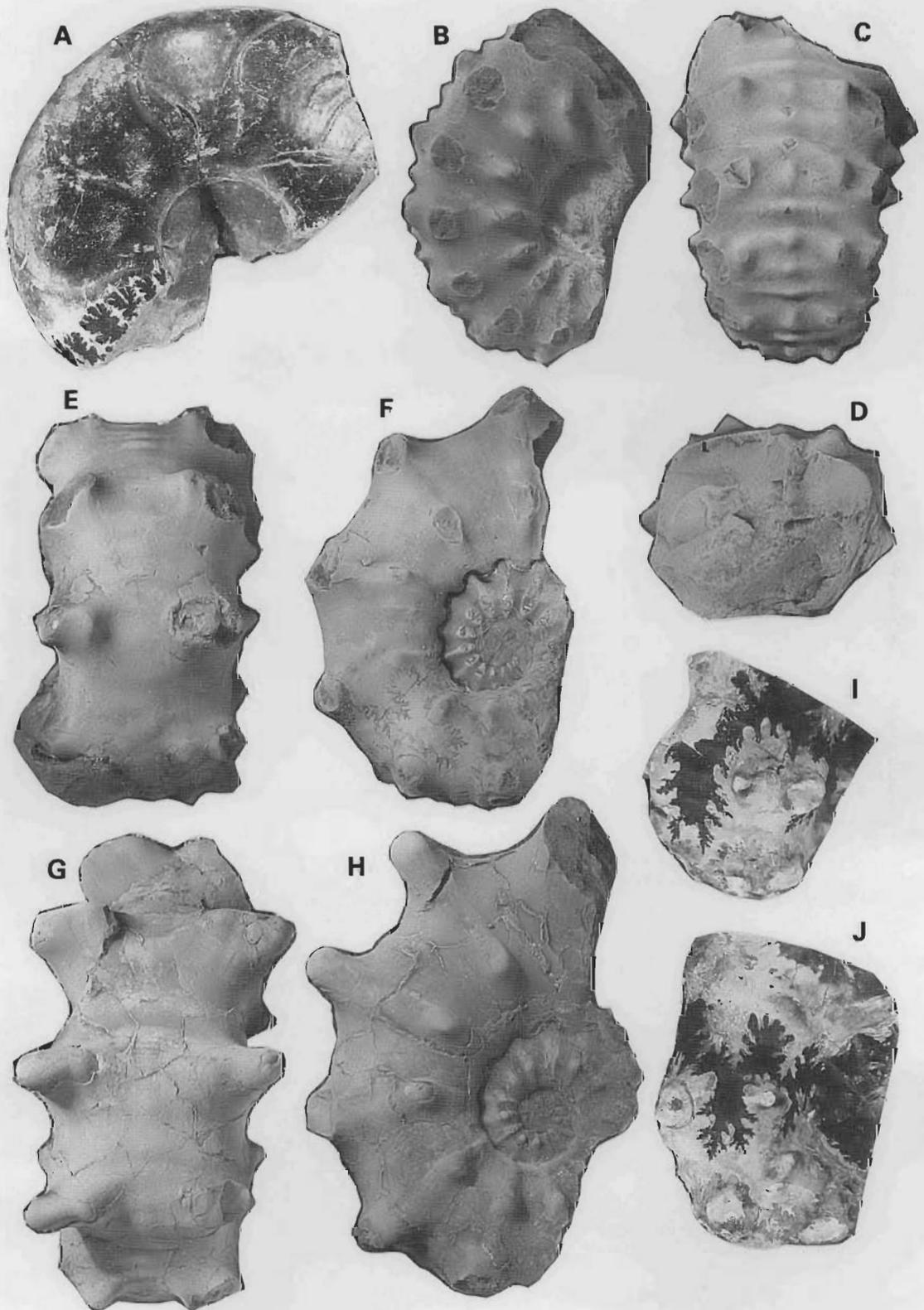


Figure 20. A. *Desmoceras (Pseudouhligella) aff. ezoanum* Matsumoto 1941. CPC 16084; Lateral view; x 7/10.
 B–J. *Cunningtoniceras cunningtoni* (Sharpe 1856).
 (B–D) CPC 16075, juvenile; lateral, ventral, and end-on views; x 1.
 E, F. CPC 16079, adult; ventral and lateral views; x 7/10.
 G, H. CPC 16080, adult; ventral and lateral views; x 0.55.
 I, J. CPC 16079, showing the last second suture with black and white: external lobe E and E/L saddle in I; lateral lobes L, U2 and auxiliary in J. All from locality 79 [= F 2148], Mingenda Dome, Chimbu — Mount Hagen area, Cenomanian.
 B–H. coated with ammonium chloride.
 A, I, J. not coated.

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Appendix

Stratigraphic terminology

For the readers who may not be acquainted with local formation names, the stratigraphic terminology of the Cretaceous Papuan Basin is concisely shown in Table 10 below, with some additional remarks.

Remarks. Correlation in the table below is approximate. The **Maril Fm** is mainly black shale. **Kondaku** is volcanogenic and

is Early Cretaceous. **Kerabi** is part-volcanic-derived, sandy, and is Early to Late Cretaceous (including Cenomanian) and in part distal equivalent of Kondaku. **Chim** is mainly mudstone and is Late Cretaceous and may be in part distal equivalent of Kerabi. "Tubu Shale" was once used by field geologists but it was not defined clearly; hence it has not survived. Presumably it may have included a part of Maril or Chim or otherwise. The ages of units in Welsh's framework are based on a palynological zonation; J/K: Kimmeridgian–earliest Valanginian. K1: Valanginian–Early Aptian, K2: Late Aptian–Early Albian, K3: Middle Albian–Late Albian, K4: Early Cenomanian–Middle Cenomanian, and K5: Late Cenomanian–Turonian.

Table 10. Stratigraphic terminology of the Papuan Basin.

		<i>Formation name</i>		<i>Sequence</i>	<i>Age</i>					
<i>S. Central P.N.G.</i>		<i>Northwestern P.N.G.</i>		<i>(Welsh, 1990)</i>						
Wahgi Group	{	Chim	Feing Group	{	Ieru	K5	Late Cretaceous			
		Kerabi						Toro	K1	Early Cretaceous
		Kondaku						Imburu	J/K	Late Jurassic
		Maril								



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