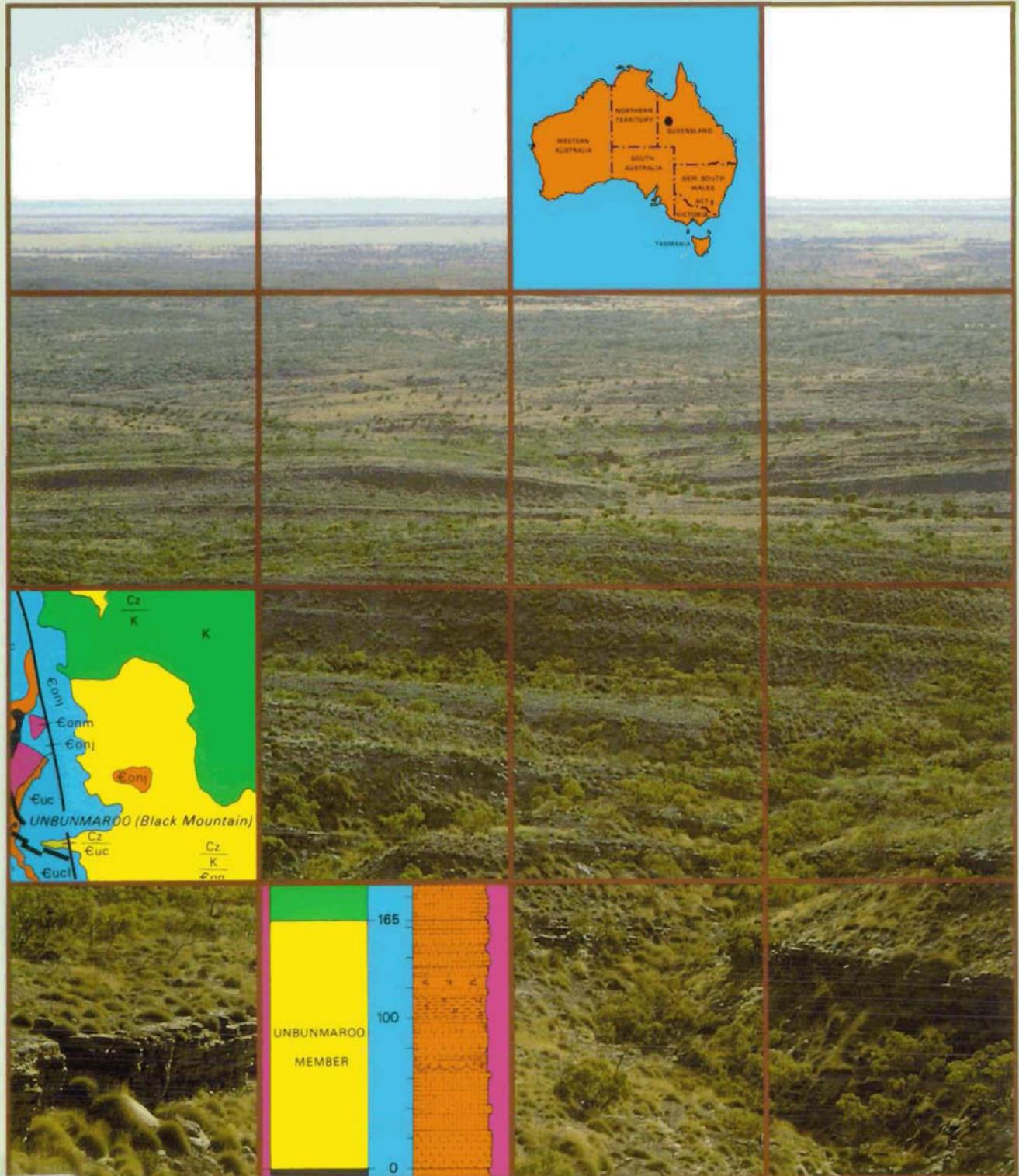


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Front cover: Upper part of the Ninmaroo formation, Black Mountain (Unbunmaroo), 59 km northeast of Boulia, Burke River Structural Belt, western Queensland. Gently dipping beds of this unit contain the Cambrian–Ordovician boundary interval, and are the source of the species of *Cordylodus* discussed in a paper by Nicoll in this issue.

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# Pleistocene to Holocene planktic foraminiferal biostratigraphy of the Coral Sea, offshore Queensland, Australia.

George C.H. Chaproniere<sup>1</sup>

Fifteen of 27 potential planktic foraminiferal biostratigraphic events from the latest Pliocene–Holocene have been examined; most of the early Pleistocene was not able to be studied because of a hiatus in the one core which penetrated through the Pleistocene into the top of the Pliocene. Four of these events have been recognised for the first time, and some have been used to establish a formal zonal and subzonal scheme for the region. Two new subzones are proposed, the *Globigerinoides quadrilobatus fistulosus* Subzone (for the basal part of Zone N.22) and the *Bolliella praeadamsi* Subzone (for the top part of Zone N.22). These changes have made necessary the redefinition of both the *Globorotalia (Truncorotalia) crassaformis viola* and the *Globorotalia (Truncorotalia) crassaformis hessi* Subzones. There is

little evidence that changes in palaeoceanographic conditions are related to the faunal changes observed in the cores, although there are strong indications of reworking at some levels within some of the cores (such as late Miocene Zone N.17 in one core), which may have been related to sea-level fluctuations. The assemblages from the cores show a marked stability, with the faunas being dominated by spinose, oligotrophic taxa. Temperate water forms are either very rare or absent, whereas tropical and subtropical species are dominant. A single new species, *Bolliella praeadamsi* has been described because of its biostratigraphic utility. This species is an evolutionary intermediate between *Bo. calida praecalida* and *Bo. adamsi*.

## Introduction

This study is based on a number of cores taken from the eastern Coral Sea over the period December 1981 to December 1987 (Fig. 1). These cores were taken to try to unravel the Pleistocene history of the region and apply the results to the history of the Great Barrier Reef. A planktic foraminiferal study of the cores was made to attempt to establish a biostratigraphic zonation on which palaeoceanographic, palaeotemperature and sea level changes could be correlated. Oxygen isotope stratigraphic studies on one of the cores, 76PC06, by Peerdeman (ANU, personal communication 1990), have enabled some of the biostratigraphic events discussed in this study to be correlated with the oxygen isotope stratigraphic scheme. The zonation covers the interval from the latest Pliocene to the basal Pleistocene (that part of the Matuyama Chron to the top of the Olduvai Subchron), and the interval of the Bruhnes Chron, representing the last 760 000 years (the latest Middle Pleistocene to Holocene, following Berggren & others (1985, p. 227), but the ties to the isotope stratigraphic scheme are restricted to oxygen isotope stage 12 (440 000 yr BP) and younger (Shackleton & Opdyke, 1976).

There have been few attempts to subdivide the Pleistocene in detail using planktic foraminiferids, and these have been summarised in Figure 2. Jenkins (1967) proposed eight subzones for his *Globorotalia inflata* Zone based on coiling changes in *Neogloboquadrina pachyderma* for the New Zealand Pleistocene–Holocene. Ericson & Wollin (1968) proposed a biostratigraphic zonation in which the Pleistocene was divided into eight subdivisions based on the presence/absence of *Globorotalia menardii* (= *Gr. cultrata* sensu lato and *Gr. tumida* sensu lato in this paper) for the Atlantic Ocean Pleistocene. They suggested that the distribution of this species was related to the North American glacial cycles. Blow (1969) subdivided the Pleistocene–Holocene interval into two zones. His N.22, based on the FAD (first appearance datum) of *Globorotalia truncatulinoides*, spanned the Pleistocene, and N.23, based on the FAD of *Globigerinella calida calida*, covered the Holocene.

Lamb & Beard (1972) attempted a more detailed biostratigraphic subdivision of the late Neogene, based on material from the Caribbean, Gulf of Mexico and Italian stratotypes, and concentrated mainly on the Pliocene. Two zones were

proposed for the Pleistocene–Holocene interval: the *Globorotalia truncatulinoides* Zone covered the Pleistocene, and the *Globorotalia tumida* Zone covered the Holocene. The *Gr. truncatulinoides* Zone was divided into three subzones: a lower *Gr. tosaensis* Subzone, succeeded by the *Globoquadrina dutertrei* Subzone, and then by the *Pulleniatina finalis* Subzone.

Bolli & Premoli Silva (1973) also used material from the Caribbean, but proposed a new subdivision. The Pleistocene–Holocene interval was covered by a single zone, the *Globorotalia truncatulinoides truncatulinoides* Zone. This zone was subdivided into five subzones: the Pleistocene *Globorotalia crassaformis viola* Subzone, *Globorotalia hessi* Subzone, *Globigerina calida calida* Subzone, and *Globigerina bermudezi* Subzone, and the Holocene *Globorotalia fimbriata* Subzone.

Poag & Valentine (1976), in a study of the Louisiana–Texas Basin, proposed a subdivision of the Pleistocene into 12 biostratigraphic and ecostratigraphic zones based mainly on changes in the proportions of *Gr. (Globoconella) inflata* and *Gr. (Gr.) cultrata*; the Holocene was recognised by the *Gr. (Gr.) unguata* Zone.

In the Red Sea area, Herman (1968) proposed five zones for the last 150 000 years, based on abundance changes in *Gds. quadrilobatus sacculifer* and *Gds. ruber*, as well as the presence or absence of planktic forms. Berggren & Boersma (1969) reached a similar conclusion to that of Herman (1968), based on climatically controlled changes in distribution patterns of planktic species. Reiss & others (1980) slightly modified Herman's (1968) zonation and this was adopted by Locke & Thunell (1988).

Rögl (1974) was the first to apply one of the zonal schemes to sections within the tropical–subtropical Indo-Pacific; he was not able to recognise the two youngest subzones proposed by Bolli & Premoli Silva (1973) in the Timor Sea area because of the absence of the nominate taxa (which are apparently restricted to the Caribbean area).

Thunell (1984) summarised the problems associated with Pleistocene planktic foraminiferal biostratigraphy. He noted that there were two types of zonal scheme. Some used qualitative criteria such as presence/absence data (e.g. the distribution of *Globorotalia cultrata* group; Ericson & Wollin, 1968), or the first or last appearance datums used in most schemes. Others used quantitative criteria such as single-

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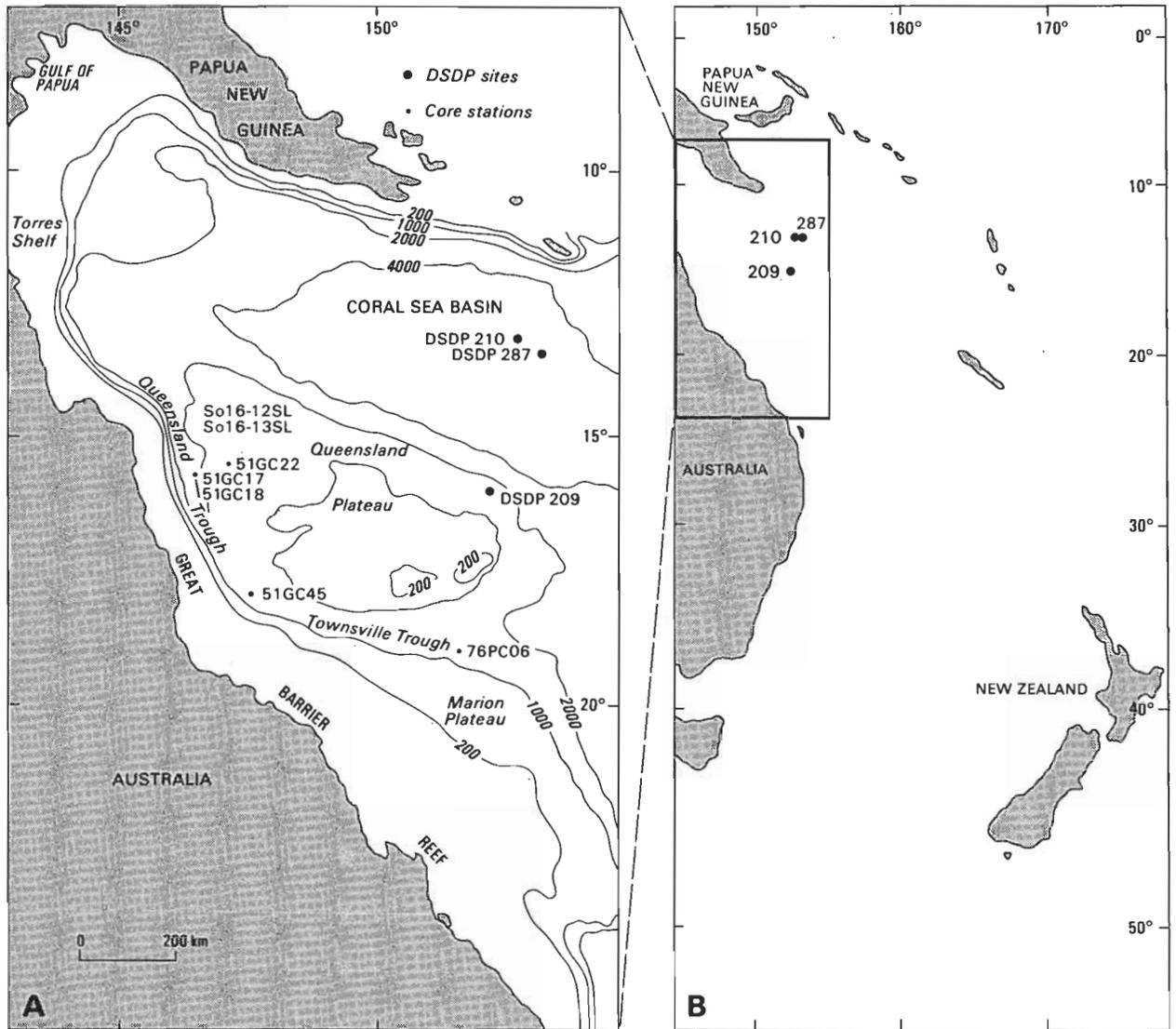


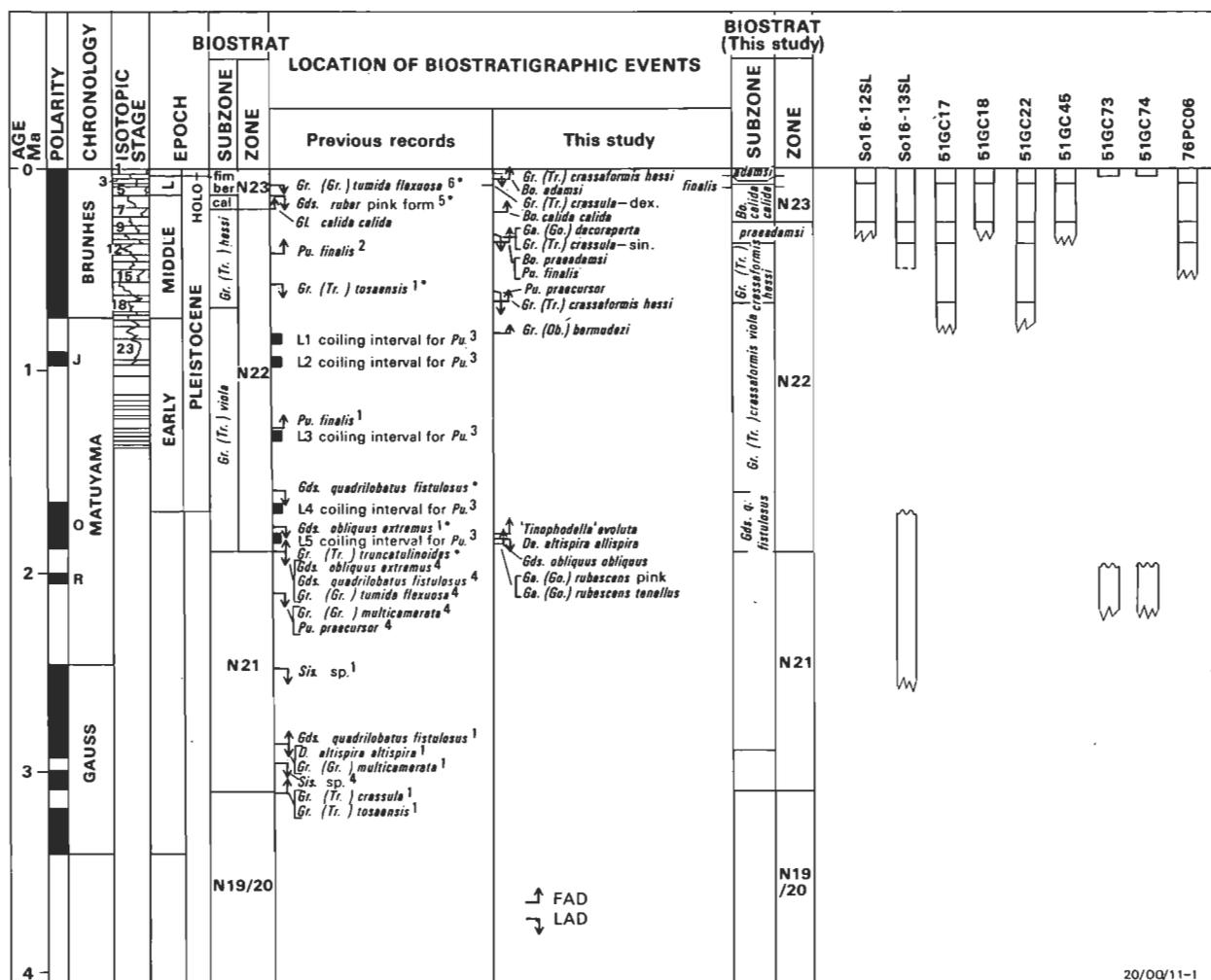
Figure 1. Locality map showing locations of cores used in this study.

species abundances (e.g. Herman, 1968; Thunell & others, 1977), coiling ratios (e.g. Kennett, 1976), or relative abundances of species in the total planktic assemblage (e.g. Kennett & Huddleston, 1972). Qualitative schemes such as those of Ericson & Wollin (1968) are very useful in the Atlantic Ocean Pleistocene, especially in areas where temperature changes had maximum impact on the faunas. This distribution of the *Gr. cultrata* group is not observed in the Indo-Pacific region (Thunell, 1984). Similarly, most of the quantitative schemes also rely on temperature-linked effects (such as coiling changes in *Neogloboquadrina pachyderma*; see Jenkins, 1967), and are best for regions where temperature variations have been greatest.

All the biostratigraphic zonations discussed above, except Blow (1969) and Rögl (1974), are based on sections deposited either in temperate areas or near the subtropical-temperate transition; that of Blow (1969) is based on sections from the subtropical-tropical Atlantic, whilst that of Rögl (1974) is from the eastern tropical Indian Ocean. The maximum impact of temperature and oceanographic changes on faunal assemblages during the Pleistocene-Holocene interval was probably in boundary areas between climatic zones; changes within these faunal assemblages were due mainly to migratory rather than evolutionary events. Thus the greatest problem for the use of these schemes in warm water areas is the potential absence of

key taxa due to their often restricted geographic ranges; sea-level changes and climatic factors are less marked in these areas, and so have little effect on fossil assemblages. Such climatic and oceanographic effects would be expected to have most effect on faunas in the transitional areas between climatic belts.

The Pleistocene-Pliocene boundary is no longer believed to be equivalent to the Zone N.21/N.22 boundary, as the marker event, the FAD of *Gr. (Tr.) truncatulinoides*, took place within the latest Pliocene (Rio & others, 1984a,b). Furthermore, this FAD is diachronous, occurring at older stratigraphic levels in higher latitudes and being oldest in the southwest Pacific area (Dowsett, 1989; Hills & Thierstein, 1989). In spite of this, biostratigraphic evidence suggests that the age of this event is consistent for global low latitudes and the use of this FAD to mark the N.21/22 boundary (Blow's (1969) criterion for the base of Zone N.22) is therefore retained for this study. Though the FAD of *Gr. (Tr.) truncatulinoides* was once used to mark the Pliocene-Pleistocene boundary (Blow, 1969; Kennett & Srinivasan, 1983), Rio & others (1984a,b) have shown that this event occurs well below the boundary in most Mediterranean sections; the FAD of *Globigerina (Globigerina) cariacensis* now marks this boundary in the Mediterranean area. However, as this species has not been recorded from the tropical Pacific, the LAD (last appearance datum) of *Gds. quadrilobatus*



1 Berggren et al 1985 2 Lamb & Beard 1975 3 Saito 1976 4 Kennett & Srinivasan, 1983 5 Thompson et al 1979 6 Bolli & Premoli Silva, 1973  
\*Previous records used in this study.

**Figure 2. Biostratigraphic summary for nine gravity and piston cores taken in the Queensland and Townsville Troughs.**  
Timescale after Bolli & Premoli Silva (1973) and Chaproniere (1985b); oxygen isotope scale after Shackleton & Opdyke (1976).

*fistulosus* appears to be the closest planktic foraminiferal event to the Pliocene–Pleistocene boundary, and is probably the most suitable to mark this boundary; this event has been dated at 1.6 Ma by Berggren & others (1985).

The biostratigraphic scheme proposed in this paper is based on both qualitative and quantitative criteria. Though FADs and LADs of the various morphotypes are the main events used, changes in coiling direction are important. Presence/absence data, changes in single species and relative species abundances have not been used, due to the faunal stability (the regional temperatures probably did not fall below those of the tropical belt during cooler periods elsewhere).

A reconnaissance oxygen isotope study was made by F. Peerdeman (ANU) on samples taken at 15 cm intervals on core 76PC06. The results of this study have been used here. Peerdeman's study shows that part of the top of the core was lost during coring operations (which is supported by the planktic foraminiferal studies). This, together with the presence of turbidites (indicated by the values of  $\delta^{18}\text{O}$ ) makes evaluation of the oxygen isotope stage uncertain. In addition, levels below 700 cm in the core are less reliable for oxygen isotope stage correlation.

Plates 1 to 4 illustrate the key biostratigraphic species as well as other biostratigraphically important forms. All type and figured

specimens are housed in the Commonwealth Palaeontological Collection of the Bureau of Mineral Resources, Canberra, with numbers prefixed by CPC.

## Sections studied

Piston and gravity cores collected during Cruise So16 of the R/V *Sonne*, and Cruises 51 and 76 of the R/V *Rig Seismic* in the southeastern margin of the Coral Sea Basin, form the basis for this study. The locations of these cores are given in Figure 1. Reworked faunas from the Late Miocene or Pliocene, mainly found in turbidites, are present in some of the cores.

All but one of the cores bottomed in middle Pleistocene sediments. Core So16-13SL bottomed in the late Pliocene (Matuyama Chron), but all the lower Pleistocene (that is, the section from the top of the Olduvai Subchron to the lower part of the Brunhes Chron, following Berggren & others, 1985) is absent. Five cores (51GC17, 51GC18, 51GC22, 51GC43 and 76PC06) penetrated into the middle Pleistocene.

## Planktic foraminiferal succession

The distribution of selected biostratigraphically important taxa is discussed below for each core separately. The distribution of all planktic taxa recorded from each core is given in Figures 3 to 9.

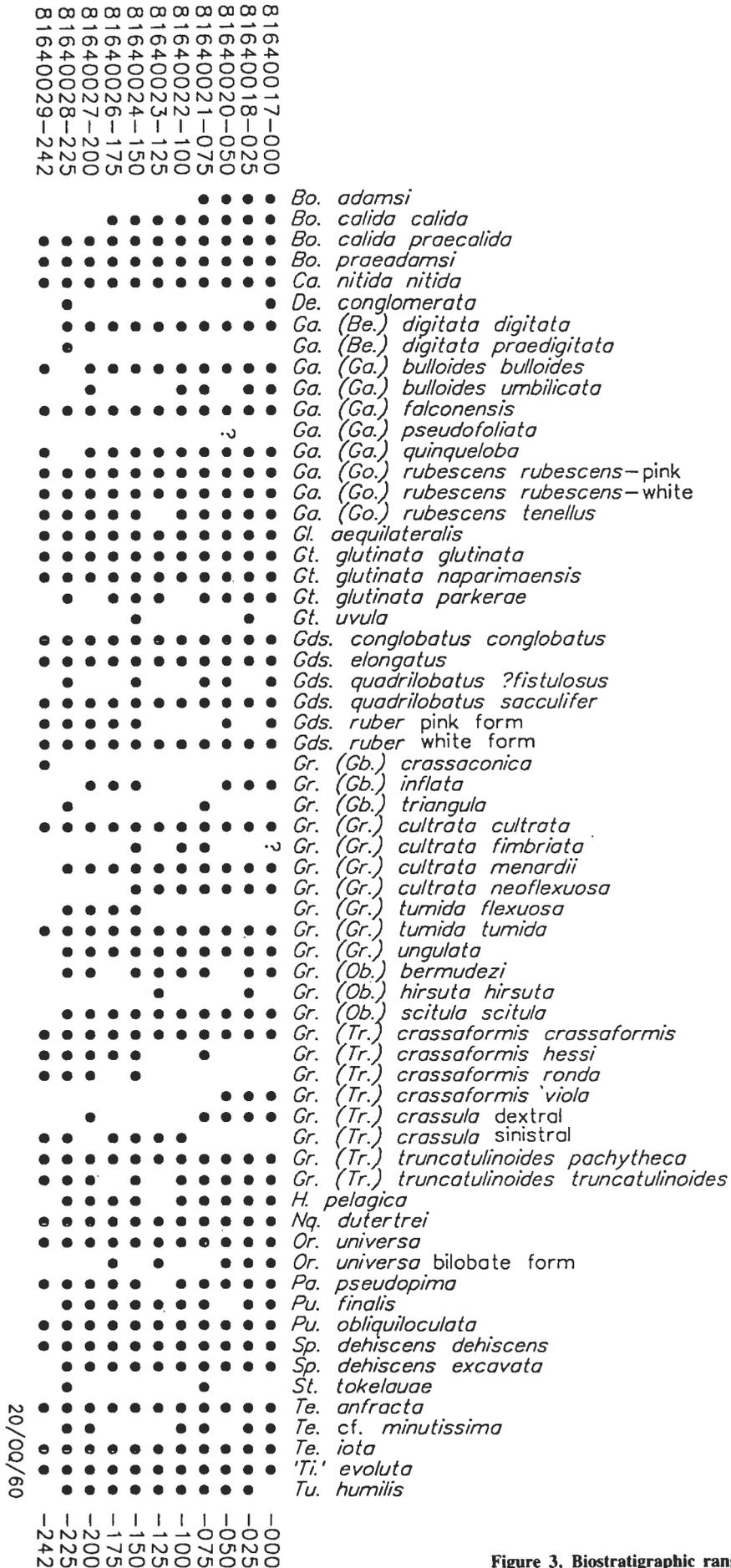
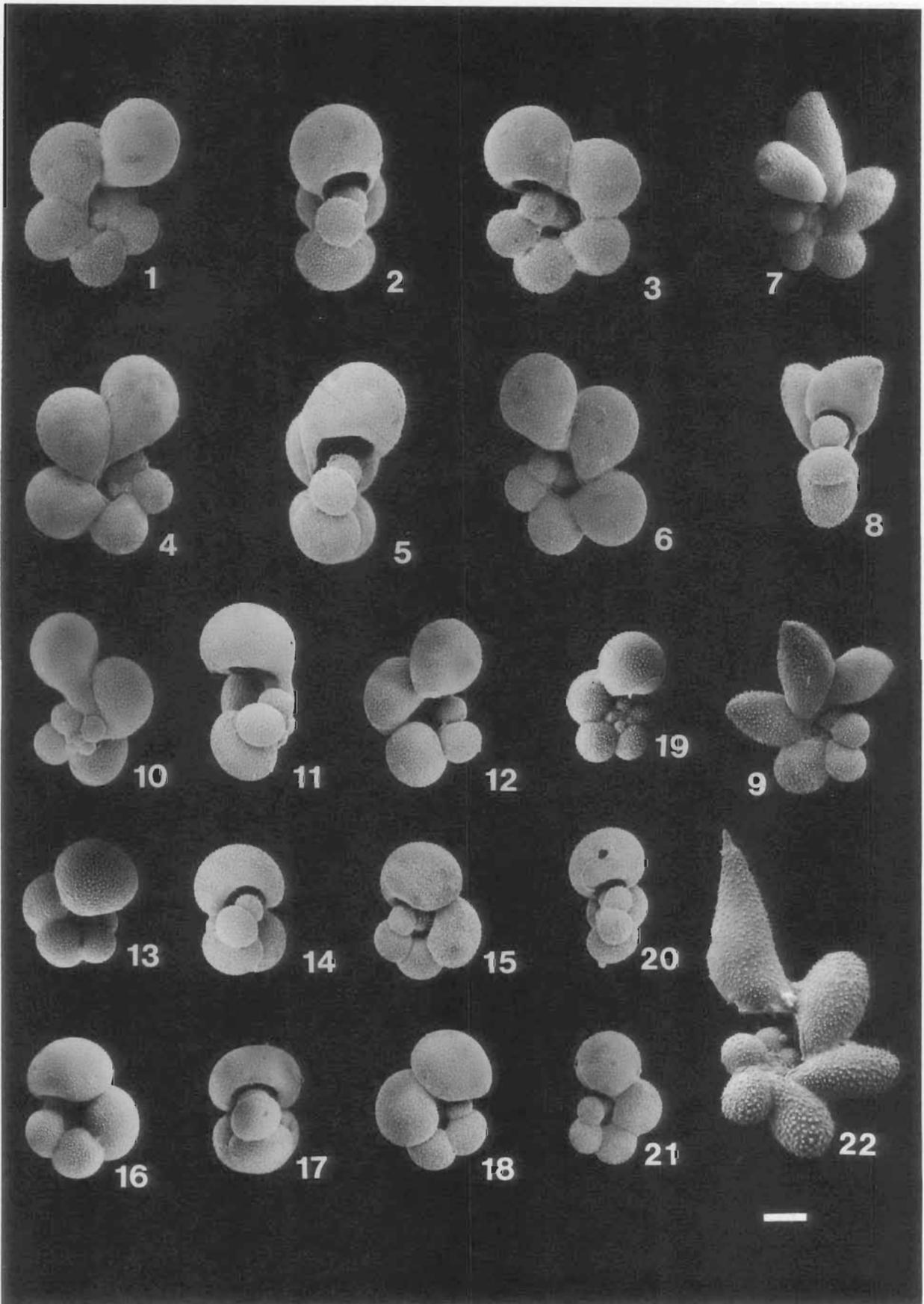


Figure 3. Biostratigraphic range chart for core So16-12SL.



**Plate 1.**  
 1-3, *Bolliella praeadamsi* n. sp., holotype. CPC30216. 4-6, 19-21, *Bolliella praeadamsi* n. sp., paratypes. CPC30217, CPC30218. 7-9, 22, *Bolliella adamsi*. CPC30219. CPC30220. 10-12, *Bolliella calida calida*. CPC30221. 13-18, *Globigerinella aequilateralis*. CPC30222. CPC30223.  
 All specimens are from sample 81640021, So16-12SL-075; scale bar 200  $\mu$ m.

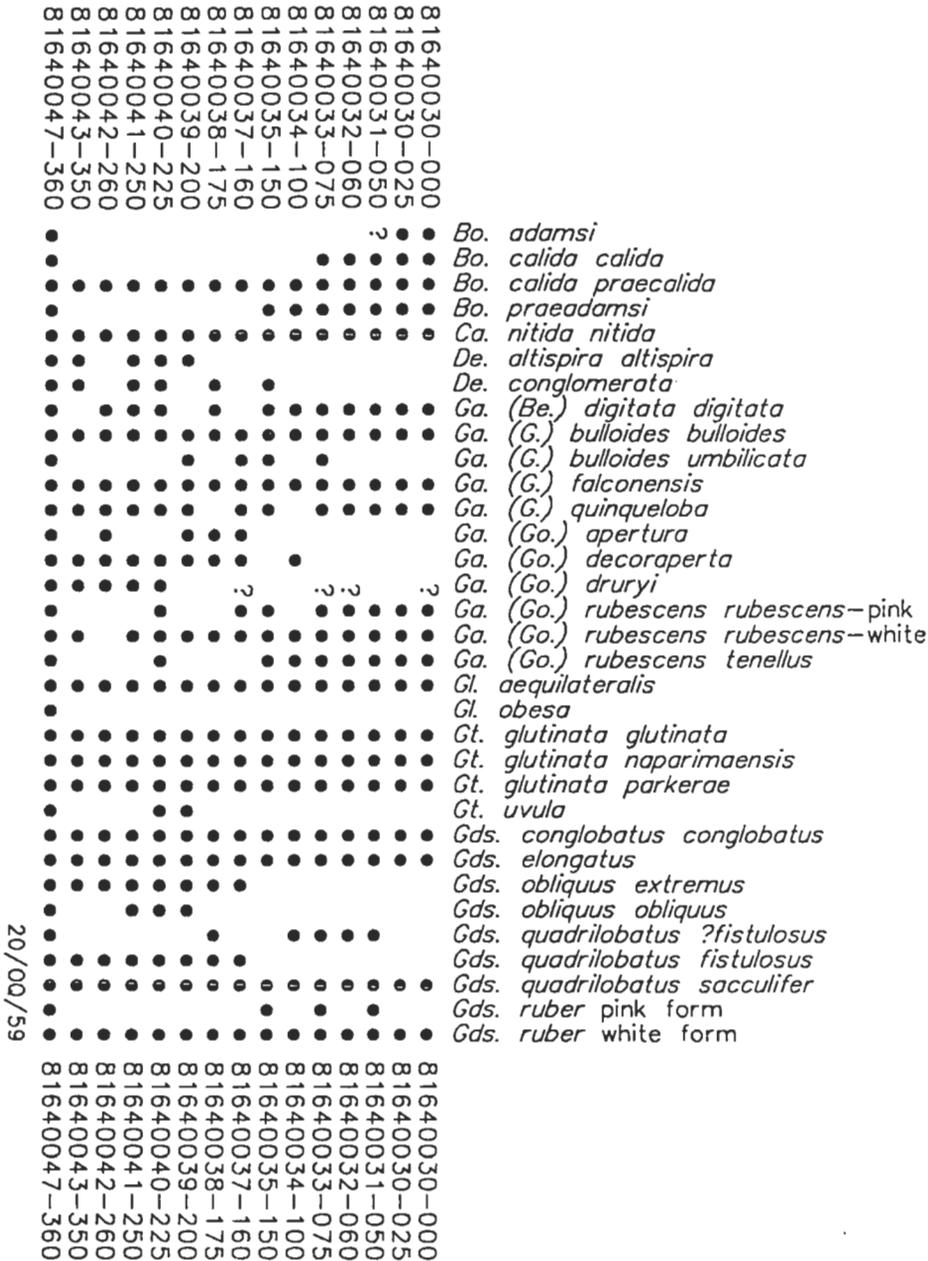


Figure 4. Biostratigraphic range chart for core So16-13SL.

**So16-12SL.** The lower part of the core (200–242 cm) contains *Globorotalia (Truncorotalia) truncatulinoides*, *Gr. (Tr.) crassaformis hessi*, *Gr. (Tr.) crassula* (sinistral), *Gr. (Gr.) tumida flexuosa*, *Gr. (Gr.) tumida tumida*, *Gr. (Obandyella) bermudezi*, *Bolliella praeadamsi* n. sp. and *Pulleniatina finalis*; *Gr. (Tr.) tosaensis* was not found. At 184 cm *Bo. calida calida* appears, and the LAD of *Gr. (Gr.) tumida flexuosa* is at 143 cm. *Gr. (Gr.) cultrata fimbriata* occurs intermittently from 143 cm to the top of the core. *Bolliella adamsi* first appears at 74 cm, and at the same time the coiling direction of *Gr. (Tr.) crassula* changes from sinistral to dextral; populations of *Pulleniatina* are dextral throughout. *Gr. (Globoconella) inflata* (including the *triangula* morphotype) is rare and occurs intermittently through the core. Pink-coloured specimens of *Gds. ruber* are present throughout the core, but above 242 cm they are rare and sporadic.

**So16-13SL.** The Pliocene section is from 160 cm to the bottom of the core at 365 cm. The fauna is typified by *Globigerinoides*

*quadrilobatus fistulosus*, *Gds. obliquus extremus*, *Globigerina (Globoturborotalia) decoraperta*, *Globorotalia (Gr.) cultrata limbata*, *Gr. (Gr.) multicamerata*, *Gr. (Gr.) tumida flexuosa*, *Gr. (Truncorotalia) tosaensis* and *Pulleniatina praecursor*. Over the interval 250 to 200 cm, the populations of *Pulleniatina* change to being dominantly sinistrally coiled; because of the overlap of these sinistral populations with *Gr. (Tr.) truncatulinoides*, this coiling event almost certainly represents level L5 (1.7 Ma) of Saito (1976). *Sphaeroidinellopsis seminulina* is present in only one sample at 350 cm. The FAD of *Gr. (Tr.) truncatulinoides* occurs at 250 cm, and that of both *Globigerina (Globoturborotalia) rubescens tenellus* and the pink form of *Ga. (Go.) rubescens rubescens* at 226 cm. The LAD of *Dentoglobigerina altispira altispira* occurs at 200 cm, coinciding with the highest sinistrally coiled populations of *Pulleniatina*. At 175 cm *Tinophodella' evoluta* appears. At 160 cm there is an increase in the sand size component in the sediments, accompanied by a faunal change. Populations of *Pulleniatina* revert to dextral coiling and *Globorotalia (Tr.)*

81640030-000	•	Gr. (Gb.) <i>crassaconica</i>
81640031-025	•	Gr. (Gb.) <i>inflata</i>
81640032-050	•	Gr. (Gr.) <i>cultrata cultrata</i>
81640033-060	•	Gr. (Gr.) <i>cultrata fimbriata</i>
81640034-075	•	Gr. (Gr.) <i>cultrata limbata</i>
81640035-100	•	Gr. (Gr.) <i>cultrata menardii</i>
81640037-150	•	Gr. (Gr.) <i>cultrata neoflexuosa</i>
81640038-160	•	Gr. (Gr.) <i>multicamerata</i>
81640039-175	•	Gr. (Gr.) <i>tumida flexuosa</i>
81640040-200	•	Gr. (Gr.) <i>tumida tumida</i>
81640041-225	•	Gr. (Gr.) <i>ungulata</i>
81640042-250	•	Gr. (Ob.) <i>bermudezi</i>
81640043-260	•	Gr. (Ob.) <i>hirsuta hirsuta</i>
81640047-350	•	Gr. (Ob.) <i>scitula scitula</i>
81640048-360	•	Gr. (Ob.) sp.
	•	Gr. (Tr.) <i>crassaformis crassaformis</i>
	•	Gr. (Tr.) <i>crassaformis hessi</i>
	•	Gr. (Tr.) <i>crassaformis oceanica</i>
	•	Gr. (Tr.) <i>crassaformis ronda</i>
	•	Gr. (Tr.) <i>crassula dextral</i>
	•	Gr. (Tr.) <i>crassula sinistral</i>
	•	Gr. (Tr.) <i>tosaensis tenuitheca</i>
	•	Gr. (Tr.) <i>tosaensis tosaensis</i>
	•	Gr. (Tr.) <i>truncatulinoides pachythea</i>
	•	Gr. (Tr.) <i>truncatulinoides truncatulinoides</i>
	•	Grs. <i>hexagona</i>
	•	H. <i>pelagica</i>
	•	Nq. <i>dutertrei</i>
	•	Or. <i>universa</i>
	•	Or. <i>universa</i> bilobate form
	•	Pa. <i>humerosa</i>
	•	Pa. <i>pseudopima</i>
	•	Pu. <i>finalis dextral</i>
	•	Pu. <i>obliquiloculata</i> dextral
	•	Pu. <i>obliquiloculata</i> sinistral
	•	Pu. <i>praecursor</i> dextral
	•	Pu. <i>praecursor</i> sinistral
	•	Sp. <i>dehiscens dehiscens</i>
	•	Sp. <i>dehiscens excavata</i>
	•	Sis. <i>seminulina seminulina</i>
	•	St. <i>tokelauae</i>
	•	Te. <i>anfracta</i>
	•	Te. cf. <i>minutissima</i>
	•	Te. <i>iota</i>
	•	Te. <i>parkeri</i>
	•	Te. sp.
	•	'Ti.' <i>evoluta</i>
	•	Tt. <i>humilis</i>
20/00/58		
81640030-000		
81640031-025		
81640032-050		
81640033-060		
81640034-075		
81640035-100		
81640037-150		
81640038-160		
81640039-175		
81640040-200		
81640041-225		
81640042-250		
81640043-260		
81640047-350		
81640048-360		

*crassaformis hessi*, *Bolliella praeadamsi*, *Pulleniatina finalis* and the pink form of *Globigerinoides ruber* appear; populations of *Gr. (Tr.) crassula* are sinistrally coiled. At 74 cm, *Bo. calida calida* and *Gr. (Ob.) bermudezi* appear, followed by *Bo. adamsi* at 50 cm. Above 74 cm, the pink form of *Gds. ruber* becomes rare and intermittent. Above 50 cm, populations of *Gr. (Tr.) crassula* are dextrally coiled.

**51GC17.** The assemblages from the lower part of this core (328–430 cm) contain *Pulleniatina praecursor*, *Gr. (Ob.) bermudezi*, *Gr. (Tr.) tosaensis* and *Gr. (Tr.) truncatulinoides*; populations of *Pulleniatina* are dextrally coiled. The LADs of *Pu. praecursor* and *Gr. (Tr.) tosaensis* occur at 328 cm. At 300 cm *Gr. (Tr.) crassaformis hessi* appears and populations of *Gr. (Tr.) crassula* change from dextral to sinistral coiling. The

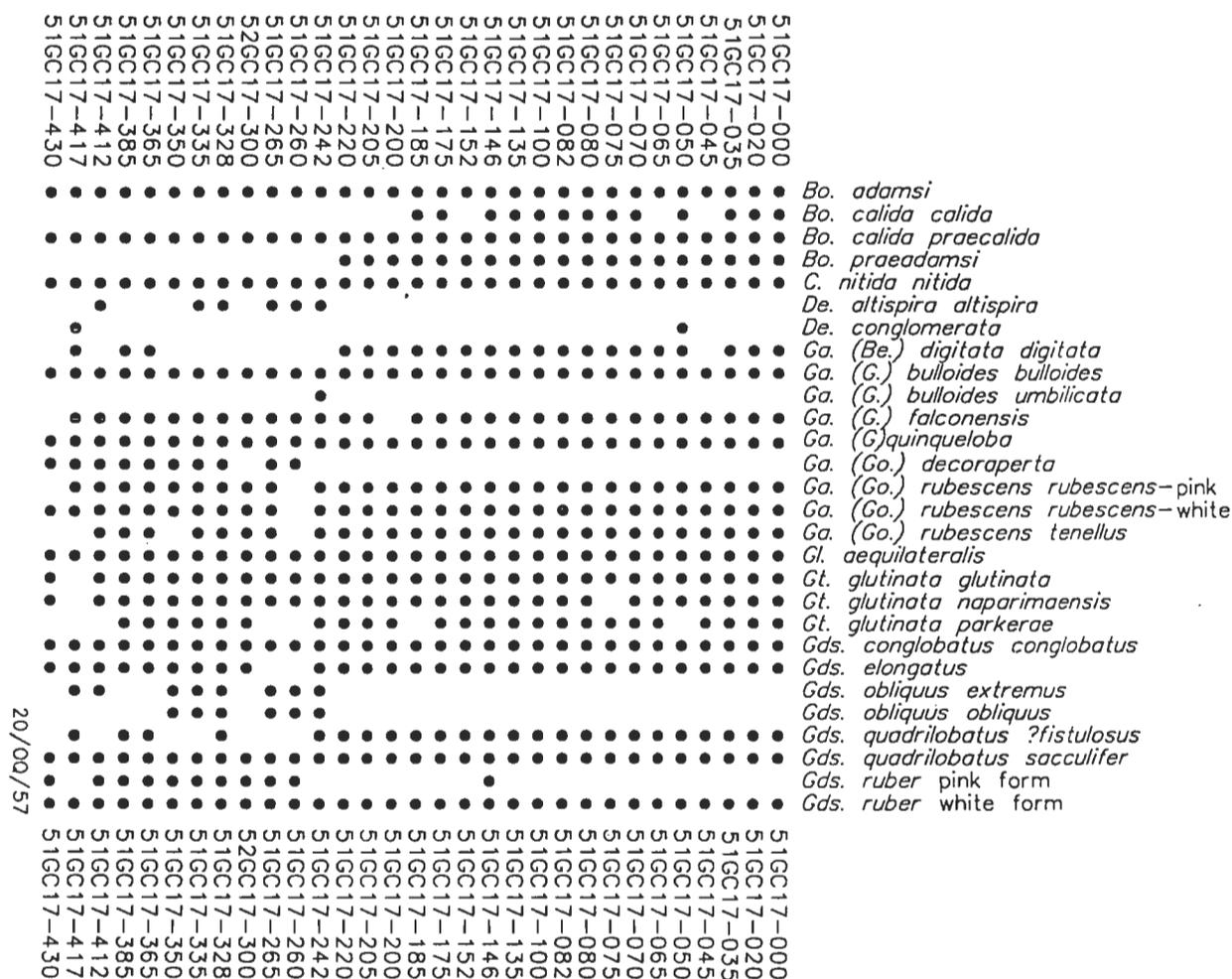


Figure 5. Biostratigraphic range chart for core 51GC17.

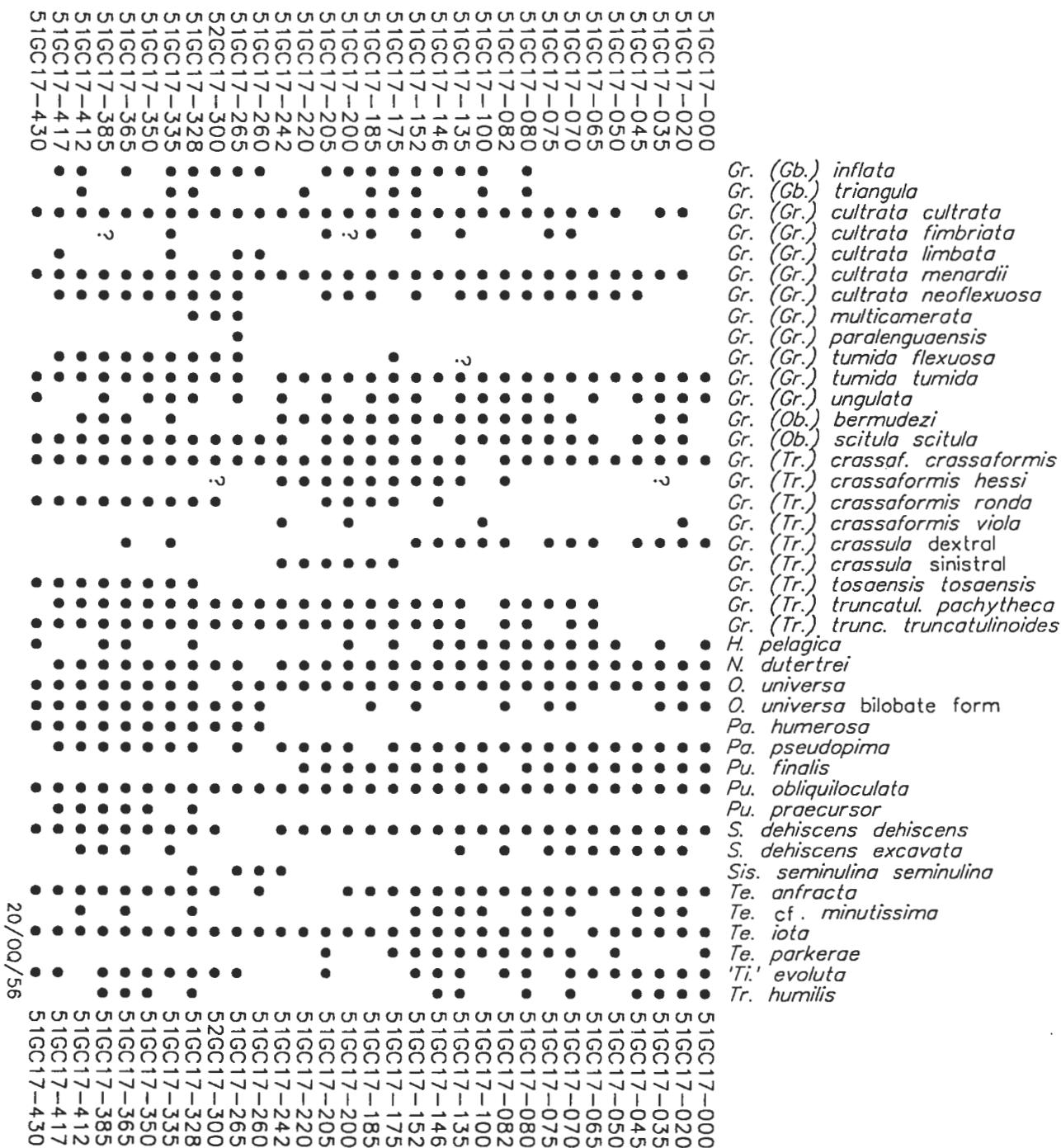
FADs of both *Pulleniatina finalis* and *Bo. praeadamsi* are at 220 cm; at 185 cm *Bo. calida calida* makes its appearance. The LAD of *Gr. (Gr.) tumida flexuosa* occurs at 175 cm, followed by the LAD of pink-coloured *Globigerinoides ruber* at 146 cm, although from 260 cm this form becomes very rare. A return to dextrally coiled populations of *Gr. (Tr.) crassula* takes place at 152 cm. At 82 cm, *Bo. adamsi* appears. *Gr. (Gr.) cultrata fimbriata* occurs rarely and intermittently above 335 cm. Between 328 and 242 cm a number of Zone N.17A (late Miocene) species (such as *Sphaeroidinellopsis seminulina*, *Gr. (Gr.) multicamerata*, *Gr. (Gr.) tumida plesiotumida*, *Gr. (Gr.) linguaensis* and *Globigerina (Go.) nepenthes*) are present, indicating reworking. In addition, taxa such as *De. altispira altispira*, *Globigerinoides obliquus extremus*, *Ga. (Go.) decoraperta* and *Gr. (Gr.) cultrata limbata* are present both below and within this interval, and may also have been reworked from older sediments, but they may be *in situ* (see below).

**51GC18.** *Pulleniatina finalis*, *Gr. (Ob.) bermudezi*, and *Bo. praeadamsi* are present throughout the core. The LAD of *Gr. (Gr.) tumida flexuosa* occurs at 250 cm, and that of pink specimens of *Gds. ruber* at 180 cm. *Bo. calida calida* appears at 180 cm, followed by *Bo. adamsi* at 100 cm. Populations of *Gr. (Tr.) crassula* are sinistrally coiled in the lower part of the core, changing to dextral coiling above 104 cm. A questionable

occurrence of *Gds. obliquus obliquus* at 180 cm may be evidence for some reworking.

**51GC22.** The LADs of *Gr. (Tr.) tosaensis* and *Pulleniatina praecursor* and the FAD of *Gr. (Tr.) crassaformis hessi* occur at 214 cm. The FADs of both *Bo. praeadamsi* and *Pu. finalis* are at 175 cm, followed by those for *Bo. calida calida* at 106 cm and *Bo. adamsi* at 40 cm, the level of the LAD for *Gr. (Tr.) crassaformis hessi*. Pink specimens of *Gds. ruber* range from the bottom of the core to 50 cm, *Gr. (Gr.) tumida flexuosa* from the bottom to 80 cm, *Gr. (Ob.) bermudezi* throughout the core, and *Gr. (Gr.) cultrata fimbriata* from 125 to 40 cm. Populations of *Gr. (Tr.) crassula* change from dextral to sinistral coiling at 175 cm, and back to dextral coiling at 70 cm. *Globigerina (Go.) decoraperta* is restricted to the lowest sample, 218 cm.

**51GC45.** *Bo. praeadamsi* and *Gr. (Ob.) bermudezi* range throughout the core, with *Pu. finalis* present from 214 cm. *Bo. calida calida* ranges from 150 cm and *Bo. adamsi* from 2 cm. *Gr. (Gr.) tumida flexuosa*, *Gr. (Tr.) crassaformis hessi* and pink specimens of *Gds. ruber* range from the bottom of the core, disappearing at 121 cm and 50 cm respectively. Populations of *Gr. (Tr.) crassula* are dextral from 230 cm, changing to sinistral coiling at 196 cm and reverting to dextral coiling at 2 cm; at two levels within the range of sinistrally coiled



populations, this species is represented by only single dextral specimens. The very short range of *Bo. adamsi* (2 cm) suggests that the uppermost part of the section is missing, perhaps lost during erosion or in coring operations.

**76PC06.** *Gr. (Tr.) crassaformis hessi* ranges from the bottom of the core (840 cm) to 230 cm. Both *Pu. finalis* and *Bo. praeadamsi* appear at 730 cm, followed by *Bo. calida calida* at 525 cm and *Bo. adamsi* at 15 cm. *Gr. (Gr.) tumida flexuosa* ranges from the base to 190 cm. Sinistrally coiled populations of *Gr. (Tr.) crassula* range from 485 to 20 cm, but between 720 and 525 cm the species is very rare and intermittent in its distribution. *Gr. (Ob.) bermudezi* and pink specimens of *Gds. ruber* are present throughout the core, with the latter suddenly reducing in numbers from approximately 350 cm. The presence

of *De. altispira*, *Globigerinoides obliquus extremus*, *Gr. (Gr.) cultrata limbata*, *Gr. (Gr.) multicamerata*, *Gr. (Gr.) paralenguaensis*, *Gr. (Tr.) tosaensis*, *Pu. praecursor* and *Sis. seminulina* indicates reworking throughout the core of latest Miocene and Pliocene faunas. These reworked faunas are confined to turbidites together with magnetic minerals (Peerdeman, ANU, personal communication, 1990). Peerdeman concluded on oxygen isotope evidence that the upper part of the core was lost, and that the top of the core was disturbed, probably during coring operations; a number of turbidites within the core probably coincide with levels where reworked foraminiferids occur. The very short stratigraphic range of *Bo. adamsi* (which is confined to the top 15 cm) compared with other cores studied, strongly supports the argument for a missing topmost section in this core.

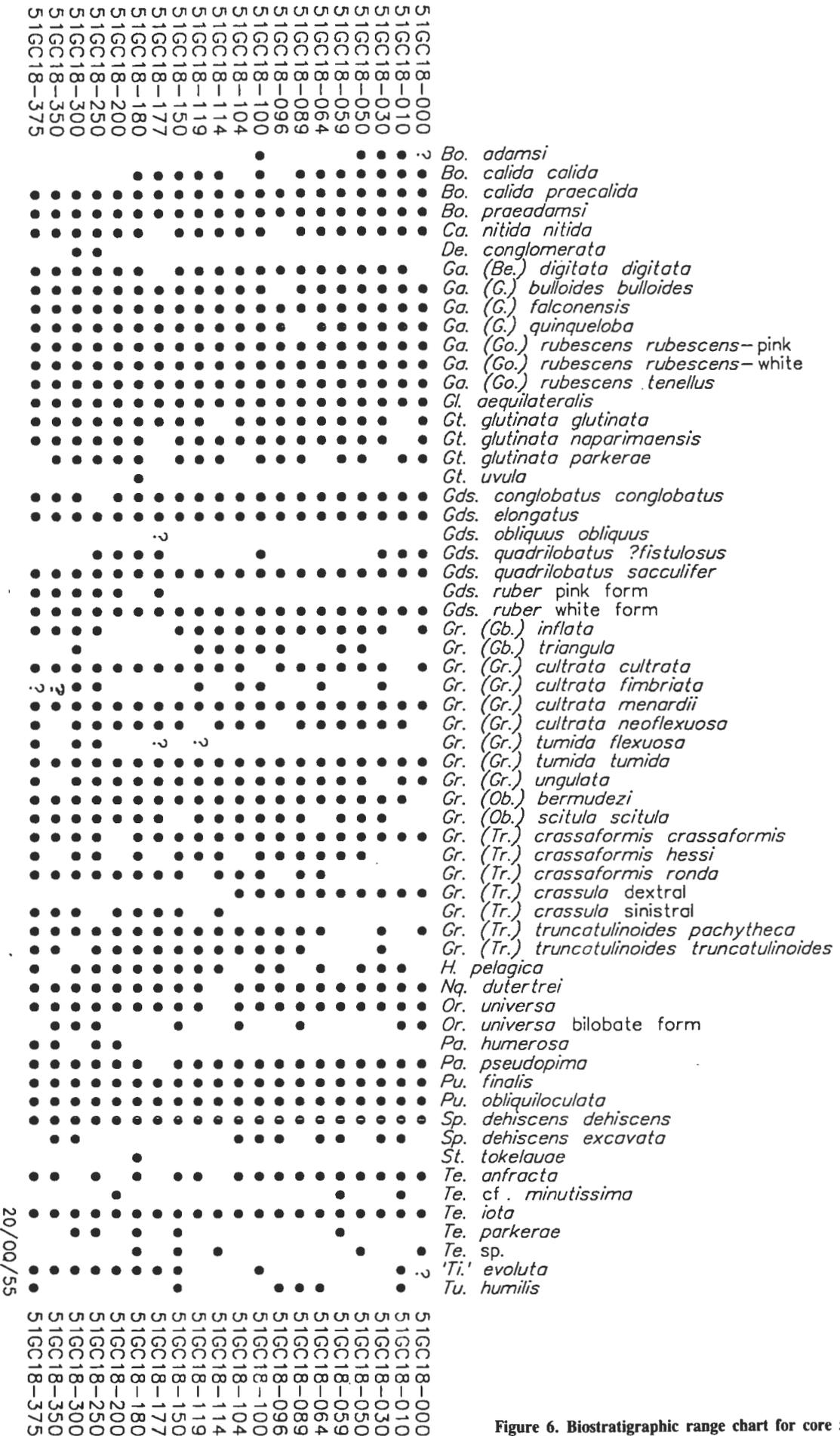


Figure 6. Biostratigraphic range chart for core 51GC18.

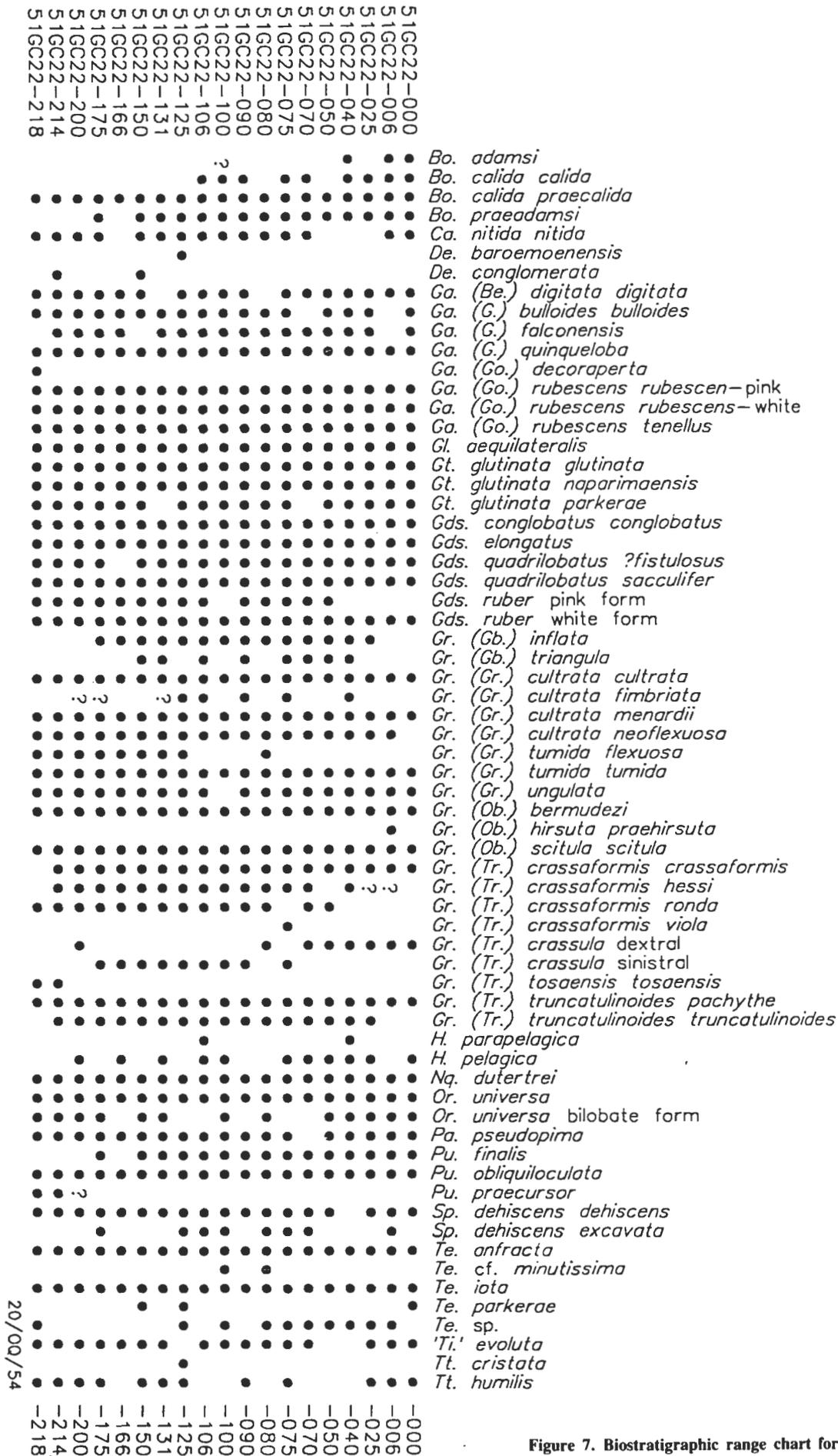


Figure 7. Biostratigraphic range chart for core 51GC22.

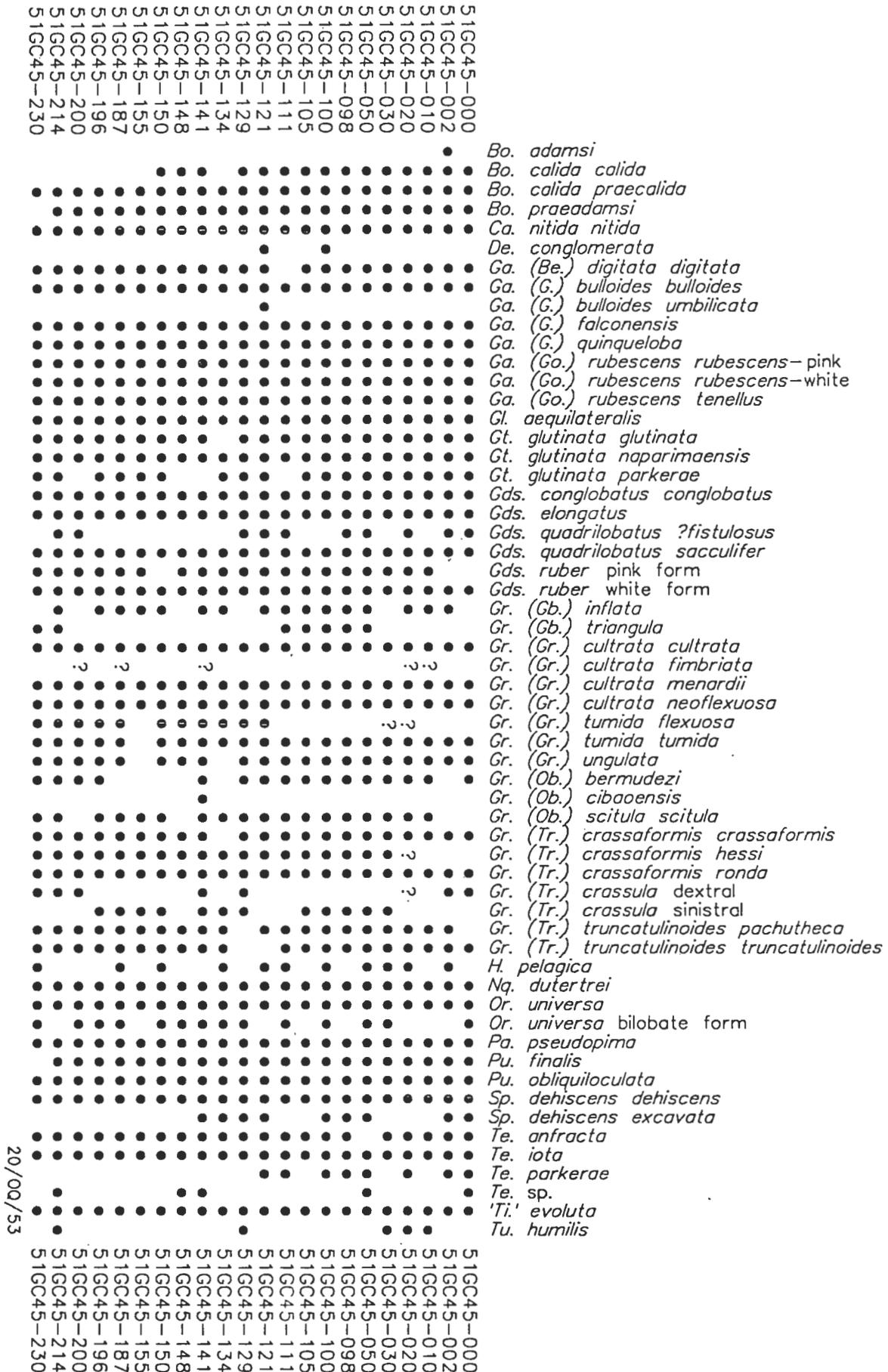
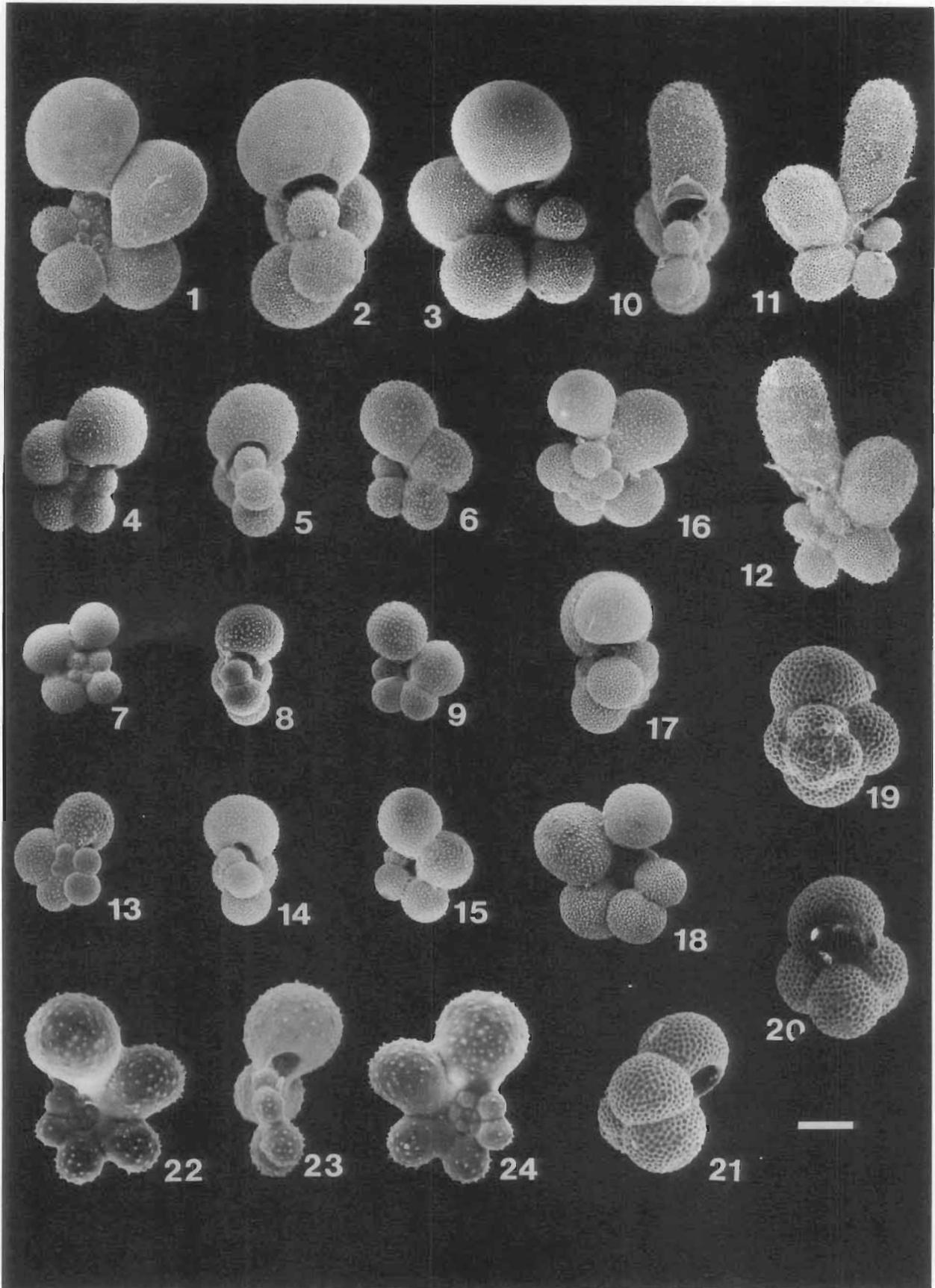


Figure 8. Biostratigraphic range chart for core 51GC45.

**Plate 2.**

1-9, *Bolliella praeadamsi* n. sp., paratypes, CPC30224, CPC30225, CPC30226. 10-12, *Bolliella adamsi*, CPC30227. 13-15, *Bolliella calida praevalida*, CPC30228. 16-18, *Bolliella calida calida*, CPC30229. 19-21, *Globigerina (Globoturborotalita) decoraperta*, CPC30230. 22-24, '*Tinophodella*' *evoluta*, CPC30231.

Figs 1-18, sample 81640021, So16-12SL-075, scale bar 180  $\mu\text{m}$ ; 19-21, sample 51GC17-260, scale bar 100  $\mu\text{m}$ ; 22-24, sample 51GC45-100, scale bar 60  $\mu\text{m}$ .

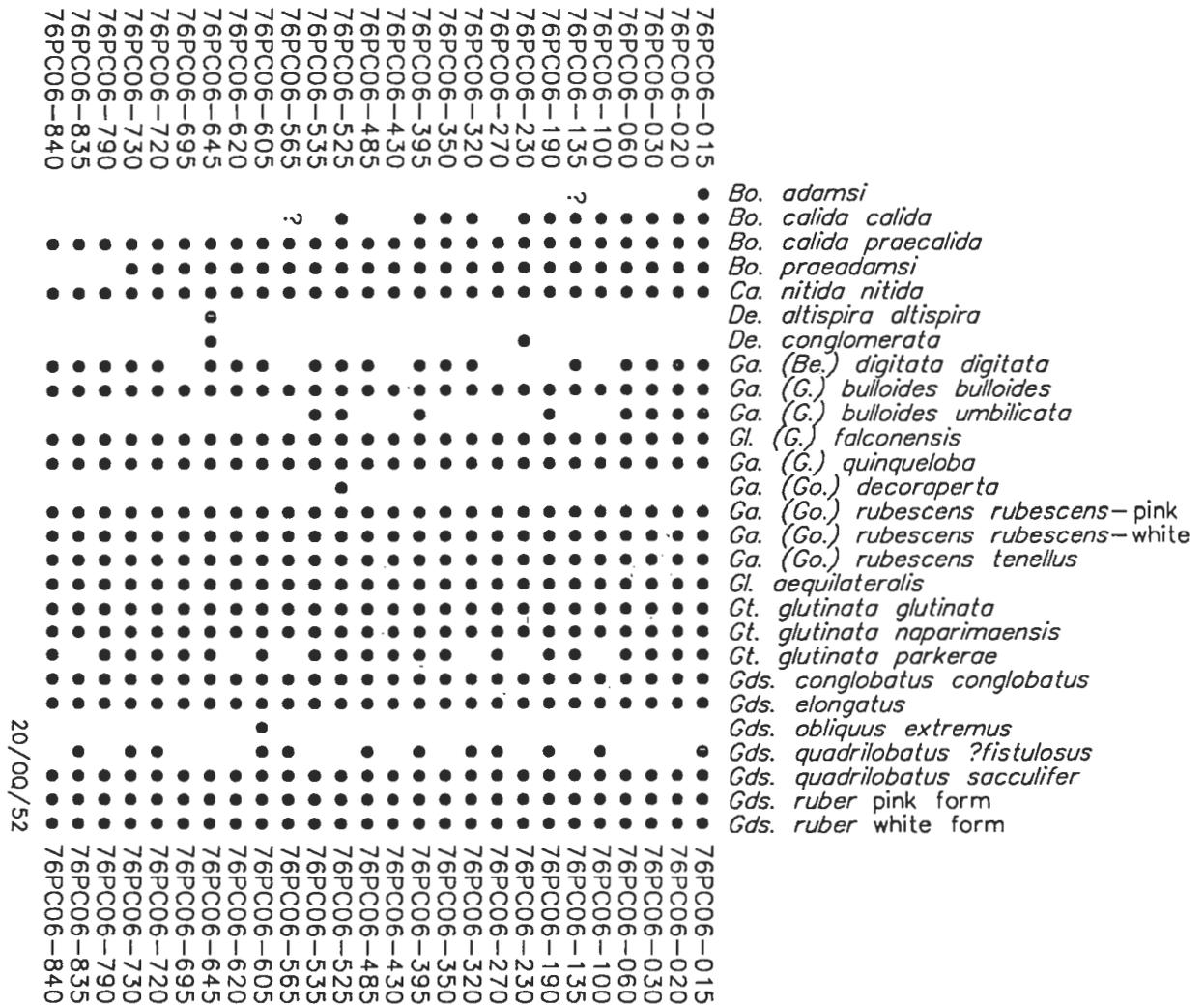


Figure 9. Biostratigraphic range chart for core 76PC06.

**Pleistocene biostratigraphy**

Examination of the literature indicates that there are 23 potential planktic foraminiferal events within the Pleistocene for the Indo-Pacific region (Table 1); in addition, four others have been revealed by this study (Table 1). Those used herein are given in Table 2. Of the 27 events, 9 have been correlated to the oxygen isotopic stratigraphic sequence in core 76PC06 (Fig. 10). The remaining events are from the sequence below 76PC06 and so cannot be correlated with the oxygen isotope sequence. In addition, some of the events listed in Table 1 are from levels within the early Pleistocene hiatus and so could not be evaluated in this study. As discussed below, one of these, the FAD of *Pulleniatina finalis*, has been given ages which differ from those proposed by some previous workers. Though some of these events have been used in other areas (e.g. the FADs of *Bo. calida calida* and *Gr. (Tr.) crassaformis hessi*), a number have not (e.g. the FADs of *Bo. praeadamsi* and *Bo. adamsi*, and the coiling change in *Gr. (Tr.) crassula*).

The composition of planktic foraminiferal assemblages in the cores from northeastern Australia is constant, a feature to be expected if the region has remained in the tropical-subtropical belt during the Pleistocene. Thus zones of influx of cooler forms are absent from the cores; cool water species (such as *Gr. (Globoconella) inflata*, *Gr. (Gb.) triangula* and *Globigerina (Globigerina) bulloides*) are present but are al-

**Table 1. Planktic foraminiferal biostratigraphic events of potential use for Pleistocene biostratigraphy.**

LAD <i>Globorotalia (Truncorotalia) crassaformis hessi</i>
FAD <i>Bolliella adamsi</i>
Change from s to d coiling in <i>Gr. (Tr.) crassula</i>
LAD <i>Gr. (Gr.) tumida flexuosa</i>
LAD <i>Globigerinoides ruber</i> pink form
FAD <i>Bolliella calida calida</i>
LAD <i>Globigerina (Globoturborotalita) decoraperta</i>
FAD <i>Bolliella praeadamsi</i>
FAD <i>Pulleniatina finalis</i>
Change from d to s coiling in <i>Gr. (Tr.) crassula</i>
LAD <i>Gr. (Tr.) tosaensis</i>
LAD <i>Pu. praecursor</i>
FAD <i>Gr. (Tr.) crassaformis hessi</i>
FAD <i>Gr. (Ob.) bermudezi</i>
L1 coiling interval for <i>Pulleniatina</i>
L2 coiling interval for <i>Pulleniatina</i>
L3 coiling interval for <i>Pulleniatina</i>
LAD <i>Gds. quadrilobatus fistulosus</i>
L4 coiling interval for <i>Pulleniatina</i>
LAD <i>Gds. obliquus extremus</i>
FAD <i>Tinophodella' evoluta</i>
LAD <i>Gds. obliquus obliquus</i>
LAD <i>Dentoglobigerina altispira altispira</i>
FAD <i>Ga. (Globoturborotalita) rubescens</i> pink form
L5 coiling interval for <i>Pulleniatina</i>
FAD <i>Ga. (Go.) rubescens tenellus</i>
FAD <i>Gr. (Tr.) truncatulinooides</i>

ways rare and form a very small component in the assemblages. This makes it impossible to utilise the presence or



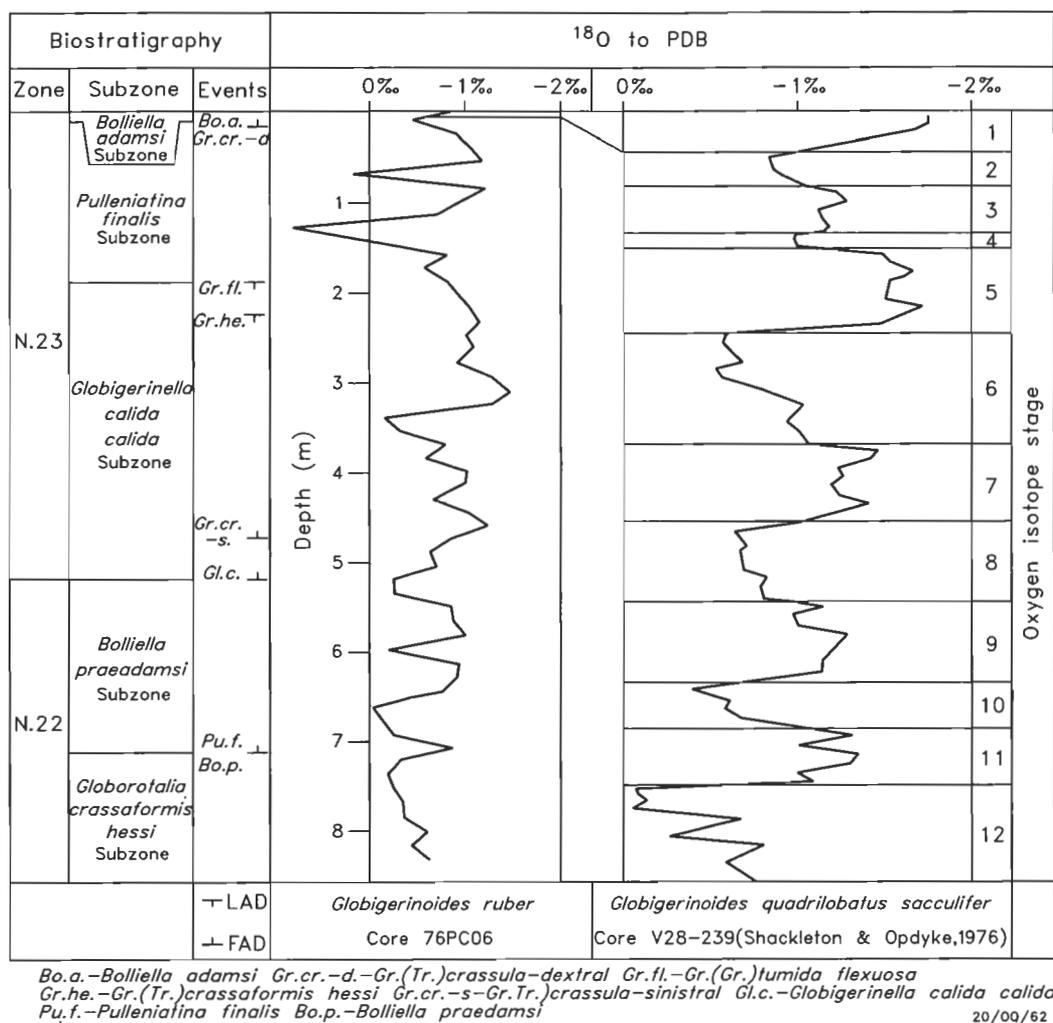


Figure 10. Relationship of biostratigraphic events and oxygen isotope stratigraphy in core 76PC06.

Oxygen isotope data from Peerdeman (ANU, personal communication).

that part of the section above the FAD of *Gr. (Tr.) crassaformis hessi*, and two others (51GC17 and 51GC22) occur below that event. In So16-13SL the latest Pliocene disconformably underlies the *Gr. (Tr.) crassaformis hessi* Subzone. Again, all events recognised in this area occurred in the same order.

### Biostratigraphic events

**LAD of *Globorotalia (Truncorotalia) crassaformis hessi*.** This event takes place with the top of Zone N.22, above the FAD of *Bo. calida calida* and below the FADs of both *Bo adamsi* and *Gr. (Gr.) tumida flexuosa* (Bolli & Saunders, 1985). In this study, the LAD of *Gr. (Tr.) crassaformis hessi* occurs above these events in all sections studied except 76PC06, where it occurs within the range of sinistrally coiled *Gr. (Tr.) crassula*, between the LAD of *Gr. (Gr.) tumida flexuosa* and the FAD of *Bo. adamsi*, within oxygen isotope stage 5. However, the top part of this core was lost during coring operations which also disturbed the topmost section. On the evidence from other cores, this FAD event is probably within oxygen isotope stage 2.

**FAD *Bolliella adamsi*.** This event occurs within the later Quaternary (Blow, 1969; Saito & others, 1981; Bolli & Saunders, 1985). Bolli & Saunders (1985, fig. 11) indicate that *Bo. adamsi* is restricted to the Holocene. This species is found

Table 2. Biostratigraphic events from the middle Gauss Chron to present used in this study.

1. LAD *Globorotalia (Truncorotalia) crassaformis hessi*
2. FAD *Bolliella adamsi*
3. Change from s to d coiling in *Gr. (Tr.) crassula*
4. LAD *Gr. (Gr.) tumida flexuosa*
5. LAD *Gds. ruber* pink form
6. FAD *Bo. calida calida*
7. LAD *Ga. (Go.) decoraperta*
8. FAD *Bo. praedamsi*
9. FAD *Pu. finalis*
10. Change from d to s coiling in *Gr. (Tr.) crassula*
11. LAD *Gr. (Tr.) tosaensis*
12. LAD *Pu. praecursor*
13. FAD *Gr. (Tr.) crassaformis hessi*
14. FAD *Gr. (Ob.) bermudezi*

#### Zonal markers

- Zone N19/20-N.21 boundary: FAD *Gr. (Tr.) tosaensis*  
 Zone N.21-N.22 boundary: FAD *Gr. (Tr.) truncatulinoides*  
 Zone N.22-N.23 boundary: FAD *Bo. calida calida*

#### Subzonal markers

- Zone N.22 Subzones  
*Gds. quadrilobatus fistulosus* subzone: FAD *Gr. (Tr.) truncatulinoides*  
*Gr. (Tr.) crassaformis viola* subzone: LAD *Gds. quadrilobatus fistulosus*  
*Gr. (Tr.) crassaformis hessi* subzone: FAD *Gr. (Tr.) crassaformis hessi*  
*Bo. praedamsi* subzone: FAD *Bo. praedamsi*  
 Zone N.23 Subzones  
*Bo. calida* subzone: FAD *Bo. calida calida*  
*Pu. finalis* subzone: LAD *Gr. (Gr.) tumida flexuosa*  
*Bo. adamsi* subzone: FAD *Bo. adamsi*

only in the upper parts of the cores studied from northeastern Australia, above the FAD of *Bo. calida calida*, and above the interval of sinistrally coiled *Gr. (Tr.) crassula*. The species occurs only in the top 15 cm of 76PC06, which is within either oxygen isotope stage 1 or 2 in the Holocene. I have used this event to define the base of the *Bolliella adamsi* Subzone (Chaproniere, 1985b).

**Coiling changes in populations of *Globorotalia (Truncorotalia) crassula*.** A change in coiling direction in populations of *Gr. (Tr.) crassula* from dominantly dextral to sinistral and then the reverse has been noted for most sections, even though the absence or rarity of this species at some levels make it difficult to accurately locate the level where the changes occur. Although populations of this species appear to be dominated by dextrally coiled individuals through most of its range, at a level immediately before the FADs of *Bolliella praeadamsi* and *Pulleniatina finalis* there is a rapid shift from dextral to sinistral coiling. Sinistrally coiled populations continue until a level between the LAD of *Gr. (Gr.) tumida flexuosa* and the FAD of *Bo. adamsi*, when the populations revert to dextral coiling. In core 76PC06 this species occurs intermittently in the lower part of the section. Though the change from dextral to sinistral coiling occurs immediately above the FAD of *Bo. calida calida* (in oxygen isotope stage 7), the specimens are extremely rare and intermittent. The apparent coiling change is therefore unreliable, especially when compared with data from other cores. In cores So16-13SL, 51GC22 and 51GC45 the FAD of *Gr. (Tr.) crassula* occurs above the base of the *Bo. praeadamsi* Subzone, and in cores So16-12SL and 51GC18 sinistral *Gr. (Tr.) crassula* ranges from within this subzone; in core 51GC17 this event occurs within the top of the *Gr. (Tr.) crassaformis hessi* Subzone. Thus, the evidence suggests that the change from dextral to sinistral coiling takes place near the boundary of the *Gr. (Tr.) crassaformis hessi* and *Bo. praeadamsi* Subzones, below oxygen isotope stage 10, possibly within oxygen isotope stage 11. The change from sinistral to dextral coiling takes place between the LAD of *Gr. (Gr.) tumida flexuosa* and the FAD of *Bo. adamsi*; this event occurs within a turbidite interval near the top of core 76PC06, making the correlation with the oxygen isotope stage chronology unreliable (Peerdeman, ANU, personal communication, 1990). Notwithstanding, this event must take place within the interval of isotope stages 1 to 4 in this core, probably within oxygen isotope stages 2 or 3. This interval of sinistral coiling in the later Pleistocene has not been recognised before.

**LAD *Globorotalia (Globorotalia) tumida flexuosa*.** Blow (1969) believed that this form did not range into Zone N.23 and so did not overlap with *Bo. calida calida*. However, Bolli & Premoli Silva (1973) used the overlap of the two taxa to define their *Globigerina calida calida* Subzone in the Caribbean region. Bolli & Saunders (1985) stated that *Gr. (Gr.) tumida flexuosa* had a very limited stratigraphic range in the Indo-Pacific region where it was confined to the early Pliocene. However, it has the same range in the vicinity of Wallis Island as that recorded from the Caribbean region (Chaproniere, 1985b; present study). The position of this event is contrary to that recorded by Kennett & Srinivasan (1983), who locate it at the Zone N.21–N.22 boundary. The highest occurrence of this subspecies is at 190 cm in core 76PC06, within oxygen isotope stage 4.

**LAD *Globigerinoides ruber* pink form.** Thompson & others (1979) concluded that this event occurred at 120 000 years BP in the Indian and Pacific Oceans, even though it is extant in the Atlantic Ocean. It could therefore be valuable for biostratigraphy for the region. I have recorded rare specimens in Holocene sediments both in the present study and near Wallis Island,

north of Fiji (Chaproniere, 1985b) and the Tongan region (Chaproniere, 1985a; in press). The specimens suggest either that it is extant in the region, or that it has been reworked from older sediments over wide areas of the subtropical–tropical southwestern Pacific. The rarity and patchy distribution of this readily identified form favour reworking. In most cores there is a rapid reduction of population size of pink individuals at levels above the FAD of *Bo. calida calida* and below the LAD of *Gr. (Gr.) tumida flexuosa*, apparently very close to the 120 000 years BP date (which corresponds to within oxygen isotope stage 5<sup>c</sup>) obtained by Thompson & others (1979). The reduction in numbers (top acme) appears to provide a useful event for the region. In core 76PC06 the sudden reduction in numbers of pink *Gds. ruber* occurs at 350 cm, within the lower part of oxygen isotope stage 5.

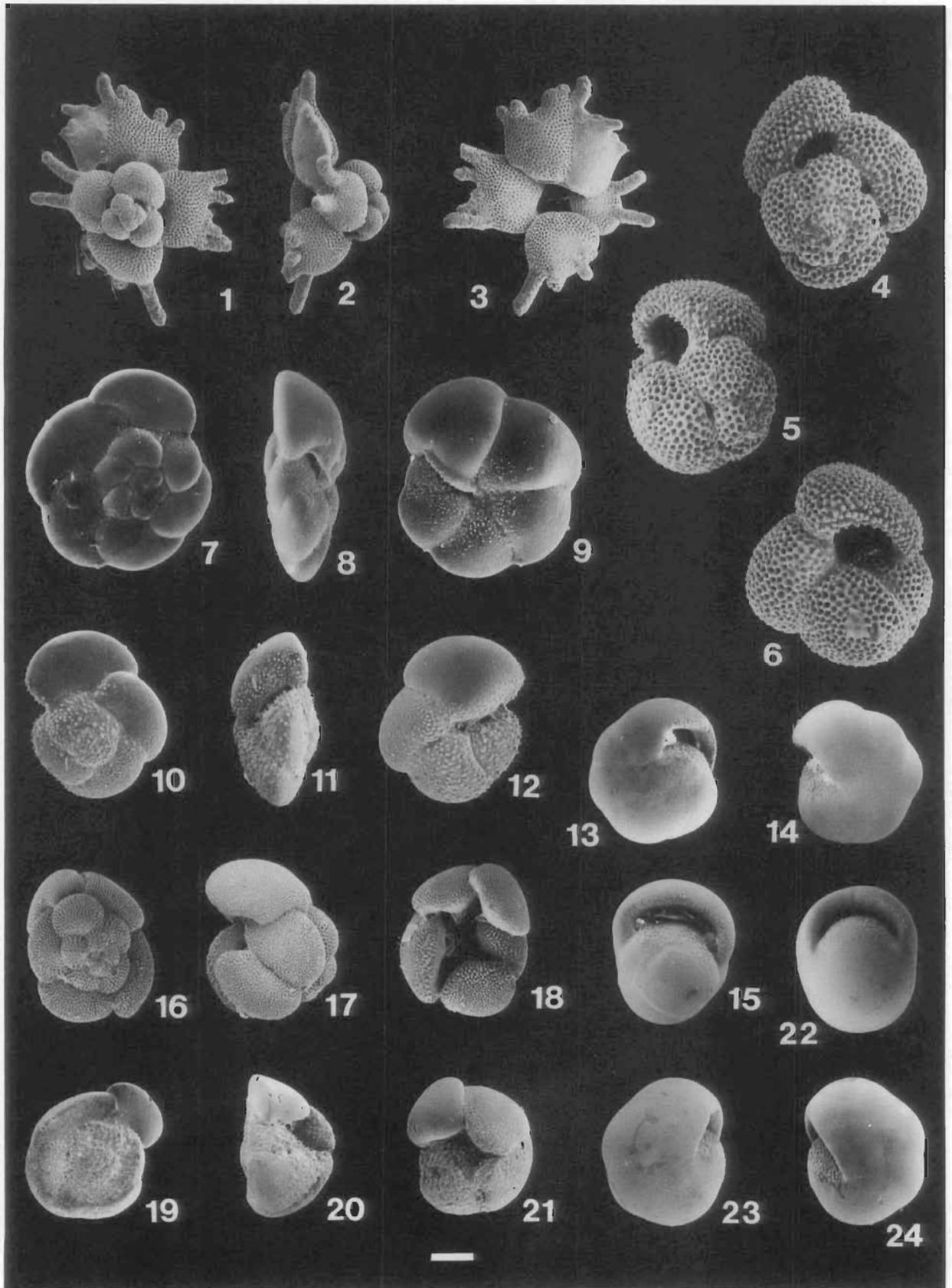
**FAD *Bolliella calida calida*.** Blow (1969) used this event to define the base of Zone N.23 which he considered to range from late Pleistocene to the Holocene. Bolli & Premoli Silva (1973) believed that the FAD of this subspecies occurred at 200 000 yrs. BP (within oxygen isotope stage 7), that is, within the latest Pleistocene. This is a similar level to that recorded in 76PC06, where the event occurs in oxygen isotope stage 7. I have strictly adhered to Blow's (1969) criteria for the separation between *calida* and *praecalida* morphotypes; thus, *calida* has a test with at least 4.5 chambers in the final whorl, and the chambers show distinct radial elongation.

**LAD *Globigerina (Globoturborotalia) decoraperta*.** This event coincides with the Zone N.21–N.22 boundary (Kennett & Srinivasan, 1983). The species is rare in the cores studied, but it persists to higher levels than previously recorded. Of the three cores from which it has been recorded, only in core So16-13SL (where it ranges into the *Bo. praeadamsi* Subzone) can reworking from older levels be rejected. In core 76PC06 it ranges into the *Bo. calida calida* Subzone, but is associated with reworked taxa. In core 51GC17 it ranges into the *Gr. crassaformis hessi* Subzone. It is sometimes but not always accompanied with reworked forms, which suggests that it is probably *in situ* in this section.

**FAD *Bolliella praeadamsi*.** This event consistently occurs at the same time as the FAD of *Pulleniatina finalis*, below oxygen isotope stage 10, and probably within isotopic stage 11 in core 76PC06.

**FAD *Pulleniatina finalis*.** There is some disagreement in the literature as to the biostratigraphic range of this species. Banner & Blow (1967) described this form from the Recent of the Atlantic Ocean, but Blow (1969) considered that it ranged from well within the Pleistocene to the present day. Subsequently, Saito & others (1975) believed its FAD to be within the lower part of the Pleistocene. Poag & Valentine (1976) found it in Subzone B of their *Turborotalia inflata* IV Bioecozone, which they correlated to a level within the Jaramillo Subchron, above the level given by Saito & others (1975). Lamb & Beard (1972) believed this event occurred within the Illinoian Glacial Stage, which ranges from oxygen isotope stages 16 to 13 (Thunell, 1984, table 2.2), and correlates with levels in the lower part of the Brunhes Chron. Bolli & Saunders (1985) claim that it appeared within the Pleistocene in the Atlantic Province, and much earlier in the Indo-Pacific Province based on evidence credited to Beckmann (1971) from the central Pacific. However, Beckmann (*in* Tracey & others, 1971a, p. 292; 1971b, p. 466) shows that the species is restricted to the Pleistocene, and gives no evidence to support the contention made by Bolli & Saunders (1985). This record of an earlier FAD is therefore discounted here.

Bolli (1966) and Belford (1988) noted that forms close to *Pu. finalis* occur in the Pliocene. These records were attributed to



**Plate 3.**

1-3, *Globigerinoides quadrilobatus fistulosus*, CPC30232, sample 81640043, So16-13SL-260. 4-6, *Globigerinoides obliquus extremus*, CPC30233, sample 81640030, So16-13SL-000. 7-9, *Globorotalia (Obandyella) bermudezi*, CPC30234, sample 51GC45-105. 10-12, *Globorotalia (Truncorotalia) crassula*, CPC30235, sample 81640034, So16-13SL-075. 13-15, *Pulleniatina praecursor*, CPC30236, sample 51GC22-214. 16-18, *Dentoglobigerina altispira altispira*, CPC30237, sample 81640040, So16-13SL-200. 19-21, *Globorotalia (Truncorotalia) crassaformis hessi*, CPC30238, sample 51GC18-050. 22-24, *Pulleniatina finalis*, CPC30239, sample 76PC06-730.

Scale bar figs 1-3, 250  $\mu\text{m}$ ; 4-9, 75  $\mu\text{m}$ ; 10-12, 135  $\mu\text{m}$ ; 13-24, 200  $\mu\text{m}$ .

environmental factors by Bolli & Saunders (1985), but the presence of these *Pu. finalis*-like forms in the early Pliocene suggests that they represent a short-lived side branch from *Pu. obliquiloculata* which was not related to the later *Pu. finalis*-stage descendant. Thus, though there is good evidence for the FAD of *Pu. finalis* within the Pleistocene, there is no general consensus on the exact level at which *Pu. finalis* first appears. This lack of consensus is probably the result of differing taxonomic interpretations of this species due to difficulties in interpreting the degree of involution of the test. In the sections used in this study, *Pu. finalis* first appears at a level approximating oxygen isotope stage 12, which is close to that recorded by Lamb & Beard (1972) from the Caribbean region, suggesting that the contention of Bolli & Saunders (1985) is incorrect. As noted above, Saito & others (1975) believed that the FAD of *Pu. finalis* occurred earlier in the Pleistocene than that recorded by Lamb & Beard (1972), Poag & Valentine (1976), or in this study. Saito & others (1975) failed to illustrate their concept of the taxon, and the illustration given by Saito & others (1981) is of specimens which appear to have some of the earlier spire visible, and are probably not entirely involute; in addition they are from the Holocene. Because Banner & Blow (1967) described *finalis* as being involute, the specimen illustrated by Saito & others (1981) should not be referred to this species, but to *Pu. obliquiloculata*. The specimens of *Pu. finalis* illustrated by Poag & Valentine (1976) fall within my interpretation of the species, but they are from the Holocene rather than from the level of its FAD in the Louisiana shelf area. The level of FAD of involute morphotypes of *Pulleniatina* is still uncertain, but it seems that the records of Saito & others (1975) and Bolli & Saunders (1985) are not reliable.

**LAD of *Globorotalia (Truncorotalia) tosaensis*.** This event was used by Kennett and Srinivasan (1983) to mark the top of their *Gr. truncatulinoides*-*Gr. tosaensis* overlap zone. As noted above, this event appears to coincide with the FAD of *Gr. (Tr.) crassaformis hessi*. The event occurs in oxygen isotope stage 15 (Thompson & Sciarrillo, 1978).

**LAD *Pulleniatina praecursor*.** *Pu. praecursor* has been found in four cores. In So 16-13SL it occurs within the lower part of the core, where it overlaps with *Gr. (Tr.) truncatulinoides* and so clearly ranges within the lower part of Zone N.22, higher than the Zone N.21 level indicated by Kennett & Srinivasan (1983). In core 51GC17 it ranges throughout the *Gr. (Tr.) crassaformis viola* Subzone, in 51GC22 into the basal part of the *Gr. (Tr.) crassaformis hessi* Subzone and in 76PC06 into the upper part of the *Gr. (Tr.) crassaformis hessi* Subzone. In core 51GC17 reworked late Miocene faunas are present at the same levels, and in core 76PC06 reworked late Pliocene to early Pleistocene faunas are present, suggesting that the specimens of *Pu. praecursor* may also be reworked. Because the FAD of *Pu. praecursor* occurs within Zone N.19/20 (Kennett & Srinivasan, 1983) it is unlikely that its presence in core 51GC17 is due to reworking, as the reworked species are from Zone N.17. However, in core 76PC06 this species occurs with taxa derived from levels above Zone N.19/20, above its FAD, suggesting that in this section it may have been reworked. In core 51GC22, however, *Pu. praecursor* is present without reworked older faunas, suggesting that it is *in situ*. Thus the evidence suggests that this species ranges at least into the early Pleistocene, but may also range as high as the base of the *Gr. (Tr.) crassaformis hessi* Subzone, that is, into the basal Brunhes Chron.

**FAD of *Globorotalia (Truncorotalia) crassaformis hessi*.** This event was used by Bolli & Premoli Silva (1973) to define the base of their *Gr. crassaformis hessi* Subzone. In the studied sections this event always pre-dates the FAD of *Bo. calida*

and post-dates the FAD of *Gr. (Tr.) truncatulinoides*. Bolli & Saunders (1985, fig. 11) show that the LAD of *Gr. (Tr.) tosaensis* pre-dates the FAD of *Gr. (Tr.) crassaformis hessi*, but in the three sections which include both events (51GC17, 51GC22, 76PC06) there is a brief overlap between the two taxa in one (51GC22) and in another (51GC17) no such overlap is observed. In the third there is considerable overlap between the two, but a number of latest Miocene or Pliocene forms (such as *De. altispira altispira*, *Gds. obliquus extremus*, *Gr. (Gr.) multicamerata*, *Gr. (Gr.) paralenguaensis*, and *Sis. seminulina*) are also present, indicating reworking. The presence of *Gr. (Tr.) tosaensis* at these levels is therefore questionable. Thus, this work suggests that both the events take place at approximately the same time, but with little overlap. For this reason I have provisionally placed this event within oxygen isotope stage 17.

**FAD *Globorotalia (Obandyella) bermudezi*.** Kennett & Srinivasan (1983) and Rögl & Bolli (1973) placed this event at the Zone N.21-N.22 boundary. The species is common in most samples from the cores studied, although its distribution is discontinuous in the lower part of its range. In some cores (51GC17, 51GC22) this event occurs within the top of the *Gr. crassaformis viola* Subzone. In others, which penetrate into only the younger part of the section, *Gr. (Ob.) bermudezi* ranges from the bottom. Although this event appears to occur within the *Gr. (Tr.) crassaformis viola* Subzone near the base of the Brunhes Chron, the absence of samples from that part of the Pleistocene below the Brunhes Chron makes it necessary to await other studies from levels lower in the Pleistocene before a full evaluation can be made.

**Coiling changes in populations of *Pulleniatina*.** Saito (1976) recognised five intervals where populations of *Pulleniatina* were dominated by sinistrally coiled individuals within Zone N.22. Though these intervals were short they could be correlated globally, based on palaeomagnetic data (Fig. 2). The sole interval of sinistrally coiled populations encountered in this study is in core So16-13SL, where they occur over a 50 cm interval coinciding with the overlap of *Gds. quadrilobatus fistulosus* and *Gr. (Tr.) truncatulinoides* near the LAD of the latter. This is at the same position as that recorded by Saito (1976) as the L5 coiling interval of *Pulleniatina*; this coincides with the base of the Olduvai Subchron, and is correlated to that interval here.

**LAD *Globigerinoides quadrilobatus fistulosus*.** The FAD of *Gr. (Tr.) truncatulinoides* and the LAD of *Gds. quadrilobatus fistulosus* coincide with the Zone N.21-N.22 boundary (Kennett & Srinivasan, 1983) even though the FAD of *Gr. (Tr.) truncatulinoides* occurs just below the base of the Olduvai event, whilst the LAD of *Gds. quadrilobatus fistulosus* occurs just above the top of the Olduvai event (Berggren & others, 1980). In this work, the LAD of *Gds. quadrilobatus fistulosus* occurs well within the lower part of Zone N.22. This is similar to the LAD recorded by Berggren & others (1985), who indicated that this event occurs immediately above the Olduvai Subchron at 1.6 Ma. In core So16-13SL this event coincides with a hiatus.

**LAD *Globigerinoides obliquus extremus*.** Kennett & Srinivasan (1983) equated this event with the Zone N.21-N.22 boundary, but Berggren & others (1980, 1985) placed it within the lower part of the Olduvai Subchron, within Zone N.22. In core So16-13SL, this subspecies is found to overlap with *Gr. (Tr.) truncatulinoides* and *Gds. quadrilobatus fistulosus*, supporting the view of Berggren & others (1980, 1985). This taxon occurs at even higher levels in two other cores, 76PC06 (in the *Bo. praeadamsi* Subzone) and 51GC17 (where it is present in the *Gr. (Tr.) crassaformis hessi* Subzone), but in both instances reworking can be demonstrated.

**FAD 'Tinophodella' evoluta.** This minute form was described from DSDP Site 208 by Fordham (1986) who considered that it was probably restricted to the Pleistocene. This species occurs in the fine fractions (<250 µm) of all cores studied. In core So16-13SL this species was found to occur from 175 cm and above, ranging from a level within the *Gds. quadrilobatus fistulosus* Subzone. The position of this event requires assessment in other areas to test its full biostratigraphic potential.

**LAD Globigerinoides obliquus obliquus.** This event occurs within the top part of Zone N.21, below the FAD of *Gr. (Tr.) truncatulinoides*, and below the LAD of *Gds. obliquus extremus* (Kennett & Srinivasan, 1983). In core So16-13SL, the LAD of *Gds. obliquus obliquus* occurs above the FAD of *Gr. (Tr.) truncatulinoides*, below the LADs of *Gds. quadrilobatus fistulosus* and *Gds. obliquus extremus*, and within the range of sinistrally coiled populations of *Pulleniatina*. These data indicate that this event takes place within the Olduvai Subchron in the Coral Sea region. Specimens of *Gds. obliquus obliquus* are also present in core 51GC17 at levels containing a number of reworked late Miocene taxa; these specimens are also believed to have been reworked.

**LAD Dentoglobigerina altispira altispira.** This event took place within the lower part of Zone N.21 (Kennett & Srinivasan, 1983), and is dated at 2.9 Ma (Berggren & others, 1985), the same level as the FAD of *Gds. quadrilobatus fistulosus*. Within core So16-13SL, this subspecies occurs with *Gr. (Tr.) truncatulinoides*, *Gds. quadrilobatus fistulosus* and *Gds. obliquus extremus*, indicating that it ranges to within the basal part of Zone N.22. There is no evidence for reworking in this core, although the presence of *De. altispira altispira* in core 51GC17 is ascribed to reworking. It is absent from the Pliocene in cores 51GC73 and 51GC74.

**FAD Globigerina (Globoturborotalita) rubescens pink form.** Pink forms of *Ga. (Go.) rubescens* seem to develop within the Pleistocene (Parker, 1967; Jenkins & Orr, 1972). However, the reliability of the FAD of the pink coloured form has not yet been fully established. I have recorded it as ranging from within the *Gr. (Tr.) crassaformis viola* Subzone near Wallis Island (Chaproniere, 1985b), and a similar range is found in the cores used in this study. In core So16-13SL, the FAD of pink forms occurs 20 cm above the FAD of *Gr. (Tr.) truncatulinoides*, within the range of *Gds. quadrilobatus fistulosus* and sinistrally coiled populations of *Pulleniatina*. As noted above, this assemblage correlates with the lower part of the Olduvai Subchron according to Saito (1976), suggesting that the FAD of pink forms of *Ga. (Go.) rubescens* occurs at this level, within the basal part of Zone N.22, in the latest Pliocene. Even though this event appears to have potential for marking the base of Zone N.22, it requires verification at additional locations.

**FAD Globigerina (Globoturborotalita) rubescens tenellus.** Kennett & Srinivasan (1983) place this event within the top of Zone N.21 (late Pliocene), but Rio & others (1984a) show it occurring above the base of Zone N.22. In core So16-13SL this event occurs 24 cm above the FAD of *Gr. (Tr.) truncatulinoides*, within the range of *Gds. quadrilobatus fistulosus* and sinistrally coiled populations of *Pulleniatina*, indicating that the FAD of *Ga. (Go.) rubescens tenellus* occurs within the lower part of the Olduvai Subchron and the lower part of Zone N.22, similar to that recorded by Rio & others (1984a).

**FAD of Globorotalia (Truncorotalia) truncatulinoides.** As noted above, it is uncertain whether this event took place at the same time in lower and higher latitudes, although it seems constant globally for low latitudes. The event has been dated as

1.9 Ma and approximates the base of the Olduvai magnetic event (Berggren & others, 1985).

## Discussion

Of the 27 events discussed above (Table 1), 23 have been recognised by earlier workers, and only four are newly recognised. Few of these have been used biostratigraphically, at least in the Indo-Pacific region, where there have been few attempts at a Pleistocene planktic foraminiferal biostratigraphy. Many of the events have been found at different levels to those previously recorded, which may be due in part to the paucity of studies in subtropical-tropical sequences, and in part to differences in taxonomic usage. Some of these events occur either in the 'missing' part of Pleistocene represented by a hiatus encountered in core So16-13SL, or at a level below that penetrated by most of the cores. Nine of the events (1 to 9 in Table 2) are present in core 76PC06, the only core for which oxygen isotope data are available (Fig. 10; Peerdeman, ANU, personal communication, 1990), and have been correlated with the oxygen isotope stratigraphic scheme. Because of the lack of information on many of these events within the western Pacific region I have used for subzonal definitions only those events which have been found elsewhere and appear to be chronologically consistent.

## Biostratigraphic zonation

As noted above, the zonal scheme of Blow (1969) forms the basis for the zonation used for this study. This scheme uses the events of the FADs of *Gr. (Tr.) tosaensis*, *Gr. (Tr.) truncatulinoides* and *Bo. calida calida* to define the bases of Zones N.21, N.22 and N.23 respectively. Bolli & Premoli Silva (1973) subdivided the last two zones into five Subzones. I found this not to be fully applicable to the region adjacent to Wallis Island (Chaproniere, 1985b), and a modified subzonal scheme was proposed. However this also proved inadequate for the area covered by this study, and so has once again been modified (Fig. 11).

**Zone N.21.** The lower section of core So16-13SL contains *Gr. (Tr.) tosaensis* and *Gds. quadrilobatus fistulosus*, without *Gr. (Tr.) truncatulinoides*, indicating a level within the top part of Zone N.21 (Kennett & Srinivasan, 1983). The assemblages from this part of the core contain *Gr. (Gr.) multicamerata* and *Pu. praecursor* indicating a level somewhat below the top of Zone N.21 (Kennett & Srinivasan, 1983; see also Fig. 2). Bolli & Saunders (1985, fig. 10), however, show *Gds. quadrilobatus fistulosus* ranging from Zone N.19 into the base of Zone N.21 (effectively restricted to the middle Pliocene), barely overlapping with *Gr. (Tr.) tosaensis*. They also show the LAD of *Gr. (Gr.) multicamerata* occurring within Zone N.20, immediately before that of *Gds. quadrilobatus fistulosus*, with both taxa becoming extinct well below the FAD of *Gr. (Tr.) truncatulinoides*. Thus, according to Bolli & Saunders (1985) the assemblages from the three cores should be assigned to the basal part of Zone N.21. This conclusion is not consistent with the evidence of Kennett & Srinivasan (1983) nor with the data from this study. However, the presence of *Gds. quadrilobatus fistulosus*, *Gr. (Gr.) multicamerata* and *Pu. praecursor* within Zone N.22 in some of the cores studied, suggests that these taxa range into higher levels than considered by either Kennett & Srinivasan (1983) or Bolli & Saunders (1985).

**Zone N.22.** The subdivisions previously used for Zone N.22 (Bolli & Premoli Silva, 1973; Chaproniere, 1985b) have proved to be inadequate for this study, necessitating the use of new or redefined subzones. The base of Zone N.22 is defined

EPOCH	BLOW, 1969	LAMB & BEARD, 1972	BOLLI & PREMOLI SILVA, 1973	CHAPRONIERE, 1985b	THIS PAPER
HOLO		<i>Globorotalia tumida</i> Zone	<i>Globorotalia fimbriata</i> Subzone	<i>Hastigerina adamsi</i> Subzone	<i>Bolliella adamsi</i> Subzone
PLEISTOCENE	N.23	<i>Globorotalia truncatulinoides</i> Zone	<i>Globigerina bermudezi</i> Subzone	<i>Pulleniatina obliquiloculata finalis</i> Subzone	<i>Pulleniatina finalis</i> Subzone
			<i>Globigerina calida calida</i> Subzone	<i>Globigerina calida calida</i> Subzone	<i>Bolliella calida calida</i> Subzone
			<i>Globorotalia hessi</i> Subzone	<i>Globorotalia crassaformis hessi</i> Subzone	<i>Bolliella praeadamsi</i> Subzone
			<i>Globorotalia crassaformis viola</i> Subzone	<i>Globorotalia crassaformis viola</i> Subzone	<i>Globorotalia crassaformis viola</i> Subzone
	N.22			<i>Globigerinoides quadrilobatus fistulosus</i> Subzone	
LATE PLIOCENE	N.21	<i>Pulleniatina obliquiloculata</i> Zone	<i>Pulleniatina truncatulinoides</i> cf. <i>tosaensis</i> Zone		N.21

† LAD *Bo.a.*–*Bolliella adamsi* *Gr.fi.*–*Globorotalia*(*Gr.*)*fimbriata* *lge. Gr.tu.*–*large Gr.*(*Gr.*)*tumida tumida*  
*Gr.fl.*–*Gr.*(*Gr.*)*tumida flexuosa* *Gl.c.*–*Globigerinella calida calida* *Bo.c.*–*Bolliella calida calida* *Pu.f.*–*Pulleniatina finalis*  
*Bo.p.*–*Bolliella praeadamsi*  
† FAD *Gr.he.*–*Gr.*(*Truncorotalia*)*crassaformis hessi* *Gd.fi.*–*Globigerinoides quadrilobatus fistulosus* *Gr.tr.*–*Gr.*(*Tr.*)*tosaensis*  
*De.a.*–*Dentoglobigerina altispira altispira*

20/00/61

Figure 11. Planktic foraminiferal biostratigraphic zonation and boundary criteria for the Quaternary as discussed in this paper.

by the FAD of *Gr. (Tr.) truncatulinoides*, and the top by the FAD of *Bo. calida calida* (Blow, 1969).

***Globigerinoides quadrilobatus fistulosus* Subzone.** This subzone is defined by the interval between the FAD of *Gr. (Tr.) truncatulinoides* and the LAD of *Gds. quadrilobatus fistulosus*. This interval represents the lower part of Zone N.22, and is in part equivalent to the lower part of the *Gr. (Tr.) crassaformis viola* Subzone of Bolli & Premoli Silva (1973). The lower part of this subzone is present in core So16-13SL, but in this core the top of the subzone is marked by a disconformity.

The FAD of *Gr. (Tr.) truncatulinoides*, which occurs at 1.9 Ma and approximates the base of the Olduvai magnetic event (Berggren & others, 1985), marks the base of the subzone. The LAD of *Gds. quadrilobatus fistulosus* is given as 1.6 Ma, approximating the top of the Olduvai event (Berggren & others, 1985). Thus the *Gds. quadrilobatus fistulosus* Subzone had a duration of approximately 0.3 Ma.

Taxa having some biostratigraphic significance which range through this subzone are *Gr. (Tr.) tosaensis* and *Gr. (Gr.) tumida flexuosa*.

Taxa having some biostratigraphic significance which disappear within this subzone are *De. altispira altispira*, *Gr. (Gr.) cultrata limbata*, *Gr. (Gr.) multicamerata* and *Pu. praecursor*.

Taxa having some biostratigraphic significance which appear within this subzone are *Ga. (Go.) rubescens* pink form and '*Tinophodella*' *evoluta*.

Other significant biostratigraphic events: At least one sinistral coiling phase of *Pu. obliquiloculata* (L5 of Saito, 1976) is found in the studied sections. It is almost certain that another sinistral coiling phase for this species (L4) occurs within this subzone, but because of the disconformity within the lower part of the Pleistocene in the region, the position of this event has not been established by this study.

***Globorotalia (Truncorotalia) crassaformis viola* Subzone.** This subzone was proposed by Bolli & Premoli Silva (1973), and was defined as that interval between the FAD of *Gr. (Tr.) truncatulinoides* and the FAD of *Gr. (Tr.) crassaformis hessi*. Because the newly defined *Gds. quadrilobatus fistulosus* Subzone is within the lower part of the *Gr. (Tr.) crassaformis viola* Subzone as originally defined, it is necessary to emend this definition. The base of the *Gr. (Tr.) crassaformis viola* Subzone is now defined by the LAD of *Gds. quadrilobatus fistulosus*, with the top being marked by the FAD of *Gr. crassaformis hessi*. Though the lower part of this subzone has not been recognised in the studied area because of the presence of a disconformity spanning part of the early Pleistocene, the top has been found in cores 51GC17 and 51GC22.

The LAD of *Gds. quadrilobatus fistulosus* has been dated at 1.6 Ma (Berggren & others, 1985). No published information is available for the FAD of *Gr. (Tr.) crassaformis hessi*, but in core 76PC06 this subspecies is present from the base of the core, and so this event must be older than oxygen isotope stage 12. However, in core 51GC22 both *hessi* and *tosaensis* are seen to overlap, and in core 51GC17 the two events are separated by 86 cm. Thus, the two events appear to be of similar age. The LAD of *Gr. (Tr.) tosaensis* has been given as 0.6 Ma by Berggren & others, (1985) giving a time interval of approximately 1.0 Ma for this subzone. Because few biostratigraphic events occur within this subzonal interval (Fig. 2), they are of little use for additional zonal subdivision. Only three occur at the very top (the FAD of *Gr. (Ob.) bermudezi*, and the LADs of *Pu. praecursor* and *Ga. (Go.) decoraperta*). Three intervals of sinistrally coiled populations of *Pulleniatina* seem to occur within the subzone (Saito, 1976), but these fall within the interval represented by a disconformity within the sections studied, indicating that only the top part of the subzone occurs within the study area.

***Globorotalia (Truncorotalia) crassaformis hessi* Subzone.** This subzone was proposed by Bolli & Premoli Silva (1973) with the base defined by the FAD of *Gr. (Tr.) crassaformis hessi* and the top by the FAD of *Bo. calida calida*. Because the newly defined *Bolliella praeadamsi* Subzone occurs within the top part of this subzone as originally defined, it has been necessary to redefine the upper boundary on the FAD of *Bo. praeadamsi*. The *Gr. (Tr.) crassaformis hessi* Subzone succeeds the *Gr. (Tr.) crassaformis viola* Subzone in cores 51GC17 and 51GC22, but it is missing in core Sol6-13SL because a disconformity separates the *Globigerinoides quadrilobatus fistulosus* and *Bolliella praeadamsi* Subzones. The LAD of *Gr. (Tr.) tosaensis* occurs very close to the FAD of the subzonal marker and may be useful to indicate this interval in the absence of *Gr. (Tr.) crassaformis hessi*; indeed Kennett & Srinivasan (1983) have used the LAD of *Gr. (Tr.) tosaensis* to define the top of their *Gr. (Tr.) truncatulinoides-Gr. (Tr.) tosaensis* Zone. Berggren & others (1985) give the age of the LAD of *Gr. (Tr.) tosaensis* as 0.6 Ma which places it in oxygen isotope stage 16. The basal part of core 76PC06 falls within the *Gr. (Tr.) crassaformis hessi* Subzone and is older than oxygen isotope stage 10, evidence which does not dispute the conclusions of Berggren & others (1985). In core 76PC06 the top of the subzone falls below oxygen isotope stage 10, and is possibly within oxygen isotope stage 11 which is at approximately 0.36 Ma; thus, on the basis of this evidence, the subzone lasted approximately 0.24 Ma.

***Bolliella praeadamsi* Subzone.** The base of this subzone is defined on the FAD of *Bo. praeadamsi*; the FAD of *Pu. finalis* occurs at the same time and so can be used as a supplementary definition. The top of the subzone is defined by the FAD of *Bo. calida calida*, an event which also marks the top of Zone N.22. As defined, the subzone falls within the upper part of the *Gr. (Tr.) crassaformis hessi* Subzone of Bolli & Premoli Silva (1973), making it necessary to emend that subzonal definition. The *Bolliella praeadamsi* Subzone is found in all cores studied, but the lower boundary occurs only in cores 51GC17, 51GC22, 51GC45 and 76PC06. As noted above, the base may fall within oxygen isotope stage 11 (0.36 Ma) in core 76PC06, and the top in oxygen isotope stage 8 (ca. 0.25 Ma). Bolli & Premoli Silva (1973) show the age of the FAD of *Bo. calida calida* to be 0.2 Ma, a date which falls within oxygen isotope stage 7, and is a similar level to that found in core 76PC06. Thus the interval of time occupied by the *Bolliella praeadamsi* Subzone ranges from 0.11 to 0.16 Ma.

**Zone N.23.** Bolli & Premoli Silva (1973) recognised three subzones within Zone N.23 in the Caribbean region, but I was

able to recognise only one of these (as the *Globigerinella calida calida* Subzone) near Wallis Island (Chaproniere, 1985b). Instead, I recognised two different subzones (the *Pulleniatina finalis* Subzone and the *Hastigerina adamsi* Subzone) (Fig. 2); the base of the *Pulleniatina finalis* Subzone was defined by the LAD of *Gr. (Gr.) tumida flexuosa* and the top by the FAD of *Hastigerina adamsi* (= *Bolliella adamsi* in this study). I have also been able to recognise the same sequence of subzones in the Coral Sea area. As noted above the FAD of *Bo. calida calida* occurs within oxygen isotope stage 7 in this region. Brönnimann & Resig (1971) noted the difficulty in separating the *praecalida* and *calida* morphotypes and so criticised the basis for Zone N.23.

***Bolliella calida calida* Subzone.** The base of this subzone is defined by the FAD of *Bo. calida calida*, and the top by the LAD of *Gr. tumida flexuosa*, following Bolli & Premoli Silva (1973). This subzone has been recognised in all cores.

Two events occur within this subzone: the LAD of the pink form of *Gds. ruber*, and a change in the coiling direction for populations of *Gr. (Tr.) crassula* from dextral to sinistral. The coiling change takes place within oxygen isotope stage 7 in core 76PC06.

***Pulleniatina finalis* Subzone.** Lamb & Beard (1972) described this subzone from the Caribbean region, and defined its base on the FAD of *Pu. finalis* and the top by the appearance of large specimens of *Gr. (Gr.) tumida tumida*. Because this sudden change in size of *Gr. (Gr.) tumida tumida* has not been observed in the Indo-Pacific region, I emended the definition of the subzone (Chaproniere, 1985b), defining the base on the LAD of *Gr. (Gr.) tumida flexuosa* and the top on the FAD of *Bo. adamsi*. This subzone can be recognised in all but one of the cores (51GC18), where the LAD of *Gr. (Gr.) tumida flexuosa* occurs below the FAD of *Bo. calida calida*. Over the upper part of its range this *Gr. (Gr.) tumida flexuosa* becomes rare and sporadic.

One biostratigraphic event occurs within this subzone, this being the change in coiling direction for populations of *Gr. (Tr.) crassula* from sinistral to dextral. This event occurs within a turbidite interval near the top of core 76PC06, making the correlation with the oxygen isotope stage chronology unreliable (Peerdeman, ANU, personal communication, 1990). Notwithstanding, this event must take place within the interval of isotope stages 1 to 4 in this core.

***Bolliella adamsi* Subzone.** I defined the base of this subzone on the FAD of *Bo. adamsi* (Chaproniere, 1985b). This event occurs above the peak level of pink forms of *Gds. ruber*, an event which probably equates to that noted by Thompson & others (1979), who dated it at 120 000 BP. Rare specimens of this pink form are present in Holocene sediments, both in the northern Australian region, as well as further to the east (Chaproniere, 1985b), which limits its biostratigraphic usefulness. However, in all cores there is a sudden reduction in population size, and this event appears to be biostratigraphically useful. This subzone is present in all cores. In core 76PC06 the FAD of *Bo. adamsi* occurs only in the disturbed upper part, making correlation with the oxygen isotope stratigraphy inappropriate. However, this event must take place within either isotope stages 1 or 2, making it a possible marker for the Holocene.

The LAD of *Gr. (Tr.) crassaformis hessi* is the only event to take place within this subzone. Towards the end of its range this subspecies becomes very rare, reducing its potential as a zonal indicator.

## Comparison with previous zonations

Figure 11 illustrates a comparison between the zonal scheme proposed in this paper and those of other papers and shows the relationship of events to the oxygen isotope stratigraphic scheme established in the Coral Sea area. The region studied for this paper has been within the tropical belt throughout the Pleistocene, and so has been minimally affected by the temperature changes which occurred over this time interval. All other studies are based on areas near the subtropical/warm temperate transition, and their zonal schemes consequently reflect the faunal changes related to fluctuations in water temperature. In addition, a degree of provincialism can be recognised in the faunas from the different areas, making it necessary for new subzones to be established for the Coral Sea region.

## Environmental controls

The association *Globigerinita glutinata*, *Gds. conglobatus*, *Gds. ruber*, *Gds. sacculifer*, *Gr. (Tr.) crassaformis*, *Gr. (Gr.) tumida*, *N. dutertrei* and *Pu. obliquiloculata* is generally considered to be tropical (Bé & Tolderlund, 1971), being typical of waters north of 15°S in the western Atlantic Ocean (van Leeuwen, 1989). In these associations *N. dutertrei* is always dominantly dextrally coiled. Further, *Gr. (Tr.) truncatulinoidea* is dominated by dextrally coiled individuals in subtropical and tropical seas (Healy-Williams, 1983). However, for many species temperature does not appear to be the main controlling factor; the physical and chemical properties of the water mass are more important (Bé, 1977). For example, Thiede (1971) found that salinity appears to have controlled the coiling direction of *Gr. (Tr.) truncatulinoidea* during the north Atlantic Quaternary, with sinistrally coiled populations being typical of interglacial sediments. Thiede (1971) concluded that changes in salinity due to expansion of the central north Atlantic water mass controlled coiling direction. Bé & Tolderlund (1971) also showed that there was a sharp boundary between sinistral and dextrally coiled populations at 25°S in the Indian Ocean, where there appears to be no major change in physical oceanographic characteristics. More recently, van Leeuwen (1989) and Auras-Schudnagies & others (1989) have shown that nutrient levels control the distribution of some species; for example *Globigerina (Ga.) bulloides* occurs in nutrient-rich areas such as upwellings, whereas *Globigerinoides sacculifer* and *Gds. ruber* are typical of oligotrophic areas.

The Pleistocene planktic foraminiferal faunas from the cores show a marked stability, with the assemblages dominated by oligotrophic, warm water species such as *Gds. quadrilobatus sacculifer*, *Gds. ruber* and *Gr. (Gr.) cultrata*. *Pulleniatina*, *Neogloboquadrina* (both dextrally coiled), *Sphaeroidinella dehiscens* and *Gr. (Gr.) tumida*, though never abundant, are universally present. Thus, on the faunal evidence, warm oligotrophic conditions similar to those today have been stable in the region since at least the middle Pleistocene.

## Conclusions

The study of seven cores from the Coral Sea off northeastern Australia has permitted the assessment of 27 planktic foraminiferal biostratigraphic events from the latest Pliocene, basal Pleistocene and mid to late Pleistocene; most of the early Pleistocene could not be studied because of a hiatus in the one core which penetrated through the Pleistocene into the top of the Pliocene. Some of these events have been used to erect a formal zonal and subzonal scheme for the region, building upon studies by Blow (1969), Bolli & Premoli Silva (1973),

Rögl (1974) and Chaproniere (1985b). Following my earlier study (Chaproniere, 1985b), Zones N.22 and N.23 of Blow (1969) have been used, and the modified subzonal scheme of Bolli & Premoli Silva (1973), used by Chaproniere (1985b) has been modified slightly, with the addition of the new *Globigerinoides quadrilobatus fistulosus* and the *Bolliella praeadamsi* Subzones. This has made necessary the redefinition of the *Globorotalia (Truncorotalia) crassaformis viola* and the *Globorotalia (Truncorotalia) crassaformis hessi* Subzones of Bolli & Premoli Silva (1973). There is little faunal evidence for changes in palaeoceanographic conditions being related to the faunal changes observed in the cores, although there is strong evidence of reworking at some levels within some of the cores (such as late Miocene Zone N.17 in core 51GC17), which may have been related to sea-level fluctuations. The assemblages from the cores show a marked stability, with the faunas being dominated by spinose, oligotrophic taxa. Temperate water forms are either very rare or absent, whereas tropical and subtropical species are dominant.

A single new species, *Bolliella praeadamsi*, has been described because of its biostratigraphic utility. This species is an evolutionary intermediate between *Bo. calida praealida* and *Bo. adamsi*.

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## Systematic description

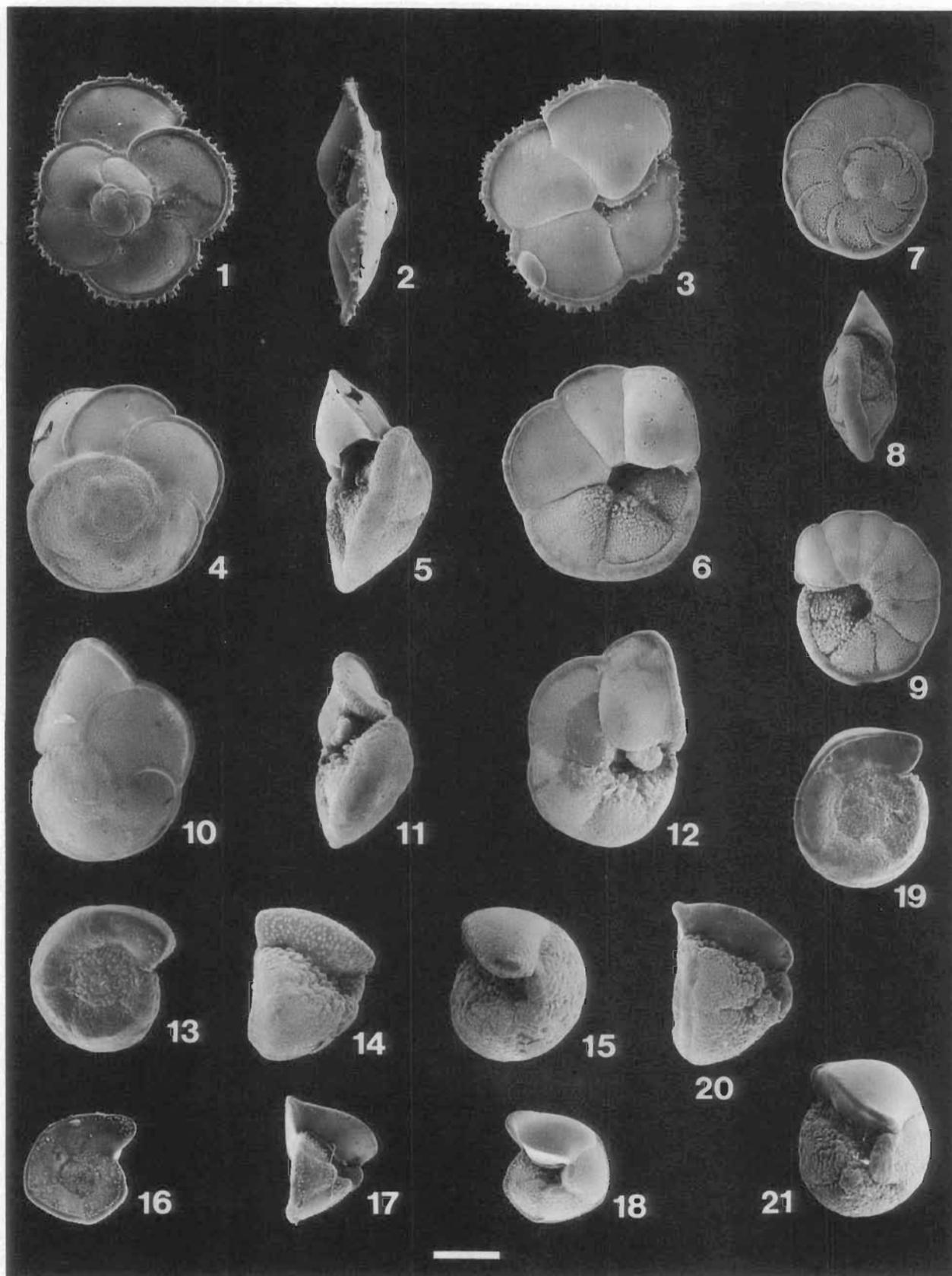
### Family Globigerinidae Subfamily Hastigerininae

The following discussion is restricted to the hastigerines in order to describe a new species which has biostratigraphic importance for the region. The taxonomic nomenclature used herein is mainly in accordance with Kennett & Srinivasan (1983), Saito & others (1981) and Loeblich & Tappan (1988).

### Genus *Bolliella* Banner & Blow, 1959

**Type species.** *Hastigerina (Bolliella) adamsi* Banner & Blow, 1959; by original designation.

Banner & Blow (1959) established *Bolliella* as a subgenus of *Hastigerina* on the basis that the chambers were radially elongate in the adult. Included in the concept of *Hastigerina* was *Globigerinella* following Bolli & others (1957). Banner & Blow (1960) maintained their previous concept of *Hastigerina* and considered *Globigerinella aequilateralis* a junior synonym of *H. siphonifera*. Loeblich & Tappan (1964) elevated *Bolliella* to full generic status. Bé (1967, 1969) believed that spine shape was an important taxonomic character and used it to separate *Hastigerina* from *Globigerinella*; both were shown to have triradiate spines, but *Globigerinella* differed in having simple spines also. This separation has been supported by Loeblich & Tappan (1988) who considered that *Bolliella* had an apertural lip which was absent in *Globigerinella*. Saito & others (1981), without giving reasons, believed *Bolliella* to be a junior synonym for *Globigerinella* and referred *adamsi* to that genus. Kroon (1988) noted that in the 125 to 250 µm size fraction, specimens of *adamsi*, *calida* and *siphonifera* were difficult to separate.



**Plate 4.**

1-3, *Globorotalia (Globorotalia) cultrata fimbriata*, CPC30240, sample 81640043, So16-13SL-260. 4-6, *Globorotalia (Globorotalia) cultrata neoflexuosa*, CPC30241, sample 51GC45-121. 7-9, *Globorotalia (Globorotalia) multicamerata*, CPC30242, sample 81640043, So16-13SL-260. 10-12, *Globorotalia (Globorotalia) tumida flexuosa*, CPC30243, sample 76PC06-190. 13-15, *Globorotalia (Truncorotalia) tosaensis*, CPC30244, sample 51GC17-328. 16-18, *Globorotalia (Truncorotalia) truncatulinoides truncatulinoides*, CPC30245, sample 51GC22-040. 19-21, *Globorotalia (Truncorotalia) truncatulinoides pachythecca*, CPC30246, sample 51GC22-040.

Scale bar figs 1-12, 16-21, 300  $\mu\text{m}$ ; 13-15, 200  $\mu\text{m}$ .

*Hastigerina* differs from both *Globigerinella* and *Bolliella* in having only triradiate spines, whilst the two other genera have both rounded and triradiate spines. The evidence presented by Saito & others (1976) showing that the surface texture of *Bolliella* and *Globigerinella* to be very similar lead them to consider that both *Bo. adamsi* and *Gl. siphonifera* were closely related, with *Bo. calida* probably being the ancestral form of *Bo. adamsi*. Though both spine shape and surface texture are important morphologic features, the presence of an apertural lip also appears important (Loeblich & Tappan, 1988). The type species of *Globigerinella*, *Gl. aequilateralis*, lacks an apertural lip (Saito & others, 1981) a feature observed in this study (Plate 1, figs 14, 17), whilst the *adamsi*, *calida* and *praeadamsi* morphotypes invariably possess a thin apertural lip. Even though a number of workers believe that *Bolliella* should be considered a junior synonym of *Globigerinella*, I believe the chamber elongation and the presence of an apertural lip in *Bolliella* to be sufficient and easily recognisable morphologic characters for distinguishing *Bolliella* from *Globigerinella*. In addition I believe that the *adamsi*, *calida*, *praeacalida* and *praeadamsi* morphotypes share enough characteristics for them all to be referred to *Bolliella*. Furthermore, on phylogenetic grounds it is best to maintain this separation.

Saito & others (1976) considered that *Bo. calida* was the most probable ancestor of *Bo. adamsi*, and noted that the only characters separating the two species were the chamber elongation and the planispiral coiling of *Bo. adamsi*.

#### ***Bolliella praeadamsi* new species**

Plate 1, figs 1–6, 19–21; Plate 2, figs 1–9

**Types.** Holotype and 5 paratypes from sample 81640021, So16-12SL-075, and are filed under numbers CPC30216–30218 and CPC30224–30226 in the Commonwealth Palaeontology Collection, BMR, Canberra.

**Diagnosis.** A hastigerine with the final 1 to 4 chambers arranged planispirally, and which may or may not show some radial elongation; the earlier part of the final whorl is clearly trochospiral.

**Description.** Test medium to large, with 5 or 6 chambers in the final whorl. Initial stage a low trochospire, with the last 1 to 4 chambers planispirally arranged and well separated from the previous whorl. Chambers initially spherical and globular becoming ovate; may finally be radially elongate in large specimens. Chambers increase rapidly in size throughout ontogeny, each separated from the previous chamber by a depressed radial suture. Aperture umbilical–extra-umbilical and a low asymmetrical arch on the earlier chambers of the final whorl, becoming a high and wide symmetrical arch with a distinct thin lip. Wall calcareous, spinose, densely perforate with large circular pores, with randomly distributed, rounded and raised spine bases. Spines round becoming triradiate.

**Remarks.** In side view this species is very similar to *Bo. calida* sensu lato in having a narrow test, but differs by having 1–4 chambers arranged in a planispire, clearly separated from the previous whorl. In addition, some of the final chambers may show some degree of radial elongation. *Bo. praeadamsi* differs from *Bo. adamsi* in having rounded, subglobular chambers, rather than the pointed distal chamber apex of *Bo. adamsi*. It differs from *Gl. aequilateralis* (1) in having only the last few chambers of the test arranged planispirally, with a distinct trochospiral part of the final whorl as viewed from the spiral side, (2) by having more chambers in the final whorl, the earlier part of the test being somewhat narrower in side view, (3) by having the last few chambers separated from the

previous whorl, and (4) by having a distinct apertural lip. The chambers of *Gl. aequilateralis* are more globular and expand more rapidly in diameter as the test increases in size, leading to a thicker test as seen in side view. Saito & others (1981) show that the test wall of *Bo. calida* is very similar to that of *Bo. adamsi*, a feature not found in this study. The wall texture of both *Bo. adamsi* and *Bo. praeadamsi* is identical, but it has distinctly larger diameter pores than those of *Bo. calida*. This may be an environmental factor, although specimens illustrated by Saito & others (1981) were collected from the southwestern equatorial Pacific, not far from the present study area.

This species has almost certainly been recorded either as *Gl. aequilateralis* (= *Gl. siphonifera*) or as *Bo. adamsi*, with which it has many features in common. It is readily differentiated from *Gl. aequilateralis* in side view. It is very similar to both *Bo. calida* and *Bo. adamsi* in side view in its slow rate of chamber expansion, resulting in a lower trochospire than that of *Gl. aequilateralis*.

**Stratigraphic Range.** Middle Pleistocene, Zone N.22 (*Bo. praeadamsi* Subzone) to Recent (oxygen isotope stages 1 to 11 or 12).

**Phylogeny.** Two phylogenies for the hastigerines have been proposed. Blow (1969) traced the phylogenetic origins of this group to *Gl. obesa*. He believed that this morphotype graded into the planispiral forms *Gl. praesiphonifera* (within Zone N.7), *Gl. aequilateralis* (= *siphonifera*) in Zone N.12, and *Bo. adamsi* within the Pleistocene (Banner & Blow, 1960). Blow (1969) considered that *Bo. calida praeacalida* had its origins within the *Globigerina praebulloides* group and gave rise to *Bo. calida calida*, which is thus unrelated to *Hastigerina*. *H. pelagica* was considered to have had an unknown ancestry (Banner & Blow, 1960). Kennett & Srinivasan (1983, text fig. 26) proposed a phylogenetic scheme for the group, with the same lineage (*Gl. obesa*–*Gl. praesiphonifera*–*Gl. aequilateralis*) as in Banner & Blow (1960). However, *H. pelagica* and *Bo. calida* (including both the *praeacalida* and *calida* morphotypes) were both derived from *Gl. aequilateralis* (within Zones N.17A and N.19, respectively). Srinivasan & Kennett (1975) believed that *Bolliella* evolved from *Globigerinella*.

As noted above, the presence of an apertural lip and the arrangement of the initial coil of *Bo. calida praeacalida*, *Bo. calida calida*, *Bo. praeadamsi* and *Bo. adamsi* distinguishes the group from other spinose forms such as *Globigerina bulloides*, *Gl. aequilateralis* and *Hastigerina pelagica*. On the basis of wall structure (size and pattern of pores, characteristics of spines and spine bases), the *Bo. calida* group and *Bolliella* are close to *Gl. aequilateralis*, but distinct from *Hastigerina*. The FAD of *Bo. praeadamsi* occurs before the FAD of *Bo. calida calida*, indicating that the latter cannot be the ancestral form. As noted above, the early ontogenetic stage of *Bo. praeadamsi* is very similar to *Bo. calida praeacalida*, and this appears to be the preferred ancestral form of *Bo. praeadamsi*.

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## Differentiation of Late Cambrian–Early Ordovician species of *Cordylodus* (Conodonta) with biapical basal cavities

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Four species of the conodont genus *Cordylodus* are recognised, containing elements that have two apices in the basal cavity (biapical), one extending into the cusp and the other into the first denticle of the posterior process. They are *C. prion* Lindström 1955, *C. lindstromi* Druce & Jones, 1971, *C. prolindstromi* sp. nov. and *C. sp. nov. B*. *Cordylodus* sp. nov. B has been found only in a single sample and insufficient material is available to establish limits of element morphological variability. In the Ninmaroo Formation of the Georgina Basin, northern Australia, *C. prolindstromi* sp. nov. is found stratigraphically below the first occurrence of *C. lindstromi*. This relationship may be important in the resolution of the placement of the Cambrian–

Ordovician boundary. In all four species, the biapical cavity is best developed in the S elements, poorly developed in the P elements and, except in *C. prion*, absent in the M element. Multiple basal cavity apices that extend into the cusp and into the base of one or more denticles of the posterior process, may be found in aberrant specimens of most species of *Cordylodus*, but the consistent presence of the biapical cavity seems to be limited to these four species of the genus. There has been some confusion in the literature about the application of the name *Cordylodus lindstromi* and most previous identifications of *C. lindstromi* now need re-evaluation in the light of the species definitions established here.

### Introduction

The interpretation of species of the conodont genus *Cordylodus* with two apices in the basal cavity, the primary extending into the cusp and the secondary into the first denticle of the posterior process, has caused much taxonomic and biostratigraphic confusion. Most of these biapical specimens have either been assigned to *Cordylodus lindstromi* Druce & Jones or been considered aberrant specimens of a form normally having only a single apex to the basal cavity (Landing & others, 1980). However, Nicoll (1990) examined type and topotype material of *C. lindstromi* from the Ninmaroo Formation (Georgina Basin, western Queensland) and comparative material from the Wilberns Formation (Texas). He concluded that a morphologically distinct species, with a full septimembrate apparatus, could be recognised. Nicoll (1990) also indicated that the 'notched' forms illustrated as *C. lindstromi* by Barnes (1988) and Andres (1988) should be assigned to a new species and that some stratigraphically old elements of *C. lindstromi* had a flattened secondary apex (Nicoll, 1990, table 3).

This paper extends the investigation of biapical basal cavities in *Cordylodus* from *C. lindstromi* to three additional species. Two of these are the notched form, which is *C. prion* Lindström (1955), and the flattened tip form, which is herein named *C. prolindstromi* sp. nov. The accurate differentiation of these three species is critical in the recognition of one of the proposed levels of the Cambrian–Ordovician boundary. The third additional species, *C. sp. nov. B*, has been recovered from a single sample from the upper part of the Ninmaroo Formation, but too few specimens have been found to define the complete apparatus structure.

Several conodont species and faunas have been re-examined recently in investigating the Cambrian–Ordovician boundary (Nicoll, 1990; Nicoll & Shergold, 1991; this study), and some key samples containing species relevant to the understanding of speciation of the genus *Cordylodus* have been examined. These include the Stora Backor sample 5 (Västergötland, Sweden), from the Lindström (1955) study of the Ordovician of central Sweden, and new samples from the Ninmaroo Formation at Black Mountain in western Queensland (Druce & Jones, 1971; Nicoll & Shergold, 1991; Shergold & Nicoll, in press).

Sample 5 from the Lindström (1955) section in the Ånga Quarry at Stora Backor contained a new species of *Cordylodus*, *C. prion*, as well as other taxa important to the understanding of Early Ordovician conodont speciation. Lindström (1955) identified 20 form species (subsequently reduced to about 10 multielement taxa) in the sample. Olgun (1987) identified 22 species from the same interval, but many of them are considered here to be reworked Cambrian and earlier Ordovician forms. For this study I analysed a single block of limestone (collected by John Repetski, U.S Geological Survey, Reston, Va) from the nodular bed of Lindström's section diagram (1955, fig. 1). The 822 g sample was processed in buffered acid and sieved using a 75 micron sieve. The residue was subjected to magnetic separation to remove the abundant glauconite. Over 5000 of the better preserved ramiform elements and representative coniform elements were then selected for study.

At the Black Mountain section (Fig. 1) in the Georgina Basin of western Queensland, two sets of samples, one collected by R.L. Ripperdan and J.L. Kirschvink (California Institute of Technology) in 1989 and the second by J.H. Shergold, R.S. Nicoll, J.R. Laurie, B.M. Radke, R.W. Brown (Bureau of Mineral Resources) and A.T. Nielsen (University of Copenhagen) in 1990, have recently been taken through the Chatsworth Limestone and Ninmaroo Formation for biostratigraphic and palaeomagnetic study (Ripperdan & others, 1990; Nicoll & Shergold, 1991). A total of 303 new samples, 65 from the Chatsworth Limestone and 238 from the Ninmaroo Formation, were collected through this 1000 m thick section and have been examined for conodonts. Revisions of the conodont biostratigraphy of the pre-*Cordylodus* interval have been published (Nicoll & Shergold, 1991) and preparation of the fauna from the rest of the section is in progress.

### Evolutionary development of *Cordylodus*

The genus *Cordylodus* can be divided into a root stock and three distinct lineages based on gross morphological differences, especially in the cusp of the P elements. The root stock is the evolutionary lineage of *C. primitivus* Bagnoli & others (1987) — *C. proavus* Müller (1959) — *C. caboti* Bagnoli & others (1987), a group that is structurally simple, but which show increasing morphological complexity. The first branch from this stock consists of species with biapical basal cavities

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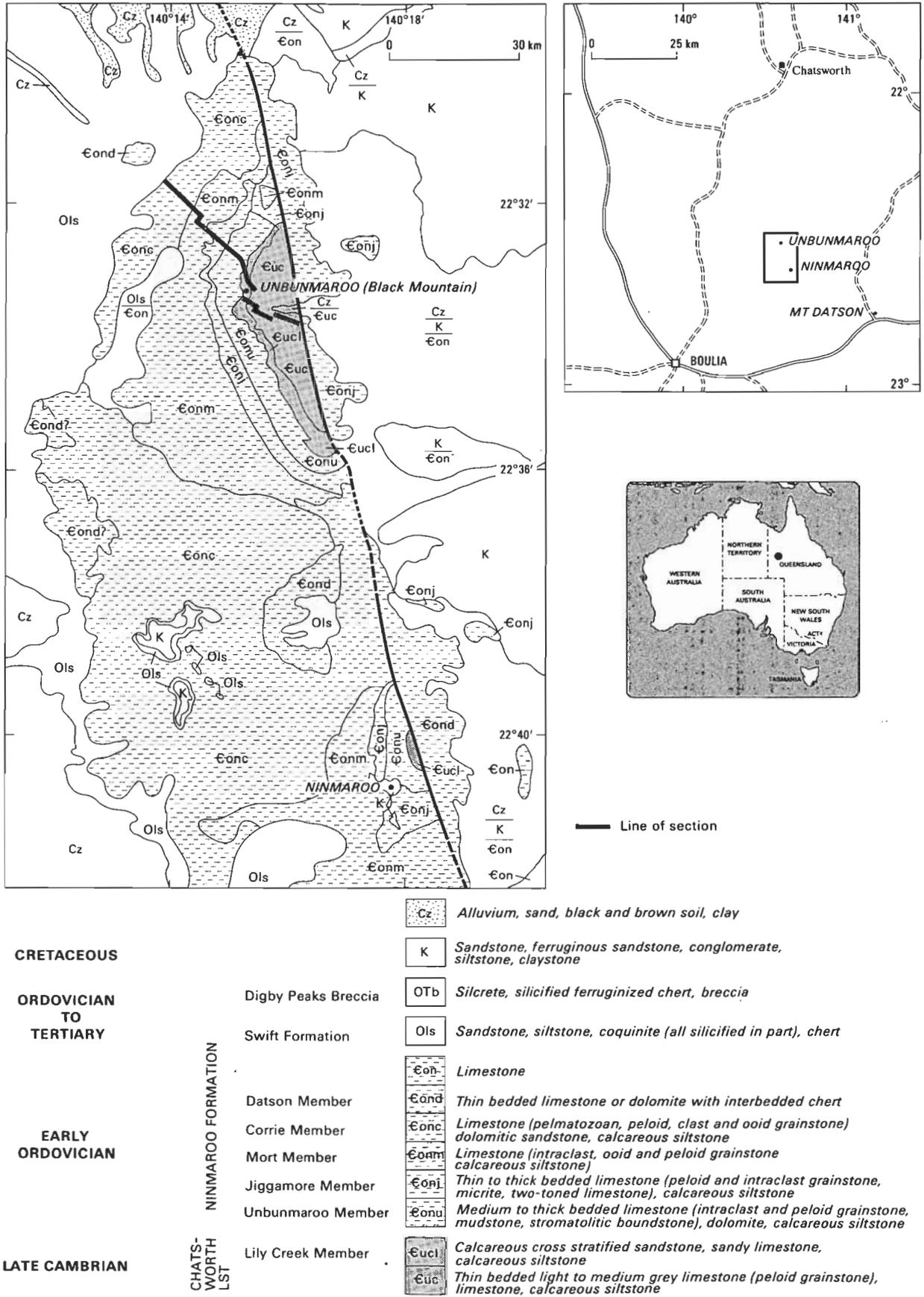


Figure 1. Locality map, showing geology of the Black Mountain (Unbunmaroo) and Ninmaroo inliers. The location of the section line is indicated.

and erect cusps on P elements: *C. prolindstromi* — *C. lindstromi* — *C. sp. nov. B* and *C. prion*. The second consists of species with laterally compressed S elements and P elements in which the anterior margin of the basal cavity curves around in a groove to meet the antero-basal corner: *C. angulatus* Pander (1856) and *C. horridus* Barnes & Poplawski (1973). The third lineage consists of the robust forms with P elements that have rounded anterior margins and cusps that are round in section and strongly recurved: *C. paratundatus* Olgun (1987), *C. caseyi* Druce & Jones (1971) and *Cordylodus ramosus* Hadding (1913).

Four species of the biapical lineage (Fig. 2) are distinguished in this study. Two species, *C. prion* Lindström, 1955, and *C. lindstromi* Druce & Jones, 1971 have been previously recognised. One species, *C. prolindstromi* sp. nov., is named in this paper and a fourth species, *C. sp. nov. B*, remains in open nomenclature. These four species are regarded as representing a distinct branch of the genus *Cordylodus*, but are not considered to be significantly distinct to warrant establishment of a new genus to contain this evolutionary lineage. The presence of multiple apices in basal cavities of early forms such as *C. proavus* (Andres, 1988) supports this approach.

Stratigraphic distribution and morphological similarity indicate that *Cordylodus prolindstromi*, the earliest member of the biapical lineage, probably evolved from *C. caboti*. The two species are distinguished by the shape of the P elements and by the biapical basal cavity in *C. prolindstromi*.

### Significance of the biapical basal cavity

The presence of a biapical basal cavity in conodonts is not restricted to some species of *Cordylodus*, but is also found in genera such as *Icriodus*, *Iapetognathus* and *Pelekysgnathus*. In *Cordylodus* the anterior, or primary, cavity apex extends into the cusp, and the secondary cavity apex extends into the first denticle of the posterior process. Andres (1988) has illustrated specimens of *C. proavus* with up to five secondary cavity apices extending into denticles along the entire the posterior process, but the species detailed here have only two apices.

The biapical basal cavity is best developed in the S elements and is sometimes observable in some P elements. The M element usually lacks a second cavity apex, except in *C. prion*.

The function of the secondary cavity apex is not apparent. In the material examined, the secondary cavity extends only a short distance toward the oral surface of the element and does not reach the white matter in the denticle. The pointed apex of the basal cavity of conodonts is a reduction of the cavity that in primitive conodonts extended up the hollow cone to the cusp apex. There seems to be no physiological or structural advantage in developing a hollow cone in a second denticle or cusp. The depth of the secondary apex is not great enough to strengthen the adhesion of the cusp to the basal cavity.

The secondary basal cavity apex does not appear to have biological advantage for the animal, but it is a useful morphological character in the recognition of a group of *Cordylodus* species.

### Biostratigraphic implications

In the Black Mountain type section of the Ninmaroo Formation (Radke, 1981), the ranges of *C. caboti*, *C. prolindstromi*, *C. lindstromi* and *C. sp. nov. B* have been documented in the recent sample set (Fig. 3). The highest appearance of *C. caboti* is 316 m, above the base of the formation (sample BMA 115).

*C. prolindstromi* first appears at 329 m (sample GB90-002/3) and continues through to 390 m (sample GB90-002/38). *C. lindstromi* first appears at 404 m (sample GB90-002/51) and continues through to 572 m (sample GB90-002/109). *C. sp. nov. B* occurs only at 495.8 m (sample GB-002/96). *C. prion* has not been found in the Ninmaroo Formation, or at any other locality in Australia.

Nicoll (1990, table 3) has noted the presence of biapical *Cordylodus* elements with flattened second apex in samples of the Ninmaroo Formation collected by Druce & Jones (1971). Such elements occur in both the Mt Datson and Mt Ninmaroo sections, below the first appearance of 'normal' elements of *C. lindstromi*. These elements are now interpreted as elements of *C. prolindstromi* and their stratigraphic distribution agrees with that observed in the Black Mountain section.

The identification of *C. prolindstromi* as a precursor species at a stratigraphic level just below the first occurrence of *C. lindstromi* should allow the first appearance datum (FAD) for *C. lindstromi* to be used as an accurate time line for correlation. If other sections with the same faunal succession can be located, the *C. prolindstromi*–*C. lindstromi* boundary could have great biostratigraphic significance.

The relationship of *C. prion* to other biapical *Cordylodus* species is difficult to determine until more is known about its stratigraphic range. This will require re-examination of material from other sections, such as Green Point, Newfoundland, where Barnes (1988, fig. 13k,l) illustrates a specimen that conforms to the definition of *C. prion* used here. Barnes (1988) recovered the specimen from Green Point sample 52, which is very low in the reported range of *C. lindstromi* and just above the last occurrence of *Hirsutodontus simplex*. *C. prion* may have evolved directly from *C. prolindstromi*, and would thus be essentially time equivalent with *C. lindstromi*.

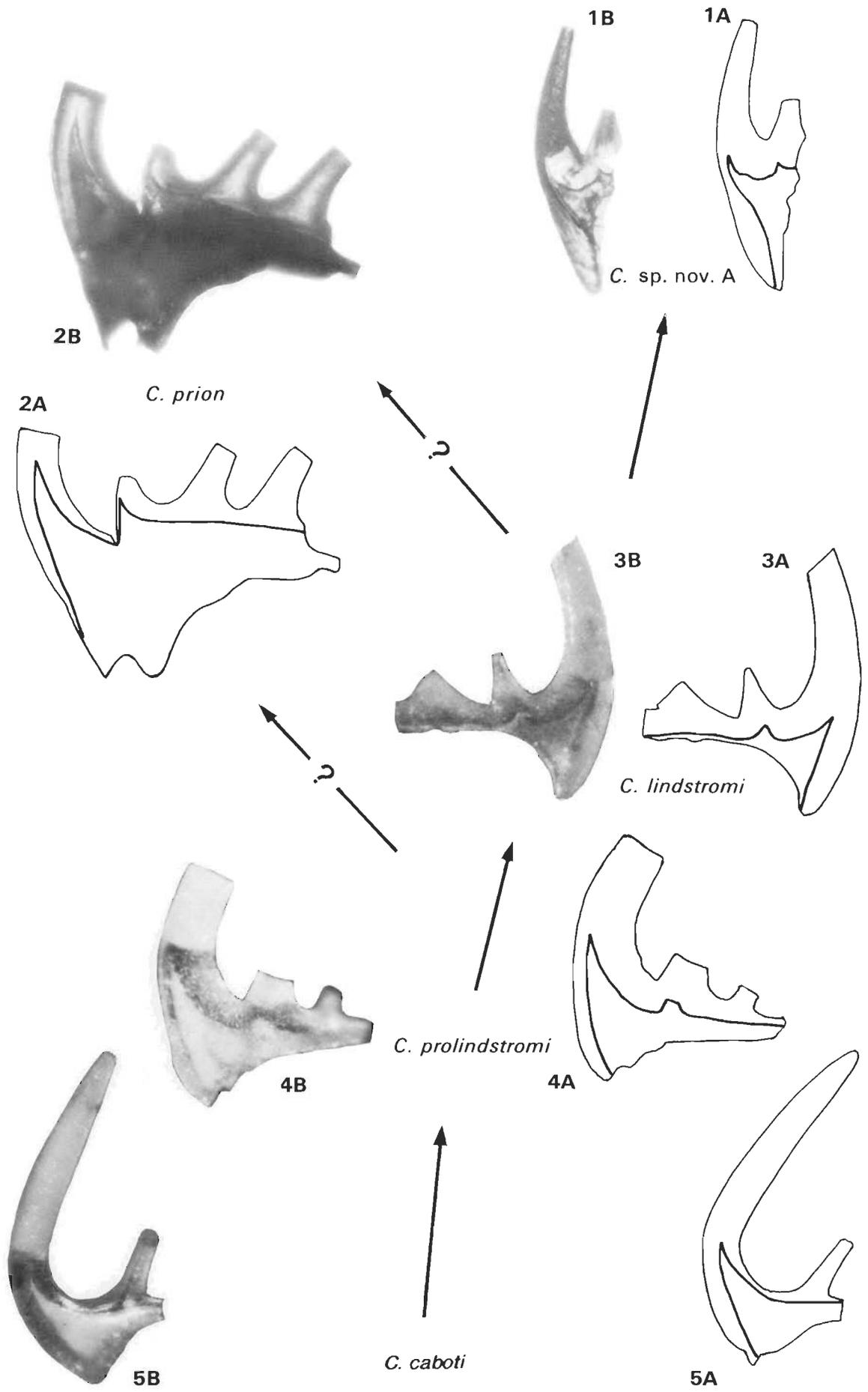
The type of *C. prion*, at Stora Backor sample 5 (Lindström, 1955) (where this species co-occurs with *C. angulatus*) occurs in a conodont fauna that has many reworked elements from a variety of Late Cambrian or Early Ordovician ages. Some species of *Cordylodus* in the Stora Backor sample may be reworked, and thus provide no stratigraphic information about the range of the genus or its species.

### Conclusions

This study has distinguished four species of *Cordylodus*, all with biapical basal cavities. Three of these species have been recovered from samples of the Ninmaroo Formation in the Georgina Basin of Australia. Two species, *C. prolindstromi* and *C. lindstromi*, are distinguished by the degree of development of the secondary apex of the basal cavity, as well as other morphological characteristics. In the Ninmaroo Formation, *C. prolindstromi* occurs stratigraphically below *C. lindstromi*. *C. lindstromi* probably therefore evolved from *C. prolindstromi* with the modification of the second basal cavity apex from flat to pointed.

Evidence of the possible evolution of *C. lindstromi* from *C. prolindstromi* makes the FAD of the former a closely controlled datum that might be the appropriate level for the Cambrian–Ordovician boundary. However, this relationship would have to be documented in other sections to be acceptable.

The third species, *C. sp. nov. B*, appears to have evolved from *C. lindstromi* as the elements become very laterally compressed.



The relationship of *C. prion* to *C. lindstromi* will have to be determined in sections in Europe and North America, rather than in Australia, where the former species has not been recorded.

## Taxonomy

### *Cordylodus* Pander, 1856

**Type species.** *Cordylodus angulatus* Pander, 1856

**Diagnosis (emended).** Septimembrate apparatus of ramiform elements. The element types M, Sa, Sc, Sb, Sd, Pb and Pa are distinguished. The upper portion of the cusp is composed of white matter. The S and P elements have a denticulate posterior process, and the M element a lateral process, which may or may not be denticulate. Extent of penetration of the basal cavity into cusp highly variable and species-dependent. Some species may have two apices to the basal cavity (biapical), with the primary apex extending into the cusp and the secondary apex into first denticle of the posterior process. Occasional elements may have more than two basal cavity apices, with apices extending into several denticles along the posterior process (Andres, 1988). Short adentate lateral processes may be found on some elements of some species. Element surface smooth, lacking micro-ornamentation, but some elements have carina or keels.

**Remarks.** Nicoll (1990) has recently examined the apparatus structure of the genus *Cordylodus* and the fauna examined in this study appears to confirm his observations.

***Cordylodus caboti*** Bagnoli, Barnes & Stevens, 1987  
Fig. 2.5

### Synonymy

- v. 1971 *Cordylodus oklahomensis* Müller; Druce & Jones, p. 69, pl. 5, figs 6,7, text-fig. 23j
- 1987 *Cordylodus caboti* n. sp.; Bagnoli, Barnes & Stevens, p. 152, pl. 1, figs 10–14
- 1987 *Cordylodus intermedius* Furnish; Bagnoli, Barnes & Stevens, pp. 153–154, pl. 1, figs 15–18
- v. 1990 *Cordylodus* sp. nov. A; Nicoll, pp. 552–554, fig. 23

**Remarks.** Nicoll (1990) indicated that his *Cordylodus* sp. nov. A might be assigned to *C. caboti*; additional material now confirms that assignment. Bagnoli & others (1987) believed that they could separate *C. caboti* and *C. intermedius*. Material examined from the Ninmaroo Formation indicates that these species should be considered as conspecific. Nicoll (1990) indicated that the type of *C. intermedius* Furnish (1938) is conspecific with *C. angulatus*. Much of the *Cordylodus* material from the *Hirsutodontus simplex* Zone that has previously been assigned to *C. intermedius* should therefore probably be assigned to *C. caboti*. The basal cavity of *C. caboti* has a single basal cavity apex.

**Distribution.** At Black Mountain: Jiggamore Member, Ninmaroo Formation, below 316 m (highest recovery sample BMA 115).

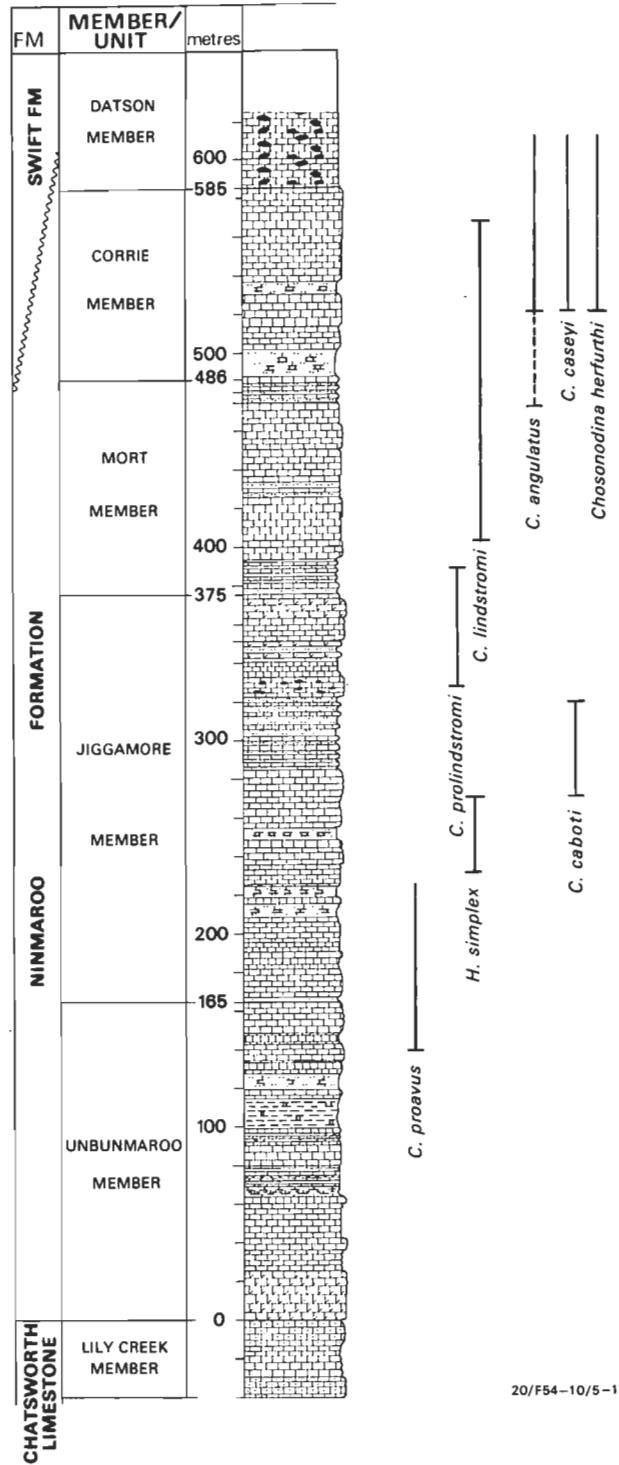
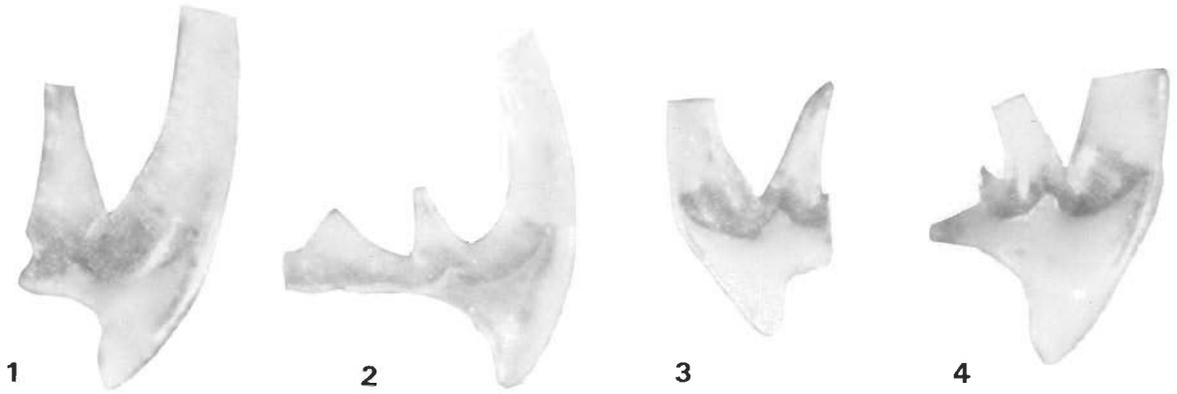


Figure 3. Stratigraphic distribution of selected conodont species in the Ninmaroo Formation section, Black Mountain, Georgina Basin, Queensland.

### Figure 2 (facing page). Evolution of the basal cavity shape in S elements of *Cordylodus*.

The sequence from *C. caboti* to *C. sp. nov. B* is documented in the Ninmaroo Formation at Black Mountain (Figure 3). *C. prion* has not been found in Australia and its precise relationship in the evolutionary sequence is not known. The A view sketches highlight the basal cavity outline and white matter distribution from the optical photographs of the B views. All figures are lateral views,  $\times 115$ .

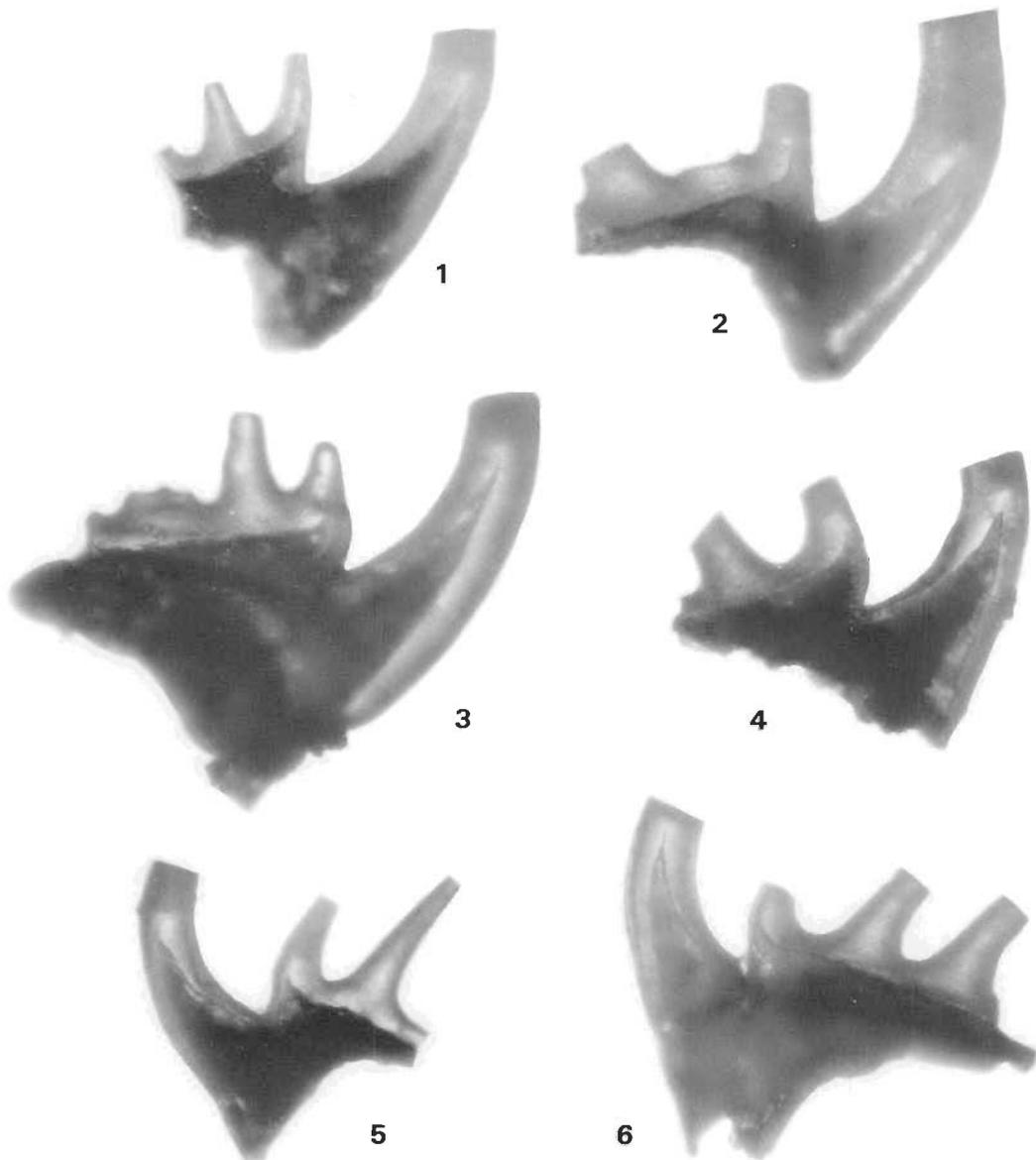
1. *C. sp. nov. B*, Sc element (CPC 23132)[GB90-002/96] right element.
2. *C. prion* Sd element (CPC23082)[JR8-26-82E] left element.
3. *C. lindstromi* Sc element (CPC 23074)[GB90-002/89] left element.
4. *C. prolindstromi* Sb element (CPC 23118)[GB90-002/6] right element.
5. *C. caboti* Sb element (CPC 23072)[BM-JHS-276m] right element.



**Figure 4. *Cordylodus lindstromi*; lateral views of S elements showing the shape of the basal cavity.**

The posterior process of the Sa, Sb and Sd elements is broken beyond the first denticle. All figures  $\times 125$ , except as noted.

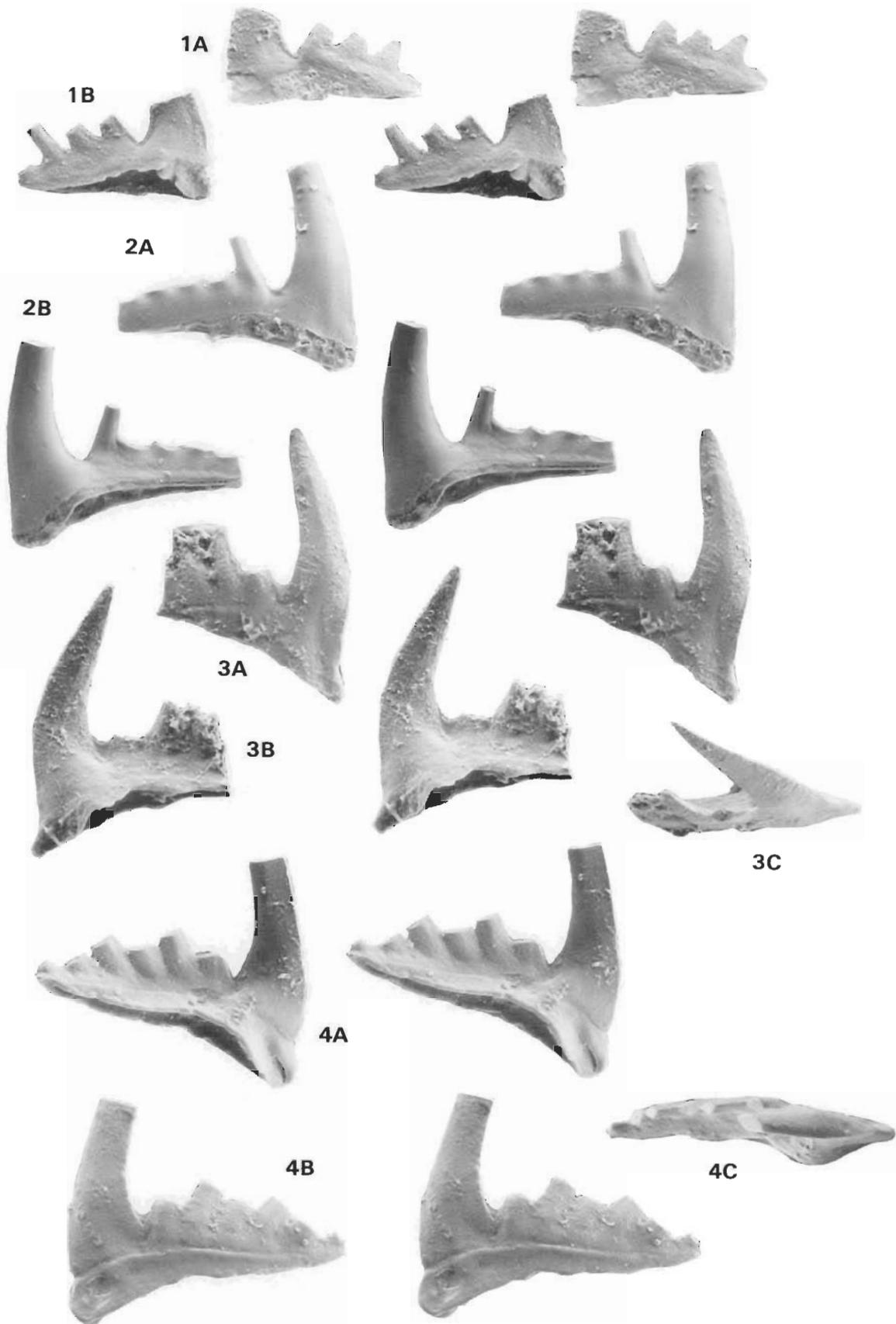
**1. Sa element** (CPC 23073)[GB90-002/61] symmetrical element. **2. Sc element** (CPC 23074)[GB90-002/89] left element, inner lateral view,  $\times 110$ . **3. Sb element** (CPC 23075)[GB90-002/61] left element, outer lateral view,  $\times 115$ . **4. Sd element** (CPC 23076)[GB90-002/61] right element, outer lateral view.



**Figure 5. *Cordylodus prion*; lateral views of S elements showing outline shape of dual tipped basal cavity.**

All figures  $\times 120$ .

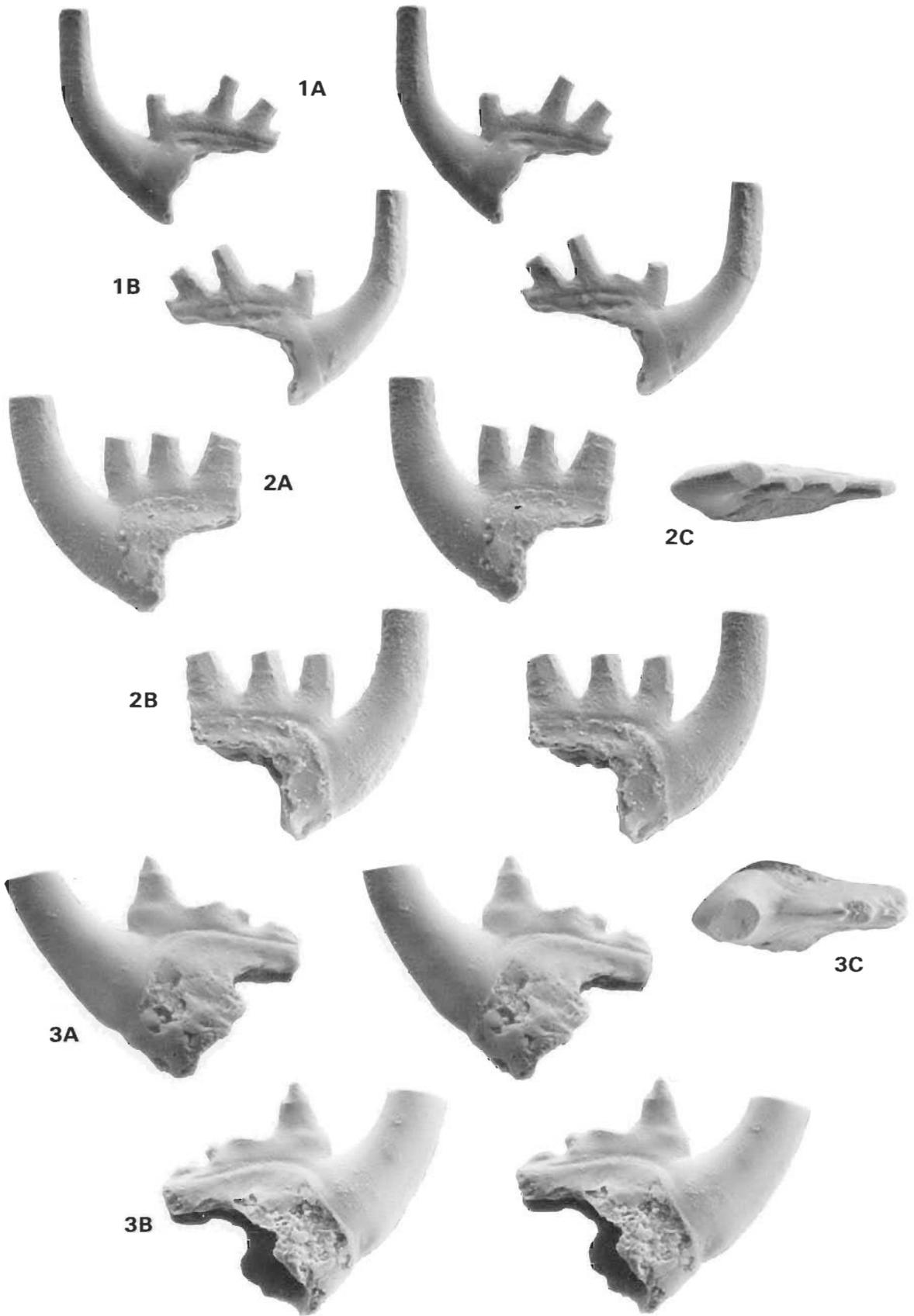
**1. Sa element** (CPC 23077)[JR8-26-82E] symmetrical element. **2. Sa element** (CPC 23078)[JR8-26-82E] symmetrical element. **3. Sb element** (CPC 23079)[JR8-26-82E] right element, outer lateral view. **4. Sc element** (CPC 23080)[JR8-26-82E] left element, inner lateral view. **5. Sd element** (CPC 23081)[JR8-26-82E] left element, outer lateral view. **6. Sd element** (CPC 23082)[JR8-26-82E] left element, outer lateral view.



**Figure 6.** *Cordylodus prion*; M elements.

All figures  $\times 65$ .

**1.** Left element (CPC 23083)[JR8-26-82E]; a, stereo pair, anterior view; b, stereo pair, posterior view. **2.** Right element (CPC 23084)[JR8-26-82E]; a, stereo pair, anterior view; b, stereo pair, posterior view. **3.** Right element (CPC 23085)[JR8-26-82E]; a, stereo pair, anterior view; b, stereo pair, posterior view; c, oral view. **4.** Left element (CPC 23086)[JR8-26-82E]; a, stereo pair, posterior view; b, stereo pair, anterior view; c, oral view.



**Figure 7.** *Cordylodus prion*; Sa elements.

All figures  $\times 65$ .

1. (CPC 23087)[JR8-26-82E]; a, stereo pair, left lateral view; b, stereo pair, right lateral view. 2. (CPC 23088)[JR8-26-82E]; a, stereo pair, left lateral view; b, stereo pair, right lateral view; c, oral view. 3. (CPC 23089)[JR8-26-82E]; a, stereo pair, left lateral view; b, stereo pair, right lateral view, c, oral view.

***Cordylodus lindstromi* Druce & Jones, 1971**  
 Figures 2.3, 2.4

**Synonymy.**

- v. 1971 *Cordylodus lindstromi* n. sp.; Druce & Jones, pp. 68–69, pl. 1, figs 7–9, pl. 2, fig. 8, text-fig. 23h. [Pl. 1, fig. 7 is an Sc element, fig. 8 is an Sc element, fig. 9 is a Pb element and pl. 2, fig. 8 is an Sd element]
- v. 1971 *Cordylodus prion* Lindström; Druce & Jones, p. 70, pl. 2, figs 1–7, text-figs. 23i, k-o. [Fig. 1 is a Pa element, figs 2–7 are M elements]
- 1980 *Cordylodus lindstromi* Druce & Jones; Miller, pp. 18–19, pl. 1, figs 18, 19, text-fig. 4l. [Fig. 18 is an S element and fig. 19 is a Pa element]
- 1980 *Cordylodus intermedius* Furnish; Miller, pp. 17–18, pl. 1, fig. 17 only. [P element]
- 1980 *Cordylodus angulatus* Pander; Miller, pp. 13–16, pl. 1, fig. 23 only. [P element]
- 1981 *Cordylodus caseyi* Druce & Jones; Ethington & Clark, pp. 31–32, pl. 2, fig. 25. [Sd element]
- v. 1990 *Cordylodus lindstromi* Druce & Jones; Nicoll, pp. 545–550, figs 3 (2a–c), 16–18.

**Material studied.** More than 600 elements.

**Diagnosis.** Septimembrate apparatus of ramiform elements with biapical basal cavity in the S elements and some of the P elements. In most elements the apex of the secondary basal cavity is pointed. The M element is makellate, the Sa element is alate and the remaining elements are dolobrate and asymmetrical. The first denticle of the posterior process is usually very close to the cusp and is frequently touching the posterior cusp margin. Larger elements frequently have a recessive basal margin.

**Remarks.** Nicoll (1990) re-examined *C. lindstromi* and the material recovered as part of this study does not modify those observations.

**Distribution.** At Black Mountain: Mort and Corrie Members, Ninmaroo Formation, 404–572 m (samples GB90-002/51 to 109).

***Cordylodus prion* Lindström, 1955**  
 Figures 2.2, 5–12

**Synonymy.**

- 1955 *Cordylodus prion* n. sp. Lindström, pp. 552–553, pl. 5, figs 14–16. [14 M element, 15 Pa element, 16 Sc element]
- 1988 *Cordylodus lindstromi* Druce & Jones; Barnes, p. 410, figs 13j–l, 14 c (only). [13j M element, 13k, l Sa element]
- 1988 *Cordylodus lindstromi* Druce & Jones; Andres, text-figs 36, 37

**Material studied.** 355 elements (M 22, Sa 42, Sc 116, Sb 88, Sd 44, Pb 30, Pa 13.)

**Diagnosis.** Septimembrate ramiform apparatus of M, S and P elements. The M element is makellate and denticulate, the Sa element is dolobrate and symmetrical and the Sc, Sb and Sd elements are dolobrate and asymmetrical. The Pb and Pa elements are dolobrate and asymmetrical. The lateral (M element) and posterior processes (S and P elements) are separated from the cusp by a notch and the secondary basal cavity apex is located under the first denticle of the process. All elements have the biapical cavity, but in thicker elements it may be difficult to observe and identification is based on the presence of the notch. The notch and biapical cavity are less prominent in the P elements than in the S elements. The

extension of the cavity under the posterior process is offset upward, above the level of the bottom of the notch between the cusp and the first process denticle.

**Description.** A septimembrate apparatus of *Cordylodus* in which the basal cavity of all elements has a secondary apex extending into the first denticle of the process. In the S elements the posterior process is separated from the cusp by a notch, and the connection of process to cusp is very narrow and weak. If not supported by the basal plate, the posterior process of elements of this species is frequently broken at this point. The extension of the basal cavity from the secondary apex along the underside of the process is higher (Fig. 2.2) than the bottom of the notch separating the process and cusp. This gives the impression of offsetting the posterior process upward. This factor, along with the delectate construction of the process, contributes to the breakage of the process from the cusp.

The Pa and Pb elements (Figs 11, 12) are dolobrate and the basal cavity opens downward with a groove extending posteriorly under the posterior process. In both elements the upper part of the cusp is inside the axial line of the posterior process. Denticles are laterally compressed and usually have sharp keels.

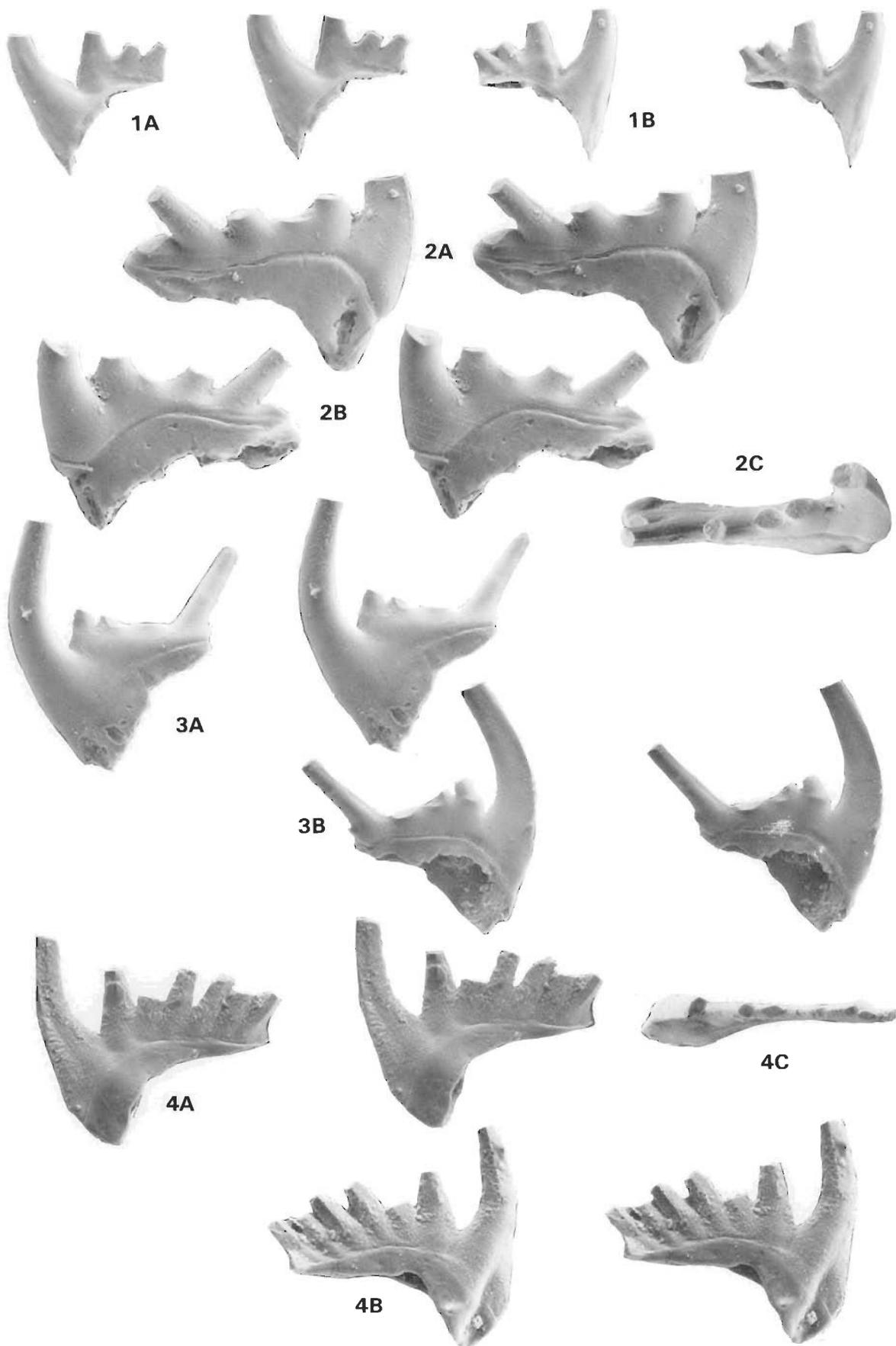
The Pa element is laterally compressed and the cusp is relatively longer, as a proportion of the total element length, than the cusp of the Pb element. The Pa element cusp is reclined; the denticles are also reclined and closely spaced. The keel on the anterior margin of the cusp terminates above the base and the anterobasal corner is rounded.

The Pb element has an erect cusp at the base, but is gently recurved posteriorly above the apex of the basal cavity. As in the Pa element, the anterior margin of the cusp may have a sharp keeled margin extending toward the anterobasal corner, but this keel stops above the base and the anterobasal margin is rounded. The process denticles of the Pb element are not usually as closely spaced as those of the Pa element, and they are usually taller and more erect.

The M element (Fig. 6) is makellate; the outer lateral process supports 6 or more denticles in large elements. The very short antiscup lacks denticles. The anterior margin of the base is essentially straight and the anterior side of the cusp is convex. The cusp is erect, recurved over the buttress, and slightly twisted. The notch between the cusp and the first process denticle is more prominent when viewed from the anterior side, but can also be seen from the posterior side. Process denticles are compressed with sharp keels along the axis of the process. They are appressed at the base but discrete a short distance above the process. Basal plates are well developed on many specimens. The basal cavity opens downward and is broad, extending under the process to the outer lateral tip.

The S elements are all similar, and differ mostly in section view. The posterior process supports 3–5 (occasionally 6 or 7) tall, discrete, laterally compressed denticles that may be fused at the base. The base of the process lacks height, and consists of a series of denticles, fused at their base, resting on the expansive basal plate. The basal cavity opens posteriorly, a feature accentuated by the well-preserved basal plates.

The Sa element is dolobrate and symmetrical; the other S elements are dolobrate and asymmetrical. The posterior process supports up to six discrete laterally compressed ovate denticles. The denticles are erect to recurved. The cusps are similar in lateral view and all extend anteriorly and curve upward.



The Sa element (Fig. 7) is symmetrical; the connection of cusp to process is very narrow. The posterior process is straight and supports up to 4 discrete, erect and laterally compressed denticles.

The Sc element (Fig. 8) is asymmetrical; the cusp has a flattened inner cusp face, a convex outer face and a relatively sharp anterior margin. The outer side of the cusp is convex. The cusp is slightly twisted and the upper part may be just outside the axial line of the process. The posterior process is either straight or slightly twisted.

The Sb element (Figs. 9.1, 9.2, 9.4) differs from the Sc element in having a cusp cross-section which is biconvex to rounded. The posterior process is bowed outward.

The Sd element (Figs 9.3, 10) is similar to the Sb element except for a carina on the inner margin of the cusp which extends the inner anterolateral basal margin of the cusp base below the comparable level of the outer anterolateral margin. The anterior face of the Sd element also tends to be flattened. The posterior process appears to be shorter than that of the Sb element.

**Remarks.** *Cordylodus prion* can be distinguished from *C. lindstromi* by the shape of the basal cavity, the presence of the notch between cusp and process and the greater length of the posterior process. The shapes of the basal cavity of the S elements of *C. caboti*, *C. prion*, *C. prolindstromi*, *C. lindstromi* and *C. sp. nov.* B are shown in Fig. 2. In *C. prion* the extension of the basal cavity under the posterior process is above the level of the low point of the cavity between cusp and first denticle. In *C. lindstromi* and *C. prolindstromi* the basal cavity extension is essentially at the same level as the low point. *C. prion* is the only species of this group to have a secondary cusp tip in the M element.

In *C. prion* the Sa element is dolabrate with a rounded anterior margin. In *C. prolindstromi* the Sa element is also usually rounded, but in some elements the anterior margin is flattened and the element thus appears to be tending toward an alate form. In *C. lindstromi* the Sa element is becoming obviously alate. Thus the dolabrate Sa element of *C. prion* is closer in morphology to *C. prolindstromi* than to *C. lindstromi*. It is possible that *C. prion* evolved directly from *C. prolindstromi*.

In *Cordylodus prion* the connection of the posterior process to the cusp is weak because the upward offset of the basal cavity has reduced the area of the lateral face of the process in contact with the base of the cusp. In *C. lindstromi* and *C. prolindstromi* the process-base cusp join is stronger and the posterior process of these elements is usually intact, or at least not broken between cusp and process.

Reconstruction of the apparatus of *C. prion* from the fauna of the Stora Backor sample was relatively easy. All elements of this species have a biapical cavity and it is the only species with a biapical cavity in the fauna. After all the biapical elements were segregated, the similarity of element type morphologies to those of other species of *Cordylodus* made it easier to sort the elements into element types (M, Sa, etc.).

The stratigraphic relationship of *C. prion* and *C. lindstromi* is not well defined because much of the literature has not

distinguished the two species. The species are not known to co-occur in Australia or Oklahoma (Miller & others, 1982). Both are found in Newfoundland (Barnes, 1988) low in the range of *C. lindstromi*. The material from Sweden may be reworked, and the association of *C. angulatus* and *C. prion* probably does not indicate true stratigraphic range.

### *Cordylodus prolindstromi* sp. nov.

Figures 2.4, 13-16

**Derivation of name.** *Pro.*, before; *lindstromi*, for *Cordylodus lindstromi*.

**Material studied.** 192 elements (M 52, Sa 18, Sc 49, Sb 31, Sd 31, Pb 6, Pa 5; Table 1)

**Diagnosis.** Septimembrate apparatus of ramiform elements with an imperfectly developed biapical basal cavity in the S elements and some of the P elements. The M element is makellate, the Sa element dolabrate or alate, and the rest of the elements dolabrate and asymmetrical. The first denticle of the posterior process is usually very close to the cusp and is frequently touching the posterior cusp margin.

**Description.** The P elements (Fig. 16) are dolabrate, asymmetrical and laterally compressed with rounded anterobasal margin. They have nearly straight posterior processes that have three or four denticles. The cusp of both Pa and Pb elements is straight rather than recurved as in the S elements. In the Pa element the cusp is twisted slightly inward from the plane of the denticles of the posterior process, but in the Pb element the cusp is not inwardly twisted and is in the same plane as the process denticles. The anterior and posterior margins of the cusp are keeled. The basal cavity is shallow, opens downward, and extends posteriorly under the posterior process. The P elements do not have a consistent or well developed secondary basal cavity apex. Some elements (Fig. 16.4) appear to have no hint of a secondary cavity apex. Other elements (Fig. 16.2) have only minor irregularities in the basal cavity in the area under the first process denticle, and some (Fig. 16.1, 16.3) have a distinct irregularity under the denticle, but not a well defined secondary apex.

**Table 1. Distribution of *Cordylodus prolindstromi* in the Nimmaroo Formation, Black Mountain, Queensland.**

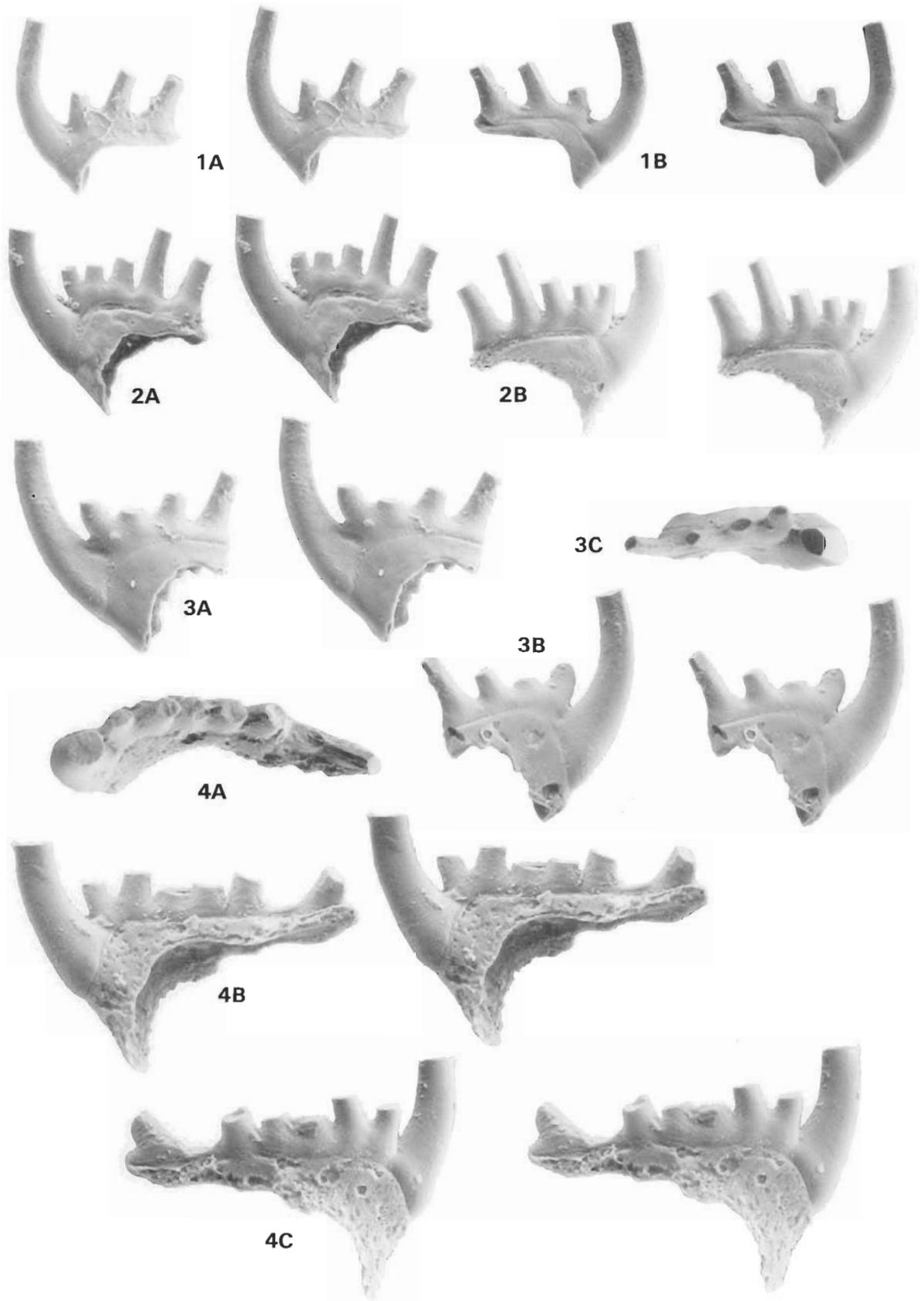
All samples are from section GB90-002, collected in September, 1990, by the author.

Sample	M	Sa	Sc	Sb	Sd	Pb	Pa
3	11	4	5	5	7	1	—
4	3	—	2	2	2	—	—
5	2	1	3	2	1	—	—
6	5	5	5	4	6	—	1
7	2	3	3	—	3	—	—
8	10	1	14	2	6	2	2
9	10	—	4	—	2	—	—
10	1	—	—	1	—	—	—
11	1	—	1	3	1	—	—
12	—	—	—	4	1	—	—
13	1	—	1	1	—	—	—
14	—	—	2	2	—	—	—
18	2	1	1	1	—	—	1
19	—	—	1	1	—	—	—
20	2	2	3	4	1	—	1
24	2	1	1	—	—	—	—
38	—	—	3	—	1	3	—
Total	52	18	49	31	31	6	5

**Figure 8 (facing page).** *Cordylodus prion*; Sc elements.

All figures  $\times 70$ .

1. **Right element** (CPC 23090)[JR8-26-82E]: a, stereo pair, inner lateral view; b, stereo pair, outer lateral view. 2. **Left element** (CPC 23091)[JR8-26-82E]: a, stereo pair, inner lateral view; b, stereo pair, outer lateral view; c, oral view. 3. **Left element** (CPC 23092)[JR8-26-82E]: a, stereo pair, outer lateral view; b, stereo pair, inner lateral view. 4. **Right element** (CPC 23093)[JR8-26-82E]: a, stereo pair, inner lateral view; b, stereo pair, outer lateral view; c, oral view.



**Figure 9.** *Cordylodus prion*; Sb and Sd elements.

All figures  $\times 70$ .

**1. Sb element** (CPC 23094)[JR8-26-82E] left element; **a**, stereo pair, outer lateral view; **b**, stereo pair, inner lateral view. **2. Sb element** (CPC 23095)[JR8-26-82E] right element; **a**, stereo pair, inner lateral view; **b**, stereo pair, outer lateral view. **3. Sd element** (CPC 23096)[JR8-26-82E] left element; **a**, stereo pair, outer lateral view; **b**, stereo pair, inner lateral view; **c**, oral view. **4. Sb element** (CPC 23097)[JR8-26-82E] right element; **a**, oral view; **b**, stereo pair, inner lateral view; **c**, stereo pair, outer lateral view.

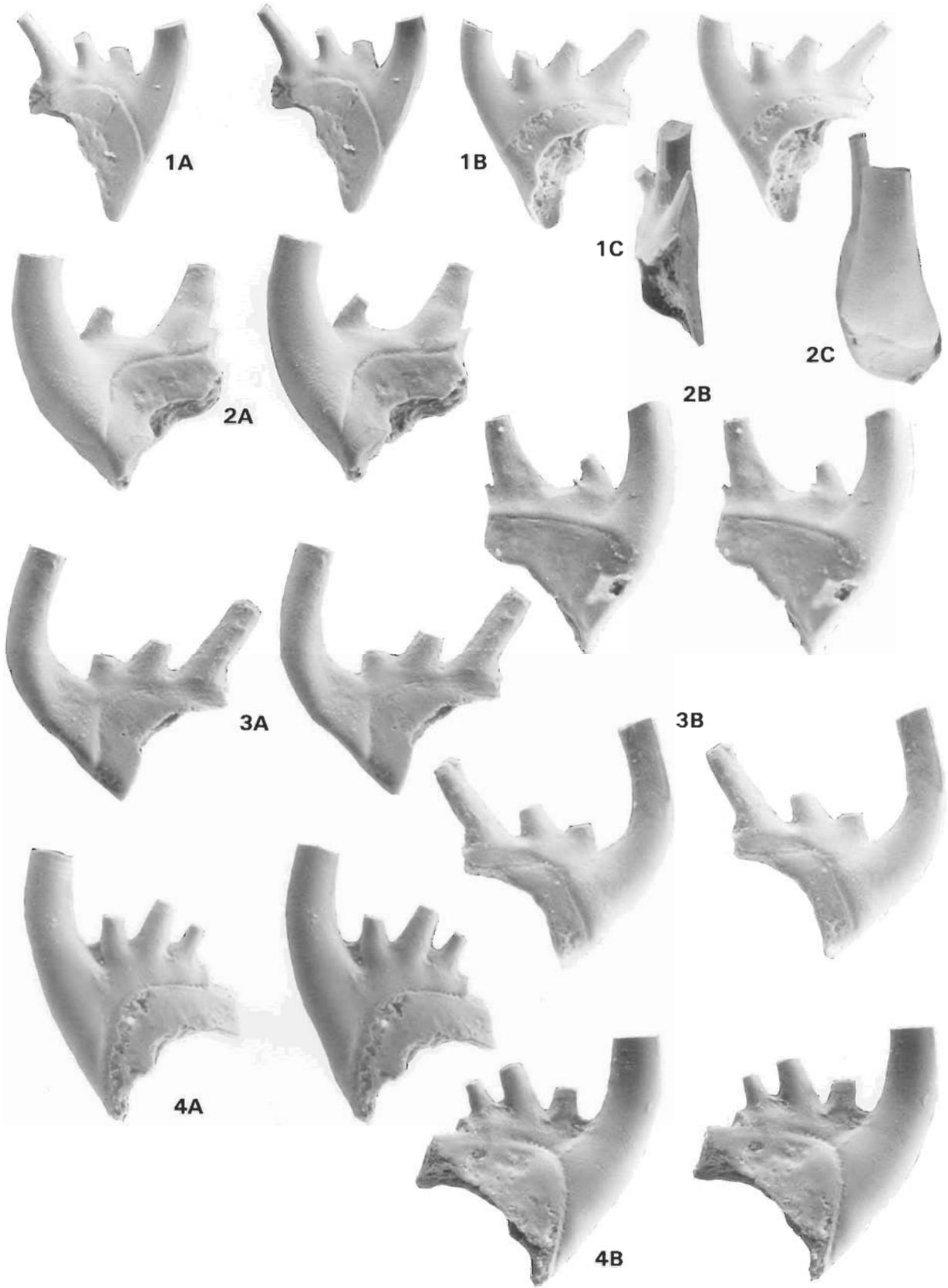
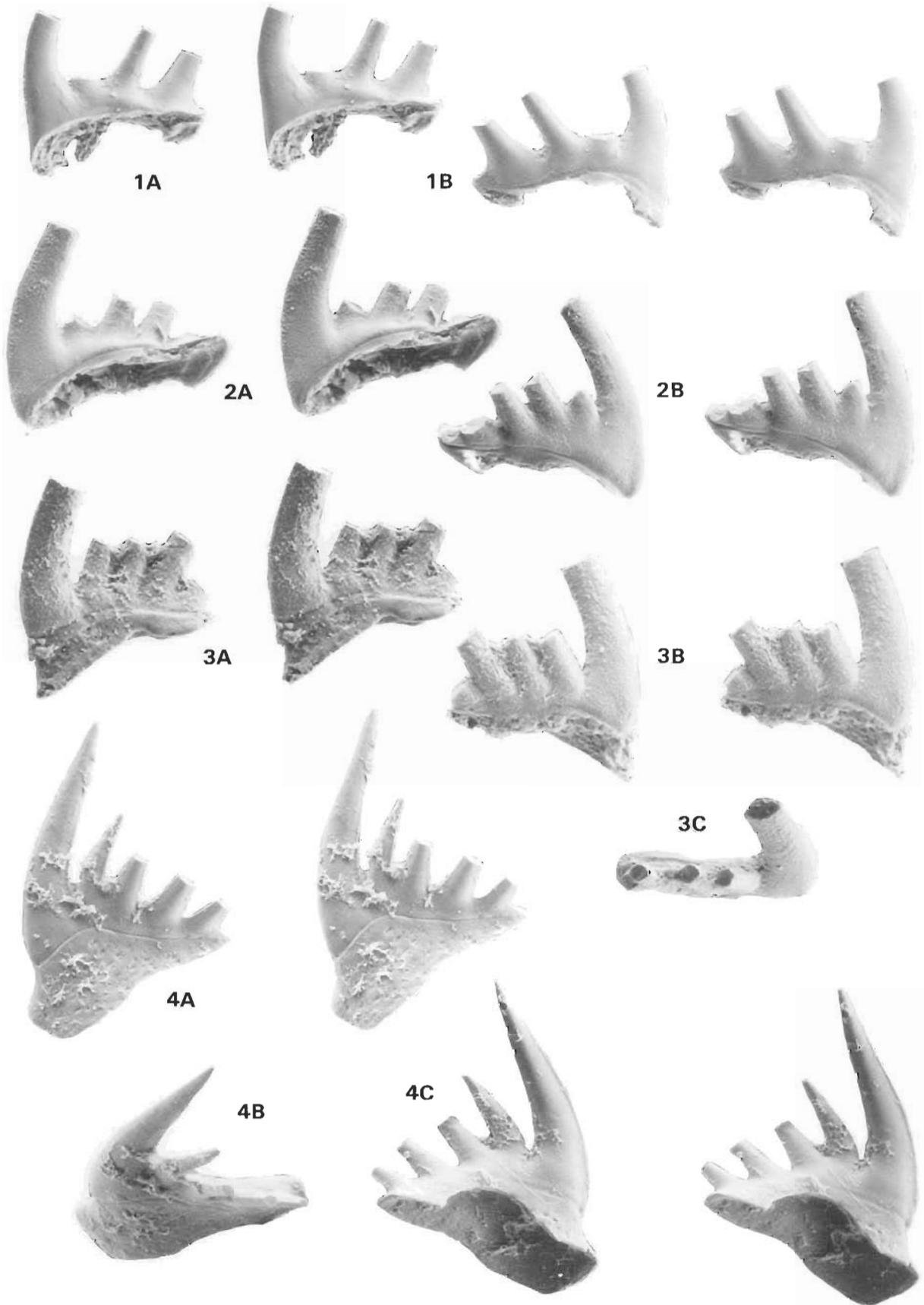


Figure 10. *Cordylodus prion*; Sd elements.

All figures  $\times 70$ .

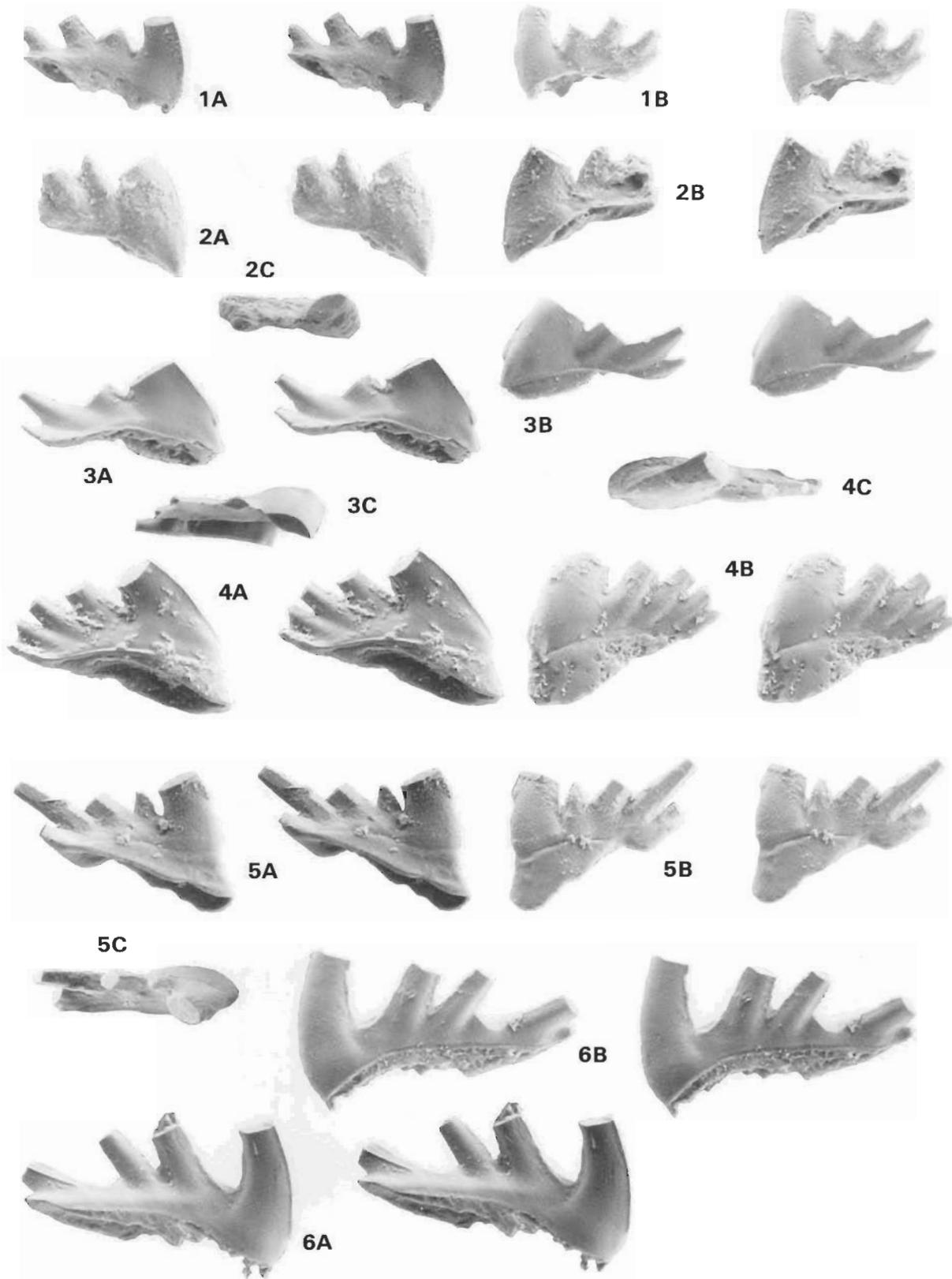
1. Left element (CPC 23098)[JR8-26-82E]; a, stereo pair, inner lateral view; b, stereo pair, outer lateral view; c, posterior view. 2. Right element (CPC 23099)[JR8-26-82E] a, stereo pair, outer lateral view; b, stereo pair, inner lateral view; c, anterior view. 3. Right element (CPC 23100)[JR8-26-82E]; a, stereo pair, inner lateral view; b, stereo pair, outer lateral view. 4. Left element (CPC 23101)[JR8-26-82E]; a, stereo pair, outer lateral view; b, stereo pair, inner lateral view.



**Figure 11.** *Cordylodus prion*; Pb elements.

All figures  $\times 70$ .

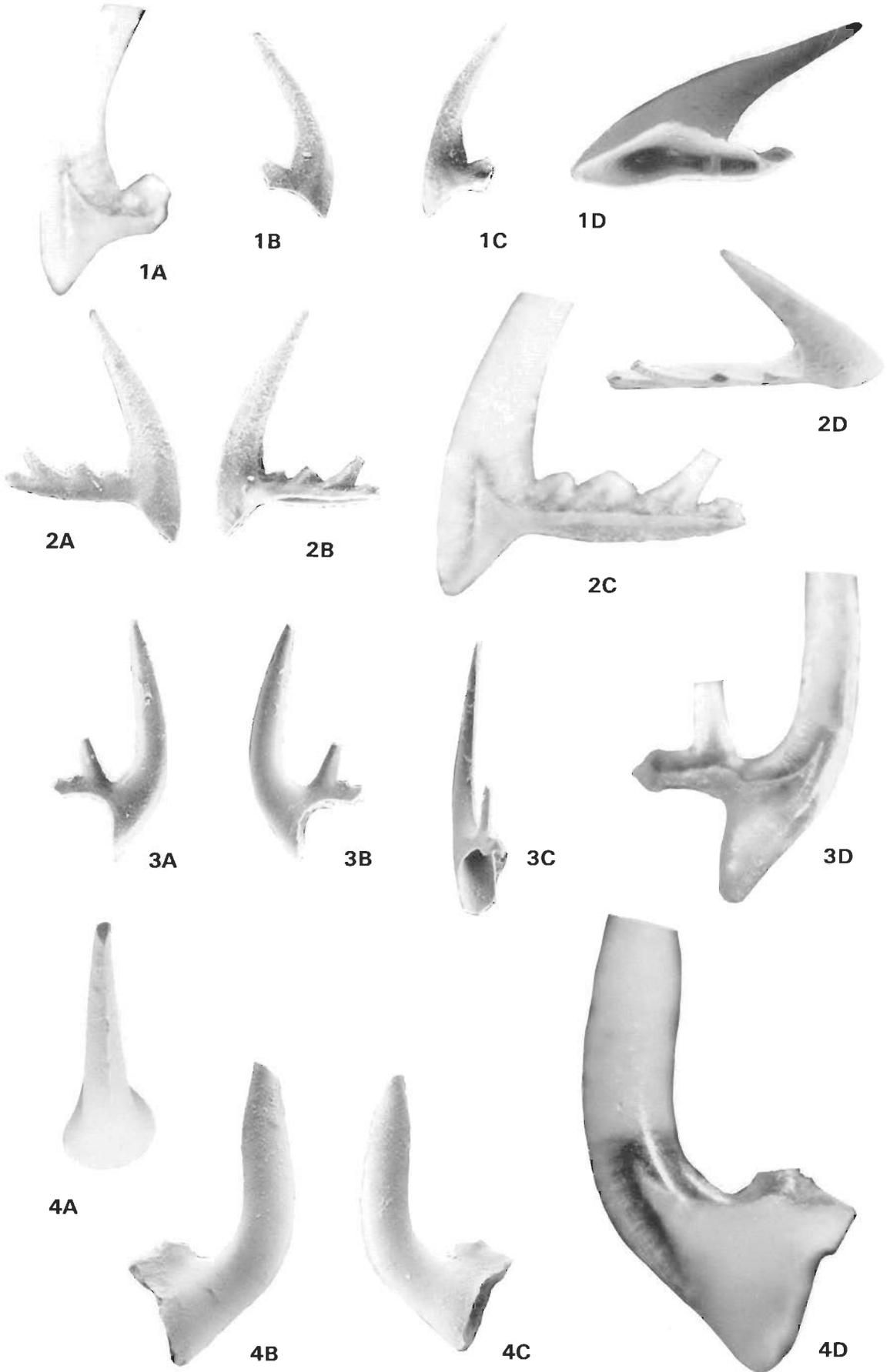
**1. Right element** (CPC 23102)[JR8-26-82E] : a, stereo pair, inner lateral view; b, stereo pair, outer lateral view. **2. Right element** (CPC 23103)[JR8-26-82E] a, stereo pair, inner lateral view; b, stereo pair, outer lateral view. **3. Right element** (CPC 23104)[JR8-26-82E]; a, stereo pair, inner lateral view; b, stereo pair, outer lateral view; c, oral view. **4. Left element** (CPC 23105)[JR8-26-82E]; a, stereo pair, outer lateral view; b, oral view; c, stereo pair, inner lateral view.



**Figure 12.** *Cordylodus prion*; Pa and Pb elements.

All figures  $\times 70$ .

**1. Pb element** (CPC 23106)[JR8-26-82E] left element; **a**, stereo pair, inner lateral view; **b**, stereo pair, outer lateral view. **2. Pa element** (CPC 23107)[JR8-26-82E] right element; **a**, stereo pair, outer lateral view; **b**, stereo pair, inner lateral view; **c**, oral view. **3. Pa element** (CPC 23108) left element; **a**, stereo pair, inner lateral view; **b**, stereo pair, outer lateral view; **c**, oral view. **4. Pa element** (CPC 23109)[JR8-26-82E] left element; **a**, stereo pair, inner lateral view; **b**, stereo pair, outer lateral view; **c**, oral view. **5. Pb element** (CPC 23110) left element; **a**, inner lateral view; **b**, stereo pair, outer lateral view, **c**, oral view. **6. Pb element** (CPC 23111)[JR8-26-82E] left element; **a**, stereo pair, inner lateral view; **b**, stereo pair, outer lateral view.



The M element (Fig. 13) is makellate and has an erect, antero-posteriorly compressed cusp with a buttress on the posterior face, and a denticulate outer-lateral process. The process supports four to six triangular denticles that are appressed at the base. The cusp is slightly recurved posteriorly over the buttress. The M element has only a single basal cavity apex.

The S elements have erect to recurved cusps composed of white matter extending down to the apex of the basal cavity. The apex of the primary basal cavity is central in some elements and close to the anterior margin in others. The secondary basal cavity is located under the first denticle of the posterior process; its shape and degree of development are variable. The basal cavity opens posteriorly and downward with a groove extending under the posterior process. The cusp is laterally compressed with a sharp margin or keel on both anterior and posterior margins where the cusp is composed of white matter. Process denticles are laterally compressed with sharp margins.

The Sa element (Fig. 13) is dolabrate, becoming alate in some elements, and bilaterally symmetrical with a short denticulate posterior process and laterally compressed cusp that has keels on both the anterior and posterior margins. The keel of the anterior margin disappears toward the base and the anterobasal margin is rounded.

The Sc element (Fig. 14) is dolabrate and asymmetrical with the inner side flattened and the outer side convex. The inner anterior edge is only slightly thickened and the anterior margin is sharp. The Sb element (Fig. 14) is dolabrate and similar to the Sc element except that it is biconvex with a rounded lower anterior margin.

The Sd element (Fig. 15) is dolabrate and asymmetrical with a convex outer side and a slightly concave inner side. The inner lateral rim near the anterior margin is sharp in juvenile forms, but becomes rounded and more prominent in older specimens. The posterior process is bent slightly inward after the first process denticle.

**Remarks.** *Cordylodus prolindstromi* can be distinguished from *C. lindstromi* by a number of morphological characters. In *C. prolindstromi* the second apex of the basal cavity is usually truncated, frequently with a flat top, while in *C. lindstromi* the second cavity apex is usually pointed. In *C. prolindstromi* the anterior margin of the Sa element is rounded, but in *C. lindstromi* it is flattened, especially toward the base. The Sd element of *C. lindstromi* has the posterior process bent strongly inward, but in *C. prolindstromi* the posterior process is only slightly bent. In the material examined, no elements of *C. prolindstromi* have recessive basal margins, a feature observed in some larger elements of *C. lindstromi*.

**Distribution.** At Black Mountain: Jiggamore and lower part Mort Members, Ninmaroo Formation, 331–385 m (samples GB90-002/3 to 43).

*Cordylodus* sp. nov. B  
Figures 2.1, 17–18

**Material studied.** 8 elements (M 2, Sa 1, Sc 2, Sb? 2, P 1)

**Diagnosis.** Multimembrate ramiform apparatus of gracile, laterally compressed elements. Probable septimembrate apparatus with 5 element types (M, Sa, Sc, Sb or Sd, and P) recognised in this study. The S elements have a biapical basal cavity.

**Description.** The single P element recovered (Fig. 18.3) is dolabrate, asymmetrical and laterally compressed, and is dominated by a tall triangular cusp with a low carina on the inner face that extends toward the basal margin. The anterior and posterior margins are sharp with a posterior process that is broken, but which has two preserved denticles. The basal outline is biconvex; the basal cavity has a single apex extending into the cusp and a shallow channel extending posteriorly under the process. The element illustrated is probably a Pb element because the cusp and process denticles are in the same plane, but without more material Pa and Pb elements cannot be safely differentiated.

The M element (Fig 17.1, 2) is makellate, anteriorly-posteriorly compressed with a flat anterior face and a very small buttress on the posterior face. The outer lateral process supports at least two denticles that are laterally appressed at the base with sharp margins. The basal cavity has a single apex extending into the cusp to the base of the white matter, about one quarter to one third of the height of the cusp.

The S elements, like the M and P elements, are compressed. They have a low, but prominent, secondary cavity apex. The primary basal cavity apex terminates near the anterior margin of the element. The Sa element (Fig. 17.3) is dolabrate, trending toward being alate, symmetrical, and has a flattened anterior margin with sharp lateral edges. There is at least one denticle on the posterior process.

The Sc element (Fig. 17.4,5) is dolabrate and asymmetrical. The outer face is convex with a rounded outer lateral margin. The inner face is flat and the inner antero-lateral margin is sharp. The antero-basal area is large and points downward, almost like the anticusp of an M element. There is at least one laterally compressed denticle on the posterior process.

The remaining element (Fig. 18.2,3) is probably an Sb element, or, less likely, an Sd element. The anterior margin appears rounded, a characteristic feature of the Sb element. The element is dolabrate, biconvex and asymmetrical in cross-section with the anterior margin bent inward.

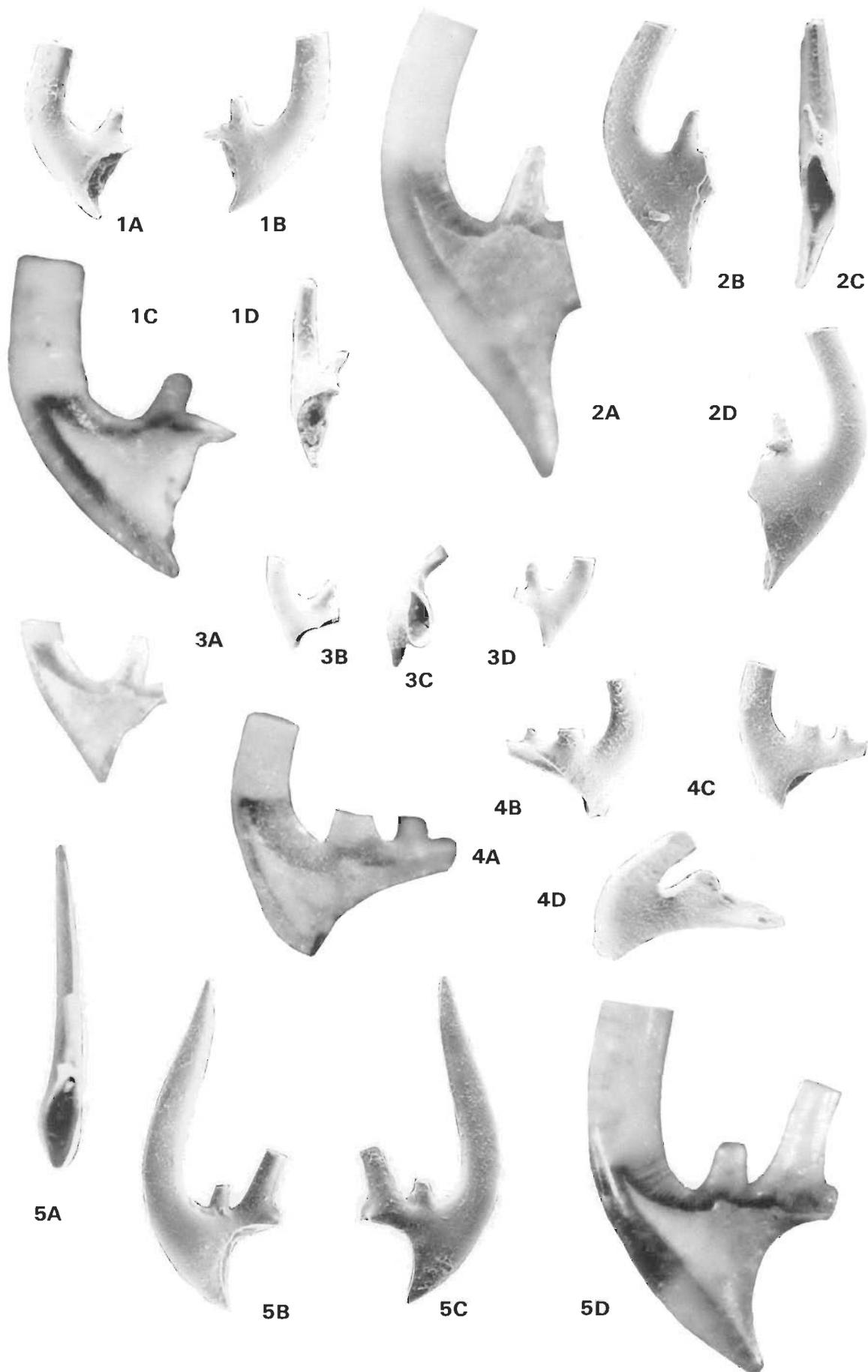
**Remarks.** Too few elements of *Cordylodus* sp. nov. B have been recovered to describe this species accurately or fully. The eight elements from sample GB90-002/96 can be assigned to five element types. However, all of the elements are markedly laterally compressed, much more so than the S elements of *C. angulatus*. The S elements also have a biapical basal cavity. On these two characters alone, elements assigned to *C. sp. nov. B* should be easily differentiated from other species of *Cordylodus*. The large triangular (in lateral view) cusp of the P element could have been derived from an elongation of the cusp of *C. lindstromi*.

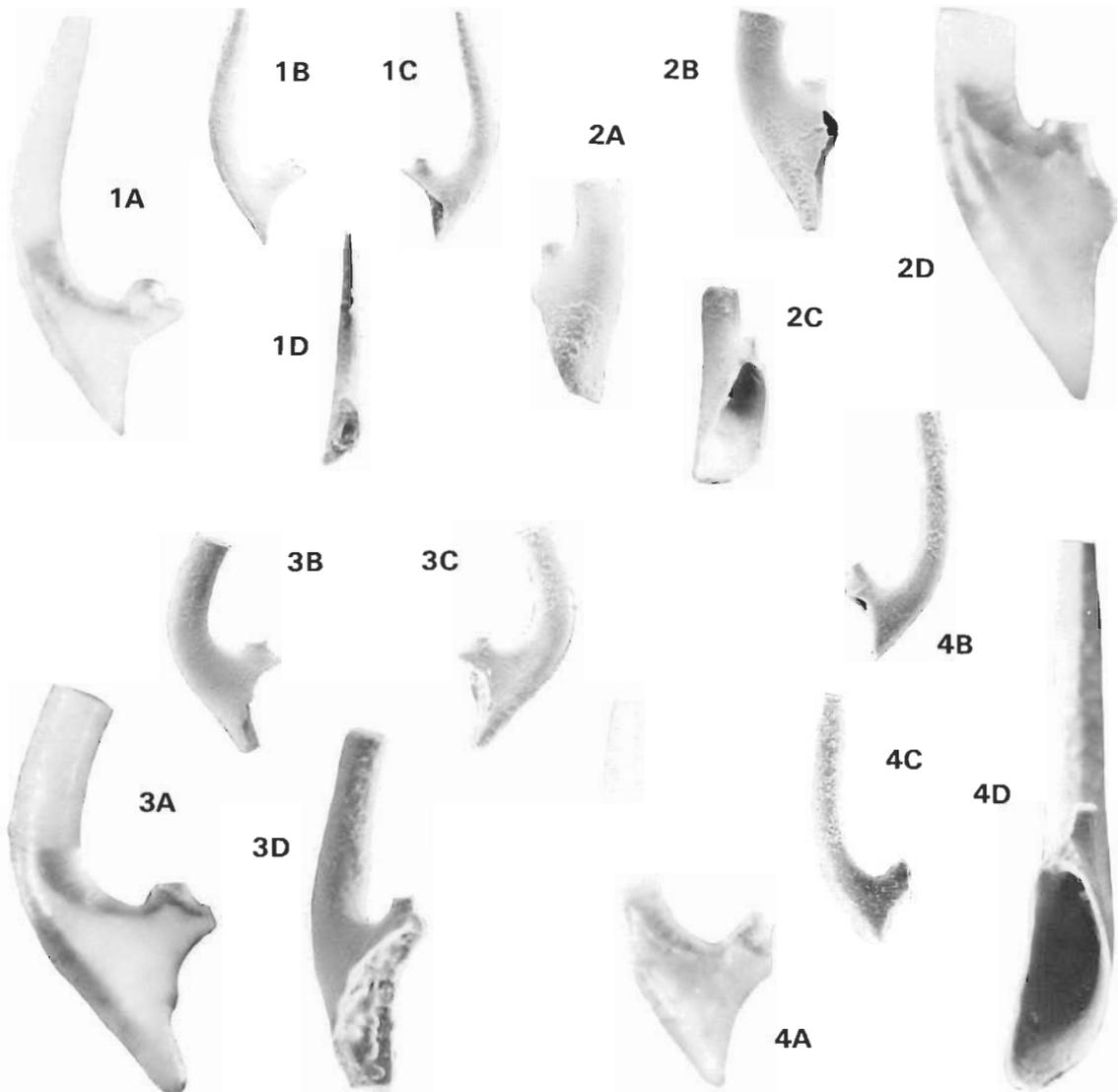
**Distribution.** At Black Mountain: lower part of the Corrie Member, Ninmaroo Formation, 495.8 m (sample GB90-002/96).

**Figure 13 (facing page).** *Cordylodus prolindstromi*; M and Sa elements.

All figures  $\times 70$ , except as noted.

1. M element (paratype CPC 23112)[GB90-002/9] right element; a, posterior view to show basal cavity outline ( $\times 120$ ); b, anterior view; c, posterior view; d, basal view ( $\times 170$ ). 2. M element (paratype CPC 23113)[GB90-002/9] right element; a, anterior view; b, posterior view; c, posterior view showing outline of the basal cavity ( $\times 120$ ); d, oral view ( $\times 110$ ). 3. Sa element (holotype CPC 23114)[GB90-002/20] symmetrical element; a, right lateral view; b, left lateral view; c, posterior view; d, right lateral view showing basal cavity outline ( $\times 115$ ). 4. Sa element (paratype CPC 23115)[GB90-002/6] symmetrical element; a, anterior view; b, right lateral view; c, left lateral view; d, left lateral view showing outline of basal cavity ( $\times 140$ ).





**Figure 15.** *Cordylodus prolindstromi*; Sd elements.

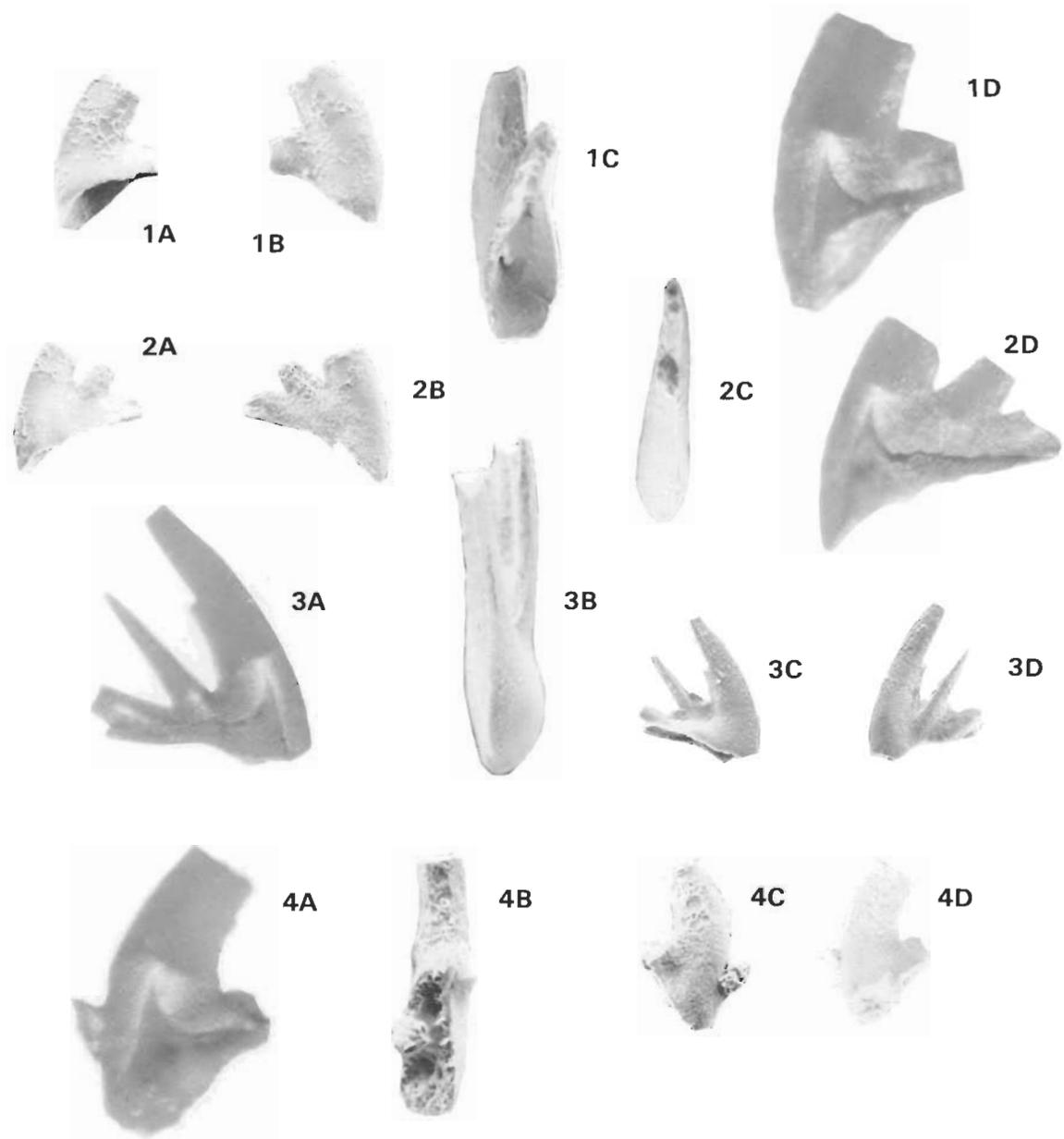
All figures  $\times 70$ , except as noted.

**1. Right element** (paratype CPC 23121)[GB90-002/9]; **a**, inner lateral view showing basal cavity outline ( $\times 120$ ); **b**, inner lateral view; **c**, outer lateral view; **d**, posterior view. **2. Right element** (paratype CPC 23122)[GB90-002/8]; **a**, outer lateral view; **b**, inner lateral view; **c**, posterior view; **d**, inner lateral view showing basal cavity outline ( $\times 125$ ). **3. Left element** (paratype CPC 23123)[GB90-002/6]; **a**, outer lateral view showing basal cavity outline; **b**, outer lateral view; **c**, inner lateral view ( $\times 120$ ); **d**, posterior view ( $\times 120$ ). **4. Right element** (paratype CPC 23124)[GB90-002/3]; **a**, inner lateral view showing basal cavity outline ( $\times 125$ ); **b**, outer lateral view; **c**, inner lateral view; **d**, posterior view ( $\times 195$ ).

**Figure 14 (facing page).** *Cordylodus prolindstromi*; Sc and Sb elements.

All figures  $\times 75$ , except as noted.

**1. Sc element** (paratype CPC 23116)[GB90-002/20] left element,  $\times 65$ ; **a**, outer lateral view; **b**, inner lateral view; **c**, outer lateral view showing basal cavity outline ( $\times 115$ ); **d**, posterior view. **2. Sc element** (paratype CPC 23117)[GB90-002/20] right element,  $\times 65$ ; **a**, inner lateral view showing basal cavity outline ( $\times 120$ ); **b**, inner lateral view; **c**, posterior view; **d**, outer lateral view. **3. Sb element** (paratype CPC 23118)[GB90-002/3] right element; **a**, inner lateral view showing outline of basal cavity ( $\times 135$ ); **b**, inner lateral view; **c**, basal view; **d**, outer lateral view. **4. Sb element** (paratype CPC 23119)[GB90-002/6] right element; **a**, inner lateral view showing basal cavity outline ( $\times 130$ ); **b**, outer lateral view; **c**, inner lateral view; **d**, oblique oral view. **5. Sb element** (paratype CPC 23120)[GB90-002/20] right element; **a**, posterior view; **b**, inner lateral view; **c**, outer lateral view; **d**, inner lateral view showing basal cavity outline ( $\times 130$ ).



**Figure 16.** *Cordylodus prolindstromi*; Pb and Pa elements.

All figures  $\times 70$ , except as noted.

**1. Pb element** (paratype CPC 23125)[GB90-002/3] right element; **a**, inner lateral view; **b**, outer lateral view; **c**, basal view ( $\times 110$ ); **d**, inner lateral view showing basal cavity outline ( $\times 110$ ). **2. Pb element** (paratype CPC 23126)[GB90-002/38] right element; **a**, inner lateral view; **b**, outer lateral view; **c**, oral view ( $\times 125$ ); **d**, inner lateral view showing basal cavity outline ( $\times 125$ ). **3. Pa element** (paratype CPC 23127)[GB90-002/6] left element; **a**, inner lateral view showing basal cavity outline ( $\times 135$ ); **b**, oral view ( $\times 210$ ); **c**, inner lateral view; **d**, outer lateral view. **4. Pa element** (paratype CPC 23128)[GB90-220/8] right element; **a**, inner lateral view showing basal cavity outline ( $\times 110$ ); **b**, basal view (110); **c**, outer lateral view; **d**, inner lateral view.

### Locality information

The samples for this study were collected from the line of the Radke (1981) measured section of the Ninmaroo Formation on Black Mountain (Unbunmaroo). This corresponds approximately to the measured section of Druce & Jones (1971) at Black Mountain. For locality details see Druce & Jones (1971), Radke (1981) or Nicoll & Shergold (1991).

### Acknowledgements

This paper was critically reviewed by Barry J. Cooper (South Australian Department of Industry, Trade and Technology) and

Arne T. Nielsen (University of Copenhagen). Barry Cooper proposed the term biapical to describe the basal cavity with two apices. The author wishes to thank John Repetski for providing the Stora Backor sample and for discussions concerning matters raised by this investigation. Photography was the work of Arthur T. Wilson. Material illustrated is deposited in the Commonwealth Palaeontological Collection (CPC) at the Bureau of Mineral Resources, Canberra.

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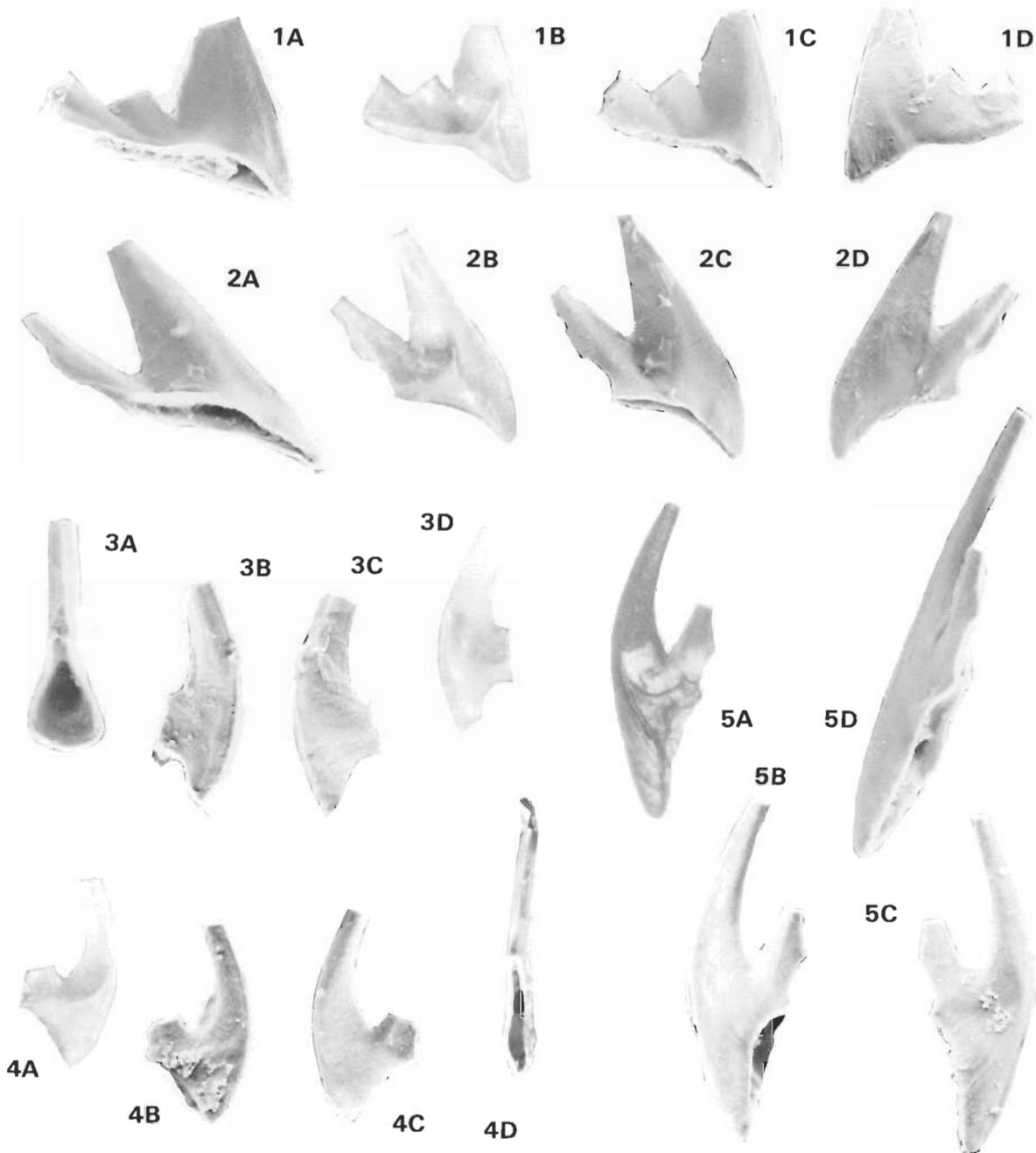


Figure 17. *Cordylodus* sp. nov. B; M, Sa and Sc elements.

All figures  $\times 140$ , except as noted.

1. M element (CPC 23129)[GB90-002/96] left element; a, oblique posterior view ( $\times 175$ ); b, posterior lateral view showing basal cavity outline ( $\times 120$ ); c, posterior view; d, anterior view. 2. M element (CPC 23130)[GB90-002/96] left element; a, oblique posterior view showing basal cavity outline ( $\times 205$ ); b, posterior view showing basal cavity outline ( $\times 125$ ); c, posterior view; d, anterior view. 3. Sa element (CPC 23131)[GB90-002/96] symmetrical element; a, posterior view; b, right lateral view; c, left lateral view; d, left lateral view showing basal cavity outline ( $\times 130$ ). 4. Sc element (CPC 23132)[GB90-002/96] left element; a, inner lateral view showing basal cavity outline ( $\times 130$ ); b, inner lateral view; c, outer lateral view; d, posterior view ( $\times 170$ ). 5. Sc element (CPC 23133)[GB90-002/96] right element; a, inner lateral view showing basal cavity outline; b, inner lateral view; c, outer lateral view; d, oblique posterior view ( $\times 190$ ).

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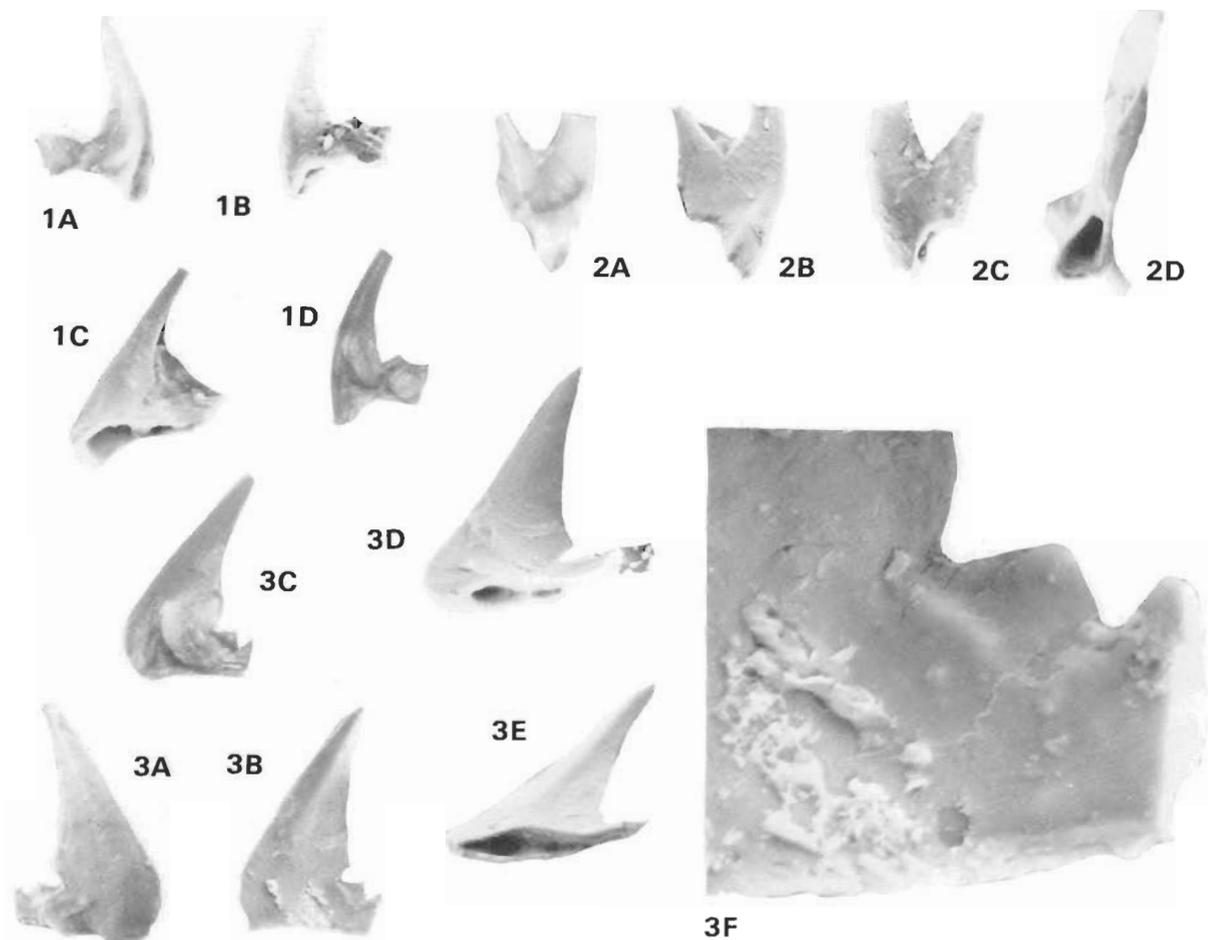


Figure 18. *Cordylodus* sp. nov. B; S and P elements.

All figures  $\times 140$ , except as noted.

1. S (Sb or Sd) element (CPC 23134)[GB90-002/96] right element: a, outer lateral view; b, inner lateral view; c, oblique basal view ( $\times 170$ ); d, inner lateral view showing basal cavity outline ( $\times 110$ ). 2. S (Sb or Sd) element (CPC 23135)[GB90-002/96] right element: a, outer lateral view showing basal cavity outline ( $\times 120$ ); b, outer lateral view; c, inner lateral view; d, posterior view ( $\times 200$ ). 3. P (Pb or Pa) element (CPC 23136)[GB90-002/96] right element: a, outer lateral view; b, inner lateral view; c, inner lateral view showing basal cavity outline ( $\times 120$ ); d, oblique lateral view ( $\times 220$ ); e, oblique basal view ( $\times 220$ ); f, enlargement of inner lateral view of posterior process showing compressed posterior process and denticles ( $\times 650$ ).

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# Ammonites of the Cretaceous Ieru Formation, western Papua New Guinea

Tatsuro Matsumoto<sup>1</sup> & S.K. Skwarko<sup>2</sup>

Eleven ammonite species from five localities in the Ieru Formation, western Papua New Guinea, are described. Four are identified with the well known and widely distributed Cenomanian species of the Acanthoceratidae, *Calycocheras* (*Newboldiceras*) *newboldi* (Kossmat), *C. (N.) cf. orientale* Matsumoto & others, *C. (N.) annulatum* Collignon and *Acanthoceras rhotomagense* (Brongniart). Other Cenomanian taxa are three indeterminable acanthoceratid species, *C. (Calycocheras) sp.*

*nov. (?)*, *Calycocheras* subgenus et sp. indet., and *Acanthoceras* sp. indet., as well as *Pachydesmoceras* sp. nov. and *Chimbuites* aff. *mirindowensis* Wright. The Turonian species *Romaniceras deverioides* (de Grossouvre) was found with *Placenticeras* aff. *tamulicum* (Blanford); several fragments, probably from the Star Mountains, are also referred to *P. aff. tamulicum*.

## Introduction

In this paper we describe eleven ammonite taxa from the Cretaceous Ieru Formation, which crops out widely in the Ok Tedi 1:250 000 Sheet area, Blucher Range, western Papua New Guinea. The area was mapped in 1971, mostly by geologists of the Australian Bureau of Mineral Resources, Geology & Geophysics (BMR), and was visited in 1976 by geologists of the Papua New Guinea Geological Survey. One of the authors (SKS) began descriptions of fossils collected on these occasions, at the BMR in Canberra; the other subsequently contributed to the work.

The ammonites came from a rugged, mountainous, jungle-covered region. The material is insufficient for both taxonomic and biostratigraphic purposes, and inadequate for the resolution of palaeogeographic problems. However, given the poor knowledge of Cretaceous macrofossils from Papua New Guinea, we believe the collections are worthy of description. Few Cretaceous ammonites have been described from Papua New Guinea; this paper may provide incentive for further palaeontological studies there.

## Stratigraphy

A (Middle Jurassic–Paleocene) fossiliferous group of strata is distributed extensively along the central mountains backbone of the island of New Guinea. The Ieru Formation is the youngest unit of this group. It was defined by Davies & Norvick (1974; 1977), and informally subdivided into six units on the basis of work outside the Ok Tedi Sheet area (Findlay & Leckie, 1973; White & others, 1973).

In the Ok Tedi Sheet area the Ieru Formation consists of 1300–1500 m of bioturbated, fine, glauconitic quartzose sandstone and siltstone with recessive glauconitic mudstone and siltstone. It has abundant large cone-in-cone structures developed in intervals of fine sandstone and siltstone in mid-section and at the top. It is mainly of Albian–Maastrichtian age, conformable on the Neocomian–Albian Toro Sandstone, and is disconformably overlain by the Eocene–Miocene Darai Limestone. The formation passes laterally into the undivided Feing Group in the north, and into Kembelangan Formation in Irian Jaya in the west. It is widespread in the south, east, and southeast of the Sheet area (Skwarko, 1978).

## Localities

The Ieru Formation ammonites described in this paper were obtained at five localities within the Ok Tedi 1:250 000 Sheet

area (Fig. 1); their positions cannot be precisely established. They are held in the Commonwealth Palaeontological Collections (CPC), BMR, Canberra. Plaster casts of them are kept in the Geological Collections (GK), Kyushu University, Fukuoka, Japan.

The ammonites from Papua New Guinea Ieru Formation described in this paper are:

**Locality 13:** *Placenticeras* aff. *tamulicum* (Blanford), *Romaniceras deverioides* (de Grossouvre);

**Locality 47:** *Acanthoceras rhotomagense* (Brongniart);

**Locality 167:** *Calycocheras* (*Newboldiceras*) *newboldi* (Kossmat), *Calycocheras* (*Calycocheras*) sp. nov. (?), *Calycocheras* subgenus & sp. indet., *Acanthoceras* sp. indet.;

**Locality 187:** *Pachydesmoceras* sp. nov., *Chimbuites* aff. *mirindowensis* Wright, *Calycocheras* (*Newboldiceras*) *newboldi* (Kossmat), *Calycocheras* (*Newboldiceras*) *annulatum* Collignon;

**Unnumbered Star Mountains locality:** *Placenticeras* aff. *tamulicum* (Blanford).

Because of discontinuous outcrop and occurrence of some ammonites in river boulders and in landslides, the relative stratigraphic relationships of the ammonite faunules from the five localities cannot be determined. However, locality 47 might represent a horizon older than those of localities 167 and 187 (Dr H.L. Davies, BMR, personal communication, 1983). (The stratigraphic position of localities 167 and 187 is probably the same.)

## Systematic descriptions

Morphological terms are from Arkell & others (1957) and Wright & Kennedy (1981). Measurements of specimens described here and those of some comparable specimens are shown in Tables 1–10. See Table 1 for abbreviations used in descriptions. Measurements of species not described in this paper are either those made by one of us (TM) at the holding institutions or from the literature.

### Family Puzosiidae Spath 1922 Genus *Pachydesmoceras* Spath 1922

**Type species.** *Ammonites denisonianus* Stoliczka 1865 (see Matsumoto, 1987)

**Remarks.** This genus is typically represented by *P. denisonianum*, *P. kossmati* and *P. pachydiscoides* Matsumoto (Matsumoto, 1988). Atypical species such as *P. rarecostatum* Collignon 1961, *P. radaodyi* Collignon 1964 and *P. mihoense* (Matsumoto, 1954) are also included in *Pachydesmoceras*. The latter subgroup is characterised by the development of thick, widely spaced major ribs on the outer whorl, and is similar to

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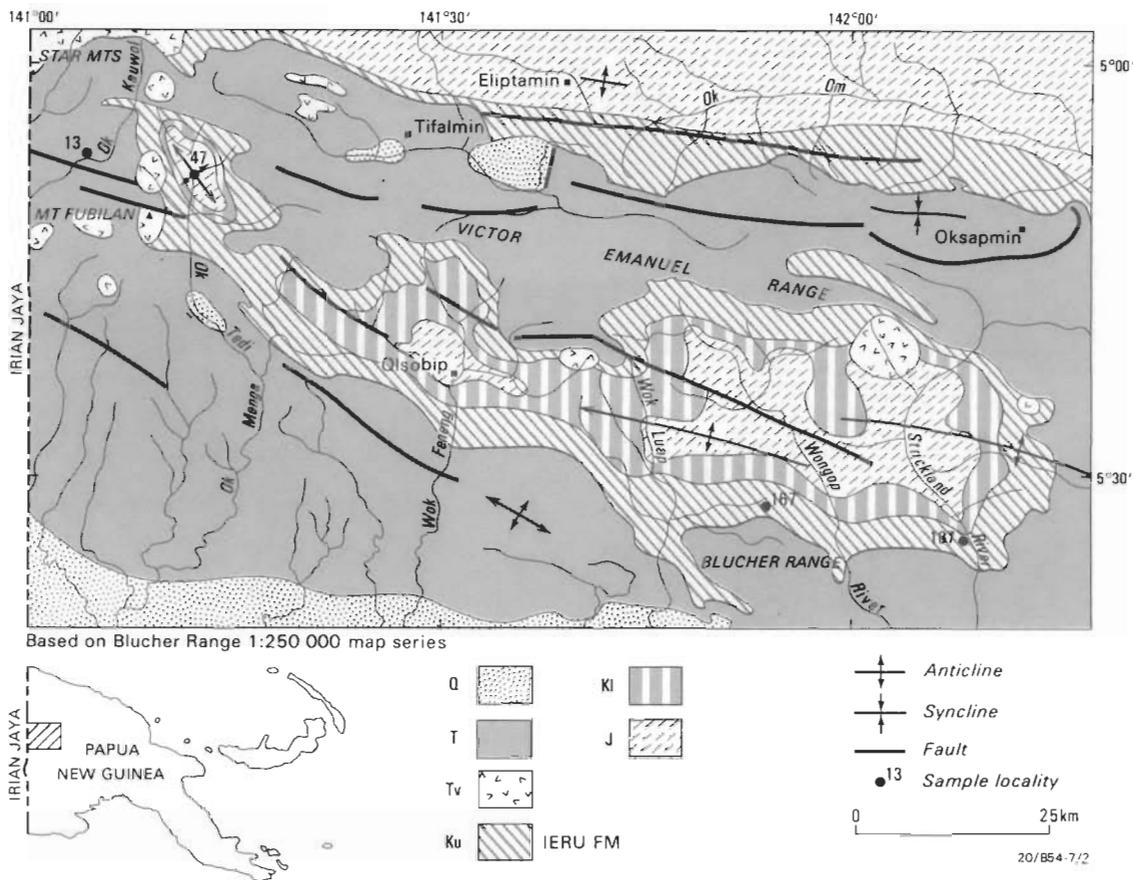


Fig. 1. Location map of the Ok Tedi area (based on Blucher Range 1: 250 000 map series), showing sites where ammonites described in this paper were collected.

Q Quaternary, T Tertiary, Tv Tertiary volcanics, Ku Upper Cretaceous, KI Lower Cretaceous, J Jurassic.  
**Locality 13:** Outcrop along Ok Kauwol. 5°07'02"S, 141°04'30"E. In the Star Mountains, northwestern part of the Sheet area. Collected in December, 1976. **Locality 47:** Float in the headwaters of Ok Tedi, northwestern part of the Sheet area. **Locality 167:** In mud flow below land slip between Wok Luap (Palmer River) and Wongop (Murray River), just north of Blucher Range, southeastern part of the Sheet area. **Locality 187:** West bank of the Strickland River, southeastern part of the Sheet area. **Unnumbered locality:** Position not known, possibly in the Star Mountains several days walk from the Olsobip Patrol Post.

*Anupuzosia* Matsumoto 1954. *Pachydesmoceras* sp. nov. described below is an example of this atypical subgroup.

***Pachydesmoceras* sp. nov.**  
 (Plate 1 fig. 4; Text-fig. 2)

**Material.** CPC 18126 from locality 187, Strickland River. This is a large, partly shelly, incomplete specimen, consisting of about half the outer whorl, which represents the last part (for about 140°) of phragmocone and the beginning of the body chamber (for about 40°).

**Description.** Very large shell; assuming a body chamber of a little over half the whorl, the entire shell would have been about 500 mm in diameter. Rate of whorl expansion is low ( $H/h = 1.30$ ) and the umbilicus is fairly wide ( $U/D = 0.44$ ). The whorl is slightly compressed, with maximum breadth somewhat below the mid-flank, and subrounded in cross-section, having a steeply inclined umbilical wall, a rounded umbilical shoulder, gently convex flanks, and a moderately rounded venter.

Thick, widely spaced, fold-like major ribs (8 on the outer half whorl) are disposed radially on the main part of the flank. On the ventrolateral and ventral parts there are more numerous and weaker minor ribs or riblets which curve gently forward. Some of these are on the extension of a major rib, as if they were

branched from the latter but have become independent, whereas others are distinctly intercalated between the extensions of major ones. Occasionally, an intercalated minor rib is somewhat longer, appearing at about the middle of the flank. The ventral riblets are generally four times as numerous as the major flank ribs. Their interspaces are concave and somewhat

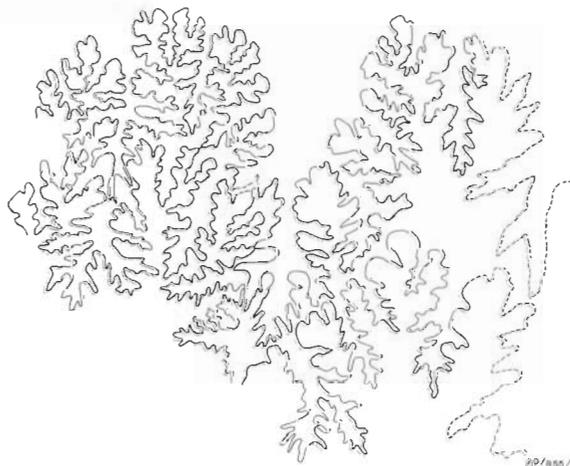


Figure 2. *Pachydesmoceras* sp. nov. Partial suture of CPC 18126.  $\times \frac{1}{15}$ , at H = 106 mm and B = 92 mm.

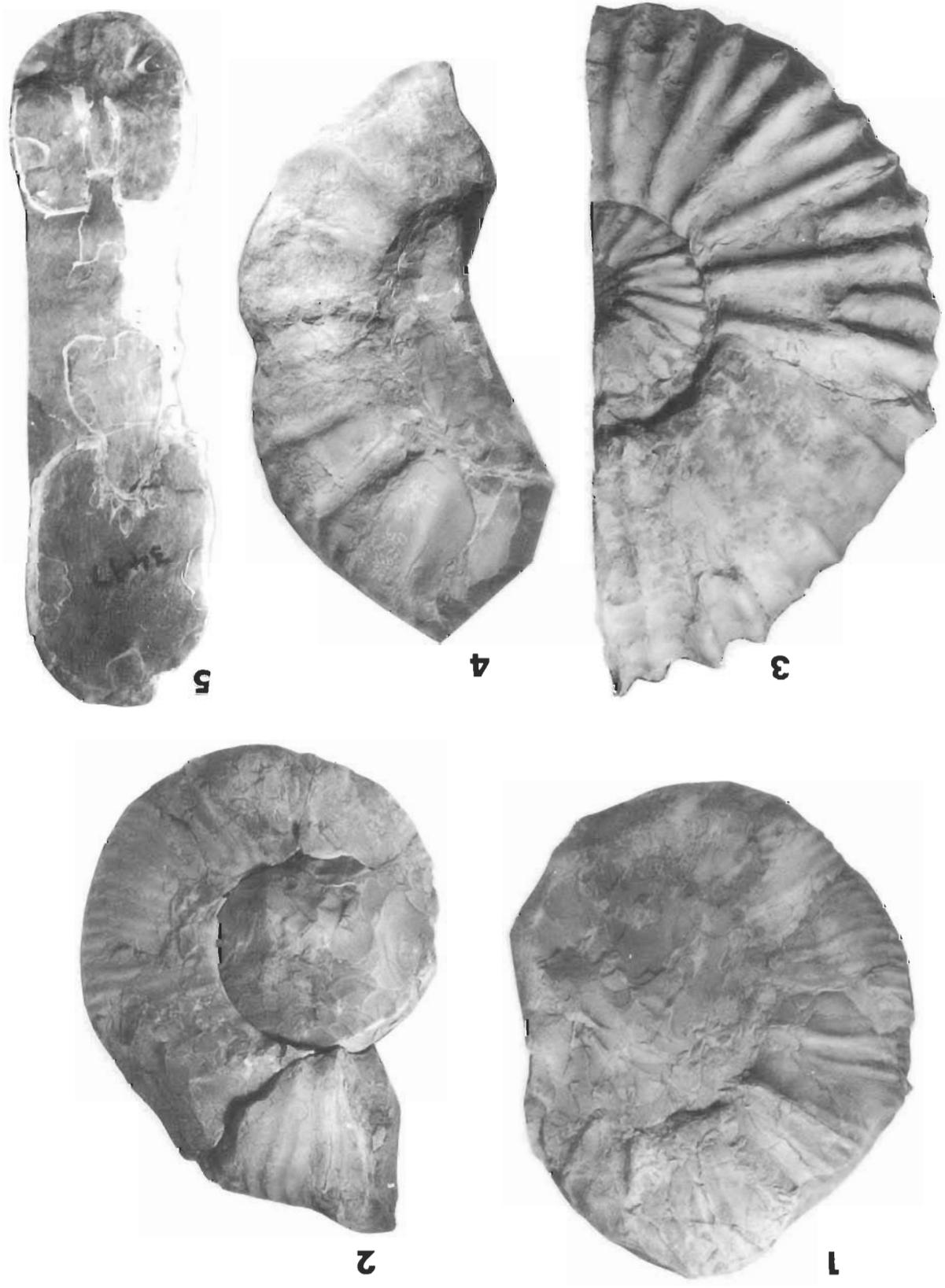


Plate 1.

All specimens coated with ammonium chloride and photographed in lateral view unless otherwise stated.  
1, 2. *Chambulites* aff. *multidowensis* Wright 1963; locality 187, Strickland River; Cenomanian. 1. CPC 18124 Somewhat crushed,  $\times \frac{1}{4}$ . 2. CPC 18125 Somewhat crushed,  $\times \frac{1}{4}$ . 3, 5. *Calycoceras* subgenus et sp. indet. CPC 16071; locality 167, north of Blucher Range; Cenomanian. 5. (Not coated with ammonium chloride) specimen, with adapical portion of the body chamber at its preserved end,  $\times \frac{1}{4}$ .  
4. *Fachydesmoceras* sp. nov. CPC 18126; locality 187, Strickland River; Cenomanian. Very large but incomplete end-on view; highly compressed secondarily,  $\times \frac{1}{4}$ .

**Table 1. Measurements of *Pachydesmoceras* sp. nov. and allied species.**

Specimen and position	D	U	U/D	H	B	B/H	h	H/h	NC
CPC 18126, E (c)	420	185	.44	133	126	.95	102	1.30	8
CPC 18126, E-70° (c)				121	112	.93			
CPC 18126, E-80° (ic)				119	99	.83			
<i>P. rarecostatum</i> <sup>1</sup> (ic) E	163	56	.34	69	72	1.04	45	1.53	10
<i>P. radaodyi</i> <sup>2</sup> (ic) E	235	62	.26	102	108	1.06	71	1.44	7
<i>P. mihoense</i> <sup>3</sup> (ic) E	182.5	78.5	.43	59.5	58	.98	44.5	1.34	9

D diameter, U umbilicus, H whorl height, B whorl breadth, h whorl height at the point a half whorl adapical from H.

Position means the measured point, where E preserved end, LS last septum, i.e. the beginning of the body chamber, E - 90° at a point a quarter whorl adapical from E, and so on; c costal, ic intercostal

NC Number of major ribs in a half of the last whorl.

<sup>1</sup> After Collignon (1961, pl. 9, fig. 1).

<sup>2</sup> After Collignon (1964, p. 58).

<sup>3</sup> After Matsumoto (1988, fig. 65)

broader than the riblets. The ribs which show through rock matrix obscuring the next inner whorl are moderately coarse.

The suture is finely and deeply incised and of Puzosiid pattern. The lateral lobe (L) is the largest lobe and is asymmetrically tripartite. The auxiliaries are descending.

**Dimensions.** See Table 1.

**Comparison and discussion.** The specimen is somewhat similar to *Pachydesmoceras rarecostatum* Collignon (1961, p. 40, pl. 9, figs 1, 1a) from the Cenomanian of the Malagasy Republic, in its widely spaced major ribs on the outer whorl, but it is distinguished by a wider umbilicus, more compressed outer whorl, coarser, more widely spaced, more rectiradiate major flank ribs, and more numerous and weaker minor ribs (see Table 1).

In the fairly wide umbilicus, subrounded whorl-section with B/H = slightly less than 1, and widely spaced, thick major ribs, the specimen resembles a macroconch of *P. mihoense* (see the example from the Coniacian of Hokkaido figured by Matsumoto, 1988, fig. 65). The Papua New Guinea form is, however, much larger, with more numerous, shorter minor ribs, and its major ribs do not extend onto the venter.

*P. radaodyi* Collignon (1964, p. 58, pl. 333, fig. 1498), from the Middle Cenomanian of the Malagasy Republic, has more pronounced major ribs which run across the venter without branching, fewer riblets, more convex flanks, and distinctly narrower and deeper umbilicus than the present specimen.

The specimen also resembles the outer whorl of the holotype of *Anapuzosia buenaventura* (Anderson) (1938, p. 185, pl. 41, figs 1, 2) from the Albian of California. The latter, however, lacks the minor ribs on the venter of this species and has, in addition to periodic flares and constrictions, numerous flexuous dense narrow ribs on the inner whorls.

The specimen probably represents a new species, but is inadequate for a proper definition. Because of coarse ribs on the poorly exposed inner whorl and despite the absence of the main part of the body chamber, we regard it as an atypical *Pachydesmoceras* rather than an *Anapuzosia*.

**Occurrence.** See material above.

Family **Hoplitidae** H. Douville 1890  
Genus ***Chimbuities*** Casey & Glaessner 1958

**Type species.** *C. sinuocostatus* Casey & Glaessner 1958 (in Glaessner, 1958); OD.

**Remarks.** In addition to its original description from Papua New Guinea, *Chimbuities* has been reported — as *C. mirindowensis* Wright 1963 — from the Cenomanian *Cunnington-icerias*-bearing rocks of northern Australia. Wright (1963, p. 604) suggested that the age of *C. sinuocostatus* is also Cenomanian.

Casey in Glaessner (1958, p. 213) referred *Chimbuities* to the family Hoplitidae in a broad sense, although the exact affinities of this genus are questionable. The material available at present is too limited to significantly add to our knowledge of *Chimbuities*.

***Chimbuities* aff. *mirindowensis* Wright 1963**  
(Plate 1 figs 1, 2)

cf. 1963 *Chimbuities mirindowensis* Wright, p. 603, pl. 82 figs 1, 2

**Material.** CPC 18124 and CPC 18125, from locality 187, Strickland River. Two large, somewhat crushed specimens with inner whorls concealed by matrix.

**Description.** The shell is large. The position of the last suture is approximately at D = 270 mm in CPC 18124, whose body chamber is about 180° but crushed. CPC 18125 is almost wholly septate. If the body chamber occupied a half whorl, CPC 18124 would be about 365 mm in a restored outline, whereas 18124 must have been originally still larger.

The rate of whorl expansion is rather low and the umbilicus is fairly wide, with U/D of 0.39 or 0.40. The last whorl is somewhat compressed, broadest at the umbilical bulla; flanks are nearly flat or slightly convex, converging to tightly arched ventrolateral shoulders; venter is flat or only slightly convex.

Ribs on the early part of the outer whorl up to a whorl height of about 65 mm are numerous, densely spaced and somewhat sinuous, becoming moderately spaced, more gently sinuous and moderately coarse later. The primary ribs arise as bullae on the umbilical shoulder. Some of them are single and others branch, normally at or near the umbilical bulla but occasionally on the outer flank. One to three secondary ribs of unequal length are intercalated between the primaries. Some primaries may be accompanied by deeper interspaces which may look like shallow or obscurely marked constrictions. On the inner flank of the preserved last quarter whorl of CPC 18124 (i.e. later half of the body chamber), the bullae are strengthened and extend to the thick and nearly rectiradiate primary ribs, each of which branches into two secondaries of normal coarseness on the outer flank. All the ribs of the outer whorl curve forward on the ventrolateral shoulder and end slightly thickened on either side of the slightly flattened mid-ventral zone. Sutures are poorly exposed but show fairly complex incisions and a lateral lobe (L) of moderate breadth.

**Dimensions.** See Table 2.

**Comparison and discussion.** The two specimens described above differ from each other in shell size, relative whorl breadth (B/H), and coarseness and sinuosity of the ribs. Their dissimilarity is attributed to intraspecific variation.

In what little can be seen of the early growth stages, they resemble *Chimbuities mirindowensis* Wright (1963, p. 603, pl. 82 figs 1, 2) from the Cenomanian of Bathurst Island, northern Australia. *C. mirindowensis* is, however, much smaller and differs considerably in umbilicus width. The slight thickening of ribs on either side of a flattened mid-venter on the large outer

Table 2. Approximate measurements of *Chimbuites* aff. *mirindowensis* Wright.

Specimen and position	D	U	U/D	H	B	B/H	h	H/h	Remarks
CPC 18124, E	~365	142	.39	130	—	—	93	1.40	} Secondarily compressed
CPC 18124, E-180°	~265	107	.40	93	62	.67	67	1.39	
CPC 18125, E	~312	123	.39	105	88	.84	84	1.25	
CPC 18125, E-90° (ic)	~260	—	—	92	80	.87	—	—	
CPC 18125, E-90° (c)	~260	—	—	93	83	.89	—	—	

whorl may be a feature unique to the present form. However, smaller shells of both *C. mirindowensis* and *C. sinuocostatus* Casey & Glaessner (in Glaessner, 1958, p. 214, pl. 24 fig. 3; pl. 25 figs 1, 2; text-fig. 4), the latter from about 320 km east-southeast of locality 187 in the Eastern Highlands of Papua New Guinea, also have more or less flattened venters. Therefore, the present form is best referred to *Chimbuites*, and probably represents a species allied to but not conspecific with *C. mirindowensis*. In view of the limitations of our material we do not establish a new species.

Family **Placenticeratidae** Hyatt 1900  
Genus **Placenticer** Meek 1876

**Type species.** *Ammonites placenta* De Kay 1828

**Remarks.** This genus and other genera of the family Placenticeratidae have been reviewed by Kennedy & Wright (1983, pp. 867–870), whom we generally follow. They have demonstrated strong dimorphism in *Placenticer* *polyopsis* (Dujardin, 1837).

***Placenticer* aff. *tamulicum*** (Blanford 1862)  
(Plate 2 figs 1–12; Plate 3 figs 5, 6; Text-figs 3, 4)

cf. 1862 *Ammonites tamulicus* Blanford, p. 118

**Material.** Five whorl fragments, CPC 15679–15683, from unknown location, possibly in the Star Mountains; CPC 19122, a wholly septate but partly crushed specimen from locality 13 in the Star Mountains.

**Description.** The shell is involute, with a moderate rate of whorl expansion. The umbilicus is narrow, encircled by fairly steeply inclined wall and subangular or abruptly rounded

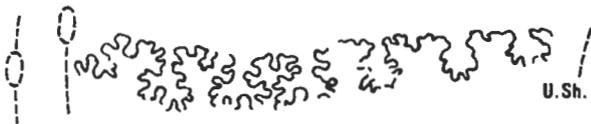


Figure 3. *Placenticer* aff. *tamulicum* (Blanford).  
Suture of CPC 15679,  $\times 2\frac{1}{2}$ , at  $H = 26$  mm.  
u.sh. umbilical shoulder.

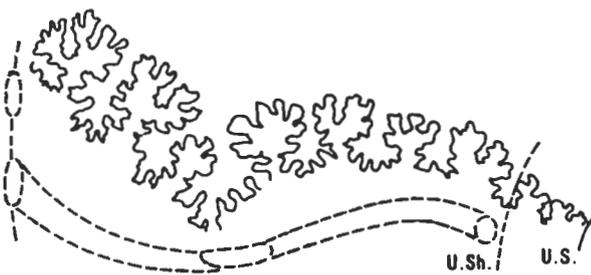


Figure 4. *Placenticer* aff. *tamulicum* (Blanford).  
Suture of CPC 19122,  $\times 1\frac{1}{2}$ , at  $H = 40$  mm.  
u.sh. umbilical shoulder; u.s. umbilical seam.

shoulder, appearing funnel-shaped. The whorl is compressed, with B/H of 0.5–>0.7, narrowly trapezoid in cross-section, broadest near the umbilical shoulder, and with gently convex to nearly flat flanks converging to a narrow, nearly flat venter, which is demarcated on either side by sharp ventrolateral shoulders with alternating clavate tubercles.

The umbilical tubercles are widely separated, six to a whorl. The outer flank tubercles are blunt, resting on low or very weak, somewhat flexuous and prorsiradiate ribs which originate from the umbilical tubercles. Ventrolateral clavi are twice as numerous as the umbilical or lateral tubercles. For each that marks the end of a rib another is intercalated, sometimes connected with the subjacent lateral node by a rursiradiate, branched riblet.

One specimen, CPC 15683 (Pl. 2, figs 7, 12), is an incomplete body chamber representing two thirds of a whorl, and has the last septum at its adapical end. If the body chamber originally occupied a little over half the last whorl, the entire shell diameter would have been approximately 100 mm. This is much smaller than CPC 19122 (Pl. 3, figs 5, 6), which is almost wholly septate and must have been at least 240 mm in diameter at the apertural end of the lost body chamber.

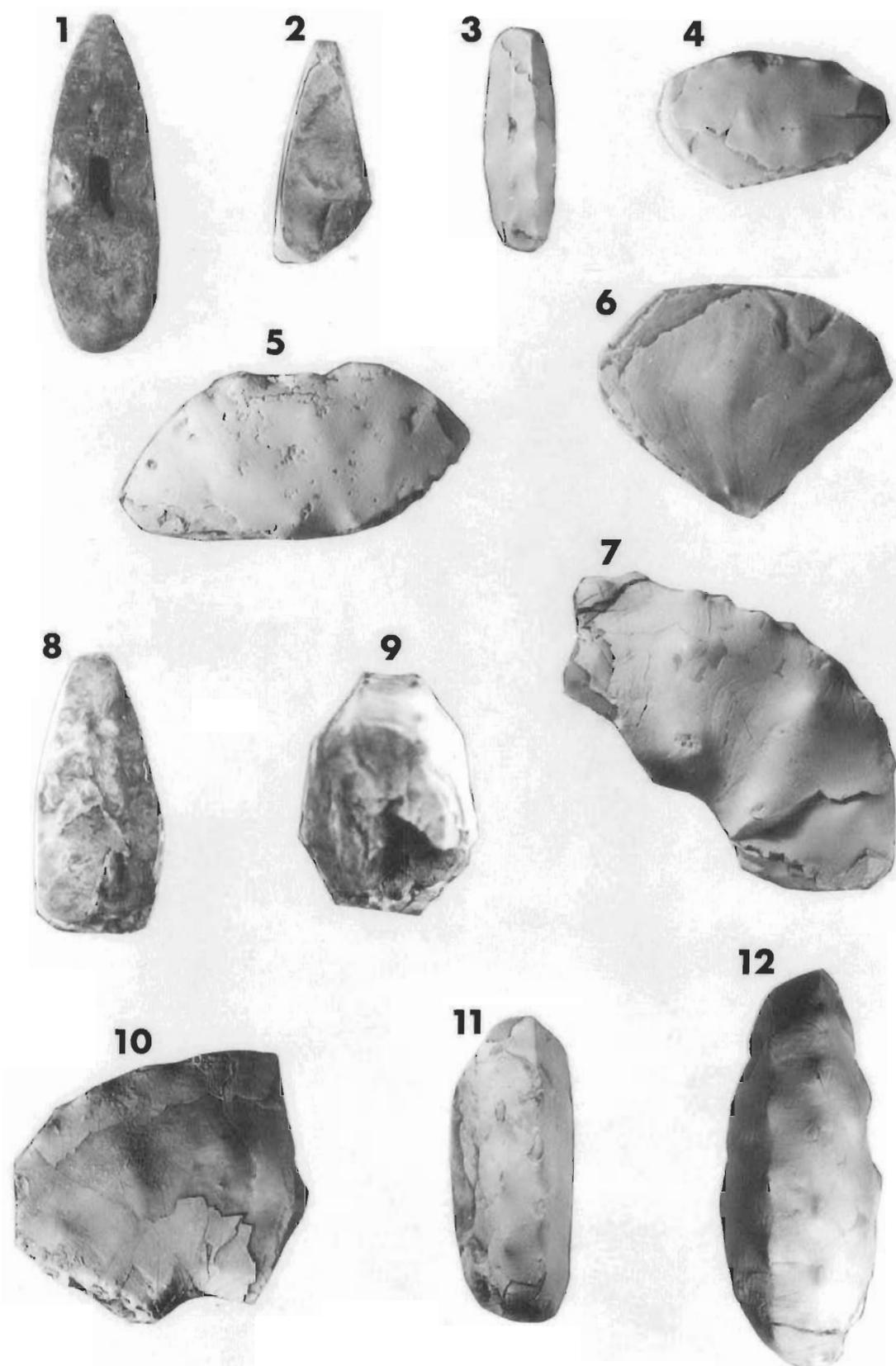
CPC 15683 (Pl. 2, figs 7, 9, 12) is robust with a broader whorl and stronger tubercles than the other five specimens. It is probably a microconch. The prominent growth lines or lirae curve gently forward on the umbilical wall and are prorsiradiate on the inner part of the flank. They form a fairly pronounced but rounded projection at about the mid-flank and then describe a forwardly concave, asymmetric curve on the outer flank, and straighten to cross the venter with little or no deflection.

CPC 19122 (Pl. 3, figs 5, 6) is slender, and the tubercles on the umbilical shoulder small and pointed, with peripheral clavi persisting at least up to the preserved end (diameter 135 mm). The four fragmentary specimens, CPC 15679–15682, are similar to CPC 19122 in essential points. One of them (CPC 15680) (Pl. 2, fig. 6) shows sinuous or falcoid growth lines or lirae, with a pronounced and rather subangular projection at about mid-flank. This curvature is similar to but not quite identical to that of CPC 15683.

Sutures are exposed in all six specimens, though sometimes incompletely. They are of general *Placenticer* pattern (Text-figs 3, 4) (see discussion below).

**Dimensions.** See Table 3.

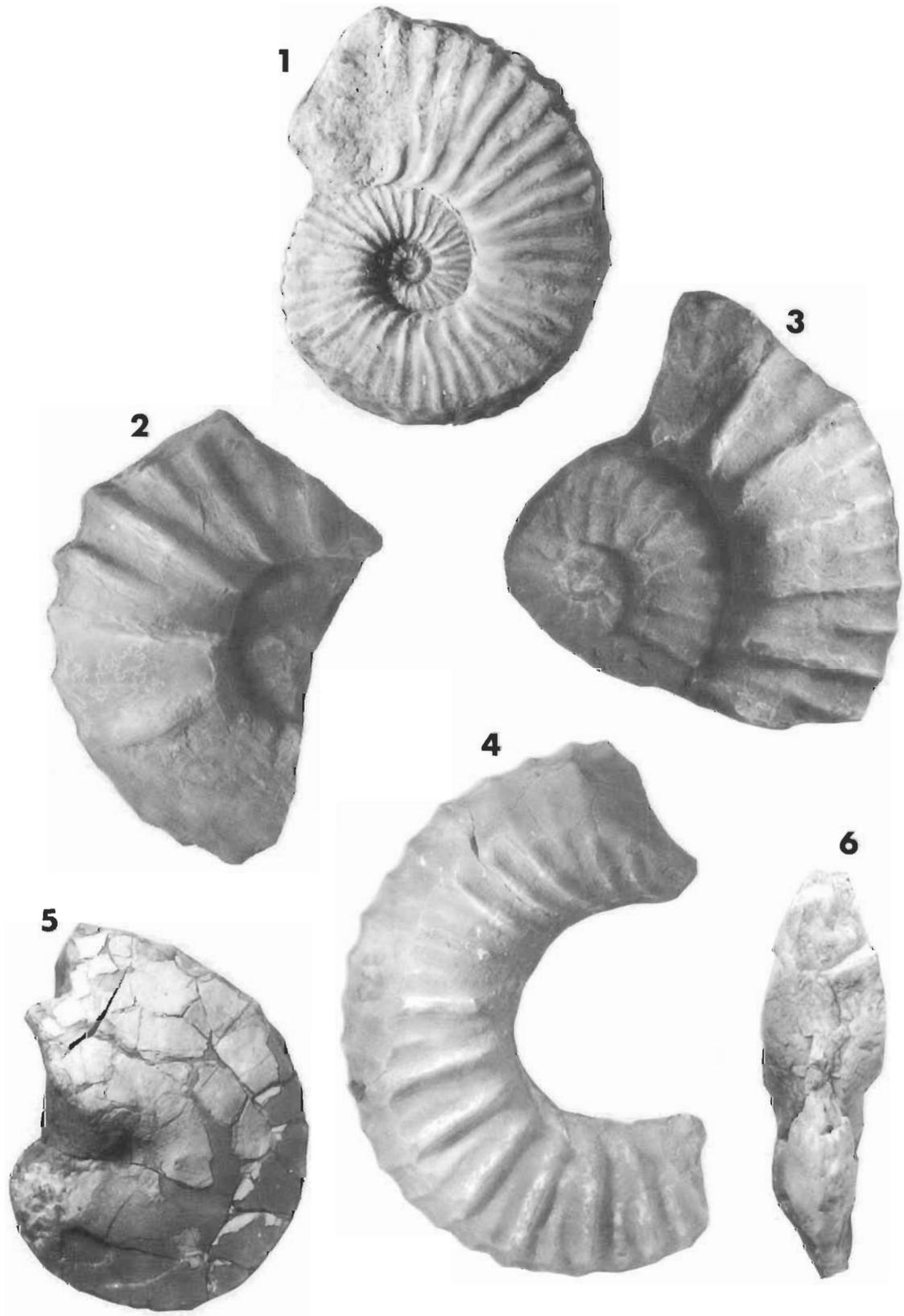
**Comparison and discussion.** Our specimens from the Ieru Formation seem to exhibit dimorphism generally similar to that in *Placenticer tamulicum* (Blanford) (= *Placenticer syntale* Morton var. *tamulicum* (Blanford) cf. Boule & others, 1907, and *Ammonites quadalupe* Stoliczka 1865 non Roemer) which has a slender but large form with weak tubercles (as in Stoliczka, 1865, pl. 47 fig. 1 and pl. 48 figs 1, 1a; Kossmat, 1895, pl. 22 figs 1a, 6; Boule & others, 1907, pl. 5 figs 3, 3a) and a robust form with strong tubercles (Stoliczka, 1865, pl. 47 fig. 2; Boule & others, 1907, pl. 5 fig. 4).



**Plate 2.**

All specimens coated with ammonium chloride except specimens 1, 2, 8, 9 (uncoated).

1–12. *Placenticerus* aff. *tamulicum* (Blanford 1962) (Star Mountains?, Irian Jaya. Middle Turonian–Santonian). 1, 5. CPC 15679 End-on and lateral views; 1, slightly larger than  $\times 1$ ; 5,  $\times 1$ . 2, 6. CPC 15680 End-on and lateral views;  $\times 1$ . 3, 4. CPC 15681 Ventral and lateral views;  $\times 1$ . 7, 9, 12. CPC 15683 Lateral, end-on and ventral views; 7, 12  $\times 1$ ; 9, slightly larger than  $\times 1$ . 8, 10, 11. CPC 15682 End-on, lateral and ventral views,  $\times 1$



**Plate 3.**

All specimens coated with ammonium chloride and photographed in lateral view unless otherwise stated.

1. *Calycoceras (Calycoceras) sp. nov. (?)*. CPC 16072; locality 167, north of Blucher Range; Cenomanian;  $\times \frac{1}{2}$ . 2-4. *Calycoceras (Newboldiceras) annulatum* Collignon 1964; locality 187, Strickland River; Cenomanian. 2, CPC 18128;  $\times \frac{1}{4}$ . 3, CPC 18129;  $\times \frac{1}{4}$ . 4, CPC 18130;  $\times \frac{1}{4}$ . 5, 6. *Placentoceras aff. lamulicum* (Blanford 1862); locality 13, Star Mountains; Middle Turonian?;  $\times \frac{1}{2}$ . CPC 19122 6 End-on view.

**Table 3. Measurements of *Placenticer* aff. *tamulicum* and *P. tamulicum*.**

Specimen and position	D	U	UID	H	B	B/H	h	H/h	NT
CPC 15683 (c)				33.0	27.0	.82			3
CPC 15683 (ic)				32.4	24.0	.74			3
CPC 15682 (ic)				40.5	20.5	.51			4
CPC 15679 (c)				29.5	17.5	.59			3
CPC 19122 (E, c)	135.0	15.5	.11	72.0	38.5	.53	47.0	1.53	4
CPC 19122 (E-240°, ic)				38.0	22.0	.58			3.5
Kossmat, 22-1	63	10	.16	32	16	.50	21.5	1.49	5.5
Stoliczka, 47-1	180	28	.16	90					5
Stoliczka, 47-2 (ic)	125			61	49	.80			
Stoliczka, 48-1 (c)	120	19	.16	59	33	.56	42	1.41	4-5
Boule & others, 12-3	89	13.5	.15	45	28	.62	30.5	1.48	3.5
Boule & others, 12-4 (ic)	106	20	.19	50	41	.82	36	1.39	3.5

NT Number of ventral tubercles in the interval as long as H; other abbreviations as in Table 1. Kossmat, 22-1: Kossmat, 1895, pl. 22, fig. 1; Stoliczka, 47-1: Stoliczka, 1864, pl. 47, fig. 1; Stoliczka, 48-1: Stoliczka, 1864, pl. 48, fig. 1; Boule & others, 12-3: Boule & others, 1906, pl. 12, fig. 3; Boule & others, 12-4: Boule & others, 1906, pl. 12, fig. 4. The width of umbilicus was measured by Stoliczka (1864, p. 90) at the umbilical shoulder, but in this paper it is at the umbilical seam.

In *P. tamulicum* the bifurcation or intercalation of ribs sometimes occurs at or near the umbilical tubercles or on the inner part of flank, and accordingly the lateral nodes are more numerous than the umbilical tubercles. In the Ieru Formation species, each of the lateral nodes is on a single rib extending from each of the umbilical tubercles; the bifurcation or intercalation occurs at the level of the lateral nodes and the ventrolateral clavi are twice as numerous as the lateral nodes. The lateral nodes are disposed at wide intervals; they are slightly ventral of the mid-flank in the slender form, but lie more on the outer flank in the robust form. In *P. tamulicum* the flank nodes are more numerous than the umbilical tubercles and are on the ventral flank, close to the peripheral clavi. Bifurcation of ribs at the nodes on outer flank is infrequent in *P. tamulicum*; this species has slightly fewer peripheral clavi than the Ieru species.

*Placenticer* *cumminsi* Cragin 1893 from the Upper Cenomanian of Texas, New Mexico, etc. (see Kennedy, 1988, p. 26; Cobban & others, 1989, p. 20), although extremely variable, is generally similar to *P. tamulicum* in shell-form and ornamentation. The suture of *P. cumminsi* has a fourth lateral lobe smaller than the fifth (Cobban, in Cobban & others, 1989, fig. 20). Cobban accordingly refers that species to the subgenus *P. (Karamaites)*. In the Ieru species the fourth and fifth lateral lobes are nearly the same size. In the suture of *P. tamulicum* illustrated by Kossmat (1895, pl. 22 fig. 1c), the fourth lobe is larger than the fifth.

To sum up, the specimens from the Ieru Formation represent a species which is allied to but distinguishable from *P. tamulicum*. It is probably new, but we refrain from establishing a new species, as the material is fragmentary and most cannot be precisely located.

**Occurrence.** The specimen from locality 13 was associated with *Romaniceras deverioides* (de Grossouvre), which indicates a (probably middle) Turonian age.

In southern India *P. tamulicum* occurs abundantly in the upper part of the Trichinopoly Group (Kossmat, 1895). Sastry & others (1968) placed the Zone of *P. tamulicum* above the Zone of *Kossmaticeras theobaldianum*, but pointed out that *P. tamulicum* occasionally occurs also in the latter zone. This suggests a Coniacian-Lower Santonian(?) range for this species in southern India. Boule & others (1907) recorded *P. tamulicum* from the Senonian of Diego-Suarez, northern Malagasy Republic, and Lewy & Raab (1978, p. 12) from the lowest Coniacian (Zone CA1) of the Middle East.

*P. (K.) cumminsi* occurs typically in the Upper Cenomanian Zone of *Sciponoceras gracile* of Texas and adjacent areas of

North America. Kennedy (1988) included in the same species a series of forms by Hyatt (1903) from the Lower to Middle Turonian (Zones of *Mammites nodosoides*, *Collignoniceras woolgari* to *Prionocyclus hyatti*).

#### Family Acanthoceratidae de Grossouvre 1894

**Remarks.** Acanthoceratidae has been recently revised by Wright & Kennedy (1987) who transferred the genera *Acomp-soceras* Hyatt 1903 and *Calycoceras* Hyatt 1900, with a number of subgenera, from the subfamily Mantelliceratinae to the Subfamily Acanthoceratinae. Some details of the phyletic origins of *Calycoceras* and *Acanthoceras* are uncertain, but we generally accept this revision.

#### Genus *Calycoceras* Hyatt 1900

**Type species.** *Ammonites navicularis* Mantell 1822

**Remarks.** We follow Wright & Kennedy (1981, p. 33), who now recognise the subgenera *Calycoceras*, *Gentoniceras*, *Newboldiceras* and *Proeucalycoceras* Thomel 1972, *Lotzeites* Wiedmann 1960, and *Conlinoceras* Cobban & Scott 1972. For some typical species, such as *C. (C.) naviculare* and *C. (N.) newboldi*, it is convenient to use subgeneric names. However, our subgeneric assignments, particularly for those Ieru Formation forms which are too incomplete to allow investigation of the change of characters with growth, are tentative.

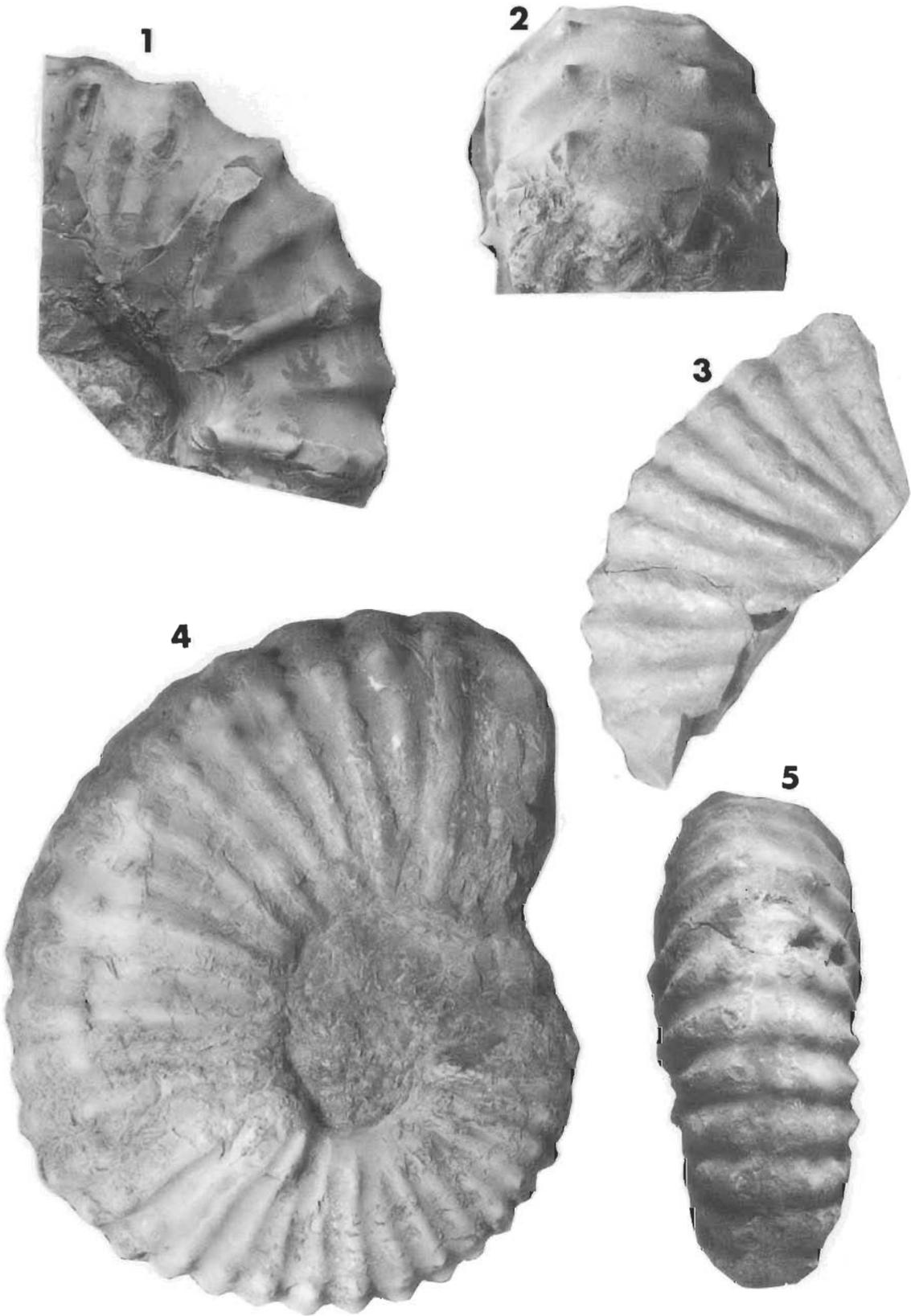
#### Subgenus *Newboldiceras* Thomel 1972

**Type species.** *Acanthoceras newboldi* Kossmat 1897

**Remarks.** The genus *Newboldiceras* was established by Thomel (1972) as a member of the subfamily Acanthoceratinae, but we agree with Wright & Kennedy (1981) who reduced it to subgeneric status because of its closeness to *C. (Calycoceras)*.

#### *Calycoceras (Newboldiceras) newboldi* (Kossmat 1897) (Plate 4 fig. 4)

1864 *Ammonites rhotomagensis* DeFrance; Stoliczka, p. 66, pl. 34 figs 3, 4; pl. 35 fig. 1; pl. 36 fig. 1; pl. 37 figs 1, 2  
1897 *Acanthoceras newboldi* Kossmat (typical form), p. 5, pl. 1 figs 2, 3; pl. 2 fig. 2  
1964 *Calycoceras newboldi* (Kossmat); Collignon, p. 120, pl. 362, fig. 1585



**Plate 4**

All specimens coated with ammonium chloride and photographed in lateral view unless otherwise stated.

1, 2. *Acanthoceras* sp. indet.; locality 167, north of Blucher Range; Cenomanian. CPC 16076.  $\times \frac{3}{4}$ , incomplete specimen. 1, lateral. 2, ventral (partly omitted). 3, 5. *Calycoceras* (*Newboldiceras*) cf. *orientale* Matsumoto, Saito & Fukada 1957; locality 187, Strickland River; Cenomanian. CPC 18127.  $\times \frac{1}{4}$ , fragment of large specimen. 3, lateral view (upside-down, with posterior above). 5, ventral view. 4. *Calycoceras* (*Newboldiceras*) *newboldi* (Kossmat 1879); locality 167, north of Blucher Range; Cenomanian,  $\times \frac{1}{2}$ . CPC 16073, a somewhat distorted specimen.

- 1971 *Calycoceras newboldi newboldi* (Kossmat); Kennedy, p. 75, pl. 39 fig. 2; pl. 40 fig. 2  
 1972 *Newboldiceras (Newboldiceras) newboldi* (Kossmat); Thomel, p. 106, pl. 34 figs 1–3; pl. 38 figs 1–2; pl. 39 figs 1–3; pl. 40 figs 1–3; pl. 41; pl. 42 figs 3, 4  
 1987 *Calycoceras (Newboldiceras) newboldi* (Kossmat); Matsumoto & Suekane, p. 5, pl. 1 fig. 4; pl. 2 figs 1–3

**Material.** CPC 16073 from locality 167, Blucher Range, comprising a fairly large outer whorl showing the last part of phragmocone and a somewhat distorted incomplete body chamber.

**Description.** The shell is fairly large, presumably 270 mm or so at the end of a restored body chamber of half a whorl. The umbilicus is of moderate width, surrounded by a steep wall and an abruptly rounded shoulder. The whorl is somewhat broader than high, with a subquadrate to subrounded intercostal and polygonal costal cross-section.

Ribs are moderately dense and numerous, about 18 in a half whorl, with primaries generally alternating with secondaries, separated by interspaces nearly of the same width. The primary ribs have bullate tubercles at the umbilical shoulder and are nearly rectiradiate or gently arcuate, raised and steep-sided on the flank. The secondary ribs arise dorsal of the mid-flank, sometimes near the umbilical shoulder and without umbilical bulla.

On the outer part of the whorl all the ribs are equally strong, with inner and outer ventrolateral tubercles of similar size. They cross the venter with some broadening and lowering, but are not greatly diminished in size. Clavate siphonal tubercles become progressively weaker with the whorl growth. The last part of the body chamber where ventrolateral tubercles should weaken and primary ribs predominate is not preserved.

Sutures are similar to those in the specimen illustrated by Kossmat (1897, pl. 3 fig. 2).

**Dimensions.** See Table 4.

**Comparison and discussion.** The described specimen conforms well in essential characters to the typical form of *C. (N.) newboldi*. It is similar to the large specimen from southern India illustrated by Stoliczka (1865, pl. 36 fig. 1), but its ventral tubercles persist to a more advanced growth stage than shown by that form. This may suggest an apparent approach to *C. (N.) spinosum* (Kossmat) (= *C. (N.) newboldi spinosum* of some authors), but the present specimen has fewer tubercles and ribs.

**Occurrence.** Apart from Blucher Range, *C. (N.) newboldi* has been reported from the Cenomanian of southern India, the Malagasy Republic, northern Africa, southeastern France, southern England and Japan. It is common in the Middle Cenomanian Zone of *Acanthoceras rhotomagense* (especially

the upper part) of England and in the same zone in France. Its record from the Lower Cenomanian Zone of *Mantelliceras mantelli* and *Calycoceras newboldi* of Malagasy Republic (Collignon, 1964) requires reinvestigation.

***Calycoceras (Newboldiceras) cf. orientale***  
 Matsumoto, Saito & Fukada 1957  
 (Plate 4 figs 3, 5)

- cf. 1957 *Calycoceras orientale* Matsumoto, Saito & Fukada, p. 16, pl. 5 figs 1a–c; pl. 7 fig. 1  
 1982 *Calycoceras cf. orientale* Matsumoto, Saito & Fukada; Matsumoto, p. 37, pl. 3, fig. 1.

**Material.** CPC 18127, a large outer whorl fragment, from locality 187, Strickland River.

**Description.** The whorl is slightly compressed, with B/H of 0.85 at the second-last septum, and with a suboval to subelliptical intercostal section. Flanks are gently convex, passing to an arched venter.

Ribs are numerous and would have numbered approximately 36 on a complete whorl. They swing very gently forward on the flanks, and cross the venter at right angles to the siphonal line. They are of two orders: primaries which arise from bullate tubercles at the umbilical shoulder and secondaries which arise on the dorsal flanks. All the ribs are of equally moderate relief on the outer flank, separated by slightly broader, concave interspaces, with moderately strong inner and outer ventrolateral tubercles, and are slightly lowered on the venter. Siphonal tubercles are scarcely discernible. The tubercles gradually decrease in strength from the beginning of the body chamber.

The suture is of *Calycoceras* pattern, with deep E, massive bipartite E/L saddle and L of moderate breadth; minor incisions are small.

**Comparison and discussion.** Our incomplete specimen is best compared with *C. (N.) orientale* because of its higher whorl and the type of ribbing and tuberculation.

*C. (N.) newboldi* var. *madagascarensis* Collignon (1937, p. 40, pl. 3 figs 6, 6a; pl. 8 fig. 7; 1964, p. 124, pl. 364, fig. 1590) from the Malagasy Republic resembles *C. (N.) orientale* in higher whorl with flatter flanks than the typical form of *C. (N.) newboldi*, but it has more numerous, crowded ribs.

**Occurrence.** In Japan *C. (N.) orientale* occurs in the Middle Cenomanian.

***Calycoceras (Newboldiceras) annulatum***  
 Collignon 1964  
 (Plate 3 figs 2–4)

- 1964 *Calycoceras annulatum* Collignon, p. 127, pl. 366 fig. 1597

**Table 4.** Measurements of *Calycoceras (Newboldiceras) newboldi*.

Specimen and position	D	U	UID	H	H/D	B	B/D	B/H	h	H/h	NC
CPC 16073 (c)	233	74	.32	96	.41	100	.43	1.04	63	1.52	18
CPC 16073 (–180°) (c)				63		69		1.10			18
India 1 (c)	113	69	.33	49	.43	52	.46	1.06	32	1.53	18
India 2 (c)	210	69	.33	85	.40	89	.42	1.05	58	1.47	20
Madagascar (c)	109	34	.31	45	.41	58	.53	1.18	30	1.5	18
Japan (c)	170	52	.31	70	.41	78	.46	1.11	48	1.46	18

India 1: Kossmat, 1897, pl. 1, fig. 1; India 2: Stoliczka, 1865, pl. 36, fig. 1; Madagascar: Collignon, 1964, pl. 362, fig. 1585; Japan: Matsumoto & Suekane, 1987, pl. 3, figs. 1–3 (YCM 714); these are all typical forms.  
 NC Number of ribs per half whorl.

1972 *Calycoceras* (*Calycoceras*) sp. aff. *annulatum* Collignon;

Thomel, p. 64, pl. 16 figs 6–7; pl. 18 figs 1, 2

1973 *Calycoceras annulatum* Collignon; Cooper, p. 34, figs 8A–C

1985 *Calycoceras* (*Newboldiceras*) *annulatum* Collignon; Zaborski, p. 32, figs 35, 36

**Material.** CPC 18128, CPC 18129 and CPC 18130, three large but somewhat incomplete specimens from locality 187, Strickland River.

**Description.** The shell is very large. The end of the septate whorl is at  $H = 113$  mm in CPC 18128,  $H = 114$  mm in CPC 18130 and presumably between 110 and 120 mm in CPC 18129 whose outer whorl is poorly preserved. The body chamber occupies at least a half whorl, as shown by CPC 18130. The diameter of the entire shell is about 410 mm in CPC 18130 and presumably not much different in the restored outline of the other two specimens. The whorl expands at a low rate, with  $H/h = 1.31$  in the measurable specimens, and with slight overlapping. Accordingly the umbilicus is fairly wide: 36% of diameter in a restored outline for CPC 18128 and 43% in CPC 18130. The whorl is almost equidimensional and subtrapezoid to subrounded in cross-section, with a steep, high umbilical wall, abruptly rounded umbilical border, gently to moderately convex, convergent flanks, and an almost flat venter in early growth stages that becomes moderately arched at maturity.

The ribs on an inner whorl, as shown by CPC 18129 and in part by CPC 18130, are of variable length, with longer ones normally alternating with, and occasional branching to, shorter ones. They are of moderate relief and density, numbering 26 per whorl, separated by interspaces somewhat wider than the ribs themselves. Fairly prominent tubercles are located on the long ribs outside the umbilical edge. The inner and outer ventrolateral tubercles are distinct on every rib, forming a sloping ventrolateral facet. Siphonal tubercles are weak.

The ribs on the outer or later whorl are robust, much elevated, separated by broader interspaces, and nearly rectiradiate. In lateral view the ribs are alternately long and short, but long ribs on one side pass to short ones on the other. Each long rib has a prominent tubercle at the umbilical edge. Slight lateral bulges are discernible on many long ribs. Inner and outer ventrolateral tubercles on septate whorls persist to the living chamber as angulations. Siphonal tubercles disappear, while ribs cross the venter without loss of prominence.

On the last part of the body chamber long ribs predominate, with only occasional intercalations of shorter ones, and all tubercles and angulations disappear.

There is some variation in the density of ribs even on the outer whorl. In a quarter whorl there are 8 ribs on CPC 18128, compared with 10 on CPC 18129 and CPC 18130.

Suture pattern is as in *Calycoceras* (*Calycoceras*) (e.g. Matsumoto, 1959, text-fig. 32 for *C. (C.) boulei* Collignon).

**Dimensions.** See Table 5.

**Table 5.** Measurements of *Calycoceras* (*Newboldiceras*) *annulatum*.

Specimen and position	D	U	H	B	B/H	h	H/h
CPC 18130 (c)	390	180 (.46)	123 (.32)	117 (.30)	-0.95	92	1.34
CPC (-150°) (c)	—	—	96	90	0.94	—	—
CPC 18129 (inner whorl)	-187	-67 (.36)	-78 (.42)	-69 (.39)	-0.88	—	—
CPC 18128 (c)	—	—	127	122	0.96	—	—
Collignon (holotype)	111	41 (.37)	43 (.39)	39 (.35)	0.91	—	—
Collignon (paratype)	97	34 (.35)	37 (.38)	35 (.36)	0.95	—	—
Zaborski, 1985, p. 32	166	70 (.42)	54 (.33)	54 (.33)	1.00	42	1.29

**Comparison and discussion.** The three specimens described above represent a distinct ammonite allied to *C. (C.) annulatum* Collignon from the Malagasy Republic in essential points. A long rib with an umbilical tubercle on one flank extending to a short one on the other is clearly shown (although not mentioned) by Collignon (1964, p. 127, pl. 366 fig. 1598). This feature was also noted by Zaborski (1985, pp. 32–33, figs 35, 36) on a specimen from Nigeria.

Our form has a somewhat higher whorl than the form from the Malagasy Republic, but this may be due partly to the change of B/H with growth and partly to secondary compression. A more obvious difference is the much larger size of our specimens. This suggests dimorphism, with our specimens representing macroconchs and the holotype and paratype illustrated by Collignon (1964, pl. 366 figs 1597, 1598) representing microconchs. The specimens from southeastern France described under *C. (C.)* aff. *annulatum* by Thomel (1972, p. 64, pl. 16 figs 6, 7; pl. 18 figs 1, 2) are probably microconchs. Zaborski's specimen from Nigeria, BM C83477, which looks very similar to our CPC 18130, may be a macroconch, although it is somewhat smaller.

The septate part of CPC 18130 and the inner whorl of CPC 18129 show fairly distinctly, like BM C83477, the inner and outer ventrolateral tubercles on the ribs, which form an oblique ventrolateral facet. This feature is characteristic of *C. (Newboldiceras)*. Collignon (1964, p. 127) noted that the inner whorl had a trapezoidal section and that in some part of the outer whorl the ventrolateral tubercles were not so prominent, with the result that the costal as well as intercostal sections were subrounded. In view of the characters of the inner or earlier part of shell, we are inclined to refer our specimens to the subgenus *C. (Newboldiceras)*, even though the features of the outer or later whorls suggest a close relationship between *C. (Calycoceras)* and *C. (Newboldiceras)*.

**Occurrence.** French specimens occur in the Upper Cenomanian Zone 5 of Thomel (1972). Collignon's original material from the Malagasy Republic was recorded as Lower Cenomanian, which needs confirmation. Zaborski (1985) reported a specimen from the Middle Cenomanian of Nigeria.

#### Subgenus *Calycoceras* Hyatt 1900

**Type species.** *Ammonites navicularis* Mantell 1822

#### *Calycoceras* (*Calycoceras*) sp. nov.(?) (Plate 3 fig. 1)

**Material.** CPC 16072 from locality 167, Blucher Range. This is a fairly well preserved specimen, with a slightly abraded outer whorl venter and only the adapical part of the body chamber preserved.

**Description.** The specimen consists of the phragmocone and an incompletely preserved body chamber. If the body chamber occupied half a whorl, the entire shell diameter must have been nearly 210 mm.

**Table 6.** Measurements of *C. (Calycoceras)* sp. nov. and other species.

Specimen and position	D	U	H	B	B/H	h	H/h	NC
CPC 16072. (c)	140.0 (1)	43.0 (.31)	61.5 (.44)	—	—	35.5	1.73	21
CPC 16072. -50° (c)	125.0 (1)	37.5 (.30)	55.5 (.45)	67.0 (.54)	1.21	32.0	1.73	21
CPC 16072. -220° (c)	—	—	35.0	42.0	1.20	—	—	22
<i>C. boulei</i> LT	121.0 (1)	33.0 (.27)	53.0 (.44)	67.0 (.55)	1.26	38.0	1.51	?20
<i>C. pauci nodatum</i> HT	65.0 (1)	20.0 (.30)	27.0 (.42)	30.0 (.46)	1.11	18.0	1.5	19

NC Number of ribs per half whorl; HT holotype; LT lectotype.

The whorl expands rapidly in height with involution of about 40%. The umbilicus is relatively narrow, about 30% of diameter.

The whorl is somewhat depressed, subrounded in cross-section, with steep, high umbilical wall, abruptly rounded umbilical shoulder, gently convex flanks and moderately arched venter which broadens with growth.

In the middle to later growth stages, the ribs are numerous, 21 per half whorl, and of two orders, with longer primaries alternating with shorter secondaries. They are nearly rectiradiate or slightly flexuous on the flank and very gently projected on the venter. Primary ribs are fairly strong, arising at the umbilical seam, nearly rectiradiate in early growth and later somewhat rursiradiate on the umbilical wall, and with prominent tubercles at the umbilical shoulder. Secondary ribs arise at about the mid-flank in early middle growth stages and later on inner flanks or even near the umbilical shoulder. The ribs become gradually coarser in the late growth, when they are faintly bulged at the mid-flank.

On the younger third inner whorl the primary ribs are less numerous. In the middle stage, the siphonal tubercles disappear and the inner and outer ventrolateral ones weaken considerably or almost disappear. In the preserved late stage the inner and outer ventrolateral tubercles become moderately distinct. Whether these tubercles persist or weaken and disappear again on the last part of the absent body chamber, is not known.

The suture shows the normal acanthoceratid pattern as illustrated by Collignon (1937, pl. 8 figs 9, 11; pl. 9 fig. 1).

**Dimensions.** See Table 6.

**Comparison and discussion.** The specimen seems similar to certain forms described as *Calycoceras paucinodatum* (Crick 1907, p. 203, pl. 13 fig. 3) by various authors (e.g. Collignon, 1937, p. 24, pl. 4 fig. 4; pl. 9 fig. 1; Kennedy, 1971, p. 77, pl. 44 figs 1, 2; pl. 45 figs 1-3; pl. 46 figs 1, 2; pl. 47 figs 6-8), from South Africa, the Malagasy Republic and England. According to Wright (Geological Collections, University Museum, Oxford, personal communication, 1989) all species of the so-called *C. paucinodatum* in Kennedy (1971) are *C. (Gentoniceras) gentoni* and Crick's original appears to be a synonym of *C. (G.) sarthacense* (Bayle 1847). Our specimen is certainly not *C. (G.) sarthacense*, because 'the latter has the whorl section higher than wide until the last whorl and the venter is tabulate' (Wright, Geological Collections, University Museum, Oxford, personal communication, 1989). The whorl of our form is broadly subrounded in section and has a moderately arched venter.

Kennedy (1971) mentioned considerable variability in the British material. Our form exceeds the limits of that variability in the much larger original size and in the development of distinct ventrolateral tubercles in at least an early substage of the adult whorl. It may represent a new species. According to Wright & Kennedy (1987, p. 218), macroconchs of *C.*

(*Gentoniceras*) are up to 120 mm in diameter. Our form is much bigger and shows a subrounded, broader whorl section in the main growth stages.

In the genus *Calycoceras* subgeneric separation can be readily applied to certain typical species, but there could remain other species in which the subgeneric characters are not so clearly manifested and the true relationship with typical species is uncertain (see Matsumoto, 1975, p. 101). The present specimen may be an example of such a case.

Our form is somewhat similar to *C. (Calycoceras) boulei* Collignon 1937 (p. 43, pl. 5 figs 2-4; pl. 8 figs 9-11; 1964, p. 126, pl. 365 fig. 1594; Matsumoto, 1959, p. 75 figs 31, 32; pl. 20 fig. 1), especially in the fairly distinct ventrolateral tubercles at a certain late substage. *C. (Calycoceras) boulei* has on average a larger ratio of B/H (1.25 in the lectotype but may reach 1.48 in some others) than that of our form, *C. (Calycoceras) boulei* being closer to typical *C. (C.) naviculare*; the ribs are somewhat bulged at the middle of flank (see Matsumoto, 1959, fig. 31; Kennedy, 1971, p. 73). A similar feature is faintly discernible in the preserved late part (i.e. the middle of late stage) of our specimen.

On the grounds of some affinity with *C. (C.) boulei*, we tentatively refer our form to the subgenus *C. (Calycoceras)*. As only a single specimen from an uncertain stratigraphic position is available, erection of a new species is premature.

*Calycoceras* sp. (subgenus et species indet.)  
(Plate 1 figs 3, 5; Text-fig. 5)

**Material.** CPC 16071 from locality 167, Blucher Range, is incomplete and secondarily compressed as shown by the peculiar narrowing of the next inner whorl.

**Description.** This is a large specimen, about 365 mm in diameter, and entirely septate. Assuming that it is the complete phragmocone and is followed by the body chamber of half a whorl, the diameter of the original shell would exceed 500 mm.

The secondarily compressed whorl expands with a moderate rate and the umbilicus is of moderate width. The preserved half



**Figure 5.** *Calycoceras* sp. indet.  
Suture of CPC 16071,  $\times 7/10$ , at H = 120 mm.  
u.s. umbilical shoulder.

Table 7. Measurements of *Calycoceras* sp. indet. and a slender form of *C. (C.) naviculare*.

Specimen and position	D	U	H	B	B/H	H/h
CPC 16071, E (c)	365 (1)	110 (.32)	143 (.39)	112 <sup>1</sup> (.31)	0.78	1.38
CPC 16071, E-180° (c)	—	—	104	106 <sup>1</sup>	1.02	—
USNM 166367 (c) <sup>2</sup>	155 (1)	43 (.28)	70 (.45)	68 (.44)	0.97	1.56

<sup>1</sup> As the right side is more compressed than the left, B is calculated from the less deformed left half, but the original outline is hardly restored.

<sup>2</sup> A slender form of *C. (C.) naviculare* measured and figured by Cobban (1971, table 2, pl. 15, figs. 1–2).

of the outer whorl is as high as broad followed with rather flat flanks; the venter is well rounded; the umbilical edge is abruptly rounded and the umbilical wall moderately high, steep and slightly incurved. The original shape of the whorl section cannot be estimated accurately because of crushing.

On the preserved part of the outer whorl, primary ribs are robust, arise on the umbilical wall, are elevated and slightly thickened at the umbilical shoulder, nearly rectiradial or slightly prorsiradial on the flanks, and cross the venter with undiminished relief. Secondary ribs normally alternate with primaries and arise at, or inside, the mid-flank. Ribs (20 per half whorl) are elevated and steep-sided where test is preserved, separated by concave, slightly broader interspaces. No tubercles remain on the ribs in the ventral part of the outer whorl, but some of the primary ribs are very gently bulged at about the middle of flank.

On the next inner whorl, ribs are of moderate relief and usually alternately long and short; primaries are more elevated than secondaries and provided with umbilical bullae. Because of preservation, the characters of ventro-lateral and siphonal tubercles are not known.

The suture is of acanthoceratid type, with broad and bifid E/L saddle and L of moderate breadth (Text-fig. 5).

**Dimensions.** See Table 7.

**Comparison and discussion.** As this specimen is badly crushed and the ornament on the venter of its inner whorl is not known, even its subgeneric affinities are difficult to assign. If its flanks were originally more convex, it might be referred to the subgenus *Calycoceras*. Cobban (1971) described *C. (C.) naviculare* from numerous specimens from the Western Interior province, in which some (e.g. Cobban, 1971, pl. 15 figs 1–2; text-fig. 13A) are unusually slender, compared with the much inflated typical forms.

### Genus *Acanthoceras* Neumayr 1875

**Type species.** *Ammonites rhotomagensis* Brongniart 1822 (by subsequent designation of de Grossouvre, 1894).

**Remarks.** For general account of this genus see Kennedy & Hancock (1970, pp. 462–466), Kennedy (1971, pp. 84–85) and especially Wright & Kennedy (1987, pp. 153–156).

Table 8. Measurements of *Acanthoceras rhotomagensis*.

Specimen and position	D	U	U/D	H	B	B/H	h	b	b/h	H/h	C/C + c
CPC 16078, E (c)	94.0	22.5	.24	43.0	47.0 <sup>1</sup>	1.07	28.5	29.8	1.05	1.51	13/22
CPC 16078, LS + (ic)	86.8	20.8	.24	40.0	41.0	1.03	—	—	—	—	12/20
CPC 16078, LS (c)	86.5	19.0	.22	40.0	42.0	1.05	27.5	28.5	1.04	1.45	—
F. 15817, near E (c)	108.5	28.5	.26	50.0	51.0	1.02	30(?)	—	—	1.6(?)	(6/11)
BM. C 18174 (c)	75.0	17.0	.25	36.0	38.0	1.06	22.0	23.0	1.05	1.64	14/25
GK. H 9295 (c)	93.5	26.0	.28	40.0	40.0	1.00	27.5	30.0	1.09	1.46	13/18

*B* is 42 mm because the right side is secondarily compressed; the undeformed left half of *B* is 23.5 mm, which gives 47.0 mm for restored *B*. F. 15817: holotype of *A. merialampiense*, in which (C/C + c) is counted per half whorl. BM. C 18174: holotype of *A. flexuosum* Crick. GK. H 9295: plaster cast of the French specimen in MNHN (Paris) which is similar to but not the same as *Amm. rhotomagensis* of d'Orbigny (1841, pl. 106). C Number of primary ribs, c number of secondary ribs per whorl.

### *Acanthoceras rhotomagensis* (Brongniart 1822) (Plate 5 figs 1, 4, 6)

**Synonymy.** See Wright & Kennedy (1987, pp. 156–158).

**Material.** CPC 16078, from locality 47, Ok Tedi headwaters, a fairly well preserved internal mould with a small part of body chamber preserved.

**Description.** This specimen is 86.5 mm in diameter at the end of its phragmocone. If its body chamber was as long as half the whorl, the entire shell diameter would be about 150 mm. Coiling is less evolute than normal for the genus; the umbilical seam of the outer whorl is inside the row of ventrolateral tubercles of the next inner whorl. The whorl expands at a fairly high rate and the umbilicus is fairly narrow.

Whorls are subquadrate in cross-section, nearly as high as broad, with a flattened venter, moderately sloping ventrolateral facets nearly parallel, flat, or slightly convex flanks, abruptly rounded umbilical shoulders and nearly vertical umbilical walls.

Ribs are of two orders with 13 major and 9 minor ones on the preserved last whorl. Most are gently flexiradial and a few nearly rectiradial; major ribs usually alternate with minor ones. Major ribs start at the umbilical wall, and are moderately to distinctly elevated at the umbilical edge, forming bullate tubercles. Minor ribs start well inside the mid-flank, sometimes near the umbilical margin, but lack distinct umbilical bullae. Ribs are separated by wider interspaces on the flanks, broadened, lowered, projected and tuberculate on ventrolateral part, and very low and broad on the venter, crossing straight across the siphonal line.

Inner ventrolateral tubercles are moderately strong and conical or sometimes slightly clavate; outer ventrolateral tubercles distinctly clavate, prominent and upright, forming wavy outline on the outer margin in lateral view. Siphonal tubercles are also clavate but much weaker (i.e. narrow and lower) than outer ventrolateral ones especially at late growth stages.

Sutures are well exposed, showing pattern typical of *Acanthoceras*, with a broad and bipartite E/L saddle, moderately narrow and deep L, and smaller U2.

**Dimensions.** See Table 8.

**Comparison and discussion.** Our specimen closely resembles the holotype of *Acanthoceras mirialampiense* Wright (1963, p. 606, pl. 85 fig. 1), from the Cenomanian of northern Australia. The latter is, however, regarded as a synonym of *A. rhotomagense* by Wright & Kennedy (1987, p. 157; Wright, Geological Collections, University Museum, Oxford, personal communication, 1989).

Given the high variability in the European population of *A. rhotomagense* (Kennedy & Hancock, 1970; Wright & Kennedy, 1987), this specimen should be identified with *A. rhotomagense*. Some French specimens are similar to, or identical to, the original of *Amm. rhotomagensis* in d'Orbigny (1841, pl. 105, figs 5–6). The latter is the holotype of *Pseudaspidoceras diademum* Hyatt 1903, now generally regarded as a variant of *A. rhotomagense*. Our specimen resembles it in the distinctly clavate outer ventrolateral tubercles and weakening siphonal clavi, as well as in the subquadrate whorl section. A similar feature is shown by the specimen illustrated by Kennedy & Hancock (1970, pl. 96 fig. 1) as 'an intermediate form between *A. rhotomagense* and *A. rhotomagense* var. *clavatum*'. The ribs in these French specimens are somewhat more distant and less flexuous, with fewer intercalated minor ribs than those of our specimen.

In this respect CPC 16078 is similar to BM C18174, the holotype of *Acanthoceras flexuosum* Crick (1907, p. 184, pl. 12 figs 1, 1a) from South Africa, which one of us (T.M.) has examined in London. The latter is now regarded as a variant of *A. rhotomagense* by Wright & Kennedy (1987, p. 189, text-figs 72C, 73A).

***Acanthoceras* sp. indet.**  
(Plate 4 figs 1, 2; Text-fig. 6)

**Material.** CPC 16176 from locality 167, Blucher Range, a fragmentary whorl, mainly internal mould which consists of the last portion of the phragmocone and the adapical part of the body chamber.

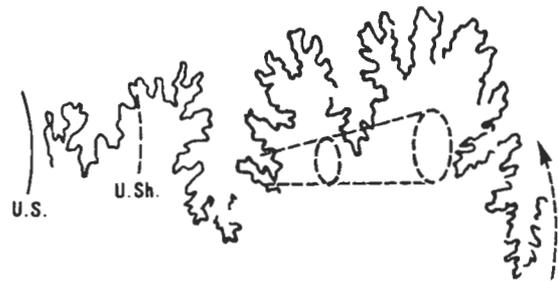
**Description.** The specimen is incomplete but shows fairly characteristic features, such as depressed whorls, with B/H about 1.4 in costal section and 1.25 in intercostal section (Table 9), broadest between the umbilical shoulders, with a broadly arched ventral part, moderately inflated flanks and nearly vertical umbilical wall; coarse ribs alternately long and short in the preserved part, separated by wider interspaces; prominent tubercles at the umbilical shoulder on the primary ribs with inner ventrolateral tubercles stronger on the primary ribs than on the secondaries, outer ventrolateral tubercles clavate and equally of moderate intensity, and only faint traces of clavate siphonal tubercles on the lowered and broadened ribs on the preserved early part of the venter; suture of *Acanthoceras* pattern, with large and deep E, wide, squarish and bifid E/L saddle and rather narrow L (see Text-fig. 6)

**Dimensions.** See Table 9

**Table 9. Measurements of *Acanthoceras* sp. and comparable specimens.**

Specimen and position	D	U	H	B	B/H	H/h	NC
CPC 16076, E (c)	—	—	53	75	1.41	—	5–6
CPC 16076, LS (ic)	—	—	52	65	1.25	—	—
Collignon, 1937 (c)	124 (1)	44 (.35)	48 (.39)	63 (.51)	1.31	—	8
Collignon, 1964 (c)	94 (1)	31 (.33)	37 (.39)	53 (.56)	1.43	1.42	7–8
Crick, 1907 (c)	111 (1)	33 (.29)	47 (.42)	55 (.49)	1.17	1.50	6
Crick, 1907 (ic)	—	—	49	62	1.27	—	5

NC number of ribs per quarter whorl; Collignon, 1937: *A. cottreau*, holotype; Collignon, 1964: *A. cottreau*, hypotype; Crick, 1907: *A. quadratum*, holotype.



**Figure 6. *Acanthoceras* sp. indet.**

Suture of CPC 16076,  $\times \frac{1}{4}$ , at H(ic) = 52 mm and B(ic) = 65 mm. u.sh. umbilical shoulder; u.s. umbilical seam.

**Comparison and discussion.** This specimen resembles the holotype and another illustrated example of *Acanthoceras cottreau* (Collignon) (1937, p. 57, pl. 7 figs 7, 7a; pl. 9 fig. 6; 1964, p. 140, pl. 371 fig. 1615) from the Middle Cenomanian of the Malagasy Republic. However, the difference in size (Table 9) in the preserved part is considerable. The body chamber is about half the whorl in the two specimens from the Malagasy Republic. If the body chamber of this specimen was equally long, the restored outline would be about 180 mm. This is evidently larger than the holotype and other specimens of *A. cottreau*, although dimorphism might explain the size difference.

The ribs in our specimen are more widely spaced and thus less numerous than those on the outer whorl of *A. cottreau*. In the mode of ribbing as well as the pattern of suture, our specimen is similar to the holotype of *A. quadratum* Crick 1907 (Wright & Kennedy, 1987, text figs 72 D–E) from the Middle Cenomanian of Zululand. Crick's specimen differs from ours in its quadrate whorl section. It is now regarded as a synonym of *A. rhotomagense* (Wright & Kennedy, 1987, p. 189).

In our specimen the width of umbilicus cannot be accurately measured and the characters of the inner whorl are not shown.

### Genus *Romaniceras* Spath 1923

**Type species.** *Ammonites deverianus* d'Orbigny 1841

**Remarks.** Kennedy & others (1980) revised *Romaniceras* Spath 1923, concluding that it descended from *Kamerunoceras* Reyment 1954, which in turn was derived from *Euomphaloceras*. They also propose to classify, as subgenera of the genus *Romaniceras* Spath 1923, *Romaniceras* sensu stricto with nine rows of tubercles, *Yubariceras* Matsumoto & others 1957 with 11 rows of tubercles, and *Obiraceras* Matsumoto 1975 with doubling of both the inner and outer ventrolateral nodes, but otherwise similar to *Yubariceras*.

*Neomhaloceras* Matsumoto & Obata 1982 has been added for the ammonites which have 9 rows of tubercles but develop ventrolateral horns or spinose, strong tubercles in the adult stage — a hereditary character from ancestral *Cunnington-*

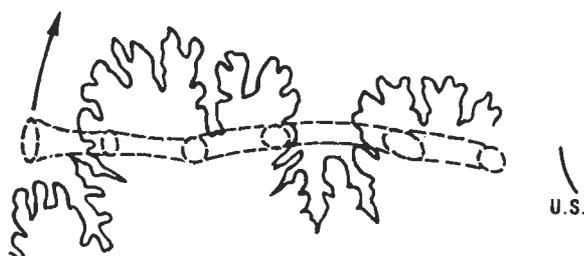


Figure 7. *Romaniceras deverioides* (de Grossouvre).

Suture of CPC 18123,  $\times \frac{7}{8}$ , at H(c) = 63 mm.

u.sh = umbilical shoulder; u.s. = umbilical seam.

*iceras*. *Yubariceras* is defined as an ammonite with 11 rows of tubercles of which ventrolateral ones strengthen on adult shells. We hesitate to use *Yubariceras* for the subgroup of *Romaniceras*. In that group there are initially 11 rows of tubercles; later the ventrolateral ones weaken and are absorbed by prominent ribs in the adult stage. No adequate subgeneric name for this subgroup exists, but *Neomphaloceras* can be ranked as a subgenus of *Yubariceras* in our sense.

***Romaniceras deverioides*** (de Grossouvre 1889)  
(Plate 5 figs 2, 3, 5; Text-fig. 7)

1889 *Ammonites deverioides* de Grossouvre, p. 524, pl. 12 figs 1, 2

1959 *Romaniceras deverioide* (de Grossouvre); Matsumoto, p. 87, pl. 25 fig. 1; pl. 26 fig. 1; pl. 28 fig. 1; pl. 29 fig. 4; text-figs 40–45 (with full synonymy list).

1975 *Romaniceras deverioide* (de Grossouvre); Matsumoto, p. 121, pl. 15 fig. 2; text-fig. 7

1980 *Romaniceras (Yubariceras) ornatissimum* (Stoliczka) (pars); Kennedy & others, p. 348, pl. 39 figs 1–6, 17, 18; pl. 40 fig. 1; pl. 45 fig. 1; pl. 48 figs 1, 2; pl. 49 fig. 8; pl. 50 figs 1–4; text-figs 3C, E, 8

**Material.** CPC 18123, from the Star Mountains, is a reasonably well preserved, probably adult body chamber and the last part of the phragmocone, with somewhat crushed earlier part.

**Description.** A fairly large shell, about 195 mm in diameter at the preserved last part, which is secondarily distorted. The whorl is somewhat depressed (see Table 10), with rounded venter in septate stage and broad, rather flat venter on adoral half of body chamber.

Ribs are of two orders and fairly numerous, 15 for half whorl, separated by interspaces slightly broader than ribs in the septate stage and somewhat broader than ribs on body chamber; normally one, occasionally two, secondary ribs are intercalated between the longer primary ribs.

Tubercles are distinct on septate whorls, in 11 rows of which outer 7 rows are moderately strong and developed on all the ribs. Umbilical and inner lateral tubercles occur on the primary ribs alone, giving the appearance of double tubercles because of closeness. Those of inner lateral row are most prominent on several long ribs at and near the site of the last septum.

On the body chamber, tubercles persist to some extent, with a tendency to weaken and become obsolete towards the aperture, where the median ventral tubercle disappears and upper and lower ventrolateral tubercles are united into bullate culmination on the rib, forming a subrounded ventrolateral shoulder. The outer lateral tubercle gradually changes to a bullate swelling on each rib and inner lateral and umbilical tubercles tend to be united into a bullate thickening of long ribs around umbilicus. The preserved last part of body chamber is heavily ribbed.

**Dimensions.** See Table 10.

**Comparison and discussion.** *Romaniceras deverioides* (de Grossouvre) is known from the Middle Turonian of France, southern England, Tunisia, the Middle East, Malagasy Republic, Mexico, Texas, California and Japan.

On the basis of a large collection from the type area of France, Kennedy & others (1980) recognised great variability of *R. deverioides*, and concluded that *Ammonites deverioides* de Grossouvre 1889 is a synonym of *A. ornatissimum* Stoliczka 1865 from southern India. The latter was established on a single imperfect specimen, and there has been no subsequent study of its population in southern India. We believe that the available material from India is insufficient for an adequate comparison, and we do not use *R. ornatissimum* for our specimen, although Ayyasami & Banerji (1984) followed Kennedy & others (1980) in regarding *R. deverioides* as identical with *R. ornatissimum*. The holotype of *A. ornatissimum* has an inner lateral tubercle widely separated from the umbilical tubercle and situated at the mid-flank on both the outer and the next inner whorls. The tubercles in the ventral three rows are weakened on the preserved part of the body chamber, but other tubercles persist distinctly.

**Occurrence.** *R. deverioides* occurs characteristically in the Middle Turonian of the stratotype section of France and has a worldwide distribution.

Kossmat (1897, p. 18) recorded the locality of Stoliczka's holotype as 'east of Odium' from dark coloured sandstone of upper division (in tripartite scale) of the Utatur Group, which should be referred to Lower Turonian. Ayyasami & Banerji (1984) stated that Kossmat's assignment was incorrect and that *R. ornatissimum* and *R. deverianum* (d'Orbigny) (= *Ammonites medlicotianus* Stoliczka) belong to the lower part of the Trichinopoly Group and consequently are Middle Turonian in age.

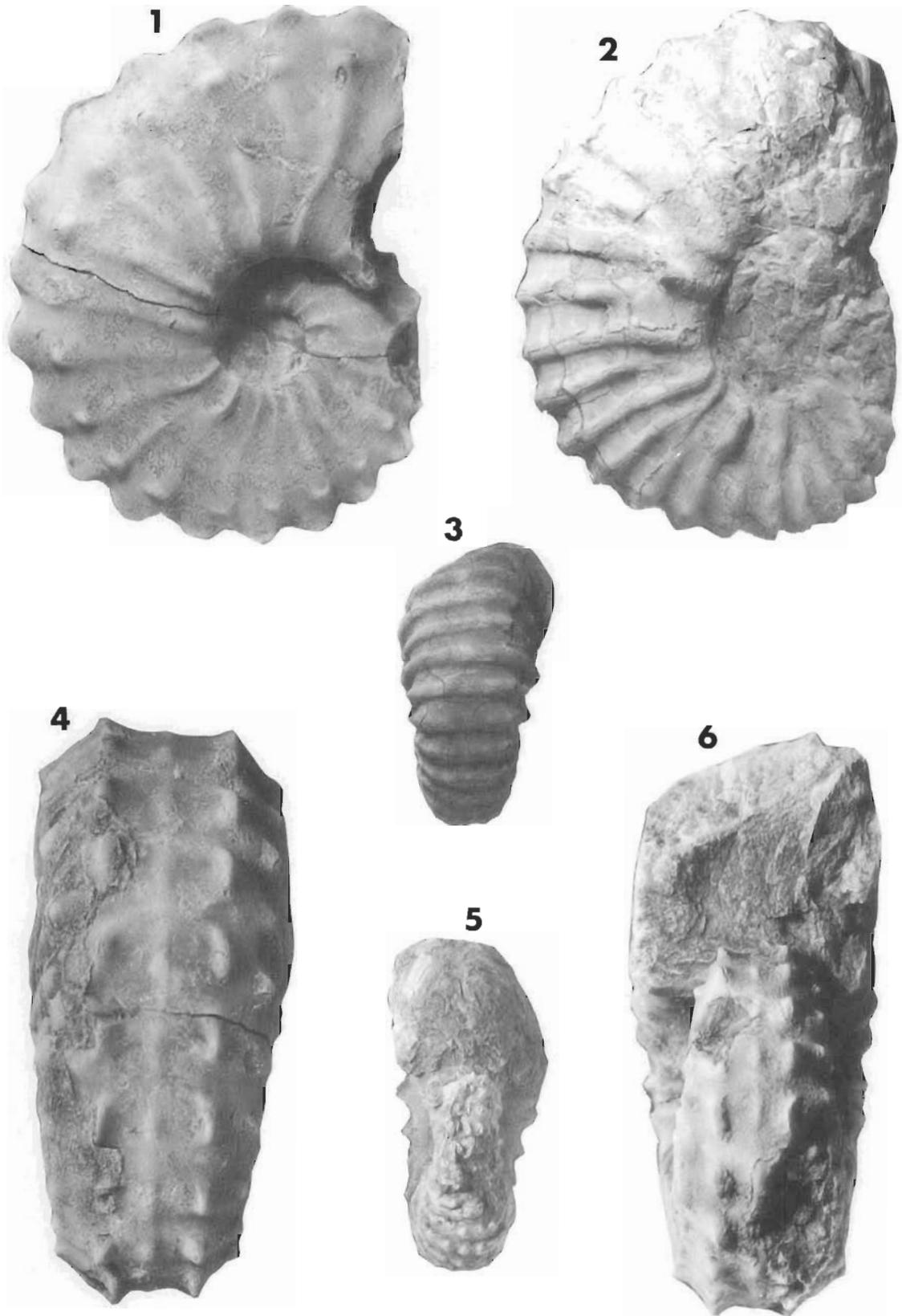
## Conclusions

Of the 11 species described here from the Ieru Formation, 5 are identified with well known species of widespread distribution. Two others (*Chimbuites* aff. *mirindowensis* and *Placenticeras* aff. *tamulicum*) are allied to, or identical to, known species. Only one species, *Pachydesmoceras* sp. nov., is certainly new; another, *Calycoceras* (C.) sp. nov. (?), is possibly so. From the occurrence of previously known species, the age of the faunas at localities 47, 167, and 187 is Cenomanian (probably Middle Cenomanian), that of locality 13 is probably Middle Turonian, and that of the Star Mountains specimens Middle Turonian–Santonian.

Table 10. Measurements of *Romaniceras deverioides*.

Specimen and position	D	U	H	B	B/H	NC
CPC 18125, E-50° (c)	180.0 (1)	51.0 (.28)	78.0 (.43)	90.0 (.50)	1.15	14–15
CPC 18125 E-180° at LS (c)	126.0 (1)	35.0 (.28)	56.0 (.44)	68.0 (.54)	1.21	14–15
Lectotype, LS + 90° (c)	123.0 (1)	38.0 (.31)	52.0 (.42)	~59 (.48)	~1.13	13–14

NC number of ribs for a half whorl. The illustration of lectotype by Kennedy & others (1980, pl. 48, figs 1–2) is  $\times 1.12$ .



**Plate 5.**

All specimens are coated with ammonium chloride and photographed in lateral view unless otherwise stated.

**1, 4, 6.** *Acanthoceras rhotomagense* (Brongniart 1822); locality 47, headwaters of Ok Tedi; Cenomanian;  $\times 1$ . CPC 16078, a fairly well preserved specimen. **1**, lateral view. **4**, ventral view. **6**, end-on view. **2, 3, 5.** *Romaniceras deverioides* (de Grossouvre 1889); locality 134, Star Mountains; Middle Turonian? CPC 18123, a partly distorted and obscured specimen. **2**, lateral view,  $\times \frac{1}{2}$ . **3**, ventral view,  $\times \frac{2}{3}$ . **5**, end-on view,  $\times \frac{1}{2}$ .

Species of *Chimbuites* are taxonomically and palaeobiogeographically problematic. The occurrence of a very large, probably new form allied to *C. mirindowensis* in the Cenomanian of western Papua New Guinea is noteworthy.

## Acknowledgements

We thank the Director of the Bureau of Mineral Resources, Canberra, and the Director of the Papua New Guinea Geological Survey for the permission to publish on the fossils collected by their geologists. We wish to thank Professor G.E.G. Westermann and Dr. C.W. Wright for their critical reading of the manuscript. Thanks are extended to Miss Akiko Murakami and Miss Kazuko Hara, both of Fukuoka, for preparing the final typescript.

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\* Accessible on Geological Survey Papua New Guinea data catalogue.

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## Earthquake fatalities in Australia

H. A. Doyle<sup>1</sup>

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It has usually been assumed that the first known fatal earthquake in Australian history was that at Newcastle, New South Wales, on December 28 1989, when 12 deaths resulted (McCue & others, 1990).

However, in a note in the newspaper *The Western Australian* of January 25 1940, the State Government Astronomer of the time, Mr H. B. Curlewis, mentions 'tremors' in the Kalgoorlie district on August 29 1917 which resulted in the death of one man and injury of several others. Mr Curlewis wrote that 'the tremors caused a loud collapsing of rock masses from the roofs of tunnelling' and 'were accompanied by loud reports and peculiar rumblings', and that they were also felt at Denmark, Albany and Breaksea Island. These occurrences were listed by Everingham (1968).

It is likely that this was a natural earthquake (perhaps several) and that the death was the first recorded in our earthquake history. Optimistically Mr Curlewis went on to say that 'resting as it does on firm granite foundations the State is never likely to

be disturbed by anything of a serious nature'. Recent history has not confirmed his optimism.

I also recall a small earthquake near Wollongong in 1963 at the time of a rock-fall in an underground coal mine which caused a fatality. Whether this was caused by a natural tremor is uncertain.

Spottiswoode & McGarr (1975) report that far-field measurements indicate that mine tremors (rock-bursts) are highly similar, if not identical, to natural crustal earthquakes.

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## ABSTRACTS: ARID ZONE WATER CONFERENCE, 11-14 APRIL 1991, ALICE SPRINGS

### Arid zone water: a finite resource

The conference, held at Alice Springs from 11-14 April 1991, was organised by the ANU Centre for Continuing Education (as one of its series on Issues in Water Management) in co-operation with the BMR and Northern Territory Power and Water Authority. It was attended by 125 people, representing community organisations, government agencies and mining companies. The conference was opened by the Hon Fred Finch, Northern Territory Minister for Transport and Works, and the keynote address was given by the Hon Ernie Bridge, Western Australian Minister for Water Resources.

The conference drew attention to the special needs of arid zone communities, which result from low population, remoteness, high climatic extremes, and variability of resources available. Assessment, development and operation of water supply systems is therefore expensive. On a national scale, arid zone hydrological and water supply problems have been given relatively little attention compared with the problems of major cities and agricultural regions.

Arid zone water resources (mainly groundwater) are generally adequate overall for present development, but are subject to local depletion. In water-scarce areas, various strategies can be used to conserve and manage water resources more effectively. These include appropriate horticulture and water care strategies which have been used successfully in certain planned mining towns. Wider application requires that individuals and communities take responsibility for their water usage. Education, community involvement and appropriate pricing structure are necessary to achieve this.

Water supplies in remote small communities are commonly inadequate in quantity or quality. People living in remote communities have a right to basic safe water supplies. Special considerations apply to remote Aboriginal communities where community involvement and ownership of water supplies are necessary to ensure that cultural values are taken into account in developing appropriate technical decisions.

Arid zone water features, such as rock pools, mound springs and salt lakes, are ecologically fragile, and are increasingly at risk from tourism and other developments. These water features need appropriate protection.

Further development and management of arid zone water resources will require improved and accessible information systems such as water-bore data bases and groundwater resources maps. The conference also identified research and development needs, including techniques for improving water use efficiency and widening the scope for saline water use. Im-

portant research needs are better definition of arid zone groundwater recharge with regard to the sustainable development of local aquifers, and the development of desalination technology appropriate for small settlements.

G. Jacobson<sup>1</sup>  
(for the Organising Committee)

<sup>1</sup> Groundwater Program, Bureau of Mineral Resources, Canberra

### Water resources development in the Northern Territory's arid zone

Peter McDonald<sup>1</sup>

The arid zone of the Northern Territory is one of the world's more sparsely populated areas, with an estimated population of 45 000 occupying 12% of Australia's land mass. The region is mainly dependent on groundwater for provision of water supplies. Annual water usage for all purposes is estimated at 45 000 ML. Compared with the estimated divertible groundwater resources of 2 870 000 ML, the rate of extraction is insignificant.

Problems of resource overuse are, however, of growing concern, due to the spatial distribution of readily usable water sources, and the difficulty of matching these to development requirements and community expectations. Due to climatic realities, the oft-expressed concept of 'greening the red heart' is unattainable. There is, however, the potential for intensive and sustainable water-dependent development, subject to rigorous assessment of both water source potential and site economics, and sound resource management practice.

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### An overview of arid zone water supplies in Western Australia

Derek Hopkins<sup>1</sup>

Western Australia occupies about one-third of the Australian continent and is mostly arid and semi-arid. It has a large and increasing number of remote communities and activities dependent upon local water supplies in these arid regions.

Surface water supplies are often not available because of the irregular and infrequent nature of the rainfall. In those areas where large surface water flows provide potential for development, high evaporation losses make potable-quality surface water supply development almost impossible without the conjunctive use of groundwater. Two major conjunctive use schemes operate within the Pilbara region, providing freshwater for town water supplies and mining developments.

Limited use is made of desalination of non-potable quality water. However, as the costs of

this technology fall, it is becoming a more favourable option to that of transporting freshwater over long distances.

The Water Authority operates 17 water supply schemes for towns in the arid zone, and more than 150 schemes for aboriginal community water supplies. These schemes vary in size, the largest drawing up to 11.5 ML/year. Aboriginal communities and outstations present the fastest growing area for water supply development and present opportunities for innovation in development and treatment. Facilities range from hand pumps, low capacity 12-volt pumps and solar systems to more conventional electric and diesel installations.

Exploitation of fresh groundwater resources is on a sustainable yield basis, which presents a considerable challenge in areas where recharge rates are often less than 1% of rainfall. There is also extensive use of brackish, saline and hypersaline groundwater for mining and mineral processing. The management of these resources to maximise their utility is another challenge to the State.

The development of new water supplies in these arid areas is difficult because of the limited information on hydrology and hydrogeology. Investigation programmes to find and develop these supplies are often expensive and commence with considerable uncertainty about the likelihood of success. The varied hydrogeological environments present opportunities for a wide range of investigation techniques.

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### Saline water resources in arid zone drainage basins of Australia

Aro Arakel<sup>1</sup>

Saline groundwater is a ubiquitous feature of inland drainage and palaeodrainage basins in arid regions of Australia, recorded from over two-thirds of the continent. The highest concentrations of saline water are recorded from playa lakes developed in topographic or structural depressions of drainage basins, where a delicate balance between groundwater inflow and excessive evaporation maintains the watertable within the upper few metres of the playa beds. Shallow unconfined aquifers may also contain highly concentrated groundwater solutions confined to buried, but often interconnected, channels of the palaeodrainage systems.

Most palaeodrainage basins in the Australian arid zone date back to Tertiary and Quaternary times (2-70 Ma B.P.), when the drainage channels were progressively being filled in with fluvial and lacustrine sediments. From

the Pleistocene (120 000 years B.P.) onwards, with the incidence of sustained periods of aridity, the drainages and lakes contracted, resulting in chemical sedimentation. As a result internal drainage basins were developed, where the modern playa lakes now act as outlets for discharge of shallow and highly saline groundwater.

Limited investigations of the internal drainage basins in Australia indicate that chemical deposition of silicates (authigenic feldspars, clays, silica, zeolites, etc.), carbonates (calcrites, dolomite, magnesite) and evaporites (sulphate and/or chloride salts) occurs in distinct hydrological zones. This particularly applies to evaporite deposits which are confined mainly to playa beds and contain the bulk of highly saline groundwater solutions.

During recent years, exploration for industrial minerals in arid zone drainage basins of Australia and overseas has entered a new phase of activity, as mineral economists have begun to identify near surface high-value salt minerals and brines ideal for low-cost resource development. The commercial potential for such commodities is reflected in high market prices and increasing demand for industrial salt minerals for established and emerging applications. Recent investigations indicate that some of the arid zone drainage basins in central Australia contain large volumes of hypersaline groundwater with chemical characteristics suitable for sequential extraction of a number of commercially valuable industrial salts. Results from limited experimental work carried out so far on such brines indicate the possibility of producing a variety of industrial salts by multiple evaporation and cooling techniques, using natural variations in local climatic conditions to achieve thermodynamic requirements. Saline groundwater may also be utilised to modify silicate mineral structures to increase their absorption capacities by sieving effects. The resultant mineral products could have a wide range of industrial applications, including waste water treatment, and hence offer further opportunities for arid zone resource development. Other important but indirect application areas of saline water relate to solar energy technology (e.g. as a medium for immersion of solar panels to increase the heat retention capacity of the panels) and biotechnology (e.g. algae production and brine shrimp harvesting).

Overall, because of simplicity and minimal requirements for controlling the operational conditions during changes in environmental conditions, salt production from saline groundwater of the arid zone drainage basins appears to be technically and commercially viable in the short to medium term. At present, apart from halite, most high-value industrial salts required for utilisation by Australian manufacturing, chemical, rural and mineral industries are imported at elevated costs. Thus, saline groundwater is potentially a prime target for resource development in a cost-effective and environmentally friendly way. Unfortunately, a proper assessment of the brine resources in Australian arid zone is overdue, despite strong support by state and federal governments for technological research in new minerals and processing fields. A meaningful evaluation of such resources for establishing a viable salt industry with 'down-

stream' developments would require generation of new information to satisfy technical requirements, as well as the socio-economic and environmental impacts. For example, consideration should be given to inherited constraints commonly associated with sustainable development in our arid regions. Of particular relevance to this meeting are the questions of groundwater requirements for resource development, and whether alternative technologies with lower water requirements but relatively higher overhead costs are economically viable. Knowledge acquired in assessing salt production technology and economics can also be utilised to develop new technologies for processing saline waste water — a common environmental problem menacing agricultural, mining and industrial activities in many Australian arid and semi-arid regions.

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## Water and mining in the arid zone

### D. Armstrong<sup>1</sup>

There are four major areas in which the mining industry and the nation's water resources interface:

- water supply
  - township supplies (potable water)
  - industrial process water (including dust suppression)
- mine dewatering (including disposal of re-use of water)
- process waste disposal (slimes dams)
- sewage effluent disposal.

All have the potential to impact on the environment and for new mining ventures are carefully scrutinised under the process associated with the Environmental Impact Statement (EIS).

In the arid zone the most critical aspect of a mining feasibility study, assuming that a commercial ore deposit has been found, is usually related to the provision of an adequate water supply for both the human and industrial needs of the project. Where surface water is scarce, the salinity of groundwater is often too high to be of direct use for domestic purposes but the scale and economics of a major mining venture may allow for desalination of at least the township supplies.

The scarcity and high cost of water in arid zone mining centres has resulted in water conservation practices which are often unmatched in the cities. Water is re-used wherever possible, for instance in irrigation of playing fields with treated sewage effluent, the use of mine dewatering water for dust suppression and to supplement process water, and harvesting stormwater run-off for re-use. Conjunctive use of surface and groundwater and innovative horticultural water use are also practiced by the mining industry in the arid zone.

Advances in extractive metallurgical processing technology have enabled many gold mines to operate with highly saline process water.

Mining projects contribute to our knowledge of arid zone hydrology and hydrogeology by keeping comprehensive records of rainfall and

groundwater response, which are reviewed by government agencies.

The potential environmental impacts of mining industry water supply schemes have been put forward by the anti-mining lobby as reasons for not proceeding with new mines, usually without any valid scientific support or understanding of the physical processes involved and, most importantly, without grasping the fact that a mineral deposit is finite and a mine will have a finite life which is extremely short in the time scale of natural processes and events in the arid zone.

One of the greatest threats to the stability of the arid zone environment comes from the recreational activities of the mining community and tourists drawn to the area because a centre of population with some facilities has been established at the mine site.

Four mines in very different geological settings will serve to illustrate some of the interesting features of mines and their water supply systems in the arid zone.

**Leigh Creek** (Coal mine — Electricity Trust of South Australia) in the northern Flinders Ranges, South Australia, has an average annual rainfall of 180 mm and evaporation in excess of 2500 mm. The original township and mine, established in 1944, depended on water from a nearby abandoned copper mine (Sliding Rock) until the completion of Aroona Dam in 1955. Expansion of the mine and the development of a new township at Leigh Creek South in 1980 necessitated a review of water supply arrangements. Available climatic records were analysed, and inflows to Aroona Dam were predicted to be insufficiently regular to sustain the larger population. An intensive search for groundwater (Read, 1990) located adequate supplies in fractured rock at salinity levels which required desalination, and during the period 1982–86 four stages of reverse osmosis plant were installed. Apart from regular running to ensure that the plant operates, only the pretreatment section of the plant has been extensively used to clarify Aroona Dam water either when levels are low or after a major intake when suspended solids are high. Major rainfall events have been more frequent than predicted. Several minor recharge events have been recorded in observation wells at the borefields, and the groundwater system, an excellent, if expensive, insurance policy, would be used in a drought.

**Telfer Gold Mine** (Newmont Australia Ltd), at the edge of the Great Sandy Desert in Western Australia, has an average annual rainfall of around 250 mm and evaporation of 3800 mm. The water supply for the mine and township comes from fractured rocks via 36 pumping wells in 5 geological settings, only two of which supply potable water. The maximum estimated process water requirement of 4.8 million m<sup>3</sup>/year will come partly from borefields whose primary objective is dewatering of the mine workings, and partly from water supply borefields up to 20 km from the mine. Since mining began in 1977, 65 production bores have been commissioned; 29 of these have been lost either from expansion of the mine working or depletion of the groundwater resource. In the Aggregate Fault borefield, two bores operated from 1976 to

1980 at 300 m<sup>3</sup>/day until the operating water level approached the pump inlets and the field was abandoned. The Passmore Fault borefield, in what appears to be a similar geological setting, has been operating successfully since 1975 with 9 bores and an installed capacity of 5760 m<sup>3</sup>/day. The mine has ore reserves which, depending on economics, could last for more than 100 years. It will be interesting to see whether the limiting factor on the life of the mine is ore reserves or water supply. If 5 million m<sup>3</sup>/year of water is used, a storage of 500 million m<sup>3</sup> will be needed over 100 years, which might occupy a volume of about 500 km<sup>2</sup> saturated to a depth of 100 m if the water resource is considered to be fixed. Alternatively, the same 500 km<sup>2</sup> would require an average annual recharge of 10 mm to meet the projected demand. A review of monitoring well hydrographs in conjunction with rainfall records will indicate whether or not any recharge is occurring.

The **Olympic Dam** copper/gold/uranium mine (WMC/BP), on the Stuart Shelf in South Australia, has an average annual rainfall of 150 mm and evaporation of >3000 mm. Groundwater near this major underground mine is saline (20 000mg/<L) and occurs sparsely in fractured quartzite which overlies the orebody. The mine's water supply comes from the southern margin of the Great Artesian Basin via a 100 km pipeline which carries raw water (2000mg/<L), most of which is used as process water. At the mine site a reverse osmosis plant reduces salinity to potable levels to supply the township of Roxby Downs. Groundwater entering the mine workings is pumped to surface and together with additional water from a local 'saltwater' borefield is used for dust suppression. In addition, the occasional stormwater runoff is harvested and used for irrigation. Some claypans in the general vicinity of the mine still contain significant quantities of fresh water after the heavy rains of March 1989. Access to some of this water either for consumption or recreational use is not permitted out of respect for the wishes of the local aboriginal community. The water supply from the Great Artesian Basin is secure and at 10 ML/day represents only a small percentage of the total water discharging from the Great Artesian Basin in South Australia through controlled and uncontrolled water wells, discharge associated with the production of oil and gas, natural springs and evaporative discharge.

During the preparation of the EIS much was made of the sensitivity of the mound springs, their biological and cultural significance and possibility of degradation by impacts of the mine water supply scheme. Environmentally sensitive springs were identified and are protected by the management strategy which does not regulate the withdrawal of water by volume but does so by limiting the permitted drawdown observed at the boundary of a proclaimed area. This boundary passes within 4 km of the Hermit Hill group of springs which was identified as being of particular significance. Monitoring, discussed by Waterhouse & Armstrong (in press), reveals that about half the permitted drawdown has occurred at that boundary and no impact has been seen on spring flow or aquifer pressure at Hermit Hill. Woods & others (in press) indicate that, at the southern margin of the GAB,

water is moving upwards and evaporating in the soil, just below the surface, at the rate of a few millimetres per annum. Over a large area, reduction or reversal of this flow accounts for a significant portion of the water produced in the borefield and explains the restricted area within which drawdown due to pumping can be observed.

**Granites Gold Mine** (North Flinders Mines Ltd), in the Tanami Desert, Northern Territory, has an average annual rainfall of around 430 mm and evaporation of 3750 mm. The mine has a fly-in fly-out population with 150 people on site at any one time. Its water supply is derived from a palaeodrainage system composed of calcrete overlying alluvium. In contrast to the other mines described, the production wells are very shallow and the water requirements very modest (0.5 million m<sup>3</sup>/year). Domahidy (1990) describes the hydrogeology of the area surrounding the mine and estimates that the annual recharge to the palaeodrainage system could be as much as 150 times annual usage at the mine.

If the life of a mine which depends on a limited groundwater storage is shorter than the estimated life of the water resource, there is no problem when the mine is the only user of that resource. The water resource is being 'mined' but will outlast the demand and may even experience a major recharge event during the life of the mine. A probabilistic approach to forecasting such events may have some merit in terms of forecasting the life span of a limited resource and the recovery of that resource on completion of mining. To prohibit mining of a mineral deposit because of apparent limitations to water supply is a pointless exercise especially if there is no other demand upon that resource (although the ultimate in resource conservation is to not use the resource at all). The mining company takes a calculated risk based on economic considerations and takes the consequences if it runs out of water just as it does when estimating ore reserves. Current thinking on the assessment of quantities of water available in the arid zone tend to be based on an assumption that resources are static (finite) when in fact they are dynamic although on a time scale that is perhaps erratic and very different from that of a temperate zone water system.

Although the mining phase is finite, mining wastes are a permanent residue which may or may not be modified by weathering processes. To avoid undesirable environmental impacts, mine tailings, dams or other structures must be engineered to contain toxic wastes where such wastes exist. It must also be remembered that before mining, the minerals were exposed to the native groundwater system either above or below the water table.

Like all other industries, the mining industry will tend to comply with the lowest possible standards in order to reduce costs. In the past, there were no standards and the industry had a reputation for causing environmental disasters which is very hard to cast off. The community, through its legislators, must ensure that standards are set and understood, so that safe and environmentally acceptable disposal of wastes is considered in the early stages of feasibility analysis and financial provision is made for

maintenance after the cessation of mining if necessary.

Technical aspects of water in mining in the context of environmental protection are receiving increasing attention (International Mine Water Association, 1982, 1985, 1988). Mining in the sparsely populated arid zone may have very little impact on people but the need remains for careful management, especially of the disposal of wastes.

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## Industrial use of saline water for gold processing in Western Australia

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The gold mining industry in Western Australia is mainly located within the Eastern Goldfields region, centred on the town of Kalgoorlie. The growth of the region, and of the gold mining industry, was restricted in the late 1890s by the lack of available fresh water. Potable water was imported into the region by camel trains; later, desalination plants were established using wood-burning condensing batteries which led to the creation of both water supply and wood cutting companies. The absence of sufficient fresh water, both groundwater and surface water, resulted in the construction of a pipeline to Kalgoorlie from Mundaring Weir, some 600 km away near Perth. The famous original wood stave pipeline, commissioned in 1903, has long since been replaced by steel pipe and the water supply network progressively expanded to include smaller mining centres and farming communities along the way. The pipeline, now known as the Goldfields and Agricultural Water Supply (G & AWS) scheme, provided an assured supply of

fresh water, enabling the permanent establishment of industry in the Goldfields.

The use of fresh water by the mining industry was not only convenient, but there were penalties for those companies using alternative water supplies if water was available to them from the pipeline (Dundon, 1988). The by-laws of the Agreement between the Minister for Works and The Kalgoorlie and Boulder Water Trust included provisions allowing the Minister to impose fines of £500 upon offending members of the Trust. In addition to this inducement, the convenience of a reliable fresh water supply resulted in the gold mining industry using this water almost exclusively until the early 1980s.

Therefore, for a long period from 1903 to 1980, there was little exploration for groundwater for mining purposes in the Eastern Goldfields, except for those smaller operations not connected to the G & AWS scheme. The rapid growth of gold mining activity in the 1980s and the commensurate increase in water demand began to stress the supply capability of the G & AWS scheme to the point that an upgrade to the pipeline was becoming a real possibility. However, because the capital cost of the upgrade would be borne by the mining companies on a pro-rata basis with new water allocations, and these capital contributions would be large, the companies began to consider other options. It was quickly realised that the only alternative supply available in sufficient quantities was saline groundwater.

#### Metallurgical factors

Until the 1980s, it was widely accepted by the operators that saline water either would not work for gold processing or would be prohibitively expensive. This belief was largely due to the fact that, before the 1980s resurgence of the gold industry, the existing mines were generally processing high grade refractory ores. With refractory ores, saline water does cause problems such as gold volatilisation in roasters (due to the high chloride content), corrosion in pressure vessels, and the death of beneficial bacteria.

However, the new projects of the 1980s mostly were mining oxide ores and using the relatively new CIP/CIL (carbon in pulp/carbon in leach) gold recovery processes. Although the operators still preferred fresh water, it was soon discovered that there were no insurmountable problems associated with the use of saline and even hypersaline water in the CIP/CIL circuits. There is an increase in reagent costs to raise the pH to 9–9.5, and a higher cyanide consumption when operating in this pH range.

Although cyanidation is more efficient in the pH range 9.5–10.5, a pH above 9.5 leads to significant precipitation of metals and salts from the saline water and can cause severe scaling and carbon fouling. Most operators therefore accept a lower cyanidation efficiency to avoid these more troublesome side effects at a higher pH. Corrosion control and maintenance are generally not major problems if the plant design anticipated the use of saline water. In addition to the large scale use of saline water, small quantities of potable water are still required in the gold elution circuit and

for on-site domestic purposes. These fresh-water supplies are generally drawn from the G & AWS scheme and, if this is not possible, supplied by desalination.

#### Climate

The climate of the region is semi-arid to arid with an increase in rainfall towards the south-southwest. Kalgoorlie receives an average annual rainfall of ~230 mm, with a range from about 120 mm to 490 mm. The open pan evaporation (Australian Sunken Tank) is ~2400 mm/year. The occurrence of rainfall is irregular, particularly in the northern part of the Eastern Goldfields; most large rain events are related to tropical cyclone activity from January to April. Although cyclonic disturbances are rarely seen this far south, their effects are significant. The largest monthly rainfall of 314 mm one February was the result of such an event. Most rainfall within the region is received from eastwards-moving cold fronts originating in the Indian and Southern Oceans during the cooler winter months. Local thunderstorm activity in summer adds to the totals. Monthly pan evaporation greatly exceeds the average monthly rainfall in all months except when the infrequent cyclonic-influenced events occur.

#### Geology and hydrogeology

The Eastern Goldfields Province covers ~350 000 km<sup>2</sup> and occupies the eastern half of the Archaean Yilgarn Block. The geology has been described in detail by Williams (1975) and Griffin (1989)

Intrusive granite and gneiss approximately 2900–2500 Ma old comprise 70% of the province and underlie, enfold and envelop metavolcanic and metasedimentary rocks that are generally older than the granitoid rocks. The metamorphic rocks, or greenstone belts, usually occur in north- or northwest-trending assemblages. The granite rocks are, in general, deeply weathered with poor exposure, and this results in large areas of sandplain and kaolinised pallid zones beneath a superficial ferruginous cover. The greenstone belts are more resistant to weathering and form most of the significant topographic features of the region. The local relief in and around these hilly areas rarely exceeds 200 m.

The Province has been subjected to terrestrial conditions since at least the early Mesozoic. Lateritic profiles developed during the warm and humid conditions which prevailed during the Tertiary. Well developed major surface drainages were active at this time, flowing southeastwards toward the sea which occupied what is now the Eucla Basin. These drainages became choked with sediment with the onset of arid conditions during the mid-Tertiary and now comprise chains of salt lakes which dominate the physiography of the Eastern Goldfields. Active surface drainage between the salt lakes is now extremely rare.

Tertiary fluvial sediments of clays, silts, and sands and gravels, mantled by Recent sediments, now occupy the palaeochannels. The palaeochannels are incised into the basement rock complexes and the coarser basal deposits are up to 1 km wide, although more commonly ~500 m. The sands, a basal lag deposit, range in thickness from <1 m near

the headwaters to >50 m in the downstream trunk channels.

The stratigraphy of the Tertiary sediments has recently been described by Kern & Commander (1990) who have divided the sediments into two formations. The sands and gravels comprise the Wollubar Sandstone of Middle Eocene age, and the overlying clays define the Perkolilli Shale of the Late Eocene. The combined thickness of the two formations is typically around 50 m, increasing to 100 m further downstream in the trunk drainages. Groundwater occurs within the fractured and weathered basement rocks, the surficial alluvium and the deep Tertiary sediments. In the Kalgoorlie region the Wollubar Sandstone is by far the most significant aquifer in terms of distribution, yield and total groundwater storage. The generally unconsolidated sands are highly permeable, and typically result in individual bore yields of 500–2000 kL/day. The aquifer is usually found confined by the Perkolilli Shale and there have been very few reliable tests of the specific yield. The lithology suggests that the linked porosity is in the range 15–20% and that the specific yield would be similar.

#### Groundwater quality

Groundwater quality has been observed over the range from potable to hypersaline within the various rock units. Most workers recognise four broad water quality classifications (although the boundaries may differ somewhat):

potable	<1500 mg/L
brackish	1500–10 000 mg/L
saline	10 000–50 000 mg/L
hypersaline	>50 000 mg/L.

The Wollubar Sandstone aquifer consists of saline and hypersaline groundwater. In the central drainage areas, salinity is generally >100 000 mg/L and commonly above 200 000 mg/L. With distance away from the central valley areas, both towards the headwaters of the catchment and along tributary channels, salinity is markedly lower, down to ~20 000 mg/L.

Sodium and chloride are the dominant ions in the saline and hypersaline waters, forming ~99% of the total dissolved salts. The relative concentrations of magnesium and sulphate are highest towards the catchment margins, as are calcium and bicarbonate, but these constituents progressively precipitate out as the salinity increases down-gradient towards the salt lakes.

#### Groundwater resources and utilisation

Several studies have been carried out to estimate the total groundwater resources available, particularly those of the Wollubar Sandstone. A regional study of water demand and availability (BHPE and AGC, 1988) concluded that this palaeochannel aquifer has a total groundwater storage of 1400 x 10<sup>6</sup> kL within a 100 km radius of Kalgoorlie. A stratigraphic drilling investigation of the Roe Palaeodrainage (the major palaeocatchment in the region) concluded that the Wollubar Sandstone contains a groundwater storage of approximately 600 x 10<sup>6</sup> kL (Commander & others, 1990), which compares well with 700 x 10<sup>6</sup> kL calculated for the same area in the BHPE and AGC (1988) study.

The combined groundwater resources of all

other aquifers in the region are approximately an order of magnitude less than that of the Wollubar Sandstone. However, although much lesser in quantity, these resources are commonly significant, because they are better quality and provide the limited groundwater used by pastoralists and the smaller mining operations located away from the palaeochannels.

The large increase in mining activity and the importance of saline and hypersaline groundwater to this growth is demonstrated by the water consumption totals for the region, shown in Table 1.

**Table 1. Water consumption in the eastern Goldfields region.**

Year	Fresh water (10 <sup>6</sup> kL/year)	Saline water (10 <sup>6</sup> kL/year)
1984	4.3	1.2
1988	5.4	15.4
1990 (projected)	6.5	32.6

Source: BHPE and AGC, 1988

There are no reliable data for the actual 1990 consumption, but it is unlikely that the projected demand for the saline water was achieved. Several proposed large projects either failed to reach fruition or did so at a reduced scale of operation, and other planned expansions to existing mines were postponed or cancelled. Based on the actual consumption totals for approximately half the mines and a subjective appraisal of the others, it seems likely that the 1990 saline water consumption was about 15–20 × 10<sup>6</sup> kL. Recycling of process water via tailings dam recovery systems averaged around 25%.

The proven or reliably estimated groundwater resources within the immediate vicinity of the existing or proposed gold mining operations are many times the projected demand and are expected to supply the industry for the foreseeable future.

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### Progress in the development of a water care ethic for the Pilbara region of Western Australia

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Nicholson & Edgecombe (1986) described water conservation techniques being applied in the arid Pilbara region of Western Australia. This paper outlines what has been happening since then.

The Karratha scenario is a daunting one for water conservation, with compacted heavy clay water-shedding soils, an evaporation rate ten times the mean annual rainfall (<300 mm), summer temperatures above 40°C, and long periods without rain. Like all Pilbara mining towns, Karratha was developed from bare ground over the past 25 years. Water supplies were drawn mainly from underground sources and domestic consumption was heavily subsidised. Water was used copiously to create gardens reminiscent of a less harsh environment.

Since the boom times, mining companies have adopted more realistic policies on private and public water use. With the introduction of home ownership schemes, they replaced water subsidies with generous incentives to convert gardens to low water use. Major reductions in water consumption were achieved by this means: in Dampier (Hamersley Iron) 50% reduction in total town consumption 1985–1990, in Karratha (Hamersley Iron and Woodside Offshore Petroleum) 38% reduction in household consumption 1980–1990, and in Wickham (Robe River Iron) 39% reduction in household consumption 1984–1990.

However, economic responses to resource depletion may be short lived. For sustainable reduction in consumption, everyone must understand that water conservation makes good economic sense. It also has immense benefits in the form of better understanding and appreciation of the natural environment, and improved capacity to cope with environmental stresses such as drought and the greenhouse effect. The water conservation ethic widens into a more holistic environmental ethic. Public education programs to encourage new attitudes to the environment, and extension services to provide practical information, advice and support are essential elements in a water conservation strategy.

The gaps in basic information identified by Nicholson & Edgecombe have largely been filled since 1986. References such as Western Australian Water Resources Council (1986), Tyler (1988), Hill & Nicholson (1989), Royal Melbourne Institute of Technology (1989) and Water Sensitive Design Group (1990) contain good practical advice, with illustrations, on the design and establishment of gardens, and guidelines for policy development in urban areas. Some of this information has been distributed in pamphlet form by mining companies and government agencies.

Effective water conservation strategies require action by individuals, industry and government. Some important community-based initiatives were developed in the 1980s by highly motivated people, within and outside govern-

ment and industry. Closure of the Department of Conservation and Land Management nursery in Karratha, in favour of a rationalised system centred on Broome, was a turning point for many people. The loss of an efficient, personalised service and of the source of large quantities of cheap native plants stimulated local residents to develop their own projects. They became involved in native plant nurseries, arid landscaping for remote Aboriginal communities, demonstration garden projects, horticultural courses and programs to help disadvantaged people acquire work skills.

In 1987 the Pilbara Water Conservation Advisory Committee was set up under Section 17 of the Water Authority Act, the first committee of its kind in Western Australia. With support from the Water Authority in Karratha, the Committee is undertaking a community education program, and compiling and distributing information to schools, households and local government.

At the local government level, the Shire of Roeburne (which includes Karratha, Wickham and Dampier) adopted a policy which makes low water landscaping a condition of approval for all new development proposals. In Port Hedland, the council invited officers from the Townscape Programme, Department of Planning and Urban Development, to help prepare concept plans for a town enhancement project in consultation with local people. The plans were based on the principles of water conservation and emphasised the need to build on the natural character of the area.

Outside the Pilbara, the enthusiasm of Kalgoorlie people and support from the mining industry combined to initiate a major water harvesting project on Gribble Creek. The periodic flooding of the creek will be managed and a linear park through the town created.

In Broome, a recent study proposed total water management strategies for the future development of the town. The basic work on water conservation in the Pilbara has been done. There are active community groups, and commitment to water conservation principles within industry and in state and local government.

The principles which evolved from the Karratha experience can be applied in other areas. In water care programs everyone has a role. At the community level, individuals and groups can promote the water care ethic, create gardens and nurseries, and lobby for policies, incentives, funding and research. In Karratha, the value of a native plant nursery as a focal point for local people and a source of advice and plants was clearly demonstrated.

Many knowledgeable and enthusiastic people work for local councils and in government agencies and they are well placed to recommend the adoption of policies, by-laws and regulations to ensure that water conservation principles are applied to all developments.

The support of industry, through funding and personal involvement, contributes to the success of local projects. Scientists, engineers, horticulturists and landscape architects can apply their skills and experience to public

education, research, trials, demonstrations and workshops.

The funding of regional and local projects and research, the establishment of Water Conservation Advisory Committees, liaison with local groups and promotion of a holistic environmental ethic are all appropriate activities for the State and Federal Governments.

The Landcare movement is a good model. The problems which made Landcare, and now Water Care, necessary have their roots in attitudes to the whole environment. The issue of water conservation cannot be tackled in isolation from other conservation issues.

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### Low water use horticulture — the Leigh Creek experience

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In 1985, the Electricity Trust of South Australia (ETSA) completed Leigh Creek, a remote, fully planned and water efficient township (population 2000), to service the Leigh Creek Coal Mine in the hot arid north of South Australia. Potable water is a limited and expensive commodity. ETSA was, by choice, committed to a high level of landscape development and has implemented a range of effective water conservation practices to achieve this. Through the careful selection of appropriate plant species, the extensive use of drip irrigation and surface mulches, the re-use

of sewage effluent and a public awareness program, public and domestic plantings are highly efficient water users.

The new township of Leigh Creek (30°28'S; 138°25'E; elevation 200 m), next to the Northern Flinders Ranges, approximately 500 km north of Adelaide, replaces the original Leigh Creek township (population 900), which was abandoned due to the encroachment of mining activities. The climate is characterised by low and erratic rainfall, high evaporation, high maximum temperatures in summer and low minimum temperatures in winter. Rainfall is equally likely to occur in any month of the year, but with a summer incidence of high intensity events associated with convective thunderstorms.

Soils on the town site range from skeletal, sandy loam overlying fractured dolomite or quartzite bedrock on hills, to deep (900–1700 mm) sandy loams with light clay at depth in valleys and on lower hill slopes. The skeletal soils have obvious limitations in moisture retention, fertility and plant root penetration. Surface soils are structureless and red-brown (except for those which overlie dolomitic parent material and are grey-white). Analysis of the deeper soil profiles indicates that the sandy topsoil should provide good drainage, and the clay subsoils a good moisture reserve. Soils are generally extremely alkaline (pH 8.1–10.0), saline (EC 6.5–56.5 dS/m) and often sodic (ESP 2.1–28.9). Soils with an ESP greater than 10 tend to be dispersive, resulting in poor infiltration, impeded drainage and a high propensity to erode during intense rainfall events. With the action of low rainfall and high evaporation, soils with these characteristics are readily salinised by poor irrigation practices. Fertility is low but adequate for a large range of adapted species. Free lime is present in the deeper soil profiles, and on highly alkaline sites plants may suffer from lime-induced nutrient deficiencies.

Great care was taken to retain existing trees and shrubs during the township's construction. The natural vegetation cover consisted of mallee woodland (*Eucalyptus socialis* association) on some hills, with chenopod shrubland the main groundcover over the rest of the site.

Water has traditionally been, and continues to be, supplied free to town residents but irrigation water is not available for commercial food production. Aroona Dam, completed in 1955, has been the primary source of potable water for both the old and new townships since then. At construction, the dam's capacity was 7500 ML; silting has now reduced this to approximately 5000 ML. Land rehabilitation undertaken in the catchment since the mid 1980s has been successful in arresting further siltation. Storage losses from the dam of 25% to seepage and 50% to evaporation leave a maximum of 25% available for pumping (Eastham, 1983).

With the increase in population required for the expansion of the mine, and the deterioration of storage capacity, a reverse osmosis (RO) plant was constructed to desalinate water from nine production bores. At the product water quality of 500 mg/L, the plant has a potable water output of 3.4 ML/day, enough to meet the town's peak summer daily

demand. The current estimated cost of delivering a kL of dam water to the township is \$0.45; RO water is \$2.70. Although the cost per unit of RO water reduces as throughput increases, dam water remains the cheapest source. Water use policy requires that while dam water of a suitable quality is available, it is to be used exclusively. All potable water pumped to the township is filtered and chlorinated. If dam water quality deteriorates, the quality of water pumped to the township may be maintained, cost effectively, by 'shandy-ing' with RO water, or water from the one potable-quality production bore. Approximately 50 ML of secondary treated sewage effluent (TDS 1080 mg/L) is available annually for irrigation purposes (at an estimated \$0.10/kL delivered to the township), for which it is ideally suited.

In the old town, despite the example set by ETSA, inappropriate species were often planted and extreme overwatering of gardens was commonplace, causing the development of a perched watertable beneath the township. An exceptionally wet series of years from 1973 to 1975 caused the highly saline watertable (20 480 mg/L) to encroach into the root zone of established trees. Deaths due to salinity and waterlogging were widespread amongst the town's large trees and shrubs.

To create a cool, shady and relaxed environment, which can alleviate social problems in isolated communities (Wilson, 1980), some 250 000 (predominantly native) trees, shrubs, groundcover and climbing plants have now been established. Species selection was based on the evaluation of plantings in the old town, a review of the scant literature and rigorous assessment of species growing in a number of outback towns. Species chosen for use in the public areas were, with one exception (*Vitis amurensis*, Crimson Glory Vine), Australian native species. About 300 (mostly native) plant species were chosen for use in home gardens, grown in a nursery established for the purpose, and provided free to householders. The drought and salt tolerant Kikuyu grass (*Pennisetum clandestinum*) is used for all public grassed areas, and seed or runners were provided at no cost to householders. An information booklet was also provided free to householders, with guidelines for watering lawns and the use of drip irrigation in home gardens.

Horticultural water use efficiency was achieved by the use of: *drip irrigation* in all public areas, and its encouragement by incentives for home gardens (drip watering systems use ~33% of the water used by sprinkler systems and as little as 10% of that required by flood irrigation, for the same effect: Adams & others, 1978); *surface mulching* with screened creek pebbles (20–70 mm diameter) and woodchips (used extensively throughout public plantings and provided free for home gardens), to reduce moisture loss from the soil surface, facilitates rainfall infiltration, minimises salt accumulation and controls weed growth; *calculating an irrigation program* for grassed areas using the Penman and Pan Evaporation Method (Doorenbos & Pruitt, 1977); *night watering* (all public grassed areas are watered automatically at night, and householders are required to water lawns at night); *limiting grassed areas*, both in the public

landscape (parks and streets) and home garden (the maximum allowable size for lawns in home gardens is 100 m<sup>2</sup>); *public education* (talks to school and community groups, reminder leaflets and the frequent imposition of water use restrictions); *re-use of sewage effluent water* (to irrigate the town's two ovals: 30 ML annually, the partially grassed nine hole golf course: 17 ML annually, and approximately 7000 trees: 2.5 ML annually); and *soil amendments* (gypsum dressings and fertilisation).

Five different landscape treatment classifications with specific irrigation requirements have been identified.

1. The **buffer zone** consists of a fenced and protected area of natural vegetation, and a broad belt of densely planted trees to visually and physically ameliorate the impact of sun, wind and dust. Planting density varies from 5 to 7 m centres, and a natural appearance has been achieved by 'ripping in' driplines along a sinusoidal curve. Species used in this area are very drought tolerant and receive minimal irrigation. Weed control is achieved using a 1 m<sup>2</sup>, UV-stabilised sheet of black polythene and/or regular applications of a glyphosate herbicide. By the fourth year, trees do not receive irrigation unless drought conditions prevail. For plantations with trees less than three years old, drip emitters should be operated for 4–6 hours during, or shortly after, a rainfall event greater than 5 mm. This leaches away salts that have accumulated on the soil surface through evaporation and would otherwise be flushed into the young plant's root zone by rainfall.

2. The **streetscape** is the 'linear park' landscape treatment of the 12 km of streets, using plants selected from those species used in the buffer zone plus others with slightly higher water requirements. The entire streetscape area (~200 000 m<sup>2</sup>) is mulched by a continuous, 100 mm deep layer of creek pebble mulch.

3. The town's five **parks** have been developed with the same range of species and planting density, and drip irrigation schedule, as the streetscape. Continuous pebble mulching is used on most plantings. Because of their high water requirement, grassed areas are small and strategically located.

4. **Town centre.** The community services are clustered centrally within the town plan. To achieve the variety of foliage, form and flower colour desired, a wider range of species than that used for the streetscape and parks has been adopted. The level of landscape development in the town centre is higher than elsewhere.

5. **Home gardens** usually have a wider range of plant species and greater density of planting than public landscaping; recommended irrigation guidelines were distributed to householders.

The mean annual potable water use for the old town (population 900) was 506 ML, or 0.56 ML/person/year. Based on this figure, and given greater water use efficiency, the projected annual consumption for the new township (population 2000) was 800 ML. The actual figure for 1990 was 625 ML, or

0.31 ML/person/year. This low figure is even more remarkable considering that the ducted evaporative air coolers installed in all dwellings of the new town are estimated, collectively, to use 45 ML annually. Of the 625 ML, it is estimated that 75% is used for horticultural purposes (both public and domestic).

Regardless of the other relative merits of closed (company) versus open towns, the largely closed status of Leigh Creek has facilitated a consistent 'Australian' theme in the town's landscape development. In addition, it has enabled the balanced and consistent application of incentives, controls and community education to implement an integrated package of horticultural water conservation measures. This contrasts with the often ad hoc landscape development of many other townships in Australia's arid and semi-arid areas.

The following improvements could be made: — Greater use could be made of stormwater runoff from paved areas (e.g. storage and re-use, contour banking and water spreading).

— Dual domestic water reticulation and/or the construction of storage for surplus sewage effluent would enable more complete use of this valuable resource.

— If each drip irrigation unit was confined to one soil type (i.e. within a unit, all drippers are either on or off together), scheduling could be adjusted according to the characteristics of the different soil types.

— Application of 'high tech' methods for monitoring irrigation effectiveness, such as neutron or capacitance probes and nests of tensiometers, could significantly improve irrigation efficiency.

### Conclusions

Compared with the old Leigh Creek, the new township has achieved high levels of potable water use efficiency for both horticultural and indoor purposes. Despite an increase in population of 220% and a vast increase in the number of plants established, total potable water consumption has increased by only 23.5%.

Species selection determines absolute water use by plantings. Of the strategies for horticultural water conservation discussed, the extensive use of drip irrigation is the single greatest influence on efficiency of water use, landscape potential and aerial extent of plantings possible.

Although costs are not considered in this paper, under the conditions at Leigh Creek, reticulated drip irrigation is a cost effective, low maintenance technique for irrigating arid zone plantings.

Regardless of the level of technology used for irrigation, water use efficiency comes down to knowing when to turn a tap on or off. Skilled staff and effective community education programs are therefore essential. The principles applied at Leigh Creek apply across a broad range of climatic conditions and scales of development, wherever potable water supply is limiting.

I am pleased to acknowledge the timely and willing assistance of Mr Beat Odermatt and Dr Rob Ainslie of the Electricity Trust of South Australia.

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### Great Artesian Basin rehabilitation program

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The Great Artesian Basin is one of the largest artesian basins, if not the largest, in the world. It underlies part of Queensland, New South Wales, South Australia and the Northern Territory, an area of 1.7 x 10<sup>6</sup> km<sup>2</sup> or about one-fifth of Australia. The first bores to tap the Basin were constructed in New South Wales and Queensland over 100 years ago. Many towns and station properties depend totally on the Basin for water. It has been the key element in the development of the grazing industries in these areas, but its use for stock watering has been very inefficient. The Great Artesian Basin Rehabilitation Program provides an opportunity for better management policies.

Initially, wells were drilled on the shallow margins of the Basin in New South Wales and South Australia. The first deep flowing bore in Queensland near Cunnamulla struck an artesian flow in February 1887 at a depth of >329 m. Rapid development of the deeper parts of the Basin followed, providing reliable town water supplies, which appreciably improved the living conditions, social stability and health of western communities. Very early in the development of the Basin there was a rapid build-up in the number of bores, and total flow from the basin reached a peak of about 750 000 ML/year (585 000 ML of which was in Queensland) in about 1914. Since then, the rate of flow has declined, although the number of bores has increased steadily. The present discharge from the Basin in Queensland is some 280 000 ML/year.

The flows obtained during the early development phases were often very large, but diminished rapidly in areas that were heavily tapped. As a result, legislative controls were imposed in the early 1900s. In Queensland, a hydraulic survey (the first attempt at monitoring flow) which had begun in 1895 was revived in 1910, and was completed in 1925. Almost from the very first strike of deep flowing artesian water, it was realised that monitoring of flows and pressures would be necessary. Progressive diminution of flowing supplies caused everyone concern. Monitoring ensures that bores are operated within licence conditions, providing a check for any deterioration in

bores or headworks, through inspection of all bores. It also indicates the performance of the Basin, so that management decisions can be made.

Since the Queensland hydraulic survey, monitoring by the relevant State authorities has continued, at varying levels of intensity. Bores have been visited, flows and pressures measured and flow tests carried out to determine the storage and transmission characteristics of the Basin, which is one of the best monitored large sedimentary basins in the world.

With the advent of the Australian Water Resources Council in the early 1960s, attention was once more focused on the Basin. In Queensland, a review of the 1954 report *Artesian water supplies in Queensland* was carried out between 1967 and 1969. From 1971 to 1978 a basin-wide study of the Basin was instituted by the Council. The Bureau of Mineral Resources assembled data from both States and the Commonwealth, and constructed a computer model of the Basin (Habermehl, 1980; Seidel, 1980).

Management policies have changed over the years to accommodate new or revised views of the resources of the Basin. In Queensland, for example, because of the limited resource and the priorities set for use, irrigation from the Basin was initially not permitted. A number of graziers carried out illegal irrigation, mainly in the Richmond area, for over 20 years. In recent years, policy has changed to allow irrigation anywhere in the Basin provided this does not result in a net increase in use from the Basin. Irrigation with increased use is now favourably considered in intake areas provided there is no significant interference with bores on neighbouring properties or reduction of recharge to the aquifer. In addition, industry use is permitted in some areas where this does not interfere with existing users.

In the last two decades, there has been growing unease among users at wastage of water in the Great Artesian Basin. As competition for a valuable commodity increases, managers and planners are becoming more aware of the present scale of wastage in the Basin. Much of the water is distributed by bore drains which allow large seepage and evaporation losses and require regular maintenance. About 90–98% of water which enters the bore drain system is wasted by these means. About one-third of the total flow from the Basin is via flow from uncontrollable bores into even less efficient swamps and water courses. The result is that only about 5% of the flow from the Basin is used beneficially.

The Groundwater Committee of the Australian Water Resources Council in 1985 proposed to review matters concerning the Great Artesian Basin and to define future activities. As a result, the Great Artesian Basin Sub-Committee was established, reported on its deliberations in 1987, and was disbanded. It concluded that there was a very substantial waste of water from the Basin, because of an inefficient distribution system and a large number of unserviceable bores (total estimated flow 1220 ML/day; estimated waste 1040 ML/day) and that better management on a basin-wide basis was necessary.

The Australian Water Resources Council in 1987 endorsed the following recommendations made by the water authorities of New South Wales, Queensland and South Australia:

1. Bores should be constructed to exclude corrosive water and prevent leakage up the outside of the casing. In corrosive areas the use of inert material should be considered for bore casing, recognising that such casing may make future augmentation difficult.
2. To reduce wastage adequate headworks should be installed on all new and rehabilitated bores and to ensure proper maintenance bores should be inspected regularly.
3. States should set up programs to identify bores requiring rehabilitation.
4. As a first priority new uses from the Basin should be set up converting wastage to beneficial use but equal to sustainable yield should be the overall objective.
5. The BMR should be asked to formulate and propose a program and network for monitoring the pressure, flows and chemistry of the Basin for submission to the States.
6. States should promote an educational and public awareness program explaining the benefits and significance of the Great Artesian Basin to the community.
7. A States working group be established and maintained to formulate and review a proposed program of future activities directed towards data gathering and analysis, study of Basin performance, environmental issues, benefits from control of the Basin, and review of legislative provisions in each State for control of the Basin.

An Interstate Working Group was formed with members from Queensland, New South Wales and South Australia. Because of its tremendous involvement in the Great Artesian Basin over the past 20 years, the BMR was also invited to join. The Working Group has prepared a standard for bore construction which has been implemented by the States; rehabilitation of uncontrollable bores in Queensland, New South Wales and South Australia has commenced and has been accepted as part of the Federal Water Resources Assistance Program (FWRAP), although it may take 10–15 years to complete; bores have been drilled in recharge areas to monitor the effect of recharge events; a network of monitoring bores is almost complete; areas of corrosive water are being identified; educational matter (brochures, and a video on reconditioning bores in Queensland) has been produced, and public meetings have been held.

#### Rehabilitation program

The federally and state funded program for the rehabilitation of uncontrollable bores, begun in 1989/90, involves the reconditioning or plugging and replacement of uncontrollable bores. It involves about 1100 bores, of which approximately 750 are in Queensland. The estimated cost in 1987 was \$22.5 million, comprising \$16.5 million in Queensland and \$3 million each in New South Wales and South Australia. It does not involve the piping of water to effect the major saving in water, although it is hoped that many landowners will undertake the reticulation themselves.

Under the FWRAP scheme, federal funds could be provided for the investigation, planning and rehabilitation of bores; ongoing monitoring would be the State's role. Bore owners are expected to keep the bores in good order after rehabilitation. If landowners decide to take the Scheme to its logical conclusion, all bores will be controlled and all water distribution will be by pipeline. The total cost, including bore rehabilitation and pipelines replacing some 24 000 km of bore drains, in Queensland would be ~\$136 million. The annual saving of water for other uses would be about 250 000–265 000 ML, which means a total cost of about \$500 to provide an assured supply (unaffected by drought conditions) of 1 ML/year.

Although South Australia and, to a lesser extent, Queensland began reconditioning bores many years ago, the rehabilitation program is in its infancy. In Queensland, a considerable amount of money has been spent in the first two years in purchasing stock and equipment for future rehabilitation work as well as working on the program. New South Wales joined the program in 1990/91, and was still in the planning stage at the end of December 1990.

Progress since the program was included in the Federal Water Resources Assistance Program is shown in Tables 1 and 2 (expenditure is expected to increase substantially in future years). Discharge from the Basin in Queensland alone at December 31 1990 has been reduced by some 6700 ML/year at a cost of \$132/ML saved. It is expected that this unit cost will fall as the program proceeds.

**Table 1. Bores reconditioned, plugged or replaced since July 1989.**

Year	QLD	NSW	SA	Total
1989/90	6	—	7	13
1990/91 to 31.12.90)	20	—	16	36
Total	26	—	23	49

**Table 2. Expenditure on rehabilitation program.**

Year	Qld	NSW	SA	Total
1989/90 (expenditure)				
State	195 000	—	95 000	290 000
Commonwealth	100 000	—	75 000	175 000
Landowner	33 000	—	—	33 000
Subtotal	328 000	—	170 000	498 000
1990/91 (allocations)				
State	430 000	150 000	150 000	730 000
Commonwealth	330 000	150 000	150 000	630 000
Landowner	165 000	75 000	—	240 000
Subtotal	925 000	375 000	300 000	1 600 000

Economic efficiencies of water conservation are not the only advantages of better management:

— Prickly acacia is spreading uncontrollably in western Queensland and endangering the grazing land. The rapid spread is directly associated with water distribution by bore drains. Control of the bores and distribution by pipelines will help to control this spread.

— In some areas, the fluoride content of the water is very high and evaporation along the bore drains can bring this concentration to a toxic level.

— The Great Artesian Basin area, like most of Australia, experiences extremes of weather from flood to drought. Conservation of water by reducing wastage will allow more effective water use, e.g. drought-proofing, and irrigation of small areas on each property. Apart from stabilising stocking numbers, such a scheme would reduce the dependency on Government drought subsidy.

— Piping the water, using the Basin's natural pressure, will also enable more flexibility in watering properties, allowing some bore drains to be used if required for, say, watering lambs.

### Conclusions

The Great Artesian Basin Rehabilitation Program is a Program of national benefit. It aims to reduce the wastage of water from this vast natural resource. In so doing it makes water available for more effective use as well as protecting the land from further degradation by the spread of prickly acacia. The inclusion of the Rehabilitation Program in the FWRAP Program will provide long term benefits. It allows landowners to improve their management techniques by reticulating water by pipelines; water thus saved could be used to irrigate small areas to assist in drought-proofing the properties. As landowners control bores, pressure in the Basin will build up; there is already evidence of this in the Aramac area of Queensland. The Working Group overseeing the program is operating satisfactorily and will continue to meet frequently enough to achieve its aims. Co-operation between the States is enabling better operation and management of the Basin for the benefit of the community.

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### Unique aquatic communities in the arid zone: how dependent are they on groundwater?

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Central Australian waterbodies were sampled in July and December 1986 to determine the composition of the aquatic invertebrate communities and to determine biogeographical relationships with the fauna of stream systems elsewhere in Australia.

The region is one of the driest in Australia. The climate is characterised by extreme diurnal

and seasonal temperature differences; average rainfall is 250 mm/year but this is non-seasonal and in some years no rain may fall. Despite the aridity of the area freshwater ecosystems are present, mainly within the gorges of the area known as the Central Ranges. The waters of the George Gill Range (220 km southwest of Alice Springs) are of special interest because they represent the largest group of streams within the Central Ranges. The impact of cattle and feral camels, horses and donkeys has led to excessive nutrient enrichment and generally poor water quality in many central Australian waterbodies. However, the isolated and inaccessible nature of much of the George Gill Range has resulted in the preservation of some small aquatic ecosystems in a relatively undisturbed state.

European knowledge of the area began with the arrival of the explorer Ernest Giles in 1872. The country at the foot of the Range was by far the best he had seen in the region (Giles, 1889) but he appears to have been extremely fortunate to arrive at the Range after substantial rains had fallen. The first scientific expedition to central Australia, the Horn Expedition, led by Baldwin Spencer, visited the George Gill Range 22 years later in 1894. The Horn Expedition appeared to have visited the Range in drier times than that of Giles but Spencer was still greatly impressed by the richness of the flora and fauna (Spencer, 1896). We believe that the work described here, undertaken almost 90 years later, is the only study since the Horn Expedition to examine the aquatic communities of central Australia. In addition to seven stream systems within the George Gill Range, waterbodies sampled included Oasis Creek (a tributary of the Finke River at Palm Valley), the Boggy Hole and Running Waters sections of the Finke River, Simpsons Gap in the West MacDonnell Range and Giles Springs in the Chewings Range. All of these sites are west or southwest of Alice Springs.

Water varied from acidic at Giles Springs (pH4.8) to alkaline at Boggy Hole (pH9.6). The waters of the George Gill Range varied from slightly acidic (pH5.7) to near neutral (pH6.9) and were generally very dilute (27 MicroS cm<sup>-1</sup> to 573 MicroS cm<sup>-1</sup>). Giles Spring in the Chewings Range was also very dilute (53 MicroS cm<sup>-1</sup>); the water associated with the Finke River was more saline (6110 MicroS cm<sup>-1</sup> at Boggy Hole).

The waterbodies in the George Gill Range were mesotrophic with respect to total phosphorus. The presence of low concentrations of ammonia and high concentrations of nitrate suggested that these systems were not organically enriched. Orthophosphates were low, indicating that large external sources of phosphorus such as those that occur in agricultural or urban areas elsewhere in Australia were not present here, although low levels may also be the result of this nutrient being rapidly utilised for algal growth.

The richness of the aquatic invertebrate fauna of the George Gill Range was comparable with that of temporary and permanent streams elsewhere in Australia and overseas (Boulton & Suter, 1986). Sampling at other waterbodies was not as extensive but a further four species were recorded at Giles Springs, one at Simp-

sons Gap, six at the Finke River sites (Running Waters and Boggy Hole) and one at Oasis Creek (Palm Valley).

Several groups which occur elsewhere in Australia were absent. The Plecoptera (stoneflies), which are generally regarded as requiring cool waters, are probably excluded from central Australia by summer temperatures which exceed their thermal tolerances. The absence of isopods and amphipods may reflect lower inputs of an important food source, riparian plant material. Riparian vegetation in the arid region is considerably sparser than in temperate regions.

Giles Springs contained the richest macroinvertebrate fauna of the other waterbodies sampled, and displayed the greatest affinities with the fauna of the George Gill Range. The lower species richness of the other sites may be related to greater thermal variability and disturbance. The waterbody at Simpsons Gap appeared to be enriched because much filamentous algae was present (although no nutrient analyses were undertaken). The waters were less shaded than those of the George Gill Range and the species which were common to both areas were probably those most tolerant of thermal extremes. The waters of Oasis Creek, in Palm Valley, would also be subject to greater thermal extremes (because they were not contained within gorges) and appeared to be largely ephemeral. Boggy Hole and Running Waters on the Finke River were semi-permanent wetlands with much evidence of disturbance by cattle. Macroinvertebrates found at these latter sites must be tolerant of thermal extremes and dramatic changes in the presence of water.

Most species occurring at the Range have cosmopolitan or southern distributions. Relatively few species have primarily northern distributions. The southern coastal regions (and coastal northeastern Queensland where there is some cool, high altitude habitat) have the greatest numbers of species in common with central Australia. Chippendale (1963) regarded some of the ranges of Central Australia, including the MacDonnell, James, Krichauff and George Gill, as relict areas 'where plants of a higher rainfall period have survived'.

The George Gill Range is very rich floristically, and a small but significant percentage of the flora is estimated to be rare or of relict distribution (Latz & others, 1981). Similarly a small proportion of the aquatic fauna present at the George Gill Range appears to be a relict stream fauna. Species such as the waterpenny, *Sclerocyphon fuscus*, with an aquatic larva and a cryptic adult capable of only limited flight (Davis, 1986), would not be capable of dispersal across the large tracts of arid land that now separate the George Gill Range from the southern regions of Australia where it also occurs. The presence of other stream dwelling species of apparently low vagility such as *Atalophebia australis*, *Hellyethira simplex* and *Ecnomus continentalis* support this notion of a relict lotic fauna. These species would have been more widespread when the continent was much wetter than it is today. The predominantly southern distribution of many species at the Range, particularly the less vagile ones, suggests that the most likely route of dispersal to

the Range was through the Finke River–Lake Eyre system from southeastern Australia. The exact period when the George Gill Range may have been in some form of aquatic continuity with southeastern Australia is not known.

Some fauna at the Range may have survived from ancestral forms present since the early Tertiary when Australia was characterised by both widespread humidity and warmer temperatures than present (Kemp, 1981). However Keast (1981) notes that central Australia contained abundant water during the Pleistocene and that most of the inland rivers and lakes systems antedated the Pleistocene.

Nix's (1982) statement that 'present day distributions reflect present day environments' is applicable to the George Gill Range. Although elements of a temperate zone stream fauna are present the community also represents one that is unique to central Australia. Increasing seasonality of both thermal and water regimes has been a primary factor in the evolution of the Australian flora and fauna (Nix, 1982). Increasing aridity, unpredictable flow and a highly seasonal thermal regime are likely to have acted as an 'ecological sieve' on aquatic communities at the George Gill Range. These conditions have probably resulted in the local extinction of stream-dwelling species that were intolerant of warmer waters, episodic flow regimes and a lack of organic matter as riparian vegetation diminished with increasing aridity.

The occurrence of new species in the Central Ranges indicates that it is also a site of allopatric speciation within some groups. Aquatic habitats and communities in central Australia have extremely high conservation value, because of the relict nature of some elements of the fauna and because these systems represent unique biotic communities within arid Australia. We need to conserve unique and localised environments because 'the rare, relict and disjunct populations of today may be the source of the biotic patterns of tomorrow' (Nix, 1982). In addition to more taxonomic and ecological information, we need a much better knowledge of the hydrological balances to manage these systems properly. We do not know how much groundwater (the only consistent water source in the Amadeus Basin: Lloyd & Jacobson, 1987) contributes to aquatic systems such as those within the George Gill and Chewings Ranges.

The George Gill Range consists of Mereenie Sandstone, deposited approximately 360 Ma ago, overlying Carmichael Sandstone deposited approximately 440 Ma ago (Bagas, 1988). The lower permeability of the Carmichael Sandstone compared with the Mereenie Sandstone is indicated by the intermittent presence of a seepage line at contact (Lloyd & Jacobson, 1987). Seepage from the Mereenie aquifer probably therefore provides a permanent source of water in the George Gill Range. In addition, deep rock pools appear to act as reservoirs of surface run off. We do not know whether pumping of groundwater elsewhere in the basin, for example, to provide the water supply for Alice Springs, which lies at the eastern end of the Mereenie aquifer, will affect arid zone aquatic communities.

Although this study has primarily drawn attention to the conservation values of waterbodies

in the George Gill and Chewings Range, we also wish to acknowledge the high social amenity attached to the more accessible waterbodies of the MacDonnell Ranges and the Finke River system. The role that groundwater may play in maintaining these culturally important sites also needs investigation.

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#### High nitrate groundwater in the Australian arid zone

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Groundwater in the Australian arid zone is typically very saline, often considerably more saline than seawater. However, it is possible to find locally extensive areas of groundwater of low to moderate salinity (<1500 mg/L total dissolved solids) which are potentially suitable for human consumption. Such water is generally found in shallow unconfined aquifers, and its chemistry (high bicarbonate, low sodium chloride) suggests a relatively recent origin. At Uluru (Ayers Rock) as well as at other sites in the Northern Territory (see McDonald, 1988), such water is often contaminated with high concentrations of nitrate (up to 50 mg/L NO<sub>3</sub>-N; the WHO limit is 10 mg/L NO<sub>3</sub>-N) thus rendering it unsuitable for potable water supply without treatment.

Analyses of water samples taken from bores near the Uluru tourist village, Yulara, show that nitrate concentrations decrease and sodium chloride concentrations increase, along flow lines inferred from piezometric levels in the bores. This suggests that nitrate may be transported from the surface in recharge water which infiltrates through the unsaturated zone to the watertable.

The pattern of nitrate concentration at or near the soil surface in this area revealed a number of possible sources. In addition, shallow soil profiles revealed complex distributions of soil nitrate concentrations. Of the sites examined, total nitrate concentrations (integrated over approximately the top 2 m) were greatest under apparently bare soil (sand), with slightly reduced levels under grass (spinifex and other species) and lowest concentrations under Mulga (*Acacia aneura*). This last result was surprising, given the ability of this species to form nitrogenous root nodules. It suggested that in the presence of a sufficient supply of inorganic nitrogen from other sources, Mulga becomes a net consumer rather than a producer. On investigation, a number of different types of cyanobacteria (blue-green algae) were identified in surface crusts taken from the soil surface, which were capable of

acetylene production (Smith & others, 1990). These nitrogen-fixing bacteria presumably rapidly fix nitrogen during infrequent wet periods, and are able to survive the extreme desiccation experienced by the soil surfaces, with recorded surface temperatures of over 60°C under dry conditions. Soil profiles often exhibited relatively high concentrations of nitrate at the surface, which decreased rapidly with depth, and occasionally a secondary peak at around 1 m depth. The origin of these secondary peaks was assumed to be evidence of surficial nitrate which has been washed into the profile by a rainfall event of suitable size. Sampling after a large and subsequent rainfall event showed no evidence of this secondary peak, which had presumably been leached through the profile.

A large difference in surficial soil nitrate concentrations was found on sampling either side of a fire scar; high concentrations were found in the ash. Given the important and periodic role of fire in the arid zone, and its effect on transpiration and infiltration, it is possible that fire may play a role in the transport of nitrate to the watertable.

The largest concentrations of surface nitrate were found on termite mounds. Termites are ubiquitous in the area, with termite mounds in the form of low domes (0.5 m) associated with more or less circular pavements of about 2 m diameter often only about 10–15 m apart. A tentative identification of the species has been made as *Drepanotermes perniger*. These termites appear to feed on a variety of food sources, including grasses (particularly spinifex) and also mulga wood, where available. Measurements of nitrate concentration in the surface soil of the mounds revealed concentrations of up to 2000 ppm nitrate-N, or at least 2 orders of magnitude greater than in the surrounding soils and surface crusts. Further investigation of profiles through a termite mound showed that both nitrate and ammonia concentrations were elevated within the mound, rising to a maximum near the surface.

Within the body of the mound nitrate concentrations were generally an order of magnitude lower than ammonia concentrations. At the surface, nitrate concentrations suddenly increased by two orders of magnitude, whereas ammonia concentrations remained steady. The inference is that bacteria within the mound (either in the hind gut of the termites, or free-living bacteria in the body of the mound) fix nitrate in a form which eventually ends up as ammonia, and which may in turn be oxidised to nitrate by other soil bacteria, a process which is speeded up by the presence of water. As the mound dries out, nitrate is leached to the surface of the mound by capillary action, while the less mobile ammonium ion remains behind. Further rain then runs off the relatively impermeable outer surface of the mound, picking up the very soluble nitrate and transporting it into the sandy soil, and eventually into the watertable. Estimation of the total production of nitrate by termite mounds in this way is difficult, because of the absence of reliable quantitative information on numbers and sizes of termite mounds, of production rates of nitrate in the mounds, and differences between species.

Although the high nitrate concentrations were observed in apparently only one species (the

most common) at Yulara, similar concentrations have also been observed on the surface of pillar like mounds (1–1.5 m) made by a completely different species (tentatively identified as *Amitermes*) at another location near Mulga Bore, in the Ti-Tree Basin, 100 km north of Alice Springs. The shallow surface water in this region is also noted for very high nitrate concentrations (up to 80 mg/l NO<sub>3</sub>-N).

The above model of nitrate contamination assumes a significant component of diffuse recharge. In April 1989, a major recharge event occurred, with 500 mm of rainfall falling in two days. The bores in the Yulara area showed a very delayed response, with water levels reaching a peak only after a delay of 6 months, typical of what might be expected from a diffuse recharge response.

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## Aboriginal and islander water supplies: the five R's

Bruce W. Walker<sup>1</sup>

This paper discusses five fundamental issues in the provision of water supplies to Aboriginal and Islander communities. It is argued that complaints of inadequacy of water supply in these communities may be explained through reference to one or more of the 5 R's. Technical issues are often only symptoms of the five causal factors: resource values, racism, rivalry, remoteness and rights. These factors are examined historically to indicate the depth and range of the problem and the basis of the attitudes of both aboriginal and islander people and non-aboriginal technocrats and bureaucrats. The paper identifies a number of implications for technology choice based on the analysis of the underlying causal factors.

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## The Roe Creek borefield, Alice Springs

P.B. Jolly<sup>1</sup> & D.N. Chin<sup>1</sup>

Alice Springs water supply requirements are obtained from the Roe Creek borefield 15 km southwest of the town. This borefield was commissioned in 1964 when the existing supply from the alluvial sediments beneath the town became inadequate. The borefield currently consists of 20 production bores constructed to extract water from four discrete aquifers located within the following formations — the Mereenie Sandstone, the Pacoota

Sandstone (two aquifers) and the Shannon Formation.

Annual extraction is of the order of 10 million cubic metres with more than 80% coming from the Mereenie Sandstone. Peak daily extraction rates reach 55 thousand cubic metres. Regional investigations have shown that the Mereenie Sandstone will continue to be the major source of Alice Springs water supply.

To determine the economically sustainable yield from the Roe Creek borefield computerised models have been developed. These models indicate that a mining situation exists where drawdown can be directly correlated with the total withdrawal from each aquifer.

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## Alice Springs water management strategy

Ian Smith<sup>1</sup>

Alice Springs is the second largest population centre in the Northern Territory. Water demand has grown at high rates over the past twenty years, with supply being drawn throughout this period from Roe Creek borefield. There are other potential water supply sources in the region, but the aquifer systems of Roe Creek borefield are the only sources close to Alice Springs big enough for current levels of demand. The city will continue to depend on these aquifers as the primary source of water supply well into the future. This heavy dependence has two main effects. Firstly, the demand for water exceeds recharge, so aquifers are being mined. Secondly, there has been significant salinisation of the town basin groundwater system.

Alice Springs, although at the arid centre of Australia, is reasonably well served with potential water supply sources. Significant groundwater and surface water resources are known within a 60 km radius of the city. Water supply development to meet continuously rising demands has been investigated for nearly four decades, but little formal attention has been given to demand management. A more integrated approach is needed to manage water demand, supply and waste water disposal in Alice Springs. High per capita water use, capital costs of new works, ongoing operating costs, commercial orientation of the water supply authority and increasing public awareness of economic and environmental issues contribute to the need for an overall plan of water supply management.

The Power and Water Authority is preparing a water management strategy for growth in Alice Springs to a population of 60 000 and eventually to 90 000. (About 25 000 residents can be accommodated with new development and redevelopment of existing urban areas; further growth will be met by expansion to the east through Undoolya Valley). The Authority is considering broader resource use issues first. The major issues at this stage are the sustainability of Roe Creek borefield and rehabilitation of the town basin.

Potable water sources capable of significantly

contributing to water supply, within 60 km of Alice Springs, are described.

The Mereenie Sandstone dominates water supply sources in the region. Roe Creek borefield, 15 km south of Alice Springs, the major developed source, draws about 85 per cent of the city's water needs from the Mereenie Sandstone. Water is drawn from fracture zones within the sandstone at 150–200 m depth. Standing water level has declined by some 50 m since pumping began in 1964 to a depth of ~145 m now. Recent modelling indicates that negligible recharge occurs to Roe Creek borefield, and that drawdown under longterm pumping is linear with cumulative extraction (2.7 m per 10 000 ML withdrawal). In 1990, approximately 10 000 ML was pumped from the Mereenie Sandstone. Water quality is good but moderately high in total dissolved salts (TDS) (500–600 mg/L). It is possible that quality will deteriorate with depth.

Limited investigation has been conducted on another Mereenie Sandstone outcrop area at Rocky Hill, about 20 km southeast of Alice Springs. Water quality in this area, at 700 mg/L TDS, is marginally inferior to that at Roe Creek borefield. Regional modelling suggests that this location is a groundwater discharge area, with outflow of about 5 ML/day. The difference in geological setting means that drawdown rate under medium term pumping is expected to be less than half that at Roe Creek borefield. Roe Creek borefield also draws water from the Pacoota Sandstone and Shannon Formation. Further assessment is required, but these sources might sustain up to 4000 ML/year under longterm pumping.

Water supply up to 1964 was drawn from the town basin. Several aquifers have been identified within the unconsolidated sediments of the basin. The most permeable part, however, is a strip associated with the prior course of the Todd River. Natural recharge to the basin is from the river, and subsurface outflow from the basin occurs at The Gap. Under natural recharge conditions, the safe yield of the town basin is 600 ML/year, allowing 100 ML/year outflow at The Gap. Until 1964, water quality in the basin varied from <400 mg/L TDS in the more permeable areas to >2000 mg/L at outer areas. Reduced pumpage and high rainfall years since 1964 have resulted in significant alteration to the groundwater regime; standing water levels have risen by more than 3 m above 'historically full' levels and water quality has deteriorated to between 1000 mg/L and 4000 mg/L TDS.

Assessments have been undertaken for major dam sites on 3 rivers in the region. Dams on the Todd River within 10 km north of Alice Springs and on Jay Creek, 40 km west, may each be capable of 3000 ML/year supply. Yield from a dam on the Hugh River, some 60 km west of the city, has been assessed at 5000 ML/year. (The yields for Jay Creek and Hugh River are preliminary estimates.)

Alice Springs is serviced by a trunk sewerage system with final disposal to evaporation ponds. No data have been collected for the rate of waste water generation, but it is probably nearly 0.1 ML/person/year, giving a total annual waste water flow of 2600 ML/year in 1990. Waste water entering the evaporation

ponds has 1000 mg/L TDS. It is considered that up to 10 per cent of flow at the ponds is groundwater ingress due to the elevated water-tables of the town basin.

In the 25 years of supply from Roe Creek borefield (1965–1990); the population of Alice Springs has increased from 6000 to 23 800. The pattern of annual growth was not uniform, but averaged 712/year.

Total annual pumpage rose from 1250 ML in 1965 to 10 700 ML in 1990. Annual growth rates were not uniform and the effect of wet years is particularly evident. Falls in total annual pumpage occurred on 5 occasions, with recovery to former levels following as much as 3 years later. While a simple linear growth rate of 378 ML/year describes the trend over the whole period, a lower rate of 261 ML/year seems to apply to the last 10 years up to 1990.

The per capita consumption rate (annual pumpage divided by total population) shows patterns of fluctuation similar to those for pumpage, as would be expected. The consumption rate for the 10 years up to 1990 oscillates between 0.5 ML/person/year and 0.4 ML/person/year. The apparent median value is 0.45 ML/person/year. Estimated total supply in 1990 for residential consumption and landscape irrigation was 12 650 ML (Table 1).

**Table 1. Water supply and usage, Alice Springs 1990.**

	Amount (ML)	Percentage of total supply
<i>Source of supply</i>		
Roe Creek borefield (0.45 ML/person/yr)	10 700	85
Waste water reuse	1 150	9
Town basin	800	6
<i>Water use</i>		
Residential (0.40ML/person/yr.)	9 650	76
Irrigation	3 000	24
<i>Roe Creek borefield</i>		
Metered water	7 750	72
Unaccounted water	1 900	18
Irrigation	1 050	10

If 750 ML of the irrigation demand on Roe Creek borefield could be met directly from the town basin, there would be a residual irrigation demand of 300 ML/year.

#### Water demand beyond 1990

Two rates of population growth have been used to predict future water demands: a growth rate of 1.7%/year until 2010 with extrapolation at 1.5%/year, and a growth rate of 1.7%/year until 2010 followed by an additional 712 residents/year, the equivalent linear rate for growth in population from 1965 to 1990.

Using these rates, population would reach 60 000 between 2040 and 2050, and 90 000 between 2075 and 2085. The Undoolya Valley would be fully developed in about 50 years time, and development to the full residential capacity for greater Alice Springs might take another 50 years beyond that.

Annual water demand has been predicted on the basis of the population growth rates described above with a residential water demand of 0.40 ML/head/year plus 300 ML/year for residual irrigation demand (Table 2). The

probable lifetime for the Roe Creek borefield will be reached when drawdown equals 200 m. On the criterion of resource drawdown, and given demand predicted above, the Roe Creek borefield has about a 20 year lifetime. Over this time, it will be necessary to decommission some bores, deepen and rehabilitate others and drill new deeper bores. As drawdown increases, so will the cost of pumpage.

**Table 2. Predicted annual water demand.**

Year	Annual demand
1990	9950
2015	14 800–17 000
2040	21 500–24 100
2065	31 200–31 300
2090	38 300–45 700

With full residential development of the existing urban area of Alice Springs, net salt importation into the town basin from continuing total reliance on Roe Creek borefield for domestic demands and residual irrigation would rise to 3500–4000 tonnes/year. Some 10 000 ML/year of total water supplied will be taken up in the city area by evaporation, transpiration and seepage. Full development of the current urban area of Alice Springs will generate ~2600 ML/year; full development of Undoolya Valley will result in a further 3400 ML/year of sewage generation.

#### Water supply management

Two broad issues are being considered: the need for augmentation and/or replacement of Roe Creek borefield; and the need and options for rehabilitation of the town basin.

**Roe Creek borefield.** An economic analysis for the development of a borefield in the Rocky Hill area from 1990 to 2010 has been undertaken. This analysis assumed that groundwater at Rocky Hill was the only alternative source to Roe Creek borefield water for Alice Springs. Three options were considered: continuing with Roe Creek borefield; completely supplanting Roe Creek borefield in 1995; and implementation of the new borefield in two steps to meet half the demand in 1995 and all of the demand in 2005. Under present conditions, there is a clear economic advantage in continuing with Roe Creek borefield as the sole source of supply until 2010. There is no apparent urgency for a supplement to the current borefield, although the potential of the Rocky Hill area should be investigated over the next 10 years while continuing to monitor water supply demand and the response in watertables in Roe Creek borefield.

**Rehabilitation of the town basin.** A program to develop irrigation supply bores has been implemented to increase extraction from storage and to leach saline soils. Increased usage of the resource and the reduced importing of Roe Creek borefield water into the basin have also been investigated. Strategies considered were: maximised use of raw town basin water for irrigation only, treated town basin water for domestic consumption; treated sewage waste water for irrigation reuse, and maximised extraction from storage in the town basin. Demand on Roe Creek borefield could be reduced by around 30% by combined use of town basin water and reuse of sewage, although the cost of any of these options is high.

Given the current lack of economic incentive, community preference will probably be needed before proceeding with either rehabilitation of the town basin or reuse of waste water. Further economic analyses should provide a better idea of the real need, costs and benefits for sewage reuse and expanded utilisation of the town basin.

### Conclusions

The first stage in developing a water management strategy for Alice Springs is an assessment of the resource. We must calculate the length of time we can continue to rely on Roe Creek borefield, and how we can reduce demand.

Under the existing operating conditions, the Roe Creek borefield will probably last 20 years. Maximising utilisation of the town basin and reuse of sewage to meet potential irrigation demand and to supplement potable water supply have been considered.

The next stage of the strategy should develop ways of reducing demand on Roe Creek borefield, in coordination with the results of work already done on the town basin and waste water reuse, and more efficient operation of the borefield and water supply system (including risk analysis for restricted water supply). The opportunities for community involvement in reducing water consumption should also be investigated.

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### Water usage

Simon Smith<sup>1</sup>

The Central Australian Conservation Council, a community based voluntary organisation in Alice Springs, Northern Territory, has been actively campaigning for many years to reduce water consumption in central Australia.

Overuse of water in Central Australia is due primarily to ignorance and apathy on the part of many householders, a general lack of appreciation of what 'arid' means by most planners, engineers, architects and landscape architects, and lack of vision and poor public education in government departments and local authorities.

The Northern Territory Power and Water Authority has raised community awareness of certain water wasting practices through media and other campaigns. Unfortunately these campaigns have aimed to reduce water consumption in high water-requiring gardens, rather than encouraging the development of gardens with low water demands.

The Power and Water Authority's campaigns have had only a limited effect on water consumption in Alice Springs (Power and Water Authority, 1988/89). Local councils have done little to reduce their own consumption, let alone that of the ratepayers. For example, street trees in Alice Springs are flood irrigated by water trucks, even though this practice uses far more water than drip irrigation would. Ovals and public lawns are still watered during the day. The Power and Water Authority

maintains large areas of lawn and retains totally inappropriate gardens around its public buildings.

With governments failing to lead by example, and public awareness campaigns that do not address the core of the problem, it is not surprising that the Northern Territory has not reduced garden water consumption to anything approaching acceptable levels.

The Central Australian Conservation Council feels that only a change in the garden design philosophy of local residents, developers and government departments will yield an appreciable reduction in garden water usage.

Fortunately, Alice Springs has some marvellous examples of arid zone landscaping. The Olive Pink Flora Reserve is a wonderful display garden and local plant arboretum. The Conservation Commission of the Northern Territory has pursued a low water demand/local species design policy there for many years, and the Alice Springs Town Council has constructed examples of appropriate landscaping for central Australia. Other examples of suitable design can be seen in private gardens and some public buildings, particularly the Araluen Arts Centre.

Most people in arid Australia are recent arrivals from cooler, wetter areas, so it is understandable that their perception of a home garden, a motel landscape or public streetscape is biased towards settings familiar in temperate zones. As arid Australia does not have predictable or frequent rainfall, a different style of garden is appropriate. In 1989, the Central Australian Conservation Council produced the only publication readily available in the Northern Territory that aims to reduce water demands through appropriate garden design (Central Australian Conservation Council, 1989).

### Appropriate gardens

Gardens in central Australia usually include the elements of lawn, planting, mulching and irrigation.

1. **Lawns: the worst offender.** Lawn irrigation is the greatest water waster in Alice Springs. Arid zone gardens should be designed with the minimum possible area of lawn, ideally zero. Home owners and developers must be encouraged to create a landscape that incorporates only a small functional area of lawn. Front lawns should be permitted only where no back lawn is possible, and irrigated nature strips/verges should be banned. The shape of a lawn can increase the visual impact. Groundcover species such as Creeping boobialla (*Myoporum parviflorum*) and Lippia (*Phyla nodiflora*) can be used as a substitute or to visually extend the existing lawn area. Lippia is remarkably hardwearing and can be used as a lawn where traffic is not heavy. If a lawn is not required, don't have one. All lawn areas must receive full sun for most of the day and should be built at a lower level than surrounding surfaces to enable rainwater run-off to pond. Discharging of washing machine water and bath water should be encouraged. Town planners, landscape architects and resort developers must treat lawn as a luxury to be used only when functionally necessary.

2. **Planting.** Maximum use should be made of

native plant species. Plants that have evolved in an area are best suited to the prevailing conditions! The use of exotic species should be encouraged only in areas, such as around buildings, where a suitable microclimate exists. Non-local native species should be used only when a suitable local plant does not exist. Nurseries must be encouraged (perhaps even subsidised) to grow and promote suitable local species. Direct seeding with local seed should be used to reduce costs on large projects and germination of seed by home owners should be supported. Specific horticultural information may be required for certain species but hardy, adaptable and long lived endemic varieties should be the 'backbone' of all domestic gardens, street plantings, commercial and resort landscapes. Inspirational display gardens, such as the Olive Pink Flora Reserve in Alice Springs, need to be promoted and expanded. The preservation of existing vegetation should be a priority in all large developments and resorts. There are many other ecological and social reasons for promoting local species, but the need for only minimal watering once established is compelling.

3. **Mulching.** All arid zone gardens need mulching. Mulches greatly reduce evaporation and soil temperature fluctuation, and suppress weed growth. In most arid areas, inorganic mulches such as gravels, sands and river stone are the cheapest and most practical solution. Woodchips or other organic mulches can be used for feature beds or to highlight certain areas. Colours and features of mulches can be used as a design element. The Japanese have developed this into an art form, and careful mulch treatment can provide a pleasing aspect of arid zone garden design, especially for the new garden. Garden debris can be used to build up an organic mulch.

4. **Irrigation.** When evaporation exceeds precipitation by a factor of ten, as it does in Alice Springs, the need for irrigation, at least during the establishment of a garden, is obvious. Most people have no idea of the duration and frequency of watering required by their lawn and garden, and tend to grossly overwater to 'be on the safe side'. The Power and Water Authority has been partially successful in encouraging night or evening watering but most residents remain ignorant of how long and how often to water. Drip irrigation is now the norm and fixed pop-up sprinklers are becoming widespread, but these tools for efficient irrigation are also dangerous weapons when employed by the ignorant. Public education must very simply and in non-technical terms explain the connection between precipitation rates, infiltration rates, the crop factor and the root zone of particular plant or grass species, in particular soil conditions. Automatic controls for watering systems on larger projects and domestic settings should be encouraged. Incredible amounts of water are wasted by people forgetting to turn sprinklers off. In central Australia most people need to be informed that yellowing of lawns is caused by overwatering leaching away nutrients, rather than lack of water, and that frosts cause lawns to 'die off' in winter, and that heavy watering only compounds the problems.

### What can be done?

The Central Australian Conservation Council strongly believes that users of excessively high

amounts of garden water should have to pay the actual cost of water over a certain limit, rather than a subsidised cost.

The Power and Water Authority should inform consistently high users of garden water of their intention to increase charges, say two quarters in advance. Such contact should include advice on irrigation programs and assistance in reducing water demands of the particular garden.

Timer taps should be made available free or at subsidised rates to all residents. Incentive schemes should be established to encourage residents to convert high water gardens to more appropriate ones.

Public education campaigns must be directed at changing 'temperate' perceptions of garden-

ing in central Australia. Information on appropriate garden designs for arid areas and a guide to developing and maintaining such gardens should be freely available to all residents.

#### Conclusions

The Northern Territory Power and Water Authority and local councils in central Australia now have no excuse for not developing and implementing a co-ordinated program for reducing water use in central Australian gardens.

The examples supplied in this conference from Leigh Creek and the Pilbara region (note the Roebourne Shire landscaping policy) show what can be achieved if governments and the public are committed to reducing water usage. The Alice Springs and Tennant Creek town

councils and the Power and Water Authority can, like the Central Australian Conservation Council, help educate the central Australian public on reducing water consumption through appropriate garden design.

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