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

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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.) ungulata* 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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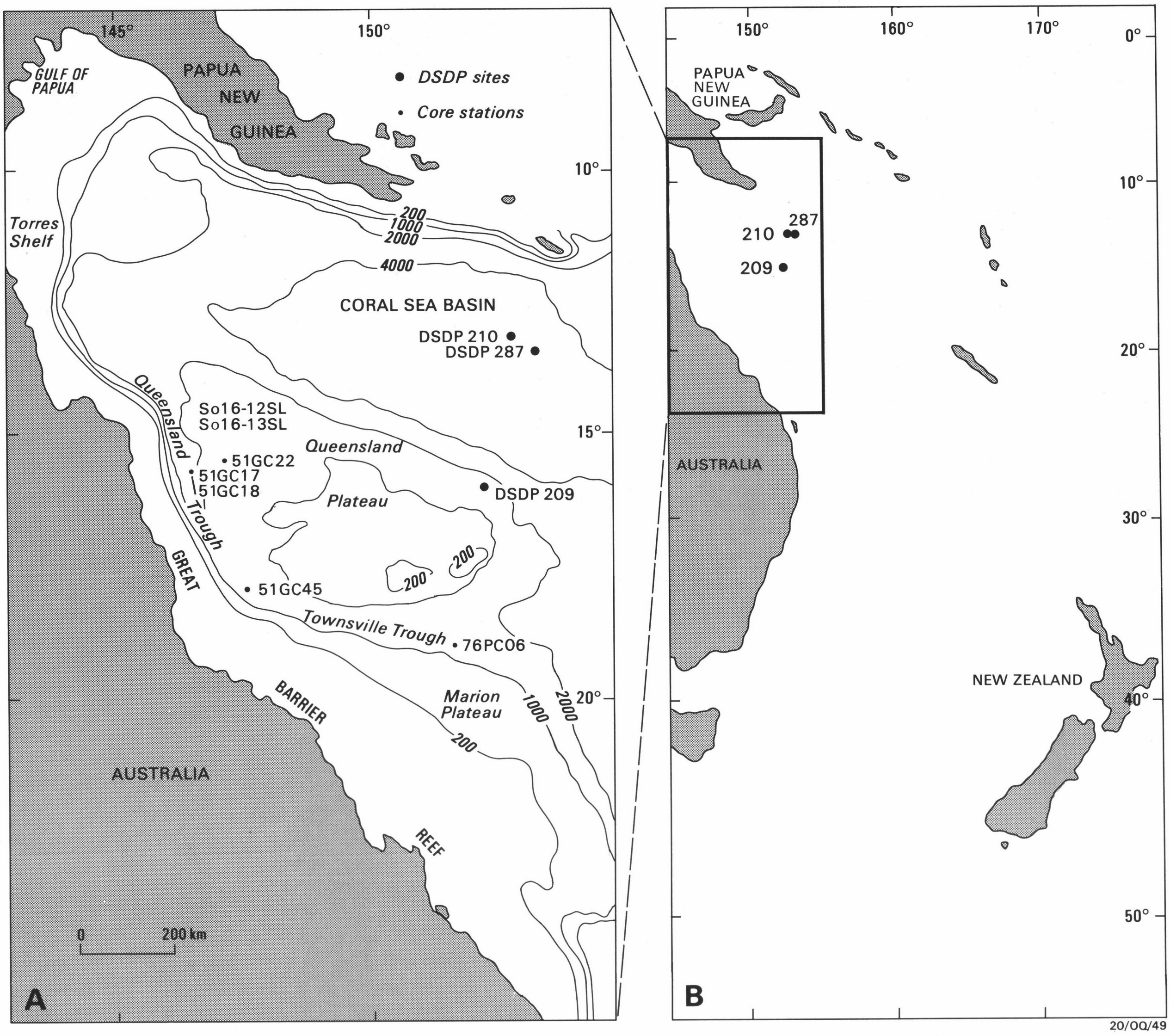
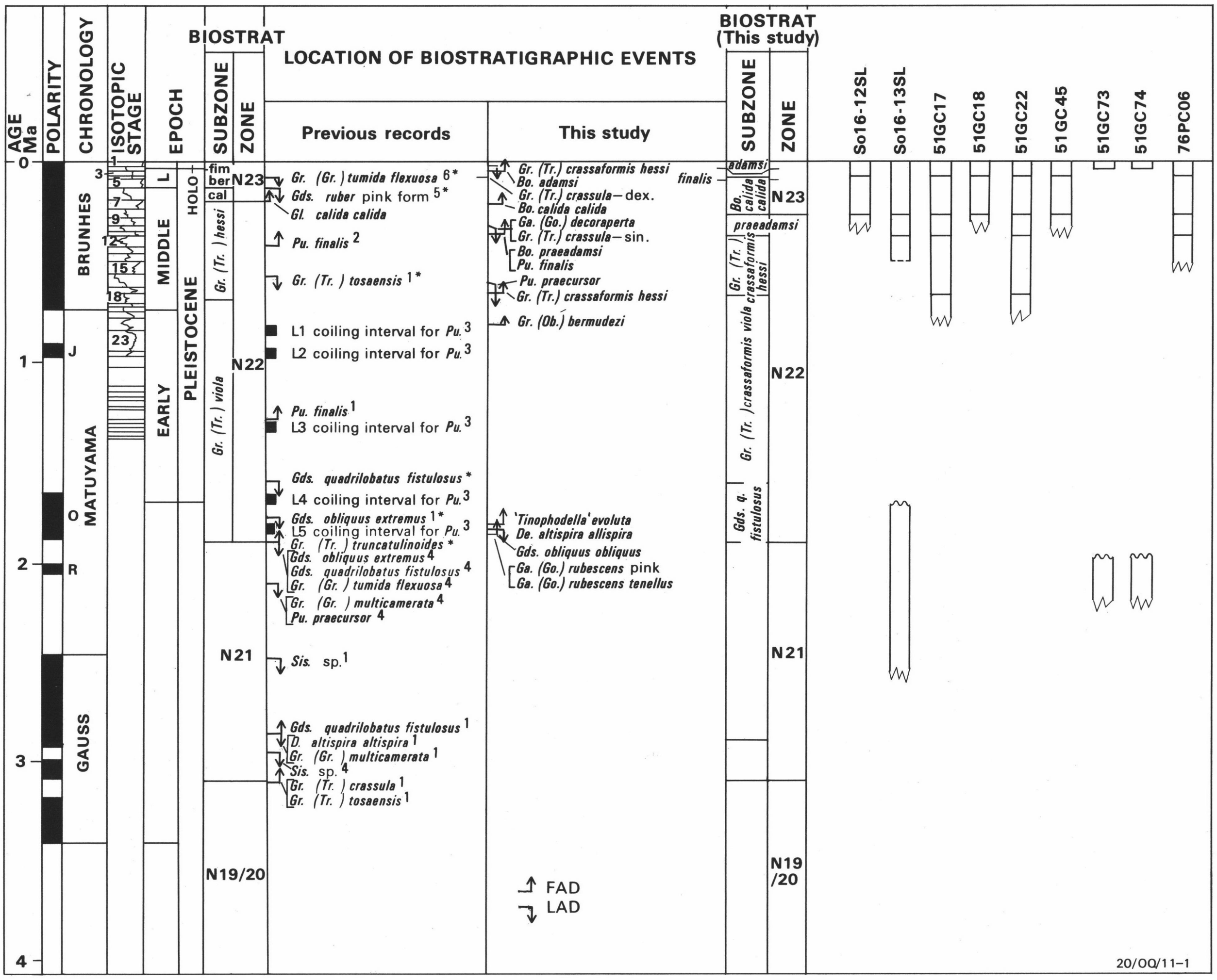


Figure 1. Locality map showing locations of cores used in this study.

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 & Huddlestun, 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) cariacoensis* 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 $\delta^{18}O$) 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 Bruhnes 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.

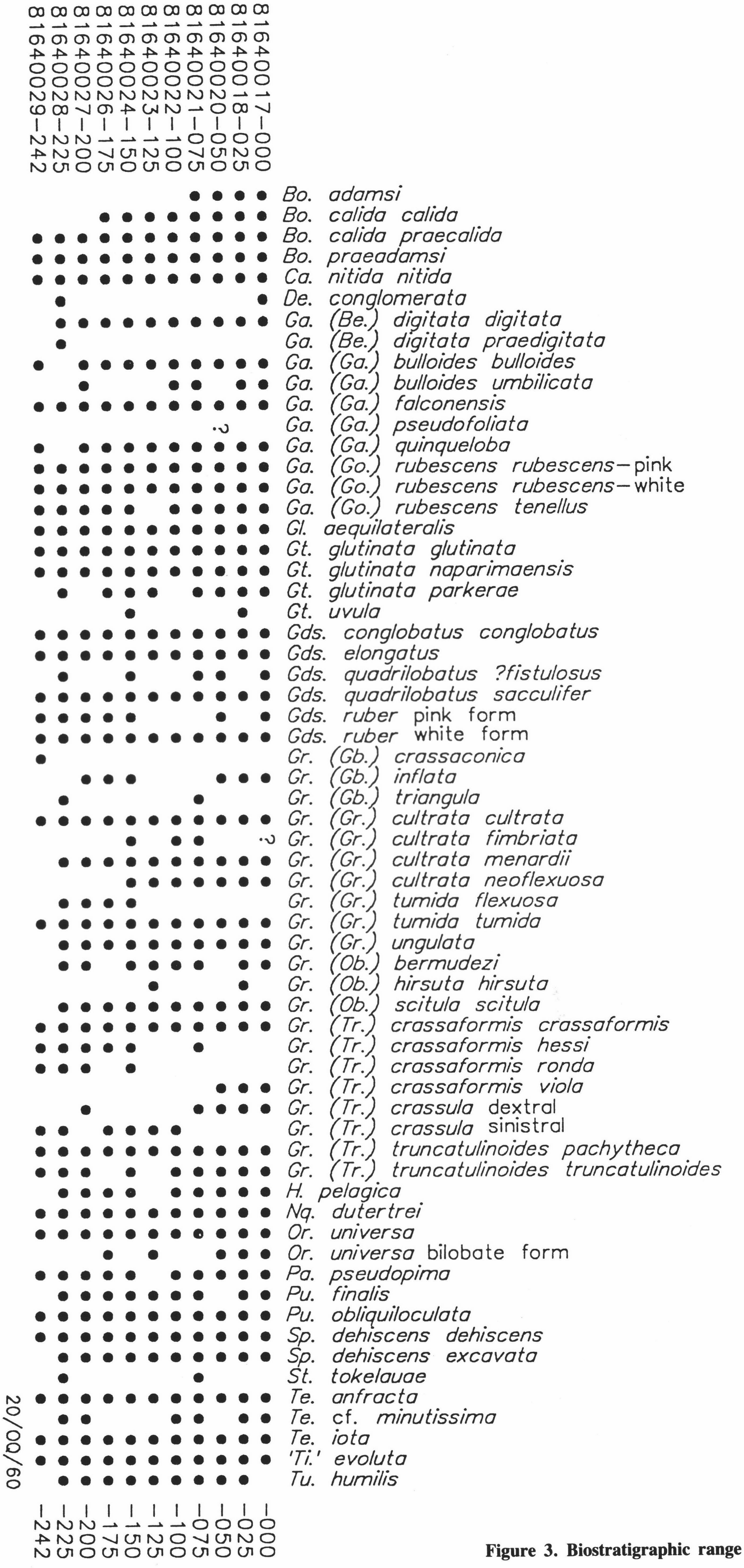


Figure 3. Biostratigraphic range chart for core So16-12SL.

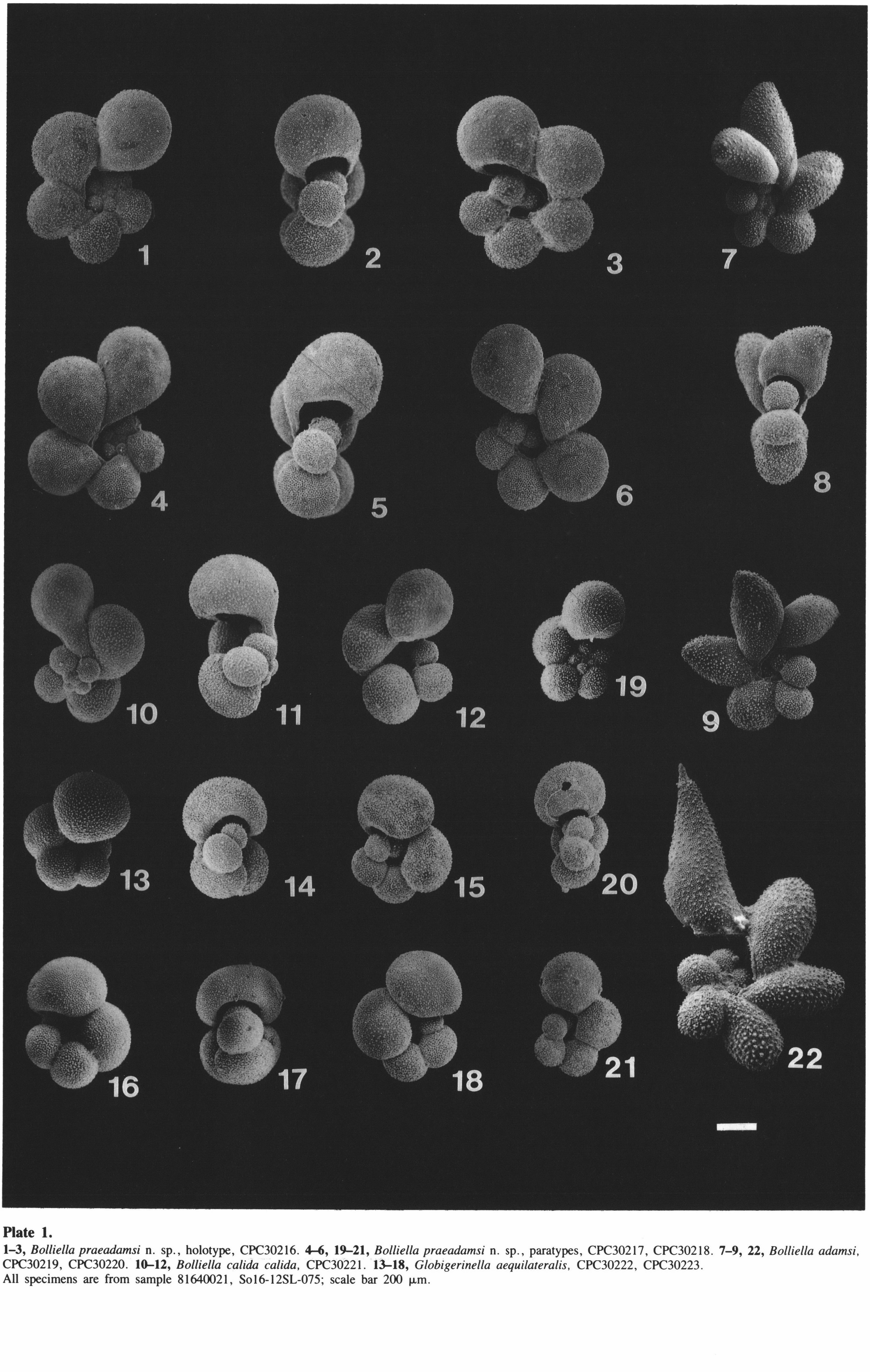


Plate 1.

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 μm.

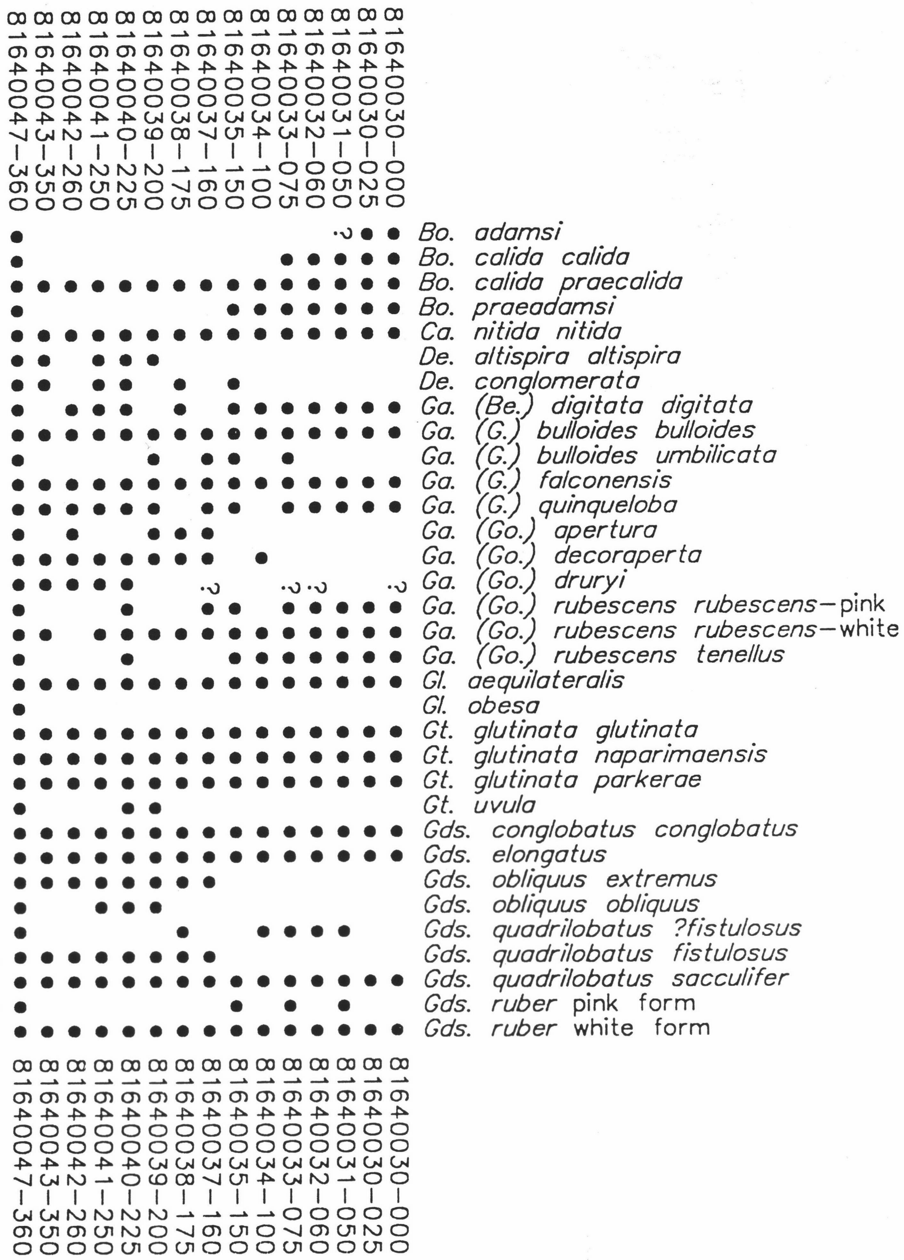
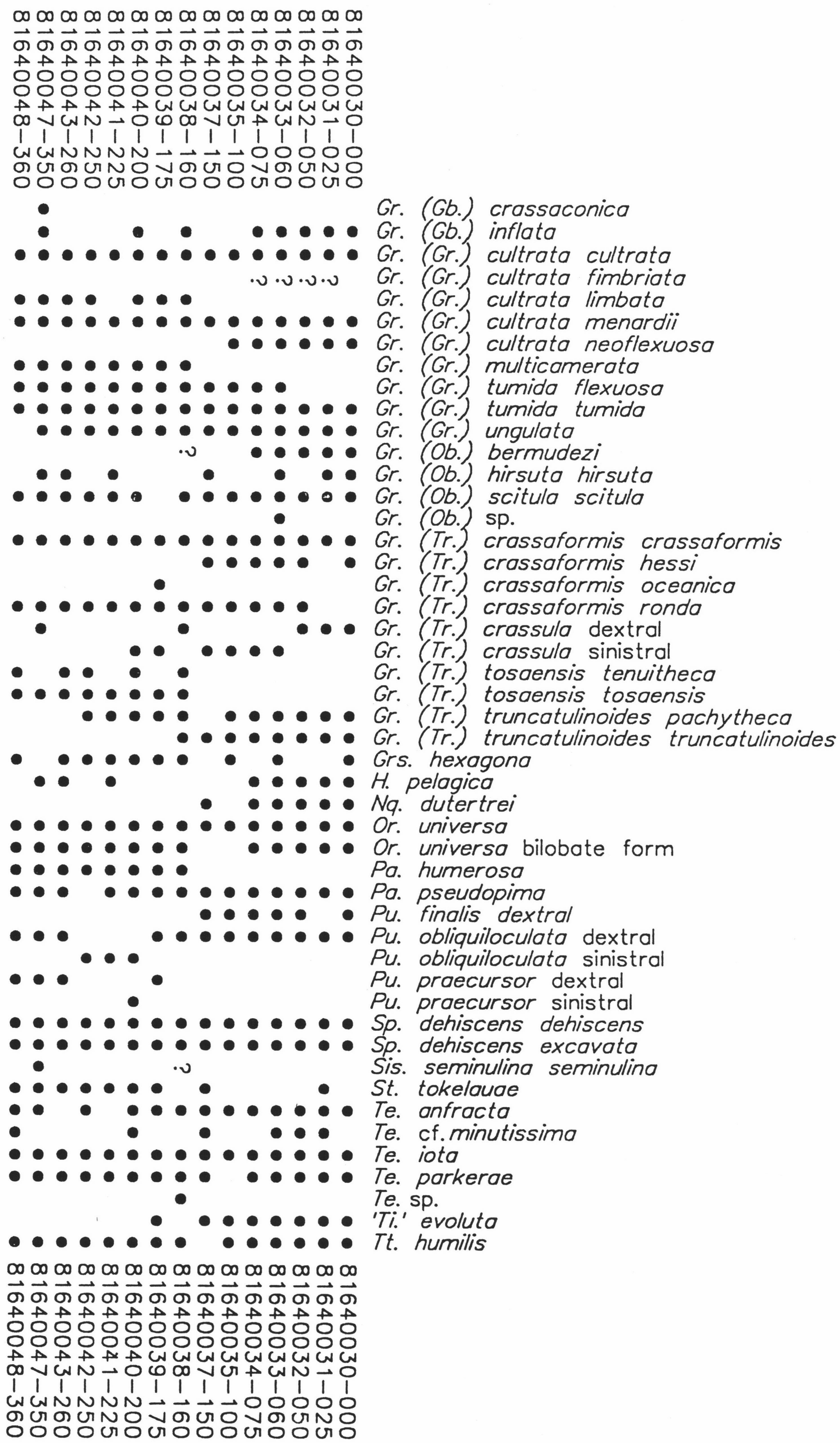


Figure 4. Biostratigraphic range chart for core So16-13SL.

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 (Globoturborotalita) 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 (Globoturborotalita) 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.)*



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

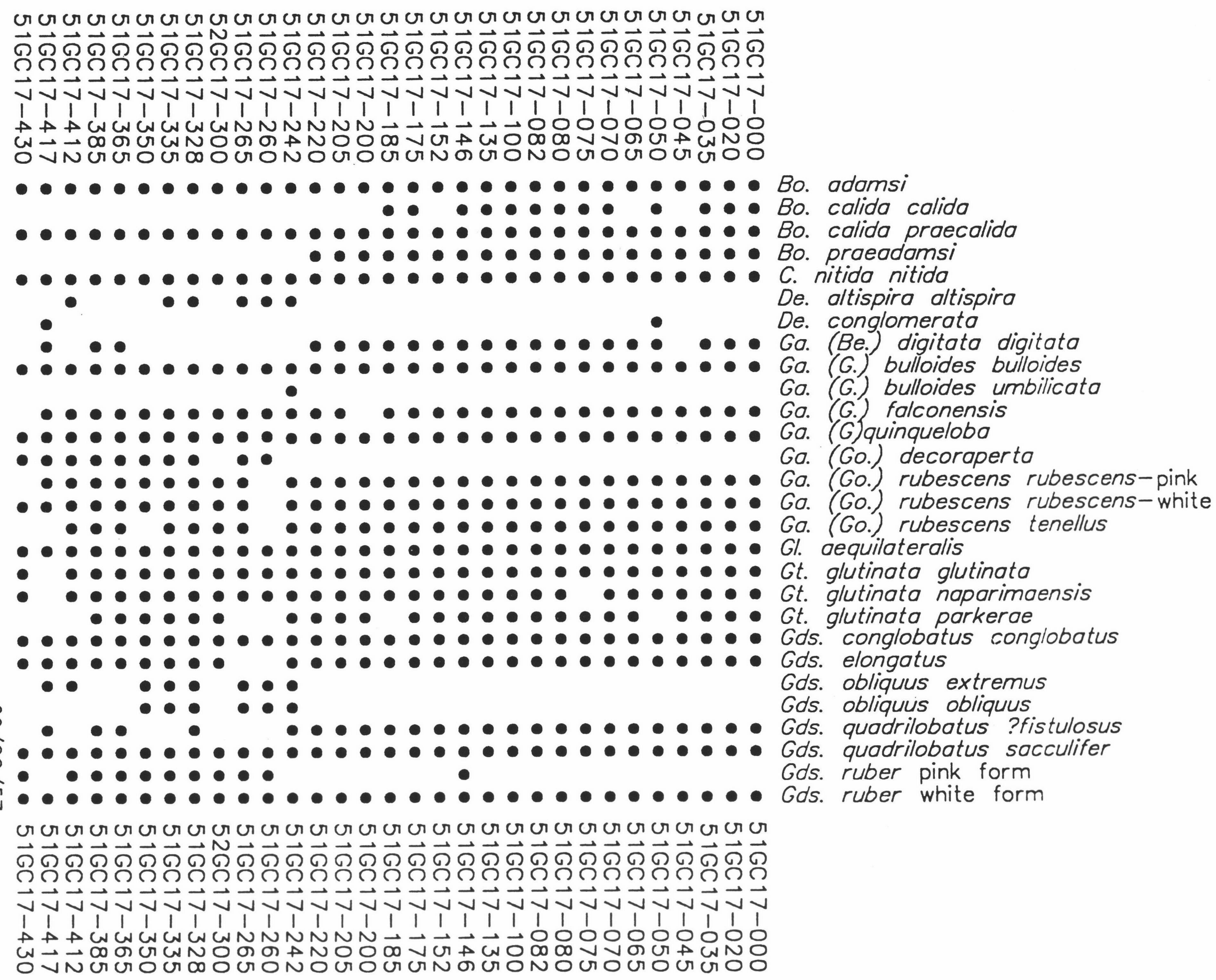


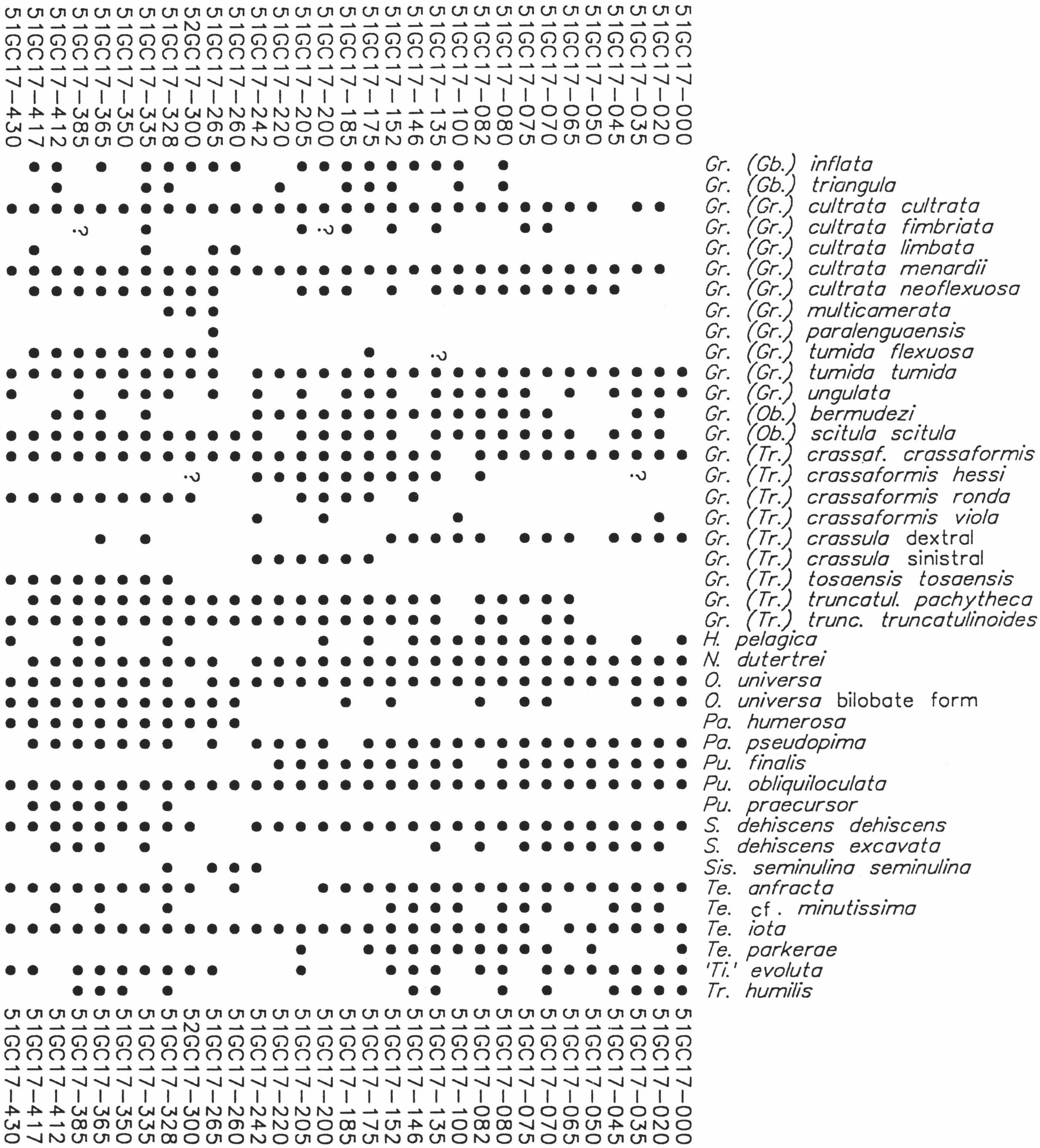
Figure 5. Biostratigraphic range chart for core 51GC17.

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.) lenguaensis* 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.

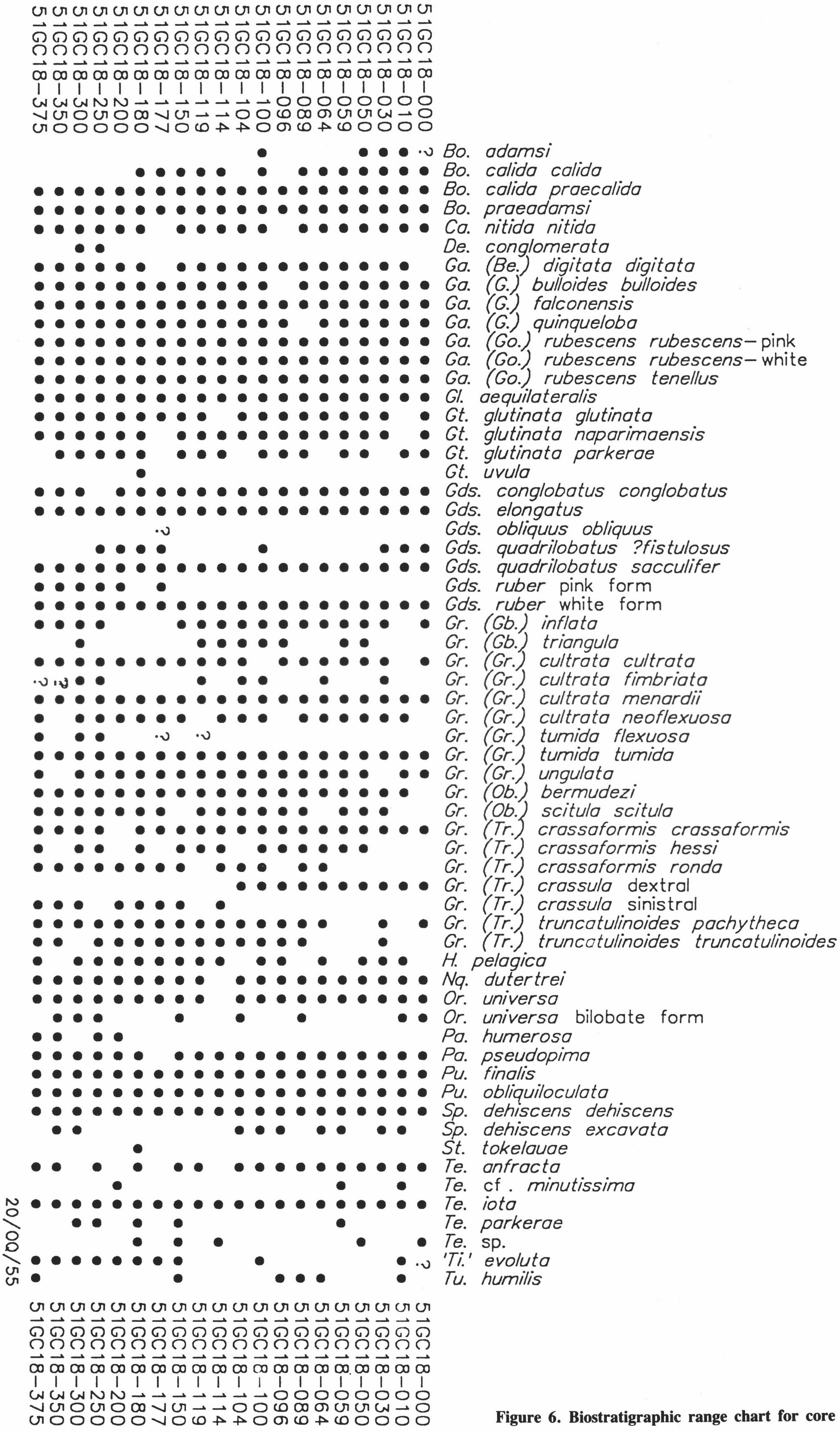


Figure 6. Biostratigraphic range chart for core 51GC18.

51GC22-218	51GC22-214	51GC22-200	51GC22-175	51GC22-166	51GC22-150	51GC22-131	51GC22-125	51GC22-106	51GC22-100	51GC22-090	51GC22-080	51GC22-075	51GC22-070	51GC22-050	51GC22-040	51GC22-025	51GC22-006	51GC22-000	
									?						●		●	●	*Bo. adamsi*
								●	●	●		●	●		●	●	●	●	*Bo. calida calida*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Bo. calida praecalida*
			●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Bo. praeadamsi*
●	●	●	●		●	●	●	●	●	●	●	●	●				●	●	*Ca. nitida nitida*
							●												*De. baroemoenensis*
	●				●														*De. conglomerata*
●	●	●	●	●	●		●	●	●	●		●	●	●	●	●	●	●	*Ga. (Be.) digitata digitata*
●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●		●	*Ga. (G.) bulloides bulloides*
	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●		●	*Ga. (G.) falconensis*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Ga. (G.) quinqueloba*
●																			*Ga. (Go.) decoraperta*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Ga. (Go.) rubescens rubescen*—pink
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Ga. (Go.) rubescens rubescens*—white
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Ga. (Go.) rubescens tenellus*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gl. aequilateralis*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gt. glutinata glutinata*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gt. glutinata naparimaensis*
●	●	●	●	●	●		●	●	●	●	●	●		●	●	●	●	●	*Gt. glutinata parkerae*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gds. conglobatus conglobatus*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gds. elongatus*
●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gds. quadrilobatus ?fistulosus*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gds. quadrilobatus sacculifer*
●	●	●	●	●	●	●	●	●		●	●	●	●	●					*Gds. ruber* pink form
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gds. ruber* white form
			●	●	●	●	●	●	●	●	●	●	●	●	●	●			*Gr. (Gb.) inflata*
					●	●		●		●		●	●	●	●				*Gr. (Gb.) triangula*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gr. (Gr.) cultrata cultrata*
		?	?			?	●	●		●		●			●				*Gr. (Gr.) cultrata fimbriata*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gr. (Gr.) cultrata menardii*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		*Gr. (Gr.) cultrata neoflexuosa*
●	●	●	●	●	●	●	●				●								*Gr. (Gr.) tumida flexuosa*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gr. (Gr.) tumida tumida*
●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	*Gr. (Gr.) ungulata*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gr. (Ob.) bermudezi*
																	●		*Gr. (Ob.) hirsuta praehirsuta*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gr. (Ob.) scitula scitula*
	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gr. (Tr.) crassaformis crassaformis*
	●	●	●	●	●	●	●	●	●	●	●	●	●		●	?	?		*Gr. (Tr.) crassaformis hessi*
●	●	●	●	●	●	●	●	●	●	●	●		●	●					*Gr. (Tr.) crassaformis ronda*
												●							*Gr. (Tr.) crassaformis viola*
		●									●		●	●	●	●	●	●	*Gr. (Tr.) crassula* dextral
			●	●	●	●	●	●	●	●		●							*Gr. (Tr.) crassula* sinistral
●	●																		*Gr. (Tr.) tosaensis tosaensis*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Gr. (Tr.) truncatulinoides pachythe*
	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			*Gr. (Tr.) truncatulinoides truncatulinoides*
								●							●				*H. parapelagica*
		●		●		●		●	●			●	●	●	●	●		●	*H. pelagica*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Nq. dutertrei*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Or. universa*
●	●	●	●		●	●			●		●			●	●	●	●	●	*Or. universa* bilobate form
●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	*Pa. pseudopima*
			●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Pu. finalis*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Pu. obliquiloculata*
●	●	?																	*Pu. praecursor*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	*Sp. dehiscens dehiscens*
			●				●	●	●		●	●	●				●		*Sp. dehiscens excavata*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Te. anfracta*
									●		●								*Te.* cf. *minutissima*
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	*Te. iota*
					●		●											●	*Te. parkerae*
●							●		●		●	●	●	●	●	●	●		*Te.* sp.
●	●	●	●	●	●	●		●	●	●	●	●	●			●	●	●	*'Ti.' evoluta*
							●												*Tt. cristata*
●	●	●	●		●	●	●			●		●				●	●	●	*Tt. humilis*
-218	-214	-200	-175	-166	-150	-131	-125	-106	-100	-090	-080	-075	-070	-050	-040	-025	-006	-000	

20/00/54

Figure 7. Biostratigraphic range chart for core 51GC22.

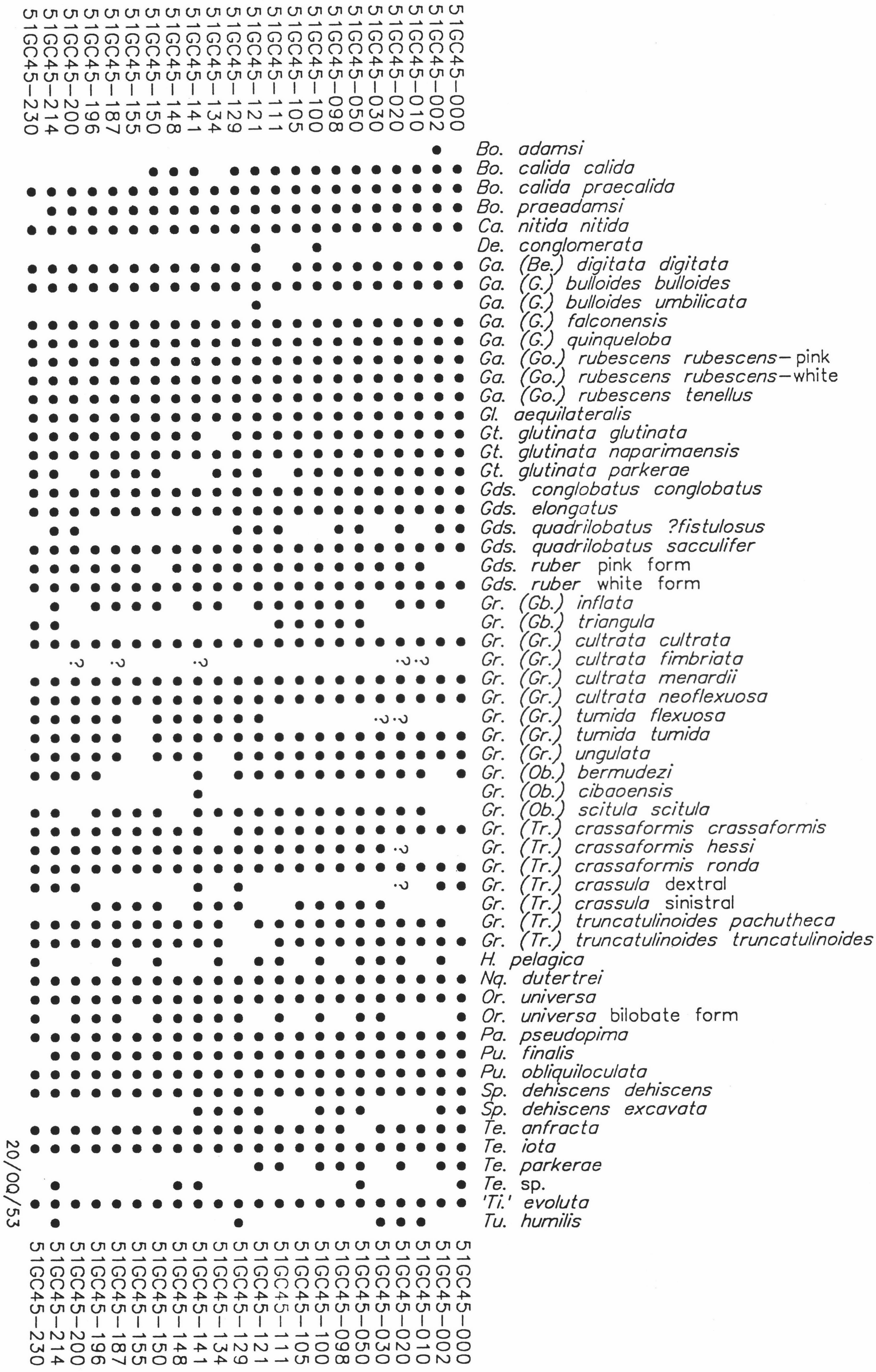


Figure 8. Biostratigraphic range chart for core 51GC45.

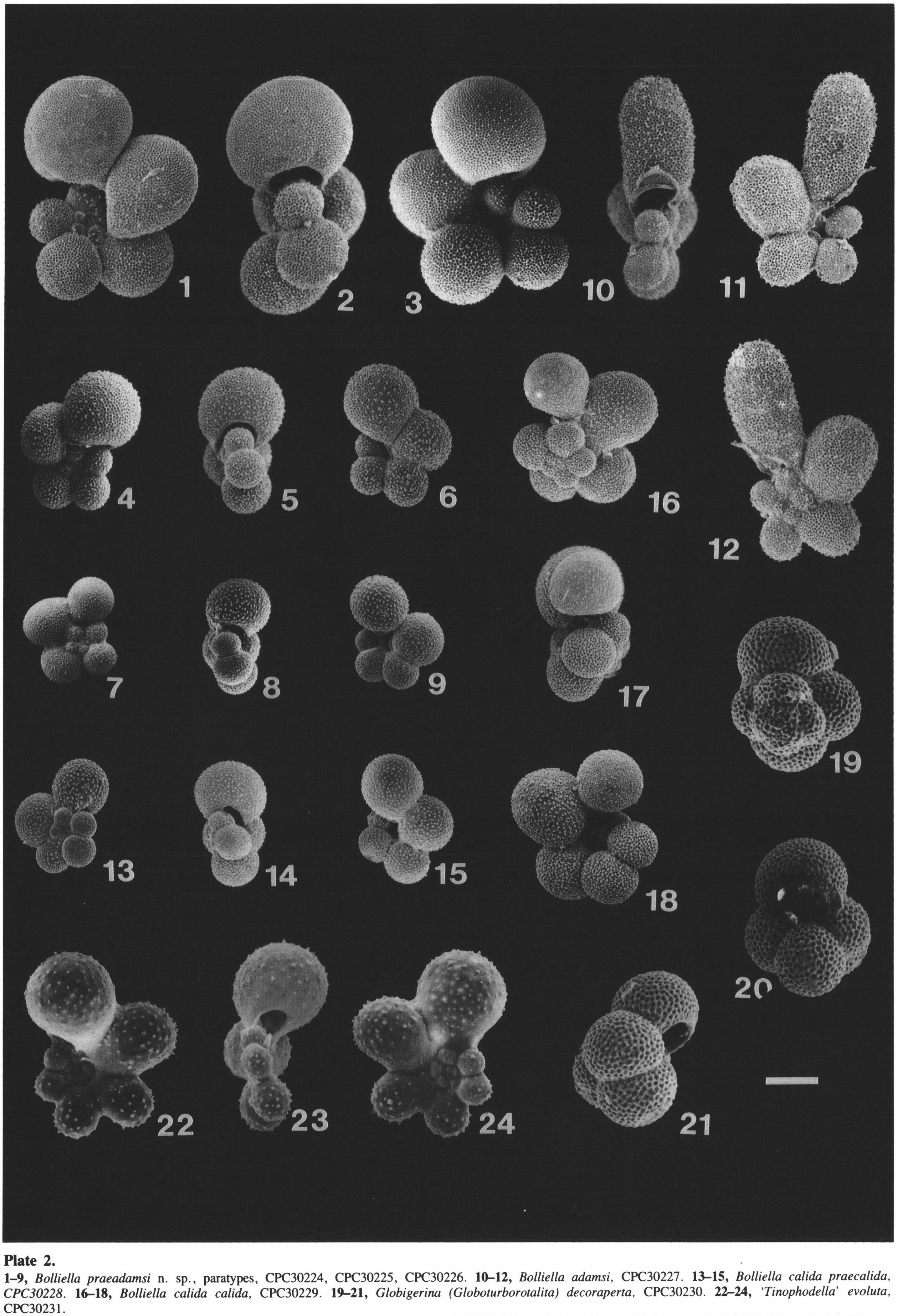


Plate 2.
1–9, *Bolliella praeadamsi* n. sp., paratypes, CPC30224, CPC30225, CPC30226. **10–12,** *Bolliella adamsi*, CPC30227. **13–15,** *Bolliella calida praecalida, CPC30228.* **16–18,** *Bolliella calida calida*, CPC30229. **19–21,** *Globigerina (Globoturborotalita) decoraperta*, CPC30230. **22–24,** *'Tinophodella' evoluta*, CPC30231.
Figs 1–18, sample 81640021, So16-12SL-075, scale bar 180 μm; 19–21, sample 51GC17-260, scale bar 100 μm; 22–24, sample 51GC45-100, scale bar 60 μm.

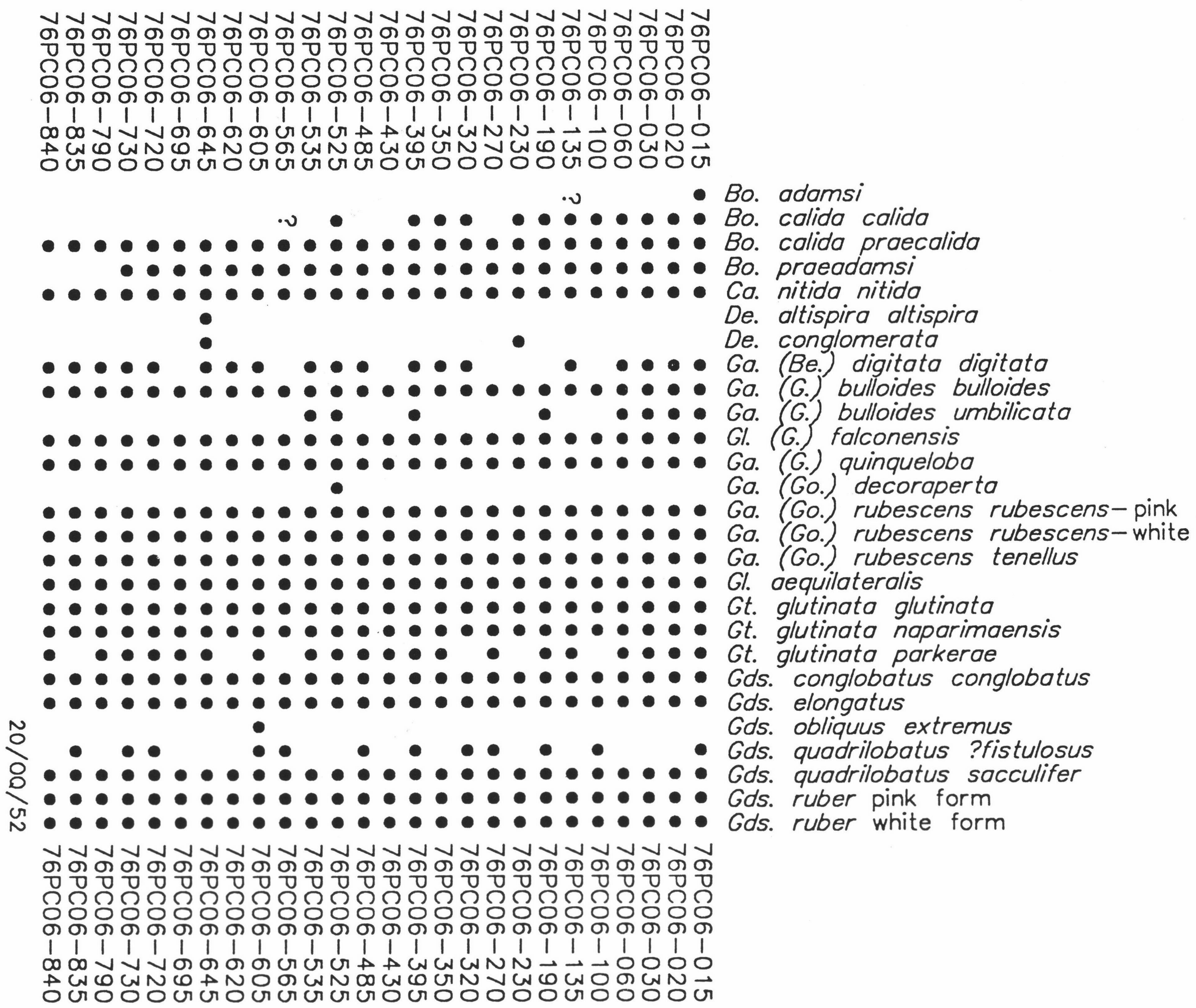


Figure 9. Biostratigraphic range chart for core 76PC06.

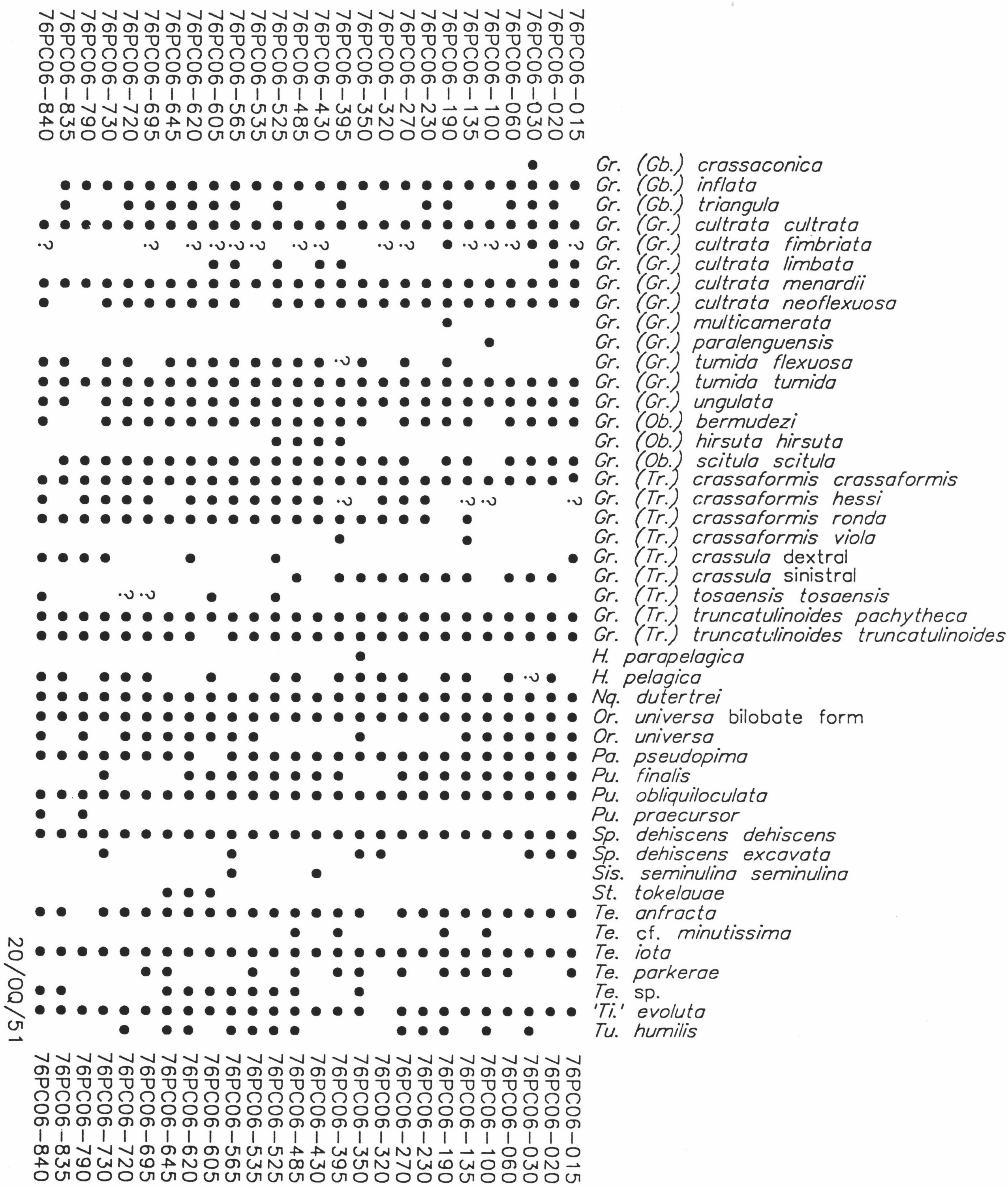
Pleistocene biostratigraphy

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).*

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

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

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



absence of temperature-controlled forms in the Coral Sea area as has been possible in other places (such as the Gulf of Mexico).

Reworking is obvious in some cores, particularly in 51GC17 and 76PC06. In most cases this represents reworking from the late Pliocene (forms such as *Gr. (Tr.) tosaensis* and *Pu. praecursor)* although some from the late Miocene *(Gr. (Gr.) paralenguaensis* and *Gr. (Gr.) tumida plesiotumida)* is evident. Reworking does not pose problems for the biostratigraphy of the middle and late Pleistocene, as all species involved had become extinct by the lowermost Pleistocene.

Evolutionary bioseries have provided useful markers for this study, in particular the *Bo. calida praecalida–Bo. calida calida*, the *Bo. calida praecalida–Bo. praeadamsi–Bo. adamsi* and *Gr. (Tr.) crassaformis ronda–Gr. (Tr.) crassaformis hessi* lineages. A change in coiling dominance in populations of *Gr. (Tr.) crassula* has also been particularly useful.

All of the cores studied contain the section above the FAD of *Bo. praeadamsi*. In this part, the events shown in Table 1 consistently occur in the same order, testifying to their reliability, at least for the Coral Sea region adjacent to northern Australia. Two cores (So16-13SL and 76PC06) penetrated into

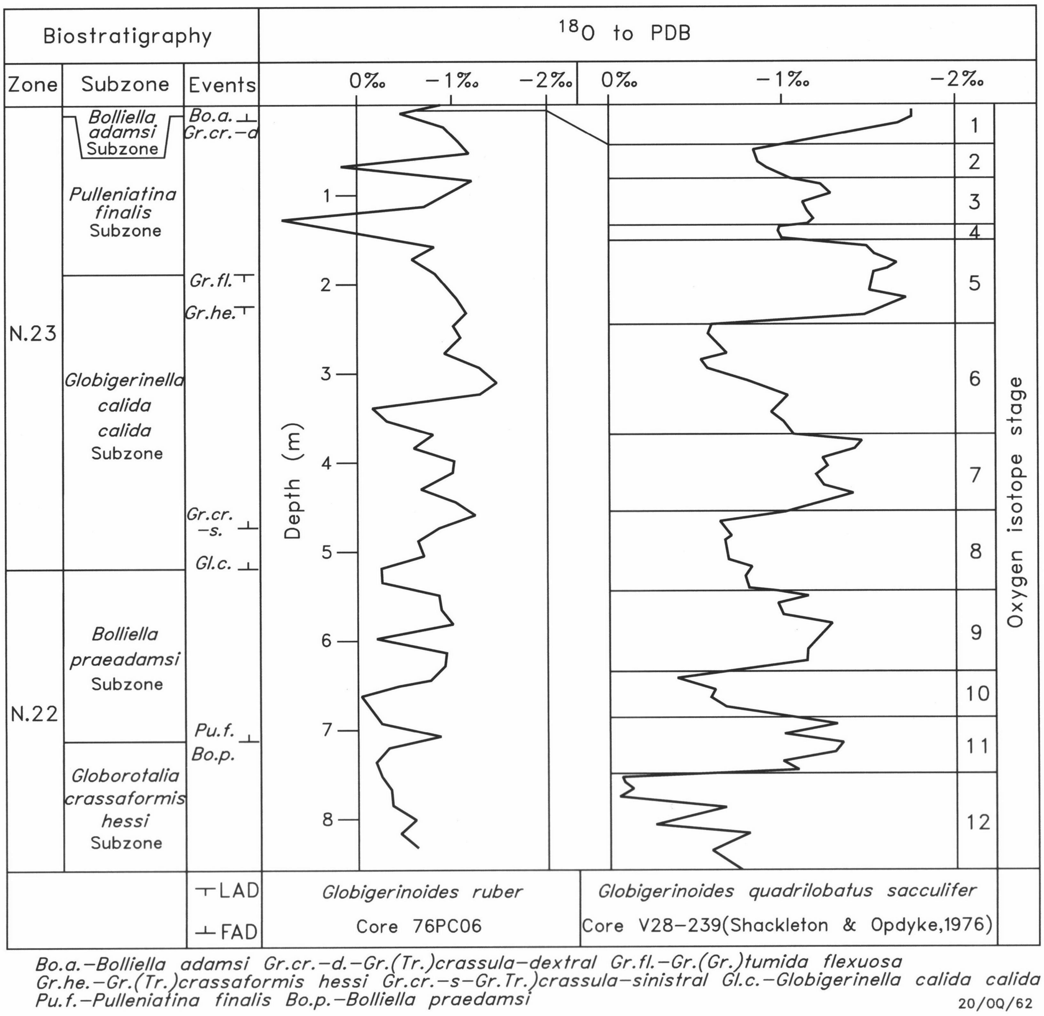


Figure 10. Relationship of biostratigraphic events and oxygen isotope stratigraphy in core 76PC06. Oxygen isotope data from Peerdeman (ANU, personal communication).

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. praeadamsi*
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. praeadamsi subzone: FAD *Bo. praeadamsi*
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^{e}) 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 (Globoturborotalita) 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

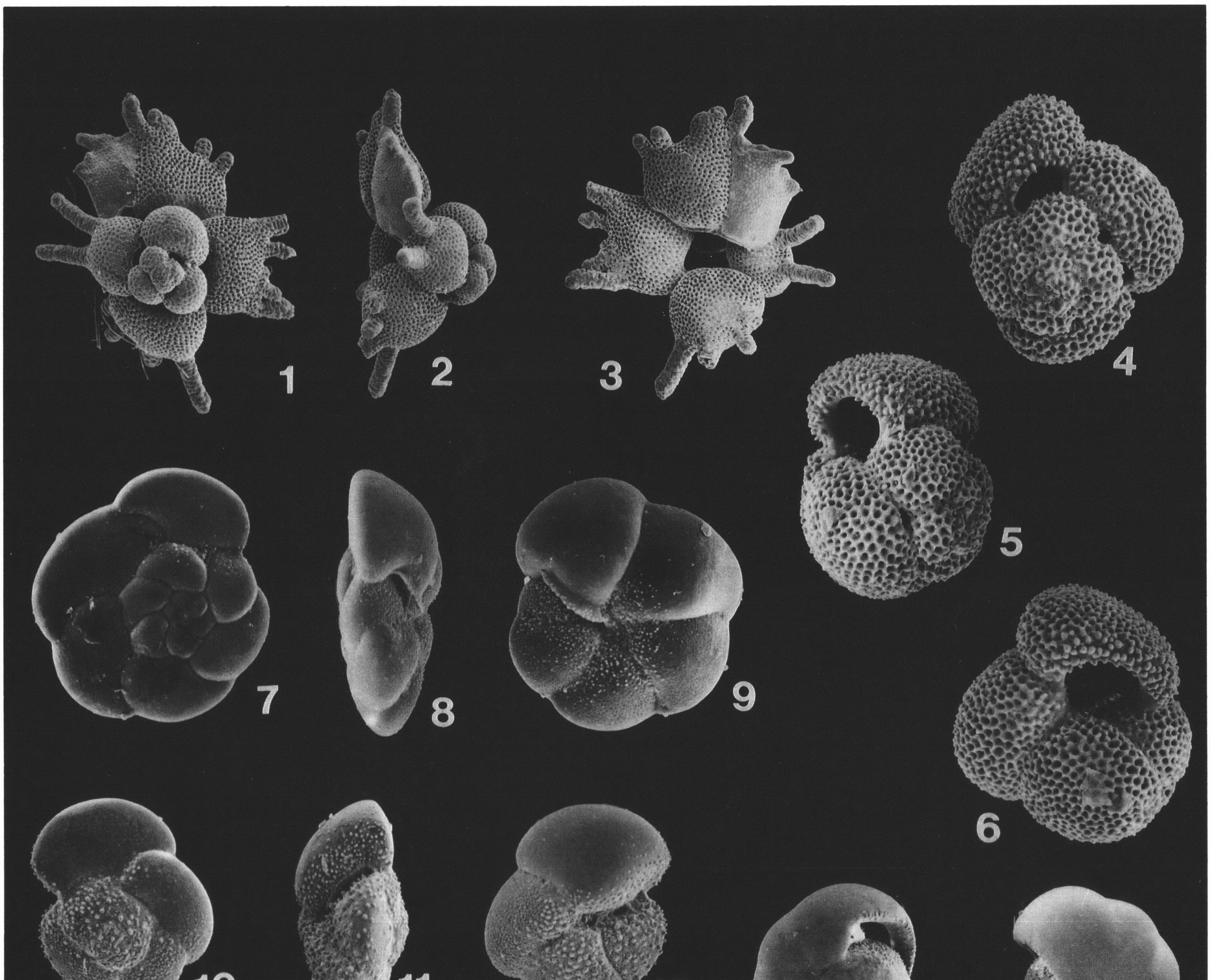


Plate 3.

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 μm; 4–9, 75 μm; 10–12, 135 μm; 13–24, 200 μm.

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 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

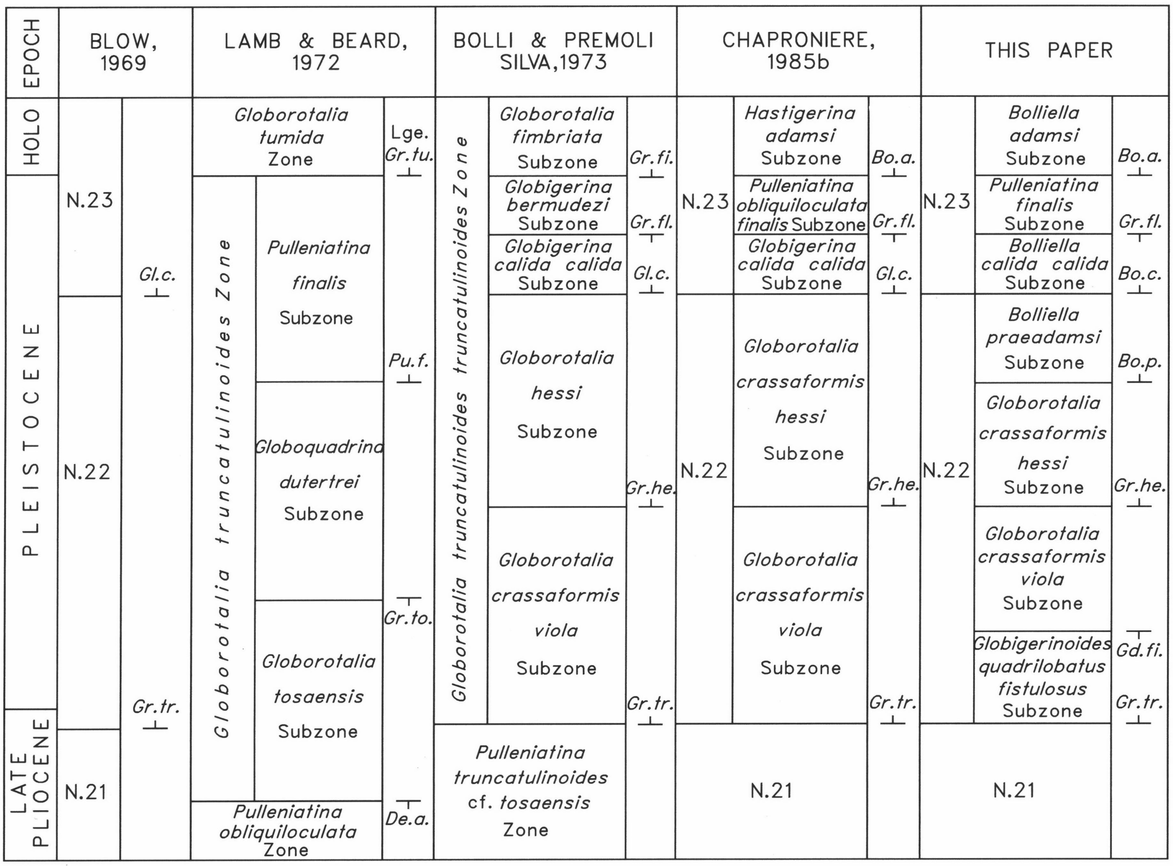
Of the 27 events discussed above (Table 1), 23 have been recognised by earlier workers, and only four are newly recognised. Few of these have been used biostratigraphically, at least in the Indo-Pacific region, where there have been few attempts at a Pleistocene planktic foraminiferal biostratigraphy. 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



┬ 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

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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 So16-13SL 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.) truncatulinoides* 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.) truncatulinoides* 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 praecalida* 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.

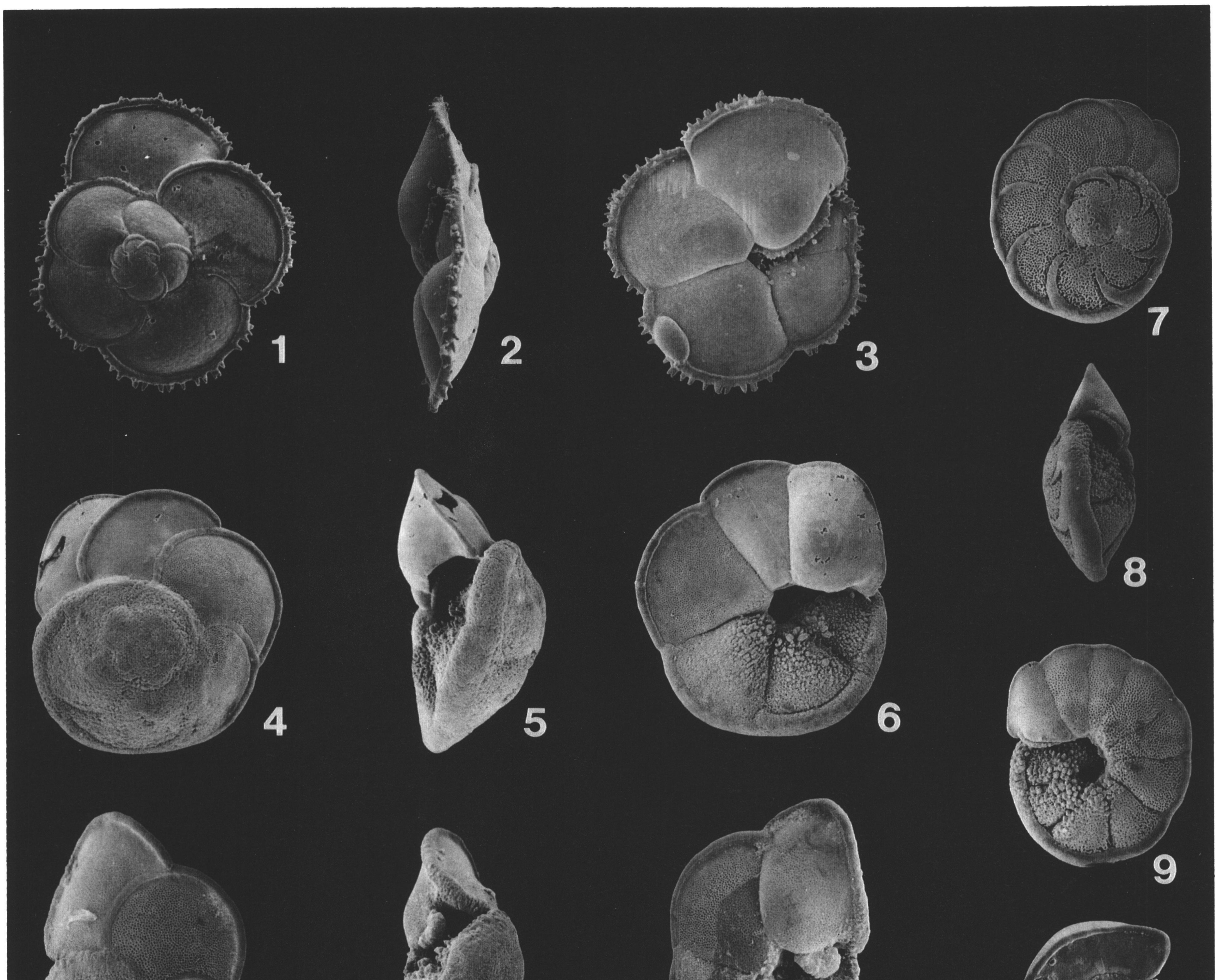

Plate 4.

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 pachytheca*, CPC30246, sample 51GC22-040.

Scale bar figs 1–12, 16–21, 300 μm; 13–15, 200 μm.

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, praecalida* 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 praecalida* 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 *praecalida* 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 praecalida, 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 praecalida,* and this appears to be the preferred ancestral form of *Bo. praeadamsi*.

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