

39. NEOGENE PLANKTONIC FORAMINIFERS FROM SITES 761 AND 762 OFF NORTHWEST AUSTRALIA¹

W. J. Zachariasse²

ABSTRACT

Diverse, warm-water planktonic foraminiferal faunas prevailed on the Wombat and Exmouth plateaus during the Neogene, in spite of the northward drift of Australia across 10° to 15° latitude since the early Miocene. Invasions of cool-water species occurred during periods of global cooling in the late middle Miocene, late Miocene, and Pleistocene, and reflect periods of increased northward transport of cool surface water, probably via the West Australian Current.

The sedimentary record of the Neogene on Wombat and Exmouth Plateau is interrupted by two hiatuses (lower Miocene, Zone N5, and upper middle to upper Miocene, Zones N15–N17), and one redeposited section of upper Miocene to uppermost Pliocene sediments. Mechanical erosion or nondeposition by increased deep-water flow or tilting and uplift of Wombat and Exmouth plateaus, resulting in sediment shedding, are the most likely explanations for these Miocene hiatuses, but which of these processes were actually operative on the Wombat and Exmouth plateaus is uncertain. The redeposited section of upper Miocene to uppermost Pliocene sediments in Hole 761B, however, certainly reflects a latest Pliocene period of uplift and tilting of the Wombat Plateau.

An important finding was the occurrence of Zone N15-correlative sediments in Hole 762B without any representative of *Neogloboquadrina*. Similar findings in Java and Jamaica indicate that the earliest spreading of *Neogloboquadrina acostaensis* in the tropical region resulted from migration. The evolution of this species, therefore, must have taken place in higher latitudes. I suggest that *Neogloboquadrina acostaensis* evolved from *Neogloboquadrina atlantica* in the North Atlantic within Zone NN9, but how and where in the region this speciation took place is still uncertain.

INTRODUCTION

The main objective of this study was to ascertain the uncertain phylogenetic origin of *Neogloboquadrina acostaensis*. The initial evolutionary appearance of this species defines the base of planktonic foraminiferal Zone N16 (Blow, 1969), and is generally equated with the middle/late Miocene boundary; the origin of this species, however, is nowhere firmly documented. The Exmouth and Wombat plateaus off northwest Australia were thought to offer potentially good sites for clarifying the ancestry of *Neogloboquadrina acostaensis*; thus, Sites 761 and 762, both having a continuously cored Neogene sequence, were selected for this study (Fig. 1). Preliminary planktonic foraminiferal data (Haq, von Rad, O'Connell, et al., 1990) suggested that both Holes 762B and 761B contained complete sequences of pelagic oozes over the critical stratigraphic interval of Zones N14 to N16. Calcareous nannofossil data from Hole 762B (Haq, von Rad, O'Connell, et al., 1990), however, suggest that Zone NN8 (uppermost middle Miocene) is missing.

This paper discusses the Neogene planktonic foraminiferal biostratigraphy and the erosional and paleoclimatic events at Sites 761 and 762, followed by a discussion of the ancestry of *Neogloboquadrina acostaensis*.

BIOSTRATIGRAPHIC SUMMARY OF HOLE 762B

Twenty-four samples were available from Cores 122-762B-12H to -15H of Hole 762B. Figure 2 shows the stratigraphic ranges of the most common planktonic foraminiferal species (larger than 125 μm) and the datum levels used to define 10

biozones. The studied interval corresponds to the early to late Miocene.

Reworked middle to late Eocene and late Oligocene to early Miocene species are numerous as far upward as the lower middle Miocene *Praeorbulina glomerosa* Zone. No reworked elements were found at higher levels. Figure 2 shows that the *Globorotalia fohsi* and *Orbulina* lineages are fully recorded, although representatives of *Globorotalia fohsi* are scarcer than earlier stages of the *Globorotalia fohsi* lineage. *Globorotalia menardii* first occurs in the upper middle Miocene. Early stages of the *Globorotalia menardii* lineage are absent, with the exception of a single sample in the lower middle Miocene *Praeorbulina glomerosa* Zone, where *Globorotalia archeomenardii* is relatively abundant. The small, coarsely perforated, 5- to 6-chambered *Globorotalia birnageae* seems to merge into *Globorotalia peripheroronda* in the upper part of the upper lower Miocene *Globigerinatella insueta* Zone, by enlarging the size and the number of chambers in the final whorl (Pl. 1, Figs. 1–11). This evidence suggests that the *Globorotalia fohsi* lineage roots in *Globorotalia birnageae* and not in *Globorotalia kugleri*, as championed by Kennett and Srinivasan (1983). The last occurrence of *Paragloborotalia mayeri* is recorded at 120.4 meters below seafloor (mbsf) (Sample 122-762B-14H-2, 48–50 cm) and is followed directly by the first occurrence of *Globorotalia partimlabiata* at 118.9 mbsf (Sample 122-762B-14H-1, 48–50 cm). The latter species remains present as far upward as 112.4 mbsf (Sample 122-762B-13H-3, 46–48 cm), and defines the *Globorotalia partimlabiata* Zone. This zone is furthermore characterized by the absence of *Neogloboquadrina acostaensis* and, therefore, correlates by definition with the upper middle Miocene *Globorotalia menardii* Zone (= N15). The combined presence of *Globigerinoides extremus*, *Neogloboquadrina humerosa*, *Globorotalia margaritae*, *Globorotalia plesiotumida*, *Pulleniatina primalis*, *Candeina nitida*, and

¹ von Rad, U., Haq, B. U., et al., 1992. *Proc. ODP, Sci. Results*, 122: College Station, TX (Ocean Drilling Program).

² Institute of Earth Sciences, University of Utrecht, Budapestlaan 4, 3584 CD Utrecht, The Netherlands.

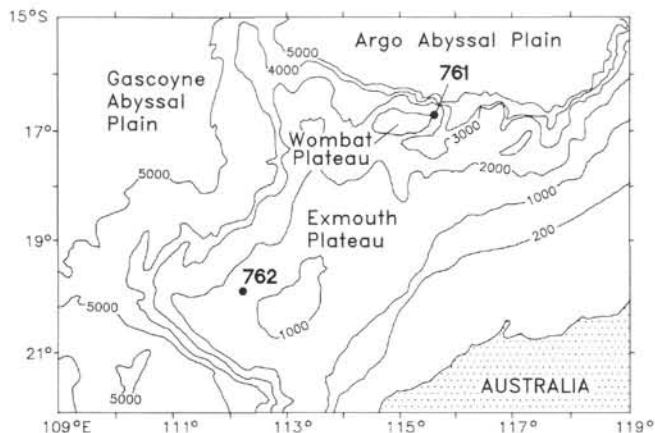


Figure 1. Location of Leg 122 Sites 761 (Wombat Plateau) and 762 (Exmouth Plateau), off northwest Australia.

Globigerinoides conglobatus at 110.9 mbsf (Sample 122-762B-13H-2, 46–48 cm) is indicative of the upper Miocene *Neogloboquadrina humerosa* Zone or Zone N17. Thus, the interval between 112.4 and 110.9 mbsf contains a clear-cut hiatus, with Zone N15-correlative sediments below and Zone N17-correlative sediments above. The absence of *Globorotalia tumida* as far upward as 102.8 mbsf indicates that Zone N17-correlative sediments extend from 110.9 to 102.8 mbsf. This Zone N17-correlative interval contains two distinct bioevents: (1) a coiling change in *Neogloboquadrina humerosa* from left to right between 109.4 (Sample 122-762B-13H-1, 46–48 cm) and 108.9 mbsf (Sample 122-762B-12H-7, 47–49 cm), and (2) the arrival of representatives of the *Globorotalia conoidea* group at 105.9 mbsf (Sample 122-762B-12H-5, 46–48 cm). The first true *Pulleniatina primalis* is coincident with the coiling change in *Neogloboquadrina humerosa*. Unfortunately, no samples were available from the interval above 102.8 mbsf; therefore, I cannot report on the faunal succession across the Miocene/Pliocene boundary.

BIOSTRATIGRAPHIC SUMMARY OF HOLE 761B

Forty-one samples were available from Cores 122-761B-1H to -8H of Hole 761B. Figure 3 shows the stratigraphic ranges of the most common planktonic foraminiferal species (larger than 125 μm) and the datum levels employed to subdivide the sequence into 13 biostratigraphic units. The studied interval corresponds to the late Oligocene to Holocene.

Reworked (middle) Eocene species occur sporadically in the upper Oligocene *Globigerina ciproensis* Zone and in the lower Miocene *Globorotalia kugleri* Zone, indicating that reworking is less intense and ends earlier than in Hole 762B. All stages of the *Globorotalia kugleri*, *Globorotalia foysi*, and *Orbulina* lineages are present. The distribution of representatives of the *Globorotalia menardii* lineage is similar to that recorded in the time-correlative part of Hole 762B. As in Hole 762B, *Globorotalia menardii* first occurs in the upper middle Miocene, and remains present until the Holocene. *Globorotalia archeomenardii* is briefly present in the *Praeorbulina glomerosa* Zone, and this matches perfectly with its distribution in Hole 762B. Hole 761B also provides evidence for a morphological change from *Globorotalia birnageae* to *Globorotalia peripheroronda* in the upper lower Miocene *Globigerinatella insueta* Zone. The paucity of representatives of *Globigerinoides* in the lower Miocene *Globorotalia kugleri* Zone is not well understood, but increased numbers of fragmented planktonic foraminifers suggest that this paucity may

be due to a slight increase in carbonate dissolution at that time.

The first occurrences of *Globorotalia birnageae* and *Sphaeroidinellopsis disjuncta* (50.2 mbsf) directly above the last appearance of *Globorotalia kugleri* (52.1 mbsf) are considerably older than those reported in the literature (e.g., Kennett and Srinivasan, 1983; Bolli and Saunders, 1985). The section between last appearances of *Globorotalia kugleri* and *Catapsydrax dissimilis* (48.7 mbsf), however, is strongly condensed with an anomalously low accumulation rate of 0.08 cm/k.y. (using the biochronology of Berggren et al., 1985). Thus, the early occurrences of *Globorotalia birnageae* and *Sphaeroidinellopsis disjuncta* point to the presence of a hiatus between 50.2 and 52.1 mbsf. The short overlap between *Globorotalia birnageae*, *Sphaeroidinellopsis disjuncta*, and *Catapsydrax dissimilis* directly above this hiatus indicates that Zone N5-correlative sediments are missing.

The level at 32.9 mbsf (Sample 122-761B-5H-1, 60–62 cm) marks the base of an unusual interval, as shown by the anomalous composition of species with different time-stratigraphic ranges. This interval with mixed faunas extends as far upward as 23.8 mbsf (Fig. 3). Faunal mixing does not occur from 23.8 mbsf to the top of Hole 761B. The autochthonous fauna directly above the mixed faunas (Sample 122-761B-3H-7, 60–62 cm) contains *Globorotalia truncatulinoides* and the last appearance of *Globigerinoides fistulosus*. *Globigerinoides fistulosus* has its last appearance just above the Olduvai Subchron (Berggren et al., 1985), which level correlates with the Pliocene/Pleistocene boundary in the boundary stratotype section of Vrica in southern Italy (Tauxe et al., 1983). This position indicates that the mixed-fauna interval is covered by a thin section (160 cm) of latest Pliocene age. The mixed fauna itself includes *Globorotalia plesiotumida*, *Globorotalia tumida*, *Globorotalia conoidea*, *Globorotalia margaritae*, *Globorotalia tosaensis*, *Globorotalia truncatulinoides*, *Neogloboquadrina humerosa*, *Pulleniatina primalis*, *Sphaeroidinella dehiscens*, *Sphaeroidinellopsis seminulina*, *Globoturborotalita nepenthes*, and *Globigerinoides fistulosus*. This mixture of late Miocene to latest Pliocene elements between 33 and 23.8 mbsf is puzzling, especially since this interval contains two successive samples (122-761B-4H-5, 60–62 cm, and 122-761B-4H-4, 60–62 cm) with a pure late Miocene fauna including *Globorotalia plesiotumida*, *Neogloboquadrina humerosa*, *Globigerinoides extremus*, and primitive *Globorotalia margaritae* (Fig. 3). Moreover, mixed faunas from this interval are not reported in the site report (Haq, von Rad, O'Connell, et al., 1990). Downhole contamination of Pliocene elements during drilling is unlikely because no autochthonous Pliocene sediments are present. The most likely explanation for this faunal mixture is that the interval between 33 and 23.8 mbsf consists of redeposited upper Miocene to uppermost Pliocene sediments although this is not immediately obvious from the core photographs. The pure late Miocene faunas halfway through the redeposited section suggest the incorporation of a 3-m-thick (from 30.7 to 27.5 mbsf) interval of displaced upper Miocene sediments. The basal sample of the redeposited section (122-761B-5H-1, 60–62 cm) includes older elements, such as *Paragloborotalia mayeri*, *Globorotalia partimlabiata*, and *Catapsydrax parvulus* (Fig. 3), in addition to late Miocene to latest Pliocene species. These pre-late Miocene elements at the base of the redeposited section indicate erosion of Zone N15 and (upper) Zone N14-correlative sediments.

It is difficult to ascertain whether sediments correlative to the *Neogloboquadrina acostaensis* Zone (N16) are incorporated in the redeposited section, or whether they are absent

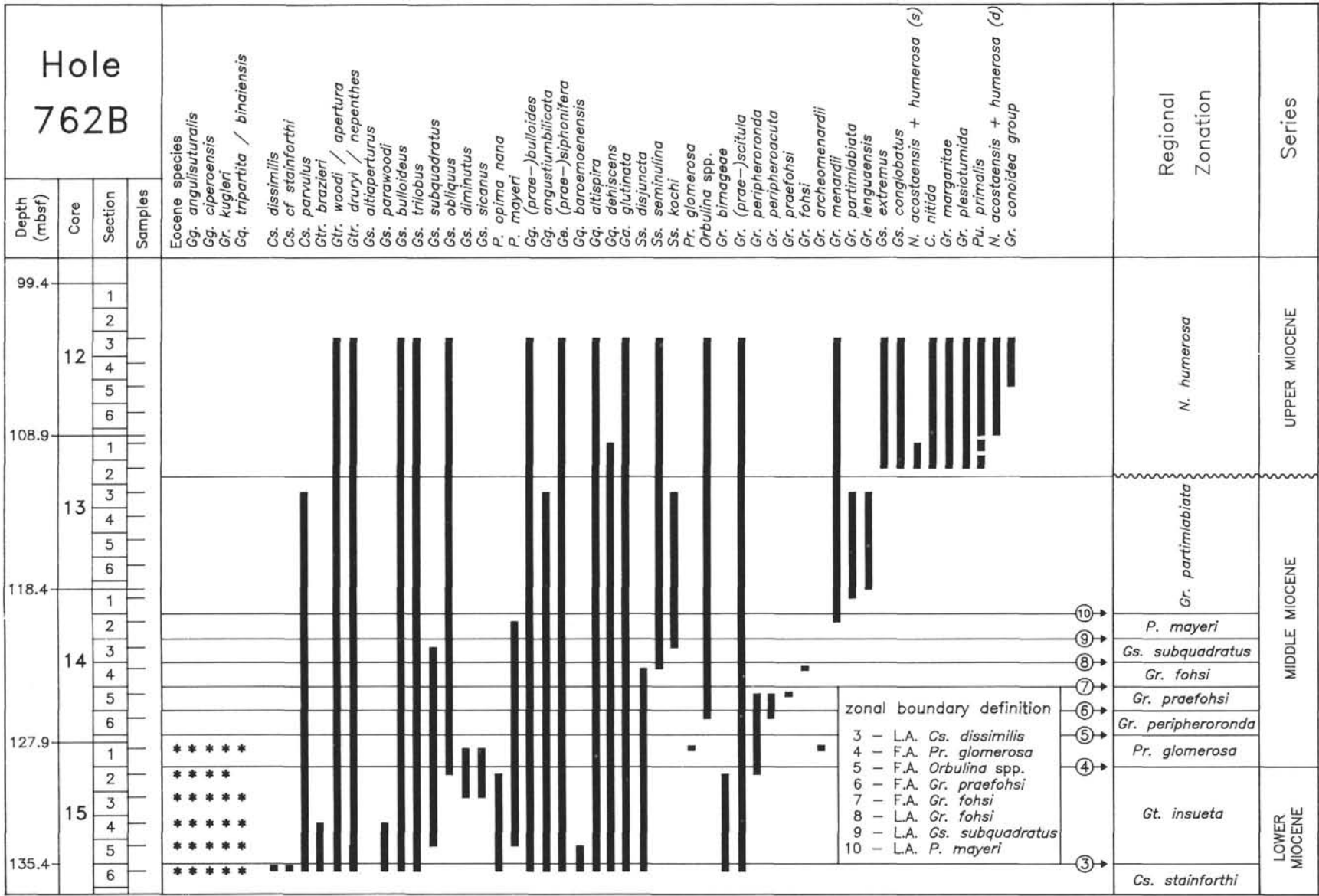


Figure 2. Stratigraphic distribution of the most common planktonic foraminiferal species in the Neogene of Hole 762B. Asterisk (*) denotes reworked elements. L.A. = last appearance; F.A. = first appearance.

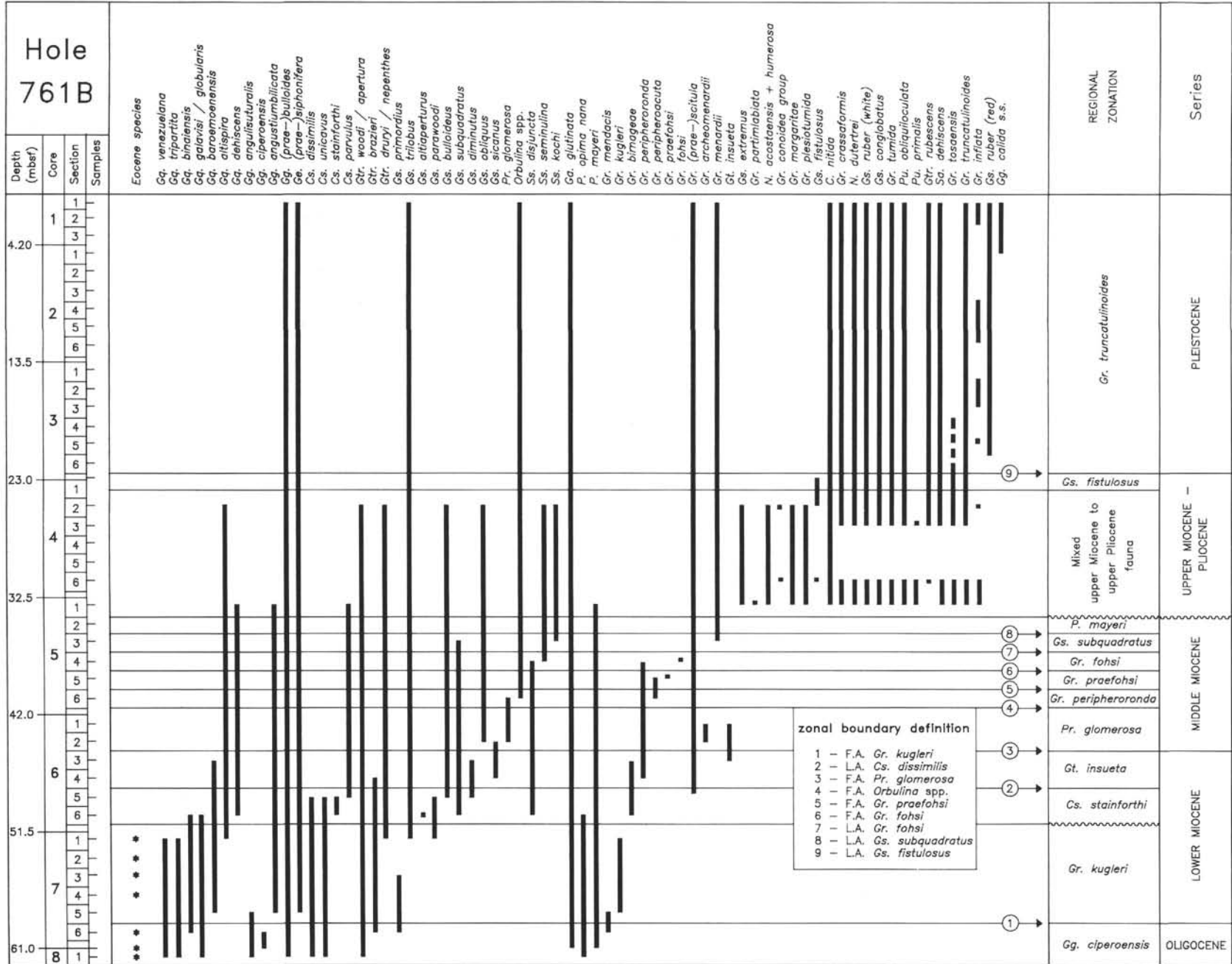


Figure 3. Stratigraphic distribution of the most common planktonic foraminiferal species in the Neogene of Hole 761B. Asterisk (*) denotes reworked elements. L.A. = last appearance; F.A. = first appearance.

due to the presence of a late Miocene hiatus, as recorded in Hole 762B on the Exmouth Plateau. Direct evidence for the absence of Zone N16-correlative sediments is lacking because no planktonic foraminiferal species are restricted exclusively to Zone N16. *Catapsydrax parvulus* is a senior synonym of *Globorotaloides falconarae*, which, in the Mediterranean and North Atlantic, ranges up into Zone N16 (Iaccarino, 1985; Chamley et al., 1986). Its absence in the redeposited section may indicate that Zone N16-correlative sediments are not incorporated in the redeposited section. Also significant is the absence of *Globoquadrina dehiscens* in the redeposited section. This species terminates in upper Zone N17-correlative sediments of Hole 762B, but is abundant in Zone N15-correlative sediments. The absence of *Globoquadrina dehiscens* in the redeposited section, therefore, provides another indication that Zone N16-correlative sediments are missing in Hole 761B. Thus, it appears that the upper middle to upper Miocene hiatus on Exmouth Plateau also occurs on Wombat Plateau.

EROSIONAL EVENTS

The correlation between the zonal sequences of Holes 762B and 761B and the low-latitude standard zonations of Blow (1969) and Bolli and Saunders (1985) is given in Figure 4. This figure shows that the sedimentary record of the Neogene on the Wombat and Exmouth plateaus is interrupted by two hiatuses (lower Miocene and upper middle to upper Miocene), and one redeposited section of upper Miocene to uppermost Pliocene.

The lower Miocene hiatus is identified in Hole 761B. The short overlap between *Globorotalia birnageae*, *Sphaeroidinellopsis disjuncta*, and *Catapsydrax dissimilis* directly above this hiatus indicates that Zone N5-correlative sediments are missing (Fig. 4).

The upper middle to upper Miocene hiatus is distinct and well-constrained in Hole 762B (Fig. 4), but is less easily identified in Hole 761B because of a redeposited section directly above the middle Miocene *Paragloborotalia mayeri* Zone (Fig. 3). The presence of *Paragloborotalia mayeri* and *Globorotalia partimlabiata* at the base of the redeposited section indicates erosion of Zone N15 to (upper) Zone N14-correlative sediments. All other elements in the redeposited section signify Zones N17 to N22, indicating that Zone N16-correlative sediments are missing in Hole 761B. This suggests that the upper Miocene hiatus on Exmouth Plateau also occurs on Wombat Plateau. A similar hiatus is recorded in Buffon-1 well on the northern Northwest Shelf where Zone N17-correlative slope sediments overlie middle Miocene outer shelf limestones (Apthorpe, 1988).

The cause and mechanism of these Miocene hiatuses is not clear. To invoke carbonate dissolution as an explanation of these hiatuses would require a rise of several thousands of meters of the carbonate compensation depth (CCD), compared with its present position for this region at about 4500 m (Ludden, Gradstein, et al., 1990, p. 111). Such a dramatic rise would result in the deposition of a thin clayey layer but there is no indication of such a layer.

Mechanical erosion or nondeposition by increased flow of deep water or tilting and uplift of the Wombat and Exmouth plateaus, resulting in sediment shedding, are the most likely explanations for these Miocene hiatuses, but it is difficult to ascertain which of these processes were actually operative on the Wombat and Exmouth plateaus. The upper middle to upper Miocene hiatus could have been caused by increased deep-water flow in response to increased ice accumulation in West Antarctica during the late Miocene (Kennett and Barker, 1990), but it could equally well have been formed by tectonic activity since

reactivation of normal faults has been reported from the Northwest Shelf during the late Miocene (Woods, 1988).

A third erosional event is recorded by a redeposited section of upper Miocene to uppermost Pliocene sediments in Hole 761B. The last occurrence of *Globigerinoides fistulosus* and the presence of *Globorotalia truncatulinoides* above this section indicates that this redeposited section reflects a latest Pliocene period of tilting and uplift of the Wombat Plateau; no time-correlative samples were available from Exmouth Plateau. This latest Pliocene period of tilting and uplift occurred slightly before the 1.6-Ma last-appearance level of *Globigerinoides fistulosus* (Berggren et al., 1985), and is also recorded on the northern Northwest Shelf, where upper Miocene to Pliocene sediments are locally missing (Apthorpe, 1988).

This latest Pliocene period of tilting and uplift of Wombat Plateau is probably related to the so-called Third Timor subduction phase of Johnston and Bowin (1981).

PALEOCLIMATIC EVENTS

Diverse, warm-water planktonic foraminiferal faunas prevailed on the Wombat and Exmouth plateaus during the Neogene, in spite of the northward drift of Australia across some 10° to 15° latitude since the early Miocene (Scotese et al., 1988). The overall warm-water fauna was invaded several times by cool-water species, reflecting periods of increased northward transport of cool surface water, probably via the West Australian Current.

One of these migratory events occurred in the late middle Miocene (Hole 762B) and corresponds with the replacement of *Paragloborotalia mayeri* by *Globorotalia partimlabiata* (Fig. 2). *Globorotalia partimlabiata* Ruggieri and Sprovieri (1970) (Pl. 2, Figs. 1–4; Pl. 3, Figs. 1–4) seems to be a senior synonym of *Globorotalia challengerii* Srinivasan and Kennett (1981) and is a cool-water species in the North Atlantic and South Pacific (Srinivasan and Kennett, 1981; Chamley et al., 1986). *Paragloborotalia mayeri* is a warm-water species (Kennett and Srinivasan, 1983) and the arrival of substantial numbers of *Globorotalia partimlabiata* just above the last appearance level of *Paragloborotalia mayeri* in Hole 762B indicates increased northward transport of cool water to Exmouth Plateau. The replacement of *Paragloborotalia mayeri* by *Globorotalia partimlabiata* on the Exmouth Plateau is surprising because a similar faunal change is reported from the Mediterranean and adjacent North Atlantic (Chamley et al., 1986). At these locations, *Globorotalia partimlabiata* arrived slightly before the last appearance of *Paragloborotalia mayeri*, together with the cool-water species *Neogloboquadrina atlantica* (= *Neogloboquadrina continuosa* sensu Zachariasse, 1975; see also below). The replacement of *Paragloborotalia mayeri* by *Globorotalia partimlabiata* and *Neogloboquadrina atlantica* in the Mediterranean and adjacent North Atlantic was interpreted in terms of increased southward transport of cool water via the Canary Current at times of cooling (Chamley et al., 1986). The correlative areal expansion of the cool-water species *Globorotalia partimlabiata* in both hemispheres at the N14/N15 zonal boundary reflects global cooling during the middle Miocene when there was a rapid growth of the east Antarctic ice sheet (Kennett, 1986; Kennett and Barker, 1990).

The arrival of a substantial number of specimens of the cool-water species *Globorotalia conoidea* just after the coiling change in *Neogloboquadrina humerosa* in Hole 762B marks a late Miocene climatic cooling. This late Miocene cooling began slightly later than 5.8 Ma, the age given for the coiling change in *Neogloboquadrina humerosa* (Berggren et al., 1985). This cooling is probably related to the rapid expansion of the west Antarctic ice cap (Ciesielski et al., 1982; Kennett and Barker, 1990).

| Epoch | Low-latitude Zonation | | Hole 762B | Hole 761B | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|-------------|-----------------------------|---------------------------|----------------------|--|--|----------------------|----------------------|----------------------|----------------------|------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| | Bolli & Saunders, 1985 | Blow, 1969 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Pleistocene | <i>Gr. truncatulinoides</i> | N23-N22 | No samples available | <i>Gr. truncatulinoides</i> <i>Gs. fistulosus</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Pliocene | <i>Gr. tosaensis</i> | N21 | | No samples available | Redeposited sediments of late Miocene (N17) to late Pliocene (N22) age | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | <i>Gr. miocenica</i> | N20-N19 | No samples available | | No samples available | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | <i>Gr. margaritae</i> | | | | | N18 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | late | <i>N. humerosa</i> | | | | | N17 | No samples available | No samples available | | | | | | | | | | | | | | | | | | | | | | | | |
| | <i>N. acostaensis</i> | N16 | | | | No samples available | No samples available | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | middle | <i>Gr. menardii</i> | | | | | | | | N15 | No samples available | No samples available | | | | | | | | | | | | | | | | | | | | | |
| | | <i>P. mayeri</i> | | | | | | | | N14-N13 | | | No samples available | No samples available | | | | | | | | | | | | | | | | | | | |
| | | <i>Gs. subquadratus</i> | | | | | | | | | | | | | No samples available | No samples available | | | | | | | | | | | | | | | | | |
| | | <i>Gr. robusta</i> | | | | | | | | | | | | | | | No samples available | No samples available | | | | | | | | | | | | | | | |
| | | <i>Gr. lobata</i> | | | | | | | | N12 | | | | | | | | | No samples available | No samples available | | | | | | | | | | | | | |
| | | <i>Gr. fohsi</i> | | | | | | | | N11 | | | | | | | | | | | No samples available | No samples available | | | | | | | | | | | |
| | | <i>Gr. peripheroronda</i> | | | | | | | | N10-N9 | | | | | | | | | | | | | No samples available | No samples available | | | | | | | | | |
| | | <i>Pr. glomerosa</i> | | | | | | | | | | | | | | | | | | | | | | | N8 | | | | | | | | |
| | | early | | | | | | | | <i>Gt. insueta</i> | | | | | | | | | | | | | | | N7 | No samples available | No samples available | | | | | | |
| | | | | | | | | | | <i>Cs. stainforthi</i> | | | | | | | | | | | | | | | N6 | | | No samples available | No samples available | | | | |
| | <i>Cs. dissimilis</i> | | | | | | | | | N5 | | | | | | | | | | | | | | | No samples available | | | | | No samples available | | | |
| | <i>Gs. primordius</i> | | | | | | | | | N4 | | | | | | | | | | | | | | | | | | | | | No samples available | No samples available | |
| | <i>Gr. kugleri</i> | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | No samples available |
| | Oligocene | <i>Gg. ciperensis</i> | | | | | | | | N3 | | | | | | | | | | | | | | | | | | | | | | | |

Figure 4. Correlation diagram of the Neogene sequences of Holes 762B and 761B to the low-latitude zonal schemes of Bolli and Saunders (1985) and Blow (1969). Zones of Bolli and Saunders (1985) are equally spaced.

Recurrent invasions of cool-water elements also occurred in the Pleistocene of Hole 761B, where intervals containing high numbers of the cool-water species *Globorotalia inflata* alternate with intervals in which this species is absent (Fig. 3). This variability in abundance of *Globorotalia inflata* reflects repeated fluctuations in the northward transport of cool surface water connected with Pleistocene glacial cycles.

THE ORIGIN OF NEOGLOBOQUADRINA ACOSTAENSIS

The genus *Neogloboquadrina* encloses a phylogenetically coherent group of non-spinose, cancellate species consisting of *Neogloboquadrina acostaensis*, *N. humerosa*, *N. dutertrei* (= type species), and *N. pachyderma* (Srinivasan and Ken-

nett, 1976). All these species actually represent end-member morphologies within one evolving biogeographic cline (Srinivasan and Kennett, 1976). The genus also includes *Neogloboquadrina atlantica* (Poore and Berggren, 1975). This taxon is probably a discrete species, the phylogenetic relationship of which with the other members of the *Neogloboquadrina* group is still unclear.

Globorotalia continuosa Blow is commonly considered the ancestor of all neogloboquadrinids. This species is thought to have evolved into the low-latitude *Neogloboquadrina acostaensis* at the N15/N16 zonal boundary (Blow, 1969; Kennett and Srinivasan, 1980, 1983) and into the high-latitude *Neogloboquadrina pachyderma* at a time-equivalent level (Kennett and Srinivasan, 1980, 1983). The evolution from *Globorotalia continuosa* into *Neogloboquadrina acostaensis*, however, was refuted by Bolli and Saunders (1985), who consider *Globorotalia continuosa* Blow as a four-chambered variant of *Paragloborotalia mayeri*. Both forms vanish simultaneously at the top of Zone N14 and show no stratigraphic continuity with *Neogloboquadrina acostaensis*. This eliminates *Globorotalia continuosa* Blow (= *Paragloborotalia mayeri*) as ancestor of *Neogloboquadrina acostaensis*. Such a phylogenetic linkage between both species would have been strange anyhow since *Paragloborotalia mayeri* is spinose (Cifelli, 1982) and it remains to be shown that spinose species evolved into non-spinose ones.

The interval lacking *Paragloborotalia mayeri* and *Neogloboquadrina acostaensis* correlates by definition with Zone N15 and is well-documented in Java (Bolli, 1966) and recently also in Jamaica (W. A. Berggren, pers. comm., 1991). Zone N15 at these locations lacks any representative of *Neogloboquadrina*. A similar situation exists in Hole 762B, where Zone N15-correlative sediments below the upper middle to upper Miocene hiatus are characterized by abundant *Globorotalia partimlabiata*, without any representative of *Neogloboquadrina*.

Thus, it appears that the earliest spreading of *Neogloboquadrina acostaensis* in the low latitudes resulted from migration. This suggests that the evolution of this species must have taken place in higher latitudes. The question is where in the higher latitudes this evolution took place and from which species.

There are two possibilities. The first one is that *Globorotalia continuosa* in Kennett (1973), Srinivasan and Kennett (1976), and Kennett and Srinivasan (1980, 1983) represents a Southern Hemisphere, cool-water species unrelated to the warm-water *Globorotalia continuosa* Blow (= *Paragloborotalia mayeri*). This cool-water species may have evolved into *Neogloboquadrina pachyderma*, whereafter it invaded the tropical region meanwhile changing into *Neogloboquadrina acostaensis*. The changing morphology of *Neogloboquadrina pachyderma* with decreasing latitude is conceivable if *Neogloboquadrina pachyderma* and *Neogloboquadrina acostaensis* represent end-members within one biogeographic cline (Srinivasan and Kennett, 1976). Figured specimens of *Globorotalia continuosa* in Kennett (1973, pl. 14, figs. 3–6) and in Kennett and Srinivasan (1980, pl. 8, figs. 4–7), however, suggest that what they consider as *Globorotalia continuosa* is actually close to or identical with *Globorotalia nympha*. *Globorotalia nympha* Jenkins (1967) is a middle Miocene cool-water species in the southwest Pacific (Jenkins and Srinivasan, 1986) and southern Indian oceans (Berggren, in press). This species shows some resemblance to *Neogloboquadrina pachyderma* but differs in the smoother (non-cancellate) final chamber and the somewhat angular axial periphery. In these aspects *Globorotalia*

nympha is closer to *Globorotalia partimlabiata* than to *Neogloboquadrina pachyderma*. The evolution from *Globorotalia nympha* to *Neogloboquadrina pachyderma*, therefore, remains to be shown, all the more because both species show different stratigraphic ranges on the Kerguelen Plateau (Berggren, in press).

The second possibility is preferred here and assumes that the ancestor of *Neogloboquadrina acostaensis* occurred in the North Atlantic. The most likely candidate is a species described as *Globorotalia continuosa* by Cita and Blow (1969) and Zachariasse (1975) from the middle Miocene of the Mediterranean. A recent evaluation has revealed that this species is actually a small phenotype of *Neogloboquadrina atlantica* which, at some levels, co-occurs with typical robust forms (Zachariasse, unpubl. data). The earliest occurrence of *Neogloboquadrina atlantica* in the Mediterranean has been found in the upper part of Zone N14 (e.g., the stratigraphic range of *Globorotalia continuosa* in Chamley et al., 1986), which agrees well with a similar observation made by Poore (1979) at North Atlantic DSDP Sites 407 and 408. This pattern indicates that *Neogloboquadrina atlantica* is the oldest known neogloboquadrinid and it seems therefore plausible that this species is the ancestor of *Neogloboquadrina acostaensis*. Since *Neogloboquadrina atlantica* is endemic to the North Atlantic (Poore and Berggren, 1975), its evolution into *Neogloboquadrina acostaensis* must have taken place in this region. This evolution probably took place within Zone NN9 since an early occurrence of small *Neogloboquadrina acostaensis* (Pl. 2, Figs. 5–6; Pl. 3, Figs. 5–6) has been found in the reference locality of Zone NN9 on Trinidad (sample T10C 178.890, Martini, 1971). The problem to be solved is how and where in the North Atlantic the speciation between *Neogloboquadrina atlantica* and *Neogloboquadrina acostaensis* took place. Unlike earlier views (Cita and Blow, 1969; Zachariasse, 1975) this speciation probably did not occur in the Mediterranean.

CONCLUSIONS

Diverse, warm-water planktonic foraminiferal species dominated the Neogene assemblages on the Exmouth and Wombat plateaus. Invasions of cool-water species during the late middle Miocene, late Miocene, and Pleistocene occurred in periods of increased northward flow of cool surface water and in periods of global cooling.

The sedimentary record of the Neogene on the Exmouth and Wombat plateaus is interrupted by two hiatuses (lower Miocene, Zone N5, and upper middle to upper Miocene, Zones N15–N17), and one redeposited section of upper Miocene to uppermost Pliocene sediments. Mechanical erosion or nondeposition by increased deep-water flow or tilting and uplift of the Wombat and Exmouth plateaus, resulting in shedding of sediments, are the most likely explanations for these Miocene hiatuses, but which of these processes were actually operative is uncertain. The redeposited section of upper Miocene to uppermost Pliocene sediments in Hole 761B, however, certainly reflects a latest Pliocene period of uplift and tilting of Wombat Plateau.

An important finding was the occurrence of Zone N15-correlative sediments in Hole 762B without any representative of *Neogloboquadrina*. Similar findings in Java and Jamaica indicate that the earliest spreading of *Neogloboquadrina acostaensis* in the tropical region resulted from migration. The evolution of this species, therefore, must have taken place in higher latitudes. I suggest that *Neogloboquadrina acostaensis* evolved from *Neogloboquadrina atlantica* in the North Atlantic within Zone NN9, but how and where in this region this speciation took place is still uncertain.

ACKNOWLEDGMENTS

I would like to thank U. von Rad and B. Haq, co-chief scientists for Leg 122, for their permission to study samples from the Neogene of Sites 761 and 762. Discussions with W. Berggren, S. Cloetingh, E. Koster, E. Rohling, and M. Wortel are gratefully acknowledged. The critical reviews by E. Thomas and W. Berggren are highly appreciated.

REFERENCES

- Apthorpe, M., 1988. Cainozoic depositional history of the North West Shelf. In Purcell, P. G., and Purcell, R. R. (Eds.), *The North West Shelf, Australia*: Proc. Pet. Expl. Soc. Aust. Symp., 55–84.
- Berggren, W. A., in press. Neogene planktonic foraminifer magneto-biostratigraphy of the southern Kerguelen Plateau (ODP Sites 747, 748, and 751). In Schlich, R., Wise, S. W., Jr., et al., *Proc. ODP, Sci. Results*, 120: College Station, TX (Ocean Drilling Program).
- Berggren, W. A., Kent, D. V., and Van Couvering, J. A., 1985. The Neogene: Part 2. Neogene geochronology and chronostratigraphy. In Snelling, N. J. (Ed.), *The Chronology of the Geological Record*. Geol. Soc. London Mem., 10:211–260.
- Blow, W. H., 1969. Late middle Eocene to Recent planktonic foraminiferal biostratigraphy. In Brönniman, P., and Renz, H. H. (Eds.), *Proc. First Int. Conf. Planktonic Microfossils*, Geneva, 1967. Leiden (E. J. Brill), 1:199–422.
- Bolli, H. M., 1966. The planktonic foraminifera in Well Bodjonegoro-I of Java. *Eclogae Geol. Helv.*, 57:541–552.
- Bolli, H. M., and Saunders, J. B., 1982. *Globorotalia mayeri* and its relationship to *Globorotalia siakensis* and *Globorotalia continuosa*. *J. Foraminiferal Res.*, 12:39–50.
- , J. B., 1985. Oligocene to Holocene low latitude planktonic foraminifera. In Bolli, H. M., Saunders, J. B., and Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*: Cambridge (Cambridge Univ. Press), 155–262.
- Chamley, H., Meulenkamp, J. E., Zachariasse, W. J., and van der Zwaan, G. J., 1986. Middle to Late Miocene marine ecostratigraphy: clay minerals, planktonic foraminifera and stable isotopes from Sicily. *Oceanol. Acta*, 9:227–238.
- Ciesielski, P. F., Ledbetter, M. T., and Ellwood, B. B., 1982. The development of Antarctic glaciation and the Neogene paleoenvironment of the Maurice Ewing Bank. *Mar. Geol.*, 46:1–51.
- Cifelli, R., 1982. Early occurrences and some phylogenetic implications of spiny, honeycomb textured planktonic foraminifera. *J. Foraminiferal Res.*, 12:105–115.
- Cita, M. B., and Blow, W. H., 1969. The biostratigraphy of the Langhian, Serravallian and Tortonian Stages in the type-sections in Italy. *Riv. Ital. Paleontol.*, 75:549–603.
- Haq, B. U., von Rad, U., O'Connell, S., et al., 1990. *Proc. ODP, Init. Repts.*, 122: College Station, TX (Ocean Drilling Program).
- Iaccarino, S., 1985. Mediterranean Miocene and Pliocene planktic foraminifera. In Bolli, H. M., Saunders, J. B., and Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*: Cambridge (Cambridge Univ. Press), 283–314.
- Jenkins, D. G., 1967. Planktonic foraminiferal zones and new taxa from the lower Miocene to the Pleistocene of New Zealand. *N. Z. J. Geol. Geophys.*, 10:1064–1078.
- Jenkins, D. G., and Srinivasan, M. S., 1986. Cenozoic planktonic foraminifera from the equator to the subantarctic of the southwest Pacific. In Kennett, J. P., von der Borch, C. C., et al., *Init. Repts. DSDP*, 90: Washington (U.S. Govt. Printing Office), 795–834.
- Johnston, C. R., and Bowin, C. O., 1981. Crustal reactions resulting from the mid-Pliocene to Recent continent-arc collision in the Timor region. *BMR J. Aust. Geol. Geophys.*, 6:223–243.
- Kennett, J. P., 1973. Middle and late Cenozoic planktonic foraminiferal biostratigraphy of the Southwest Pacific, DSDP Leg 21. In Burns, R. E., Andrews, J. E., et al., *Init. Repts. DSDP*, 21: Washington (U.S. Govt. Printing Office), 575–639.
- , 1986. Miocene to early Pliocene oxygen and carbon isotope stratigraphy of the Southwest Pacific, DSDP Leg 90. In Kennett, J. P., von der Borch, C. C., et al., *Init. Repts. DSDP*, 90 (Pt. 2): Washington (U.S. Govt. Printing Office), 1383–1411.
- Kennett, J. P., and Barker, P. F., 1990. Latest Cretaceous to Cenozoic climate and oceanographic developments in the Weddell Sea, Antarctica: an ocean-drilling perspective. In Barker, P. F., Kennett, J. P., et al., *Proc. ODP, Sci. Results*, 113: College Station, TX (Ocean Drilling Program), 937–960.
- Kennett, J. P., and Srinivasan, M. S., 1980. Surface ultrastructural variation in *Neogloboquadrina pachyderma* (Ehrenberg): phenotypic variation and phylogeny in the late Cenozoic. *Spec. Publ.—Cushman Found. Foraminiferal Res.*, 19:134–162.
- , 1983. *Neogene Planktonic Foraminifera: A Phylogenetic Atlas*: Stroudsburg, PA (Hutchinson Ross).
- Ludden, J. N., Gradstein, F. M., et al., 1990. *Proc. ODP, Init. Repts.*, 123: College Station, TX (Ocean Drilling Program).
- Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In Farinacci, A. (Ed.), *Proc. 2nd Planktonic Conf. Roma*: Rome (Ed. Technosci.), 2:739–785.
- Poore, R. Z., 1979. Oligocene through Quaternary planktonic foraminiferal biostratigraphy of the North Atlantic: DSDP Leg 49. In Luyendyk, B. P., Cann, J. R., et al., *Init. Repts. DSDP*, 49: Washington (U.S. Govt. Printing Office), 447–517.
- Poore, R. Z., and Berggren, W. A., 1975. The morphology and classification of *Neogloboquadrina atlantica* (Berggren). *J. Foraminiferal Res.*, 5:76–84.
- Ruggieri, G., and Sprovieri, R., 1970. I microforaminiferi delle Marne di S. Cipirello. *Lavori Inst. Geol. Univ. Palermo*, 10:1–26.
- Scotese, C. R., Ghagan, L. M., and Larson, R. L., 1988. Plate tectonic reconstructions of the Cretaceous and Cenozoic ocean basins. *Tectonophysics*, 155:27–48.
- Srinivasan, M. S., and Kennett, J. P., 1976. Evolution and phenotypic variation in the late Cenozoic *Neogloboquadrina dutertrei* plexus. In Takayanagi, Y., and Saito, T. (Eds.), *Progress in Micropaleontology*. Am. Mus. Nat. Hist. Micropaleontol. Press, 329–355.
- , 1981. Neogene planktonic foraminiferal biostratigraphy and evolution: equatorial to subantarctic, South Pacific. *Mar. Micropaleontol.*, 6:499–533.
- Tauxe, L., Opdyke, N. D., Pasini, G., and Elmi, C., 1983. The paleomagnetism of the Vrica section (Calabria, Italy): the proposed Pliocene/Pleistocene Boundary-stratotype section. *Nature*, 304:125–129.
- Woods, E. P., 1988. Extensional structures of the Jabiru Terrace, Vulcan Subbasin. In Purcell, P. G., and Purcell, P. R. (Eds.), *The North West Shelf, Australia*. Proc. Pet. Expl. Soc. Symp., 311–330.
- Zachariasse, W. J., 1975. Planktonic foraminiferal biostratigraphy of the late Neogene of Crete (Greece). *Utrecht Micropaleontol. Bull.*, 11.

Date of initial receipt: 15 June 1990

Date of acceptance: 18 March 1991

Ms 122B-190

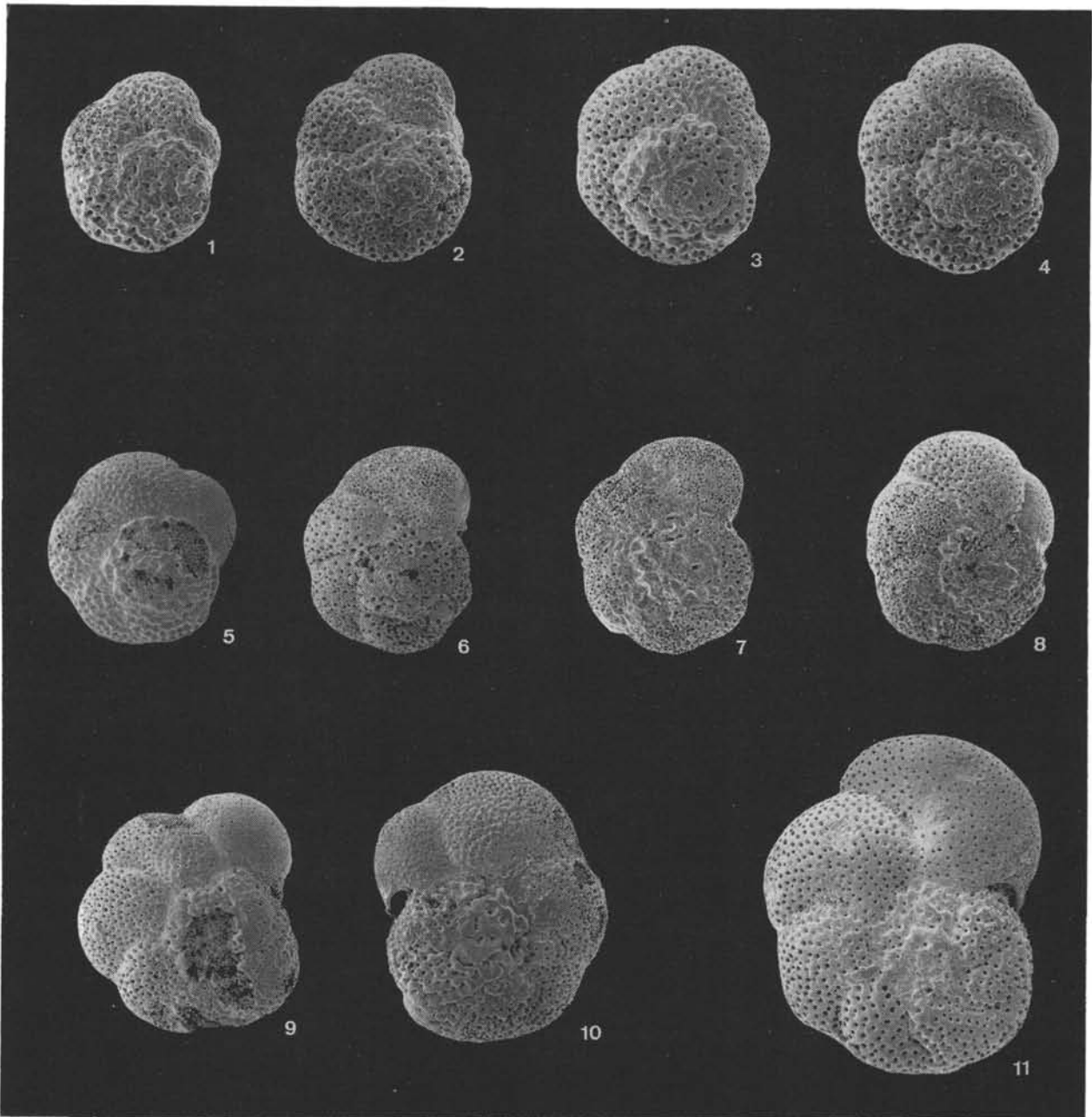


Plate 1. 1–4. *Globorotalia birnageae* Blow. Sample 122-761B-6H-4, 73–76 cm. 5–8. Transition from *Globorotalia birnageae* Blow (5) to *Globorotalia peripheroronda* Blow and Banner (8). Sample 122-761B-6H-3, 73–76 cm. 9, 10. *Globorotalia peripheroronda* Blow and Banner. Sample 122-761B-6H-2, 73–75 cm. 11. *Globorotalia peripheroronda* Blow and Banner. Sample 122-761B-6H-1, 73–75 cm. (All specimens $\times 300$.)

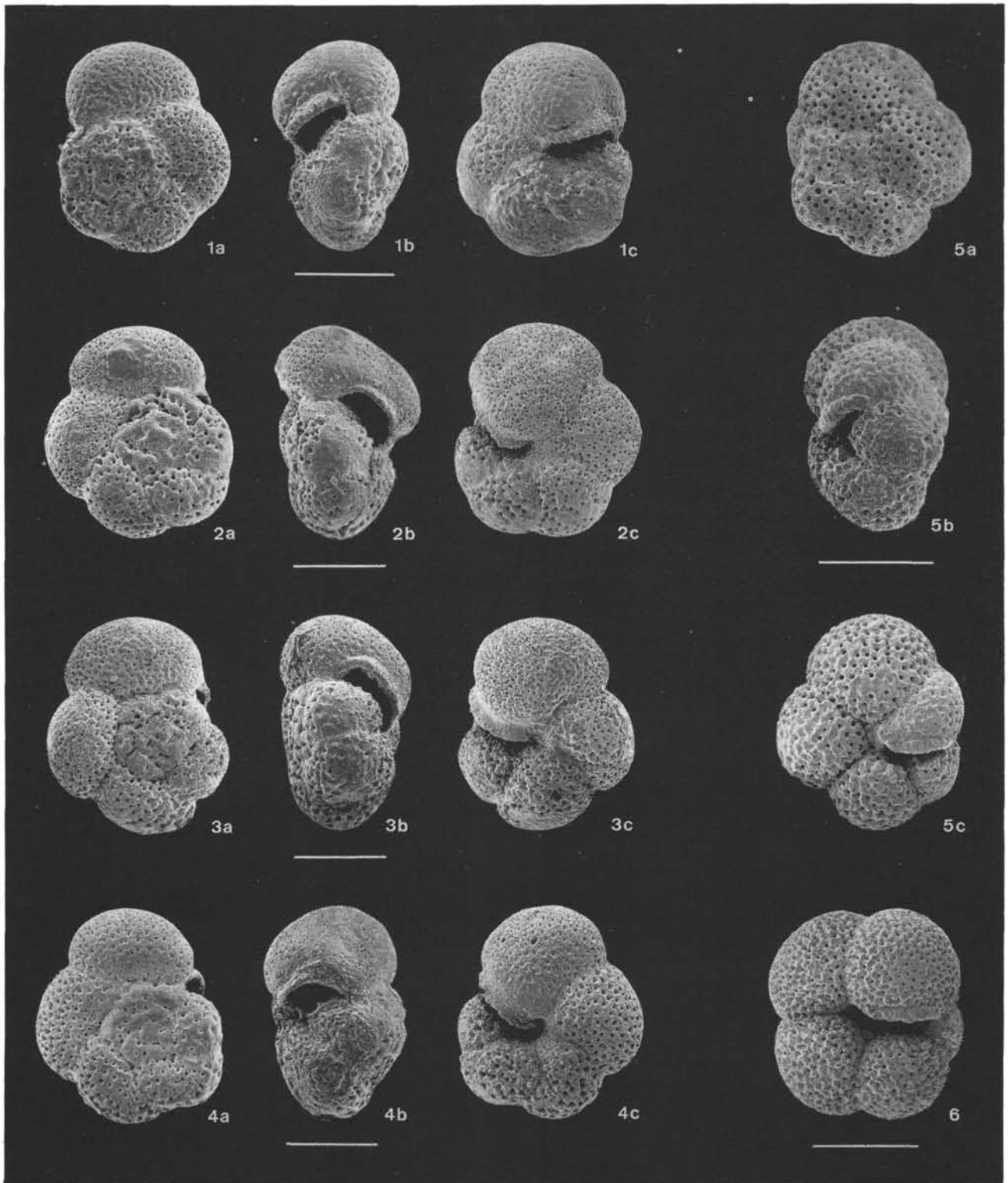


Plate 2. 1a–2c. *Globorotalia partimlabiata* Ruggieri and Sprovieri. Sample 122-762B-14H-1, 48–50 cm. 3a–4c. *Globorotalia partimlabiata* Ruggieri and Sprovieri. Sample 122-762B-13H-7, 46–48 cm. 5a–6. *Neogloboquadrina acostaensis* (Blow). Sample TTOC 178.890 (reference locality of Zone NN9 in Trinidad, Martini, 1971). (Scale bar is 100 μ m.)

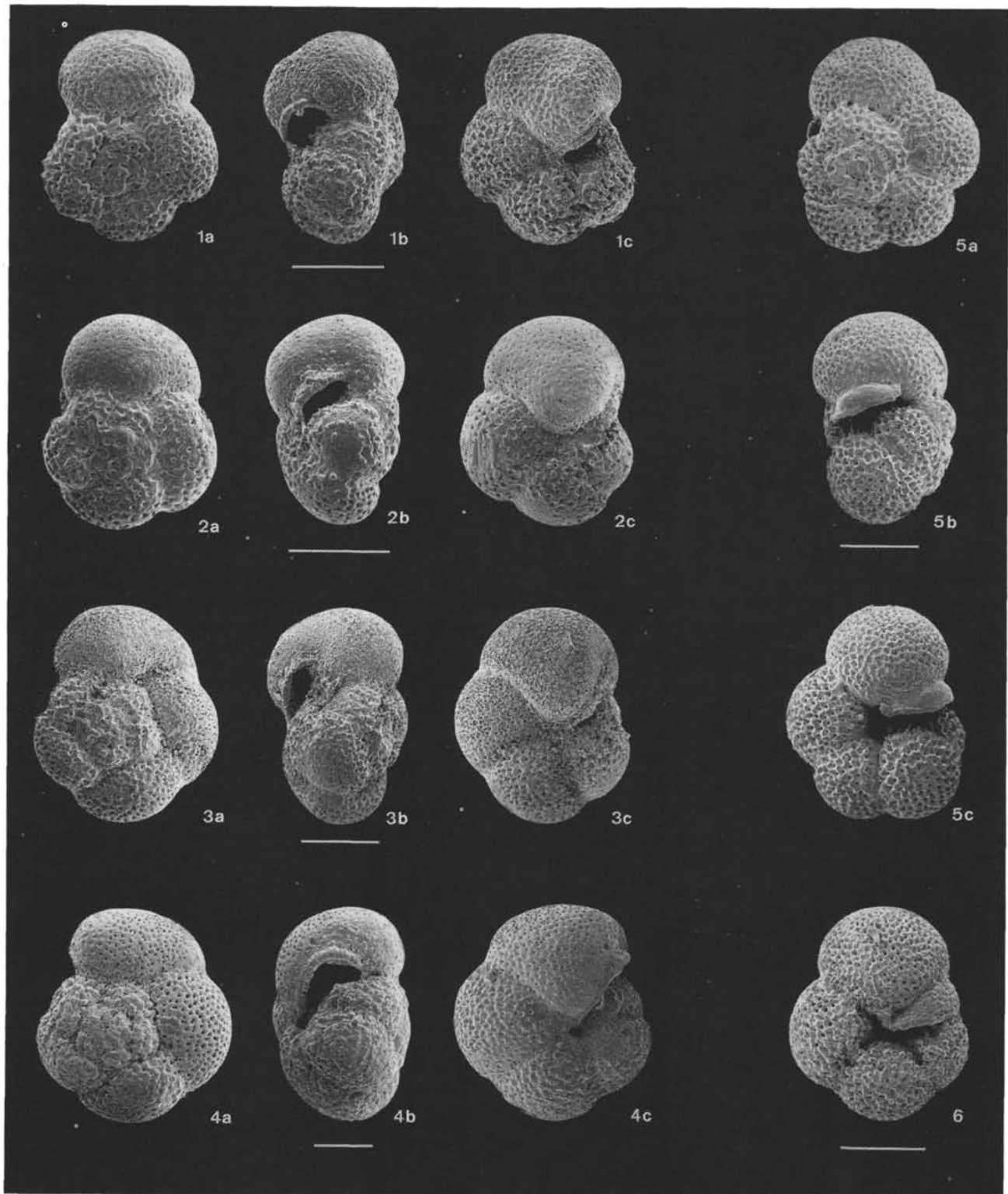


Plate 3. **1a-c.** *Globorotalia partimlabiata* Ruggieri and Sprovieri. Sample 3675, Giammoia section, Sicily (upper middle Miocene, Chamley et al., 1986). **2a-c.** *Globorotalia partimlabiata* Ruggieri and Sprovieri. Sample 3704, Giammoia section, Sicily (upper middle Miocene, Chamley et al., 1986). **3a-4c.** *Globorotalia partimlabiata* Ruggieri and Sprovieri. Sample 608-29-3, 70-72 cm, North Atlantic DSDP Site 608 (upper middle Miocene). **5a-6.** *Neogloboquadrina acostaensis* (Blow). Sample TTOC 178.890 (reference locality of Zone NN9 in Trinidad, Martini, 1971). (Scale bar is 100 μm .)