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# PLANKTIC FORAMINIFERAL FAUNAL TURNOVERS IN THE SUBTROPICAL PACIFIC DURING THE LATE PALEOCENE TO EARLY EOCENE

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## ABSTRACT

**Planktic foraminiferal analysis of sedimentary samples at 25-cm intervals (81 k.y.) at DSDP Site 577 provides a high resolution data base for deep-sea biostratigraphy and faunal changes during the late Paleocene to early Eocene. There are three major faunal turnovers, each of which occurred over a time period of 200 to 400 k.y., near the P3a/P3b, P6a/P6b and P8/P9 boundaries. These turnovers are characterized by rapid changes in species richness, large numbers of first and last appearances, and significant changes in the relative abundances of species. A chronological sequence of datum levels and faunal events of foraminifera tied to magnetostratigraphy provides biostratigraphic control at 1 m.y. intervals for the late Paleocene to early Eocene, with faunal and isotopic events near the Paleocene/Eocene boundary providing isochronous stratigraphic markers.**

## INTRODUCTION

A rapid warming episode in the Antarctic oceans during the Paleocene-Eocene transition (Kennett and Stott, 1990, 1991; Stott and others, 1990; Barrera and Huber, 1991; Lu and Keller, 1993) was associated with major changes in atmospheric circulation and oceanic chemistry as indicated by decreased terrigenous grain size in pelagic sediments (Miller and others, 1987; Hovan and Rea, 1992) and a negative shift in shell $\delta^{13}C$ values of foraminifera (Kennett and Stott, 1990, 1991; Stott and others, 1990; Katz and Miller, 1991; Barrera and Huber, 1991; Stott, 1992; Pak and Miller, 1992; Lu and Keller, 1993; Keller and others, in prep.). Major biotic changes across the Paleocene-Eocene transition have been observed in terrestrial faunas and floras (Wolfe, 1978; Gingerich, 1980, 1986; Axelrod, 1984; Greenwood and Wing, 1993), marine benthos (Tjalsma and Lohmann, 1983; Miller and others, 1987; Thomas, 1989, 1990; Katz and Miller, 1991; Nomura, 1992; Pak and Miller, 1992; Ortiz and Keller, 1993; Keller and others, in prep.), and more recently, in high-latitude and near-shore marine plankton (Lu and Keller, 1993; Canudo and others, in press). In contrast, little temperature change has been observed in low-latitude surface oceans (Miller and others, 1987; Stott, 1992; Corfield and Cartlidge, 1992) and the impact of the global warming across the Paleocene-Eocene transition on low-latitude marine plankton remains largely unknown.

DSDP Site 577 (Shatsky Rise, northwestern Pacific) is an ideal site for examining low latitude faunal changes during the late Paleocene to early Eocene because of its nearly complete core recovery, absence of major hiatuses, and excellent fossil preservation. Also available at this site are high resolution magnetostratigraphy (sample resolution of 50 cm, Bleil, 1985) and $\delta^{13}C$ stratigraphy (sample resolution of 30 cm, Shackleton and others, 1985; Pak and Miller, 1992), as well as initial biostratigraphic studies based on nannoplankton (sample resolution of 100 cm, Monechi, 1985) and planktic foraminifera (sample resolution of 150 cm, Miller and others, 1987 and Corfield, 1987). We have re-examined the planktic foraminiferal record at a sample resolution of 25 cm. Here we present a high resolution data base for species ranges and relative abundances of planktic foraminifera at Site 577 during the late Paleocene and early Eocene and apply this data base in identifying major faunal turnovers and updating present foraminiferal biostratigraphies.

## MATERIALS AND METHODS

During the late Paleocene to early Eocene (50–64 Ma), DSDP Site 577 was located between 22°N, 178°W and 15°N, 177°W at water depths from 1,800 m to 2,100 m (Fig. 1; Lancelot and Larson, 1975; Detrich and others, 1977). The average sediment accumulation rate at this site during this interval is 0.31 cm/k.y. based on magnetostratigraphy (Bleil, 1985). A total of 126 samples spanning 35 m of sediments and a time interval between 51.5 Ma and 63.5 Ma were analyzed for planktic foraminifera. This sample spacing (25 cm interval) provides an average time resolution of 81 k.y. Near the Paleocene/Eocene boundary, samples were taken at every 5 cm, which increased time resolution to 20 k.y. Each sample is 2 cm thick and thus spans, on average, 6.5 k.y.

Samples were disaggregated in water and washed through a 63 μm sieve. This procedure was repeated until foraminifers with clean surface texture were recovered. Population counts were based on random splits of about 300 specimens in the size fraction larger than 106 μm. All specimens were picked, identified and mounted on microslides for a permanent record. Number of species, number of first and last appearances as well as relative abundances of all species are available from the authors.

Determination of relative abundances and identification of first and last appearances of planktic foraminiferal species depend on the number of individuals counted and size fraction examined. We counted 300 individuals from a size fraction >106 μm to generate the data base. Buzas (1990) has shown that a count of 300 individuals is sufficient for a single sedimentary sample when species with a relative abundance of 1% approach cluster confidence limits. Confidence limits are no longer meaningful when the relative abundances of species are less than 1% (Buzas, 1990). In this study, the >106 μm size fraction was chosen because it includes the maximum number of species within the confidence limit provided by the sample size of 300 individuals. With a size fraction of >63 μm, 5–10% of the large species in the sample have relative abundances <1%. With a size fraction of <150 μm, 15–20% of the small species have relative abundance <1%. We estimate that the >106 μm

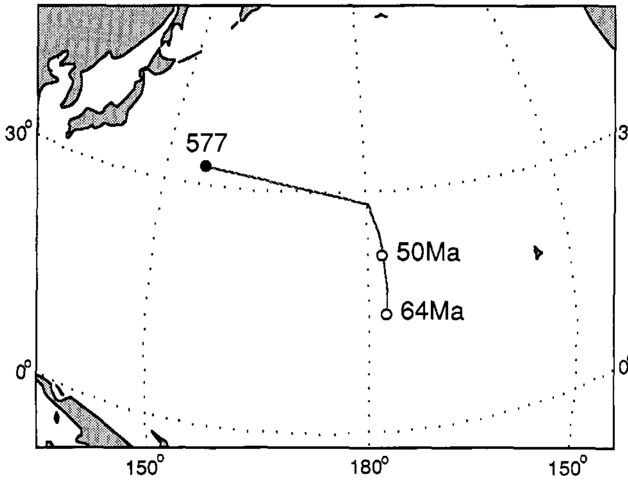


FIGURE 1. Location of DSDP Site 577 and its back-tracked path. Back-tracking was based on the sedimentary and tectonic evolution of the northwestern Pacific (Lancelot and Larson, 1975).

size fraction provides the maximum faunal information at species and relative abundance levels for this study.

A total of 107 planktic foraminiferal species were identified from Zone P3 through P9. Their ranges are illustrated in Figure 2. Based on counts of about 300 individuals, the number of species within one sedimentary sample varies from 18 to 40. The classification of genera was based on the framework discussed by Loeblich and Tappan (1988). Species identification was based on the observations of Subbotina (1953), Bolli (1957), Loeblich and Tappan (1957), Jenkins (1971), Blow (1979), and Toumarkine and Luterbacher (1985). To illustrate our species concepts, the most common species are shown in Plates 1–6, obtained from SEM digital images.

## ZONATION

Several planktic foraminiferal zonal schemes are currently in use for the late Paleocene to early Eocene interval in low latitudes (Premoli Silva and Bolli, 1973; Stainforth and others, 1975; Blow, 1979; Toumarkine and Luterbacher, 1985; Berggren and Miller, 1988). In a recent study, Berggren and Norris (1993) re-defined the zonal boundary of P3a/P3b and P4/P5, and subdivided P4 into three subzones. We have followed the zonal scheme of Berggren and Miller (1988) with changes at the P4/P5, P6b/P6c and P8/P9 zonal boundaries where the original definitions could not be applied. Relationships between Berggren and Miller's scheme (1988) and the revised version by Berggren and Norris (1993) are also examined at this site. Figure 3 illustrates the zonation and datum levels of this study as well as correlations with other currently used zonal schemes.

**Zone P3a:** P3a is defined as the partial range of *Morozovella angulata* between its first appearance datum (FAD) and the FAD of *Igorina pusilla* (Berggren and Miller, 1988). At Site 577, the relative abundance of *M. angulata* (Pl. 1, 1–3) is >30% in the lower part of P3a and declines to <5% in the upper part of this subzone. The dominant species in terms of relative abundance in P3a are the angulate and conicate morozovellids (e.g., *M. angulata, M. acuta, M. abundocamerata* and *M. conicotruncata,* Pl. 1, 1–4, 16–17, 22–23) and igorinids (e.g., *I. tadjikistanensis,* Pl. 4, 4–5). The cumulative relative abundance of these five species exceeds 70%.

**Zone P3b:** P3b is defined as the concurrent partial range of *M. angulata* between the FAD of *Igorina pusilla* (base) and the FAD of *Planorotalites pseudomenardii* (top; Berggren and Miller, 1988). In a recent study, Berggren and Norris (1993) re-define the base of P3b by the first appearance of *Igorina albeari* based on the observation that this datum event occurs above the first appearance of *I. pusilla.* At Site 577, *I. pusilla* and *I. albeari* first appear in the same sample. *Morozovella angulata* is rare in P3b. The dominant species in P3b are discoidal morozovellids (e.g., *M. occlusa* and *M. velascoensis,* Pl. 1, 5–8), conicate acarininids (e.g., *A. nitida, A. strabocella, A. mckannai* and *A. subsphaerica,* Pl. 2, 1–8), igorinids (e.g., *I. pusilla* and *I. albeari,* Pl. 4, 1–3, 6–8) and compressed subbotinids (e.g., *S. velascoensis,* Pl. 5, 8–10). These species have a combined relative abundance of more than 70%.

**Zone P4x:** P4 is defined as the total range of *P. pseudomenardii* (Berggren and Miller, 1988). However, Blow (1979) observed that this taxon ranged into his Zone P7, which correlates approximately to P6b of Berggren and Miller's (1988) scheme. Berggren and Norris (1993) also found overlap between *P. pseudomenardii* and *Morozovella subbotinae,* indicating that *P. pseudomenardii* ranged into P6a of Berggren and Miller's (1988) scheme. At Site 577, this taxon continuously accounts for 2% of the assemblage between 94.95 m and 88.00 m below seafloor (mbsf). Above 88.00 m, it is sporadic and rare (<0.3%). We tentatively name P4 as P4x and place the top of P4x at the last continuous occurrence of *P. pseudomenardii.* Close to this datum level (at 88.84 m) is the first appearance of *Acarinina soldadoensis* (Pl. 2, 18–20), which defines the P4/P5 zonal boundary in Blow's (1979) zonal scheme. The dominant species in P4x are discoidal morozovellids (e.g., *M. occlusa* and *M. velascoensis*), conicate acarininids (e.g., *A. nitida, A. subsphaerica, A. strabocella* and *A. mckannai*), igorinids (e.g., *I. pusilla*) and compressed subbotinids (e.g., *S. velascoensis*). These species account for more than 60% of the relative abundances. Near the top of P4x, rounded acarininids (e.g., *A. pseudotopilensis, A. soldadoensis* and *A. triplex,* Pl. 2, 11–13, 16–20) have their first appearances.

Berggren and Norris (1993) subdivided Zone P4 into three subzones based on the total range of *Acarinina subsphaerica* and the partial range of *Acarina acarinata.* At several low-latitude sites, including Site 577, *A. subsphaerica* ranges into P6a (Blow, 1979; Canudo and others, in press; this study), whereas the last appearance of *A. acarinata,* which underwent a morphological variation across latitudes and is usually identified as *A. intermedia* in low-latitudes (Blow, 1979; Canudo and others, in press; this study), occurred close to the first appearance of *A. soldadoensis* (Fig. 2). Thus, Subzones P4a and P4b of Berggren and Norris (1993) are approximately correlative with Zone P4x in this study.

**Zone P5x:** P5 is defined as the partial range of *Morozovella velascoensis* between the last appearance datum (LAD) of *P. pseudomenardii* and the FAD of *M. subbotinae* (Berggren and Miller, 1988). In recognizing the overlap between the LAD of *P. pseudomenardii* and the FAD of *M. subbotinae,* Berggren and Norris (1993) extend P4 to include P5 and retain P5 only for cases of delayed entry of *M. subbotinae.* In this study, we retain the definition for the top by Berggren and Miller (1988), tentatively place the base at the last continuous occurrence of *P. pseudomenardii* and name this zone P5x. Zone P5x is correlated approximately with Subzone P4c in Berggren and Norris' (1993) zonal scheme. The five most abundant species in P5x are *I. pusilla, M. occlusa, M. aequa, M. apenthesma* and *A. nitida,* which have a cumulative relative abundance of nearly 50%.

**Subzone P6a:** The top of Subzone P6a is defined by the last appearance of *Morozovella velascoensis* (Pl. 1, 6–8) by Berggren and Miller (1988). Close to this datum level are the first appearances of *Pseudohastigerina wilcoxensis* and *Acarinina wilcoxensis* (Blow, 1979; Toumarkine and Luterbacher, 1985; Berggren and Miller, 1988). At Site 577, *P. wilcoxensis* (Pl. 6, 7–8) is rare and its first appearance cannot be determined precisely. The first appearance of *A. wilcoxensis* (Pl. 2, 14–15) is 15 cm below the last appearance of *M. velascoensis.* The most abundant species in P6a are *A. soldadoensis, A. pseudotopilensis, M. apenthesma, M. occlusa* and *M. aequa,* which have a combined relative abundance of nearly 40%.

**Subzone P6bx:** Berggren and Miller (1988) defined the top of P6b by the first appearance of *Morozovella formosa* (Pl. 1, 10). At Site 577, this datum level is located 15 cm below the last appearance of *Morozovella velascoensis,* or within the upper part of Subzone P6a. Premoli Silva and Bolli (1973) and Toumarkine and Luterbacher (1985) defined the top of their *Morozovella edgari* Zone by the last appearance of *M. edgari* (Pl. 1, 20–21). This taxon ranges 174 cm above the first appearance of *Morozovella aragonensis,* or within the lower part of Zone P7 at Site 577. To subdivide this interval, we tentatively chose the last appearance of *Igorina lodoensis* (Pl. 4, 9–11) to mark the top of this subzone and name it as P6bx (Figs. 2 and 3). *I. lodoensis* has high relative abundance (about 10%) at Site 577 and is easy to separate from the coeval igorinid taxon *I. convexa* (Pl. 4, 12–14) by its thin discoidal shape.

P6bx is characterized by rapid increase in species richness (Fig. 2). Within the upper part of P6a and the lower part of P6bx, hispid morozovellid taxa (e.g., *M. aequa, M. quetra, M. subbotinae, M. marginodentata, M. gracilis* and *M. formosa,* Pl. 1, 9–15) replace discoidal morozovellid taxa (e.g., *M. occlusa, M. velascoensis* and *M. pasionensis*). In the upper part of P6bx, rounded acarininid taxa (e.g., *A. pseudotopilensis, A. triplex, A. soldadoensis, A. wilcoxensis, A. esnaensis* and *A. praepentacamerata,* Pl. 2, 9–20) replace conicate acarininid taxa (e.g., *A. nitida, A. subsphaerica, A. strabocella* and *A. mckannai*). "Turborotaliids," a group with a distinct morphology (Pl. 5, 22–27), have their maximum relative abundance in P6bx. A major faunal turnover occurred between P6a and P6b which resulted in a large number of first and last appearances (Fig. 2).

**Subzone P6cx:** We tentatively chose the last appearance of *Igorina lodoensis* to mark the base of this subzone and retain the top as defined by the FAD of *Morozovella aragoensis* (Berggren and Miller, 1988) for their Subzone P6c. This subzone is characterized by high species richness (Fig. 2). Angulate acarininids (e.g., *A. nicoli, A.* cf. *nicoli* and *A. densa,* Pl. 3, 1–5) and muricate acarininids (e.g., *A. primitiva* and *A. appressocamerata,* Pl. 3, 6–10) first appear in this subzone. Chiloguembelinids, which are present only in a short interval from P6bx to the lower part of P7 at Site 577, reach their maximum relative abundance in P6cx.

**Zone P7:** P7 is defined as the concurrent range of *M. formosa* and *M. aragonensis* (Berggren and Miller, 1988). Three dominant species in P7 (e.g., *A. primitiva, A. appressocamerata* and *I. convexa*) combine for a relative abundance of 40%. Rounded and angulate acarininids account for another 40%. Muricate morozovellids (e.g., *M. lensiformis* and *M. aragonensis*) replace hispid morozovellids in this zone.

**Zone P8x:** Berggren and Miller (1988) defined the top of P8 by the first appearance of *Planorotalites palmerae.* This taxon is not present at Site 577 (Miller and others, 1987; Corfield, 1987; this study). Blow (1979) recognized his P8/P9 zonal boundary by the first appearance of *Acarinina aspensis* (Pl. 3, 16–18), a datum level that is easy to recognize at Site 577 because of its distinct morphology and high relative abundance (20%). We therefore chose the first appearance of *A. aspensis* to mark the top of P8x in this study. Three dominant species in P8x (e.g., *A. primitiva, A. appressocamerata* and *I. convexa*) have a combined relative abundance of 50%.

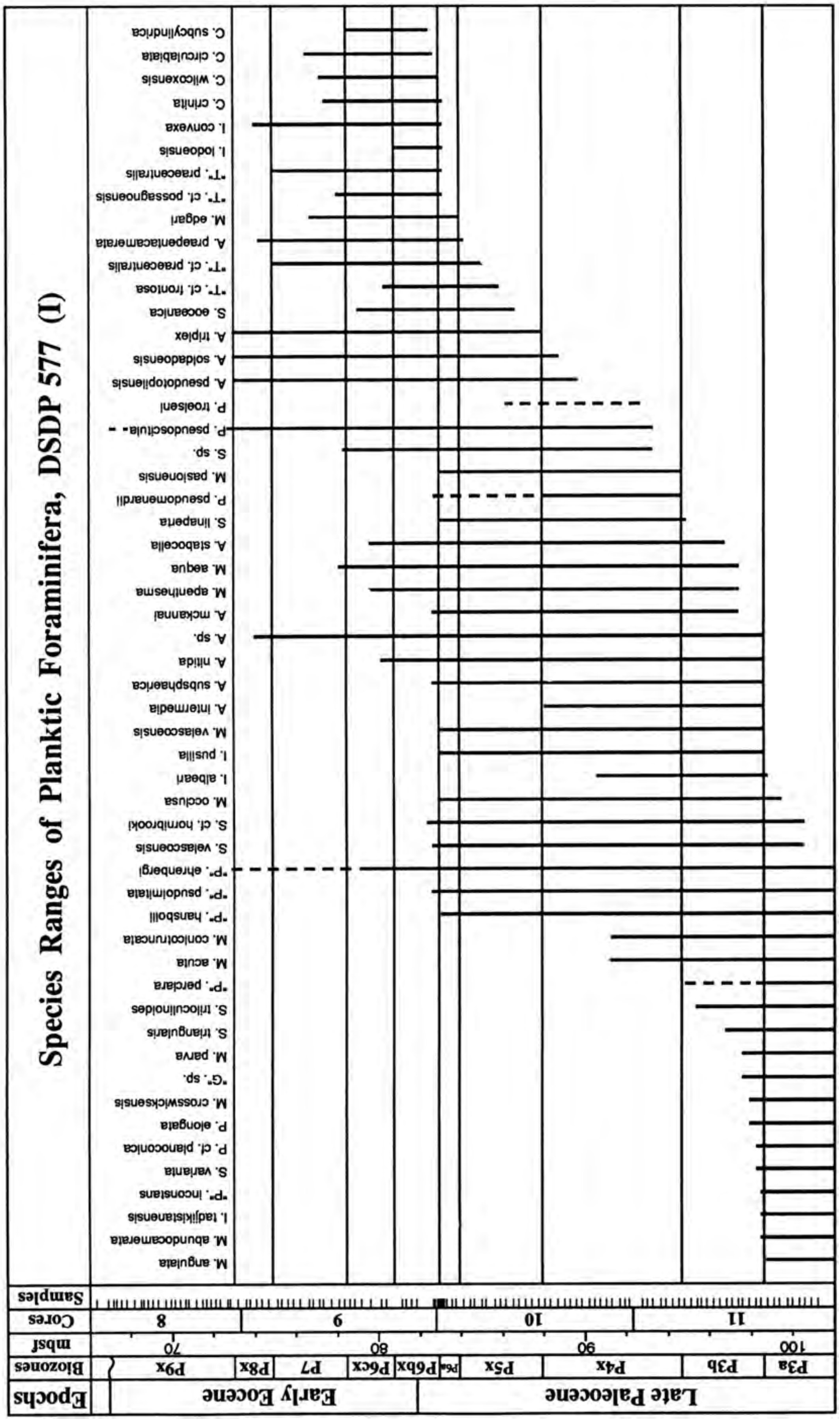
**Zone P9x:** At Site 577, the base of P9x is recognized by the FAD of *A. aspensis* and the top is not encountered in this study. The dominant species in Zone P9x, *A. matthewsae, A. cuneicamerata, A. aspensis, A. anapetes, A. aquiensis* and *Muricoglobigerina senni* (Pl. 2, 24–26; Pl. 3, 11–19, 21–22), have a cumulative relative abundance of 70%. A major faunal turnover occurred between Zone P8x and Zone P9x as marked by the replacement of rounded and angulate acarininids by muricate species.

## MAJOR FAUNAL TURNOVERS

Global oceanic environments changed dramatically during the late Paleocene and early Eocene. Associated with the changes in oceanography were major changes in planktic foraminiferal faunas, which have potential as stratigraphic markers. In this study we show that major short-term faunal turnovers in planktic foraminifera occur near the P3a/P3b, P6a/P6bx and P8x/P9x zonal boundaries. These faunal turnovers are characterized by: 1) 49% to 56% change in species, 2) 40% to 80% change in species relative abundances, and 3) occurrence over a time period of 200–400 k.y.

### P3a/P3b TURNOVER

Figure 4 illustrates the faunal turnover across the P3a/P3b boundary. All existing genera were affected with *Acarinina, Morozovella* and *Igorina* showing the most dramatic changes. Characteristic features of this turnover include: 1) first appearance of the genus *Acarinina* represented by conicate taxa (e.g., *A. nitida, A. intermedia, A. subsphaerica, A. strabocella* and *A. mckannai,* Pl. 2, 1–8); 2) decreased relative abundance in angulate and conicate morozovellids (e.g., *M. angulata, M. parva, M. acuta, M. abundocamerata* and *M. conicotruncata,* Pl. 1, 1–4, 16–17, 22–23); 3) increased relative abundance in discoidal morozovellids


Species Ranges of Planktic Foraminifera, DSDP 577 (I)
Epochs
Biozones
mbsf
Cores
Samples
Late Paleocene
Early Eocene
P3a
P3b
P4x
P5x
P6a
P6bx
P6cx
P7
P8x
P9x
100
90
80
70
11
10
9
8
M. angulata
M. abundocamerata
I. tadjikistanensis
"P". inconstans
S. varianta
P. cf. planoconica
P. elongata
M. crosswicksensis
"G". sp.
M. parva
S. triangularis
S. triloculinoides
"P". perclara
M. acuta
M. conicotruncata
"P". hansbolli
"P". psudoimitata
"P". ehrenbergi
S. velascoensis
S. cf. hornibrooki
M. occlusa
I. albeari
I. pusilla
M. velascoensis
A. intermedia
A. subsphaerica
A. nitida
A. sp.
A. mckannai
M. apanthesma
M. aequa
A. stabocella
S. linaperta
P. pseudomenardii
M. pasionensis
S. sp.
P. pseudoscitula
P. troelseni
A. pseudotopilensis
A. soldadoensis
A. triplex
S. eocaenica
"T". cf. frontosa
"T". cf. praecentralis
A. praepentacamerata
M. edgari
"T". cf. possagnoensis
"T". praecentralis
I. lodoensis
I. convexa
C. crinita
C. wilcoxensis
C. circulabiata
C. subcylindrica

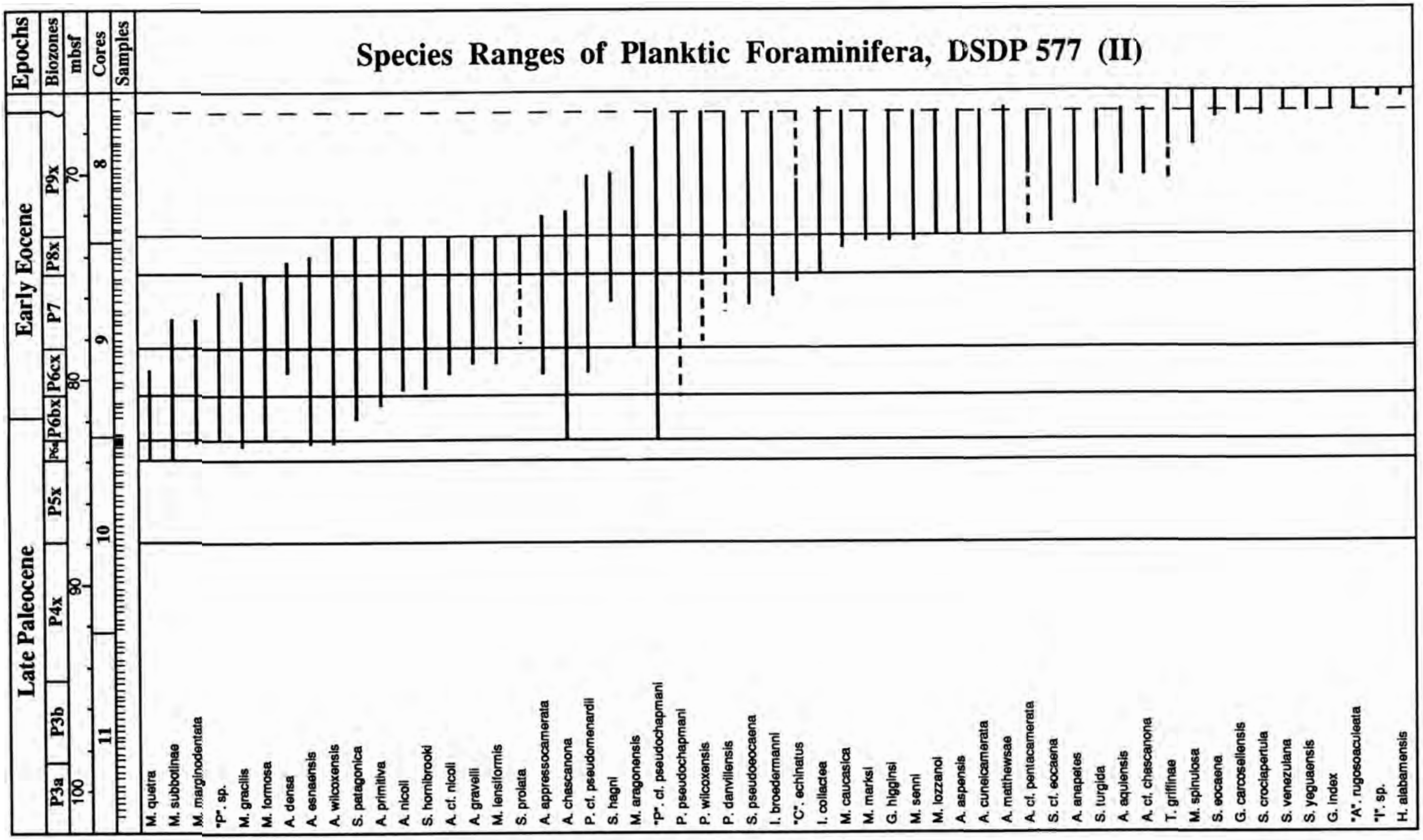


FIGURE 2. Ranges of planktic foraminiferal species at Site 577. Dashed lines indicate relative abundance <0.33% (beyond the confidence limit of the sample size).

(e.g., *M. occlusa* and *M. velascoensis,* Pl. 1, 5–8); 4) replacement of *Igorina tadjikistanensis* by *I. albeari* and *I. pusilla* (Pl. 4, 1–8) which involved only three species but 30% of the total relative abundances; and 5) decreased relative abundance in *Subbotina, Planorotalites* and ''*Planorotalites.*'' This turnover resulted in the replacement of 56% of the species having a collective relative abundance of 63%. Associated with this faunal turnover is the climatic transition from gradual cooling during the early Paleocene to gradual warming during the late Paleocene (Shackleton, 1985, 1986; Miller and others, 1987; Pak and Miller, 1992; Corfield and Cartlidge, 1992).

## P6a/P6bx TURNOVER

Figure 5 illustrates the faunal turnover near the P6a/P6bx boundary where many first and last appearances occur. Incomplete recovery between Core 9 and Core 10 (50 cm missing from 82.10 to 82.60 mbsf) coincides with the simultaneous disappearances of 6 species. A study of nearby Site 47.2 indicates that the sedimentation is apparently continuous through this interval on the Shatsky Rise (Stott, 1992).

The P6a/P6bx turnover affected all existing genera. Characteristic features of this turnover are: 1) replacement of

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### PLATE 1

Late Paleocene to early Eocene morozovellids from DSDP Site 577. Angulate morozovellids: **1–3,** *Morozovella angulata* (White), 577-11-6(139–141); **4,** *Morozovella acuta* (Toulmin), 577-11-6(139–141). Discoidal morozovellids: **5,** *Morozovella occlusa* (Loeblich and Tappan), 577-11-3(19–21); **6–8,** *Morozovella velascoensis* (Cushman), 577-11-3(19–21). Hispid morozovellids: **9,** *Morozovella gracilis* (Bolli), 577-9-6(53–55); **10,** *Morozovella formosa* (Bolli), 577-9-4(104–106); **11–13,** *Morozovella subbotinae* (Morozova), 577-9-6(53–55); **14,** *Morozovella marginodentata* (Subbotina), 577-9-4(104–106); **15,** *Morozovella aequa* (Cushman and Renz), 577-11-3(19–21). Conicate morozovellids: **16–17,** *Morozovella conicotruncata* (Subbotina), 577-11-6(139–141); **18–19,** *Morozovella apenthesma* (Loeblich and Tappan), 577–11-2(52–54); **20–21,** *Morozovella edgari* (Premoli Silva and Bolli), 577-9-4(104–106); **22–23,** *Morozovella abundocamerata* (Bolli), 577–11-6(139–141). Muricate morozovellids: **24,** *Morozovella marksi* (Martin), 577-9-3(104–106); **25–26,** *Morozovella caucasica* (Glaessner), 577-9-3(104–106).

### PLATE 2

Late Paleocene to early Eocene acarininids from DSDP Site 577. Conicate acarininids: **1–3,** *Acarinina nitida* (Martin), 577-11-3(19–21); **4–5,** *Acarinina strabocella* (Loeblich and Tappan), 577-11-3(19–21); **6–7,** *Acarinina mckannai* (White), 577-11-3(19–21); **8,** *Acarinina subsphaerica* (Subbotina), 577-11-3(19–21). Rounded acarininids: **9–10,** *Acarinina esnaensis* (LeRoy), 577-9-6(53–55); **11–13,** *Acarinina triplex* Subbotina, 577-9-6(53–55); **14–15,** *Acarinina wilcoxensis* (Cushman and Ponton), 577-9-6(53–55); **16–17,** *Acarinina pseudotopilensis* Subbotina, 577-9-6(53–55); **18–20,** *Acarinina soldadoensis* (Brönnimann), 577-9-6(53–55). High spired acarininids: **21,** *Acarinina* sp., 577-11-4(100–102); **22,** *Acarinina chascanona* (Loeblich and Tappan), 577-9-4(194–106); **23,** *Acarinina* cf. *chascanona* (Loeblich and Tappan), 577-8-4(34–36); **24–26,** *Acarinina aquiensis* (Loeblich and Tappan), 577-8-4(34–36).

### PLATE 3

Late Paleocene to early Eocene acarininids and muricoglobigerinids from DSDP Site 577. Angulate acarininids: **1–3,** *Acarinina nicoli* (Martin), 577-9-4(104–106); **4,** *Acarinina* cf. *nicoli* (Martin), 577-9-4(104–106); **5,** *Acarinina densa* (Cushman), 577-9-4(104–106). Muricate acarininids: **6–8,** *Acarinina primitiva* (Finlay), 577-9-4(104–106); **9–10,** *Acarinina appressocamerata* Blow, 577-9-3(104–106); **11–13,** *Acarinina anapetes* Blow, 577-8-4(34–36); **14–15,** *Acarinina matthewsae* Blow, 577-8-5(100–102); **16–18,** *Acarinina aspensis* (Colom), 577-8-5(100–102); **19,** *Acarinina cuneicamerata* Blow, 577-8-5(100–102); **20,** *Globigerinatheka index* (Finlay), 577-8-2(100–102). Muricoglobigerinids: **21–22,** *Muricoglobigerina senni* (Beckmann), 577-8-5(100–102); **23,** *Muricoglobigerina lozanoi* (Colom), 577-8-5(100–102).

### PLATE 4

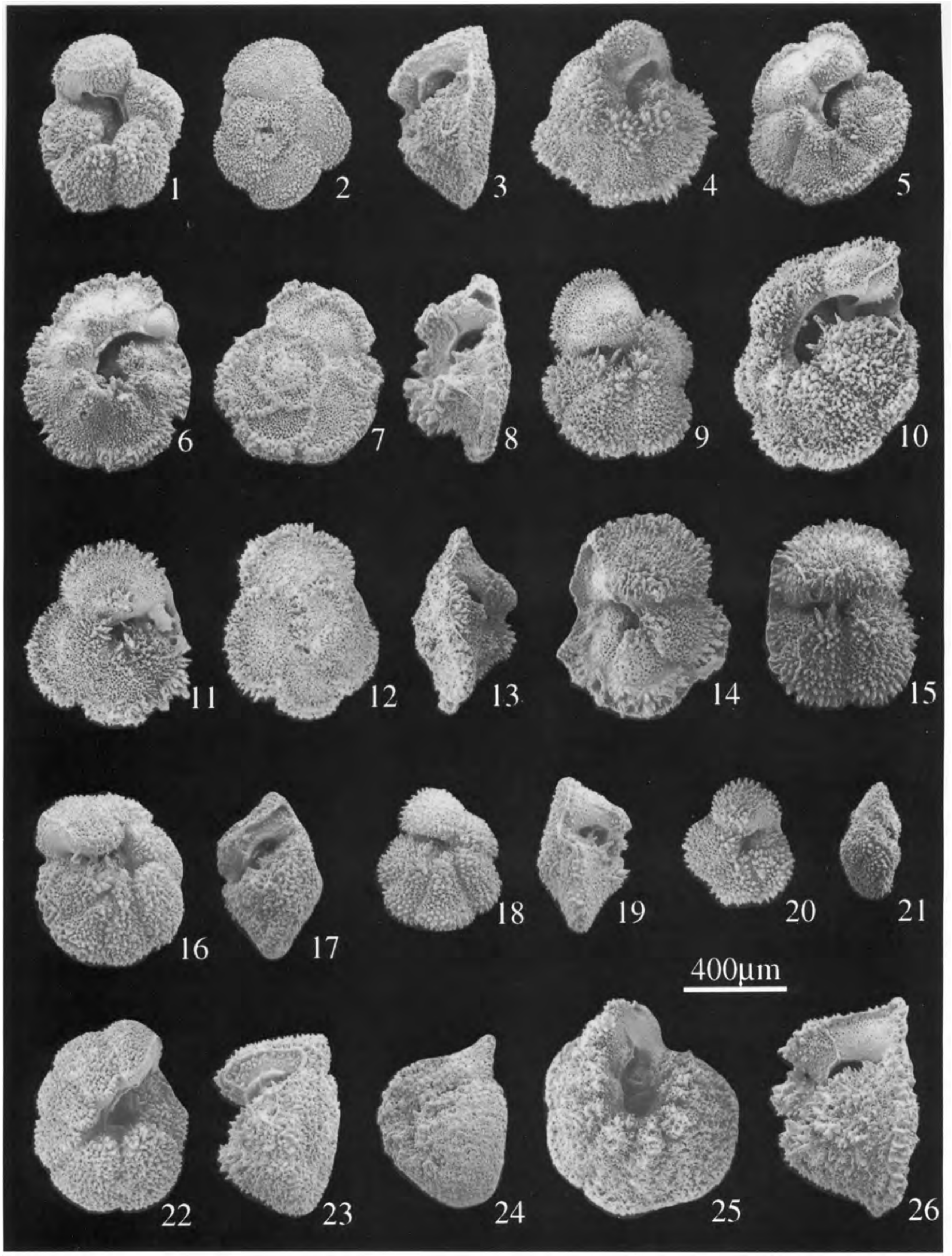
Late Paleocene to early Eocene igorinids and "planorotalitids" from DSDP Site 577. Igorinids: **1–3,** *Igorina albeari* (Cushman and Bermudez), 577-11-3(19–21); **4–5,** *Igorina tadjikistanensis* (Bykova), 577-11-6(139–141); **6–8,** *Igorina pusilla* (Bolli), 577-11-3(19–21); **9–11,** *Igorina lodoensis* (Mallory), 577-9-6(53–55); **12–14,** *Igorina convexa* (Subbotina), 577-9-6(53–55); **15,** *Igorina collactea* (Finlay), 577-8-5(100–102); **16,** *Igorina broedermanni* (Cushman and Bermudez), 577-8-5(100–102). "Planorotalitids": **17,** ''*Planorotalites*'' cf. *pseudochapmani* (Gohrbandt), 577-9-4(104–106); **18–19,** ''*Planorotalites*'' *ehrenbergi* (Bolli), 577-11-5(141–143); **20–22,** ''*Planorotalites*'' *pseudoimitata* (Blow), 577-11-5(141–143); **23,** ''*Planorotalites*'' sp., 577-9-4(104–106); **24–26,** ''*Planorotalites*'' *hansbolli* (Blow), 577-11-5(141–143); **27,** ''*Planorotalites*'' cf. *inconstans* (Subbotina), 577-11-6(139–141).

### PLATE 5

Late Paleocene to early Eocene subbotinids and "turborotaliids" from DSDP Site 577. Rounded subbotinids: **1–2,** *Subbotina linaperta* (Finlay), 577-11-2(52–54); **3–5,** *Subbotina triloculinoides* (Plumer), 577-11-6(20–22); **6,** *Subbotina* cf. *hornibrooki* (Bronnimann), 577–11-5(141–143). Compressed subbotinids: **7,** *Subbotina varianta* (Subbotina), 577-11-6(139–141); **8–10,** *Subbotina velascoensis* (Cushman), 577-11-6(20–22); **11,** *Subbotina eocaenica* (Terquem), 577-9-6(53–55). Quadratic subbotinids: **12–14,** *Subbotina patagonica* (Todd and Kniker), 577-9-6(53–55); **15,** *Subbotina hornibrooki* (Brönnimann), 577-9-3(104–106); **16,** *Subbotina turgida* (Finlay), 577-8-5(100–102); **17,** *Subbotina pseudoeocaena* (Subbotina), 577-8-5(100–102); **18–19,** *Subbotina* cf. *eocaena* (Gümbel), 577-8-5(100–102); **20,** *Subbotina eocaena* (Gümbel), 577-8-2(100–102); **21,** *Subbotina* sp., 577-11-1(49–51). "Turborotaliids": **22–23,** ''*Turborotalia*'' cf. *frontosa* (Subbotina), 577-9-6(53–55); **24,** ''*Turborotalia*'' cf. *praecentralis* (Blow), 577-9-6(53–55); **25–27,** ''*Turborotalia*'' *praecentralis* (Blow), 577-9-4(104–106).

### PLATE 6

Late Paleocene to early Eocene pseudohastigerinids, planorotalitids and chiloguembelinids from DSDP Site 577. Pseudohastigerinids: **1–3,** *Pseudohastigerina pseudochapmani* (Gohrbandt), 577-9-4(104–106); **4–6,** *Pseudohastigerina danvillensis* (Howe and Wallace), 577-8-4(34–36); **7–8,** *Pseudohastigerina wilcoxensis* (Cushman and Ponton), 577-9-4(104–106). Planorotalitids: **9–11,** *Planorotalites elongata* (Glaessner), 577-11-6(20–22); **12–14,** *Planorotalites* cf. *pseudomenardii* (Bolli), 577-9-4(104–106); **15–17,** *Planorotalites pseudoscitula* (Glaessner), 577-9-6(53–55); **18–19,** *Planorotalites pseudomenardii* (Bolli), 577-11-2(52–54). Chiloguembelinids: **20–21,** *Chiloguembelina wilcoxensis* (Cushman and Ponton), 577-9-6(53–55); **22–23,** *Chiloguembelina subcylindrica* Beckmann, 577-9-6(53–55); **24–26,** *Chiloguembelina circumlabiata* Hillebrandt, 577-9-6(53–55); **27–28,** *Chiloguembelina crinita* (Glaessner), 577-9-6(53–55).



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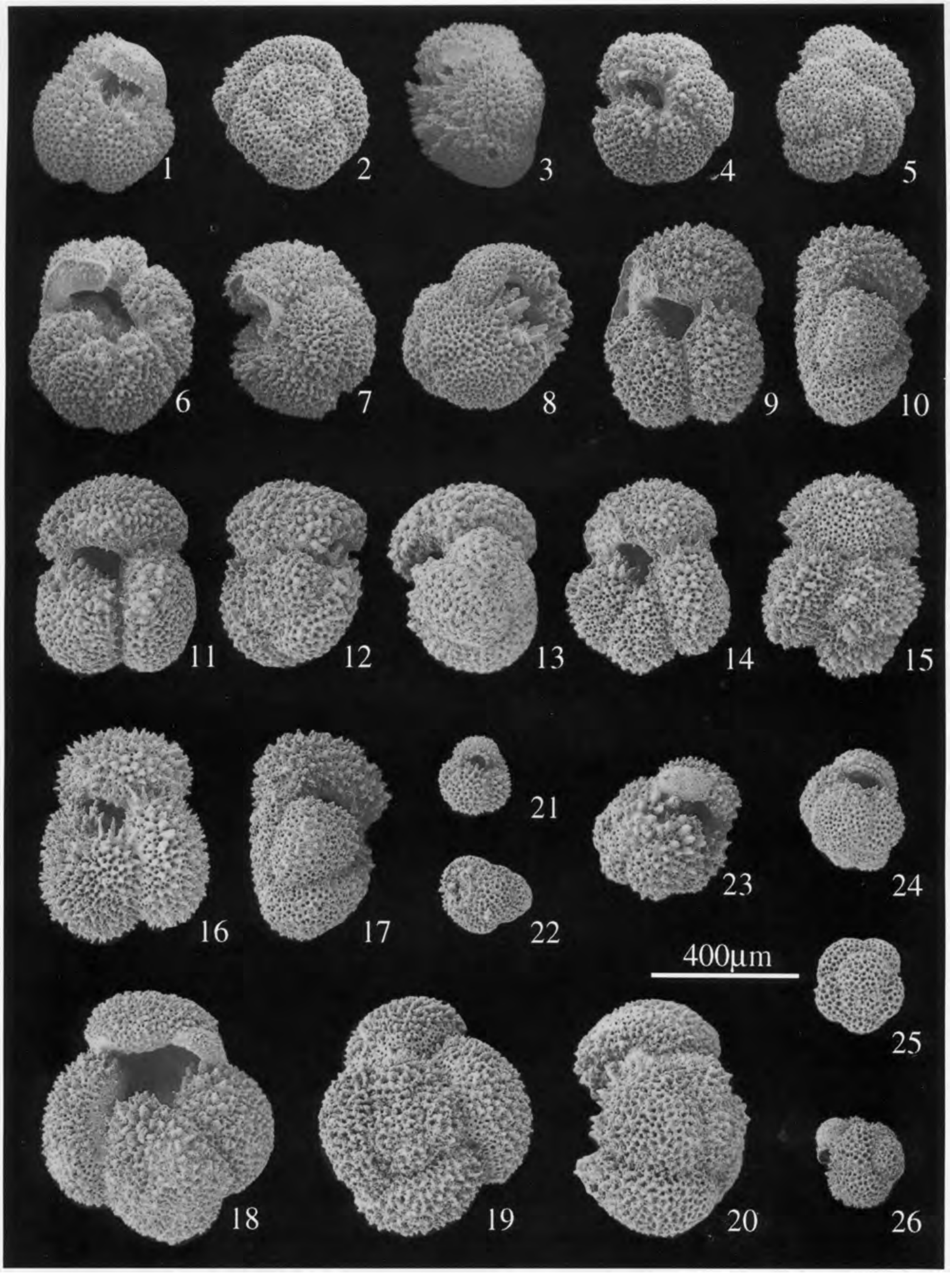

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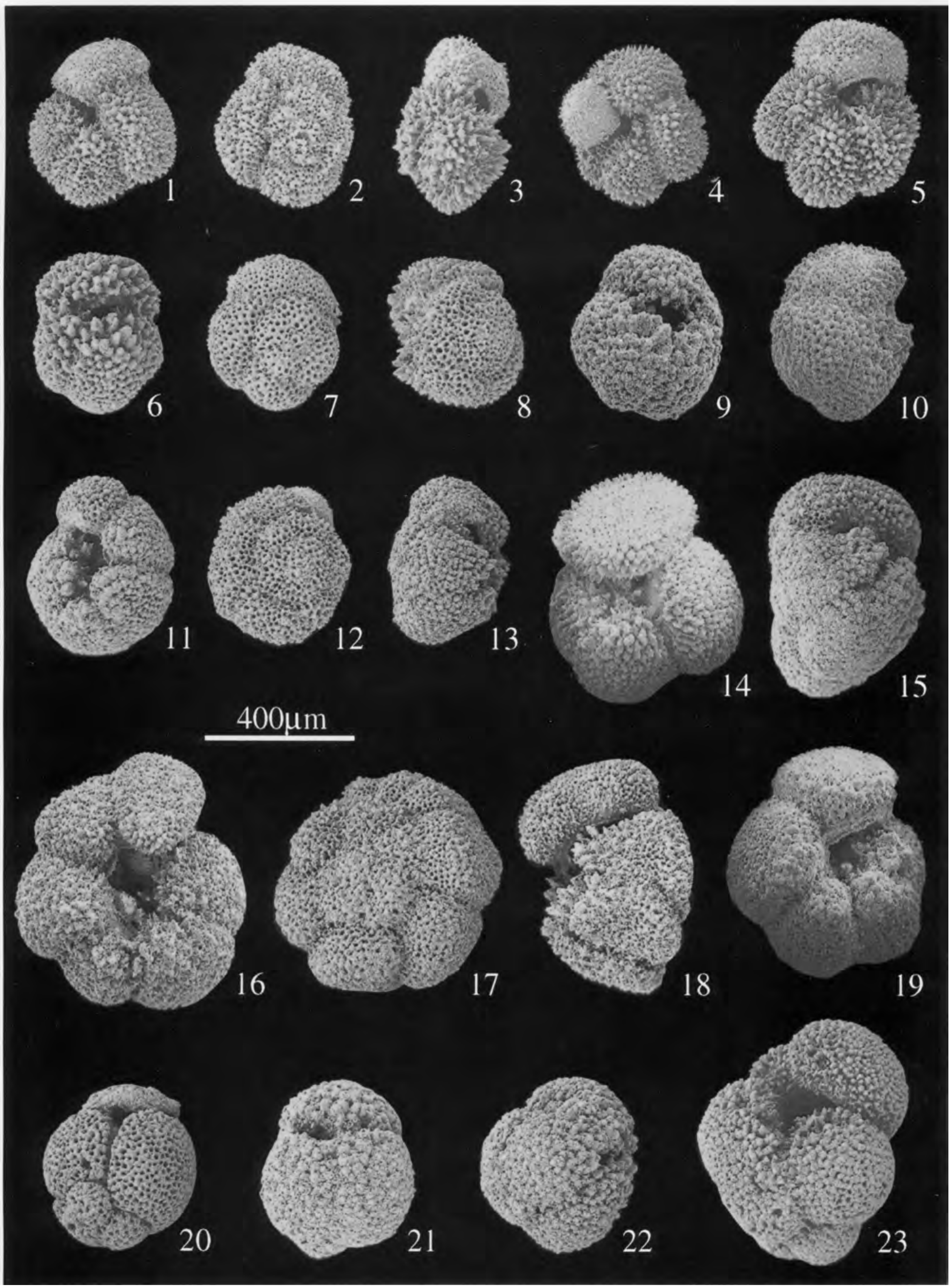

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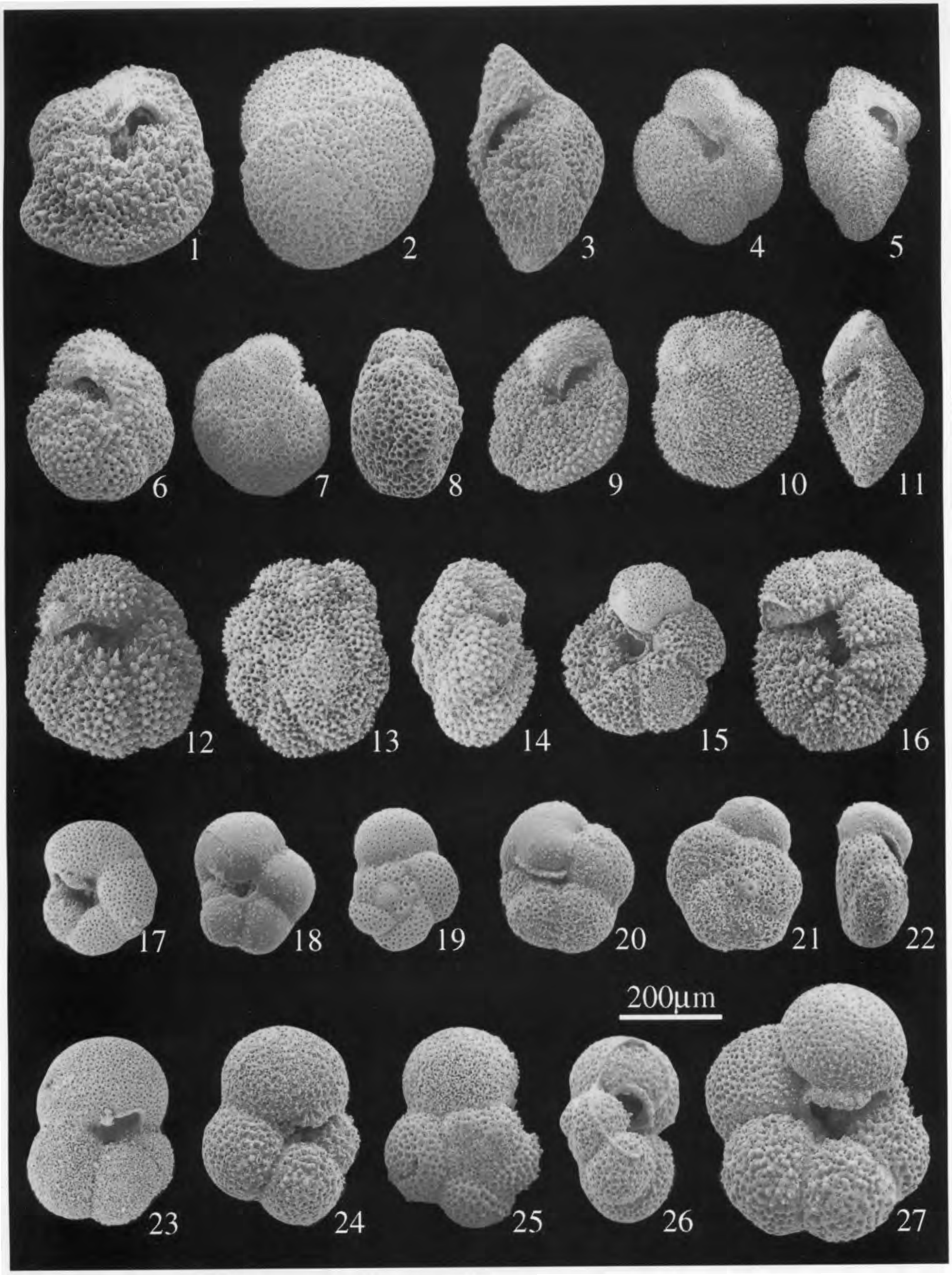
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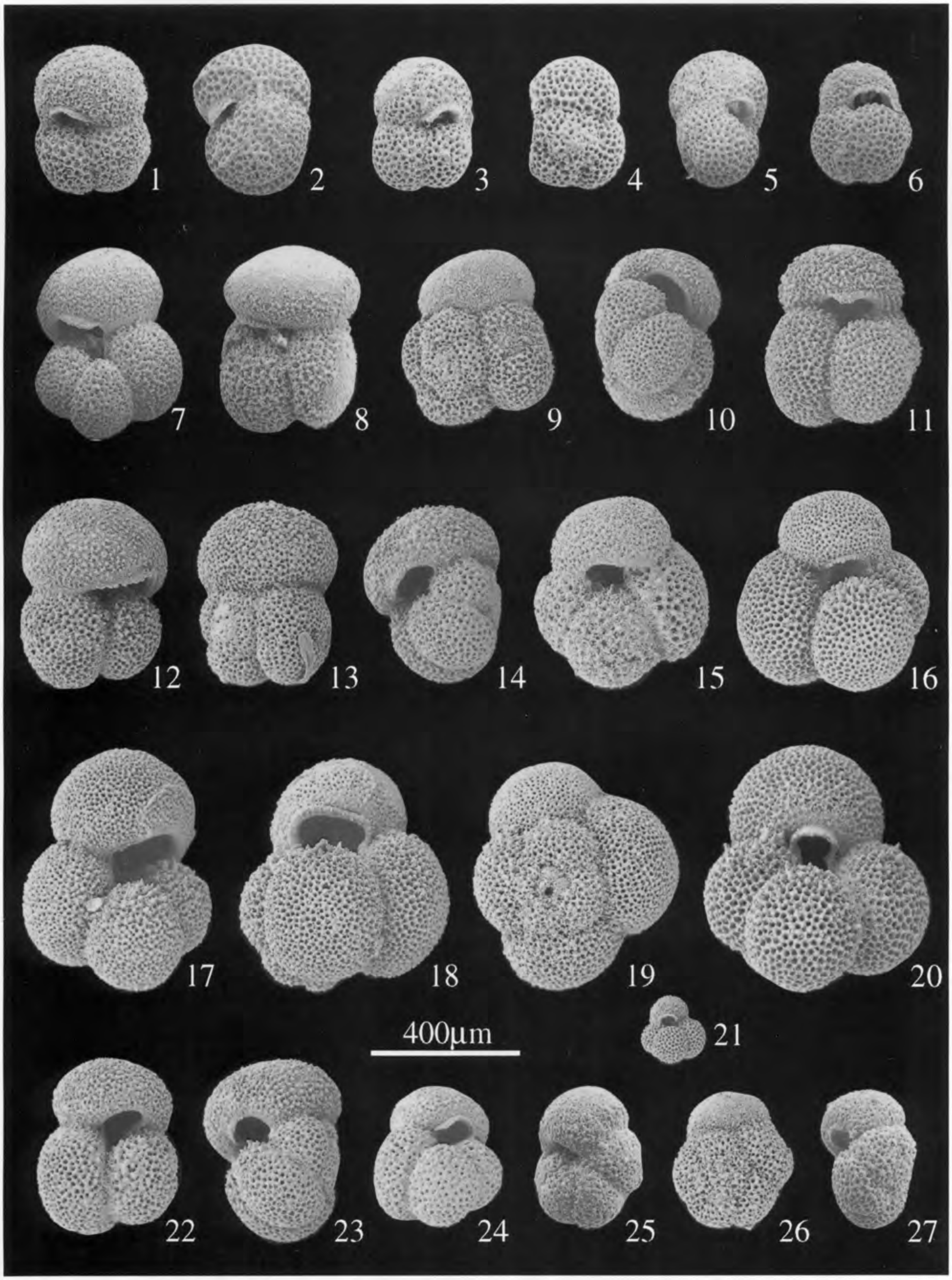
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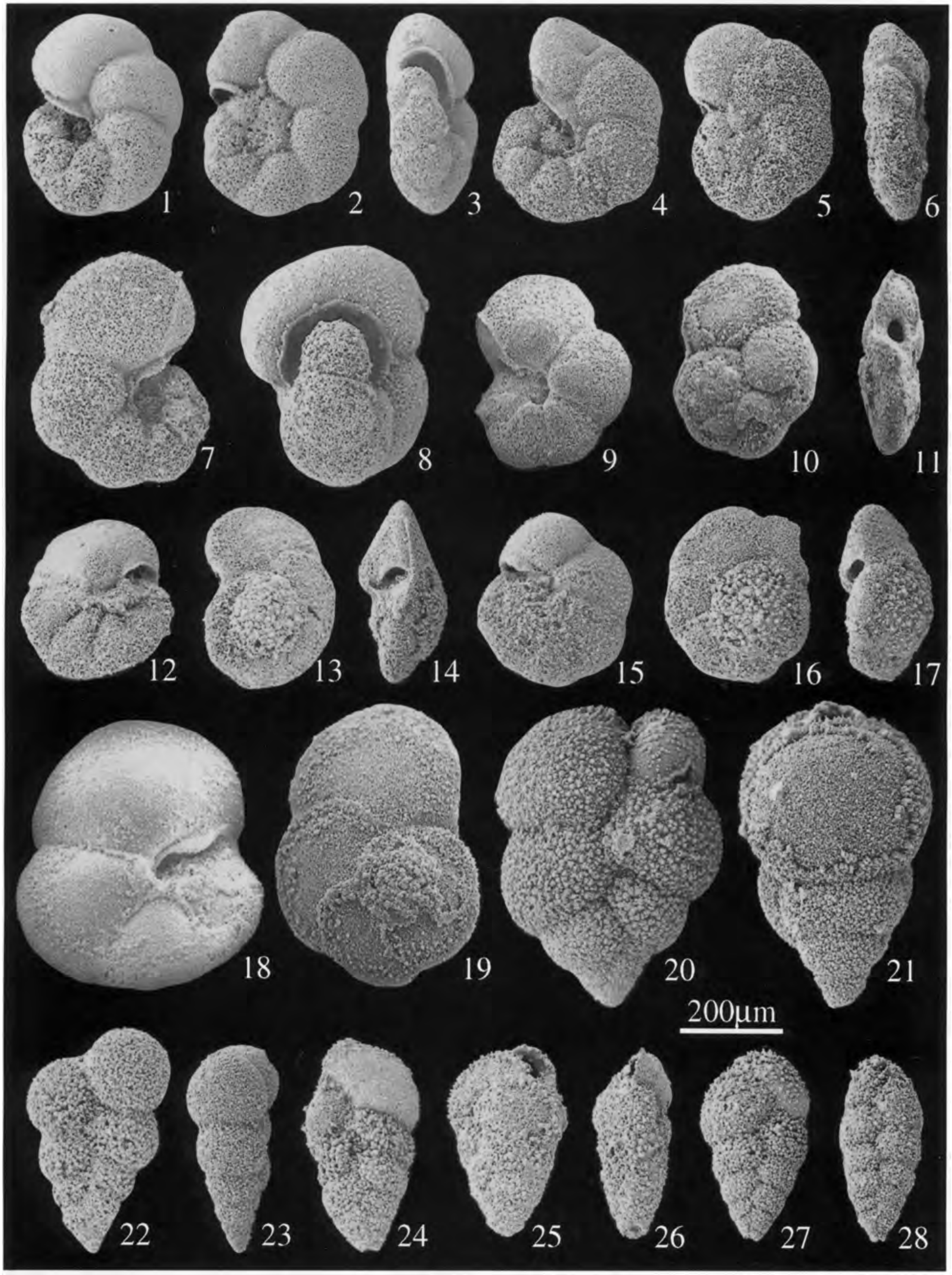
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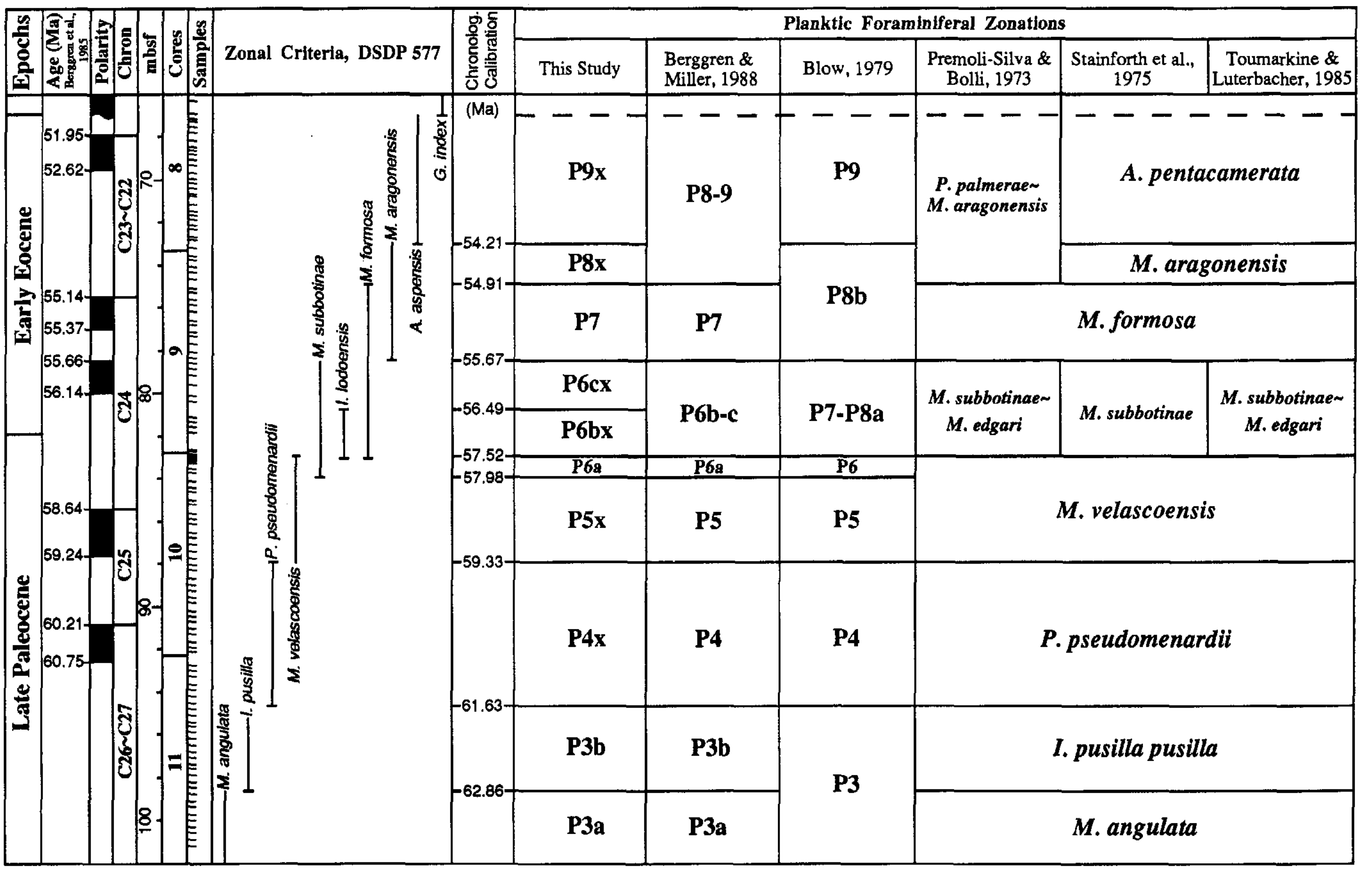

FIGURE 3. Planktic foraminiferal stratigraphy of this study and correlation with commonly used zonal schemes. The ages of zonal boundaries in this study were calibrated based on the magnetostratigraphy by Bleil (1985) and the GPTS by Berggren and others (1985).

discoidal morozovellids (*M. occlusa* and *M. velascoensis*) by hispid morozovellids (*M. aequa, M. quetra, M. subbotinae, M. marginodentata, M. gracilis* and *M. formosa*, Pl. 1, 9–15); 2) replacement of conicate acarininids (*A. subsphaerica, A. mckannai, A. strabocella and A. nitida*) by rounded acarininids (*A. pseudotopilensis, A. soldadoensis, A. triplex, A. praepentacamerata, A. esnaensis* and *A. wilcoxensis*, Pl. 2, 9–20); 3) replacement of *Igorina pusilla* by *I. lodoensis* and *I. convexa* (Pl. 4, 9–14); 4) disappearance of major "planorotalitid" taxa (*"P." hansbolli* and *"P." pseudoimitata*, Pl. 4, 20–22, 24–26); 5) disappearance of rounded and compressed subbotinids (*S.* cf. *hornibrooki, S. linaperta* and *S. velascoensis*, Pl. 5, 1–2, 6, 8–10); 6) appearance of the quadrate subbotinids (*S. patagonica*, Pl. 5, 12–14); 7) appearance of chiloguembelinids (*C. crinita, C. wilcoxensis, C. circumlabiata* and *C. subcylindrica*, Pl. 6, 20–28); and 8) appearance of "turborotaliids" (*"T."* cf. *frontosa, "T."* cf. *possagnoensis, "T."* cf. *praecentralis* and *"T." praecentralis*, Pl. 5, 22–27). This faunal turnover resulted in the replacement of 53% of the species with a cumulative relative abundance of 49%. Coinciding with this turnover in planktic foraminifera is a mass extinction in benthic foraminifera and a major excursion in shell $\delta^{13}C$ values of benthic foraminifera (Pak and Miller, 1992).

This planktic foraminiferal turnover has been observed at Caravaca and Zumaya in Spain where expanded sections of the Paleocene-Eocene transition are exposed (Canudo and others, in press). In the Spanish sections, this faunal turnover results in the last appearances of 33% of the species and first appearances of 18% of the species. Rapid changes in the relative abundances of species coincide with a $\delta^{13}C$ excursion and a 50% reduction in the species richness of benthic foraminifera in these sections (Canudo and others, in press).

In the Antarctic Indian Ocean Site 738, a major faunal turnover in planktic foraminifera has been documented near the AP4/AP5 zonal boundary, which correlates with the P6a/P6bx turnover at low latitudes based on biostratigraphy, magnetostratigraphy and $\delta^{13}C$ stratigraphy (Spieß, 1990; Stott and Kennett, 1990; Huber, 1991; Lu and Keller, 1993). This event resulted in the replacement of 45% of the species having a collective relative abundance of 45% at Site 738. During the turnover, hispid morozovellid taxa, such as *M. aequa, M. subbotinae* and *M. gracilis*, which are considered as typical low latitude species, proliferated poleward. Similar to Site 577, the relative abundance of *Chiloguembelina* increased rapidly at Site 738 during this turnover. Associated with the turnover in planktic foraminifera are the mass extinction in benthic foraminifera and the $\delta^{13}C$ excursion (Thomas, 1990; Barrera and Keller, 1991; Lu and Keller, 1993).

This faunal event coincides with a rapid warming in the deep ocean and in high latitude surface oceans as observed by the negative shift in shell $\delta^{18}O$ values in benthic and

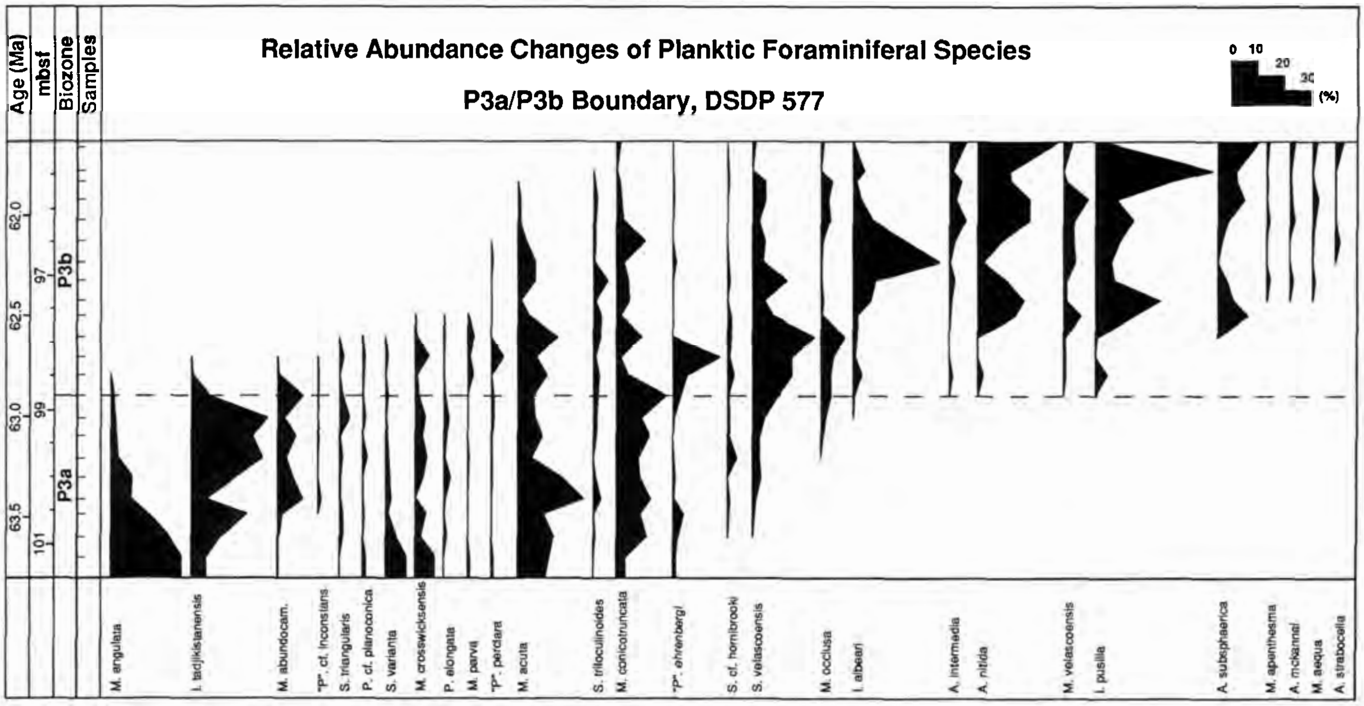

FIGURE 4. Faunal turnover near the P3a/P3b subzonal boundary. This turnover resulted in replacement of 56% of the species with a combined relative abundance of 65%. The patterns of first and last appearances appear to be sequential and associated relative abundance changes appear to be gradual, suggesting complete core recovery.

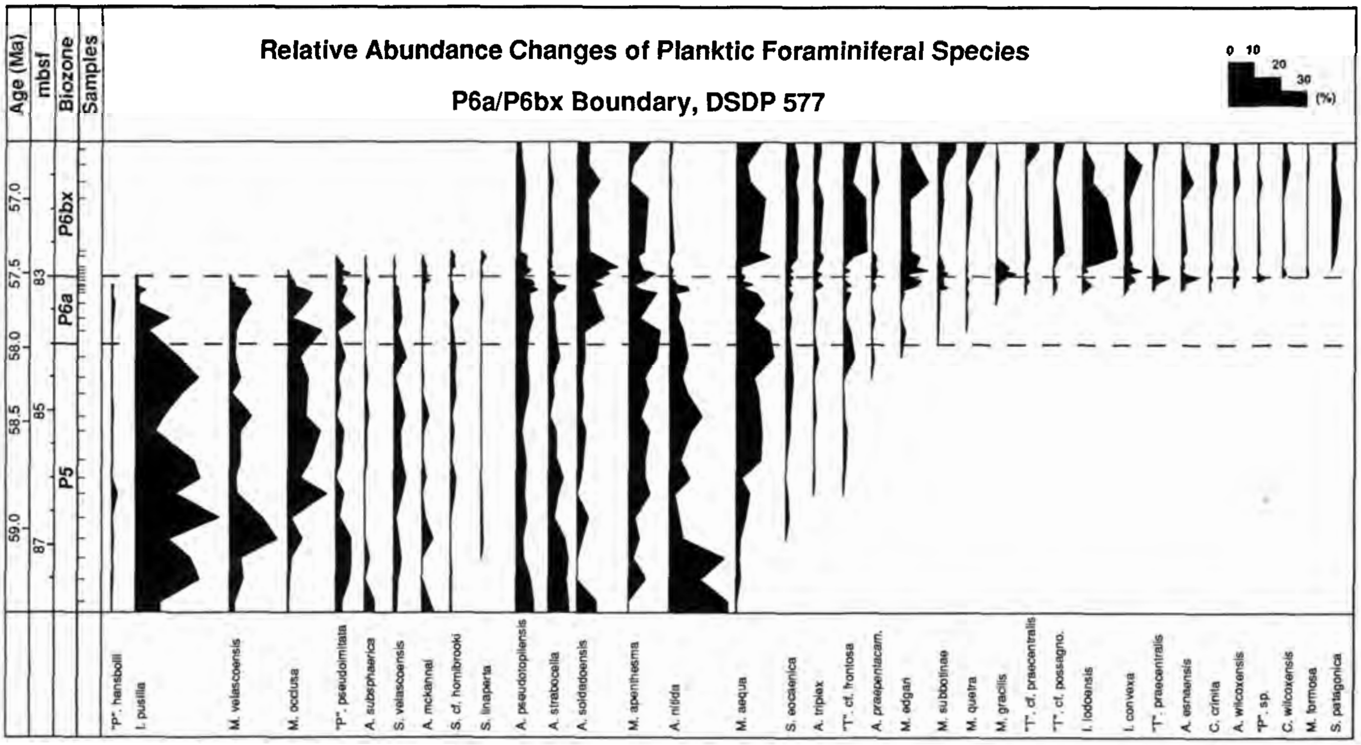

FIGURE 5. Faunal turnover near the P6a/P6bx subzonal boundary. This turnover resulted in replacement of 53% of the species with a combined relative abundance of 45%. The pattern of first appearances appears to be sequential and the associated relative abundance changes appear to be gradual. The patterns of last appearances and associated relative abundance changes appear to be abrupt, suggesting incomplete core recovery in the upper part of the turnover.

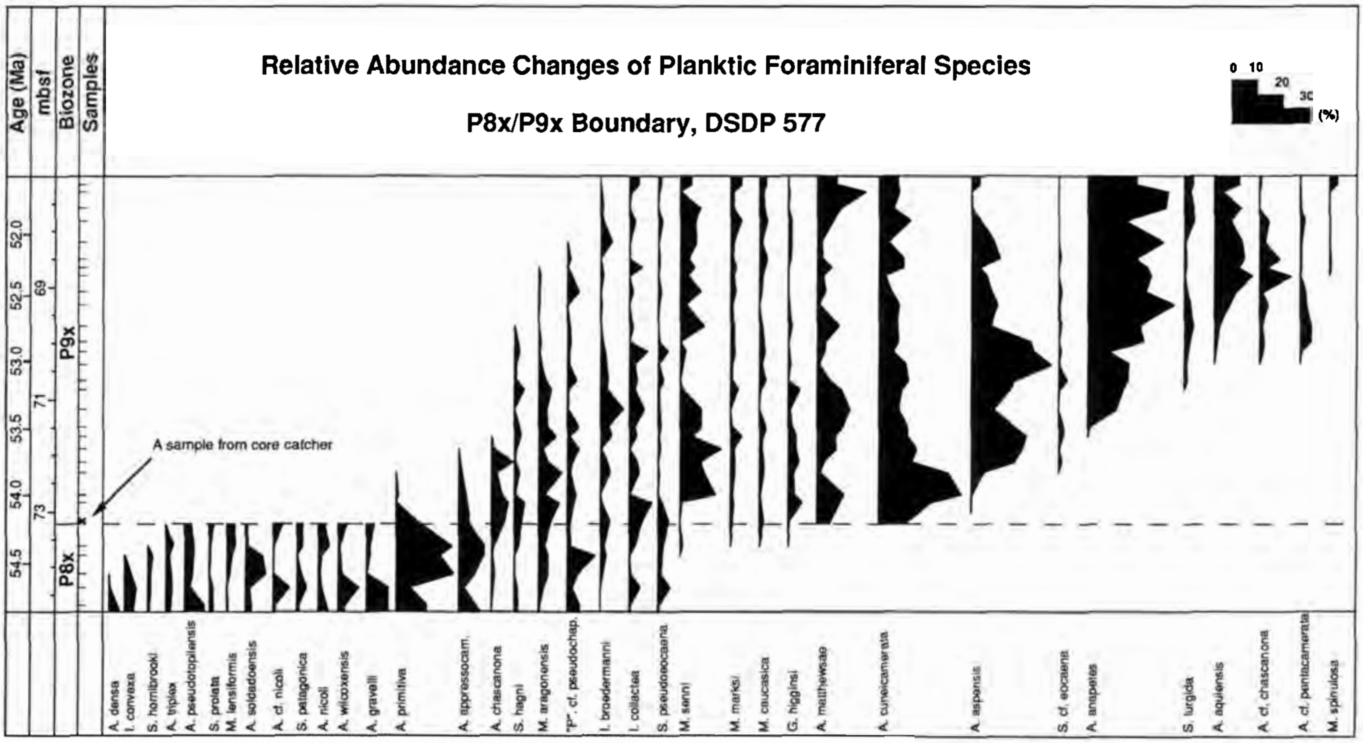

FIGURE 6. Faunal turnover near the P8x/P9x subzonal boundary at Hole 577. This turnover resulted in replacement of 49% of the species with a combined relative abundance of 80%. The patterns of first and last appearances and the associated relative abundance changes during the turnover appear to be abrupt, suggesting incomplete recovery between cores.

planktic foraminifera (Kennett and Stott, 1991; Thomas, 1991; Kennett, 1991; Barrera and Keller, 1991). Thermohaline circulation may have changed dramatically as indicated by shell $\delta^{13}C$ values of benthic foraminifera (Kennett and Stott, 1991; Pak and Miller, 1992). These changes in climate and oceanography are currently considered a likely cause for the mass extinction in benthic foraminifera (Kennett and Stott, 1991; Thomas, 1991; Pak and Miller, 1992) and the faunal turnover in planktic foraminifera (Lu and Keller, 1993).

### P8x/P9x TURNOVER

Figure 6 illustrates the faunal turnover across the P8x/P9x boundary. At Hole 577, sixteen species have their first and last appearances within one sample which is from the core catcher of Core 8. Moreover, two dominant species (e.g., *A. matthewsae* and *A. cuneicamerata*) first appear abundantly in this sample. Whether this abrupt faunal turnover is real or an artifact of incomplete core recovery can be checked in the parallel Hole 577A. We have analyzed Hole 577A across this interval (from 70.5 to 73.0 mbsf) based on samples spaced at 20 cm intervals. The results reveal a faunal change that involves the same taxa as at Hole 577, but which seems more gradual in its turnover pattern (Fig. 7). In contrast to Hole 577, the first and last appearances of species appear to be sequential with the first appearances of *A. matthewsae* and *A. cuneicamerata* occur-

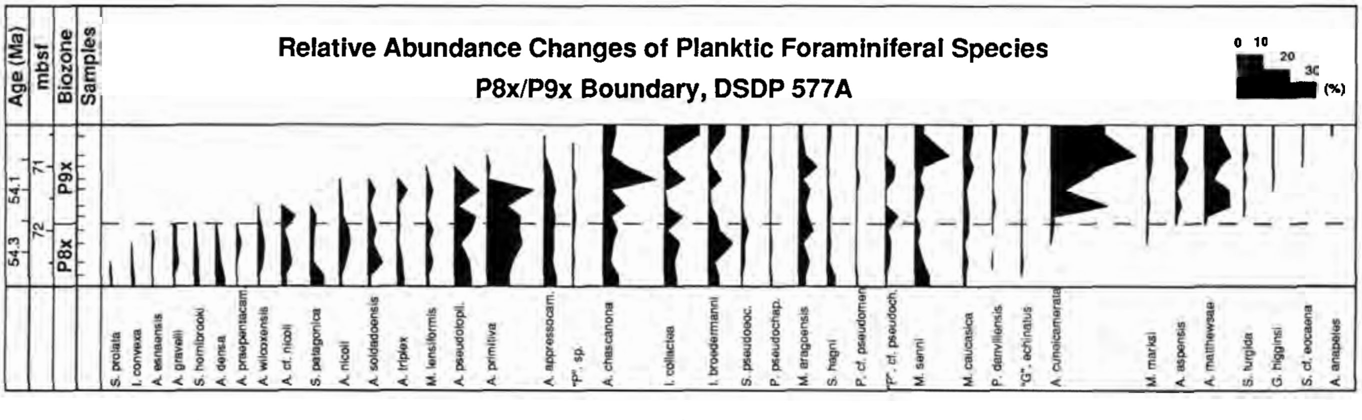

FIGURE 7. Faunal turnover near the P8x/P9x subzonal boundary at Hole 577A. The patterns of first and last appearances appear to be sequential and associated relative abundance changes appear to be gradual, suggesting complete core recovery.

ring below the rapid increase in their relative abundance. Based on our analysis of the two sections, it appears that the more rapid turnover at Hole 577 is due to incomplete core recovery. Without further evidence from other sections across this interval, we interpret the P8x/P9x faunal turnover at Hole 577A to be a continuous record.

The P8x/P9x turnover affected mainly *Acarinina.* Characteristic features of this turnover are: 1) replacement of rounded, angulate and early forms of muricate acarininids (e.g., *A. pseudotopilensis, A. soldadoensis, A. triplex, A. praepentacamerata, A. esnaensis, A. gravelli, A. wilcoxensis, A. nicoli, A.* cf. *nicoli, A. densa, A. primitiva* and *A. appressocamerata,* Pl. 2, 9–20, Pl. 3, 1–10) by new forms of muricate acarininids (e.g., *A. matthewsae, A. cuneicamerata, A. aspensis* and *A. anapetes,* Pl. 3, 11–19); and 2) first appearance of muricoglobigerinids (e.g., *M. senni* and *M. lozanoi,* Pl. 3, 21–23). This turnover resulted in the replacement of 49% of the species with a cumulative relative abundance of 80%. After the turnover, planktic foraminiferal assemblages are dominated by thick-walled taxa with muricate surfaces (e.g., muricate acarininids, muricate morozovellids and muricoglobigerinids).

At the high latitude Site 738, a major faunal turnover observed near the AP6/AP7 zonal boundary (Lu and Keller, 1993) is characterized by replacement of all existing species of *Acarinina,* similar to the P8x/P9x turnover at Site 577. Associated with this high-latitude faunal event is a polar cooling episode that is initiated in the Antarctic surface oceans and propagated gradually downward into the deep ocean (Stott and others, 1990; Barrera and Huber, 1991; Lu and Keller, 1993). A similar gradual cooling episode at low latitudes coincides with the P8x/P9x faunal turnover at Site 577 (see also Corfield and Shackleton, 1988; Corfield and Cartlidge, 1992; Pak and Miller, 1992). These similarities in the features of faunal turnovers and environmental changes suggest a possible correlation between the AP6/AP7 turnover at Site 738 and the P8x/P9x turnover at Site 577.

## CHRONOBIOSTRATIGRAPHY

Planktic foraminiferal datum levels and faunal events across the Paleocene-Eocene transition have been used in correlating sedimentary sequences, locating geomagnetic events and building age models (Miller and others, 1987; Corfield, 1987; Stott and Kennett, 1990; Huber, 1991; Stott, 1992; Pak and Miller, 1992; Lu and Keller, 1993; Canudo and others, in press). In recent years, the Paleocene-Eocene transition has been studied at increasingly high resolution reaching a time scale of less than 100 k.y. (Kennett and Stott, 1991; Thomas, 1991; Stott, 1992; Pak and Miller, 1992; Lu and Keller, 1993; Canudo and others, in press). The high resolution data set from Site 577, in conjunction with magnetostratigraphy, provides an opportunity to evaluate the present foraminiferal chronostratigraphy. Figure 8 illustrates the chronological sequence of planktic foraminiferal datum levels and faunal events at Site 577 based on sample resolution of 81 k.y. and closer sampling of 20 k.y. (this study) across the Paleocene/Eocene boundary. This chronological sequence has to be tested at other sites by high resolution studies before it can be considered as representative of low latitudes in general.

The datum levels for this chronological sequence are primarily the zonal boundary markers used in this study. Additional datum levels are selected from two intervals in Zones P4x and P9x, which are the two longest foraminiferal zones during the late Paleocene to early Eocene. At Site 577, Zone P4x spans 7 m of sediments and 2.3 m.y. Two datum levels, the last appearance of *I. albeari* (Pl. 4, 1–3) and the first appearance of *A. soldadoensis* (Pl. 2, 18–20), provide potential control points within this interval. The first appearance of *A. soldadoensis* was chosen by Blow (1979) to define the top of his Zone P4. The last appearance of *I. albeari* is utilized here because of its distinct morphology and large relative abundance. Zone P9x spans 6 m of sediments and 2.6 m.y. at Site 577. A potential control point within this interval is the first appearance of *A. aquiensis* (Pl. 2, 24–26). This datum level is chosen because it coincides with a minor faunal change at Site 577 that also involves the first appearance of *A.* cf. *chascanona* and *A.* cf. *pentacamerata.* This faunal change is easily recognized and affected 20% of the planktic foraminiferal relative abundances.

Major foraminiferal faunal events enhance the confidence in this chronological sequence. The mass extinction in benthic foraminifera near the Paleocene/Eocene boundary observed in global oceans (Tjalsma and Lohmann, 1983; Miller and others, 1987; Thomas, 1989, 1990; Katz and Miller, 1991; Nomura, 1992; Pak and Miller, 1992; Keller and others, in prep.) occurred just below the last appearance of *M. velascoensis* (Pak and Miller, 1992; Thomas, 1992; Keller and others, in prep.). The P6a/P6bx turnover in planktic foraminifera, observed at ODP Site 738 in the Antarctic Indian Ocean, Zumaya and Caravaca in Spain and DSDP Site 577 in the northwestern Pacific Ocean (Lu and Keller, 1993; Canudo and others, in press; this study) occurred prior to the last appearance of *M. velascoensis.* A faunal event similar to the P8x/P9x turnover has been observed at Site 738 (Lu and Keller, 1993), whereas the P3a/P3b turnover has not yet been observed at other sites.

### Chronological Calibration

The geomagnetic polarity time scale (GPTS) of the late Paleocene to early Eocene has been revised frequently based on new radiometric dates, marine magnetic profiles and stratigraphic correlations (Berggren and others, 1985; Aubry and others, 1988; Cande and Kent, 1992). The most recent attempt by Cande and Kent (1992) changed most of the polarity boundaries of Berggren and others (1985) by as much as 3 m.y. for this interval. Chronological calibration of the datum levels and faunal events in this study are based on the magnetostratigraphy by Bleil (1985). Ages are assigned based on both the GPTS by Berggren and others (1985) and the new GPTS by Cande and Kent (1992) as illustrated in Figure 8. The following discussion, however, is based on the GPTS of Berggren and others (1985) to facilitate correlation with published stratigraphic data.

Errors in age calibration of datum levels are primarily due to sample resolution and heterogeneous sedimentation. Sample resolutions at 50 cm intervals of a magnetostratig-

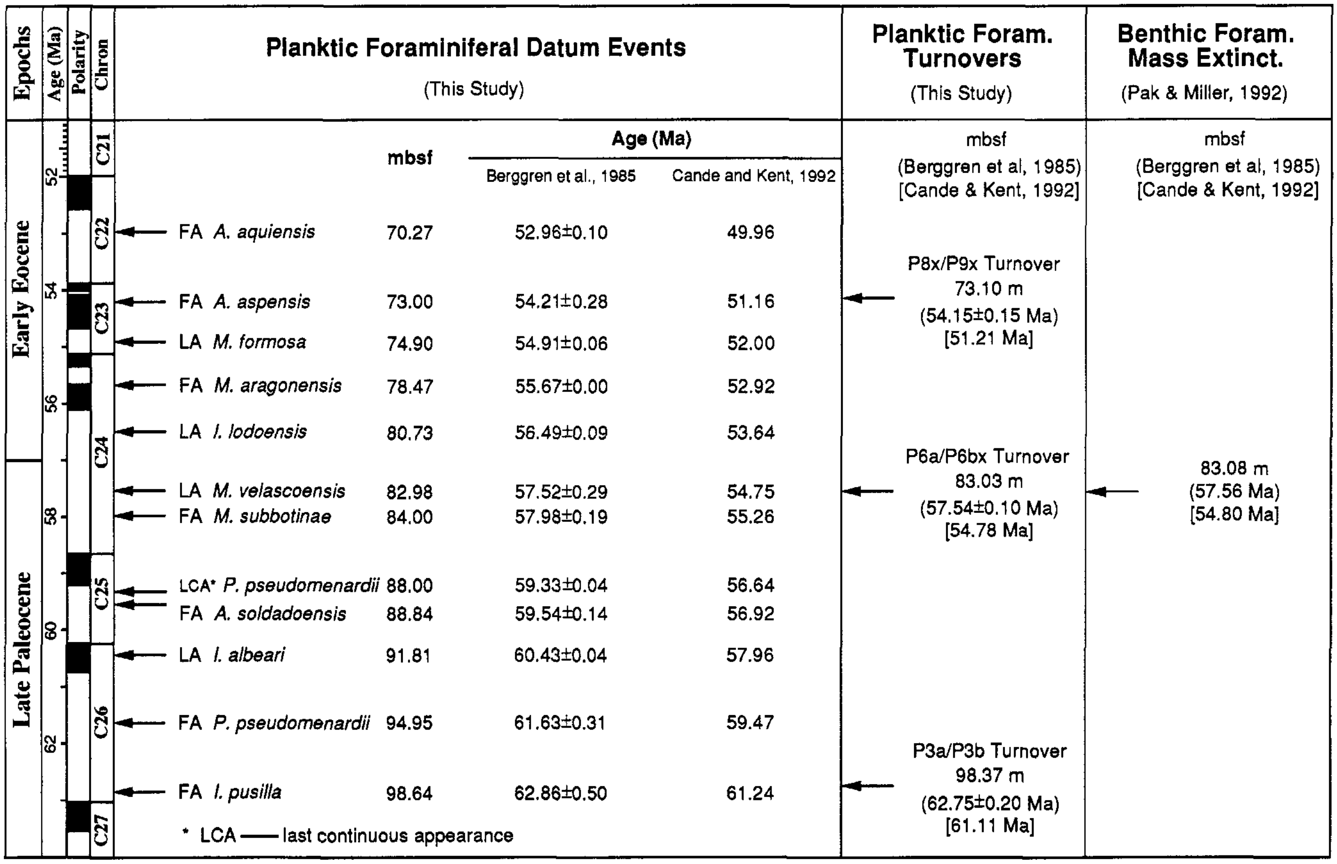

FIGURE 8. Chronologic sequence based on foraminiferal datum levels and faunal events at Site 577 during the late Paleocene and early Eocene. Age calibration is based on the magnetostratigraphy by Bleil (1985) and the GPTS's by Berggren and others (1985) and Cande and Kent (1992). Errors on ages of datum levels are estimated for heterogeneous sedimentary accumulation. Errors on ages of planktic foraminiferal turnovers give the duration of the events. This sequence provides an overall sample resolution of 100 k.y. and a higher resolution of 20 k.y. near the Paleocene/Eocene boundary.

raphy and 25 cm intervals for planktic foraminiferal stratigraphy can result in a maximum difference of 242 k.y. in age calibration of the datum levels. The mean sedimentary accumulation rate is 0.31 ± 0.10 cm/k.y. at Site 577 during the late Paleocene to early Eocene based on magnetostratigraphy. This 0.10 cm/k.y. standard error in accumulation rate can result in errors ranging from 0 to ±500 k.y. in age calibration of the datum levels, depending on the distance from the nearest polarity boundary (Fig. 8). The timing of planktic foraminiferal turnovers is given by a center age and a range of duration (Fig. 8). This range of duration is based on the first and last appearances of species as well as relative abundance changes. The age of the mass extinction in benthic foraminifera is given by a single number because this event was observed within a 14 cm interval between two samples (Pak and Miller, 1992). Its duration can therefore not be estimated precisely but is considered to be very short. Global studies have shown that the upper limit of this event varies from 14 k.y. to 50 k.y. (Thomas, 1990, 1991; Pak and Miller, 1992).

TABLE 1. Chronologic correlation of planktic foraminiferal datum levels.

| Datum levels | This study (Ma) | Berggren et al., 1985 (Ma) |
|---|---|---|
| FA *M. aragonensis* | 55.67 | 55.2 |
| LA *M. velascoensis* | 57.52 | 57.8 |
| LA *P. pseudomenardii* | 59.33 | 58.8 |
| FA *P. pseudomenardii* | 61.63 | 61.0 |
| FA *I. pusilla* | 62.86 | 62.0 |

## CHRONOLOGICAL CORRELATION

The chronology of datum levels at Site 577 can be tested via correlation with the composite foraminiferal chronologic scheme by Berggren and others (1985). Of the twelve datum levels listed in Figure 8, five have been assigned ages by Berggren and others (1985). Comparison of these ages assigned by Berggren and others (1985) with those at Site 577 (this study) indicates an average age difference of 554 k.y. (Table 1). A maximum of 242 k.y. of this age difference can be attributed to discrepant sample resolution between magnetostratigraphy and foraminiferal stratigraphy at Site 577. More than half of the age difference (312 k.y.) may be due to sample spacing in Berggren and other's (1985) study, heterogeneous sedimentation or the diachronous nature of these five datum levels.

The chronology of faunal events can be tested by correlation between low-latitude Sites 577, Zumaya and Caravaca

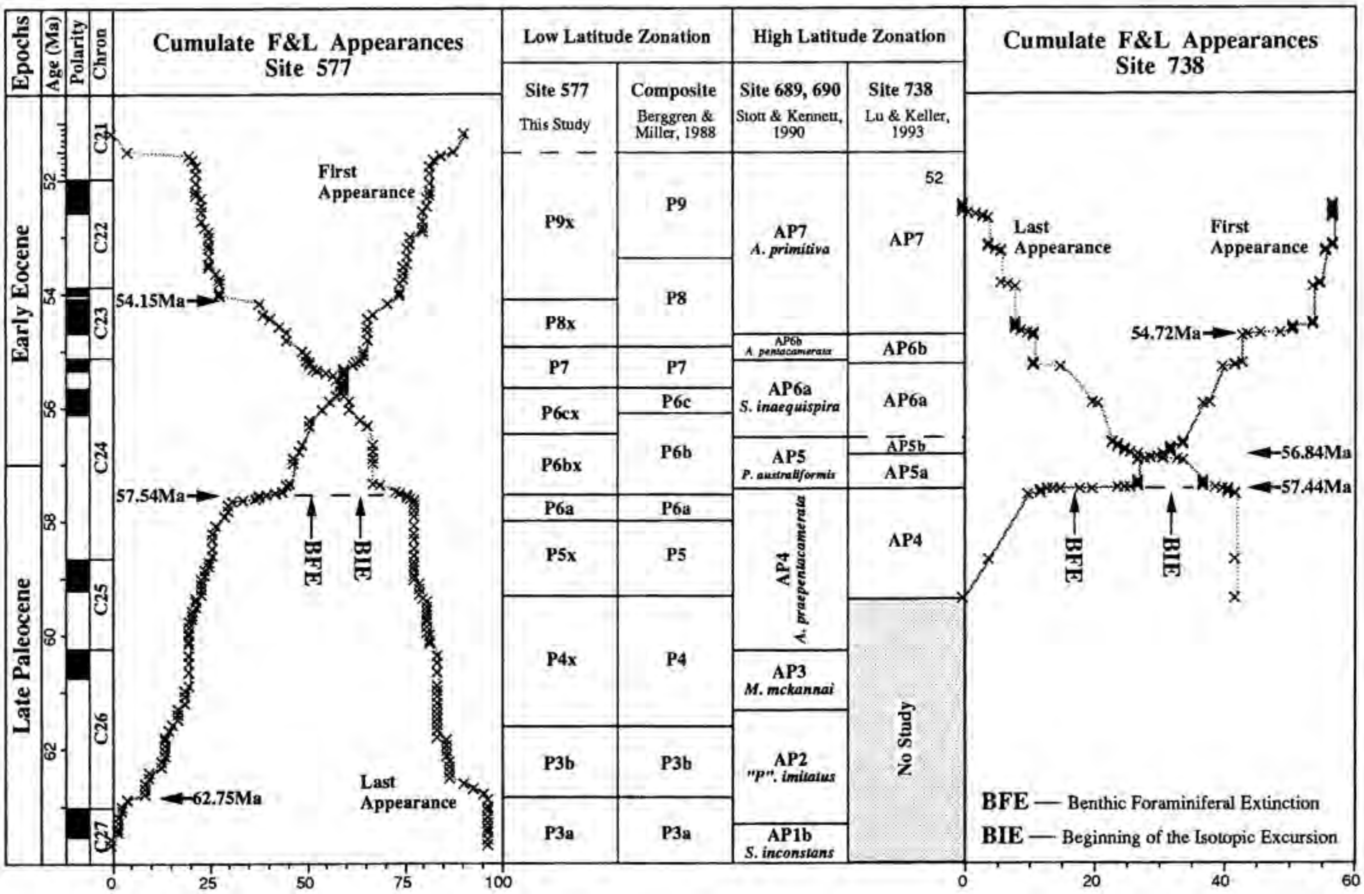

FIGURE 9. Correlation of the planktic foraminiferal zonations and major faunal changes between low latitude Site 577 and high latitude Sites 689, 690 and 738. Chronologic calibrations are based on magnetostratigraphy. Note that the event near the Paleocene/Eocene boundary is characterized by a major turnover in planktic foraminifera, a mass extinction in benthic foraminifera and an abrupt excursion in $\delta^{13}C$ values. The age difference of this event between high and low latitudes is 100 k.y., which is within the error range of chronologic calibration.

and high-latitude Sites 689, 690 and 738. The age model of the Zumaya and Caravaca sections is based on the planktic foraminiferal stratigraphic correlation with Site 577 (Canudo and others, in press). The age model of Site 738 is based on the planktic foraminiferal stratigraphic correlation with Sites 689 and 690 (Lu and Keller, 1993). The chronological correlation between high and low latitudes is based on magnetostratigraphies at Sites 577, 689 and 690 (Bleil, 1985; Spieß, 1990). The results are shown in Figure 9.

Near the Paleocene/Eocene boundary, a mass extinction in benthic foraminifera and a major turnover in planktic foraminifera have been observed in both high and low latitudes (Miller and others, 1987; Thomas, 1990; Pak and Miller, 1992; Lu and Keller, 1993; Canudo and others, in press; Keller and others, in prep.). Associated with these faunal events is a positive excursion of 1–5‰ in $\delta^{13}C$ values (Kennett and Stott, 1990, 1991; Stott and others, 1990; Kennett, 1991; Thomas, 1991; Barrera and Keller, 1991; Stott, 1992; Pak and Miller, 1992; Lu and Keller, 1993; Canudo and others, in press), which, by its nature, has a global correlation error similar to the turnover time of the ocean (about 1 k.y. for today's ocean, Broecker and Peng, 1982). In low latitudes, the faunal and isotopic events are dated between 57.54 and 57.56 Ma (54.78–54.80 Ma, Cande and Kent, 1992) based on the magnetostratigraphy by Bleil (1985). In high latitudes, this event is dated at 57.44 Ma (54.68 Ma. Cande and Kent, 1992) based on the magnetostratigraphy by Spieß (1990). Thus, the age difference between high and low latitudes is 100 k.y. (Fig. 9), which is within the error range of sample spacing and chronological calibration. These events are therefore considered synchronous across latitudes.

Chronological correlation for the faunal events above and below the Paleocene/Eocene boundary is limited by the lack of high resolution data. Correlation between the P8x/P9x turnover at Site 577 and the equivalent high-latitude AP6/AP7 turnover at Site 738 shows that the low latitude event lags by 570 k.y. This may be attributed to 1) inaccuracy of biostratigraphic correlation between Sites 738 and 689, 690; 2) inaccuracy of magnetostratigraphic correlation between high and low latitudes; or 3) diachroneity of this event across latitudes. The P3a/P3b turnover has not yet been observed at other sites.

## CONCLUSIONS

Planktic foraminiferal analysis of closely spaced (25-cm interval or 81 k.y.) samples from Site 577 provides a high resolution data base detailing biostratigraphy and faunal turnovers during the late Paleocene to early Eocene. Three major faunal turnovers in planktic foraminifera across the zonal boundaries of P3a/P3b, P6a/P6bx and P8x/P9x are characterized by rapid changes in species richness, large numbers of first and last appearances and significant changes in relative abundances of taxa. The P6a/P6bx turnover, which coincides with a mass extinction in benthic foraminifera and a major excursion in $\delta^{13}C$ values (Pak and Miller, 1992), has been observed at the Antarctic Indian Ocean Site 738 (Lu and Keller, 1993) and at near-shore sections in Zumaya and Caravaca, Spain (Canudo and others, in press). This turnover is associated with the onset of a global warming and possible changes in the thermohaline circulation. The P8/P9 turnover has also been observed at Site 738 where it occurred 570 k.y. earlier, possibly because of inaccurate correlations between high and low latitudes and/or diachronous cooling across latitudes. The P3a/P3b turnover has not yet been reported at other sites.

A chronological sequence based on datum levels and faunal events of foraminifera provides marker horizons at intervals averaging 1 m.y. during the late Paleocene to early Eocene. The datum levels were correlated with the chronological scheme by Berggren and others (1985) and the faunal events were correlated with the Antarctic Sites 689, 690 and 738. There is an average 554 k.y. age difference in datum levels between Berggren and others (1985) and this study, which may be attributed to sample spacing, diachroneity of the datum levels, and heterogeneous sedimentary accumulations. In contrast, the faunal events near the Paleocene/Eocene boundary provide the most accurate chronological markers of this interval with an age difference of only 100 k.y. between high and low latitudes.

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