

## 35. LATE CRETACEOUS THROUGH NEOGENE DEEP-SEA BENTHIC FORAMINIFERS (MAUD RISE, WEDDELL SEA, ANTARCTICA)<sup>1</sup>

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### ABSTRACT

Upper abyssal to lower bathyal benthic foraminifers from ODP Sites 689 (present water depth 2080 m) and 690 (present water depth 2941 m) on Maud Rise (eastern Weddell Sea, Antarctica) are reliable indicators of Maestrichtian through Neogene changes in the deep-water characteristics at high southern latitudes. Benthic foraminiferal faunas were divided into eight assemblages, with periods of faunal change at the early/late Maestrichtian boundary (69 Ma), at the early/late Paleocene boundary (62 Ma), in the latest Paleocene (57.5 Ma), in the middle early Eocene to late early Eocene (55–52 Ma), in the middle middle Eocene (46 Ma), in the late Eocene (38.5 Ma), and in the middle-late Miocene (14.9–11.5 Ma). These periods of faunal change may have occurred worldwide at the same time, although specific first and last appearances of deep-sea benthic foraminifers are commonly diachronous. There were minor faunal changes at the Cretaceous/Tertiary boundary (less than 14% of the species had last appearances at Site 689, less than 9% at Site 690). The most abrupt benthic foraminiferal faunal event occurred in the latest Paleocene, when the diversity dropped by 50% (more than 35% of species had last appearances) over a period of less than 25,000 years; after the extinction the diversity remained low for about 350,000 years.

The highest diversities of the post-Paleocene occurred during the middle Eocene; from that time on the diversity decreased steadily at both sites. Data on faunal composition (percentage of infaunal versus epifaunal species) suggest that the waters bathing Maud Rise were well ventilated during the Maestrichtian through early Paleocene as well as during the latest Eocene through Recent. The waters appeared to be less well ventilated during the late Paleocene as well as the late middle through early late Eocene, with the least degree of ventilation during the latest Paleocene through early Eocene. The globally recognized extinction of deep-sea benthic foraminifers in the latest Paleocene may have been caused by a change in formational processes of the deep to intermediate waters of the oceans: from formation of deep waters by sinking at high latitudes to formation of deep to intermediate water of the oceans by evaporation at low latitudes. Benthic foraminiferal data (supported by carbon and oxygen isotopic data) suggest that there was a short period of intense formation of warm, salty deep water at the end of the Paleocene (with a duration of about 0.35 m.y.), and that less intense, even shorter episodes might have occurred during the late Paleocene and early Eocene.

The faunal record from the Maud Rise sites agrees with published faunal and isotopic records, suggesting cooling of deep to intermediate waters in the middle through late Eocene.

### INTRODUCTION

The climate of the Earth and the temperature structure of the oceans have changed considerably over Earth history. The best-documented changes occurred during the Cenozoic: during this period the global environment changed from warm with equable temperatures and oceans without a well-developed thermocline to the present situation with extensive polar ice caps and strong latitudinal and vertical temperature gradients in the oceans (e.g., Douglas and Savin, 1975; Savin, 1977; Berggren and Schnitker, 1983; Barron, 1985, 1987). The world may not have been completely free of ice during the Cretaceous (Frakes and Francis, 1988; Gregory et al., 1989), but continental ice sheets were either absent or much smaller than they presently are (e.g., Frakes, 1979; Schnitker, 1980; Berger et al., 1981). The climatic changes were the most extreme at high latitudes: during the Eocene forests could grow on the Antarctic Peninsula (e.g., Askin, 1989; Birkenmayer and Zastawniak, 1989; Challoner and Creber, 1989; Mohr, this volume, chapter 36), where vegetation is much more limited today. The decrease in temperatures at high latitudes probably did not occur gradually but proceeded stepwise (e.g., Kennett, 1977; Berger et al., 1981; Miller et al., 1987a).

Strong cooling in the polar areas can be expected to cause major changes in the processes of formation of the deep and intermediate water masses in the oceans. Presently the deepest water masses in the oceans are formed at high latitudes, as has been realized by researchers since the end of the 18th century (Rumford, 1797, *vide* Warren, 1981). Important areas of deep-water formation are the Norwegian-Greenland Sea in the North Atlantic and the Weddell Sea in the Southern Ocean Atlantic Sector (e.g., Tolmazin, 1985; Whitehead, 1989). In these areas the surface waters are very cold; the salinity in the Norwegian-Greenland Sea increases by advection of lower latitude surface waters (Worthington, 1972), so that saline, cold, and thus dense waters sink and flow over the Farøe Bank Channel and through the Denmark Straits (Warren, 1981; Whitehead, 1989). In the Weddell Sea the salinity (and thus density) of surface waters increases because of extensive winter freezing of surface waters (Gill, 1973). The saline Weddell Sea Bottom Water (with a potential temperature of less than  $-0.7^{\circ}\text{C}$ ) sinks and leaves the Weddell Sea at the northern tip of the Antarctic Peninsula (Foster and Carmack, 1976; Warren, 1981). The Weddell Sea Bottom Water is probably mixed fairly rapidly into the overlying water and forms the Antarctic Bottom Water. The overlying water in the Weddell Sea is also "Antarctic Bottom Water," but "older," with properties modified by mixing. This water flows westward into the Weddell Sea (in the Weddell Gyre) close to the continent, and constitutes the Warm Deep Water (Deacon, 1976; see also Pudsey et al., 1988).

In the absence of very cold polar regions covered with extensive ice sheets, deep and intermediate waters might still have

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formed by cooling at high latitudes (e.g., Schnitker, 1980; Wilde and Berry, 1982; Manabe and Bryan, 1985; Barrera et al., 1987). Many authors, however, from Chamberlin (1906) through Hay (1988) have postulated that deep waters might have formed at subtropical latitudes where evaporation strongly exceeds precipitation. As a result of excess evaporation, dense, warm, salty deep waters could have formed, similar to the waters presently leaving the Mediterranean and Persian Gulf at mid-water depths (Brass et al., 1982; Prentice and Matthews, 1988; Woodruff and Savin, 1989). These warm, salty deep waters would have been depleted in dissolved oxygen at their formation because of the lower solubility of that gas at higher temperatures, and they could have been close to saturation with  $\text{CaCO}_3$  because this salt is less soluble at higher temperatures. Thus they would have been different from the present deep waters, which are cold, rich in dissolved oxygen, and strongly undersaturated in  $\text{CaCO}_3$  at their formation.

There has been no agreement on the timing of the period in which these hypothetical warm deep waters existed: Mount et al. (1986) agreed with Barron et al. (1981) that the formation of warm, salty, deep waters might have ended during the late Maestrichtian. Data on Cerium anomalies of sediments from the Rio Grande Rise (Hu et al., 1988) suggest that better oxygenation of deep waters in the South Atlantic started in the early Eocene; Hay (1988) suggested that circulation was halothermal (warm, salty deep waters) through the Eocene, whereas Prentice and Matthews (1988) concluded that low-latitude production of deep water was important through most of the Tertiary. On the other hand, Barrera et al. (1987) presented isotopic evidence that polar regions were sites of deep-water formation during the Late Cretaceous and Paleocene, and Miller et al. (1987b) suggested that deep waters were formed in the Antarctic region during the Paleocene, but that production may have stopped in the early Eocene. More recent data from the Atlantic sector of the Southern Oceans suggest that there was a short period of no production of deep waters at southern high latitudes at the Paleocene/Eocene boundary (Katz and Miller, in press). Thus, it is unclear whether formation of warm salty deep water did occur during the late Maestrichtian through Paleogene, and there is no agreement on when it occurred if it did occur.

It seems probable, however, that sources of deep waters changed considerably during the Cenozoic, resulting in changes in the physical and chemical properties of the deep waters, because these are dependent upon the properties of surface waters in the source area (e.g., Manabe and Bryan, 1985). Deep-sea benthic foraminiferal faunas reflect the characteristics of the deep waters (e.g., Douglas and Woodruff, 1981; Culver, 1987), and therefore it should be possible to trace changes in deep-water formational processes by studying changes in faunal composition of these organisms. The study of deep-sea benthic foraminifera from high-latitude sites is of particular interest for reconstructing the deep-water formational processes of the past, because the Cenozoic environmental changes can be expected to have had a large amplitude at these latitudes.

Until recently the southernmost sections of Paleogene deep-sea calcareous oozes containing a record of calcareous deep-sea benthic foraminifera were recovered from the Falkland Plateau (Dailey, 1983; Tjalsma, 1983). More southerly sites in the Pacific sector of the Southern Oceans and in the Ross Sea (Antarctica) do not contain deep-water calcareous sediment older than Oligocene (e.g., Leckie and Webb, 1985; Webb et al., 1986). Sediments from the James Ross Island area (Antarctic Peninsula) contain calcareous faunas but were deposited in a neritic environment (Huber, 1988). On Leg 113, Maestrichtian through Pleistocene biogenic pelagic oozes were recovered at two sites on the Maud Rise, at the eastern side of the Weddell Sea (Barker, Kennett, et al., 1988), constituting the southernmost record of

calcareous deep-sea benthic foraminifera through the Maestrichtian and Cenozoic. In this chapter quantitative data are presented on the faunal composition of these foraminifera at Sites 689 and 690, from the Maestrichtian through the Neogene; this is the longest and most complete quantitative record of deep-sea benthic foraminiferal faunas available from any location.

## MATERIAL AND METHODS

### Site Location and Stratigraphy

Sites 689 ( $64^{\circ}31.009'S$ ,  $03^{\circ}05.996'E$ , present water depth 2080 m) and 690 ( $65^{\circ}9.629'S$ ,  $1^{\circ}12.296'E$ , present water depth 2914 m) were drilled on Leg 113 (January–March 1987) on Maud Rise, an aseismic ridge at the eastern entrance of the Weddell Sea (Barker, Kennett, et al., 1988; Fig. 1A). Site 689 is on the northeastern side near the crest of Maud Rise, Site 690 is on the southwestern flank, 116 km to the southwest (Fig. 1B). At both sites biogenic sediments were recovered, with admixture of fine-grained terrigenous material in some intervals at Site 690 (Barker, Kennett, et al., 1988, p. 190–191). The sediments range from lower Maestrichtian through Pleistocene; recovery was good and core deformation minimal in most intervals (Barker, Kennett, et al., 1988). The Upper Cretaceous through lower middle Eocene consists of chalks and calcareous oozes, the upper middle Eocene through lower Miocene of a mixture of siliceous and calcareous oozes in which the silica content increases upward, and middle Miocene through Pleistocene sediments are dominantly siliceous (with calcium-carbonate-containing intervals in the upper Miocene and Pleistocene). Calcium-carbonate faunas show signs of dissolution from the upper Eocene up.

Paleodepths for the sites could not be estimated using simple thermal subsidence models because Maud Rise is an aseismic ridge with basement consisting of alkali basalts of the Ocean Island Basalt type, not of typical Mid-Oceanic Ridge Basalts (Site 690 report, in Barker, Kennett, et al., 1988). Benthic foraminiferal faunas indicate paleodepths for Site 689 of 1000–1500 m in the Cretaceous through Paleocene, increasing to 1500–2000 m in the Eocene. For Site 690 estimates are 1500–2000 m paleodepth in the Cretaceous through Paleocene, increasing to more than 2500 m in the Eocene (Site 689 and 690 reports, Barker, Kennett, et al., 1988). These depth estimates are in agreement with preliminary data on the ostracods, which indicate depths of more than 800–900 m for the oldest part of the section at Site 689 (P. Steineck, pers. comm., 1988). The depth estimates are also in close agreement with benthic foraminiferal data on ODP Leg 114 Sites (Atlantic sector of the Southern Ocean), where faunal data could be compared with depths as derived from backtracking (Katz and Miller, in press). In this chapter the following bathymetric division was used, in agreement with that in Dailey (1983) and Berggren and Miller (1989): neritic = < 200 m; upper bathyal = 200–600 m; middle bathyal = 600–1000 m; lower bathyal = 1000–2000 m; upper abyssal = 2000–3000 m; lower abyssal = > 3000 m. Thus the faunas at the sites are classified as lower bathyal for Site 689 (Maestrichtian–Neogene), as lower bathyal to upper abyssal for Site 690.

The biostratigraphic information for the Paleogene was derived from Wei and Wise (this volume: calcareous nannofossils, Oligocene–Recent), Pospichal and Wise (this volume, chapters 30, 32, and 37), Stott and Kennett (this volume, chapter 34, Cenozoic planktonic foraminifera), and Huber (Maestrichtian planktonic foraminifera, this volume). Paleomagnetic data are after Spieß (this volume, Cenozoic magnetostratigraphy) and Hamilton (this volume, Maestrichtian magnetostratigraphy). For the Neogene a combination of data on biostratigraphy of siliceous microfossils and paleomagnetic information was used (Gersonde et al., this volume). In this chapter, benthic faunal records are compared with the oxygen and carbon isotopic records in Bar-

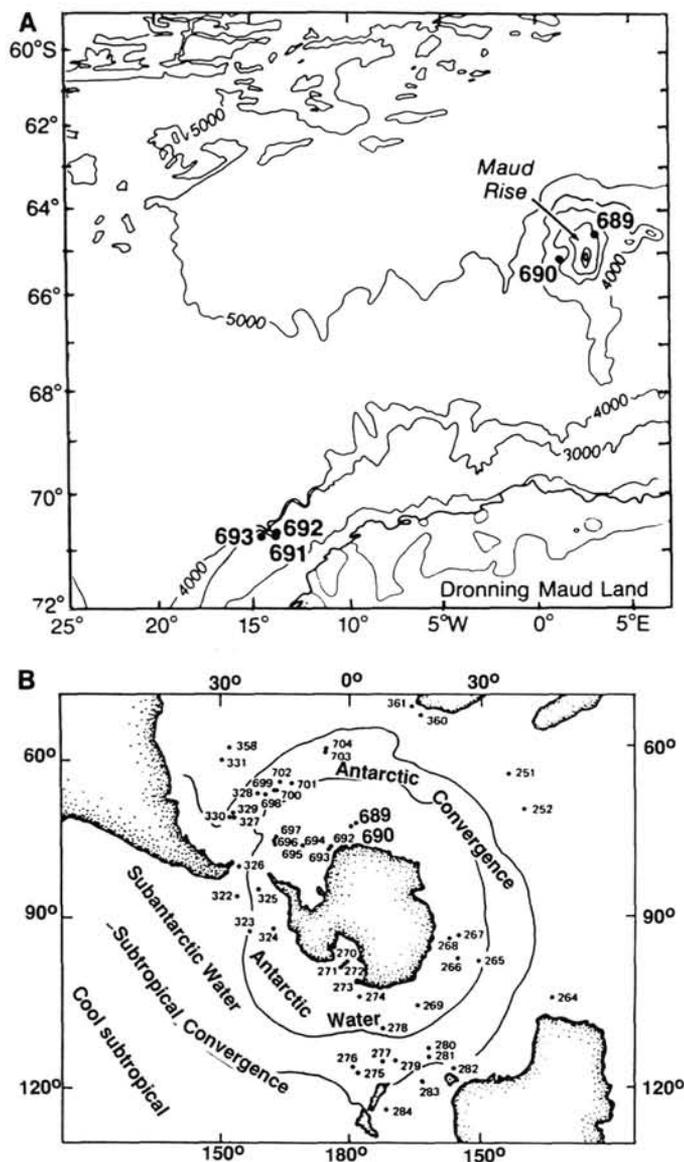


Figure 1. A. Location of Sites 689 and 690, as compared with locations of other DSDP and ODP sites at high southern latitudes. Sites 689 through 697 were drilled on Leg 113, Sites 698 through 704 on Leg 114. B. Location of Sites 689 and 690 on Maud Rise; note the difference in depth and the location at opposite sites of the Rise. Isobath interval is 1000 m.

raera and Huber (this volume, Maestrichtian planktonic and benthic taxa), Stott et al. (this volume, Cenozoic planktonic taxa) and Shackleton and Hall (this volume, bulk data for the Cenozoic), Stott and Kennett (this volume, chapter 47, planktonic and benthic taxa across the Cretaceous/Tertiary boundary) and in Kennett and Stott (this volume, Cenozoic benthic taxa). Numerical ages were derived from cross-correlation with the geomagnetic polarity time scale of Berggren et al. (1985), with modifications for the Paleogene as proposed by Aubry et al. (1988). See Thomas et al. (this volume) for an overview of biostratigraphy and correlation with magnetostratigraphy and isotope stratigraphy.

There are numerous unconformities in the Neogene parts of the section at both sites (Gersonde et al., this volume). In addition, there is a major unconformity at Site 689 in Core 113-689B-22X, corresponding to most of the lower Eocene, and an

other unconformity in the top of Core 113-689B-25X across part of the lower Paleocene. There is a short unconformity across the Cretaceous/Tertiary boundary at that site, as indicated by the absence of both nannofossil Zone CP1a and an iridium anomaly (Michel et al., this volume). At Site 690 there is a set of unconformities in Cores 113-690B-11H and 113-690B-12H, across parts of the upper and upper middle Eocene. Possibly there is an additional unconformity in Core 113-690B-15H (lower Eocene), representing part of nannofossil Zones CP10-11 (Pospichal and Wise, this volume, chapter 32) and parts of paleomagnetic Chrons C22 and C23 (Spieß, this volume). If this unconformity is indeed present at Site 690, the interval between about 53 and 55 Ma (early Eocene) is not represented in the record at Sites 690 and 689. At Site 690 there is no detectable unconformity at the Cretaceous/Tertiary boundary: there is an iridium anomaly (Michel et al., this volume), and all nannofossil and planktonic foraminiferal zones were detected. The interval just above the boundary contains the lowermost Paleocene calcareous nannofossil index form *Biscutum sparsum* (Pospichal and Wise, this volume, chapter 32), and planktonic assemblages containing *Eoglobigerina fringa*, *Eoglobigerina eobulloides*, and small heterohellicids (Stott and Kennett, this volume, chapter 34). The section across the Paleocene/Eocene boundary at Site 690 is probably the most complete section recovered at any DSDP or ODP site, as judged on the thickness of the interval corresponding to paleomagnetic Chron C24R (Spieß, this volume) and calcareous nannofossil Zone CP8 (Pospichal and Wise, this volume, chapter 37; see also Thomas, in press).

The end of the Paleocene was the time of global extinction in deep-sea benthic foraminiferal faunas (Beckmann, 1960; Braga et al., 1975; Schnitker, 1979; Tjalsma and Lohmann, 1983; Boersma, 1984; Miller et al., 1987b; Thomas in Barker et al., 1988; Thomas, 1989, in press; Katz and Miller, in press). A detailed description of benthic foraminiferal faunal events at that time, however, is difficult or impossible for many sections because of low sedimentation rates over the interval. In addition, the location of the Paleocene/Eocene boundary in the zonal schemes for different fossil groups for this interval is still under discussion (Odin and Curry, 1985; Berggren et al., 1985; Aubry et al., 1988; Obradovich, 1988). Therefore it is important to document the location of the benthic foraminiferal extinction accurately at Site 690, where sedimentation rates over the top part of the Paleocene are estimated to be about 14.4 m/m.y., if data in Spieß (this volume) are combined with the time scale by Aubry et al. (1988). The benthic foraminiferal extinction has been placed in the upper Paleocene (boundary between planktonic foraminiferal Zones P5 and P6a, Tjalsma and Lohmann, 1983), but Boersma (1984) and Miller et al. (1987b) placed the event closer to the boundary between planktonic foraminiferal Zones P6a and P6b (and thus the Paleocene/Eocene boundary as defined in Berggren et al., 1985). This zonal boundary, however, is in the upper Paleocene according to Aubry et al. (1988). Data in this chapter demonstrate that the benthic extinction occurred at about 57.5 Ma in the Aubry et al. (1988) time scale, i.e., in the latest Paleocene, almost exactly in the middle of paleomagnetic Chron C24R, and close to, but just below, the boundary between planktonic foraminiferal Zones AP4 and AP5 as proposed by Stott and Kennett (this volume, chapter 34; this boundary can be correlated to the P6a/P6b boundary at lower latitudes according to these authors). The extinction occurred about in the middle of calcareous nannofossil zone CP8, well above the first appearance of *Tribrahiatus bramlettei* (Pospichal and Wise, this volume, chapter 37).

#### Sample Preparation and Data Collection

Samples (15 cm<sup>3</sup>) were taken at 1.5 m intervals, with additional samples (0.35 m) in parts of the section where major changes occurred in the faunas. For this chapter, samples were

analyzed at 1.5 m intervals from the bottom of the hole through the lower Oligocene at Site 690, from the bottom of the hole through the middle middle Eocene at Site 689. For the higher part of the sections at Sites 689 and 690, two samples per core (9.6 m) were analyzed. All samples from the lowermost Miocene and below contained sufficient specimens for study, but samples from the middle Miocene and up were largely barren of calcareous and agglutinated forms (with the exception of an interval in the upper Miocene and close to the surface).

Samples were dried at 75°C, soaked in Calgon, and washed through a sieve with openings of 63  $\mu\text{m}$ ; residues were dried at 75°C. Specimens were studied in the larger than 63  $\mu\text{m}$  size fraction to ensure representation of smaller species (Thomas, 1985, 1986a, b; Schroeder et al., 1987). At the beginning of the study, rarefaction curves were drawn for some samples (plots of number of specimens versus number of species, obtained while counting specimens and species; Thomas, 1985). The curves became parallel to the species axis at about 270 specimens for the more diverse samples in middle Eocene and lower; at about 180 specimens for the less diverse samples from the Oligocene and up. Therefore, 300 specimens or more were counted in the lower samples; 250–300 specimens in the higher samples. A plot showing number of species versus number of specimens counted per sample for the two sites shows no correlation between these two, demonstrating that the species were well-represented within a sample size of 300 specimens (Fig. 2).

Part of each sample was spread in a tray to make an estimate of how much material would be needed to recover about 300 specimens of benthic foraminifers; then this material was added again to the rest of the sample, and a split was made of the estimated size. Additional splits were made when needed.

The most used sources of taxonomic information were Beckmann et al. (1982), Cushman (1946), Plummer (1926), Berggren and Aubert (1975; 1976a, b), Sliter (1976), Proto-Decima and

Bolli (1978), Basov and Krasheninnikov (1983), Miller (1983), Tjalsma (1983), Tjalsma and Lohmann (1983), Dailey (1983), Miller et al. (1984), Wood et al. (1985), Morkhoven et al. (1986), and Loeblich and Tappan (1988). The taxonomy in this chapter closely follows Morkhoven et al. (1986), except for the placement of the species *beccariiiformis* in the genus *Gavelinella* instead of *Stensioina*.

## RESULTS

### Presence and Preservation of Benthic Foraminifers

Benthic foraminifers were common in most samples studied (a list of all taxa recognized is in Appendix 1; counts are in Appendix 2, back pocket). Preservation varied; there was strong dissolution in samples from Neogene siliceous oozes at both sites, and most samples from the middle Miocene and higher at Site 690. The lower Miocene and higher at Site 689 were barren of calcareous benthic foraminifers or contained only very few specimens. In these samples agglutinated benthic foraminifers were rare (a few specimens of *Martinotiella antarctica* per sample) or absent. Commonly the few calcareous specimens were present within burrows, and thus probably derived from  $\text{CaCO}_3$ -containing levels higher and lower in the section. There were obvious signs of  $\text{CaCO}_3$ -dissolution in samples from the lower Miocene through the upper Eocene at both sites, with the lowermost presence of radiolarians in the  $>63 \mu\text{m}$  fraction and the lowermost signs of  $\text{CaCO}_3$ -dissolution in Cores 113-690B-12H and 689B-17H (Zone CP14a, upper middle Eocene, Wei and Wise, this volume). Below that level dissolution was no problem, but at some levels (close to unconformities) specimens were commonly bored by fungi and abraded. Specimens in samples from close to the Cretaceous/Tertiary boundary were commonly overgrown with calcite, or encrusted. In the lower part of Hole 690C and 689B (lower Maestrichtian; Barker et al., 1988) some

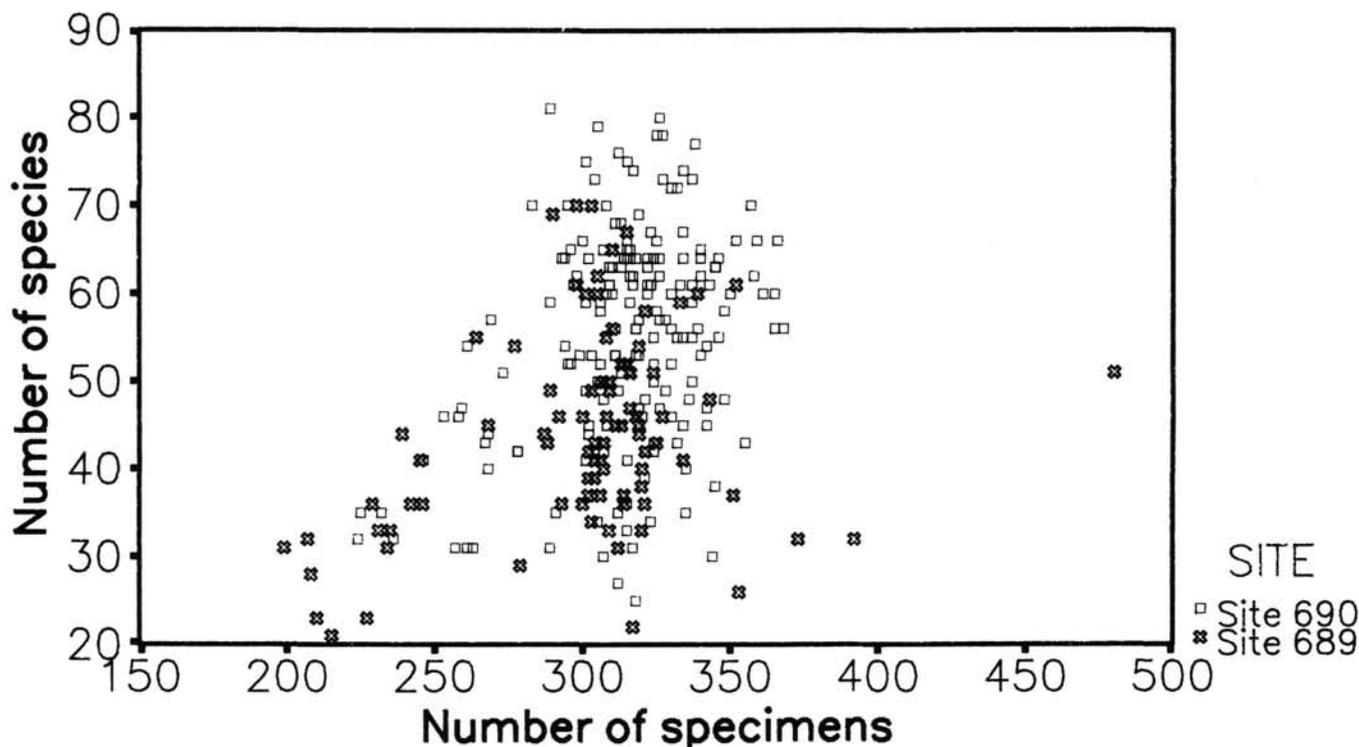


Figure 2. Plot of number of species identified in the samples versus the number of specimens counted; data for all samples from Sites 689 and 690 are included. Note the absence of a statistically significant positive correlation.

intervals are strongly indurated, and samples from these levels could not be processed.

### Benthic Foraminiferal Assemblages

Faunas at Sites 689 and 690 differ in relative abundances of some species but are similar as to species composition (Figs. 3, 4, back pocket); the diversity was lower at all times at the shallower Site 689. Deep-sea benthic foraminiferal faunas are largely cosmopolitan (e.g., Douglas and Woodruff, 1981), and the Neogene faunas from Maud Rise resemble faunas from lower latitudes in their most abundant components (Thomas, 1985; 1986a,b; Woodruff, 1985), although diversity is lower at Maud Rise. Neogene faunas also resemble Recent faunas in the Weddell Sea from the areas where deep waters enter in the Weddell Gyre (Echols, 1971; Anderson, 1975). Paleogene faunas are very similar to coeval faunas from lower latitudes, as described by Vincent et al. (1974), Proto-Decima and Bolli (1978), Schnitker (1979), Tjalsma and Lohmann (1983), Boersma (1984), Wood et al. (1985), Miller and Katz (1987b), and Katz and Miller (1988, in press). There is a particularly striking resemblance between Eocene-Oligocene faunas from Maud Rise and coeval faunas from the northern Atlantic (Berggren and Aubert, 1976a, b; Murray, 1984) because of the high relative abundance of *Stilostomella* species. Similarly, the Upper Cretaceous faunas resemble those from lower latitudes, as described by Sliter (1976) and Basov and Krashennikov (1983) from the Falkland Plateau, Dailey (1983) from the Rio Grande Rise, and Nyong and Olsson (1984) from the New Jersey continental margin and North Atlantic.

At each site eight assemblages could be recognized (Figs. 3, 4, back pocket). The assemblages were distinguished using a combination of data on presence-absence of species with a relatively short range, and relative abundances of the more common or dominant species. The boundaries between these assemblages are coeval at the two sites, at least within the presently available biostratigraphic resolution (Table 1).

#### Assemblage 8: lower Maestrichtian

Assemblage 8 occurs in samples from the bottom of Hole 689B to 257.51 mbsf (Samples 113-689B-33X, CC, through 113-689B-28X-2, 41 cm) and from the bottom of Hole 690C to 273.31 mbsf (Samples 113-690C-11X, CC, through 113-690C-18X-2, 41 cm), with an estimated age of 74–69 Ma.

The lowermost sediments at Sites 689 and 690 are either lowermost Maestrichtian or upper Campanian (Huber, this volume; Pospichal and Wise, this volume, chapter 30). Benthic foraminiferal assemblages contain several species described as having their first appearance in the upper Campanian-Maestrichtian at Hole 511, in Core 511-24 (Falkland Plateau, Basov and Krashennikov, 1983). Core 511-24 was assigned to the uppermost Campanian by Wind and Wise (1983), but the location of the Campanian/Maestrichtian boundary at that level is not certain (Pospichal and Wise, this volume, chapter 30), and typical indicators of the Campanian were not found at Sites 690 and 689, nor in Core 511-24. Planktonic foraminiferal data are in agreement with the correlation of Cores 113-689B-31X through 113-689B-33X and 113-690C-21X and 113-690C-22X with Core 511-24 (Huber, this volume).

The oldest benthic foraminiferal assemblage, assemblage 8, is slightly less diverse than the younger assemblage 7, especially at the shallower Site 689 (average number of species at Site 689: 49; at Site 690: 63). Paleodepths for this assemblage are estimated at 1000–1500 m (lower bathyal) for Site 689 and at 1500–2000 m (lower bathyal) for Site 690. *Gavelinella beccariiformis* is more abundant in this assemblage than in any other one. Other common species are *Oridorsalis nitidus*, *Spiroplectamina* aff. *spectabilis*, *Quadriformina cretacea*, *Praebulimina*

*reussi*, and *Neoeponides* species. *Globorotalites spineus* occurs in some samples in the lower part of Hole 690C, and *Coryphostoma incrassata* shows very strong fluctuations in relative abundance at both sites. *Angulogerina szajnochae* is present in many samples, as is *Quinqueloculina longirostra*. Uniserial lagenids are common and diverse, and *Stilostomella* spp. are less common than in higher assemblages but present in most samples. *Gyroidinoides quadratus* is rare or absent at Site 689, present in most samples at Site 690.

The upper boundary of the assemblage is difficult to locate precisely at Site 690, where there appears to be a zone of gradual faunal changes rather than a sharp boundary. At Site 689 the boundary was picked at the first appearance of *Alabamina creta* and *Osangularia navarroana*; at Site 690 there is an interval in which *A. creta*, *Bulimina midway*, and *O. navarroana* have their first appearance, and the boundary was picked at the top of this short interval; this is very close to (but above) the level of first appearance of the planktonic foraminiferal species *Abathomphalus mayaroensis* (Huber, this volume), at the boundary of the *Cribrosphaerella daniae*/*Nephrolithus corystus* sub-zones within the *Nephrolithus frequens* Zone (Pospichal and Wise, this volume, chapter 30), and at the boundary between Chrons C31N and C31R (Hamilton, this volume).

#### Assemblage 7: upper Maestrichtian—lower Paleocene

Assemblage 7 occurs in samples from 256.01 through 227.61 mbsf at Site 689 (Sample 113-689B-28X-1, 41 cm, through 113-689B-25X-1, 101 cm) and from 271.81 through 218.06 mbsf at Site 690 (Samples 113-690C-18X-1, 41 cm, through 113-690C-12X, CC), with an estimated age of 69 through 62 Ma.

Assemblage 7 is characterized by a slightly higher diversity than the older assemblage 8 (average number of species at Site 689: 54; at Site 690: 65), the rare to common presence of *G. beccariiformis* and *Stilostomella* spp., the absence of *B. thanetensis*, and the presence of *Bulimina midway* (although the latter is rare at Site 689). *Osangularia navarroana* is common at Site 689 and in the lower samples of the assemblage at Site 690. *Nuttallides truempyi* is consistently present (few to rare) at Site 690, and has strong fluctuations in relative abundance at Site 689; *Oridorsalis nitidus* occurs in many samples, especially at Site 689. Uniserial lagenid species and lenticulinids are common and diverse. *Gyroidinoides quadratus* occurs rarely in most samples at Site 690.

There is no major extinction event at the Cretaceous/Tertiary boundary; the boundary appears to be well represented at Site 690, where an iridium anomaly is present at 247.88 mbsf (Michel et al., this volume). At Site 689 there is an unconformity across the boundary (at 233.44 mbsf, Pospichal and Wise, this volume, chapter 32), and no iridium anomaly was detected (Michel et al., this volume). Three species have a last appearance close to that boundary at Sites 689 and 690: *Coryphostoma incrassata*, *Praebulimina reussi*, and *Spiroplectamina* aff. *spectabilis*. *Angulogerina szajnochae* has its last appearance before the Cretaceous/Tertiary boundary, and *Globorotalites conicus* is absent at Site 689 and extends into the lower Tertiary at Site 690. *Bulimina simplex* first appears just above the Cretaceous/Tertiary boundary at the two sites, and *Tappanina selmensis* first appears at the same level at Site 690 but higher at Site 689. Overall, less than 14% of all species had a last appearance within 0.5 m.y. intervals above and below the boundary at Site 689, less than 9% at Site 690 (Thomas, in press).

The upper boundary of assemblage 7 was selected at the first appearance of *B. thanetensis* and *R. carpentierae*. *Cibicidoides pseudoperlucida* has its first appearance just below this level, as does *Siphogenerinoides brevispinosa*. This boundary occurs at an unconformity (between calcareous nannofossil zones CP3 and CP7) at Site 689, close to the boundary between zones CP4

**Table 1. Benthic foraminiferal assemblages at Sites 689 and 690.**

Boundary	Site 689	Site 690
Assemblage 1/2	Barren interval 6H-3, 41 cm → 6H-CC 46.72–52.84 mbsf	Barren interval 5H-1, 41 cm → 5H-CC 31.53–40.78 mbsf
barren 14.9–11.5 Ma; middle–late Miocene (diatoms; paleomagnetic data)		
Assemblage 2/3	15H-1, 41 cm → 15H-2, 41 cm 130.31–131.81 mbsf CP15a/CP15b	11H-3, 41 cm → 11H-4, 41 cm 92.51–94.01 mbsf CP15a/CP16–hiatus
38.5 Ma; late Eocene; Chron C16; Zone P16		
Assemblage 3/4	19H-1, 41 cm → 19H-2, 41 cm 167.31–168.81 mbsf upper CP13	12H-6, 41 cm → 12H-CC 106.71–108.50 mbsf hiatus–CP13/CP14a
46 Ma; middle middle Eocene; lower Chron C20N; boundary Zones P11/P12		
Assemblage 4a/4b	22X-2, 41 cm → 22X-3, 41 cm 199.41–200.91 mbsf in CP12	15H-2, 41 cm → 15H-2, 75 cm 130.01–130.35 mbsf in CP12
52 Ma; late early Eocene; Chrons C21 R/C22N boundary; boundary Zones P9/P10		
Assemblage 4b/5	22X-4, 41 cm → 22X-5, 41 cm 202.41–203.91 mbsf unconformity	15H-4, 41 cm → 15H-4, 75 cm 133.01–133.35 mbsf unconformity(?); CP11/CP12
53–55 Ma; middle early Eocene; lower Chron C22/upper C23; boundary Zones P6/P7		
Assemblage 5/6	23X-1, 41 cm → 23X-1, 116 cm 207.61–208.36 mbsf in CP8	19H-3, 41 cm → 19H-3, 75 cm 170.31–170.65 mbsf middle CP8
57.5 Ma; latest Paleocene; in C24R; boundary Zones P6a/P6b		
Assemblage 6/7	24X-CC → 25X-1, 101 cm 19.56–227.61 mbsf hiatus(?)	C12X-2, 41 cm → C12X-CC 215.81–218.06 mbsf CP4/CP5
62 Ma; early/late Paleocene; probably in C26R; boundary Zones P3a/P3b		
Assemblage 7/8	28X-1, 41 cm → 28X-2, 41 cm 256.01–257.51 mbsf <i>N. corystum</i> / <i>C. daniae</i> Zones	C18X-1, 41 cm → C18X-2, 41 cm 271.81–273.31 mbsf <i>N. corystum</i> / <i>C. daniae</i> Zones
69 Ma; early/late Maestrichtian; C31N/C31R boundary		

Note: Ages of the boundaries were derived from calcareous nannofossil data (Pospichal and Wise, this volume, chapter 30; Wei and Wise, this volume), paleomagnetic data in Spieß (this volume) and Hamilton (this volume) and cross-correlation with the time scale of Berggren et al. (1985) as modified by Aubry et al. (1988). Correlation with planktonic foraminiferal zones was added for ease in correlating assemblages with the zonal scheme in Berggren and Miller (in press) and the range charts in Morkhoven et al. (1986), and derived from cross-correlation of the standard planktonic foraminiferal zones with the proposed Antarctic planktonic foraminiferal zones in Stott and Kennett (this volume, chapter 34).

and CP5 at Site 689 (Pospichal and Wise, this volume, chapter 37), and at the boundary between planktonic foraminiferal assemblages AP2 and AP3 (correlated with the P3a/P3b zonal boundary by Stott and Kennett, this volume, chapter 34). Paleomagnetic data are not available for this interval.

#### **Assemblage 6: upper Paleocene**

Assemblage 6 occurs in samples from 219.56 through 208.36 mbsf at Site 689 (113-689B-24X, CC, through 23X-1, 116 cm), from 215.81 through 170.65 mbsf at Site 690 (113-690C-12X-2, 41 cm, through 113-690C-19H-3, 75 cm), with an estimated age of 62 through 57.5 Ma.

Assemblage 6 is slightly less diverse than the older assemblage 7 (average number of species: 51 at Site 689, 62 at Site 690), although overall the diversity is high throughout assemblages 6 through 8 at Sites 689 and 690 (average number of species: 50 at Site 689, 64 at Site 690). At Site 690 the most common species of assemblage 6 are *Siphogenerinoides brevispinosa*, *Rectobulimina carpentierae*, *Bulimina thanetensis*, and *Stilostomella* spp., with *N. truempyi*, *Pullenia coryelli*, and *Gavelinella beccariiiformis* present in all samples. *Alabama creta*, *Oridorsalis nitidus*, and *Bolivinooides laevigatus* have a last ap-

pearance in the assemblage 6 interval but are more common in older assemblage 7. At Site 689 the assemblage occurs in a few samples only, because of the presence of an unconformity (corresponding to calcareous nannofossil Zones CP4–CP6) in Core 689B-25X-1, 12 cm. At Site 689 the same species are present as at Site 690, but *G. beccariiiformis* is much more common, whereas the relative abundance of *N. truempyi* fluctuates strongly. Uniserial lagenid and lenticulinid species are common and diverse at both sites.

The upper boundary of assemblage 6 is sharp (it occurs between Samples 113-690B-19H-3, 41 cm, and 113-690B-19H-3, 75 cm, and between Samples 113-689B-23X-1, 41 cm, and 113-689B-23X-1, 116 cm). This boundary is at the level of last appearance of many species, including *Gavelinella beccariiiformis*, *Gavelinella hyphalus*, *Neoflabellina semireticulata*, *Neoflabellina jarvisi*, *Bolivinooides delicatulus*, and *Pullenia coryelli* (Figs. 3, 4). This level is within paleomagnetic Chron C24R, within calcareous nannofossil Zone CP8 (Pospichal and Wise, this volume, chapter 37) and slightly (30 cm) below the boundary of planktonic foraminiferal Zones AP4 and AP5, which can be correlated with the P6a/P6b zonal boundary (Stott and Kennett, this volume, chapter 34).

**Assemblage 5: topmost Paleocene—lower Eocene**

Assemblage 5 occurs in samples from 207.61 through 203.91 mbsf at Site 689 (Sample 113-689B-23X-1, 41 cm through 113-689B-22X-5, 41 cm) and from 170.31 through 133.35 mbsf at Site 690 (Sample 113-690B-19H-3, 41 cm, through 113-690B-15H-2, 75 cm), with an estimated age of 57.5 through 53–55 Ma.

Assemblage 5 has an unusually low diversity (average number of 34 at Site 689, 46 at Site 690). The diversity is lowest (25–35 species) in the lower samples of the assemblage, then becomes higher at Site 690. The samples with lowest diversities are 113-690B-19H-3, 41 cm (170.31 mbsf) through 113-690B-18H-6, 41 cm (165.11 mbsf). At Site 689 the stratigraphic equivalent of the more diverse upper part of the assemblage is not represented in the sediments because of an unconformity at 113-689B-22X-4, 35–45 cm (representing nannofossil Zones CP9 through 12, i.e., the lower Eocene; Pospichal and Wise, this volume, chapter 37).

The most common constituents of the assemblage are small “buliminid” species such as *Tappanina selmensis*, *Bulimina simplex*, *Siphogenerinoides brevispinosa*, *Bolivinoidea* sp., *Bulimina ovula*, and *Fursenkoina* sp. 1. In most samples one or two of these species are dominant, but the dominant species varies. *Bulimina trinitatensis* is rare but present in most samples. *Nuttallides truempyi* is present in most samples, but at strongly varying abundances, and *N. umbonifera* is present in most samples, but few to rare specimens. *Cibicidoides pseudoperlucidus* and *Oridorsalis umbonatus* are also rare but commonly present, especially in the higher (more diverse) part of the assemblage. *Globocassidulina subglobosa* and *Pullenia bulloides* first appear in this assemblage but are rare. Unilocular species and uniserial lagenids are rare in the lowest diversity samples, more common in more diverse samples. Rare to few *Aragonia aragonensis* are present in the uppermost and lowermost samples of the assemblage only. Unilocular species and uniserial lagenids are rare in the lower diversity interval and become more abundant with increasing diversity.

The upper boundary of assemblage 5 was taken at the first appearance of *Siphogenerinoides eleganta*, occurring at the CP8-CP12 unconformity at Site 689. At Site 690 the stratigraphic level of this boundary also appears to occur at an unconformity. At this site the benthic foraminiferal boundary occurs close to the boundary between calcareous nannofossil Zones CP11 and CP12 (Pospichal and Wise, this volume, chapter 37). Zones CP10-11 and CP12 are very thin at Site 690, and there appears to be an unconformity within Core 113-690B-15H (at about 133 mbsf). Spieß (this volume) suggests that the unconformity covers the lower part of Chron C22R, and a large part of C23 (from 52.80 through 54.65 Ma), corresponding to the lower part of calcareous nannofossil Zone CP11 and the upper part of CP10. The benthic foraminiferal boundary corresponds to the planktonic foraminiferal boundary between Zones AP6b and AP7 (Stott and Kennett, this volume, chapter 47), correlated with the P9/P10 boundary by these authors.

**Assemblage 4: lower Eocene—Middle Eocene**

Assemblage 4 occurs in samples from 202.41 through 168.81 mbsf at Site 689 (Samples 113-689B-22X-4, 41 cm, through 113-689B-19H-2, 41 cm), from 133.01 through 108.50 mbsf at Site 690 (Samples 113-690B-15H-4, 41 cm, through 690B-12H, CC), with an estimated age of 53–55 through 46 Ma.

Assemblage 4 differs from the older assemblage 5 and all younger assemblages because of its greater diversity (which does not reach the even higher diversity of assemblages 6 through 8, however): the average number of species is 45 at Site 689, 55 at Site 690. The assemblage differs from all other assemblages because of the high relative abundance of large, thick-walled buliminid species, the most common of which is *Bulimina semi-*

*costata*; others are *Bulimina callahani* at Site 689 and *Bulimina trinitatensis* at both sites. *Bulimina simplex*, a small buliminid species, is also common, as are some *Fursenkoina* species and *Siphogenerinoides eleganta*. Uniserial lagenid species and lenticulinids are as common and diverse as in the older assemblages but much more common and more diverse than in the younger assemblages. *Nuttallides truempyi* is present in most samples at fluctuating relative abundances, as is *Oridorsalis umbonatus*; *Cibicidoides praemundulus* is rare in most samples, *Nonion havanense* is present in most samples. *Stilostomella* species are common.

The assemblage is subdivided in two subassemblages: assemblage 4B (the lower part) is transitional between assemblages 4 and 5. In samples of subassemblage 4B, *Bulimina semicostata* is absent, but *Siphogenerinoides eleganta* is present. In addition, several species that are abundant in assemblage 5 and absent in assemblage 4A (e.g., *Tappanina selmensis* and *Aragonia aragonensis*) are present at very low relative abundances. The boundary between subassemblages 4A and 4B is taken at the first appearance of *B. semicostata*, which is in calcareous nannofossil Zone CP12 (Pospichal and Wise, this volume, chapter 37), and close to the boundary between paleomagnetic Chrons C22R and C22N (Spieß, this volume). The nature of this assemblage boundary is uncertain, however, because just below the assemblage boundary there is a major unconformity at Site 689 (Zone CP13 on Zone CP8), and there are stratigraphic problems at Site 690 (see above; the first appearances of *Discoaster lodoensis* and *Discoaster sublodoensis* are very close to each other, and there may be an unconformity covering a large part of calcareous nannofossil Zone CP10-11). Therefore, the upward extension of ranges of the species that are typical for assemblage 5 may be due to reworking across unconformities, and “subassemblage 4B” might represent an interval in which some material from assemblage 5 is reworked into assemblage 4.

At Site 690 the upper boundary is taken at the last common appearance of *Bulimina semicostata* and *Siphogenerinoides eleganta*. At Site 690 this last appearance occurs within the lower part of Core 113-690B-12, in which core there is lithologic evidence (scour-and-fill) of several unconformities. The boundary occurs at the boundary between calcareous nannofossil Zones CP13 and CP14, in paleomagnetic Chron C20N. A few specimens of *B. semicostata* and *S. eleganta* occur above the boundary, but these specimens are abraded and might represent reworking. At Site 689 the boundary is taken at the last appearance (not the last common appearance) of these two species, which occurs just below the boundary between calcareous nannofossil Zones CP13 and CP14 (Pospichal and Wise, this volume, chapter 30), in Chron C20N (Spieß, this volume), and at the boundary between planktonic foraminiferal zones AP9 and AP10, which was correlated with the P11/P12 zonal boundary (Stott and Kennett, this volume, chapter 34).

**Assemblage 3: middle Eocene—upper Eocene**

Assemblage 3 occurs in samples from 167.31 through 131.81 mbsf at Site 689 (Samples 113-689B-19H-1, 41 cm, through 689B-15H-2, 41 cm), and from 106.71 through 94.01 mbsf at Site 690 (113-690B-12H-6, 41 cm, through 113-690B-11 H-4, 41 cm), with an estimated age of 46 through 38.5 Ma.

Assemblage 3 differs from assemblage 4 because of the absence of large buliminid species and the lower diversity (average of 39 species at Site 689, 45 at Site 690), and a much higher relative abundance of *Nuttallides umbonifera* and *Stilostomella* species. Typical of this assemblage is the common or abundant presence of *Bulimina elongata*. *Oridorsalis* spp. are common and *Cibicidoides praemundulus* is common in many samples, *Cibicidoides mundulus* in the upper samples at Site 689. *Epistominella exigua* is rare in most samples. *Nuttallides truempyi* has

its last appearance in the last sample of the assemblage at Site 690, in the middle at the shallower Site 689. *Bolivina huneri* occurs consistently in the lower samples at both sites.

The upper boundary of assemblage 3 was taken at the first appearance of *Turrilina alsatica* and the concurrent last appearance of *Bulimina elongata*. This boundary is very sharp at Site 690 because of the presence of an unconformity in Core 113-690B-11H-3 (corresponding to the duration of Zone CP15b, Wei and Wise, this volume). At Site 689 the boundary is somewhat more gradual and taken at the very sharp decrease in relative abundance of *B. elongata*, which occurs at the same place in the section as the first appearance of the calcareous nannofossil species *Isthmolithus recurvus* (the lower boundary of Zone CP15b, Wei and Wise, this volume). This level occurs within paleomagnetic Chron C16N (Spieß, this volume) and is slightly below the boundary between planktonic foraminiferal Zones AP12 and AP13 (correlated with the P16/P17 zonal boundary by Stott and Kennett, this volume, chapter 34).

#### *Assemblage 2: topmost Eocene—lower Miocene*

Assemblage 3 occurs in samples from 130.31 through 52.84 mbsf at Site 689 (113-689B-15H-1, 41 cm, through 113-689B-6H, CC) and from 92.51 through 40.78 mbsf at Site 690 (113-690B-11H-3, 41 cm, through 690B-5H, CC), with an estimated age of 38.5 through 14.5 Ma.

Sufficient specimens for study were present in all samples; the diversity is lower than in samples with assemblage 3 (average of 34 species at Site 689, 39 species at Site 690). Assemblage 2 is characterized by the very common to abundant occurrence of *Nuttallides umbonifera* and several species of *Stilostomella* (Figs. 3, 4). Assemblage 2 faunas at Sites 689 and 690 are more similar to each other than the faunas of younger assemblage 1 at both sites because there is more difference between faunas from assemblage 1 and 2 at Site 690 than there is at Site 689. Common species are *Cibicidoides mundulus*, *Oridorsalis* spp., *Pleurostomella* spp., *Epistominella exigua*, and *Globocassidulina subglobosa*. *Cibicidoides praemundulus* is present in the lower samples at Site 689, and *Turrilina alsatica* is very common to abundant in the lower samples at both sites (Figs. 3, 4).

At Sites 689 and 690 there is a barren interval between levels with assemblage 1 and those with assemblage 2; the barren interval can be dated as middle-upper Miocene (14.9–11.55 Ma) using data on the diatom and radiolarian assemblages in combination with paleomagnetic data (Gersonde et al., this volume, Thomas et al., this volume). The boundary between assemblages 2 and 1 is clearly defined at Site 690: at that site all species of *Stilostomella* and *Pleurostomella* have a last appearance, as do *C. mundulus* and *N. umbonifera*, at the same level where miliolid species first appear (Fig. 4A). At Site 689 the relative abundance of *Stilostomella* spp. and *Pleurostomella* spp. decreases, while that of the miliolid species increases (Fig. 3A). A similar decrease in relative abundance of cylindrical species concurrent with an increase in relative abundance of miliolid species occurred at the end of the early Miocene at several sites in the equatorial Pacific (Thomas, 1985).

#### *Assemblage 1: upper Miocene—Pleistocene*

This assemblage is present in the mud-line samples of both sites, and in a few upper Miocene samples in the top half of Core 113-689B-6H (45–47 mbsf) and in the lower meter of Core 113-690B-4H (30–31 mbsf; ages after Gersonde et al., this volume). In most samples from the middle Miocene and up, benthic foraminifers are absent. The diversity is low for bathyal-abyssal faunas: the average number of species was 27 (Site 689) and 34 (Site 690). Common species at both sites are *Epistominella exigua*, *Gyroidinoides* spp., *Globocassidulina subglobosa*, unilocular species, *Melonis sphaeroides*, several species of *Boli-*

*vina* and *Fursenkoina*, *Oridorsalis* spp., *Cibicidoides wuellerstorfi*, and several species of *Pyrgo* and *Quinqueloculina*. At Site 689 *Cibicidoides mundulus* and *Nuttallides umbonifera* are common to abundant, but these species are absent at Site 690.

#### **Interpretation of the Benthic Faunal Assemblages**

Data on deep-sea benthic foraminifers are difficult to present concisely because the assemblages are extremely diverse, and numerous species have to be taken into account. In this chapter the information present in the raw counts (Appendix 2, back pocket) is simplified as follows:

1. The number of first and last appearances in each sample was counted and plotted cumulatively versus sub-bottom depth (see also discussion in Thomas, 1986b) to ascertain whether these faunal events are spread evenly over the section or whether they are concentrated at some intervals.

2. The number of species in each sample was plotted versus sub-bottom depth to ascertain whether diversity fluctuated haphazardly or was subject to long-time trends.

3. Species were grouped according to their presumed environmental preference by comparing their test morphology with the morphology of the epifaunal (rounded trochospiral, planoconvex trochospiral, milioline, biconvex trochospiral) and infaunal morphogroups (rounded planispiral, flattened ovoid, tapered and flattened tapered, spherical) as described in Recent faunas by Corliss and Chen (1988); see Appendix 1 for grouping of the described taxa. A third group consists largely of cylindrical species, i.e., belonging to the uniserial lagenids *Stilostomella* spp., and *Pleurostomella* spp. (see also Thomas, 1985; 1986a, b). These species might have had an infaunal way of life (Corliss, written comm., 1989).

#### **First and Last Appearances**

The benthic foraminiferal record at Sites 689 and 690 covers the Maestrichtian and a large part of the Cenozoic, so that a long-term record of first and last appearances could be obtained. Faunal events are difficult to quantify for deep-sea benthic foraminiferal faunas because these faunas are very diverse and many species are rare (<5% relative abundance). Usually the most common species have very long ranges and the shorter-range species are rare, so their first and last appearances cannot be located precisely. In addition, first and last appearances at a specific sites are usually not coeval worldwide: deep-sea benthic species are known to migrate both laterally and vertically (Thomas and Vincent, 1987; Kurihara and Kennett, 1988). For many species it is not possible to determine from the literature whether a first or last appearance is synchronous over large distances, because of confusion in taxonomic concepts. In this chapter, all species occurring in one or two samples only were discarded from the dataset, and then the first and last appearances of all remaining species were counted. Therefore, the numbers of first and last appearances are a mixture of migratory and evolutionary events (see also discussion in Thomas, 1986b). Faunal events do not occur evenly spaced over time but are clustered within limited intervals, at the assemblage boundaries (Fig. 5). Obviously we can only consider these clusters appearing at levels where there are no detectable unconformities (see Results section, above).

At Site 689 there appear to be some intervals with an increased number of first appearances during the lower Maestrichtian, but these are probably due to recovery gaps. There was no major extinction event at the Cretaceous/Tertiary boundary at either of the two sites: at Site 689 only 13.9% of the taxa has a last appearance within 1 m.y. of the boundary, at Site 690 only 8.3% of the taxa (see also Thomas, in press). The interval with these last appearances started before the Cretaceous/Ter-

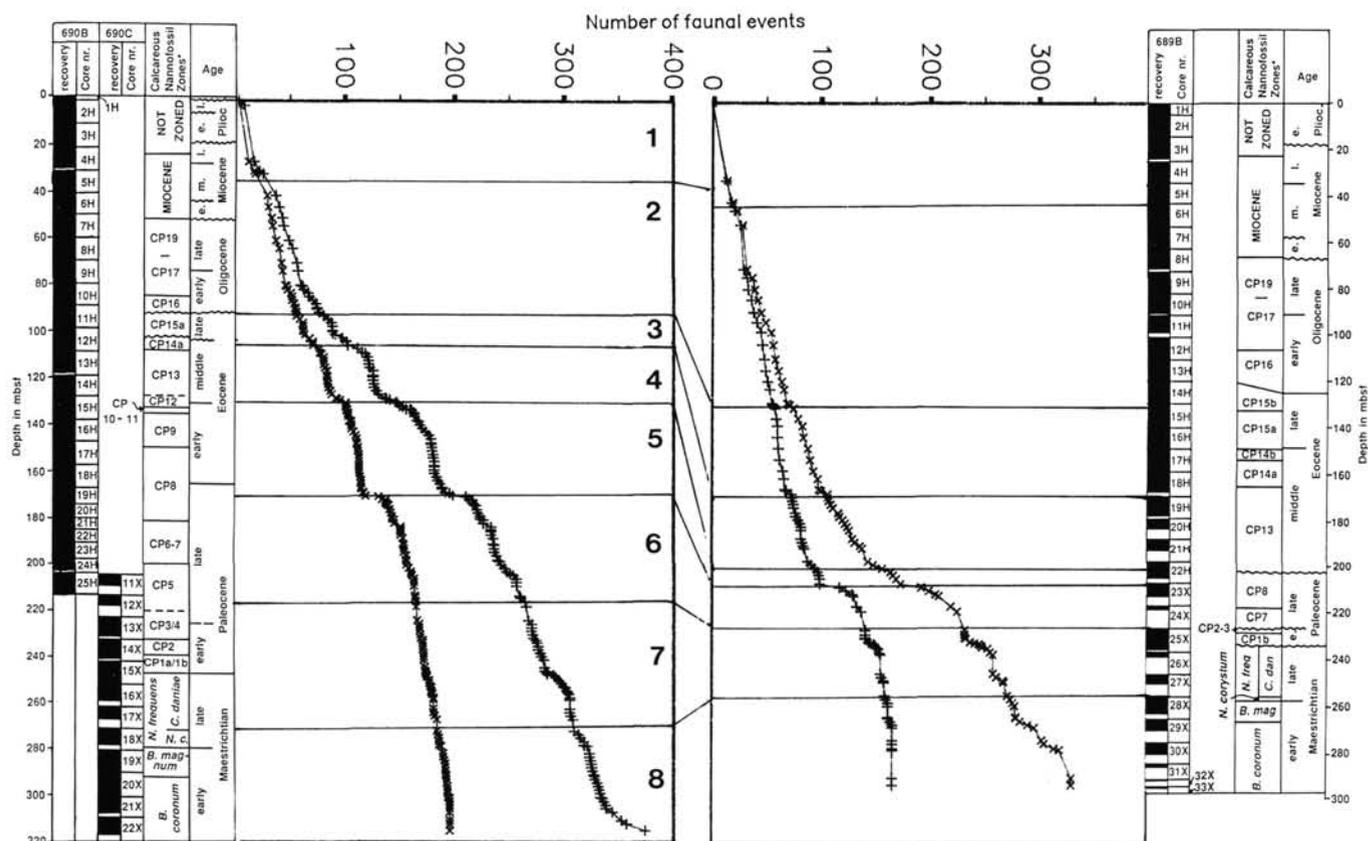


Figure 5. Number of last appearances (left curve, x) and first appearances (right curve, + marks sum of first and last appearances in each sample) plotted cumulatively versus sub-bottom depth, starting at 0 at the mud-line sample. Horizontal lines indicate the location of the assemblage boundaries, numbers 1 through 8 indicate the assemblages. Note that the first and last appearances are not necessarily evolutionary first appearances and extinctions: all first and last appearances were plotted, whether they are known to occur globally at a similar level or not (migratory first and last appearances are included). The curves give an indication of periods in which faunas were stable (curves close to parallel to the depth axis) and periods in which faunas showed turnover (curves close to parallel to the events axis). In this figure and Figures 6 through 10, core numbers, core recovery, and the calcareous nannofossil zonation after Pospichal and Wise (this volume, chapters 30, 32, and 37) and Wei and Wise (this volume) have been added. Neogene epoch boundaries after Gersonde et al. (this volume). Paleogene epoch boundaries derived from comparison of the nannofossil data as plotted and data on the planktonic foraminifera (Stott and Kennett, this volume, chapter 34) and paleomagnetic information (Spiess, this volume; Hamilton, this volume).

tiary boundary, possibly by about 0.5 m.y. (estimated using the paleomagnetic data in Hamilton, this volume).

The most important interval of last appearances is clearly the boundary between assemblages 6 and 5 (at a level where there were probably no unconformities, as described above), representing the major benthic foraminiferal extinction at the end of the Paleocene, which has been reported in many other sections (Beckmann, 1960; Braga et al., 1975; Schnitker, 1979; Tjalsma and Lohmann, 1983; Miller et al., 1987b; Katz and Miller, 1988, in press). The event is unusual in its suddenness (less than 35 cm, corresponding to less than 25,000 years at Site 690) and scope (last appearance of 37.3% of the taxa at Site 690), and stands out as the largest extinction interval (as given by the largest number of last appearances per time) during the complete period from the lower Maestrichtian through Neogene.

### Diversity

A simple measure of diversity is species richness, the number of species present in each sample (about 300 specimens, see Material and methods section). The record of the number of species present at Site 690 appears easier to read than that at Site 689 (Figs. 6A, B). At Site 690 the diversity is high, fluctuates,

but is overall constant in the part of the section containing assemblages 6 through 8 (Maestrichtian through Paleocene). There is a very sharp drop in diversity in the uppermost Paleocene and an interval with low diversity in uppermost Paleocene-lowermost Eocene (Fig. 6A). The low-diversity interval corresponds to less than 0.5 m.y. (depending upon the time-scale used), and would have been about 350,000 years according to the Aubry et al. (1988) time scale. Preliminary data on ostracode faunas from Site 690 indicate the presence of an as yet undescribed, non-analog fauna in the interval of lowest diversity of the benthic foraminifera; these ostracode faunas are at the generic level similar to the much younger (Neogene), deep-thermospheric faunas from the Mediterranean (P. Steineck, written comm., 1989). Unusually low values of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  were measured in benthic foraminifera, planktonic foraminifera, and bulk material from the short interval with low-diversity benthic foraminiferal faunas (Kennett and Stott, this volume; Stott et al., this volume; Shackleton and Hall, this volume).

The benthic foraminiferal diversity recovered partially after this period of 350,000 years but never reached the high values of the lower part of the section. The highest diversity of the section above the Paleocene occurs around the boundary between as-

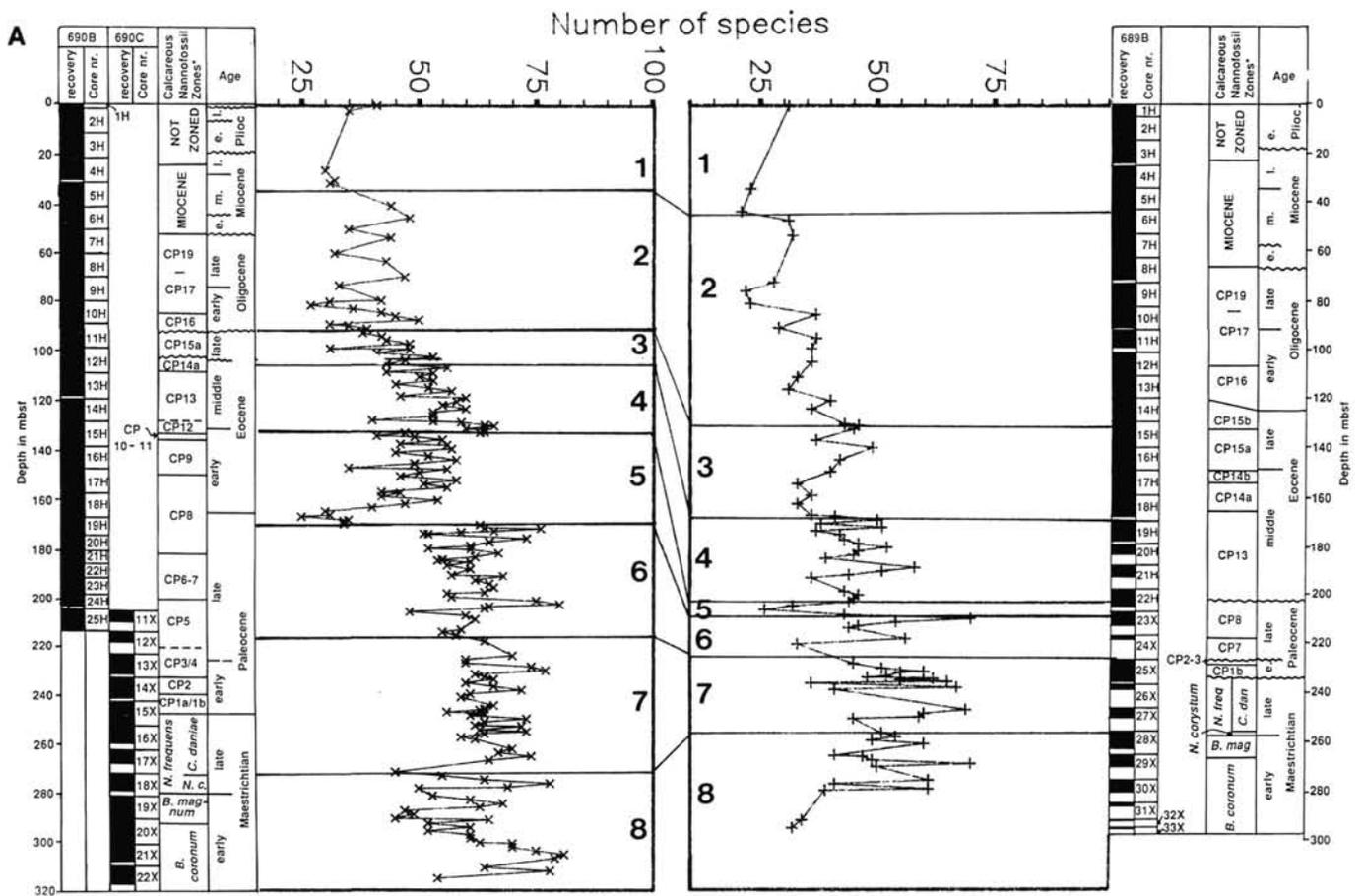


Figure 6. **A.** Number of species present in all samples studied from Sites 690 and 689 plotted versus sub-bottom depth. Horizontal lines indicate the location of the benthic foraminiferal assemblage boundaries; numbers 1 through 8 indicate the assemblages. **B.** Histogram averaging the data shown in A by assemblage. Numbers in the bars indicate the average number of species in the samples belonging to each assemblage (see Figs. 3A, B and 4A, B for numbers of samples within each assemblage).

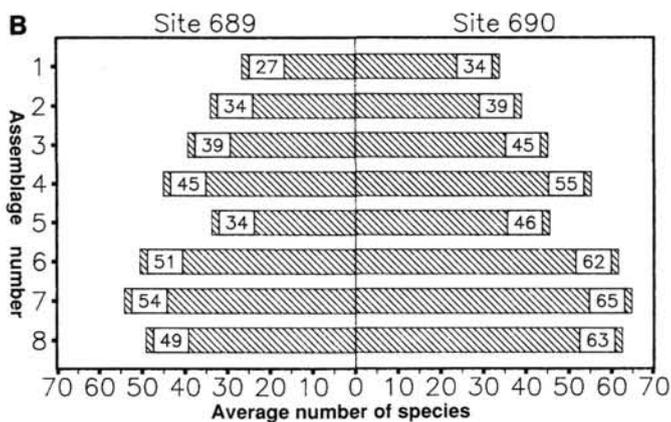


Figure 6 (continued).

assemblages 4 and 5 (46 Ma, middle Eocene); diversity then decreases up-section throughout the interval containing the upper samples from assemblage 4 and the samples from assemblage 3 (46–37.8 Ma). Throughout the interval with assemblage 2 (37.8–

14.9 Ma) the diversity fluctuates; there is another drop at the boundary between assemblages 2 and 1 (the barren interval from 14.9–11.55 Ma). The samples from the mud line have a somewhat higher diversity than lower samples from assemblage 1, but this may be a preservational effect; the mud-line samples contain several fragile agglutinated species (such as *Marsipella* sp. and *Psammosphaera fusca*) that have been reported to fall apart within the sediment (Echols, 1971). The record from Site 689 shows the same characteristics, but it is somewhat obscured by greater variability and recovery gaps in the Paleocene-Eocene part of the section. A histogram of the average values of sample number at both sites clearly demonstrates the parallel trends in species diversity at both sites (Fig. 6B), and the consistently lower diversity at the shallower Site 689.

**Faunal Composition**

The relative abundances of infaunal and epifaunal species show strong changes over time (Figs. 7A, B and 8A, B), as does the relative abundance of cylindrical species (Fig. 9A, B). Data on assemblage 1 are scarce (few samples); infaunal species were not very common in assemblage 2 (the second youngest) and assemblages 7 and 8 (the oldest). Percentages of infaunal species were higher in assemblages 3 and 6, although data on assemblage 6 are incomplete at Site 689 because of unconformities. The highest relative abundance of infaunal species is in samples

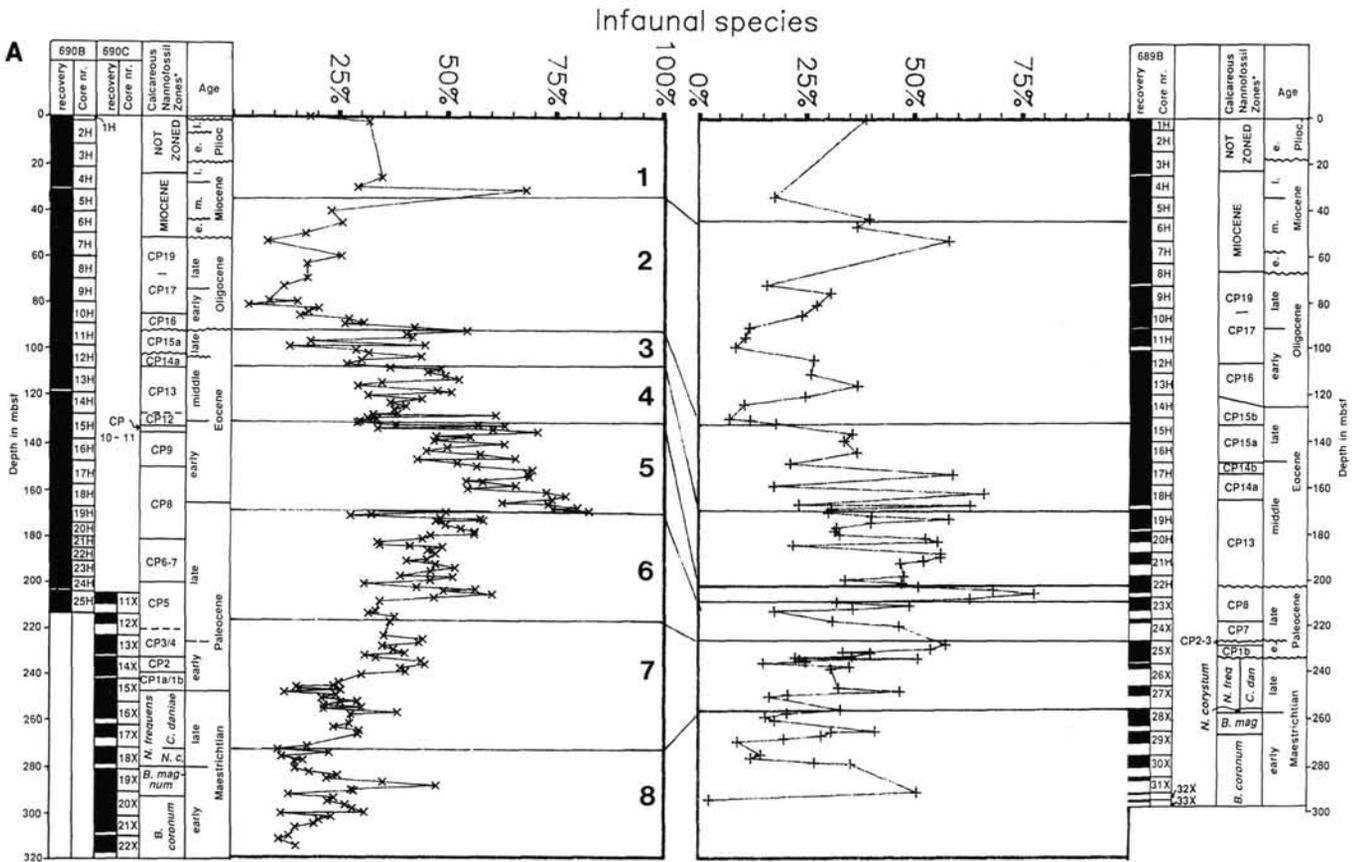


Figure 7. **A.** Percentage of the fauna belonging to infaunal species, as established from comparison of the morphology of each species with the morphology of recent species known to live infaunally (Corliss and Chen, 1988; see Appendix A). Horizontal lines indicate the locations of the benthic foraminiferal assemblage boundaries; numbers 1 through 8 indicate the assemblage. **B.** Histogram averaging the data shown in A by assemblage. Numbers in the bars indicate the average percentage of infaunal species in the samples belonging to each assemblage (see Figs. 3A, B, and 4A, B for numbers of samples within each assemblage).

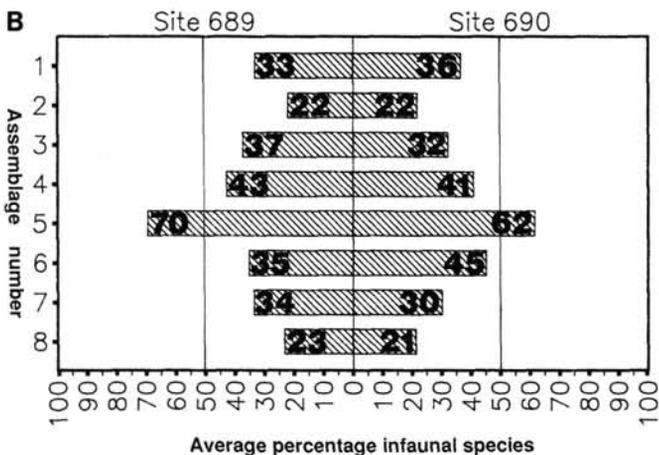


Figure 7 (continued).

from assemblage 5 (up to 85%), especially in the low-diversity samples just above the major extinction event in the uppermost Paleocene (Fig. 7A). The abundance of cylindrical species is difficult to evaluate; these species were common (present as more

than 10% of the fauna) in all assemblages except assemblage 1. They are most common in assemblages 2 through 4 at both sites, with the highest relative abundances at Site 689. The record of faunal composition at Site 689 shows a greater variability than that at Site 690, as did the record of diversity (see above, Fig. 6A, B). The number of specimens belonging to infaunal species shows a significant negative correlation to the number of species belonging to epifaunal species at Sites 689 ( $r = -0.66$ ,  $n = 88$ ) and 690 ( $r = -0.75$ ,  $n = 185$ ), and no correlation to the number of species belonging to cylindrical species (689:  $r = -0.01$ ; 690:  $r = -0.02$ ). The number of specimens belonging to epifaunal species, however, does show a significant negative correlation to the number of specimens belonging to cylindrical species (689:  $r = -0.46$ ; 690:  $r = -0.45$ ; significance  $>99.9\%$ ). This suggests that the cylindrical species might have been living infaunally, as Corliss (written comm., 1989) has suggested. Therefore additional figures are shown for the combined percentages of infaunal and cylindrical species (Figs. 10A, B). These figures are very similar to the plots for infaunal species, and the argument on the meaning of changes in relative abundances of infaunal species (see below) runs the same, whether cylindrical species are kept separate or whether they are treated as infaunal species. The overall trend in the varying relative abundances of infaunal and epifaunal species shows that there is greater resemblance between the oldest and youngest assemblages (as to morphology of the dominant taxa: dominant

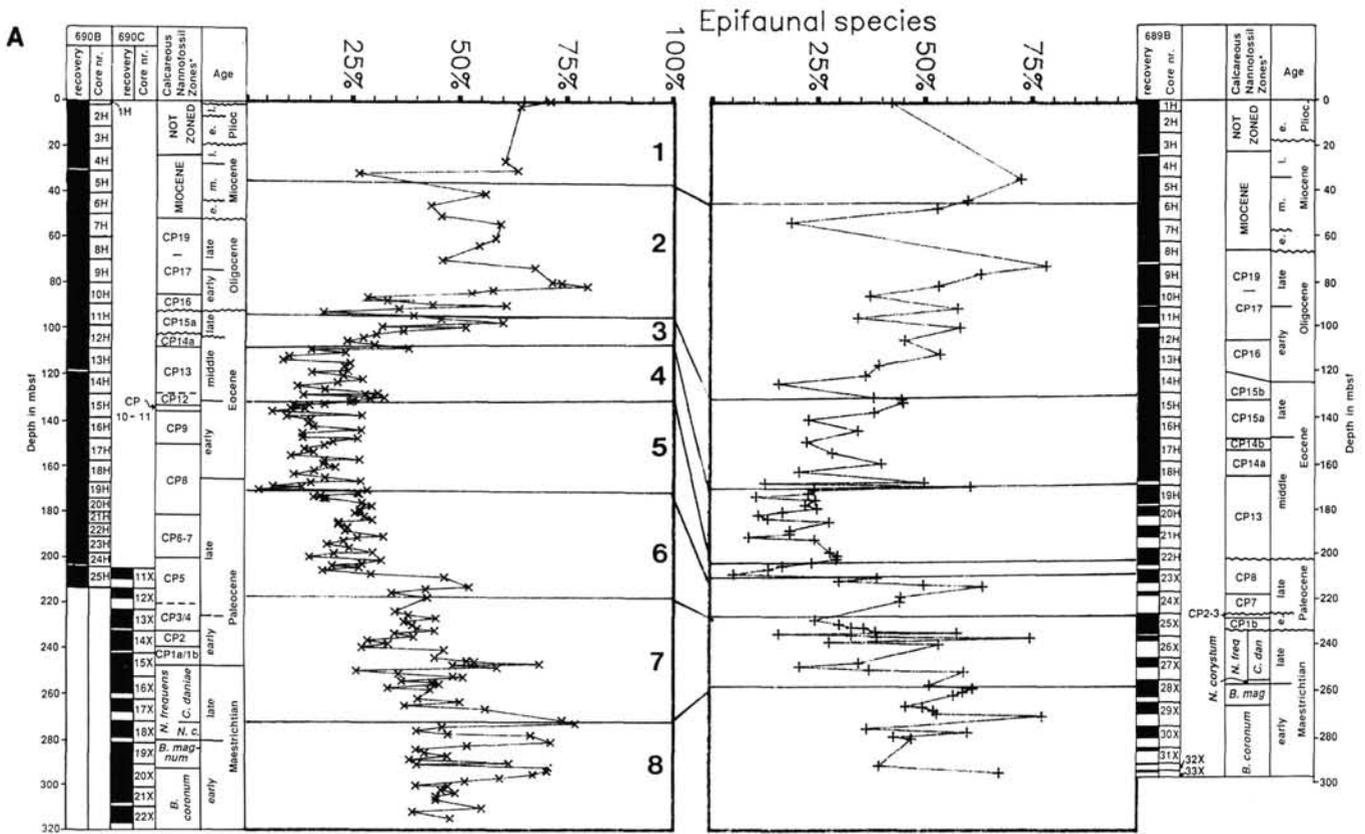


Figure 8. **A.** Percentage of the fauna belonging to epifaunal species, as established from comparison of the morphology of each species with the morphology recent species known to live epifaunally (Corliss and Chen, 1988; see Appendix A). Horizontal lines indicate the locations of the benthic foraminiferal assemblage boundaries; numbers 1 through 8 indicate the assemblage. **B.** Histogram averaging the data shown in A by assemblage. Numbers in the bars indicate the average percentage of epifaunal species in the samples belonging to each assemblage (see Figs. 3A, B, and 4A, B for numbers of samples within each assemblage).

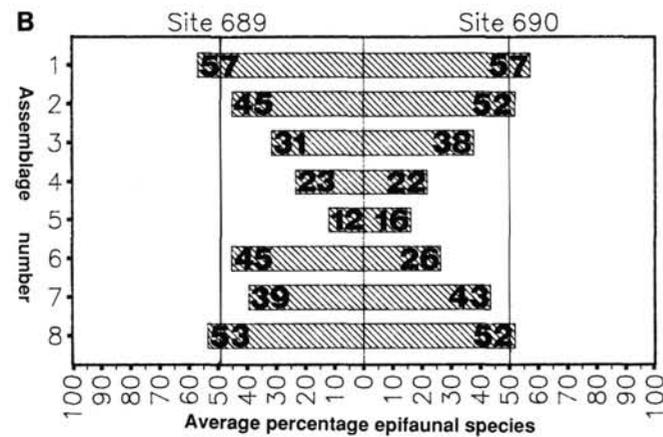


Figure 8 (continued).

epifaunal species) than between these and the taxa in the "middle" (lower Eocene), in which infaunal taxa dominate (Fig. 7B).

**DISCUSSION**

The record of deep-sea benthic foraminifers from Sites 689 and 690 is the longest available quantitative record of such faunas. Complete interpretation of the data set, however, requires

additional work to increase the resolution in the upper part of the holes at both sites. The benthic foraminiferal record alone suggests several interesting possibilities as to deep-water circulation, but the data must be combined with data on the planktonic micro- and nannofossil groups, the paleomagnetic record, and the isotopic records and the data on clay mineral content for a more complete paleoceanographic analysis.

Common deep-sea benthic foraminiferal species generally have long ranges (e.g., Boltovskoy, 1987), and usually changes in their faunas take at least 1 million years (e.g., Thomas, 1985; 1986a; Miller and Katz, 1987b; Thomas and Vincent, 1987; Thomas and Vincent, 1988; Berggren and Miller, 1989). Comparison of the benthic faunal record from Sites 689 and 690 with a proposed bathyal to abyssal benthic foraminiferal zonation (Berggren and Miller, 1989) suggests that major faunal changes in deep-water benthic foraminifers occurred globally: within the biostratigraphic resolution presently available the assemblage boundaries at the Maud Rise sites appear to be synchronous with the zonal boundaries in Berggren and Miller (1989), with the exception of the faunal changes in the late Eocene (assemblage 2/3 boundary), which occurred earlier at the Maud Rise sites (38.5 vs. 36.6 Ma). Discrete first and last appearances, however, are not coeval over long distances: most of the first and last appearances used to delineate the zonal boundaries by Berggren and Miller (1989) could not be recognized at Sites 689 and 690 either because of the rarity of the marker species proposed by these authors or because these first and last appearances occurred at different times at the Maud Rise sites. The

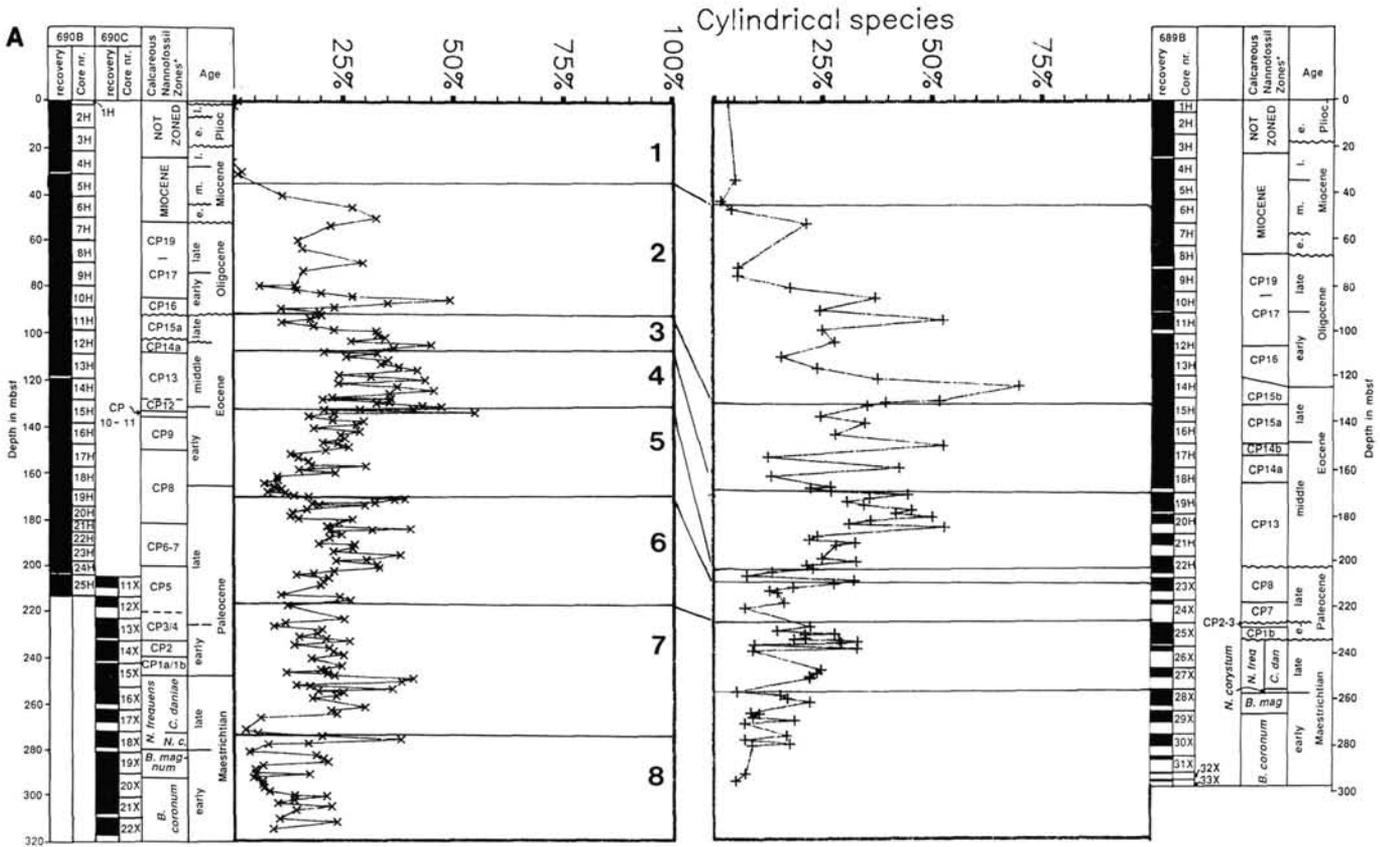


Figure 9. **A.** Percentage of the fauna belonging to cylindrical species (uniserial lagenids, *Stilostomella* spp., *Pleurostomella* spp.); the environmental preferences of this group of species are not known because of the rarity of these taxa in the present oceans. Horizontal lines indicate the locations of the benthic foraminiferal assemblage boundaries; numbers 1 through 8 indicate the assemblage. **B.** Histogram averaging the data shown in **A** by assemblage. Numbers in the bars indicate the average percentage of cylindrical species in the samples belonging to each assemblage (see Figs. 3A, B and 4A, B for numbers of samples within each assemblage).

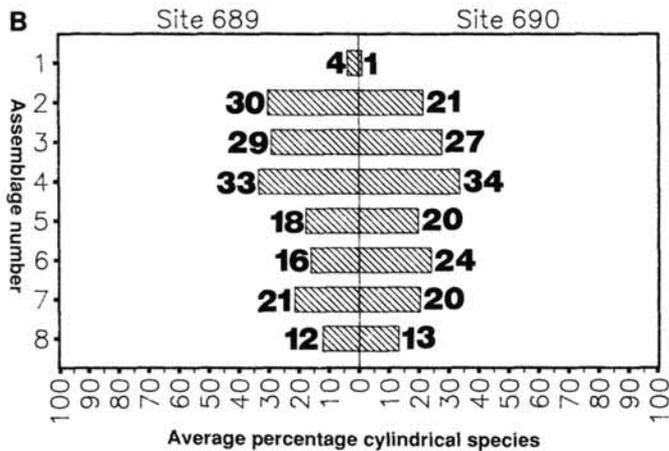


Figure 9 (continued).

range of the distinct species *Bulimina semicostata*, for instance, is much shorter at the Maud Rise sites than at many other locations (Morkhoven et al., 1986; Berggren and Miller, 1989). Therefore it is probably more useful to recognize periods of faunal change in benthic foraminiferal records and to correlate these periods of change than use formal zones and marker species (see also Thomas, 1986a).

The benthic foraminiferal record strongly suggests that the event at the end of the Paleocene was unique, both in its magnitude and in its very short duration: all other faunal changes appear to be much more gradual (see Fig. 6A for Site 690). Benthic foraminiferal faunas underwent severe extinction globally at this time (Beckmann, 1960; Braga et al., 1975; Schnitker, 1979; Tjalma and Lohmann, 1983; Miller et al., 1987b; Katz and Miller, in press), but there were no extinctions of surface-dwelling or terrestrial organisms of a comparable magnitude: it was a period of low overall extinction rates (Raup and Sepkoski, 1986). Planktonic foraminiferal faunas underwent faunal change at the Paleocene/Eocene boundary, but this change was considerably less than the major extinction at the end of the Cretaceous, whereas the reverse is true for the benthic foraminifers.

At Sites 689 and 690 many species that became extinct at the end of the Paleocene were probably trochospiral morphotypes, and as such may have been epifaunal (e.g., *Gavelinella* spp., *Gyrodonoides* spp., *Neoponides* spp.). The extinction (occurring over less than 25,000 years) was followed by a period (about 350,000 years) of low diversity and strong dominance of infaunal species (Fig. 6A). This short interval is also characterized by extremely low  $\delta^{18}O$  and  $\delta^{13}C$  values in benthic foraminifers (Kennett and Stott, this volume).

Variations in the relative abundance of infaunal and epifaunal species in Recent faunas reflect variations in the availability of organic carbon to the bottom-dwelling fauna (Corliss and Chen, 1988). Dominance of infaunal taxa has been recorded

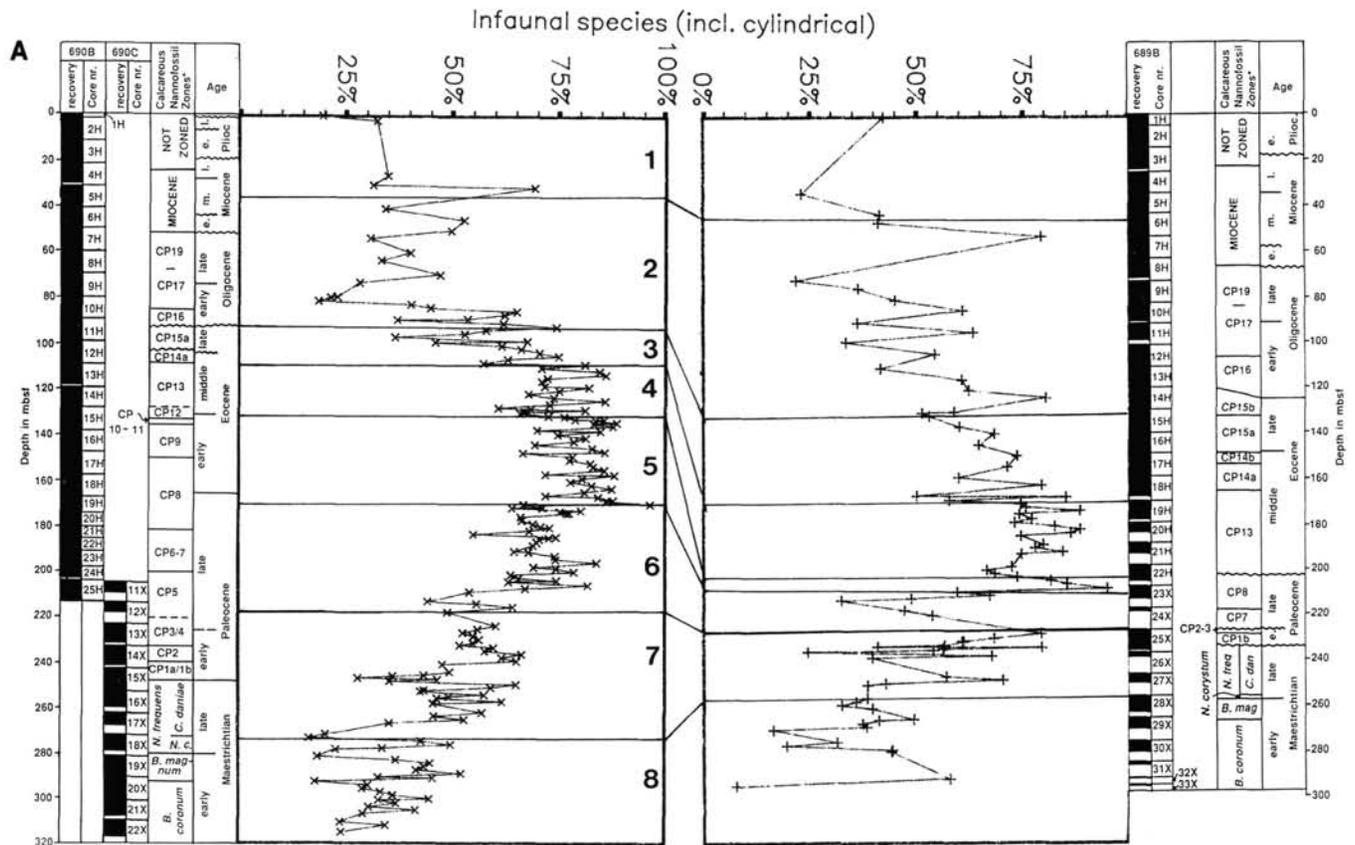


Figure 10. **A.** Percentage of specimens belonging to infaunal species, if the cylindrical taxa plotted in Figure 9A are also infaunal; i.e., the sum of the numbers plotted in Figures 7A and 9A. **B.** Histogram averaging the data shown in A by assemblage.

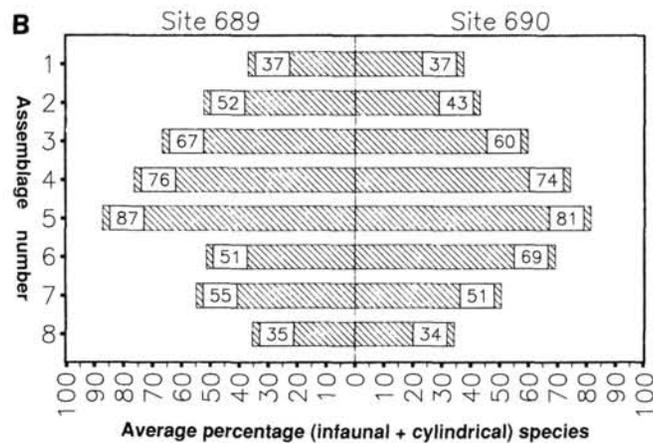


Figure 10 (continued).

from areas with a high flux of organic carbon to the ocean floor, or with low levels of dissolved oxygen in the bottom waters (e.g., Sen Gupta et al., 1981; Lutze and Coulbourn, 1984; Caralp, 1984; Thomas, 1986b; Bernard, 1986). Thus such faunas appear to indicate a high productivity of primary producers in the surface waters, or good preservation (thus lack of oxidation) of organic material, or a combination of these. The extinction at the end of the Paleocene was followed by a period of low

diversity and strong increase in relative abundance of infaunal species: comparison with data on Recent faunas thus suggests that this extinction might have been caused by an increase in surface productivity (causing the strong increase in relative abundance of infaunal species).

Increased productivity appears not to be the most probable explanation of the increase in relative abundance of infaunal species at the end of the Paleocene, however, because there is no confirmation of increased productivity in the planktonic foraminiferal or isotopic records. Shackleton et al. (1985a) and Shackleton (1987) suggested that there was a decrease in surface productivity at the end of the Paleocene, to explain the strong decrease in  $\delta^{13}C$  in bulk carbonate at sites on the Walvis Ridge (southern Atlantic Ocean) (reflecting the isotopic composition of dissolved carbonate in surface waters) at that time. This strong decrease (about 2‰, from +3.5‰ to +1.5‰) in  $\delta^{13}C$  in bulk carbonate was, however, accompanied by an equally strong decrease in  $\delta^{13}C$  in the benthic record (Miller et al., 1987b), so that there was no major change in surface-to-deep-water gradient in  $\delta^{13}C$  at the time. Such a decrease in gradient has been observed in samples from just above the Cretaceous/Tertiary boundary, a period in which surface productivity decreased dramatically (Zachos and Arthur, 1986; Arthur et al., 1987), whether this decrease was caused by the impact of an asteroid (e.g., Alvarez, 1986) or extensive volcanism (Officer et al., 1987). Thus the strong, worldwide decrease in  $\delta^{13}C$  of benthic foraminifers, planktonic foraminifers and bulk carbonate (which was also observed at Sites 689 and 690; see Kennett and Stott, this volume; Stott et al., this volume; Shackleton and Hall, this volume) probably re-

flects at least in part a change in  $\delta^{13}\text{C}$  of mean ocean water, possibly a result of a change in input/output ratio of organic carbon to carbonate carbon (Miller and Fairbanks, 1985).

The faunal changes at the end of the Paleocene cannot easily be explained as the result of a decrease in surface productivity. In the first place, the increase in relative abundance of infaunal species is not in agreement with that hypothesis. In the second place, comparison of the faunal record for the end of the Paleocene with that across the Cretaceous/Tertiary boundary at the same site shows that events during these two periods were very different as to their effect on the deep-sea benthic foraminifers. At the end of the Cretaceous the primary productivity collapsed, but there was no major extinction event of deep-sea benthic foraminifers (Thomas, in press). There is an increase in relative abundance of epifaunal species just above the Cretaceous/Tertiary boundary at Sites 689 and 690, probably reflecting a strong decrease in nutrient supply. Most of the few species that last appeared at the Cretaceous/Tertiary boundary were infaunal species (such as *Coryphostoma incrassata*), whereas several common epifaunal species that survived the Cretaceous/Tertiary boundary were the species to become extinct at the end of the Paleocene. Bathyal-abyssal foraminifers may have survived the major environmental crisis at the end of the Cretaceous because these organisms were used to low nutrient levels (common for deep-sea environments) and because of their detritus-feeding way of life (Sheehan and Hansen, 1986).

This discussion indicates that the benthic faunal extinction at the end of the Paleocene probably was neither the result of an increase of surface productivity, nor of a decrease. This leaves us many possibilities for an explanation of the extinction, but a viable cause appears to be a change in characteristics of the deep waters. The extinction occurred over a period of less than 25,000 years at Site 690, the right time-scale for a change in deep-water circulation which could have occurred over a period of a few thousand years. The oxygen and carbon isotopic records for Sites 689 and 690 demonstrate that there was a short interval (exactly corresponding to the interval of lowest benthic foraminiferal diversity, just after the extinction) of very light  $\delta^{18}\text{O}$  values in benthic foraminifers (about  $-0.8\text{‰}$  for *N. truempyi*), planktonic foraminifers (about  $-1.0\text{‰}$  for subbotinids), and bulk carbonate ( $0.5\text{‰}$ ). In the same interval the  $\delta^{13}\text{C}$  values are also unusually low ( $-0.5\text{‰}$  for *N. truempyi*,  $-0.6\text{‰}$  for subbotinid planktonic taxa, and  $-0.5\text{‰}$  for bulk carbonate; data after Kennett and Stott, this volume; Stott et al., this volume; Shackleton and Hall, this volume). Calcareous nanofossil assemblages indicate the warmest surface water temperatures of the Cenozoic for this interval (Pospichal and Wise, this volume, chapter 37). Ostracodes from the low-diversity interval of benthic foraminifers constitute non-analog faunas, which on a generic level appear to be similar to much younger (Pliocene) deep-thermospheric Mediterranean faunas (P. Steineck, pers. comm., 1989).

This combination of data indicates that the high-latitude deep and shallow waters in the Southern Ocean warmed for a short period (about 350,000 years) across the Paleocene/Eocene boundary, suggesting that a probable cause of the latest Paleocene benthic foraminiferal extinction is warming of these waters. Such an overall warming at the Maud Rise sites could have been caused by a change from the formation of intermediate and deep waters predominantly by sinking at high latitudes (producing cool, oxygen-rich waters, sinking in the proximity of Maud Rise and thus young at the Maud Rise sites) to formation of deep waters at lower latitudes. Such warm, salty deep waters would have been low in oxygen, both because of the low solubility of oxygen in warmer water and because these waters formed further away from Maud Rise, and thus must have aged considerably before reaching the sites (causing low values of  $\delta^{13}\text{C}$  in

the deep waters). Such a change in circulation could cause the change toward a much higher relative abundance of infaunal species, and the extinction of many epifaunal species that could not survive in the waters with a lower oxygen content. Data on clay minerals from the Maud Rise sites (Robert and Maillot, this volume) strongly support a change in circulation in the latest Paleocene and appear to indicate a short-term change to less oxidizing conditions for the interval of lowest benthic foraminiferal diversity. Preliminary data on the benthic foraminiferal faunal compositions and oxygen and carbon isotopic record from sites drilled on Leg 114 (Fig. 1A; Katz and Miller, in press) suggest that nutrient-depleted deep waters filled the southernmost Atlantic during the Paleocene and early Eocene but that deep water formation at high latitudes was reduced or stopped during a short period in the latest Paleocene to earliest Eocene; these authors agree that such a circulation change could have caused the benthic foraminiferal extinctions in the latest Paleocene.

The cause of such a change in deep-water circulation must remain controversial; it might have been a change in plate configuration in the area where the Indian and Asian continents collided at the end of the Paleocene, or in the northern Atlantic, where large volumes of plateau basalts formed at the time (e.g., Berggren and Schnitker, 1983; Williams, 1986). Changing plate configurations could have changed the configurations of low-latitude marginal basins, thus the evaporation balance in such basins. One of the many other possibilities includes a global warming, possibly caused by higher concentrations of  $\text{CO}_2$  in the atmosphere as a result of high sea-floor hydrothermal activity (Owen and Rea, 1986).

The overall benthic foraminiferal faunal record does not agree with the hypothesis that deep waters formed at low latitudes during the Late Cretaceous and that the circulation changed at some time during the early Tertiary (e.g., Hays, 1988): if dominance of infaunal species indeed indicates less-ventilated waters, then waters above Maud Rise were better oxygenated in the Maestrichtian through Paleocene and in the middle Eocene and later, than in the early Eocene. The Maestrichtian carbon and oxygen isotopic record (Barrera and Huber, this volume) supports the hypothesis that waters bathing Maud Rise were well-oxygenated during that time, as do data on the ostracode fauna of Sites 689 and 690 (P. Steineck, pers. comm., 1989). Thus faunal and the isotopic records appear to indicate that at least intermediate waters (bathing Maud Rise) formed by sinking at high latitudes during the Maestrichtian, in agreement with Barrera et al. (1987). This would mean that the formation of intermediate waters in the Maestrichtian was more similar to the situation proposed for the Oligocene (with formation of deep-to-intermediate waters both at low latitudes and at high latitudes; see Kennett and Stott, this volume, their Fig. 13) than to the situation proposed for the Eocene (with formation of deep to intermediate waters at low latitudes only).

The similarity of the faunas at Sites 689 and 690 strongly indicates that there was no major water mass boundary between the two sites during the Maestrichtian through Neogene; the much greater variability in faunas (both in diversity and in composition) at Site 689, however, might indicate that this shallower site was located at a depth that was close to (but slightly below) such a water mass boundary for most of its Cenozoic history.

The faunas of upper assemblage 4 and assemblage 3 (middle to late Eocene) show trends that have been described from many other sections, that is, a gradual faunal change during the late middle Eocene, with extinctions and originations throughout the middle Eocene and lowermost Oligocene (e.g., Corliss, 1981; Miller, 1983; Tjalsma and Lohmann, 1983; Corliss et al., 1984; Snyder et al., 1984; Corliss and Keigwin, 1986; Miller and Katz, 1987a; Culver, 1987; Berggren and Miller, 1989). These faunal changes parallel the oxygen isotopic record of benthic forami-

fers, which shows a continuous decrease in temperature of the deep waters starting in the middle Eocene (e.g., Corliss and Keigwin, 1986; Oberhaensli, 1986; Oberhaensli and Hsü, 1986; Shackleton, 1986; Keigwin and Corliss, 1986; Miller et al., 1987a; Kennett and Stott, this volume). It is not clear what exactly caused these long-term changes in the benthic foraminiferal faunas at the Maud Rise sites, but the parallelism between the oxygen isotopic record and benthic faunal records suggests that the temperature decrease was at least one of the causes. Possibly the decrease in temperature made  $\text{CaCO}_3$  less easily available to the deep-sea benthic foraminiferal faunas (because of its increased solubility at lower temperatures): at the Maud Rise sites the species that had last appearances during the middle to early late Eocene include all the large and heavily calcified species (such as *Bulimina semicostata*). In addition, the decrease in temperature may have caused an increase in oxygen content of the deep and intermediate waters (because of its increased solubility at lower temperatures), thus causing the local extinction of many infaunal species (such as several lenticulinid and uniserial lagenid species).

Benthic foraminiferal faunas underwent only minor extinctions at the end of the Eocene (Corliss, 1981; Miller, 1983; Tjalsma and Lohmann, 1983; Corliss et al., 1984; Miller et al., 1984; Thomas, 1985). Some extinctions occurred at the Eocene/Oligocene boundary or slightly later, at the major increase in  $\delta^{18}\text{O}$  in benthic foraminifers (e.g., Corliss, 1981; Corliss et al., 1984). At Sites 689 and 690, the end of the period of faunal change, said to extend from the middle Eocene through the lower Oligocene (e.g., Culver, 1987) apparently occurred slightly earlier than at lower latitude sites. This end of faunal turnover (and beginning of stable faunas) occurred at the lower boundary of assemblage 2. This assemblage boundary is located at an unconformity at Site 690, and thus cannot be dated precisely at that site (Pospichal and Wise, this volume, chapter 37; Stott and Kennett, this volume, chapter 34). The boundary is, however, definitely within the Eocene at Site 689, where it occurs at the calcareous nannofossil Zone CP15a/15b boundary (Pospichal and Wise, this volume, chapter 37), and below the last appearance of the planktonic foraminifer *Globigerinatheka index* (Stott and Kennett, this volume, chapter 34) (estimated at 38.4 Ma). The benthic faunal boundary is clearly below the well-documented increase in  $\delta^{18}\text{O}$  values in benthic foraminifers, which occurred worldwide in the lowermost Oligocene (at 122 mbsf at Site 689, above the benthic assemblage boundary at 130 mbsf).

There is thus no clear indication in the benthic foraminiferal record at Sites 689 (lower bathyal) and 690 (upper abyssal) of a sudden or short-lived event indicating the establishment of the psychrosphere. The Maud Rise data support many earlier records of gradual changes during the upper middle to upper Eocene (see above, and Benson et al., 1984). These faunal changes involve the disappearance and appearance of more taxa than the faunal change in benthic foraminifera during the early-middle Miocene (see below).

The last benthic foraminiferal assemblage boundary at the Maud Rise sites occurred at some time during the middle Miocene, and appears to be coeval with the faunal change recorded at that time from many other sites (e.g., Woodruff and Douglas, 1981; Thomas, 1985; Woodruff, 1985; Thomas, 1986a, 1986b; Miller and Katz, 1987a; Thomas and Vincent, 1987; Thomas and Vincent, 1988; Woodruff and Savin, 1989). Precise age determinations of this event have varied (compare Woodruff and Douglas, 1981, with Thomas and Vincent, 1987; Miller and Katz, 1987a), but at Sites 689 and 690 no precise determinations can be made because of the strong  $\text{CaCO}_3$  dissolution at this time. At both sites the assemblage boundary between assemblages 2 and 1 occurs in an interval barren of benthic foraminifers, which has been placed in the *Denticulopsis hustedtii-Den-*

*ticulopsis lauta-Nitzschia denticulinoides* diatom zone (Burckle and Gersonde in Barker et al., 1988) and in the upper *Actinomma tanyacantha* to lower *Cycladophora spongothorax* radiolarian zones (Gersonde et al., this volume); the age of the barren interval is estimated at 14.9–11.55 Ma by these authors.

## CONCLUSIONS

The conclusions of this study are as follows:

1. Major changes in deep-sea benthic foraminiferal assemblages (and thus probably in deep-water characteristics) occurred at the early/late Maestrichtian boundary, at the early/late Paleocene boundary, in the late Paleocene, in the middle early to late early Eocene, in the middle middle Eocene, in the late Eocene, and in the early-middle Miocene. These major changes probably can be recognized world-wide, although specific first and last appearances may be diachronous.

2. There was no major extinction of deep-sea benthic foraminifers at the end of the Cretaceous; the most important extinction of the Maestrichtian through Neogene occurred at the end of the Paleocene, a time at which planktonic organisms did not have a high extinction rate.

3. Records of faunal composition (percentage of specimens belonging to infaunal species) indicate that deep to intermediate waters in the Maud Rise area were well oxygenated during the Maestrichtian through early Paleocene and during the latest Eocene through the Neogene. They were less well ventilated during the late Paleocene and middle to early late Eocene, and least ventilated during the latest Paleocene through earliest Eocene.

4. The benthic foraminiferal records from Maud Rise suggest that there was no simple transition from deep-water formation at low latitudes to deep-water formation at high latitudes at some time during the Paleogene. These records suggest that waters bathing Maud Rise formed at high latitudes during the Maestrichtian through early Paleocene and the late middle Eocene through the Neogene. There was probably a period of extensive formation of deep waters at low latitudes at the end of the Paleocene, causing the benthic foraminiferal extinction.

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## REFERENCES

- Alvarez, W., 1986. Toward a theory of impact crises. *EOS (Am. Geophys. Union Trans.)*, 67:649–658.
- Anderson, J. B., 1975. Ecology and distribution of foraminifera in the Weddell Sea of Antarctica. *Micropaleontology*, 21:69–96.
- Arthur, M. A., Zachos, J. C., and Jones, D. S., 1987. Primary productivity and the Cretaceous/Tertiary boundary event in the oceans. *Cret. Res.*, 8:43–54.
- Askin, R. A., 1989. Endemism and heterochroneity in the Seymour Island Campanian to Paleocene palynofloras: implications for origins, dispersal and palaeoclimates of southern floras. In Crame, J. A. (Ed.), *Origins and evolution of Antarctic biota*. Geol. Soc. London, Spec. Publ., 47:107–120.

- Aubry, M.-P., Berggren, W. A., Kent, D. V., Flynn, J. J., Klitgord, K. D., Obradovich, J. D., and Prothero, D. R., 1988. Paleogene chronology: an integrated approach. *Paleoceanography*, 3:707-742.
- Barker, P. F., Kennett, J. P., et al., 1988. *Proc. ODP, Init. Repts.*, 113: College Station, TX (Ocean Drilling Program).
- Barrera, E., Huber, B. T., Savin, S. M., and Webb, P. N., 1987. Antarctic marine temperatures: late Campanian through early Paleocene. *Paleoceanography*, 2:21-48.
- Barron, E. J., Thompson, S. L., and Schneider, S. H., 1981. An ice-free Cretaceous?—results from climate model simulations. *Science*, 223: 1135-1141.
- Barron, E. J., 1985. Explanations of the Tertiary global cooling trend. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 50:45-61.
- , 1987. Eocene equator-to-pole surface ocean temperatures: a significant climate problem? *Paleoceanography*, 2:729-740.
- Basov, I. A., and Krasheninnikov, A., 1983. Benthic foraminifera in Mesozoic and Cenozoic sediments of the southwestern Atlantic as an indicator of paleoenvironment. In Ludwig, W. J., Krasheninnikov, V. A., et al., *Init. Repts. DSDP*, 71, pt. 2: Washington (U.S. Govt. Printing Office), 739-788.
- Beckmann, J.-P., 1960. Distribution of benthic foraminifera at the Cretaceous-Tertiary boundary of Trinidad (West-Indies). *Internat. Geol. Cong. Rept. 21st Session, Norden Part V: The Cretaceous-Tertiary Boundary*, 57-69.
- Beckmann, J.-P., Bolli, H. M., Kleboth, P., and Proto-Decima, F., 1982. Micropaleontology and biostratigraphy of the Campanian to Paleocene of the Monte Giglio, Bergamo Province, Italy. *Mem. Sci. Geol., Univ. di Padova*, 35:91-172.
- Benson, R. H., Chapman, R. E., and Deck, L. T., 1984. Paleoceneographic events and deep-sea ostracods. *Science*, 224:1334-1336.
- Berger, W. H., Vincent, E., and Thierstein, H. R., 1981. The deep-sea record: major steps in Cenozoic ocean evolution. *Soc. Econ. Paleont. Min. Pub.*, 32:489-504.
- Berggren, W. A., and Aubert, J., 1975. Paleocene benthic foraminiferal biostratigraphy, paleobiogeography and paleoecology of Atlantic-Tethyan regions: Midway-type fauna. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 18:73-192.
- , 1976a. Late Paleogene (late Eocene and Oligocene) benthic foraminiferal biostratigraphy and paleobathymetry of Rockall Bank and Hatton-Rockall Basin. *Micropaleontology*, 22:307-326.
- , 1976b. Eocene benthic foraminiferal biostratigraphy and paleobathymetry of Orphan Knoll (Labrador Sea). *Micropaleontology*, 22:327-346.
- Berggren, W. A., Kent, D. V., Flynn, J. J., and Van Couvering, J. A., 1985. Cenozoic geochronology. *Geol. Soc. Am. Bull.*, 96: 1407-1418.
- Berggren, W. A., and Miller, K. G., 1989. Cenozoic bathyal and abyssal calcareous benthic foraminiferal zonation. *Micropaleontology*, 35: 308-320.
- Berggren, W. A., and Schnitker, D., 1983. Cenozoic marine environments in the North Atlantic and Norwegian-Greenland Sea. In Bott, M.H.P., Saxov, S., Talwani, M., and Thiede, J. (Eds.), *Structure and Development of the Greenland-Scotland Ridge*. NATO Conference Series. New York (Plenum Press), 495-548.
- Bernard, J. M., 1986. Characteristic assemblages and morphologies of benthic foraminifera from anoxic, organic-rich deposits: Jurassic through Holocene. *J. Foram. Res.*, 16:207-215.
- Birkenmayer, K., and Zastawniak, E., 1989. Late Cretaceous-Tertiary floras of King George Island, West Antarctica: their stratigraphic distribution and palaeoclimatic significance. In Crame, J. A. (Ed.), *Origins and evolution of Antarctic biota*. Geol. Soc. London, Spec. Publ., 47:227-240.
- Boersma, A., 1984. Oligocene and other Tertiary benthic foraminifera from a depth traverse down Walvis Ridge, DSDP Leg 74, Southeast Atlantic. In Hay, W. W., Sibuet, J. C., et al., *Init. Repts. DSDP*, 75: Washington (U.S. Govt. Printing Office), 1273-1300.
- Boersma, A., Premoli-Silva, I., and Shackleton, N. J., 1987. Atlantic Eocene planktonic foraminiferal paleohydrographic indicators and stable isotope paleoceanography. *Paleoceanography*, 2:287-331.
- Boltovskoy, E., 1987. Tertiary benthic foraminifera in bathyal deposits of the Quaternary world ocean. *J. Foram. Res.*, 17: 279-285.
- Braga, G., deBiase, R., Grunig, A., and Proto-Decima, F., 1975. Foraminiferi bentonici del Paleocene e dell'Eocene della Sezione Posagno. *Schweiz. Pal. Abh.*, 97:85-111.
- Brass, G. W., Southam, J. R., and Peterson, W. H., 1982. Warm saline bottom water in the ancient ocean. *Nature*, 296:620-623.
- Caraip, M. H., 1984. Impact de la matière organique dans des zones de forte productivité sur certains foraminifères benthiques. *Oceanol. Acta*, 7:509-515.
- Challoner, W. G., and Creber, G. T., 1989. The phenomenon of forest growth in Antarctica: a review. In Crame, J. A. (ed.), *Origins and Evolution of Antarctic Biota*. Geol. Soc. London, Spec. Publ., 47: 85-88.
- Chamberlin, T. C., 1906. On a possible reversal of deep-sea circulation and its influence on geologic climates. *J. Geol.*, 14:363-373.
- Comiso, J. C., and Gordon, A. L., 1987. Recurring Polynyas over the Cosmonaut Sea and the Maud Rise. *J. Geophys. Res.*, 92:2819-2833.
- Corliss, B. H., 1981. Deep-sea benthic foraminiferal faunal turnover near the Eocene/Oligocene boundary. *Mar. Micropaleontol.*, 6:367-384.
- Corliss, B. H., and Chen, C., 1988. Morphotype patterns of Norwegian deep-sea benthic foraminifera and ecological implications. *Geology*, 16:716-719.
- Corliss, B. H., and Keigwin, L. D., 1986. Eocene-Oligocene paleoceanography. In *Mesozoic and Cenozoic Oceans*, *Am. Geophys. Union Geodynamics Series*, 15:101-118.
- Corliss, B. H., Aubry, M.-P., Berggren, W. A., Fenner, J. M., Keigwin, L. D., and Keller, G., 1984. The Eocene/Oligocene boundary in the Deep Sea. *Nature*, 226:806-810.
- Culver, S. J., 1987. Foraminifera. In Lipps, J. H. (Ed.), *Fossil Prokaryotes and Protists*. University of Tennessee Studies in Geology, 18: 169-212.
- Cushman, J. A., 1946. Upper Cretaceous Foraminifera of the Gulf Coastal Region of the United States and adjacent areas. *U. S. Geol. Surv. Prof. Paper*, 206, 241 p.
- Dailey, D. H., 1983. Late Cretaceous and Paleocene benthic foraminifera from Deep Sea Drilling Project Site 516, Rio Grande Rise, western South Atlantic. In Barker, P. F., Carlson, R. L., Johnson, D. A., et al., *Init. Repts. DSDP*, 74: Washington (U.S. Govt. Printing Office), 757-782.
- Deacon, G.E.R., 1976. The cyclonic circulation in the Weddell Sea. *Deep-Sea Res.*, 23:125-126.
- Douglas, R. G., and Savin, S. M., 1975. Oxygen and carbon isotope analyses of Tertiary and Cretaceous microfossils from Shatsky Rise and other sites in the North Pacific Ocean. In Larson, R. L., Moberly, R., et al., *Init. Repts. DSDP*, 32: Washington (U.S. Govt. Printing Office), 509-520.
- Douglas, R. G., and Woodruff, F., 1981. Deep sea benthic foraminifera. In Emiliani, C. (Ed.), *The Oceanic Lithosphere*. The Sea, 7:1233-1327.
- Echols, R. J., 1971. Distribution of foraminifera in sediments of the Scotia Sea area, Antarctic waters. In Reid, J. L. (Ed.), *Antarctic Oceanology*. *Am. Geophys. Union Antarctic Res. Ser.*, 15:93-168.
- Foster, T. D., and Carmack, E. C., 1976. Temperature and salinity structure in the Weddell Sea. *J. Phys. Oceanology*, 6:36-44.
- Frakes, L. A., 1979. *Climates Throughout Geologic Time*. Elsevier Scientific Publ. Co., Amsterdam (Netherlands).
- Frakes, L. A., and Francis, J. E., 1988. A guide to Phanerozoic cold polar climates from high-latitude ice-rafting in the Cretaceous. *Nature*, 333:547-549.
- Gill, A. E., 1973. Circulation and bottom water production in the Weddell Sea. *Deep Sea Res.*, 20:111-140.
- Gregory, R. T., Douthitt, C. B., Duddy, I. R., Rich, P. V., and Rich, T. H., 1989. Oxygen isotopic composition of carbonate concretions from the lower Cretaceous of Victoria, Australia: implications for the evolution of meteoric waters on the Australian continent in a paleopolar position. *Earth Planet. Sci. Lett.*, 92:27-42.
- Hay, W. W., 1988. Paleoceanography: a review for the GSA Centennial. *Geol. Soc. Am. Bull.*, 100:1934-1956.
- Hu, X., Wang, Y. L., and Schmitt, R., 1988. Geochemistry of sediments on the Rio Grande Rise and the redox evolution of the South Atlantic Ocean. *Geochim. Cosmochim. Acta*, 52:201-208.
- Huber, B. T., 1988. Upper Campanian-Paleocene foraminifera from the James Ross Island region, Antarctic Peninsula. *Geol. Soc. Am. Mem.*, 169:163-252.
- Katz, M. R., and Miller, K. G., in press. Early Paleogene benthic foraminiferal assemblage and stable isotope composition in the Southern

- Ocean, Ocean Drilling Program Leg 114. In Ciesielski, P. F., Kristofferson, Y., et al., *Proc. ODP Init. Repts.*, 114: College Station, TX (Ocean Drilling Program).
- Keigwin, L. D., and Corliss, B. H., 1986. Stable isotopes in late middle Eocene through Oligocene foraminifera. *Geol. Soc. Am. Bull.*, 97: 335-345.
- Kennett, J. P., 1977. Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Ocean, and their impact on global paleoceanography. *J. Geophys. Res.*, 82:3843-3860.
- Kurihara, K., and Kennett, J. P., 1988. Bathymetric migration of deep-sea benthic foraminifera in the Southwest Pacific during the Neogene. *J. Foraminif. Res.*, 18:75-83.
- Leckie, R. M., and Webb, P.-N., 1985. Late Paleogene and early Neogene foraminifera of Deep Sea Drilling Project Site 270, Ross Sea, Antarctica. In Kennett, J. P., Von Der Borch, C. C., et al., *Init. Repts. DSDP, 90*: Washington (U.S. Govt. Printing Office), 1093-1142.
- Loeblich, A. R., and Tappan, H., 1988. *Foraminiferal Genera and Their Classification*: New York (Van Nostrand Reinhold).
- Lutze, G. F., and Coulbourn, W. T., 1984. Recent benthic foraminifera from the continental margin of Northwest Africa: community structure and distribution. *Mar. Micropaleontol.*, 8:361-401.
- Manabe, S., and Bryan, K., 1985. CO<sub>2</sub>-induced change in a coupled ocean-atmosphere model and its paleoclimatic implications. *J. Geophys. Res.*, 90:11689-11707.
- Miller, K. G., 1983. Eocene-Oligocene paleoceanography of the deep Bay of Biscay: benthic foraminiferal evidence. *Mar. Micropaleontol.*, 7:403-440.
- Miller, K. G., Curry, W. B., and Ostermann, D. R., 1984. Late Paleogene (Eocene to Oligocene) benthic foraminiferal oceanography of the Goban Spur Region, Deep Sea Drilling Project Leg 80. In De Graciansky, P. G., Poag, C. W., et al., *Init. Repts. DSDP, 80*: Washington (U.S. Govt. Printing Office), 505-538.
- Miller, K. G., and Fairbanks, R. G., 1985. Oligocene-Miocene global carbon and abyssal circulation changes. In Sundquist, E., and Broecker, W. S., (Eds.), *The Carbon Cycle and Atmospheric CO<sub>2</sub>: Natural Variations, Archean to Present*. Am. Geophys. Union Monogr. Series, 32:469-486.
- Miller, K. G., Fairbanks, R. G., and Mountain, G. S., 1987a. Tertiary isotope synthesis, sea level history, and continental margin erosion. *Paleoceanography*, 2:1-20.
- Miller, K. G., Janecek, T. R., Katz, M. E., and Keil, D. J., 1987b. Abyssal circulation and benthic foraminiferal changes near the Paleocene/Eocene boundary. *Paleoceanography*, 2:741-761.
- Miller, K. G., and Katz, M. E., 1987a. Eocene benthic foraminiferal biofacies of the New Jersey transect. In Poag, C. W., Watts, A. B., et al., *Init. Repts. DSDP, 95*: Washington (U.S. Govt. Printing Office), 267-298.
- , 1987b. Oligocene to Miocene benthic foraminiferal and abyssal circulation changes in the North Atlantic. *Micropaleontology*, 33:97-149.
- Morkhoven, F.P.C.M. van, Berggren, W. A., and Edwards, A. S., 1986. Cenozoic cosmopolitan deep-water benthic Foraminifera. *Bull. Centres Rech. Exploration Production Elf-Aquitaine, Mem.*, 11, Pau, France, 421 p.
- Mount, J. F., Margolis, S. V., Showers, W., Ward, P., and Doehne, E., 1986. Carbon and oxygen isotope stratigraphy of the upper Maestrichtian, Zumaya, Spain: a record of oceanographic and biologic changes at the end of the Cretaceous Period. *Palaio*, 1:87-91.
- Murray, J. W., 1984. Paleogene and Neogene benthic foraminifera from Rockall Plateau. In Roberts, D. G., Schnitker, K., et al., *Init. Repts. DSDP, 81*: Washington (U.S. Govt. Printing Office), 503-534.
- Nyong, E. E., and Olsson, R. K., 1984. A paleoslope model of Campanian to lower Maestrichtian Foraminifera in the North American basin and adjacent continental margin. *Mar. Micropal.*, 8:437-477.
- Oberhaensli, H., 1986. Latest Cretaceous-early Neogene oxygen and carbon isotopic record at DSDP sites in the Indian Ocean. *Mar. Micropal.*, 10:91-115.
- Oberhaensli, H., and Hsü, K. J., 1986. Paleocene-Eocene paleoceanography. In Hsü, K. J., (Ed.), *Mesozoic and Cenozoic Oceans, Geodynamics Series Am. Geophys. Union*, 15:85-100.
- Oberhaensli, H., and Toumarkine, M., 1985. The Paleogene oxygen and carbon isotope history of Sites 522, 523, and 524 from the central south Atlantic. In Hsü, K. H., and Weissert, H. J., (Eds.), *South Atlantic Paleoceanography*, Cambridge University Press (Cambridge, U.K.): 125-147.
- Obradovich, J. D., 1988. A different perspective on glauconite as a chronometer for geologic time scale studies. *Paleoceanography*, 3: 757-770.
- Odin, G. S., and Curry, D., 1985. Palaeogene time-scale: radiometric dating versus magnetostratigraphic approach. *J. Geol. Soc. London*, 142:1179-1188.
- Officer, C. B., Hallam, A., Drake, C. L., and Devine, J. D., 1987. Late Cretaceous and paroxysmal Cretaceous/Tertiary extinctions. *Nature*, 326:143-149.
- Owen, R. M., and Rea, D. K., 1985. Sea-floor hydrothermal activity links climate to tectonics: the Eocene carbon dioxide greenhouse. *Science*, 227:166-169.
- Plummer, H. J., 1926. Foraminifera of the Midway Formation in Texas. *Univ. Texas Bull.*, 2644, 171 p.
- Prentice, M. L., and Matthews, R. K., 1988. Cenozoic ice-volume history: development of a composite oxygen isotope record. *Geology*, 16:963-966.
- Proto-Decima, F., and Bolli, H. M., 1978. Southeast Atlantic DSDP Leg 40 Paleogene benthic foraminifera. In Bolli, H. M., Ryan, W.B.F., et al., *Init. Repts. DSDP, 40*: Washington (U.S. Govt. Printing Office), 783-810.
- Pudsey, C. J., Barker, P. F., and Hamilton, N., 1988. Weddell Sea abyssal sediments: a record of Antarctic bottom water flow. *Mar. Geol.*, 81:289-314.
- Raup, D. M., and Sepkoski, J. J., 1986. Periodic extinction of families and genera. *Science*, 231:833-836.
- Savin, S. M., 1977. The history of the Earth's surface temperature during the past 100 million years. *Ann. Rev. Earth Plan. Sci.*, 5:319-344.
- Schnitker, D., 1979. Cenozoic deep-water benthic foraminifera, Bay of Biscay. In Montadert, L., Roberts, D. G., et al., *Init. Repts. DSDP, 48*: Washington (U.S. Govt. Printing Office), 377-414.
- , 1980. Global paleoceanography and its deep water linkage to the Antarctic glaciation. *Earth Sci. Rev.*, 16:1-20.
- Schroeder, C. J., Scott, D. B., and Medioli, F. S., 1987. Can smaller benthic foraminifera be ignored in paleoenvironmental analyses? *J. Foraminif. Res.*, 17:101-105.
- Sen Gupta, B. K., Lee, R. F., and Mallory, S. M., 1981. Upwelling and an unusual assemblage of benthic foraminifera on the northern Florida continental slope. *J. Paleont.*, 55:857.
- Shackleton, N. J., 1986. Paleogene stable isotope events. *Palaeoogeogr., Palaeoclimatol., Palaeoecol.*, 57:91-102.
- , 1987. The carbon isotope record of the Cenozoic: history of organic carbon burial and of oxygen in the ocean and atmosphere. In Brooks, J., and Fleet, A. J. (Eds.), *Marine Petroleum Source Rocks*, Geol. Soc. Spec. Pub., 26:423-434.
- Shackleton, N. J., Corfield, R. M., and Hall, M. A., 1985. Stable isotope data and the ontogeny of Paleocene planktic foraminifera. *J. Foraminif. Res.*, 15:321-336.
- Sheehan, P. M., and Hansen, T. A., 1986. Detritus feeding as a buffer to extinction at the end of the Cretaceous. *Geology*, 14:868-870.
- Sliter, W. V., 1976. Cretaceous foraminifera from the southwestern Atlantic Ocean, Leg 36, Deep Sea Drilling Project. In Barker, P. F., Dalziel, I.W.D., et al., *Init. Repts. DSDP, 36*: Washington (U.S. Govt. Printing Office):519-574.
- Snyder, S. W., Mueller, C., and Miller, K. G., 1984. Eocene-Oligocene boundary biostratigraphic recognition and gradual paleoceanographic change at DSDP Site 549. *Geology*, 12:112-115.
- Thomas, E., 1985. Late Eocene to Recent deep-sea benthic foraminifera from the central equatorial Pacific Ocean. In Mayer, L., Theyer, F., et al., *Init. Repts. DSDP, 85*: Washington (U.S. Govt. Printing Office): 655-694.
- , 1986a. Changes in composition of Neogene benthic foraminiferal faunas in equatorial Pacific and North Atlantic. *Palaeoogeogr., Palaeoclimatol., Palaeoecol.*, 57:47-61.
- , 1986b. Early to middle Miocene benthic foraminiferal faunas from DSDP Sites 608 and 610, North Atlantic. In Summerhayes, C. P., and Shackleton, N. J. (Eds.), *North Atlantic Palaeoceanography*. Geol. Soc. Spec. Pub., 21:205-218.
- , 1989. Development of Cenozoic deep-sea benthic foraminiferal faunas in Antarctic waters. In Crame, J. A. (Ed.), *Origins and Evolution of Antarctic Biota*. Geol. Soc. London, Spec. Publ., 47: 283-296.

- \_\_\_\_\_, in press. Late Cretaceous—early Eocene mass extinctions in the deep sea. *Global Catastrophes*. Geol. Soc. Am. Spec. Publ.
- Thomas, E., and Vincent, E., 1987. Equatorial Pacific deep-sea benthic foraminifera: faunal changes before the middle Miocene polar cooling. *Geology*, 15:1035–1039.
- \_\_\_\_\_, 1988. Early to middle Miocene deep-sea benthic foraminifera in the Pacific Ocean. *Rev. Paleobiol. Spec. Vol. 2* (BENTHOS'86): 583–588.
- Tjalsma, R. C., 1983. Eocene to Miocene benthic foraminifera from DSDP Site 516, Rio Grande Rise, South Atlantic. In Barker, P. F., Carlson, R. L., Johnson, D. A., et al., *Init. Repts. DSDP*, 74: Washington (U.S. Govt. Printing Office), 731–756.
- Tjalsma, R. C., and Lohmann, G. P., 1983. Paleocene-Eocene bathyal and abyssal benthic foraminifera from the Atlantic Ocean. *Micro-pal. Spec. Publ.*, 4, 94 p.
- Tolmazin, D., 1985. *Elements of Dynamic Oceanography*. Allen and Unwin, London.
- Vincent, E., Gibson, J. M., and Brun, L., 1974. Paleocene and early Eocene microfossils, benthic foraminifera, and paleobathymetry of Deep Sea Drilling Project Sites 236 and 237, Western Indian Ocean. In Fisher, R. L., Bunce, E. T., et al., *Init. Repts. DSDP*, 17: Washington (U.S. Govt. Printing Office), 607–671.
- Warren, B. A., 1981. Deep circulation of the world ocean. In Warren, B. A., and Wunsch, C. (Eds.), *Scientific Surveys in Honor of Henry Stommel* (MIT Press, Cambridge, Mass.):6–41.
- Webb, P. N., 1973. Upper Cretaceous-Paleocene foraminifera from Site 208 (Lord Howe Rise, Tasman Sea), DSDP Leg 21. In Burns, R. E., Andrews, J. E., et al., *Init. Repts. DSDP*, 21: Washington (U.S. Govt. Printing Office), 541–573.
- Webb, P. N., Leckie, R. M., and Ward, B. L., 1986. Foraminifera (Oligocene). In Barrett, P. J. (Ed.), *Antarctic Cenozoic history from the MSTSS-1 drillhole, McMurdo Sound. Science Information Publishing Centre, Wellington, New Zealand*: 115–125.
- Whitehead, J. A., 1989. Giant Ocean Cataracts. *Sci. Am.*, 260: 50–59.
- Wilde, P., and Berry, W.B.N., 1982. Progressive ventilation of the oceans—a potential for return to anoxic conditions in the post-Paleozoic. In Schlanger, S. O., and Cita, M. B. (Eds.), *Nature and Origin of Cretaceous Carbon-Rich Facies*: London (Academic Press), 209–224.
- Williams, C. A., 1986. An ocean-wide view of plate tectonic events. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 57:3–26.
- Wind, F. H., and Wise, S. W., 1983. Correlation of Upper Campanian-lower Maestrichtian calcareous nannofossil assemblages in drill and piston cores from the Falkland Plateau, southwest Atlantic Ocean. In Ludwig, W. J., Krashennikov, V. A., et al., *Init. Repts. DSDP*, 71, pt. 2: Washington (U.S. Govt. Printing Office), 551–564.
- Wood, K. C., Miller, K. G., and Lohmann, G. P., 1985. Middle Eocene to Oligocene benthic foraminifera from the Oceanic Formation, Barbados. *Micro-paleontology*, 31:181–197.
- Woodruff, F., 1985. Changes in Miocene deep-sea benthic foraminiferal distribution in the Pacific Ocean: relationship to paleoceanography. In Kennett, J. P. (Ed.), *The Miocene Ocean: Paleoceanography and Biogeography*. Geol. Soc. Am. Mem., 163:131–176.
- Woodruff, F., and Douglas, R. G., 1981. Response of deep-sea benthic foraminifera to Miocene paleoclimatic events, DSDP Site 289. *Mar. Micropal.*, 6:617–632.
- Woodruff, F., and Savin, S. M., 1989. Miocene deep water oceanography. *Paleoceanography*, 4:87–140.
- Worthington, L. V., 1972. On the North Atlantic circulation. *Johns Hopkins Oceanogr. Stud.*, 6, 110 p.
- Zachos, J. C., and Arthur, M. A., 1986. Paleoceanography of the Cretaceous/Tertiary boundary event: inferences from stable isotope and other data. *Paleoceanography*, 1:5–26.

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#### APPENDIX 1: FAUNAL LIST

##### Epifaunal, Infaunal, and Cylindrical Morphotypes

In subdividing the species into the different morphotypes, the classification of Corliss and Chen (1988) was followed as much as possible.

All agglutinated species were excluded from the analysis. Taxa were assigned to a specific group according to their test morphology.

Epifaunal taxa: rounded trochospiral morphotypes (*Gyroidinoides* spp.); planoconvex trochospiral morphotypes (*Alabamina*, *Anomalina*, *Anomalinoidea*, *Cibicides*, *Cibicidoides*, *Gavelinella*, *Valvulineria*); milioline morphotypes (all miliolid species); and biconvex trochospiral morphotypes (*Conorbina*, *Epistominella*, *Globorotalites*, *Nuttallides*, *Eponides*, *Lenticulina*, *Neoponides*, *Oridorsalis*, *Osangularia*).

Infaunal taxa: rounded planispiral morphotypes (*Astrononion*, *Melonis*, *Nonion*, *Nonionella*, most *Pullenia* species); flattened ovoid morphotypes (*Cassidulina*, some unilocular taxa—*Fissurina* spp.—polymorphinids); tapered and flattened-tapered morphotypes (*Aragonia*, *Bolivinoidea*, *Bulimina*, *Coryphostoma*, *Eouvigerina*, *Francesita*, *Fursenkoina*, *Globobulimina*, *Praebulimina*, *Rectobulimina*, *Reussella*, *Siphogenerinoidea*, *Tappanina*, *Turrilina*, *Uvigerina*); spherical morphotypes (*Globocassidulina*), some unilocular taxa—*Lagena* spp., *Pullenia bulloides*, *Pullenia coryelli*.

Cylindrical taxa: uniserial lagenids (including *Nodosaria* and *Dentalina* species), *Pleurostomella* spp., *Nodosarella* spp., *Stilostomella* species.

##### Alphabetic List of Species Recorded at Sites 689 and 690

- Abyssamina poagi* Schnitker and Tjalsma  
*Abyssamina quadrata* Schnitker and Tjalsma  
*Abyssamina* sp.  
 Agglutinants, other  
*Alabamina creta* (Finlay) = *Pulvinulinella creta* Finlay; synonym:  
*A. solnaesensis* Brotzen  
*Alabamina dissonata* (Cushman and Renz) = *Pulvinulinella atlantisae* Renz var. *dissonata* Cushman and Renz  
*Alabamina midwayensis* Brotzen  
*Allomorphina trigona* Reuss  
*Angulogerina earlandi* Parr  
*Angulogerina szajnochae* (Grzybowski) = *Verneuilina szajnochae* Grzybowski  
*Anomalina alazanensis* Nuttall  
*Anomalina spissiformis* Cushman and Stainforth = *Anomalina alazanensis* var. *spissiformis* Cushman and Stainforth  
*Anomalinoidea acutus* (Plummer) = *Anomalina anomalinoidea* var. *acutus* Plummer  
*Anomalinoidea capitatus* (Guembel) = *Rotalia capitata* Guembel  
*Anomalinoidea pseudogrosserugosus* (Colom) = *Anomalina pseudogrosserugosus* Colom  
*Anomalinoidea semicribratus* (Beckmann) = *Anomalina pompilioides* Galloway and Heminway var. *semicribrata* Beckmann  
*Aragonia aragonensis* (Nuttall) = *Textularia aragonensis* Nuttall  
*Aragonia* sp. 1, Morkhoven et al., p. 374, pl. 122  
*Aragonia velascoensis* (Cushman) = *Textularia velascoensis* Cushman  
*Astrononion pusillum* Hornibrook; synonym: *Astrononion novozealandicum* Cushman and Edwards in Thomas, 1985; 1986  
*Astrononion umbilicatum* Uchida  
*Bigennerina nodosaria* d'Orbigny  
*Bolivina decussata* Brady  
*Bolivina huneri* Howe  
*Bolivina pseudopunctata* Hoeglund  
*Bolivinoidea delicatulus* Cushman = *Bolivinoidea decorata* (Jones) var. *delicatula* Cushman  
*Bolivinoidea draco draco* (Marsson) = *Bolivina draco* Marsson  
*Bolivinoidea draco miliaris* Hiltermann and Koch  
*Bolivinoidea laevigatus* Marie  
*Bolivinoidea* sp. aff. *delicatulus*  
*Bolivinoidea* sp., small  
*Bulimina alazanensis* Cushman  
*Bulimina callahani* Galloway and Morrey  
*Bulimina* cf. *semicostata*  
*Bulimina elongata* d'Orbigny  
*Bulimina macilenta* Cushman and Parker  
*Bulimina ovula* Reuss = *Bulimina ovulum* Reuss; see White, 1929, p. 49, pl. 5, fig. 12  
*Bulimina semicosta* Nuttall  
*Bulimina simplex* Terquem  
*Bulimina thanetensis* Cushman and Parker  
*Bulimina trinitatisensis* Cushman and Jarvis

- Bulimina velascoensis* (Cushman) = *Gaudryina velascoensis* Cushman  
*Buliminella beaumonti* Cushman and Renz  
*Buliminella grata* Parker and Bermudez  
*Cancris* sp.  
*Cassidulina* spp.  
*Ceratobulimina* sp.  
*Charltonina madrugensis* (Cushman and Bermudez) = *Pseudoparrella madrugensis* Cushman and Bermudez  
*Chilostomella ovoidea* Reuss  
*Cibicides lobatulus* (Walker and Jacob) = *Nautilus lobatulus* Walker and Jacob  
*Cibicides variabilis* (d'Orbigny) = *Truncatulina variabilis* d'Orbigny  
*Cibicoides dayi* (White) = *Planulina dayi* White  
*Cibicoides havanensis* (Cushman and Bermudez) = *Cibicides havanensis* Cushman and Bermudez  
*Cibicoides mundulus* (Brady, Parker and Jones) = *Truncatulina mundula* Brady, Parker and Jones  
*Cibicoides perlucidus* (Nuttall) = *Cibicides perlucida* Nuttall  
*Cibicoides praemundulus* van Morkhoven, Berggren and Edwards  
*Cibicoides pseudoperlucidus* (Bykova) = *Cibicides (Gamellides) pseudoperlucidus* Bykova  
*Cibicoides robertsonianus* (Brady) = *Truncatulina robertsoniana* Brady  
*Cibicoides subspiratus* (Nuttall) = *Cibicides subspirata* Nuttall  
*Cibicoides trinitatis* (Nuttall) = *Truncatulina trinitatis* Nuttall  
*Cibicoides wuellerstorfi* (Schwager) = *Anomalina wuellerstorfi* Schwager  
*Clinapertina subplanispira* Tjalsma and Lohmann  
*Conorbina marginata* Brotzen  
*Coryphostoma incrassata* (Reuss) = *Bolivina incrassata* Reuss  
*Coryphostoma midwayensis* (Cushman) = *Bolivina midwayensis* Cushman  
*Cyclammina cancellata* Brady  
*Cyclammina* spp.  
*Dorothia oxycona* (Reuss) = *Gaudryina oxycona* Reuss  
*Dorothia trochoides* (Marsson) = *Gaudryina crassa* Marsson var. *trochoides* Marsson  
*EGgerella bradyi* (Cushman) = *Verneuillina bradyi* Cushman  
*Ehrenbergina* sp.  
*Eilohedra weddellensis* (Earland) = *Eponides weddellensis* Earland  
*Eouvigerina gracilis* Cushman  
*Eouvigerina* sp. aff. *S. brevispinosa* Cushman  
*Epistominella exigua* (Brady) = *Pulvinulina exigua* Brady  
*Eponides* sp.  
*Eponides tumidulus* (Brady) = *Truncatulina tumidula* Brady  
*Francesita advena* (Cushman) = *Virginulina? advena* Cushman  
*Frondicularia* sp.  
*Fursenkoina bradyi* (Cushman) = *Virginulina bradyi* Cushman  
*Fursenkoina davisii* (Chapman and Parr) = *Virginulina davisii* Chapman and Parr  
*Fursenkoina fusiformis* (Williamson) = *Bulimina pupoides* var. *fusiformis* Williamson  
*Fursenkoina navarroana* (Cushman) = *Virginulina navarroana* Cushman  
*Fursenkoina* sp., 1  
*Fursenkoina* sp., 2  
*Fursenkoina tegulata* (Reuss) = *Virgulina tegulata* Reuss  
*Gaudryina laevigata* Franke  
*Gavelinella beccariiiformis* (White) = *Rotalia beccariiiformis* White  
*Gavelinella eriksdalensis* (Brotzen) = *Cibicides (Cibicoides) eriksdalensis* Brotzen  
*Gavelinella hyphalus* (Fisher) = *Anomalinoides hyphalus* Fisher  
*Gavelinella rubiginosa* (Cushman) = *Anomalina rubiginosa* Cushman  
*Gavelinella stephensoni* (Cushman) = *Cibicides stephensoni* Cushman  
*Gavelinella velascoensis* (Cushman) = *Anomalina velascoensis* Cushman  
*Gavelinella* aff. *hyphalus*  
*Globimorphina* sp.  
*Globobulimina ovata* (d'Orbigny) = *Bulimina ovata* d'Orbigny  
*Globocassidulina subglobosa* (Brady) = *Cassidulina subglobosa* Brady  
*Globorotalites conicus* (Carsey) = *Truncatulina refulgens* Montfort var. *conicus* Carsey  
*Globorotalites spineus* (Cushman) = *Truncatulina spinea* Cushman  
*Gravellina narivaensis* Broennimann  
*Gyroidinoides acutus* (Boomgaard) = *Gyroidina neosoldanii* Brotzen var. *acuta* Boomgaard  
*Gyroidinoides depressus* (Alth) = *Rotalina depressa* Alth  
*Gyroidinoides girardanus* (Reuss) = *Rotalina girardana* Reuss  
*Gyroidinoides globosus* (Hagenow) = *Nonionina globosa* Hagenow  
*Gyroidinoides lamarckianus* (d'Orbigny) = *Rotalina lamarckiana* d'Orbigny  
*Gyroidinoides mediceus* (Emiliani) = *Gyroidina medicea* Emiliani  
*Gyroidinoides minutus* (White) = *Gyroidina minuta* White  
*Gyroidinoides planulatus* (Cushman and Renz) = *Gyroidina planulata* Cushman and Renz  
*Gyroidinoides quadratus* (Cushman and Church) = *Gyroidina quadrata* Cushman and Church  
*Gyroidinoides soldanii* (d'Orbigny) = *Gyroidina soldanii* d'Orbigny  
*Gyroidinoides subangulata* (Plummer) = *Rotalia soldanii* d'Orbigny var. *sublata* Plummer  
*Gyroidinoides vortex* (White) = *Gyroidina vortex* White  
*Gyroidinoides* aff. *planulatus*  
*Hanzawaia ammophila* (Guemmel) = *Rotalia ammophila* Guemmel; synonym: *Hanzawaia cushmani* (Nuttall) = *Cibicides cushman* Nuttall  
*Hanzawaia* sp.  
*Haplophragmoides* spp.  
*Heronallenia lingulata* (Burrows and Holland) = *Discorbina lingulata* Burrows and Holland  
*Karriella bradyi* (Cushman) = *Gaudryina bradyi* Cushman  
*Karriella chapapotensis* (Cole) = *Textularia chapapotensis* Cole  
*Karriella retusa* (Cushman) = *Gaudryina retusa* Cushman  
*Karriella* sp., Tjalsma and Lohmann, 1983, pl. 9, figs. 5,6  
*Karriella subglabra* (Guemmel) = *Gaudryina subglabra* Guemmel  
*Laticarinina pauperata* (Parker and Jones) = *Pulvinulina repanda* var. *menardii* subvar. *pauperata* Parker and Jones  
*Lenticulina* spp.  
*Martinotiella* spp.  
*Melonis sphaeroides* Voloshinova  
*Neoeponides hillebrandti* Fisher; synonym: *Rotalia* cf. *partschiana* White (non d'Orbigny)  
*Neoeponides lunata* (Brotzen) = *Eponides lunata* Brotzen  
*Neoflabellina jarvisi* (Cushman) = *Flabellina jarvisi* Cushman  
*Neoflabellina semireticulata* (Cushman and Jarvis) = *Flabellina semireticulata* Cushman and Jarvis  
*Nonion depressulum* (Walker and Jacob) = (*Nautilus depressulus*) Walker and Jacob  
*Nonion havanense* Cushman and Bermudez  
*Nonionella iridea* Heron-Allen and Earland  
*Nonionella labradorica* (Dawson) = *Nonionina labradorica* Dawson  
*Nonionella longicamerata* Bandy  
*Nonionella robusta* Plummer  
*Nuttallides* sp., 1  
*Nuttallides* sp., 2  
*Nuttallides truempyi* (Nuttall) = *Eponides truempyi* Nuttall (group)  
*Nuttallides umbonifera* (Cushman) = *Pulvinulinella umbonifera* Cushman  
*Nuttallinella florealis* (White) = *Gyroidina florealis* White  
*Ophthalmidium pusillum* (Earland) = *Spiroloculina pusilla* Earland  
*Oridorsalis nitidus* (Reuss) = *Rotalina nitida* Reuss  
*Oridorsalis tener* (Brady) = *Truncatulina tenera* Brady  
*Oridorsalis umbonatus* (Reuss) = *Rotalina umbonata* Reuss  
*Osangularia cordierana* (d'Orbigny) = *Rotalina cordierana* d'Orbigny  
*Osangularia interrupta* (Cushman) = *Pulvinulinella interrupta* Cushman  
*Osangularia navarroana* (Cushman) = *Pulvinulinella navarroana* Cushman  
*Osangularia velascoensis* (Cushman) = *Truncatulina velascoensis* Cushman  
*Patellina* sp.  
*Planulina* sp.  
*Pleurostomella* spp.  
*Pleurostomellids*, other  
*Polymorphinids*  
*Praebulimina carseyae* (Plummer) = *Buliminella carseyae* Plummer  
*Praebulimina reussi* (Morrow) = *Bulimina reussi* Morrow  
*Pseudoparrella* sp.; see Thomas, 1985, p. 678  
*Pseudopatellinella* sp., Basov and Krashninnikov, 1983, pl. 4, fig. 5  
*Pullenia bulloides* (d'Orbigny) = *Nonionina bulloides* d'Orbigny  
*Pullenia coryelli* White  
*Pullenia jarvisi* Cushman  
*Pullenia quadriloba* Reuss

- Pullenia quinqueloba* Reuss = *Pullenia compressiuscula* var. *quinqueloba* Reuss  
*Pullenia salisburyi* Stewart and Stewart  
*Pullenia subcarinata* (d'Orbigny) = *Nonionina subcarinata* d'Orbigny  
*Pyramidina rudita* (Cushman and Parker) = *Bulimina rudita* Cushman and Parker  
*Pyrgo* spp.  
*Quadriformina allomorphinoides* (Reuss) = *Valvulina allomorphinoides* Reuss  
*Quadriformina cretacea* (Carsey) = *Rotalia cretacea* Carsey; synonym: *Valvulineria cretacea* Cushman and Todd  
*Quadriformina profunda* Schnitker and Tjalsma  
*Quinqueloculina longirostra* d'Orbigny  
*Quinqueloculina* spp.  
*Ramulina aculeata* (d'Orbigny) = *Dentalina aculeata* d'Orbigny  
*Rectobulimina carpentierae* Marie  
*Reussella pseudospinulosa* Czjzek  
*Reussella tortuosa* Sztrakos  
*Rheophax* sp.  
*Rhezakina epigona* (Rhezak) = *Silicina epigona* Rhezak  
*Rhizammina* sp.  
*Sigmoilina tenuis* (Czjzek) = *Quinqueloculina tenuis* Czjzek  
*Sigmomorphina* sp.  
*Siphogenerinoides brevispinosa* Cushman  
*Siphogenerinoides* aff. *brevispinosa* Cushman  
*Siphogenerinoides eleganta* (Plummer) = *Siphogenerina eleganta* Plummer  
*Siphotextularia* spp.  
*Sphaeroidina bulloides* d'Orbigny  
*Spirillina vivipara* Ehrenberg  
*Spiroloculina* sp.  
*Spiroplectammina annectens* (Cushman) = *Spiroplecta annectens* Cushman  
*Stainforthia complanata* (Egger) = *Virgulina schreibersiana* var. *complanata* Egger  
*Stilostomella aculeata* (Cushman and Renz) = *Ellipsonodosaria nuttalli* Cushman and Jarvis var. *aculeata* Cushman and Renz  
*Stilostomella annulifera* (Cushman and Bermudez) = *Ellipsonodosaria annulifera* Cushman and Bermudez  
*Stilostomella consobrina* (d'Orbigny) = *Dentalina consobrina* d'Orbigny  
*Stilostomella lepidula* (Schwager) = *Nodosaria lepidula* Schwager  
*Stilostomella* sp., smooth  
*Stilostomella subspinosa* (Cushman) = *Ellipsonodosaria subspinosa* Cushman  
*Stilostomella verneuilli* (d'Orbigny) = *Dentalina verneuilli* d'Orbigny  
*Tappanina selmensis* (Cushman) = *Bolivinita selmensis* Cushman  
*Textularia alabamensis* Cushman = *Textularia mississippiensis* Cushman var. *alabamensis* Cushman  
*Textularia* sp.  
*Tritaxia aspera* (Cushman) = *Clavulina aspera* Cushman  
*Tritaxia globulifera* (ten Dam and Sigal) = *Pseudoclavulina globulifera* ten Dam and Sigal  
*Tritaxia havanensis* (Cushman and Bermudez) = *Clavulinoides havanensis* Cushman and Bermudez  
*Tritaxia paleocenica* Tjalsma and Lohmann  
*Tritaxia pyramidata* (Cushman) = *Gaudryina laevigata* Franke var. *pyramidata* Cushman  
*Trochammina globigeriniformis* (Parker and Jones) = *Lituola nautiloidea* var. *globigeriniformis* Parker and Jones  
*Trochamminoides proteus* (Karrer) = *Trochammina proteus* Karrer  
*Turrilina alsatica* Andreae  
*Turrilina brevispira* ten Dam  
*Turrilina robertsi* (Howe and Ellis) = *Bulimina robertsi* Howe and Ellis  
Unilocular species  
Uniserial lagenids  
*Uvigerina graciliformis* Papp  
*Uvigerina hispida* Schwager  
*Uvigerina peregrina* Cushman group  
*Valvulineria camerata* Brotzen  
*Valvulineria complanata* (d'Orbigny) = *Rosalina complanata* d'Orbigny  
*Vulvulina* sp.  
*Vulvulina jarvisi* Cushman  
*Vulvulina mexicana* Nuttall  
*Vulvulina spinosa* Cushman

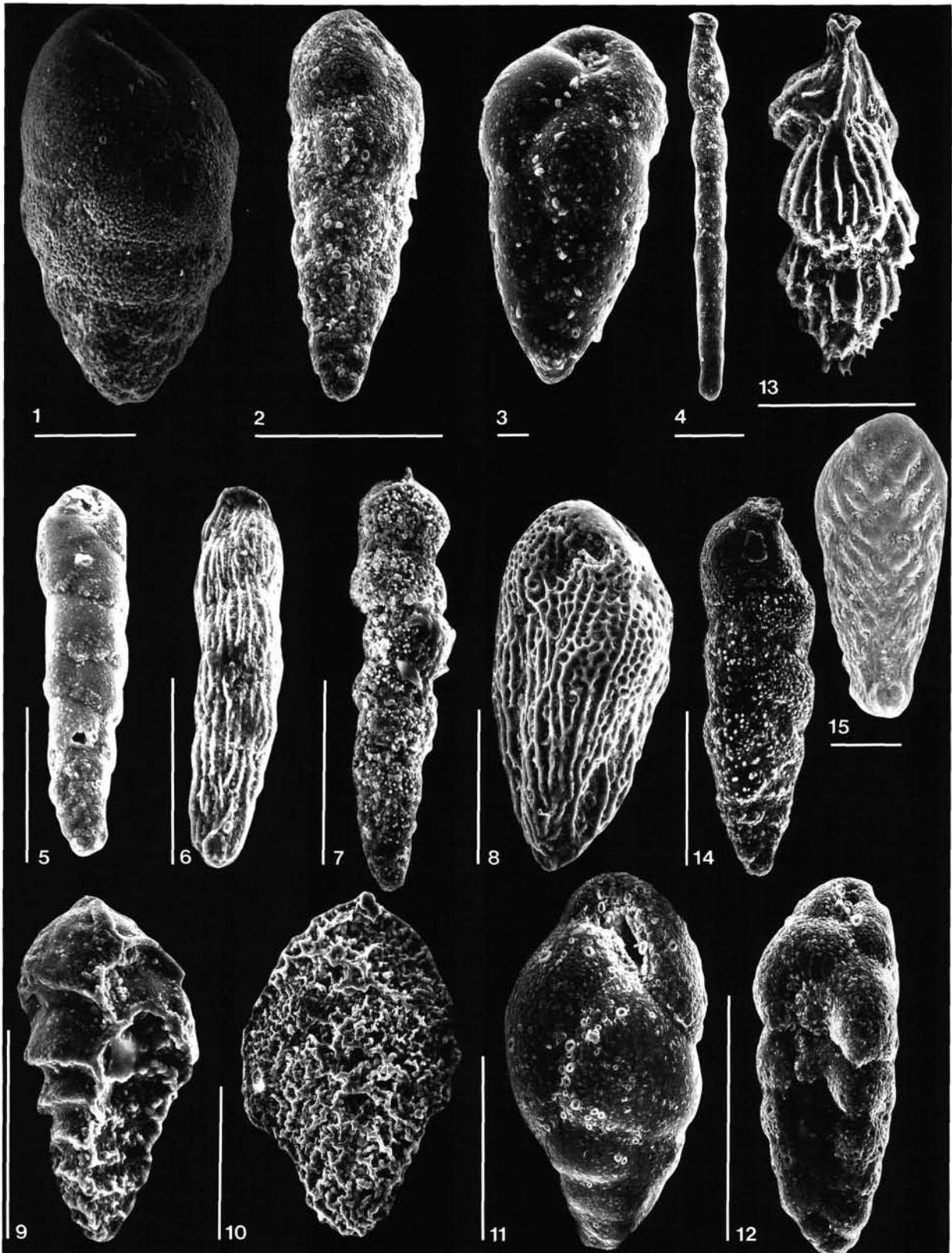


Plate 1. All bars are 100  $\mu$ m. 1. *Bulimina callahani* Galloway and Morrey, 113-689B-19H-2, 39-42 cm. 2. *Bulimina elongata* d'Orbigny, 113-690B-12H-4, 41-45 cm. 3. *Bulimina simplex* Terquem, 113-690B-13H-5, 40-42 cm. 4. *Stilostomella annulifera* (Cushman and Bermudez), 113-690B-12H-5, 40-42 cm. 5. *Bulimina thanetensis* Cushman and Parker, 113-690C-12X-2, 40-42 cm. 6. *Siphogenerinoides eleganta* (Plummer), 113-690B-12H, CC. 7. *Siphogenerinoides brevispinosa* Cushman, 113-690B-18H-4, 40-44 cm. 8. *Bulimina semicostata* Nuttall, 113-690B-12H, CC. 9. *Tappanina selmensis* (Cushman), 113-689B-22X, CC. 10. *Aragonia aragonensis* (Nuttall), 113-689B-22X, CC. 11. *Turrilina alsatica* Andreea, 113-690B-11 H-2, 40-42 cm. 12. *Reussella tortuosa* Sztrakos, 113-689B-6H, CC. 13. *Uvigerina graciliformis* Papp, 113-689B-6H, CC. 14. *Siphogenerinoides* aff. *brevispinosa*, 113-690C-13X-4, 43-49 cm. 15. *Bolivinoidea delicatulus* Cushman, 113-690B-19H, CC.

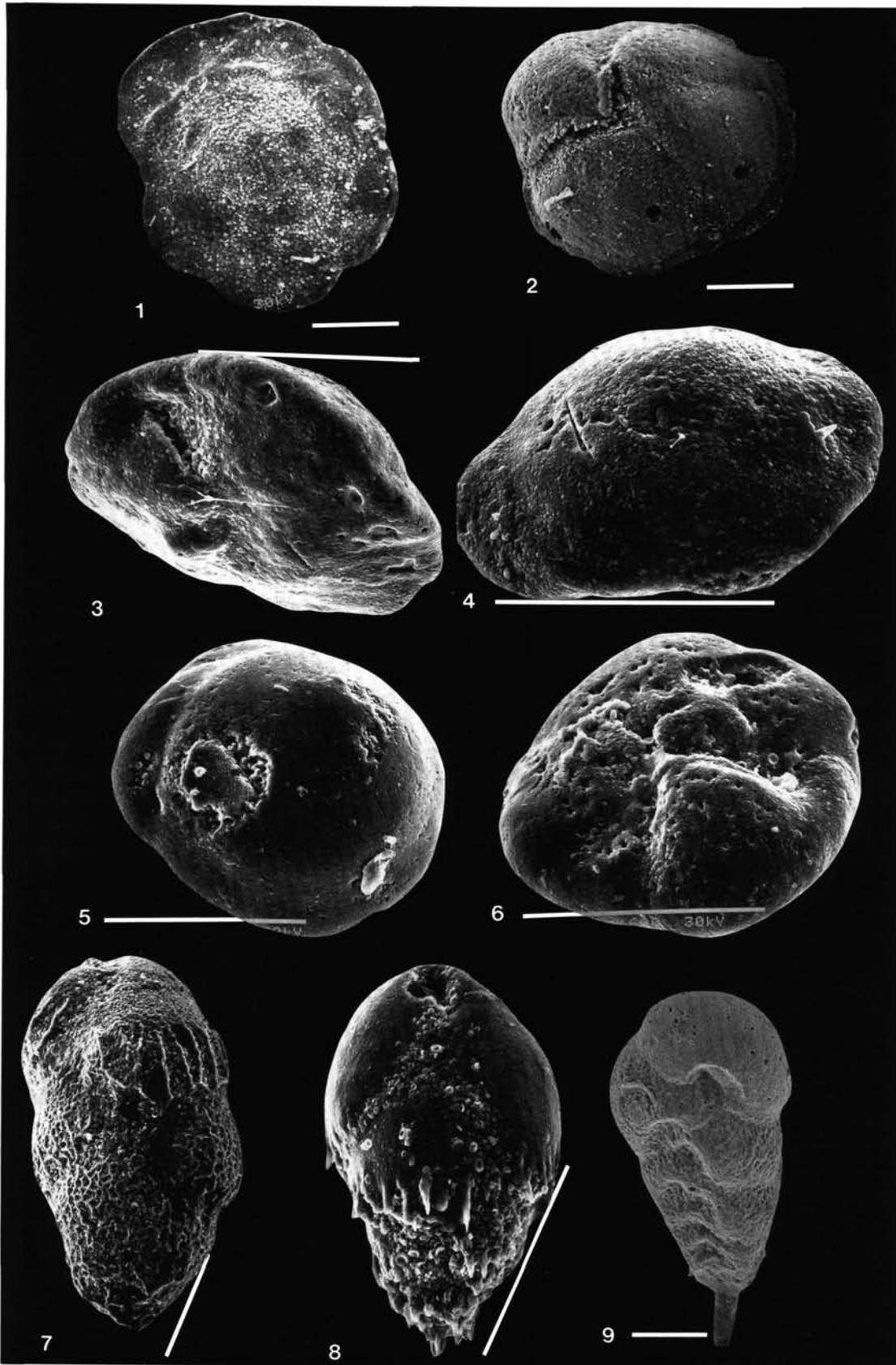


Plate 2. All bars are 100  $\mu\text{m}$ . 1. *Globorotalites conicus* (Carsey), dorsal side. 113-690C-18X-5, 41-44 cm. 2. *Globorotalites conicus* (Carsey), ventral side. 113-690C-18X-5, 41-44 cm. 3. *Neoeponides hillebrandti* Fisher, ventral side. 113-690C-18X-2, 40-44 cm. 4. *Neoeponides hillebrandti* Fisher, dorsal side. 113-690C-18X-2, 40-44 cm. 5. *Neoeponides lunata* (Brotzen), dorsal side. 113-690C-18X-2, 40-44 cm. 6. *Neoeponides lunata* (Brotzen), ventral side. 113-690C-18X-2, 40-44 cm. 7. *Bulimina trinitatis* Cushman and Jarvis, 113-690C-13X-5, 46-48 cm. 8. *Bulimina midwayensis* Cushman and Parker, 113-690C-13X, CC. 9. *Angulogerina szajnochae* (Grzybowski), 113-690C-18X, CC.

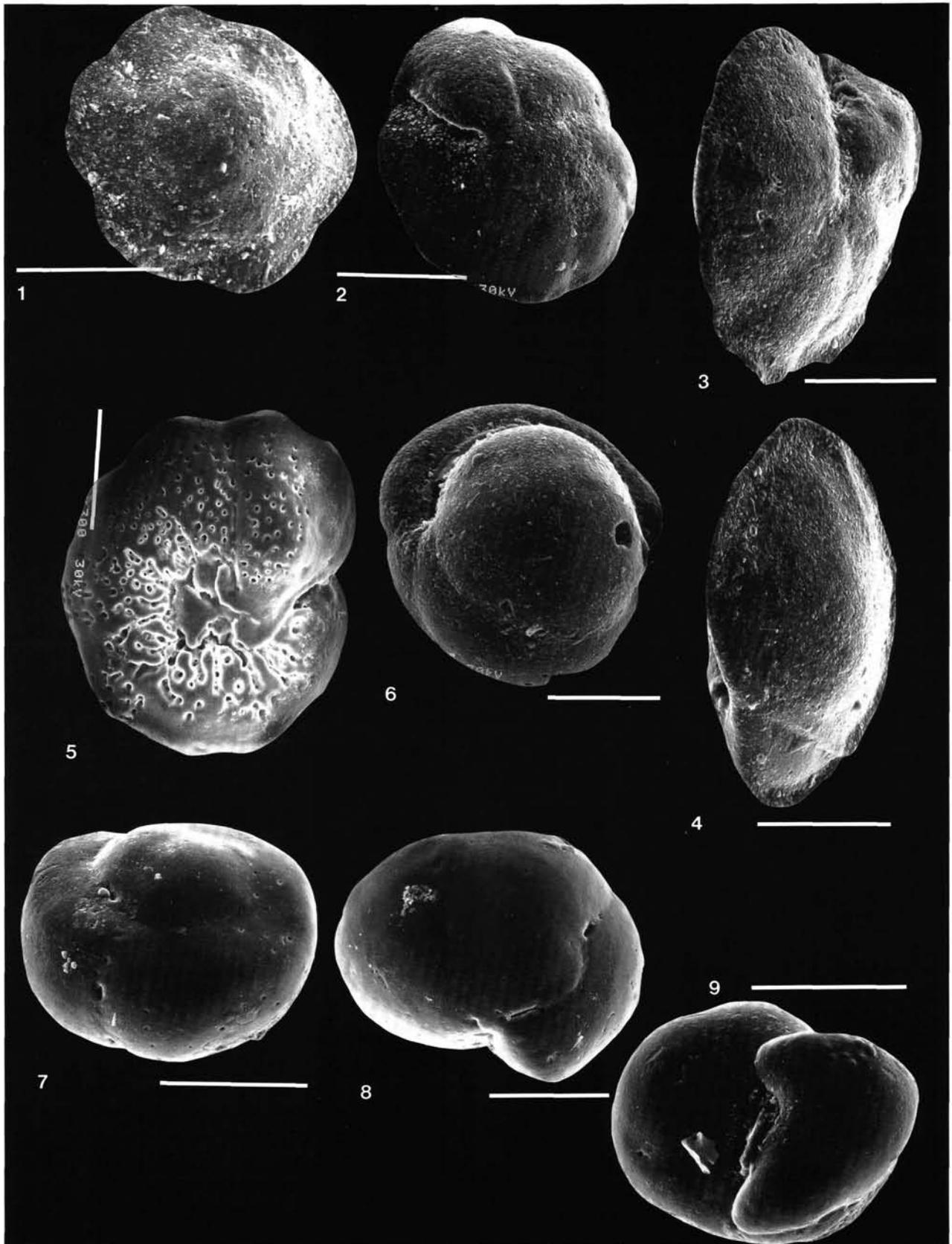


Plate 3. All bars are 100  $\mu\text{m}$ . 1. *Nuttallides truempyi* (Nuttall)—group, dorsal side. 113-690C-18X, CC. 2. *Nuttallides truempyi* (Nuttall)—group, ventral side. 113-690C-18X, CC. 3. *Osangularia navarroana* (Cushman), ventral side and aperture. 113-690C-15X, CC. 4. *Osangularia navarroana* (Cushman), dorsal side. 113-690C-15X, CC. 5. *Gavelinella beccariiiformis* (White), ventral side. 113-690C-15X, CC. 6. *Pullenia coryelli* White, apertural view. 113-690C-15X, CC. 7, 8, 9. *Oridorsalis nitidus* (Reuss), 113-690-15X, CC: 7, dorsal-side view (note secondary aperture); 8, dorsal view (note secondary apertures); 9, apertural view.