

A BENTHIC PALEOHABITAT FOR *PRAEPARAROTALIA* GEN. NOV. AND *ANTARCTICELLA* LOEBLICH AND TAPPAN

CHENGJIE LIU,¹ RICHARD K. OLSSON,¹ AND BRIAN T. HUBER²

ABSTRACT

Globorotalia inconspicua Howe, *G. aculeata* Jenkins, *G. perclara* Loeblich and Tappan (senior synonym of *G. reissi* Loeblich and Tappan), *Globigerina pauciloculata* Jenkins, and *Candeina antarctica* Leckie and Webb are Cenozoic species interpreted to have been adapted to a planktic habitat. Their restriction, however, to shallow marine or marginal marine paleoenvironments suggests that they were benthic species. These taxa are associated with reduced planktic foraminiferal diversity, a low P/B (planktic/benthic) ratio, and an inner shelf benthic foraminiferal biofacies. A new genus, *Praepararotalia*, is erected for several species interpreted to be phylogenetically related to the benthic genus *Pararotalia*. *Praepararotalia cretacea* (new species), which is described from the Maastrichtian Navesink Formation in New Jersey, gave rise to the early Paleocene species *Praepararotalia perclara*. In addition, stable isotopic ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) signatures of all praepararotaliid species in this study cluster closer to benthic foraminiferal signatures and are distinct from normal marine planktic taxa from the Cretaceous and the Paleocene.

A benthic paleohabitat is suggested for the Danian species *Antarcticella pauciloculata* (Jenkins) because of its dominant occurrence in shallow facies of marginal basins in the southern high latitudes. The species may be phylogenetically linked to *P. cretacea* n. sp. and is apparently the stem taxon of a Southern Ocean Paleogene evolutionary lineage that includes *A. cecionii* (Cañón and Ernst), *A. zeocenica* (Hornibrook and Jenkins), and *A. antarctica* (Leckie and Webb).

INTRODUCTION

The recognition of planktic genera and their species within the development of planktic foraminiferal biostratigraphy has been based for the most part on morphologic resemblance to living species and on distribution of extinct morphologies in oceanic paleoenvironments. Bolli (1957) and Loeblich and Tappan (1957a) applied the morphologic characters of the modern genus *Globorotalia* to classify genera in the Paleogene. The definitive characters of *Globorotalia* include a trochospiral test and an umbilical to extraumbilical aperture. Thus in the early development of Paleogene planktic foraminiferal biostratigraphy, numerous species were placed in this genus. Subsequent phylogenetic studies (McGowran, 1968; Berggren, 1977; Olsson and others, 1992; Liu and Olsson, 1994; Olsson, and others, in press) have shown that Paleogene planktic taxa with *Globorotalia*-

like morphology are not related to *Globorotalia* but should be placed in genera such as *Morozovella*, *Globanomalina*, and *Praemurica*.

Data from the Deep Sea Drilling Project (DSDP) and Ocean Drilling Project (ODP) confirmed the planktic oceanic habit of most Paleogene taxa previously regarded as having a planktic habit. However, there are some taxa that have been used in the development of Paleogene planktic foraminiferal biostratigraphy that differ in their morphologic characteristics from confirmed Paleogene planktic taxa. These taxa include *Globorotalia inconspicua* Howe, *Globorotalia inconspicua aculeata* Jenkins, *Globorotalia perclara* Loeblich and Tappan, *Globorotalia reissi* Loeblich and Tappan, and *Globigerina pauciloculata* Jenkins, all of which have morphologic characters that superficially resemble Paleogene planktic taxa. The purpose of this study is to evaluate these genera and species in light of their morphologic characters, phylogenetic relationships, stable isotopic ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) signatures and inferred paleohabitats.

Howe (1939) was the first to describe one of these species, a middle Eocene form which he named *Globorotalia inconspicua*. In the first study of planktic foraminiferal biostratigraphy in the Atlantic Coastal Plain, Loeblich and Tappan (1957a) described two species, *Globorotalia perclara* and *G. reissi*, which they included among their Paleocene planktic assemblages. Subsequently, Jenkins (1966) identified Howe's species in a Paleogene assemblage from New Zealand. Further, he erected *Testacarinata* as a new subgenus of *Globorotalia* and used Howe's species, *inconspicua*, as the type species (Jenkins, 1971). He also described a new species, *Globorotalia aculeata*, which he placed in the subgenus *Turborotalia*. Loeblich and Tappan (1957b), in their study of the genus *Pararotalia*, described several species from the Paleogene that have morphologic similarities to the above described species.

It has become apparent during our studies of Paleogene foraminifera that the above species are morphologically distinct from other Paleogene planktic genera. In addition, stable isotopic ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) analyses of these species indicate that their isotopic signatures are more similar to benthic species than to known planktic taxa. Hence, their paleobathymetric distribution raises doubts about whether they had, in fact, an oceanic planktic habit.

COMPARISON WITH PLANKTIC MORPHOLOGY

Wall texture is a conservative morphologic feature of planktic foraminifera (Hemleben, 1969; Bé and Tolderlund, 1971) that does not change significantly with temporary environmental perturbations. It is important not only for interpreting taxonomic placement and phylogenetic relationship (closely related species possess similar wall textures), but also for inferring the paleohabitat of fossil taxa. Wall textures could not be studied in detail until the middle 1960's when the SEM (Scanning Electron Microscope) be-

¹ Department of Geological Sciences, Rutgers University, New Brunswick, NJ 08903 U.S.A.

² E-206 MRC NHB 121, Paleobiology Department, National Museum of Natural History, Smithsonian Institution, Washington DC 20560 U.S.A.

gan to be used in micropaleontologic study. Olsson and others (1992) recently developed a classification of early Paleocene planktic foraminifera based on intensive study of wall texture. They identified four basic types of wall texture in early Paleocene planktic foraminifera: microperforate, smooth-walled normal perforate, cancellate-walled nonspinose normal perforate, and cancellate-walled spinose normal perforate. Each is derived independently from one of three Late Cretaceous planktic species that survived into the early Paleocene (Liu and Olsson; 1992, 1994; Olsson and Liu, 1993). No known Paleocene benthic foraminifera possess the types of wall textures found in early Paleocene planktic foraminifera.

GLOBOROTALIA PERCLARA LOEBLICH AND TAPPAN

Globorotalia perclara (including *Globorotalia reissi* Loeblich and Tappan, discussed later) has a trochospiral test with five to six globular, ovoid or subconical chambers in the final whorl. These characters are similar in gross morphology to those of the early Paleocene planktic foraminiferal genera *Praemurica*, *Eoglobigerina* and *Parasubbotina*. However, the wall texture of *G. perclara* is distinctly different from these earliest Paleocene planktic genera, which have cancellate walls with regularly distributed pores (2–7 μm in diameter) surrounded by funnel-like pore-pits. In addition, *Praemurica* is nonspinose while the latter two are spinose. *Globorotalia perclara* has a test surface with sporadically distributed micropores (<2 μm in diameter). Its dorsal side is smooth while the umbilical area contains scattered, blunt to moderately sharp pustules (Pl. 1, figs. 1–9). These characteristics also differentiate *G. perclara* from the smooth-walled Paleogene planktic genus *Globanomalina*.

The aperture of *Globorotalia perclara* is interiomarginal, extraumbilical in position and is an areal opening situated very close to the periphery (Pl. 1, figs. 1, 3, 9). It does not open into the umbilicus as does the aperture of *Eoglobigerina*, *Globanomalina*, *Parasubbotina*, and *Praemurica*. In fact, the umbilicus is completely closed off from the apertures of the surrounding chambers. In *G. perclara* the lower half of the aperture is covered by a thin imperforate toothplate (Pl. 1, fig. 9) that is easily broken and thus is not readily observed in many specimens of this species. Because the toothplate is usually broken and the aperture is rimmed with a thickened lip, it has the superficial appearance of a globorotaliid aperture (Pl. 1, fig. 7). *Globorotalia perclara* is similar to the Paleocene planktic microperforate (pores <1 μm in diameter) species *Parvularugoglobigerina eugubina* in having an areal aperture and a pustulose surface. However, the aperture in *P. eugubina* is slit-like, is situated on the apertural face and is without a toothplate. The pustules in *P. eugubina* are blunt and distributed on both sides of the test whereas in *G. perclara* they are restricted to the umbilical side. The pores in *P. eugubina* are smaller, more numerous, and are associated with pustules (pore mounds).

Thus, based on wall texture, gross morphology, and apertural characters, *Globorotalia perclara* can not be assigned to any known early Paleocene planktic foraminiferal genus. Its morphologic characteristics are closest to the benthic genus *Pararotalia*, which is generally common in Eocene and higher levels. The distinguishing features of *Par-*

arotalia include a low trochospiral, planoconvex test with a carinate periphery, conical chambers, a large solid umbilical plug of clear shell material, and an interiomarginal areal aperture with an imperforate toothplate that extends to the distal or outer margin of the aperture. Internally the toothplate is attached to the proximal margin of the anteriorly developed chamber (see Loeblich and Tappan, 1988, Pl. 755, fig. 21). Most Eocene species assigned to *Pararotalia* have an umbilical plug of clear shell material and a peripheral keel. Some, like *Pararotalia curryi* Loeblich and Tappan, do not possess a keel and have only a partially developed umbilical plug. This morphotype more closely resembles *G. perclara*. Furthermore, *G. perclara*, as in *Pararotalia*, has an interiomarginal, areal aperture with an imperforate toothplate that internally is attached to the proximal margin of the anteriorly developed chamber (Pl. 1, figs. 1, 4, 9). The development of a plug-like concentration of pustules is observed in the umbilical area of some individuals of *G. perclara* and of related Eocene species described below. A discontinuous peripheral keel and peripheral pseudospines (pustules) first appear in the early Eocene species *Globorotalia inconspicua* Howe. These morphological characteristics of *G. perclara* and the Eocene species described below suggest a phylogenetic relationship with *Pararotalia*, yet they distinguish these species at the generic level from *Pararotalia*. We propose a new genus, *Praepararotalia*, to include *G. perclara* and related Eocene species.

GLOBOROTALIA INCONSPICUA HOWE AND GLOBOROTALIA INCONSPICUA ACULEATA JENKINS

Globorotalia inconspicua inconspicua Howe and *G. inconspicua aculeata* Jenkins are small species (100–150 μm) that are commonly abundant in Eocene sediments in the U.S. Gulf Coastal Plain, U.S. Atlantic Coastal Plain, N.W. Europe, New Zealand, southern South America and Southeast Asia (Jenkins, 1966, 1971; Jones, 1983; Olsson and Wise, 1987; Loeblich and Tappan, 1988; Murray and others, 1989; N. Malumian, written comm., 1995). They are similar in gross morphology to juvenile specimens of the planktic foraminiferal genus *Morozovella* in having a planoconvex test, a deep, rounded umbilicus, and, in some advanced forms of *G. inconspicua*, a discontinuous keel along the equatorial margin (Pl. 1, fig. 13). Jenkins (1971) erected the monotypic subgenus *Globorotalia* (*Testacarinata*) using *Globorotalia inconspicua* Howe as the type species. He described a new subspecies *G. inconspicua aculeata* Jenkins, which he regarded as the ancestor of *G. inconspicua inconspicua* and then placed *G. aculeata* in the subgenus *Globorotalia* (*Turborotalia*). Banner (1982) recognized *Testacarinata* Jenkins as an independent genus and Loeblich and Tappan (1988) placed *Testacarinata* along with *Acarinina*, *Morozovella* and several other well known planktic genera in the family Truncorotaloididae Loeblich and Tappan. Obviously, these workers regarded *Globorotalia inconspicua inconspicua* and *G. inconspicua aculeata* as having had a planktic habit.

Several features of *G. inconspicua inconspicua* and *G. inconspicua aculeata* indicate that they differ from Paleogene planktic foraminiferal species. The apertures in these species have an areal, extraumbilical position in the aper-

tural face and a toothplate (Pl. 1, figs. 10–13; Pl. 2, figs. 13–16). They have irregular, sporadic but large and sharp pustules that are more fully developed on the umbilical side, generally more concentrated in the umbilicus. The pores are small ($<2\text{ }\mu\text{m}$ in diameter) and sparsely distributed as in *G. perclara*. In contrast, *Morozovella* has more numerous, larger pores ($2.5\text{--}4.0\text{ }\mu\text{m}$ in diameter) which are surrounded by dense, more evenly distributed pustules and a high planoconvex test. The concentration and coalescing of pustules in the umbilicus of *G. inconspicua inconspicua* forms a structure that resembles an umbilical plug. In some specimens of these species this structure is more fully developed and is similar to small umbilical plugs in species of Eocene *Pararotalia*. All of the morphological features observed in these species suggest that they should be placed in the new genus *Praepararotalia*.

In middle Eocene sediments, juvenile specimens of the planktic foraminiferal genus *Acarinina* may be mistaken for *Praepararotalia inconspicua* and *P. aculeata* because of their similarity in having a small planoconvex or biconvex test with globular to subconical chambers. Species of *Acarinina* can be readily separated from praepararotaliids by their much more elevated test, a homogenous pustulose test surface, a deep, open umbilicus, more inflated chambers and the lack of any peripheral keel or other ornamentation along the peripheral margin. In contrast, praepararotaliids have a compressed test, may possess a pustulose umbilical structure and a discontinuous peripheral keel, as well as a pseudospine on the peripheral margin of each chamber, and, most importantly, a heterogenous test surface characterized by irregularly distributed smaller pores, and pustules that are predominantly concentrated on the umbilical side.

PALEOHABITAT OF PRAEPARAROTALIIDS

The paleohabitat of fossil species can be inferred from their occurrence in certain lithofacies and from associated species whose paleohabitats have been demonstrated. We use distributional patterns, relative abundances and ecological information of co-occurring benthic species, as well as $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses to separate benthic from planktic species.

The distribution of benthic foraminiferal species is controlled by factors such as subbottom lithology, salinity, pH, eH, temperature, organic matter, oxygen, etc. Restricted distribution in certain lithofacies characterizes many benthic species and may be used as a criterion to determine a benthic habit. Planktic taxa, on the other hand, generally have a much wider geographic distribution, although some neritoplanktic species prefer upwelling areas that are associated with slope or continental shelf environments (Leckie, 1987; Kroon and Nederbragt, 1990; Liu and Olsson, 1992). Planktic species generally are excluded from shallow waters because they need a deeper water column to complete their life cycle and most are intolerant of the reduced salinities of neritic surface waters. As a consequence, they tend to be more abundant toward the open ocean.

Some opportunistic benthic species can be extremely abundant in certain environments. In this case, a benthic assemblage has a high species dominance and usually a low diversity because abnormal conditions exclude most other

species. *Praepararotalia perclara*, *P. inconspicua*, and *P. aculeata* Jenkins are abundant in shallow marine sediments of the U.S. Gulf and Atlantic coastal plains. Their maximum abundance is associated with a low planktic-benthic (P/B) ratio that is widely used as a parameter for paleodepth estimation (Smith, 1955; Murray, 1976; Gibson, 1989). In addition, these species are associated with a benthic assemblage composed predominantly of well known shallow water species that belong to genera such as *Gavelinella*, *Buliminella*, *Cibicides*, *Anomalinoidea*, *Epistominella*, and *Eponides*. Olsson and Wise (1987) identified the above praepararotaliid species as major components of their nearshore biofacies. They reported that these species were absent in deeper shelf biofacies. In addition, these species have not been reported from pelagic sediments recovered by deep sea drilling.

Paleobathymetric and sequence stratigraphic study of a basal Paleocene section at Millers Ferry, Alabama, shows that in a transgressive systems tract deposited in a paleodepth of approximately 80–100 meters (with a P/B ratio of over 30%) the relative abundance of *Praepararotalia perclara* is below 20% (Fig. 1, Table 1). The relative abundance of *P. perclara* increases to 30–50% in sediments of a high-stand systems tract that was deposited in a paleodepth of approximately 30 meters (P/B ratio declines to below 10%). This change in relative abundance clearly indicates that *P. perclara* is associated with nearshore environments and suggests a benthic habit, although it is possible that it may have had a planktic stage during early ontogeny.

STABLE ISOTOPIC SIGNATURE OF THE PRAEPARAROTALIIDS

METHODS

Stable isotope analyses were performed on samples containing *Praepararotalia inconspicua*, *P. perclara*, and *P. cretacea* to compare their values with those of co-occurring planktic and benthic foraminifera (Table 2). The samples were obtained from nearshore clastic sedimentary facies of the Atlantic Coastal Plain, including: (1) two Navesink Fm. samples (Navesink Nines #6 and #7) from Marlboro, New Jersey (lower Maastrichtian) for *P. cretacea* n. sp. (excellent preservation); (2) one Brightseat Fm. sample from the lower Paleocene at Seat Pleasant, Maryland (good preservation); and (3) two Shark River Fm. (lower Eocene) samples from 793 ft. and 798 ft. in the Island Beach, New Jersey drill core (Leg 150X; Miller, Sugarman and others, 1994) for *P. inconspicua* (good to excellent preservation). Because of the small size of these species, a large number (40 to 200 specimens) had to be picked to reach the 50 μg minimum sample weight for each analysis. Despite intensive picking, no stable isotopic results were obtained for *P. cretacea* (averaging 0.25 μg per specimen) from the Navesink Nines sample #7 or *Subbotina* spp. (averaging 1.2 μg per specimen) from the Shark River Fm. core at 793 ft. because of their small shell mass and rare occurrence.

Picked foraminiferal splits were reacted in a common acid bath of ortho-phosphoric acid at 90°C using a VG Isogas autocarbonate preparation system. Isotope ratios of purified CO_2 gas were measured on-line by a VG Prism Series II mass spectrometer at the University of Florida. All isotope

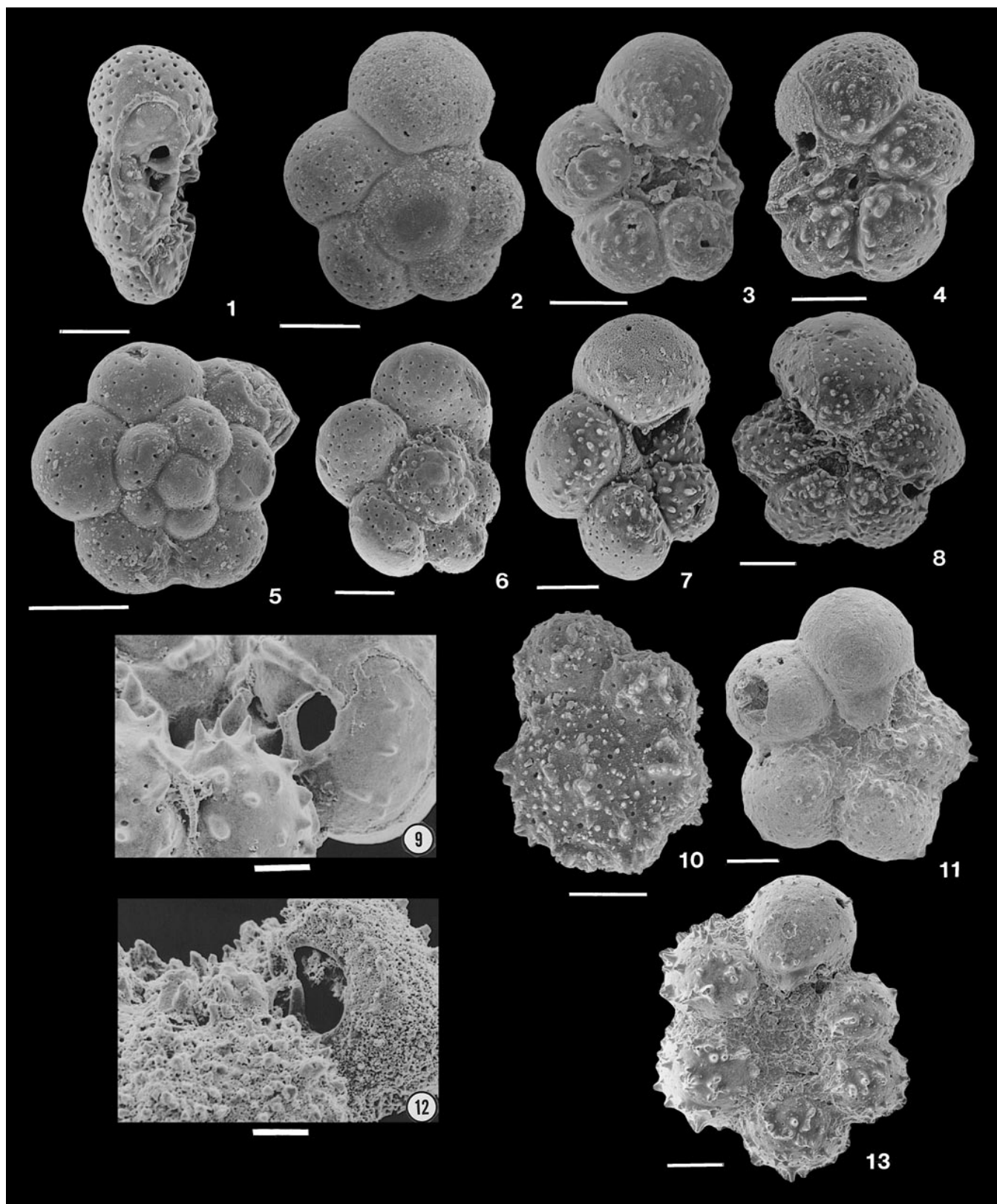


PLATE 1

(1-8, 10, 11, 13 bar = 40 µm; 9, 12 bar = 20 µm) 1-9 *Praepararotalia perclara* (Loeblich and Tappan), showing a smooth spiral side and a pustulose umbilical surface. 5 lower Subzone P1a, Clayton Formation, Borehole Core 225, Sample #140. 2 Subzone P1a, Clayton Formation, sample 40 feet. Both from Millers Ferry, Alabama. 1, 3, 4, 7, 8 showing various states of preservation of the umbilical area. 1 showing imperforate toothplate of the penultimate chamber attached to the proximal margin of the ultimate chamber, fig. 4 shows aperture of penultimate chamber with partially preserved toothplate. 7 shows broken apertural area of ultimate chamber giving the impression of a *Globorotalia*-like aperture, all, including

results are reported in standard δ notation relative to the Pee Dee Belemnite (PDB) standard. Analytical precision, based upon routine analysis of an internal carbonate standard (Carrara Marble), was better than 0.1‰ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$.

Paleotemperature estimates from oxygen isotope data are based on the paleotemperature equation of Anderson and Arthur (1983), assuming a value of -1% for an ice-free earth (Shackleton and Kennett, 1975) and a minimal $\delta^{18}\text{O}$ vital effect.

Serial dissections of *Antarcticella antarctica* were done using a finely ground needle attached to a free-standing micromanipulator. Specimens for dissection were mounted on an SEM stub with their spiral sides down in thermoplastic that had been thinned with xylene. For more details of this procedure refer to Huber (1994).

BACKGROUND

Because the $^{18}\text{O}/^{16}\text{O}$ ratio of calcite precipitated in equilibrium with seawater is temperature dependent, and temperature decreases with depth from the ocean surface, interspecies differences in $\delta^{18}\text{O}$ measured from modern foraminifera reflect growth at different levels in the water column (Emiliani, 1954; Shackleton and Vincent, 1978; Fairbanks and Weibe, 1980; Vincent and Berger, 1981; Wefer and Berger, 1991). Species that yield relatively enriched $\delta^{18}\text{O}$ values are associated with deeper (cooler) water habitats, whereas those yielding more negative $\delta^{18}\text{O}$ values are associated with surface (warmer) water conditions.

The fractionation of carbon isotopes in the upper water column is controlled by photosynthesis rather than temperature. Upper surface waters tend to be enriched in ^{13}C because the lighter carbon isotope (^{12}C) is preferentially removed from the ambient water by phytoplankton. As the phytoplankton die and sink through the water column, the ^{12}C -enriched organic matter is oxidized and released. Thus, the shells of foraminifera that calcified in the upper surface waters are relatively enriched in $\delta^{13}\text{C}$, whereas those calcified at deeper levels are more depleted in $\delta^{13}\text{C}$ (Shackleton and Vincent, 1978; Spero and Williams, 1989). Significant differences in $\delta^{13}\text{C}$ composition among benthic foraminifer species may indicate different depth preferences within the upper 5–10 cm of sediments on the seafloor. Benthic species with strongly negative carbon isotope values are characteristic of growth in a deep infaunal habitat where pore waters are enriched in ^{12}C , whereas benthic species with more positive $\delta^{13}\text{C}$ values probably lived in more shallow infaunal habitats (McCorckle and others, 1990).

Some taxa are assumed, based on independent evidence (e.g., abundance in deep sea sediments, wall textures, shell morphology, etc.) to have lived a planktic mode of life, but their shells yield stable isotopic compositions that are closer to benthic species than co-occurring planktic species. Ex-

amples of such positive oxygen and negative carbon isotopic values were obtained from Cretaceous species of *Heterohelix* (Huber and others, 1995), Paleogene species of *Chiloguembelina* and *Zeauvigerina* (Boersma and Premoli Silva, 1989; Huber and Boersma, 1994) and *Catapsydrax* (Keigwin and Corliss, 1986), and Neogene species of *Streptochilus* (Boersma and Premoli Silva, 1989). These benthic-like stable isotopic values may result from growth of the planktic foraminifera below the thermocline in an oxygen minimum layer of the open ocean (Shackleton and Vincent, 1978; Boersma and Premoli Silva, 1989; Huber and Boersma, 1994). Alternatively, some or all of these and other species may have had the ability to live as benthic organisms during part or all of their growth history. Hilbrecht and Thierstein (1996) observed that the modern planktic species *Globigerinella siphonifera* and *Globorotalia menardii* exhibit typical benthic activity (e.g., reorientation, crawling, and burrowing) when cultured in vessels containing a sediment substrate. High dominance of middle Cretaceous heterohelids, guembelitrids, favusellids, and gubkinellids in shallow, neritic environments and their rarity in open ocean settings (Leckie, 1987; Koutsoukos and others, 1989; Koutsoukos, 1994) suggest the possibility that these taxa were “neritobenthic”, i.e., they may have lived in a benthic mode in nearshore settings and a planktic mode in open ocean environments. This may also apply to *Globoconusa daubjergensis*, which was reported as the only planktic taxon in neritic lower Paleocene sediments on Seymour Island (Antarctic Peninsula; Huber, 1988) and is often one of few planktic foraminifer species that is typically found in other lower Paleocene nearshore sequences (e.g., Loeblich and Tappan, 1957; Olsson, 1960; Bertels, 1964; Mendez, 1966; Hansen, 1970). In open ocean sediments, *G. daubjergensis* has been reported as having $\delta^{18}\text{O}$ values that are comparable to other planktic species, but $\delta^{13}\text{C}$ values that are at least 1‰ more negative than co-occurring trochospiral planktic species (D’Hondt and Zachos, 1993).

Interpretation of the stable isotopic data from extinct fossil foraminifera can be complicated by the possibility that they fractionated their oxygen and/or carbon isotopic ratios out of equilibrium with the ambient water or that the primary stable isotopic signal has been altered because of diagenesis. The influence of physiological “vital effects,” such as variations in metabolic rates, respiration, and symbiont photosynthesis, on the $\delta^{18}\text{O}$ signal have generally been found to be less than 0.5‰ for most planktic species (Bouvier-Soumangac and Duplessy, 1985; Deuser, 1987). On the other hand, the $\delta^{13}\text{C}$ signals in some modern planktic species may be as much as 2‰ out of equilibrium with the ambient water because of the presence of photosymbiotic algae (Spero, 1992).

The range of $\delta^{18}\text{O}$ differences between species of coex-

6 from Zone P4, Vincenttown Formation, Whitesville Core, New Jersey, sample 220–225 feet. 9 enlarged view of aperture showing a thickened rim, an imperforate toothplate covering the lower half of the aperture and the closed off umbilicus, from Zone P1c, Brightseat Formation, Maryland. 10–13 *Praepararotalia aculeata* (Jenkins), showing a planoconvex test, 6 very slowly enlarging globular chambers in the last whorl, and a pustulose wall with scattered large coarse pustules and scattered pores. 10, 11, 13 from middle Eocene, Claiborne, Cook Mountain Formation, Couley Creek, Winn Parish, Louisiana; 12 shows the small oval, areal aperture with a thickened rim, from middle Eocene, Point Pleasant well, New Jersey, sample 310 feet.

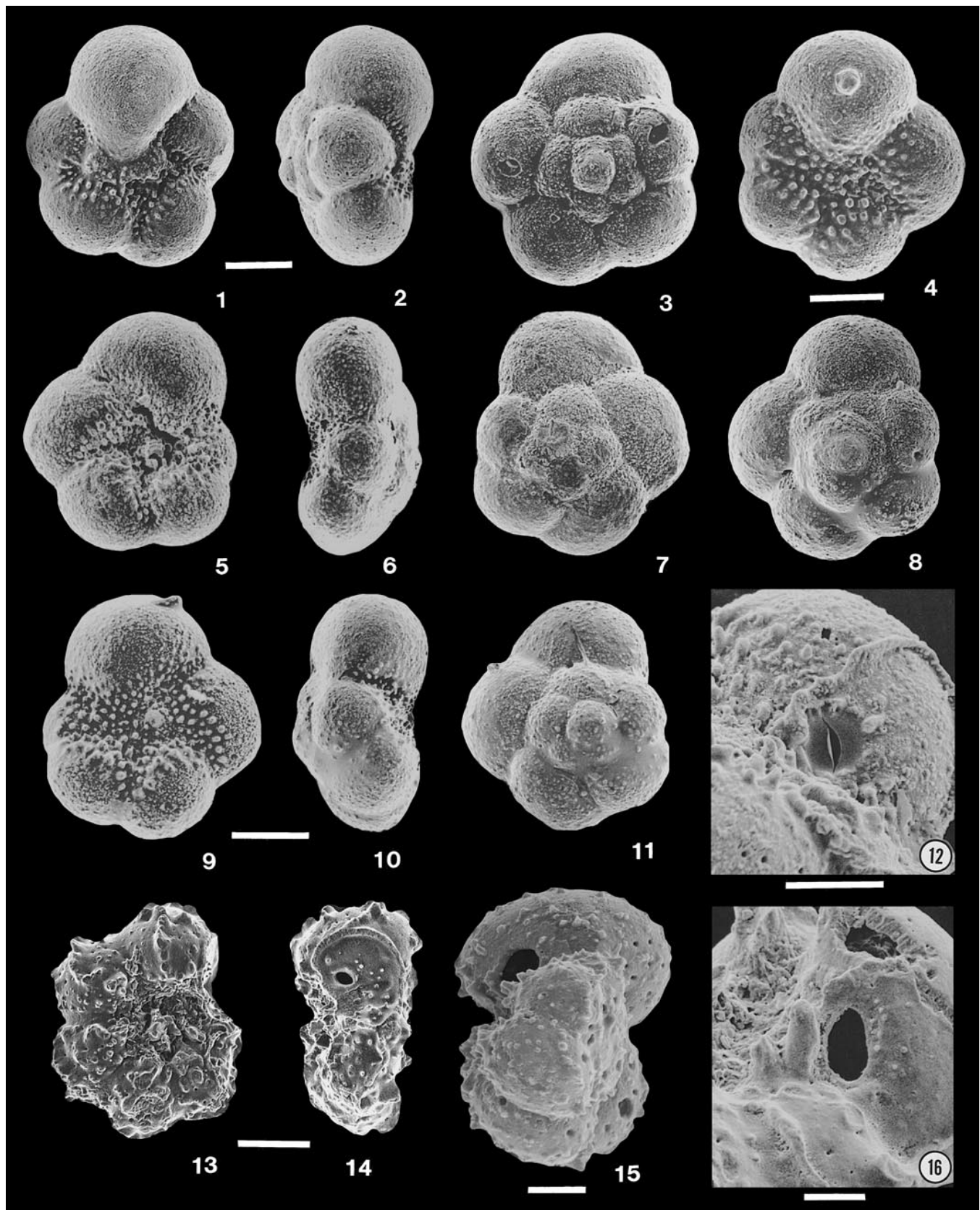
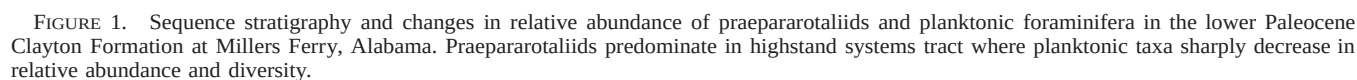


PLATE 2

(1-11, 13-15 bar = 40 μ m; 12, 16 bar = 20 μ m) 1-12 *Praepararotalia cretacea* Liu, Olsson, and Huber, n. sp., showing a smooth wall on the spiral side, a pustulose umbilical area, scattered pores, a moderately to high elevated spiral side, a large proloculus, a shallow, open umbilicus, and an extraumbilical small but high arched aperture with a large triangular lip. Sample #7, Maastrichtian, Navesink Formation, Marlboro,



rium values by as much as 2.5‰ (Woodruff and others, 1980). In most cases, disequilibrium isotopic compositions lead to depletions in the heavy carbon isotope (Grossman, 1987). Changing depth of microhabitat (Luz and Reiss, 1983; Grossman, 1987), variations in food supply (Goody, 1993), and presence or absence of photosymbionts (Langer, 1995) may also contribute to variability in the $\delta^{13}\text{C}$ values of coexisting benthic species.

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TABLE 1. Abundance of foraminifera in Borehole Core 225 at Millers Ferry, Alabama.

Sample #	Horizon (cm above K/T)	Plank- tonics	Benthics*	<i>Praepararot-</i> <i>alia</i> (n. gen)	Total count	Total benthics	P/B ratio	<i>Praepararot-</i> <i>alia</i> /benthic ratio	Planktonic %	<i>Praepararot-</i> <i>alia</i> (%)
320	226	81	146	10	237	156	0.55	0.07	34.18	4.22
312	287	135	137	13	285	150	0.99	0.09	47.37	4.56
300	364	86	159	33	278	192	0.54	0.21	30.94	11.87
294	385	98	169	47	314	216	0.58	0.28	31.21	14.97
284	468	94	166	62	322	228	0.57	0.37	29.19	19.25
278	511	111	151	58	320	209	0.74	0.38	34.69	18.12
268	570	93	186	64	343	250	0.50	0.34	27.11	18.66
262	613	74	135	83	292	218	0.55	0.61	25.34	28.42
256	656	80	153	76	309	229	0.52	0.50	25.89	24.60
248	694	64	178	66	308	244	0.36	0.37	20.78	21.43
242	733	58	158	65	281	223	0.37	0.41	20.64	23.13
234	782	71	141	84	296	225	0.50	0.60	23.99	28.38
224	826	115	162	61	338	223	0.71	0.38	34.02	18.05
216	901	89	158	63	310	221	0.56	0.40	28.71	20.32
200	1,022	124	183	71	378	254	0.68	0.39	32.80	18.78
184	1,213	73	123	112	308	235	0.59	0.91	23.70	36.36
170	1,313	23	178	157	358	335	0.13	0.88	6.42	43.85
154	1,402	43	126	117	286	243	0.34	0.93	15.03	40.91
140	1,502	13	218	55	286	273	0.06	0.25	4.55	19.32
130	1,572	16	231	63	310	294	0.07	0.27	5.16	20.32
114	1,672	23	215	126	364	341	0.11	0.59	6.32	34.62
100	1,753	18	184	117	319	301	0.10	0.64	5.64	36.68
84	1,851	24	148	81	253	229	0.16	0.55	9.49	32.02
72	1,918	21	246	73	340	319	0.09	0.30	6.18	21.47
60	1,972	10	164	132	306	296	0.06	0.80	3.27	43.14
50	2,037	8	228	52	308	300	0.04	0.32	2.60	24.68
30	2,137	6	240	72	322	316	0.03	0.32	1.86	23.60
14	2,216	10	197	100	307	297	0.05	0.51	3.26	32.57

* *Praepararotalia* are excluded.

Diagenetic alteration of the original isotopic composition of biogenic calcite is another factor that must be considered when interpreting stable isotopic data from fossil foraminifera. Dissolution and reprecipitation of calcite may affect isotopic ratios if the physical and chemical properties of pore fluids are different from the seawater in which the microfossils grew. Replacement or reprecipitation of secondary calcite can homogenize the isotopic signals of different species or selectively modify ratios in different taxa. Generally, samples with little or no diagenetic alteration show relatively constant interspecies differences, whereas similar plots from strongly altered material tend to cross or converge (Wefer and Berger, 1991).

RESULTS

Stable isotopic data obtained for *Praepararotalia cretacea* n. sp., *P. perclara*, *P. inconspicua*, and coexisting planktic and benthic foraminifera are presented in Figure 2 and Table 2. Test dissections of foraminifera from all samples analyzed reveal good to excellent preservation (i.e., minimal to no secondary calcite observed in the inner chambers of broken shells). Interspecies differences in oxygen and carbon isotopes are consistent for the foraminifera analyzed from the Navesink and Shark River formations, which further indicates that the primary stable isotopic signatures have not been compromised by diagenetic alteration.

Praepararotalia cretacea (Navesink Fm.)

The $\delta^{18}\text{O}$ value obtained for specimens of *P. cretacea* from Navesink Nines sample #6 is 0.87‰, which is within 0.1‰ of the co-occurring benthic taxon *Cibicides harperi*, and more than 1.3‰ more positive than the co-occurring planktic taxa *Rugoglobigerina rugosa* and *Heterohelix globulosa*. The $\delta^{13}\text{C}$ value obtained for *P. cretacea* is -1.19‰, which is nearly 3‰ more negative than the value obtained for *R. rugosa*, and about 1.4‰ more negative than *C. harperi*. The $\delta^{13}\text{C}$ composition of *Heterohelix globulosa* in the Navesink Nines samples is closer to *Cibicides harperi* than *R. rugosa*. This is consistent with results from other stable isotopic studies that indicate that some species of *Heterohelix* may have preferred growth in the oxygen minimum layer of the water column (Huber and others, 1995; MacLeod and Huber, 1996), although a neritobenthic mode of life may be attributed to *H. globulosa* in this nearshore setting.

Paleotemperatures estimated from the oxygen isotope values are reasonable for a middle latitude location at shelfal depths during the Maastrichtian, with the planktic species inhabiting surface waters of about 20–21°C, and *P. cretacea* and *C. harperi* living in shelf bottom water of about 15°C. The strongly negative carbon isotope signals suggest that *P. cretacea* may have lived in a deeper, more oxygen-depleted or food-enriched microhabitat than *C. harperi*.

TABLE 2. Oxygen and carbon isotope values of foraminifera analyzed in this study. Values are expressed in δ notation relative to the Pee Dee Belemnite standard.

Sample ID/species	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
Navesink Fm., Nines #6		
<i>Praepararotalia cretacea</i>	-0.87	-1.19
<i>Cibicides harperi</i> ¹	-0.77	0.24
<i>Rugoglobigerina rugosa</i> ²	-2.23	1.79
<i>Heterohelix globulosa</i> ²	-2.07	0.07
Navesink Fm., Nines #7		
<i>Cibicides harperi</i> ¹	-0.73	0.84
<i>Rugoglobigerina rugosa</i> ²	-1.87	1.84
<i>Heterohelix globulosa</i> ²	-1.85	0.33
Brightseat Fm. (base)		
<i>Praepararotalia perclara</i>	-1.70	-1.4
<i>Anomalinoidea umboniferus</i> ¹	-1.46	-1.02
<i>Globoconusa daubjergensis</i> ²	-1.69	-1.06
<i>Parasubbotina pseudobulloides</i> ²	-2.84	0.64
Shark River Fm. 798.0 ft.		
<i>Praepararotalia inconspicua</i>	-0.90	-1.19
<i>Cibicides</i> spp. ¹	-0.27	-0.16
<i>Morozovella aequa</i> ²	-2.29	2.02
Shark River Fm. 793.0 ft.		
<i>Praepararotalia inconspicua</i>	-0.78	-0.90
<i>Pararotalia inconspicua</i>	-1.13	-0.91
<i>Cibicides</i> spp. ¹	-1.09	0.07
<i>Uvigerina</i> sp. ¹	-0.80	-0.19
<i>Subbotina</i> spp. ²	-0.84	0.05
<i>Morozovella aequa</i> ²	-2.18	2.45

¹ Benthic foraminifer.

² Planktic foraminifer.

Praepararotalia perclara (Brightseat Fm.)

Analysis of *P. perclara* from the Brightseat Fm. yielded a $\delta^{18}\text{O}$ composition of -1.70‰ , which is slightly more negative than the benthic foraminifer *Anomalinoidea umboniferus* and nearly the same as the $\delta^{18}\text{O}$ value obtained for the planktic foraminifer *Globoconusa daubjergensis*. The planktic foraminifer *Parasubbotina pseudobulloides* is more than 1‰ more negative in $\delta^{18}\text{O}$ than *P. perclara*. The $\delta^{13}\text{C}$ value obtained for *P. perclara* is -1.4‰ , which is about 0.4‰ more negative than the values obtained from co-occurring *A. umboniferus* and *G. daubjergensis*, and about 2‰ more negative than *P. pseudobulloides*.

Paleotemperatures estimated from the oxygen isotope values are reasonable for nearshore waters during the early Paleocene, with *P. pseudobulloides* suggesting surface waters of $\sim 24^\circ\text{C}$ and *A. umboniferus* and *P. perclara* suggesting shelfal bottom waters of $\sim 18\text{--}19^\circ\text{C}$. The carbon isotope values of *P. perclara* suggest that this species lived in a similar microhabitat as *A. umboniferus*. The tight grouping of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of the latter two species and *G. daubjergensis* suggests that the latter may have been a neritobenthic species.

Praepararotalia inconspicua (Shark River Fm.)

Lower Eocene samples from 793 and 798 ft. of the Island Beach core (Shark River Fm.) show similar relative offsets in oxygen and carbon isotope values for *P. inconspicua* and co-occurring benthic and planktic species. The $\delta^{18}\text{O}$ value of *P. inconspicua* from 793 ft. is nearly the same as the

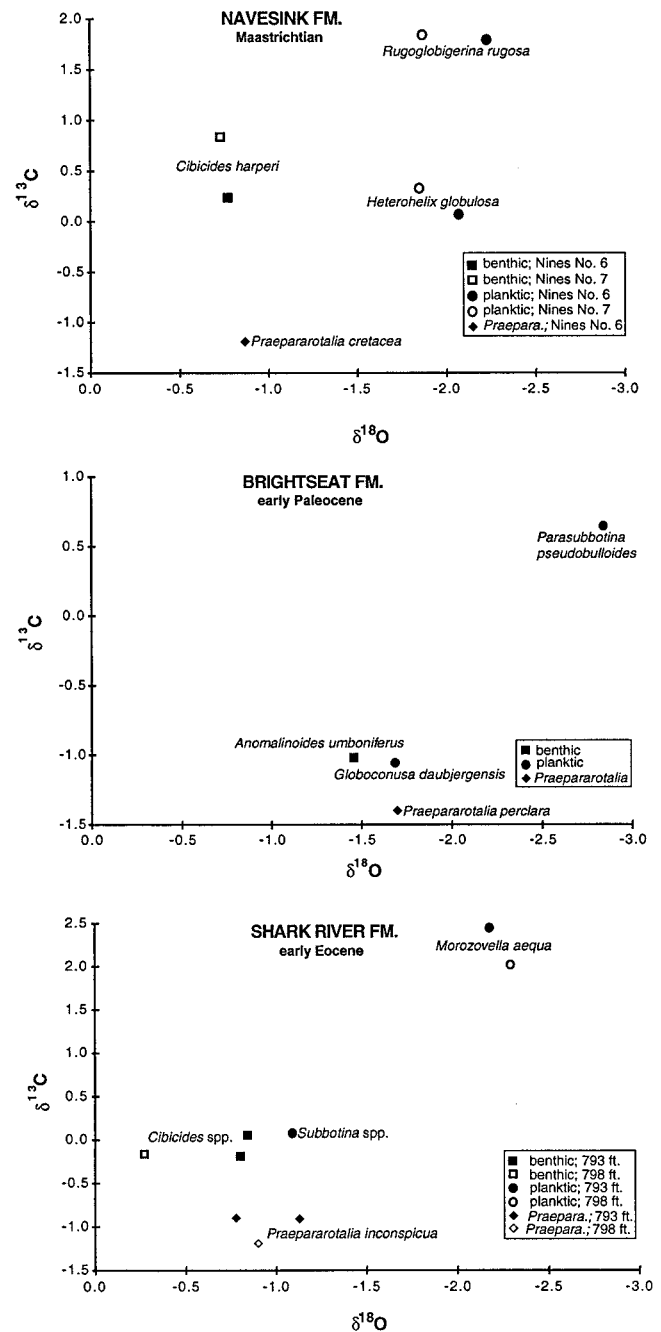


FIGURE 2. Navesink Formation (Maastrichtian) of New Jersey, plot of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for *Cibicides harperi*, *Heterohelix globulosa*, *Praepararotalia cretacea* n. sp., and *Rugoglobigerina rugosa*; Brightseat Formation (early Paleocene) of Maryland, Plot of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for *Anomalinoidea umboniferus*, *Globoconusa daubjergensis*, *Parasubbotina pseudobulloides*, and *Praepararotalia perclara*; Eocene Shark River Formation (middle Eocene) of New Jersey, plot of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for *Cibicides* spp., *Morozovella aequa*, *Praepararotalia inconspicua*, and *Uvigerina* sp. See text for discussion.

benthic foraminifera *Cibicides* spp. and *Uvigerina* sp. and more than 1‰ more positive than the planktic species *M. aequa*. At 798 ft. the $\delta^{18}\text{O}$ value of *P. inconspicua* is 0.63‰ more negative in than co-occurring specimens of *Cibicides* spp. Carbon isotope values for *P. inconspicua* are consistently the most negative of all species analyzed. Replicate

analyses of *P. inconspicua* from 793 ft. are -0.9% , which is more than 3.3% more negative than *M. aequa* from the same sample and 0.7% more negative than the most negative of the two benthic species analyzed. Similarly, the sample from 798 ft. in the Island Beach core yielded *P. inconspicua* $\delta^{13}\text{C}$ values that are more than 3% more negative than *M. aequa* and about 1% more negative than *Cibicides* spp.

Paleotemperature estimates based on these values are reasonable for middle latitude shelfal waters during the early Eocene. The $\delta^{18}\text{O}$ values from the benthic species and *P. inconspicua* suggest that shelfal bottom waters ranged from ~ 13 to 16°C and those from *M. aequa* suggest surface waters were $\sim 22^\circ\text{C}$. The strongly negative carbon isotope values obtained from *P. inconspicua* suggest that this species lived in a deeper benthic microhabitat than *Cibicides* spp. and *Uvigerina* sp.

PHYLOGENETIC RELATIONSHIP OF PRAEPARAROTALIIDS

As discussed above, Paleocene praepararotaliids are not related to Paleocene planktic foraminifera. Their presence in the basal Danian suggests that they were most probably derived from a Late Cretaceous benthic taxon. We studied well preserved shallow shelf microfossil assemblages from the Upper Cretaceous Red Bank, Navesink, and Marshalltown Formations in the New Jersey Coastal Plain and from the Prairie Bluff Formation in Alabama to look for praepararotaliids. We discovered a new benthic species, *Praepararotalia cretacea* (Pl. 2, figs. 1–12), that we believe to be ancestral to the Danian praepararotaliids from these Upper Cretaceous formations.

Praepararotalia cretacea n. sp. has a moderately elevated trochospiral test with five chambers in the final whorl and a smooth, irregularly perforated test wall except on the umbilical shoulders, which are covered by blunt pustules. The aperture, a small oval, areal opening with a thickened rim, has an interiomarginal position. These characters are similar in many aspects to those found in the early Paleocene species *P. perclara* (Loeblich and Tappan). This Late Cretaceous praepararotaliid species is here regarded as the possible ancestor of the Tertiary praepararotaliid lineages.

In their study of the genus *Pararotalia* Le Calvez, Loeblich and Tappan (1957b) described eleven species, four of which were new, from sediments of Paleocene to Miocene age. The Paleocene to Eocene species (*P. macneili* Loeblich and Tappan and *P. ishamae* Loeblich and Tappan) are small and have irregular perforate test walls, a rounded peripheral margin and gradually enlarging elliptical chambers. These characters are similar to the Danian *P. perclara*. The only differences are the initial development of an umbilical structure that leads to a prominent umbilical plug in later species of *Pararotalia* and recurved sutures on the spiral side in *P. macneili* and *P. ishamae*. In the Eocene, some specimens of *P. calvezae* Loeblich and Tappan developed a discontinuous peripheral keel, a solid rounded umbilical plug, a small elliptical to slit-like extraumbilical areal aperture and a blunt peripheral pseudospine on the margin of each chamber. Continuation of these trends leads to the typical *Pararotalia*, which has a planoconvex test, a continuous keel, wide and

deep umbilical sutures, a large solid umbilical plug and various pillars in the equatorial margin of each chamber in the last whorl. Along with those trends, the test size increases significantly in younger species (up to $700\ \mu\text{m}$). Apparently, *P. macneili* and *P. ishamae* link these typical pararotaliid species to the Danian *Praepararotalia perclara* (Fig. 3). The evolution of *Pararotalia sensu stricto* should therefore include the development of a larger planoconvex test, sharp pustules, a peripheral pseudospine on the equatorial margin of each chamber, a discontinuous to continuous keel, conical chambers and a large, solid umbilical plug. Loeblich and Tappan (1988) recorded the stratigraphic range of *Pararotalia* as Cretaceous to Holocene. The Late Cretaceous occurrence of this genus is based on the species *Rotalia fimbriatula* Cushman and Hedberg. The illustration of *Rotalia fimbriatula* shows that this species is similar to *Pararotalia* in having a pustulose surface and an umbilical plug. However, examination of the holotype and paratypes of this species shows that the pustulose appearance is due to recrystallization and that the “plug” is partially bordered by narrow apertures of the chambers in the last whorl. *Rotalia fimbriatula* is perhaps related to *Cibicides* rather than to *Pararotalia*.

PRAEPARAROTALIA AND ANTARCTICELLA

Praepararotalia cretacea n. sp. is rare in Upper Cretaceous shelf sediments in the New Jersey Coastal Plain and in Alabama. Typical *P. cretacea* has not been found in Paleocene sediments. However, a possibly related species, *Globigerina pauciloculata* Jenkins, occurs in Danian sediments at southern high latitudes. This species, which was described from the lower Danian of New Zealand (Jenkins, 1966), has a rounded and inflated test with sutural apertures along the base of the last chamber (Pl. 3, fig. 8). This distinct character suggests that it is a species of *Antarcticella* Loeblich and Tappan, 1988. Basal Danian pararotaliid specimens, identified as *Eoglobigerina edita* Subbotina, were illustrated from ODP Site 690C, Leg 113 by Stott and Kennett (1990, Pl. 1, figs. 9–10; Pl. 3, figs. 10–11, this paper). However, this form is not the cancellate-walled spinose species *Eoglobigerina edita*. It possesses many of the characteristics of *P. cretacea* and is identical to *Antarcticella pauciloculata* (Jenkins) in that it possesses sutural apertures on the spiral side of the last chamber (Pl. 3, figs. 10–11). This species is also found on Seymour Island, Antarctica (Pl. 3, figs. 12–13; Huber, 1988).

The origin of *Antarcticella pauciloculata* (Jenkins) has not previously been documented. We suggest that it may be related to *Pararotalia cretacea* due to the morphologic similarity between these two species and their distinctive pustulose umbilical surface. *Antarcticella pauciloculata* (Pl. 3, figs. 8, 10–12) differs from *P. cretacea* in its more inflated chambers and in having sutural apertures along the base of the ultimate chamber.

Antarcticella pauciloculata may be the stem taxon of a southern ocean Paleogene lineage first proposed by Leckie and Webb (1985). They proposed a Paleogene evolutionary lineage *Candeina cecionii* - *zeocenica* - *antarctica* and questioned, although not in detail, the planktic paleohabitat of this lineage. *Candeina cecionii* Cañón and Ernst (1974)

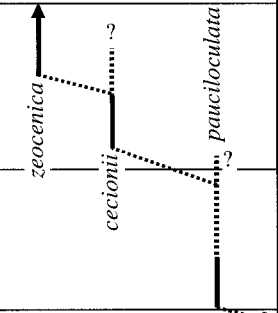
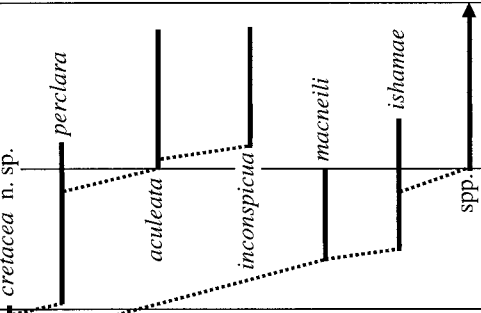
wall texture	irregularly perforate, pustulose on umbilical side, smooth or pustulose on dorsal side.			
aperture	areal, extraumbilical-marginal, with toothplate and wide apertural lip.			
genus	<i>Candeina</i>	<i>Antarcticella</i>	<i>Praepararotalia</i> n. gen.	<i>Pararotalia</i> Le Calvez
test surface	smooth on dorsal side		pustulose on dorsal, pillar on margin.	smooth dorsal side, pillars on umbilical and margin
test	biconvex		planoconvex	biconvex to planoconvex
keel	absent, round margin		without or discontinuous	without to continuous
umbilical structure	absent		fused apertural plates	umbilical plug
sutural apertures	occur		absent	
Eocene				
Paleocene				
Upper Cretac.				

FIGURE 3. Phylogenetic relationship of the Late Cretaceous and early Paleogene praepararotaliids and pararotaliids. See text for discussion.

is recorded only from the Magallanes Basin in southern Chile (Cañón and Ernst, 1974; Leckie and Webb, 1985). A comparison of this species with *Antarcticella pauciloculata* suggests that *Candeina cecionii* may be a junior synonym of *A. pauciloculata*, but the stratigraphic gap between their recorded ranges (lower Paleocene to lower Eocene) needs to be resolved. Since *Candeina antarctica* Leckie and Webb is the type species of the genus *Antarcticella* and the species itself is derived from *A. pauciloculata* through *A. zeocenica* (Hornibrook and Jenkins), *Antarcticella* may be an offshoot of *Praepararotalia* and may have had a benthic habitat. This hypothesis of a benthic paleohabitat for *Antarcticella* is supported by the dominant occurrence of *A. antarctica* in the shallower facies of marginal basins. *Antarcticella antarctica* (Pl. 3, figs. 1–7) is rare or absent from open-ocean paleoenvironments. Species of *Antarcticella* also have a restricted geographic distribution to southern high latitude shallow seas in the Oligocene - Miocene (Leckie and Webb, 1985). If *Antarcticella* is indeed a benthic genus, the relationship between it and the planktic species *Candeina nitida* d'Orbigny as suggested by Leckie and Webb (1985) will need further investigation.

ACKNOWLEDGMENTS

We thank D. G. Jenkins for encouraging and thoughtful comments and for sending collections from New Zealand for comparison. We also thank Percy Strong and Hugh Morgans (Institute of Geological & Nuclear Sciences, Ltd., Lower Hutt, New Zealand) for sending topotype specimens of *A. pauciloculata* and *A. zeocenica*; Jim Kennett and Lowell Stott for providing SEM images of *Antarcticella pauciloculata* from Leg 113; Norberto Malumián and Car-

olina Náñez for providing information on the distribution of *Antarcticella* in Argentina; and Valerie Cheshier (University of Texas at Dallas) for providing the photograph of *Candeina nitida*.

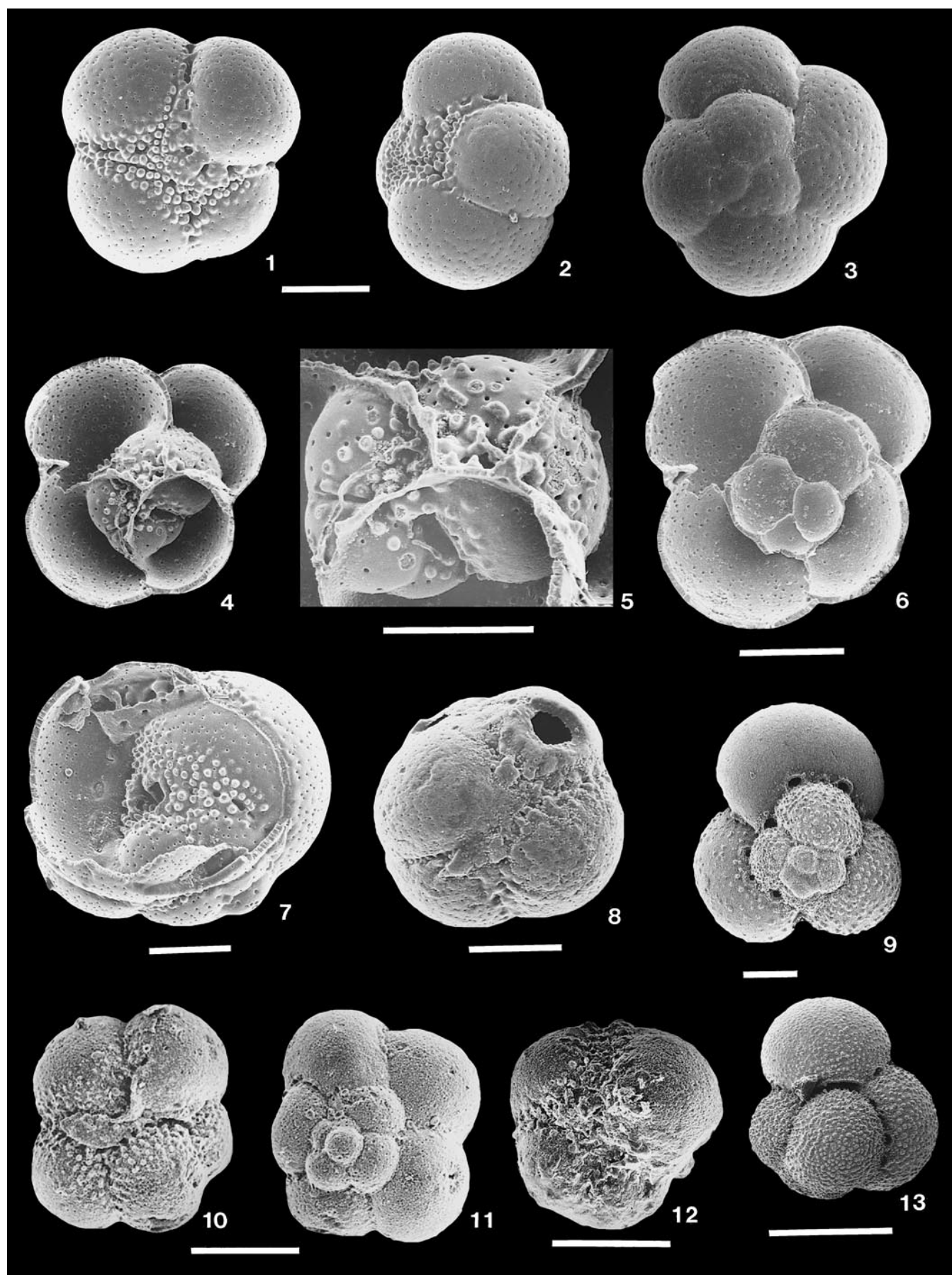
SYSTEMATIC DESCRIPTIONS

Family ROTALIIDAE Ehrenberg, 1839
Subfamily PARAROTALIINAE Reiss, 1963
Antarcticella Loeblich and Tappan, 1988

Type species. *Candeina antarctica* Leckie and Webb, 1985

Diagnosis. Test small, subglobular, biconvex, low trochospiral with 1.5 to 2 whorls of rapidly enlarging chambers, 3.5 to 5 chambers in the final whorl, equatorial outline lobate, periphery broadly rounded; proloculus large, ranging from 30 to 45 μ m in diameter, final chamber ampullate, kummerform, extending over the umbilicus; sutures slightly depressed and radial on spiral and umbilical sides, umbilicus closed; wall thin, finely perforate with a mostly smooth surface except for areas along umbilical sutures and umbilical area, which may be covered with blunt pustules; aperture a broad, low interiomarginal, umbilical-extraumbilical arch on early chambers, accessory apertures between bridgelike projections occur along the margin of the ultimate chamber or final whorl of chambers.

Remarks. Loeblich and Tappan (1988) designated this genus to accommodate species previously included in *Candeina* that lack the true sutural openings that characterize *Candeina nitida* d'Orbigny (e.g., Plate 3, figs. 9, 13). *Candeina* further differs from *Antarcticella* in that *Candeina* (1) lacks concentrations of pustules along chamber sutures or in the umbilical region, (2) has chamber surfaces that are smooth or evenly covered by fine pustules; and (3) the sutural openings are surrounded by a thickened rim on the umbilical and spiral sides of the test. *Antarcticella* currently includes, from oldest to youngest, *Globigerina pauciloculata* Jenkins, *Candeina cecionii* Cañón and Ernst, *Candeina zeocenica* Hornibrook and Jenkins, and *Candeina antarctica* Leckie and Webb. All species of this genus have restricted biogeographic distributions in the southern middle to high latitudes, and occur in shallow marine clastic sedimentary facies where planktic:benthic ratios are extremely low. On the basis of the wall textural and



morphological differences with *Candeina* and because of its restriction to neritic environments we remove *Antarcticella* from the globigerinid Subfamily Candeinidae and place it in the benthic Subfamily Pararotaliinae of the Family Rotaliidae.

Morphological similarities between *Antarcticella* and *Praepararotalia cretacea* suggest that these taxa may have been related. Both taxa have (1) a generally smooth, finely perforate wall texture with pustule concentrations along the umbilical sutures and in the umbilical region; (2) a lobate equatorial outline with a prominent proloculus; and (3) an extension of the final chamber toward the umbilicus. However, the early evolutionary history of these two genera is poorly documented.

Antarcticella antarctica (Leckie and Webb)

Pl. 3, Figs. 1–7

Candeina antarctica Leckie and Webb, 1985, p. 66, pl. 1, figs. 1–17, pl. 2, figs. 1–9, pl. 3, figs. 3, 6, 8.

Diagnosis. Test small, 130–190 μm in maximum diameter, biconvex, low trochospiral, generally quadrilobate in equatorial outline, broadly rounded in edge view; proloculus large, ranging from 30 to 45 μm in diameter; chambers subglobular, rapidly enlarging in size until final whorl, typically 8, sometimes 10 total chambers in adult specimens arranged in 1.5 to 2.5 whorls, final whorl with 3.5 to 5 chambers; sutures slightly depressed and radial on spiral and umbilical sides, umbilicus closed, sometimes covered by sutural bullae; wall finely perforated by pores that are 0.8 to 1.5 μm in diameter, with a mostly smooth surface except for areas along umbilical sutures and umbilical area, which may be covered with concentrations of blunt pustules; aperture a broad, low interiomarginal, extraumbilical-umbilical arch on early chambers, becomes obscured by bridgelike projections with accessory apertures along the umbilical suture of the ampullate final chamber.

Remarks. *Antarcticella antarctica* differs from other species of *Antarcticella* by having the accessory sutural apertures and pustules restricted to the umbilical side of the test. Serial dissection of this species reveals pre-adult chambers (Pl. 3, figs. 4–5) with more widely scattered pustules than on the final whorl chambers of adult specimens (Pl. 3, figs. 1–3) and an umbilical-extraumbilical aperture with a narrow bordering lip. One adult specimen with its final chamber partially removed reveals incomplete closure of the primary aperture by a bridgelike extension of a pustulose covering, and tube-like connections between the shell interior and exterior along umbilical suture of the final chamber (Pl. 3, fig. 7). Dissections of other species in the Pararotaliinae are necessary to determine the taxonomic significance of the tube-like connections of the accessory apertures observed in *A. antarctica*.

Antarcticella antarctica has been reported from shallow marine sediments in the Ross Sea basins of Antarctica, ranging from the latest Oligocene through middle Miocene (Leckie and Webb, 1985). It was also reported from southern Argentina in upper Eocene-lower Oligocene (Hromic, 1988, 1990) and offshore Argentina in Oligocene-lower Miocene neritic sediments (Malumian and Nández, 1996).

Antarcticella pauciloculata (Jenkins)

Pl. 3, Figs. 8, 10–12

Globigerina pauciloculata Jenkins, 1966, p. 1106, figs. 3(7–15), 3(16–41), 4(42). *Globastica daubjergensis* (Brönnimann), Huber, 1988, figs. 32(10), 32(10–11). *Eoglobigerina edita* (Subbotina), Stott and Kennett, pl. 1, figs. 9–10.

Diagnosis. Test small, 120–170 μm in maximum diameter, globular, biconvex, lobate in equatorial outline, low trochospiral with 1.5 to 2 whorls of 7 to 9 chambers in adult specimens; chambers increase rapidly in size up to the penultimate chamber, 3.5 to 4.5 in the final whorl; proloculus large, ranging from 30 to 40 μm in diameter, final chamber ampullate, kummerform, extending over the umbilicus, umbilicus sometimes covered by bullae; sutures slightly to moderately depressed and radial on spiral and umbilical sides, umbilicus closed; wall finely perforate with a mostly smooth surface except for umbilical sutures and umbilical region, which may be covered with blunt pustules; aperture a low, interiomarginal umbilical-extraumbilical arch on early chambers, with a transition to accessory apertures between bridge like projections along the umbilical sutures.

Remarks. This species was first reported Jenkins (1966, 1971) from nearshore clastic marine sediments assigned to the lower Teurian (Danian) in New Zealand where it is used to define the *A. pauciloculata* Zone. Although Jenkins's description and accompanying illustrations of *A. pauciloculata* suggest that the wall texture is cancellate, SEM micrographs of topotype specimens (e.g., Pl. 3, fig. 8) clearly show a smooth surface texture. *Antarcticella pauciloculata* has less distinct sutural apertures than *A. antarctica* and *A. zeocenica* (Hornibrook and Jenkins), and it further differs from *A. zeocenica* by possessing a lower trochospire.

Antarcticella pauciloculata appears to have been restricted to the southern high latitudes. Rare specimens of this species, incorrectly identified by Huber (1988, figs. 32.10, 32.11) as *Globastica daubjergensis*, were recovered from nearshore marine sediments of early Danian age on Seymour Island, Antarctica. One of these specimens is reillustrated in Plate 3 (fig. 12). Another incorrect identification of *A. pauciloculata* was made by Stott and Kennett (1990). These authors illustrated a specimen designated as *Eoglobigerina edita* from lower Danian pelagic carbonate sediments cored in the South Atlantic sector of the Southern Ocean (ODP Sample 690C-15X-3, 95–97 cm). Two views of this specimen are reillustrated on Plate 3 (figs. 10–11). Exhaustive search of samples above and below this core level resulted in the identification of only one specimen from a sample from immediately above the Cretaceous/Tertiary boundary (Sample 690C-15X-4, 30–35 cm). Specimens of *A. pauciloculata* (identified as *Antarcticella* sp.) have also been reported from shallow marine sediments in southern Argentina (Malumian and Caramés, 1997).

A form similar to *A. pauciloculata*, *Antarcticella cecionii* (Cañón and Ernst), was described from the Magallanes (=Austral) Basin of southern Chile (Cañón and Ernst, 1974, p. 83–84, pl. 4, figs. 6a–c). These authors originally assigned this species to the Miradorian and Gaviotian stages (upper Oligocene-Miocene), but Leckie and Webb (1985) reassigned its range to the Manzanian Stage (early middle Eocene). The latter authors also provided SEM micrographs of poorly preserved specimens recovered from deep well cores in the Magallanes Basin. Although *A. cecionii* and *A. pauciloculata* appear to be morphologically similar and, therefore, may be synonymous, the stratigraphic gap between their recorded stratigraphic ranges, poor preservation, and patchy geographic distribution render clarification of their taxonomic status difficult.

Praepararotalia Liu, Olsson, and Huber, new genus

Type species. *Globorotalia perclara* LOEBLICH AND TAPPAN, 1957

Test a very low trochospire with 11–16 chambers, 5–6 in ultimate

PLATE 3

(1–4, 6–13 bar = 50 μm ; 5 bar = 40 μm) 1–7 *Antarcticella antarctica* (Leckie and Webb) from DSDP Site 273A, sample 16-cc. 1–3 umbilical, edge, and spiral views. 4–6 serial dissection of same specimen revealing juvenile shell morphology and cross-sectional chamber outlines. 7 oblique view of adult specimen with final chamber removed. Note pustulose calcareous extension of shell wall over primary aperture of penultimate chamber and tubular openings of accessory sutural apertures of ultimate chamber. 8, 10–12 *Antarcticella pauciloculata* (Jenkins). 8 topotype specimen from Teurian (Danian) sediments in New Zealand (sample S68/197, M34/7197). 10–11 umbilical and spiral views of specimen that was previously illustrated as *Eoglobigerina edita* by Stott and Kennett (1990, pl. 1, figs. 9–10) from the lower Danian of ODP Hole 690C in the Antarctic sector of the South Atlantic (Sample 690C-15X-3, 95–97 cm). 12 umbilical view of specimen from the lower Danian of Seymour Island, Antarctica [previously illustrated as *Globastica daubjergensis* by Huber, 1988, figs. 32(10), 32(11)]. 9 and 13 *Candeina nitida* d'Orbigny from ODP Site 806, Sample 806B-26H-7, 29–31 cm). 9 spiral view revealing even distribution of fine pustules on the test surface and true sutural accessory apertures. 13 oblique view revealing absence of pustule concentrations from umbilical region or chamber sutures.

←

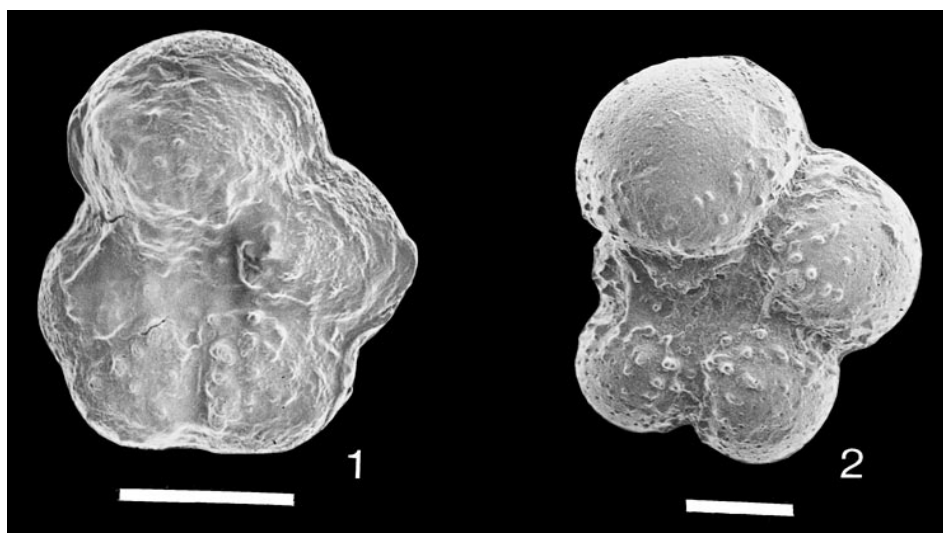


FIGURE 4. Uncoated scanning electron micrographs (SEM) of the holotype of *Globorotalia reissi* Loeblich and Tappan (USNM 5356), fig. 4-1 and the holotype of *Globorotalia perclara* Loeblich and Tappan (USNM 5835), fig. 4-2. Scale bar = 50 μm .

whorl; chambers globular to ovoid or subconical, increasing gradually in size; dorsal side of test planar to slightly convex; ventral side a low to high convex, rounded shape; aperture interiormarginal, areal, a low rounded opening at peripheral margin of test; a short rounded lip borders aperture and may extend over umbilicus; lower half of the aperture covered by an imperforate toothplate which in previously formed chambers is attached to proximal margin of anteriorly developed chamber; umbilicus a narrow depression closed, not open to surrounding chambers; umbilical area and apertural toothplate may be broken in preservation, giving impression of an open umbilicus and a globorotalia-like aperture; wall pierced by small irregularly distributed micropores ($<2\ \mu\text{m}$) and ornamented by low rounded or sharply pointed pustules more heavily concentrated on umbilical side and, in some species, along periphery of test; pustules may coalesce in umbilicus, forming a plug-like mass, and along the periphery of test as large spike-like protuberances or as discontinuous peripheral keel. Upper Cretaceous to Eocene.

Praepararotalia cretacea Liu, Olsson, and Huber, n. sp.

Pl. 2, Fig. 1–12

Holotype. Pl. 1, Figs. 1–3, Sample #7, Maastrichtian, Navesink Formation, Marlboro, New Jersey. Deposited at the U.S. National Museum of Natural History (USNM #490508).

Paratypes. Pl. 1, Figs. 7–12, Sample #7, Maastrichtian, Navesink Formation, Marlboro, New Jersey. Deposited at the U.S. National Museum of Natural History (figs. 7–9, USNM #490509 and figs. 10–12, USNM #490510). Unfigured paratype USNM #490511.

Topotypes. Plate 1, Figs. 4–6, Sample #7, Maastrichtian, Navesink Formation, Marlboro, New Jersey. Deposited in the micropaleontological collections, Department of Geological Sciences, Rutgers University.

Diagnosis. Test small, 150–250 μm in diameter, no preferential coiling direction, a total of 11–13 subglobular to oval chambers constructing a low to high trochospiral test around a large proloculus, 5 to 5½ chambers in the final whorl, with the final one frequently offset towards umbilical side; sutures slightly recurved and depressed; wall slightly perforate, with sporadic pores; spiral side smooth, umbilical side covered by blunt pustules; umbilicus wide, shallow and closed, without an umbilical structure; aperture areal, extraumbilical, apertural lip wide, often extends to cover part of umbilicus; a toothplate may close lower half of the aperture but it is generally not preserved. Upper Cretaceous to basal Paleocene.

Remarks. This new species differs from *Praepararotalia perclara* (Loeblich and Tappan) in having a less perforate, smooth wall on the spiral side, a higher trochospiral test, recurved sutures, a shallow but wide umbilicus ornamented with thick pustules, and a last chamber offset toward the umbilical side. *Antarcticella pauciloculata* (Jenkins)

is similar to this new species in wall texture, offsetting of the last chamber toward the umbilicus and the presence of pustules in the umbilicus. The difference is that the new species has more chambers (4½–6 compared to 4–4½ in *A. pauciloculata*) in the final whorl, has a lower spiral side, and lacks supplementary apertures along the sutures of the last chamber. The two are perhaps related as discussed above.

Praepararotalia perclara (Loeblich and Tappan)

Pl. 1, Figs. 1–9, Text-figure 4–2

Globorotalia perclara Loeblich and Tappan, 1957a, p. 191–192, pl. 40, figs. 7a–c; pl. 41, figs. 8a–c; pl. 42, figs. 4a–c; pl. 45, figs. 11a–c; pl. 46, figs. 3a–c; pl. 47, figs. 6a–c; pl. 50, figs. a–c; pl. 54, figs. 6a–7c; pl. 57, figs. 3a–4c; pl. 60, figs. 5a–c.

Globorotalia reissi Loeblich and Tappan, 1957a, p. 194, pl. 50, figs. 3a–c; pl. 58, figs. 3a–c; pl. 60, figs. 7a–c.

Globorotalia perclara Murray, Curry, Haynes, King, 1989, pl. 10, figs. 28–30.

Diagnosis. Test small to moderate, 120–300 μm in diameter, a planoconvex or slightly elevated trochospiral test constructed by 9–15 subglobular to oval chambers, with 5 to 6 chambers in final whorl; sutures radial and slightly depressed; wall perforate, smooth to slightly pustulose on spiral side, umbilical side covered by blunt to sharp pustules; umbilicus narrow to moderately wide, deep and closed, without an umbilical structure; aperture areal, extraumbilical, with an imperforate toothplate closing the lower half of the aperture, apertural lip often extends from the umbilicus to the periphery. Paleocene to lower Eocene.

Remarks. Loeblich and Tappan (1957a) described two species (*Globorotalia reissi* and *G. perclara*, Figs. 4–1,2) from the Paleocene and indicated that the difference between the two species is that *G. reissi* is more elevated on the dorsal side and has a smoother test surface. In this case, *G. reissi* would be closer to *P. cretacea* n. sp. and ancestral to *G. perclara*. However, in the range chart of Loeblich and Tappan (1957a), the first occurrence of *G. reissi* is later than that of *G. perclara*, which conflicts with the evolutionary trend in the lineage. Our study of the basal Paleocene assemblages from the New Jersey Coastal Plain, Millers Ferry and Braggs in Alabama suggests that the separation between the lower and higher trochospiral tests is ambiguous and that the difference in surface texture is in degree rather than in kind. Since both occur in Danian sediments, we regard the slight morphological differences as intraspecific variation and, therefore, place *reissi* as a junior synonym of *perclara*.

Praepararotalia aculeata (Howe)

Pl. 1, Figs. 10–13

Globorotalia inconspicua aculeata Jenkins, 1966, p. 1118–1119, pl. 13, figs. 119–125.

Globorotalia (Turborotalia) aculeata Jenkins, 1971, p. 111–112, pl. 10, figs. 250–256.

Diagnosis. Test small, 150–250 μm in diameter, planoconvex, 6–8 conical chambers in the final whorl, angular-conical in shape; wall strongly pustulose, pores sporadic and irregularly distributed; umbilicus wide, shallow and closed, without an umbilical structure; peripheral margin round or with thick pustules but no keel; aperture high, extraumbilical, with a toothplate which is often poorly preserved. Eocene.

Remarks. Both Jenkins (1966, 1971) and Jones (1983) recognized *Globorotalia aculeata* as the immediate ancestor of *inconspicua* and placed them in different subgenera or genera. The major difference between the two species as defined by Jenkins (1966) is the occurrence of a well developed peripheral keel in *inconspicua*, whereas in *aculeata* the peripheral margin is bordered, in varying degrees, with thick pustules. *Praepararotalia aculeata* does not possess an obvious pustulose umbilical structure, while *P. inconspicua* may have a weakly to strongly developed pustulose umbilical structure. Both species occur together in Eocene sediments in New Jersey as well as in the topotype material from Louisiana as observed by Jenkins (1966, 1971) and in this study.

Praepararotalia inconspicua (Howe)
Pl. 2, Figs. 13–16

Globorotalia inconspicua Howe, 1939, p. 85, pl. 12, figs. 20–22.

Globorotalia (Testacarinata) inconspicua, Jenkins, 1971, p. 110–111, pl. 14, figs. 398–401.

Testacarinata inconspicua, Jones, 1983, p. 36, pl. 10, figs. 1–6.

Diagnosis. Test small, 150–250 μm in diameter, planoconvex, 6–8 conical chambers in final whorl, angular-conical in shape; wall strongly pustulose, pores sporadic and irregularly distributed; umbilicus wide, shallow and closed, enclosed with a complex pustulose umbilical structure which may be weakly to strongly developed; peripheral margin sharp, usually with a distinct keel; aperture high, extraumbilical, with a toothplate which may not be preserved. Eocene.

Remarks. *Praepararotalia inconspicua* is similar to Eocene species of *Pararotalia* in the possession of a peripheral keel and an umbilical structure. The periphery is not as acute and the keel is not as strongly developed as in typical *Pararotalia*. As noted above it occurs in shallow shelf depositional environments in the Atlantic and Gulf coastal plains. The species also occurs in shallow marine facies in the Rio Turbio Fm. and the Man Aike Fm. of the Magallanes (Austral) Basin in Patagonia (Carrizo and others, 1990; Malumian, 1990).

REFERENCES

- ANDERSON, T., and ARTHUR, M. A., 1983, Stable isotopes of oxygen and carbon and their application to sedimentologic and paleoenvironmental problems, in Arthur, M. A., Anderson, T. F., Kaplan, I. R., Veizer, J., and Land, L. S. (eds.), *Stable isotopes in Sedimentary Geology*: Society of Economic Paleontologists and Mineralogists Shortcourse No. 10, p. 1–151.
- BANNER, F. T., 1982, A classification and introduction to the Globigerinacea, in Banner, F. T. and Lord, A. R. (eds.), *Aspects of Micropaleontology*: George Allen & Unwin, London, p. 142–239.
- BÉ, A. W. H., and TOLDERLUND, D. S., 1971, Distribution and ecology of living planktonic foraminifera in surface waters of the Atlantic and Indian Oceans, in Funnell, B. M., and Riedel, W. R. (eds.), *The Micropaleontology of Oceans*: Cambridge University Press, London, p. 105–149.
- BERGGREN, W. A., 1977, Atlas of Palaeogene planktonic foraminifera: some species of the genera *Subbotina*, *Planorotalites*, *Morozovella*, *Acarinina* and *Truncorotaloides*, in Ramsay, A.T.S. (ed.), *Oceanic Micropaleontology*: Academic Press, London, p. 205–300.
- BERTELS, A., 1970, Los foraminíferos planctónicos de la cuenca Cretácico-Terciaria en Patagonia Septentrional (Argentina), con consideraciones sobre la estratigrafía de Fortín General Roca (Provincia Rio Negro): *Ameghiniana*, v. 7, p. 1–57.
- , 1975, Bioestratigrafía del Paleoceno marino en la Provincia de Chubut, Republica Argentina: *Actas I Congreso Argentino de Paleontología*, v. 2, p. 271–316.
- BOERSMA, A., and PREMOLI-SILVA, I., 1989, Atlantic Paleogene biserial heterohelical foraminifera and oxygen minima: *Paleoceanography*, v. 4, p. 271–286.
- BOLLI, H. M., 1957, The genera *Globigerina* and *Globorotalia* in the Paleocene—lower Eocene Lizard Springs Formation of Trinidad, B.W.I., in *Studies in Foraminifera*, Loeblich, A. R., Jr., and collaborators: U.S. National Museum Bulletin, 215, p. 61–82.
- BOUVIER-SOUMAGNAC, Y., and DUPLESSY, J.-C., 1985, Carbon and oxygen isotopic composition of planktonic foraminifera from laboratory culture, plankton tows and recent sediment: implications for the reconstruction of paleoclimatic conditions and of the global carbon cycle: *Journal of Foraminiferal Research*, v. 15, p. 302–320.
- CANÓN, A., and ERNST, M., 1974, Part II, Magallanes Basin foraminifera, in Natland, M. L., Gonzales, E., Cañón, A., and Ernst, M., (eds.), *A System of Stages for Correlation of Magallanes Basin Sediments*: Geological Society of America Memoir 139, p. 61–117.
- CARRIZO, R., MALUMIÁN, N., NÁÑEZ, C., CARAMÉS, A., and CONCHEYRO, A., 1990, Micropaleontología y correlación del Terciario area carbonífera de Rio Turbio, Provincia de Santa Cruz, Argentina: in *Segundo simposio sobre el Terciario de Chile*, Concepción, 1990, p. 29–50.
- DEUSER, W. G., 1987, Seasonal variations in isotopic composition and deep-water fluxes of the tests of perennially abundant planktonic foraminifera of the Sargasso Sea: results from sediment-trap collections and their paleoceanographic significance: *Journal of Foraminiferal Research*, v. 17, p. 14–27.
- D'HONDT, S., and ZACHOS, J. C., 1993, On stable isotopic variation and earliest Paleocene planktonic foraminifera: *Paleoceanography*, v. 8, p. 527–547.
- EMILIANI, C., 1954, Depth habitats of some species of pelagic foraminifera as indicated by oxygen isotope ratios: *American Journal of Science*, v. 252, p. 149–158.
- FAIRBANKS, R. G., and WIEBE, P. H., 1980, Foraminifera and chlorophyll maximum: vertical distribution, seasonal succession, and paleoceanographic significance: *Science*, v. 209, p. 1524–1525.
- GOODAY, A. J., 1993, Deep-sea benthic foraminiferal species which exploit phytodetritus: Characteristic features and controls on distribution: *Marine Micropaleontology*, v. 22, p. 187–206.
- GRAHAM, D. W., CORLISS, B. H., BENDER, M. L., and KEIGWIN, L. D., 1981, Carbon and oxygen isotopic disequilibria of recent deep-sea benthic foraminifera: *Marine Micropaleontology*, v. 6, p. 483–497.
- GROSSMAN, E. L., 1987, Stable isotopes in modern benthic foraminifera: A study of vital effect: *Journal of Foraminiferal Research*, v. 17, p. 48–61.
- HANSEN, H. J., 1970, Danian foraminifera from Nügssuaq, West Greenland with special reference to species occurring in Denmark: *Muséum de Minéralogie et de Géologie de l'Université de Copenhague, Communications Paléontologiques*, v. 164, p. 1–131.
- HEMLEBEN, CH., 1969, Ultrastrukturen bei kalkschaligen foraminiferen: *Naturwissenschaften*, v. 56, p. 534–538.
- HILBRECHT, H. AND THIERSTEIN, H. R., 1996, Benthic behavior of planktic foraminifera: *Geology*, v. 24, p. 200–202.
- HORNIBROOK, N. DE B., and JENKINS, D. G., 1965, *Candeina zeocena* Hornibrook and Jenkins, a new species of foraminifera from the New Zealand Eocene and Oligocene: *New Zealand Journal of Geology and Geophysics*, v. 8, no. 5, p. 279–286.
- HOWE, H. V., 1939, Louisiana Cook Mountain Eocene foraminifera: Louisiana Geological Survey, Geological Bulletin, v. 14, p. 1–122.
- HROMIC, T., 1988, Presencia de *Antarcticella (Candeina) antarctica* (Leckie y Webb), (Protozoa, Foraminiferida, Candeinidae) en la cuenca Austral de América del Sur: *Anales del Instituto de la Patagonia, Serie Ciencias Naturales*, v. 18, p. 87–95.
- , 1990, Lista preliminar de foraminíferos plánticos terciarios de la porción chilena de cuenca Austral: in *Segundo Simposio Sobre el Terciario de Chile*, Concepción, 1990, p. 117–133.
- HUBER, B. T., 1988, Upper Campanian-Paleocene foraminifera from the James Ross Island region (Antarctic Peninsula), in Feldmann, R.M. and Woodburne, M.O. (eds.), *Geology and Paleontology of Seymour Island, Antarctica*: Geological Society of America Memoir 169, p. 163–252.
- , 1994, Ontogenetic morphometrics of some Late Cretaceous

- trochospiral planktonic foraminifera from the Austral Realm: Smithsonian Contributions to Paleobiology, No. 77, 85 p.
- , AND BOERSMA, A., 1994, Cretaceous origination of *Zeuvingerina* and its relationship to Paleocene biserial planktonic foraminifera: Journal of Foraminiferal Research, v. 24, p. 268–287.
- , HODELL, D. A., and HAMILTON, C. P., 1995, Mid- to Late Cretaceous climate of the southern high latitudes: stable isotopic evidence for minimal equator-to-pole thermal gradients: Geological Society of America Bulletin, v. 107, p. 1164–1191.
- JENKINS, D. G., 1966, Planktonic foraminiferal zones and new taxa from the Danian to lower Miocene of New Zealand: New Zealand Journal of Geology and Geophysics, v. 8, p. 1088–1126.
- , 1971, New Zealand Cenozoic planktonic foraminifera: New Zealand Geological Survey Paleontology Bulletin, v. 42, 278 p.
- JONES, G. D., 1983, Foraminifera biostratigraphy and depositional history of the middle Eocene rocks of the coastal plain of North Carolina: North Carolina Geological Survey, Special Publication no. 8, 80 p.
- KEIGWIN, L. D., and CORLISS, B. H., 1986, Stable isotopes in late middle Eocene to Oligocene foraminifera: Geological Society of America Bulletin, v. 97, p. 335–345.
- KOUTSOUKOS, E., 1994, Early stratigraphic record and phylogeny of the planktonic genus *Guembelitra* Cushman, 1933: Journal of Foraminiferal Research, v. 24, p. 288–295.
- , LEARY, P. N., and HART, M. B., 1989, *Favusella* Michael (1972): evidence of ecophenotypic adaptation of a planktonic foraminifera to shallow-water carbonate environments during the mid-Cretaceous: Journal of Foraminiferal Research, v. 19, p. 324–336.
- KROON, D., and NEDERBRAGT, A. J., 1990, Ecology and paleoecology of triserial planktic foraminifera: Marine Micropaleontology, v. 16, p. 25–38.
- LANGER, M. R., 1995, Oxygen and carbon isotopic composition of Recent larger and smaller foraminifera from the Madang Lagoon (Papua New Guinea): Marine Micropaleontology, v. 26, p. 215–221.
- LECKIE, R. M., 1987, Paleoecology of Mid-Cretaceous planktonic foraminifera: a comparison of open ocean and epicontinental sea assemblages: Micropaleontology, v. 33, p. 164–176.
- , and WEBB, P. N., 1985, *Candeina antarctica*, n. sp. and the phylogenetic history and distribution of *Candeina* spp. in the Paleogene-early Neogene of the Southern Ocean: Journal of Foraminiferal Research, v. 15, p. 65–78.
- LIU, C., and OLSSON, R. K., 1992, Evolutionary adaptive radiation of microporiferate planktonic foraminifera following the K/T mass extinction event: Journal of Foraminiferal Research, v. 22, p. 328–346.
- , and ———, 1994, On the origin of Danian normal perforate planktonic foraminifera from *Hedbergella*: Journal of Foraminiferal Research, v. 24, p. 61–74.
- LIU, C., BROWNING, J. V., MILLER, K. G., and OLSSON, R. K., 1997, Upper Cretaceous to Miocene planktonic foraminiferal biostratigraphy: results of Leg 150X, the New Jersey Coastal Plain Drilling Project, in Miller, K. G., Snyder, S. W., and others, Proceedings of Ocean Drilling Program, Scientific Results: v. 150, in press.
- LOEBLICH, A. R., JR. and TAPPAN, H., 1957a, Planktonic foraminifera of Paleocene and early Eocene age from the Gulf and Atlantic Coastal Plains, in Studies in Foraminifera, Loeblich, A. R., Jr., and collaborators: U.S. National Museum Bulletin 215, p. 173–201.
- , and ———, 1957b, Morphology and taxonomy of the foraminiferal genus *Pararotalia* Le Calvez, 1949: Smithsonian Miscellaneous Collections, v. 135, p. 1–24.
- , and ———, 1988, Foraminiferal genera and their classification: Van Nostrand Reinhold Company, New York, 970 p.
- LUZ, G., and REISS, Z., 1983, Stable carbon isotopes in Quaternary foraminifera from the Gulf of Aqaba (Elat), Red Sea, Meulenkamp, J. E. (ed.), Reconstruction of Marine Paleoenvironments. Utrecht Micropaleontological Bulletin, v. 30, p. 229–237.
- MACLEOD, K. G., and HUBER, B. T., 1996, Reorganization of deep ocean circulation accompanying a Late Cretaceous extinction event: Nature, v. 380, p. 422–425.
- MALUMIÁN, N., 1990, Foraminíferos de la Formación Man Aike (Eoceno, Sureste Lago Cardiel) Provincia de Santa Cruz: Revista de la Asociación Geológica Argentina, v. 45, p. 365–385.
- , and CARAMÉS, A., 1997, Upper Campanian-Paleogene from the Río Turbio coal measures in southern Argentina: micropaleontology and the Paleocene/Eocene boundary: Journal of South American Earth Sciences, v. 10, p. 189–201.
- MCCORKLE, D. C., KEIGWIN, L. D., CORLISS, B. H., and EMERSON, S. R., 1990, The influence of microhabitats on the carbon isotopic composition of deep-sea benthic foraminifera: Paleoceanography, v. 5, p. 161–185.
- MCGOWRAN, B., 1968, Reclassification of early Tertiary *Globorotalia*: Micropaleontology, v. 14, p. 179–198.
- MURRAY, J. W., CURRY, D., HAYNES, J. R., and KING, C., 1989, Palaeogene, in Jenkins, D. G. and Murray, J. W. (eds.), Stratigraphical atlas of fossil foraminifera, 2nd edition: Ellis Horwood Limited, England, p. 490–536.
- NÁÑEZ, C., 1990, Foraminíferos y biostratigrafía del Terciario medio de Santa Cruz oriental: Revista de la Asociación Geológica Argentina, v. 43, p. 493–517.
- OLSSON, R. K., 1960, Foraminifera of latest Cretaceous and earliest Tertiary age in the New Jersey Coastal Plain: Journal of Paleontology, v. 34, p. 1–58.
- , 1970, Planktonic foraminifera from base of Tertiary, Millers Ferry, Alabama: Journal of Paleontology, v. 44, p. 598–604.
- , and WISE, S. W., JR., 1987, Upper Paleocene to middle Eocene depositional sequences and hiatuses in the New Jersey Atlantic margin: Cushman Foundation for Foraminiferal Research, Special Publication 24, p. 99–111.
- , HEMLEBEN, CH., BERGGREN, W. A., and LIU, C., 1992, Wall texture classification of planktonic foraminifera genera in the lower Danian: Journal of Foraminiferal Research, v. 22, p. 195–213.
- , and LIU, C., 1993, Controversies on the placement of Cretaceous-Paleogene boundary and the K/P mass extinction of planktonic foraminifera: Palaios, v. 8, p. 127–139.
- , HEMLEBEN, CH., BERGGREN, W. A., and HUBER, B. T., (eds.), Atlas of Paleocene Planktonic Foraminifera: Contributions to Paleobiology, Smithsonian Press, Washington, D.C., No. 85, in press.
- SHACKLETON, N. J., and KENNETT, J. P., 1975, Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analysis in DSDP sites 277, 279, and 280, in Kennett, J. P., Houtz, R. E. and others, Initial Reports of the Deep Sea Drilling Project: U.S. Government Printing Office, Washington, v. 29, p. 743–755.
- , and VINCENT, E., 1978, Oxygen and carbon isotope studies in Recent Foraminifera from the southeast Indian Ocean: Marine Micropaleontology, v. 3, p. 1–13.
- SMITH, F. D., JR., 1955, Planktonic foraminifera as indicators of depositional environments: Micropaleontology, v. 1, p. 147–151.
- SPERO, H. J., 1992, Do planktic foraminifera accurately record shifts in the carbon isotopic composition of seawater CO₂: Marine Micropaleontology, v. 19, p. 275–285.
- , and WILLIAMS, D. J., 1989, Opening the carbon isotope “vital effect” black box 1. Seasonal temperatures in the euphotic zone: Paleoceanography, v. 4, p. 593–601.
- STOTT, L. D., and KENNETT, J. P., 1990, Antarctic Paleogene planktonic foraminifer biostratigraphy: ODP Leg 113, Site 689 and 690, in Barker, P. F. and Kennett, J. P., and others, Proceedings of Ocean Drilling Program, Scientific Results: v. 113, p. 549–570.
- VINCENT, E. and BERGER, W. H., 1981, Planktonic foraminifera and their use in paleoceanography, in Emiliani, C. (ed.), The Oceanic Lithosphere: The Sea. Wiley-Interscience, New York, v. 7, p. 1025–1119.
- VINCENT, E., KILLINGLEY, J. S., and BERGER, W. H., 1981, Stable isotopic composition of benthic foraminifera from the equatorial Pacific: Nature, v. 289, p. 639–643.
- WEFER, G. and BERGER, W. H., 1991, Isotope paleontology: growth and composition of extant calcareous species: Marine Geology, v. 100, p. 207–248.
- WOODRUFF, F., SAVIN, S. M., and DOUGLAS, R. G., 1980, Biological fractionation of oxygen and carbon isotopes by recent benthic foraminifera: Marine Micropaleontology, v. 5, p. 3–11.

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