1. PALEOCEANOGRAPHY OF UPPER MAESTRICHTIAN TO EOCENE BENTHIC FORAMINIFERAL ASSEMBLAGES AT SITES 752, 753, AND 754, EASTERN INDIAN OCEAN[1]

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ABSTRACT

Late Maestrichtian to late Eocene bathyal benthic foraminiferal faunas at Sites 752, 753, and 754 on Broken Ridge in the eastern Indian Ocean were analyzed as to their stratigraphic distribution of species to clarify the relation between faunal turnovers and paleoceanographic changes.

Based on Q-mode factor analysis, eight varimax assemblages were distinguished: the *Stensioina beccariiformis* assemblage in the upper Maestrichtian to upper Paleocene; the *Cibicidoides hyphalus* assemblage in the upper Maestrichtian; the *Cibicidoides* cf. *pseudoperlucidus* assemblage in the upper Paleocene; the *Anomalinoides capitatus/danicus* assemblage in the uppermost Paleocene to lower Eocene; the *Cibicidoides subspiratus* assemblage in the lower Eocene; the *Nuttallides truempyi* assemblage in the lower and middle Eocene; the *Osangularia* sp. 1–*Hanzawaia ammophila* assemblage in the upper Eocene; and the *Lenticulina* spp. assemblage in the uppermost Eocene, Oligocene, and lower Miocene. The presence of the *Osangularia* sp. 1–*Hanzawaia ammophila* assemblage is related to the shallowing episode on Broken Ridge (upper bathyal), as a result of the rifting event that occurred in the middle Eocene.

The most distinct faunal change (the disappearance of about 37% of the species) occurred between the *S. beccariiformis* assemblage and the *A. capitatus/danicus* assemblage, at the end of the upper Paleocene. *A. capitatus/danicus, Lenticulina* spp., and varied forms of *Cibicidoides* replaced the Velasco-type fauna at this time. The timing of this event is well correlated with the known age at South Atlantic sites (Thomas, 1990; Kennett and Stott, 1990; Katz and Miller, 1990). The primary cause of the extinction of the *Stensioina beccariiformis* assemblage is elusive, but may have resulted from the cessation of deep-water formation in the Antarctic (Katz and Miller, 1990), and subsequent arrival of warm saline deep water (Thomas, 1990; Kennett and Stott, 1990). Another possibility may be a weakened influence of high-salinity water formed at the low latitudes such as the Tethys Sea. The extinction event corresponds to the change from higher $\delta^{13}C$ values in benthic foraminifers to lower ones. An interpretation of $\delta^{13}C$ values is that the eastern Indian deep water, characterized by young and nutrient-depleted water, became old water which was devoid of a supply of new water during the latest Paleocene to early Eocene. Prior to this benthic event, signals of related faunal change were detected in the following short periods: early and late Paleocene, near the boundary of nannofossil Zone CP4, and Zone CP5 of the late Paleocene at Site 752.

Among common taxa in the upper Maestrichtian, only seven species disappeared or became extinct at the Cretaceous/Tertiary boundary at Site 752. The benthic foraminiferal population did not change for up to 2 m above the boundary, in contrast to the rapid decrease of the planktonic foraminiferal population at the boundary. A decrease in the number of benthic foraminifers occurs after that level, corresponding to an interval of decreased numbers of planktonic foraminifers and higher abundance of volcanic ash. Reduced species diversity (H') suggests a secondary effect attributable to the dissolution of foraminiferal tests. The different responses of planktonic and benthic foraminifers to the event just above the boundary suggest that the Cretaceous/Tertiary event was a surface event as also suggested by Thomas (1990a). In addition, a positive shift of $\delta^{13}C$ in benthic foraminifers after the event indicates nutrient-depleted bottom water at Site 752.

INTRODUCTION

During Ocean Drilling Program (ODP) Leg 121, we recovered an upper Maestrichtian to lower Eocene section at Site 752 on the crest of Broken Ridge (1086 m present water depth) (Fig. 1). Recovery of this section provided an opportunity to study benthic foraminiferal faunal changes across the Cretaceous/Tertiary boundary and the faunal turnover near the Paleocene/Eocene boundary.

Previous studies suggest that deep-sea benthic foraminifers were little affected by the catastrophic event at the Cretaceous/Tertiary boundary (Douglas and Woodruff, 1981; Hsü, 1986; Culver, 1987; Thomas, 1989, 1990a). The percentage of foraminiferal disappearances at the end of the Cretaceous has been estimated variably by different workers (Beckmann, 1960; Beckmann et al., 1982; Webb, 1973; Dailey, 1983; Keller, 1988;

Thomas, 1990a, 1990b), but little is known about the benthic foraminiferal extinction in the Indian Ocean. Keller (1988) and Thomas (1990a, 1990b) discussed the change of infaunal and epifaunal proportions in relation to oxygen variation and primary productivity, respectively. Faunal turnover at the Cretaceous/Tertiary boundary is suggested to be related to a low oxygen epoch (Hsü, 1986) and a secondary effect of the collapse of primary productivity (Sheehan and Hansen, 1986; Arthur et al., 1987; Thomas, 1990a).

Turnover near the Paleocene/Eocene boundary has been considered the most dramatic benthic foraminiferal event of the Cenozoic (Tjalsma and Lohmann, 1983; Tjalsma, 1976; Schnitker, 1979; Miller et al., 1987; Boltovskoy and Boltovskoy, 1989; Berggren and Miller, 1989; Thomas, 1990a, 1990b; Katz and Miller, 1990). Thomas (1990b) stated that the diversity dropped by 50% over a period of less than 25,000 yr in the latest Paleocene and that more than 35% of species last appeared at that time. The "benthic event" (Tjalsma and Lohmann, 1983) has been recognized also in the Indian Ocean (Sigal, 1974; Vincent et al., 1974).

The late Paleocene to early Eocene stable isotopes are characterized by a marked change from higher $\delta^{13}C$ values to lower ones in benthic foraminifers (Shackleton et al., 1984, 1985; Miller et
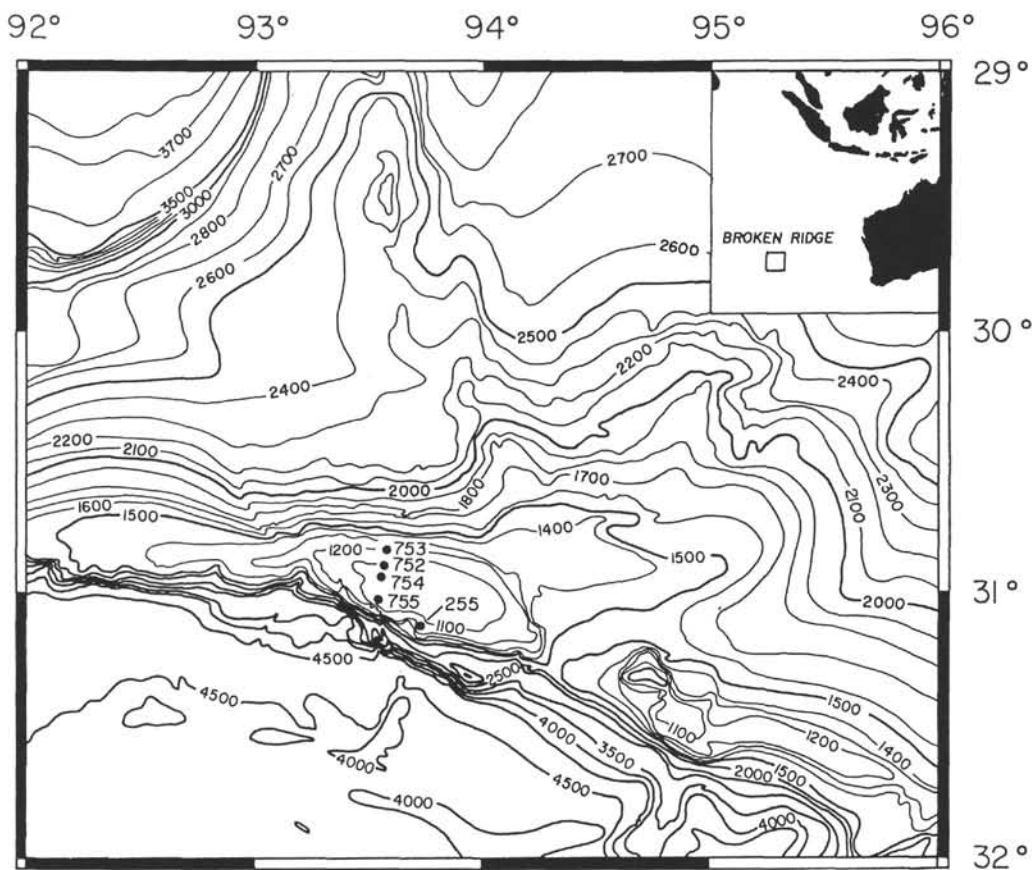
Figure 1. Location of ODP drilling sites on Broken Ridge. Site 755, where the Upper Cretaceous was recovered, is not incorporated in this study. Bathymetry in meters.

al., 1987; Katz and Miller, 1990; Kennett and Stott, 1990) and bulk carbonate (Shackleton and Hall, 1984; Shackleton et al., 1985). Benthic foraminiferal oxygen and carbon isotope changes apparently were coeval with the faunal turnover (Miller et al., 1987; Thomas, 1989, 1990a, 1990b; Katz and Miller, 1990; Kennett and Stott, 1990). The cause of the benthic foraminiferal extinction has recently been ascribed to changes in deep-water source regions (Miller et al., 1987; Thomas, 1990a, 1990b; Katz and Miller, 1990). Miller et al. (1987) and Katz and Miller (1990) stress the production of deep waters in the Antarctic during the late Paleocene, based on stable isotope analyses, and they considered that the extinction was caused by the cessation of the Antarctic deep-water formation, in agreement with Thomas (1990a, 1990b), who suggested that the deep waters were produced temporarily at low latitudes and reached the high latitudes because deep-water formation at high latitudes stopped, as proposed by Katz and Miller (1990) (hypothetical warm, saline deep water, Brass et al., 1982). The halothermal circulation characterized by warm, saline deep waters formed at low latitude (= the Tethys Sea) is referred to as the "Proteus Ocean" by Kennett and Stott (1990).

All of the above studies are based on fauna of the South Atlantic and Pacific oceans. Thus, detailed information on benthic foraminifers in the Indian Ocean can increase our understanding of how benthic foraminifers responded to these oceanographic changes. Because Broken Ridge Site 752 is situated between the Antarctic and the Tethyan region, it is particularly suited to the study of sources of deep waters. The purpose of this study is to clarify the stratigraphic distribution of benthic foraminiferal spe-

cies and to discuss the middle to lower bathyal faunal events in relation to paleoceanography.

MATERIAL AND METHODS

Sites 752, 753, and 754 are located across the crest of Broken Ridge at present water depths of 1086 m, 1176 m, and 1074 m, respectively (Fig. 1). Paleogene and upper Maestrichtian samples were recovered from the prograding, downlapping carbonate sequence below an angular unconformity. At Site 752 (30°53.475'S; 93°34.625'E), Hole 752A was cored with the advanced piston corer (APC) and extended core barrel (XCB) down to 308 mbsf and Hole 752B was rotary-cored (RCB) to a total depth of 436 mbsf. Paleogene and upper Maestrichtian sediments are light green or gray nannofossil calcareous chalk with fine lamination and bioturbation. The lithology of the Cretaceous/Tertiary boundary is exceptional, with the intercalation of dark green volcanic ash layers (Rea et al., 1990a) immediately above the boundary. The middle Eocene section at Site 753 (43.6–62.8 mbsf) was cored with the XCB. These sediments consist of white foraminifer-bearing nannofossil chalk. Upper Eocene brown nannofossil ooze was recovered from above the unconformity at Hole 754A and only Core 121-754A-14X is included in this study.

Upper Eocene Cores 121-752A-11H and -12H (Zone CP15a, -b) and 121-754A-14X (Zone CP15b), consisting of coarse-grained sediments with molluscan shell fragments, were also studied (Peirce, Weissel, et al., 1989; Rea et al., 1990a). In those cores, benthic foraminiferal fauna consist of lower neritic to upper bathyal species in association with small numbers of inner neritic

species (<30 mm) such as *Amphistegina*, *Stomatorbina*, and bryo-zoan shell fragments. In contrast with the well- to moderately preserved specimens of the outer neritic to upper bathyal fauna, however, the very badly preserved inner neritic specimens suggest downslope transport.

Samples were treated with a 3% hydrogen peroxide solution and washed through a 63-μm sieve. Sample volume was measured by putting the sediments into a graduated cylinder with water before washing. Over 200 specimens per sample were picked from aliquots of the >149-μm size fraction that facilitates taxonomic works. This size fraction is the same as Nomura (this volume) and would be quantitatively comparable with Neogene faunas. Although deep-sea foraminifers have been studied by different size fraction (>63~>300 μm; e.g., Kurihara and Kennett, 1985), earlier studies describing benthic foraminifers were based on a larger size fraction. The planktonic percentage is based on a count of over 100 individuals of both planktonic and benthic foraminifers.

Age estimates of samples are based on nannofossil biostratigraphy (Peirce, Weissel, et al., 1989; Pospichal et al., this volume) and magnetostratigraphy (Gee et al., this volume). The absolute ages are estimated by linear interpolation using sediment thickness and by the magnetic polarity time scale of Berggren et al. (1985).

In order to reduce species to a closely related species group (= assemblage), a Q-mode factor analysis (CABFAC; Klovan and Imbrie, 1971) with varimax rotation was applied to the relative abundance data. Taxa were included in this analysis if they occur at abundances >4% in each sample and were found in more than two samples (Table 4). Several taxa that occur >4% in Table 1 (back pocket) were not included because they were stratigraphically unimportant. The data set for the factor analysis is based on the composite faunal data from Sites 752 (upper Maestrichtian to lower Eocene and upper Eocene), 753 (middle Eocene), and 754 (upper Eocene). The faunal data from these sites represent different ages, except for the short overlap of the upper Eocene between Site 752 and Site 754. Thus, the results plotted and tabulated reveal the time-series faunal variation at Broken Ridge.

RESULTS

Relative Abundance

The stratigraphic distribution of benthic foraminifers at Sites 752, 753, and 754 is shown in Tables 1 (back pocket), 2, and 3, and the relative abundances of the most common species, plotted vs. depth below seafloor, are shown in Figure 2. The greatest change in relative abundances was near the Paleocene/Eocene boundary. Through the Maestrichtian and Paleocene, *Stensioina beccariiformis* attained 10% to 45%, with an average of 25%, but it became extinct in the upper part of Zone CP8 (Sample 121-752A-20X-1, 70–75 cm; 181.4 mbsf). A similar change of relative abundance and extinction is found in *Pullenia coryelli* (3%–19%) and *Cibicidoides hyphalus* (0%–21%) in the Maestrichtian to the Paleocene. *Cibicidoides* cf. *pseudoperlucidus* occurs in Zones CP4 to CP8, with relative abundance of 4%–31%, but decreases in relative abundance in Zone CP8 and became extinct in this zone.

The following three species are abundant in the lower Eocene: *Alabamina dissonata* (peak abundance 9%), *Bulimina tuxpamensis* (peak abundance 15%), *Cibicidoides subspiratus* (peak abundance 27%), and *Cibicidoides* sp. 6 (peak abundance 5%). *Nuttallides truempyi* occurs continuously through the Paleocene to the middle Eocene, except for seven upper Paleocene samples, but it does not occur in the upper Eocene samples. The extinction of *N. truempyi* has been attributed to bottom-water cooling during the middle to late Eocene (Corliss and Keigwin, 1986). *Hanzawaia ammophila* and *Osangularia* sp. 1, making up 13% and

Table 2. Occurrence of benthic foraminifers at Site 753.

Hole Core, section Interval (cm)	753A- 6H-1 70–75	6H-5 70–75	7H-1 70–75	7H-5 70–75
Alabamina dissonata		3	3	
Anomalinoides danicus	2	7	19	10
Anomalinoides semicribratus			5	
Anomalinoides spissiformis	11	1	24	6
Astacolus spp.	3		3	
Bathysiphon sp.				1
Bulimina macilenta	1		1	
Bulimina trinitatensis			1	
Cibicides lobatulus		1		
Cibicidina walli		1		
Cibicidoides cf. *alazanensis*	3	8	14	11
Cibicidoides cf. *bradyi*			11	7
Cibicidoides sp. 12		36	26	
Cibicidoides sp. 18	29	40	69	27
Cibicidoides spp.	2	3	3	2
Clavulina sp.		4	3	
Dentalina colei			3	
Dentalina multilineata	2	1		
Dentalina obliquata	6	5		1
Dentalina sp.	1		1	
Ellipsoidina abbreviata				1
Ellipsoidina cf. *abbreviata*			2	
Fissurina sp.		1		
Gaudryina cf. *laevigata*			1	
Guttulina problema		1		
Gyroidina soldanii	15	22	17	13
Gyroidina sp. 1		4		
Heronallenia sp.		1		
Karreriella cf. *subglabra*	1	1		5
Lagena spp.		3		
Lenticulina spp.	14	13	39	25
Marginulina spp.	2	1		
Martinottiella sp.				1
Nodosarella sp.	3			
Nodosarella subnodosa			1	1
Nodosaria vertebralis			2	1
Nodosaria spp.	2	2		1
Nonion havanensis	1	2	4	1
Nonion sp.		1		
Nuttallides truempyi	30	34	94	31
Oolina spp.	1	2		
Oridorsalis umbonatus	9	21	15	6
Osangularia mexicana	3	6	8	5
Planulina costata	26	36	1	17
Pleurostomella acuta	2			3
Pleurostomella incrassata		4		
Pleurostomella spp.	3	1	4	
Pseudonodosaria sp.		1		
Pullenia eocenica	8	6		1
Pullenia quadriloba		7	17	6
Pullenia subcarinata		4	1	
Pullenia sp.	2			
Pyrulinoides sp.	2			
Ramulina gloobulifera	6	1		
Saracenaria sp.	1			
Sphaeroidina sp.		1		
Spiroplectammina spectablis				4
Spiroplectammina sp.	1			
Stilostomella aculeata			2	
Stilostomella gracillima	2	2	6	
Stilostomella subspinosa	6	1	1	3
Textularia ? sp.			1	
Turrilina brevispira	8	46	5	2
Uvigerina elongata	1			3
Vaginulina mexicana			3	
Vaginulina sp.				6
Vulvulina mexicana		1	3	
Total number of specimens	209	330	419	201

Table 3. Occurrence of benthic foraminifers at Site 754.

Hole 754A Core, section Interval (cm)	14X-1 16–17	14X-1 70–75	14X-3 70–75
Alabamina dissonata			5
Anomalinoides semicribratus			2
Aragonia sp.	2		
Bulimina macilenta	1	1	2
Bulimina trinitatensis	1		1
Bulimina tuxpamensis	1		2
Bulimina cf. tuxpamensis		2	
Bulimina sp.		3	
Cibicides cf. aknerianus	2	9	
Cibicidina walli			3
Cibicidoides bradyi	11	14	1
Cibicidoides eocaenus		22	1
Cibicidoides subspiratus	1		23
Cibicidoides truncanus	3	30	15
Cibicidoides sp. 1	2	28	19
Cibicidoides sp. 3	1	7	
Cibicidoides sp.	7	8	11
Clavulina sp.		4	
Dentalina vertebralis		5	
Dentalina spp.		4	4
Fissurina sp.	1	1	
Gaudryina ? sp.			1
Globocassidulina globosa	7	8	8
Globocassidulina punctata			3
Globocassidulina sp. 1	1	25	
Globocassidulina spp.		1	
Guttulina problema	1	1	
Gyrodina soldanii	5	18	4
Hanzawaia sp. 1			15
Karreriella subglabra	2	4	
Karreriella sp.			4
Lagena spp.	4	5	1
Lenticulina spp.	10	68	23
Marginulina spp.		1	1
Melonis pompilioides			3
Nodosarella subcompacta			1
Nodosaria limbata		1	
Nodosaria spp.	2	10	
Nonion havanensis	8	9	2
Nonionella ? sp.	1		
Oolina spp.		4	1
Oridorsalis umbonatus	13	15	5
Orthomorphina antillea	2	3	
Orthomorphina challenge- riana	1		
Osangularia sp. 1	6	27	26
Planulina costata	9	19	
Planulina sp. 1		6	
Planulina sp.			1
Pleurostomella ? sp.	1		
Polymorphina	1	1	
Pullenia spp.	6	1	
Pullenia eocenica	2	1	
Pullenia eocenica (?)			1
Pullenia quadriloba		11	
Ramulina globulifera		1	
Saracenaria spp.		2	2
Stilostomella aculeata		4	
Stilostomella gracillima	5	13	4
Stilostomella modesta		1	1
Stilostomella subspinosa	1		
Trifarina wilcoxensis			8
Trifarina sp.		7	
Uvigerina elongata			7
Uvigerina resurgens	42	128	
Uvigerina sp. 3		10	3
Uvigerina sp. 4			2
Uvigerina spp.	2	5	1
Vulvulina mexicana	1		
Vulvulina spinosa		3	
Total number of specimens	170	581	255

12% of the total fauna, respectively, in the upper Eocene (CP15), occur in Samples 121-752A-11H-1, 70–75 cm, to 121-752A-11H-5, 70–75 cm, and Samples 121-752A-12X-1, 13–15 cm, to 121-752A-12X-1, 24–26 cm. *Cibicidina walli* is similar to the two above-mentioned species in occurrence and its relative abundance. *Hanzawaia ammophila* and *C. walli* are considered as indicating shallower paleodepths (outer neritic to upper bathyal; van Morkhoven et al., 1986). The occurrence of these species corresponds to the rifting event at Broken Ridge, which had ended by the time of seafloor spreading in magnetic anomaly 18 (Peirce, Weissel, et al., 1989). *Anomalinoides capitatus/danicus* occurs from Zone CP1 to the middle Eocene at Site 752. Its relative abundance increases in the Paleocene and Eocene. *Bulimina trinitatensis* occurs in the Paleocene and Eocene, with several small peak abundances of less than 16%. *Oridorsalis umbonatus* is commonly found in the Eocene, with a peak abundance of up to 33%, but it is rare in the Paleocene samples despite its long range and cosmopolitan occurrence. *Lenticulina* spp. is represented throughout the section at Sites 752, 753, and 754.

Gyroidinoides quadratus forms 1%–12% of the total fauna in the upper Maestrichtian, along with rare species such as *Bolivinoides draco* and *Cibicidoides dayi*. This last species appears within the Cretaceous nannofossil Zone CC25. Smaller-sized *Globocassidulina globosa* appears in the lower Eocene, with a relative abundance up to 11% of the assemblage. *Uvigerina resurgens* makes up 25% of the total fauna (Sample 121-754A-14X-1, 16–17 cm) in the upper Eocene.

Stratigraphic Ranges of Selected Benthic Foraminifers

During the last decade, a large number of biostratigraphic and systematic studies on deep-sea benthic foraminifers has revealed that the first and last occurrences of some bathyal and abyssal species may be useful in constructing a biostratigraphic zonation (Tjalsma and Lohmann, 1983; van Morkhoven et al., 1986). Based on the synthesis of previous reports, Berggren and Miller (1989) proposed four zones for Paleocene to Eocene bathyal species. In this section, the stratigraphic ranges of selected species at Sites 752, 753, and 754 are compared with the results of these workers (Fig. 3).

The last occurrence datum of *Coryphostoma incrassata* occurs in the short interval across the Cretaceous/Tertiary boundary that is defined by the last appearance of Cretaceous planktonic foraminifers and the first appearance of Tertiary nannofossils. *Bolivinoides draco* was not found in Sample 121-752B-11R-3, 112–114 cm, just below the Cretaceous/Tertiary boundary. The extinction horizon of these species agrees with the results of van Morkhoven et al. (1986), who emphasized these forms as Late Cretaceous guide fossils. *Cibicidoides dayi* disappears in the upper Maestrichtian samples at Site 752, although its occurrence is recorded until planktonic foraminiferal P5 Zone by van Morkhoven et al. (1986) and Berggren and Miller's (1989) BB1. Tjalsma and Lohmann (1983) pointed out that many Paleocene species become extinct at the boundary between planktonic foraminiferal Zones P5 and P6a. Recently Thomas (1990a, 1990b) estimated that the latest Paleocene faunal turnover occurred at 57.5 Ma in the Aubry et al. (1988) time scale (middle of CP8). The extinctions of *Stensioina beccariiformis*, *Coryphostoma midwayensis*, *Cibicidoides hyphalus*, and *Cibicidoides velascoensis* occurred in the latest Zone CP8 at Site 752. The last occurrences of *Osangularia velascoensis* and *Gyroidinoides globosus* are in Zones CP4–CP5 at Site 752, which is somewhat earlier than the last appearance in planktonic foraminiferal Zones P5 and P6a (Tjalsma and Lohmann, 1983; van Morkhoven et al., 1986). This difference may be attributed to the rare and sporadic occurrences of these species in Paleocene samples, so that the species may have been missed in the examination of Broken Ridge samples.
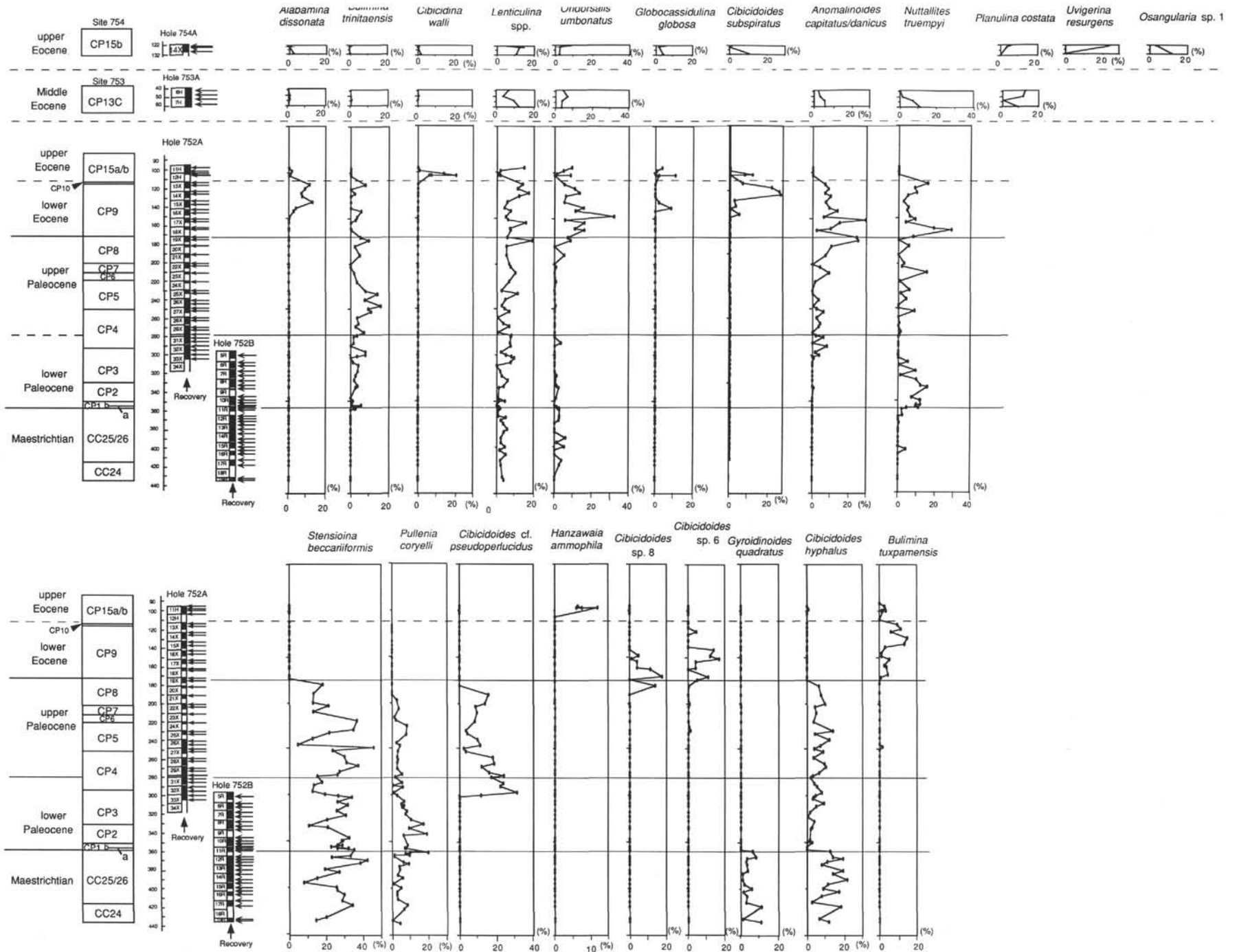
Figure 2. Relative abundance of selected benthic foraminifers plotted against depth.

Figure 3. Stratigraphic range chart of selected benthic foraminifers. Fine lines indicate previously known stratigraphic ranges from the data of Tjalsma and Lohmann (1983) and van Morkhoven et al. (1986). The stratigraphic range in terms of planktonic foraminiferal zones is described after the species name. Zones with parentheses are from Tjalsma and Lohmann (1983).

Turrilina brevispira first occurs in Sample 121-752A-18X-2, 67–70 cm, which is assigned to the lower part of Zone CP9a, but its first appearance is known from Zone P6a (= Zone CP8b) (van Morkhoven et al., 1986). *Cibicidoides subspiratus* ranges from the uppermost lower Eocene (Zone P9) to the middle Eocene (Zone P13) (van Morkhoven et al., 1986; Zone BB3 of Berggren and Miller, 1989), but at Site 752 it occurs from the lowermost Eocene (Zone CP9a [~Zone P6b]). *Pullenia eocenica* occurs from the uppermost Paleocene (Zone CP8) to the lower Eocene at Site 752 and to the middle Eocene at Site 753. Tjalsma and Lohmann (1983) reported its first appearance in the lower Eocene (Zone P9 (= CP11–12a)). The first appearance of *Bulimina macilenta* is in the lowermost Eocene sample (121-752A-19X-1, 70–75 cm, CP9a), almost the same as the first appearance (P6a–P6b) determined by Tjalsma and Lohmann (1983). *Alabamina dissonata* ranges from lower Eocene (upper part of Zone CP9a) to upper Eocene (Zone CP15b) at Site 752, but van Morkhoven et al. (1986) records its first appearance from the Paleocene (P6a). *Cibicidoides eocaenus* is abundant in the lower Eocene at Site 752; its first occurrence is in Zone CP9a. *Cibicidoides truncanus,* known to have a rather short stratigraphic range useful as a biostratigraphic indicator (Zones P13–P16; van Morkhoven et al., 1986; Berggren and Miller, 1989), is found only in the upper Eocene Samples 121-752A-11H-1, 70–75 cm, to 121-752A-11H-5, 70–75 cm (95.4–101.4 mbsf; Zone CP15b). *Hanzawaia ammophila* is reported to have long range (uppermost Paleocene [Zone P6a] to middle Miocene [Zone N11]; van Morkhoven et al., 1986), but in the Broken Ridge cores, *H. ammophila* occurs only in upper Eocene samples immediately above the erosional unconformity (Zone CP15b). *Globocassidulina punctata* has been known from the Miocene (van Morkhoven et al., 1986), but rare specimens of this species occur from the upper Eocene (Sample 121-754A-14X-3, 70–75 cm; CP15b).

Diversity

The number of species per sample varies widely, probably in response to paleoenvironmental differences. In general, the species number per 100 specimens ranges from 10 to 20, with an average of 15.22 in Maestrichtian to Paleocene samples. Lower Eocene samples show less variation, with about 10 species per 100 specimens (Fig. 4). The lowermost Eocene Sample 121-752A-19X-1, 70–75 cm (171.80 mbsf), has the lowest average number of species (5.7). This horizon is correlated with the interval just above the Paleocene/Eocene boundary event. By contrast, high numbers of species are found in the upper Eocene, which correspond to shallowing of Broken Ridge as a result of the rifting event (Peirce, Weissel, et al., 1989).

In order to evaluate faunal diversity and equitability, the Shannon-Wiener Information Function (H') and E ($E = e^{H'}$/the total number of species in a sample), respectively, were calculated (Fig. 5). Maestrichtian and Paleocene diversity values fall within the range of 3–4.5, and somewhat lower values are found near the Cretaceous/Tertiary boundary and in the upper part of nannofossil Zone CP4. Lower Eocene values are generally lower than Maestrichtian and Paleocene samples. Shannon-Wiener values of the middle Eocene at Site 753 and the upper Eocene at Sites 752 and 754 are much higher than those of older intervals, and exhibit less variation. The difference in diversity values between the lower and middle Eocene suggests paleoceanographic changes, and the values from the middle Eocene up to lower Miocene demonstrate a clear increase in faunal diversity.

Equitability (E), which is used as an index of the evenness of distribution of species among species, reveals no significant differences from upper Maestrichtian to upper Eocene. Sample 121-

752B-11R-1, 44–47 cm, in the ash layer above the Cretaceous/Tertiary boundary, which is characterized by somewhat badly preserved *Stensioina beccariiformis* and *Nuttallides truempyi,* shows an exceptionally high value, however, which may be partly due to dissolution of foraminiferal tests.

Faunal Analysis

The result of factor analysis shows that the first eight factors explain 82.5% of the faunal variation in the data set (Tables 4 and 5). These factors are here recognized as varimax assemblages, with characteristic stratigraphic distributions as shown in Figure 6. Samples having factor loadings of >0.5 were used to represent various assemblages (Fig. 7).

Stensioina beccariiformis varimax assemblage (factor 1; 39.21% of the total variance) is characterized by the occurrence of *S. beccariiformis* in association with *Pullenia coryelli, Nuttallides truempyi,* and *Cibicidoides velascoensis.* This assemblage occurred in the upper Maestrichtian and Paleocene. The main constituents of this assemblage are included in the Velasco-type fauna of Berggren (1974) and Berggren and Aubert (1975). This assemblage is replaced by lower Eocene assemblages in Zone CP8 (between Samples 121-752A-19X-3, 75–79 cm, and 121-754A-20X-1, 70–75 cm; 174.85–181.40 mbsf), just before the Paleocene/Eocene boundary. Distinctly reduced factor loadings are detected in upper Zone CP3 (Samples 121-752A-32X-5, 70–75 cm, to 121-752A-32X-1, 70–75 cm) and lower Zone CP5 (Sample 121-752A-26X-5, 97–100 cm).

Anomalinoides capitatus/danicus varimax assemblage (factor 2; 8.5% of the total variance) is characterized by *Anomalinoides capitatus/danicus, Oridorsalis umbonatus, Cibicidoides* sp. 6, and *Cibicidoides* sp 8. This assemblage ranges from the uppermost Paleocene to lower Eocene (Samples 121-752A-13X-1, 70–75 cm, to 121-752A-19X-3, 75–79 cm; 113.60–174.85 mbsf) and corresponds to a period of reduced species diversity.

Cibicidoides cf. *pseudoperlucidus* varimax assemblage (factor 3; 11.86% of the total variance) is characterized by *Cibicidoides* cf. *pseudoperlucidus, Bulimina trinitatensis,* and *Cibicidoides hyphalus.* This assemblage is intercalated in the *Stensioina beccariiformis* varimax assemblage in the upper Paleocene.

Osangularia sp. 1–*Hanzawaia ammophila* varimax assemblage (factor 4; 4.76% of the total variance) is recognized only in the upper Eocene samples (121-752A-11H-3, 70–75 cm, to 121-752A-12X-1, 24–26 cm). This assemblage is characterized by *Osangularia* sp. 1 and *H. ammophila.*

Nuttallides truempyi varimax assemblage (factor 5; 5.68% of the total variance) is dominated by *N. truempyi* and *Cibicidoides* sp. 18. This assemblage characterizes the middle Eocene fauna (Zone CP13c) at Site 753 (121-753A-6H-1, 70–75 cm, to 121-753A-7H-5, 70–75 cm; 44.3–59.9 mbsf), although this assemblage is distributed in several horizons such as Zones CP2, CP7, and CP9–10 at Site 752.

Lenticulina spp. varimax assemblage (factor 6; 4.33% of the total variance) is represented by *Lenticulina* spp., *Uvigerina resurgens,* and *Osangularia umbonatus.* This assemblage represents the upper Eocene, Oligocene, and lower Miocene faunas at Broken Ridge.

Cibicidoides hyphalus varimax assemblage (factor 7; 4.05% of the total variance) co-occurs with the *Stensioina beccariiformis* varimax assemblage in the upper Maestrichtian and is represented by *Cibicidoides hyphalus, Gyroidinoides quadratus,* and *N. truempyi.* The value of factor loadings drops across the Maestrichtian and Paleocene boundary, though the values are too small to be significant (Figs. 6 and 7).
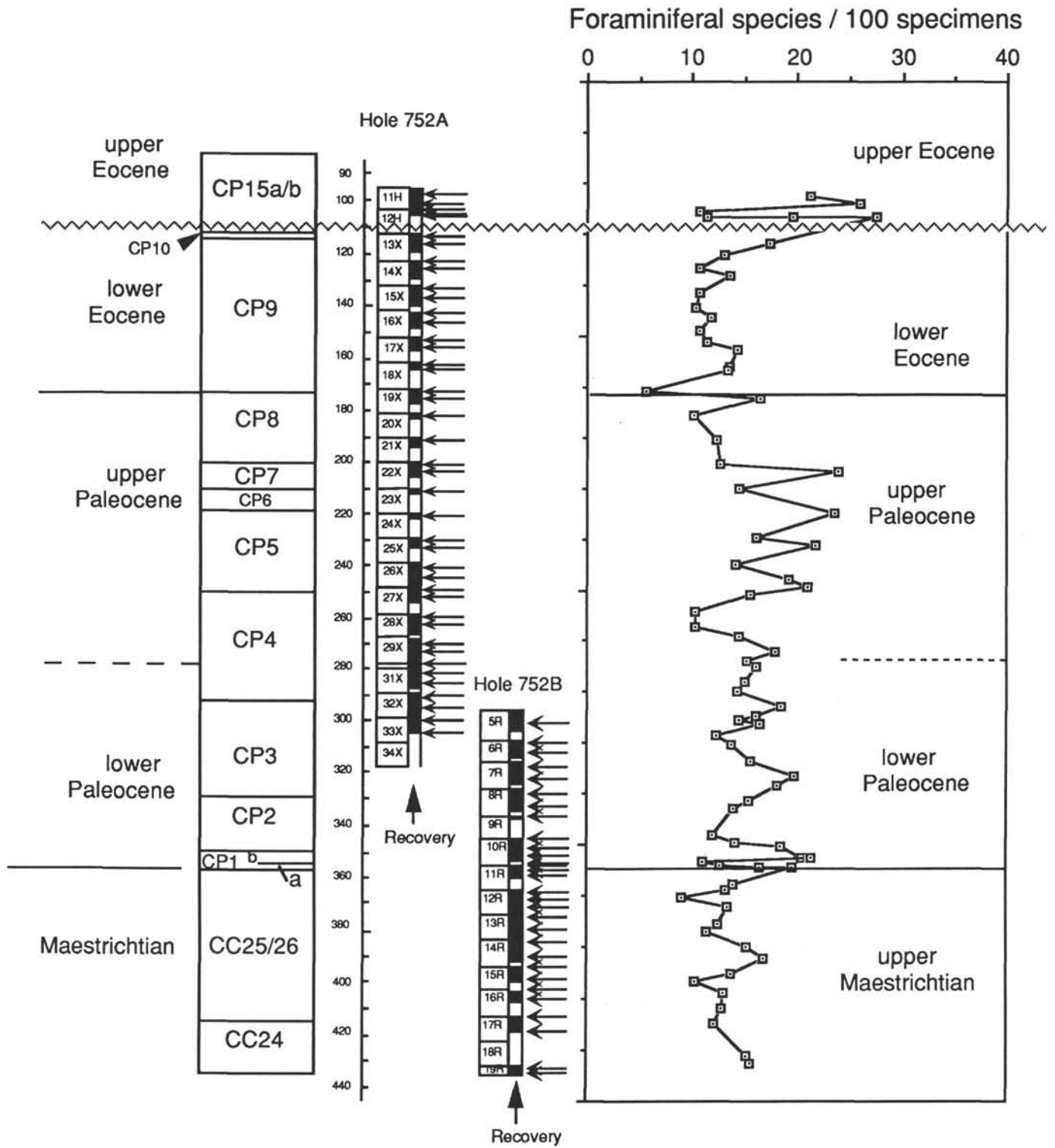
Figure 4. Number of species per 100 benthic foraminifer individuals at Site 752.

Cibicidoides subspiratus varimax assemblage (factor 8; 4.05% of the total variance) is in the middle lower Eocene (Samples 121-752A-13X-4, 62–67 cm, to 121-752A-15X-1, 70–75 cm; 118.02–133 mbsf). The main species of this assemblage are *C. subspiratus, Alabamina dissonata, Lenticulina* spp., and *Bulimina tuxpamensis.*

Benthic Foraminiferal Occurrence Across the Cretaceous/Tertiary Boundary

Benthic foraminifers present an important source of information on the deep-seafloor environment across the Cretaceous/Tertiary boundary. Among the common or rare taxa in the upper
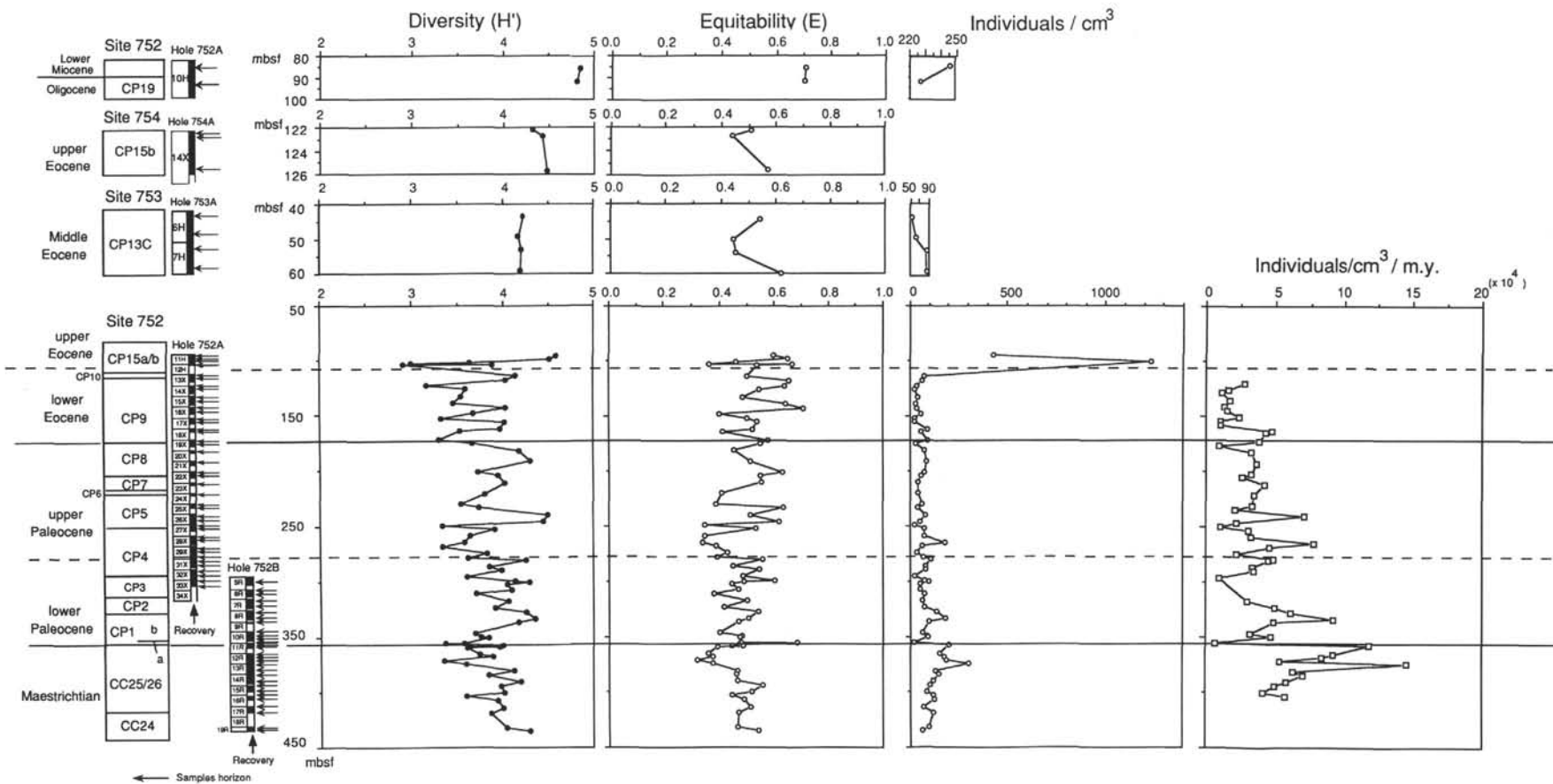
Figure 5. Benthic foraminiferal diversity, equitability, number of individuals per cm³, and number of individuals per million years.

Table 4. Varimax factor loadings from factor analysis at Sites 752, 753, and 754.

Core, section, interval (cm)	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8
121-754A-									
14X-1, 16–17	0.4691	0.0286	0.0999	−0.0154	0.0976	0.0398	0.6672	−0.0187	0.0372
14X-1, 70–75	0.5648	0.0362	0.0856	0.0352	0.1583	0.0593	0.7251	−0.0221	−0.0110
14X-3, 70–75	0.6934	0.0193	0.0728	0.0602	0.5166	0.0409	0.4588	0.0193	−0.4523
121-753A-									
6H-1, 70–75	0.8430	0.0634	0.1179	0.0164	−0.0012	0.8807	0.2151	0.0331	−0.0421
6H-5, 70–75	0.6738	0.0311	0.1384	0.0117	−0.0098	0.7792	0.2038	0.0663	−0.0193
7H-1, 70–75	0.8583	0.0939	0.2689	0.0154	0.0022	0.8707	0.0990	−0.0338	−0.0884
7H-5, 70–75	0.6867	0.0062	0.2138	0.1248	−0.0300	0.6607	0.4142	0.1017	−0.0779
121-752A-									
10H-1, 70–75	0.5084	0.0362	0.1648	0.0604	−0.0072	0.1954	0.6516	0.0180	−0.1145
10H-5, 70–75	0.3935	0.0330	0.0986	0.0308	0.0995	0.1394	0.5882	−0.0179	−0.0780
11H-1, 70–75	0.7875	0.0352	0.3272	0.0950	0.0572	0.1803	0.7721	0.0856	−0.1760
11H-3, 70–75	0.5435	0.0054	0.1195	−0.0098	0.6529	0.0202	0.3152	0.0519	0.0192
11H-5, 70–75	0.7277	−0.0099	0.0376	0.0100	0.8460	0.0398	0.0714	0.0210	0.0576
12X-1, 5–7	0.8929	−0.0138	−0.0252	0.0106	0.9434	−0.0012	−0.0035	0.0042	−0.0450
12X-1, 13–15	0.8537	−0.0077	−0.0116	0.0018	0.8332	−0.0308	0.1003	−0.0061	−0.3850
12X-1, 24–26	0.8866	−0.0115	−0.0184	0.0125	0.9384	−0.0049	0.0388	0.0028	−0.0623
13X-1, 70–75	0.7224	0.1014	0.5063	0.1085	0.0415	0.4723	0.1446	−0.0831	−0.4374
13X-4, 62–67	0.8234	0.0459	0.5690	0.0382	0.0460	0.3438	0.2097	0.0305	−0.5753
14X-1, 70–75	0.9400	0.0492	0.4858	0.0457	0.0982	0.2090	0.2190	0.0148	−0.7733
14X-3, 70–75	0.9308	0.0162	0.3643	0.0631	0.1249	0.0905	0.1134	0.0161	−0.8700
15X-1, 70–75	0.9087	0.0119	0.2547	0.0066	0.1322	0.0130	0.0225	0.0224	−0.9083
15X-5, 70–75	0.4780	0.0236	0.5467	−0.0288	0.0894	0.0868	0.1914	0.0283	−0.3533
16X-1, 70–75	0.7992	0.0101	0.8534	0.0976	0.0319	0.0777	0.1292	0.0209	−0.1927
16X-5, 25–30	0.6053	0.0255	0.7201	−0.0224	0.0268	0.1350	0.2418	0.0787	−0.0460
17X-1, 70–75	0.7726	0.0003	0.8591	0.1086	0.0362	0.0822	−0.0625	−0.0122	−0.1033
17X-3, 70–75	0.8723	0.0139	0.8314	0.0896	−0.0005	0.1649	0.3461	0.0818	−0.1384
18X-1, 71–75	0.7287	0.0903	0.6769	−0.0094	0.0295	0.5042	0.0249	−0.0480	−0.0644
18X-2, 67–70	0.7230	0.1319	0.5271	−0.0743	0.0367	0.6386	0.0381	−0.0671	−0.0849
19X-1, 70–75	0.8169	0.0099	0.8897	0.0947	0.0325	0.1092	−0.0552	−0.0080	0.0138
19X-3, 75–79	0.7613	−0.0097	0.7933	0.2289	−0.0144	0.0253	0.2591	0.0354	−0.1008
20X-1, 70–75	0.6941	0.6505	0.4293	0.2214	0.0289	0.0843	−0.0324	0.1662	0.0311
21X-1, 70–75	0.9151	0.4645	0.2613	0.7707	0.0121	0.0381	0.0657	0.1729	−0.0373
22X-1, 70–75	0.8516	0.4843	0.0268	0.7217	0.0088	0.1432	0.0606	0.2615	−0.0524
22X-3, 70–75	0.9181	0.7706	0.1511	0.5231	−0.0016	0.0136	0.1155	0.1054	−0.0565
23X-1, 54–56	0.8486	0.5537	0.3523	0.4620	0.0181	0.4376	−0.0134	−0.0216	−0.1097
24X-1, 70–73	0.9525	0.8765	0.0398	0.4121	0.0000	−0.0497	0.1013	0.0030	−0.0137
25X-1, 79–84	0.8703	0.8427	0.0601	0.3406	0.0112	0.0146	−0.0162	0.1992	0.0123
25X-3, 79–84	0.7551	0.6997	0.1242	0.4679	−0.0018	0.0117	0.1684	0.0083	−0.0508
26X-1, 97–100	0.9070	0.5334	0.1638	0.7007	0.0176	0.1398	−0.0464	0.2862	−0.0272
26X-5, 97–100	0.5973	0.1774	0.0953	0.7340	0.0218	0.0700	−0.0033	0.1113	0.0154
27X-1, 70–75	0.8969	0.8894	0.0629	0.2865	−0.0011	−0.1286	0.0576	−0.0018	0.0009
27X-3, 70–75	0.8766	0.7845	0.2491	0.3996	0.0118	0.1471	−0.0070	0.1280	−0.0346
28X-1, 70–75	0.9260	0.7174	−0.0063	0.6339	0.0046	−0.0904	−0.0150	−0.0233	0.0226
28X-5, 70–75	0.9569	0.7120	0.0456	0.6613	0.0069	−0.0585	−0.0074	0.0842	0.0028
29X-1, 70–73	0.9485	0.8074	0.0452	0.5145	−0.0018	−0.0817	0.0639	0.1375	−0.0123
29X-5, 70–73	0.9439	0.7223	−0.0311	0.6469	0.0120	−0.0289	−0.0267	0.0257	0.0214
30X-1, 73–76	0.9167	0.5720	0.0190	0.7613	−0.0040	−0.0261	0.0830	−0.0268	−0.0339
31X-1, 70–75	0.8617	0.4888	0.1172	0.7729	0.0010	0.0320	0.0898	−0.0139	−0.0484
31X-5, 70–75	0.8849	0.4405	0.0000	0.8224	−0.0009	0.0212	0.1112	0.0006	−0.0407
32X-1, 70–75	0.8621	0.3364	0.1260	0.8516	−0.0004	0.0280	0.0496	0.0468	−0.0486
32X-5, 70–75	0.9121	0.2509	−0.0208	0.9183	0.0144	0.0346	−0.0640	0.0029	−0.0005
33X-1, 68–71	0.8593	0.6511	0.1109	0.6465	0.0048	−0.0338	0.0324	0.0514	−0.0177
33X-3, 57–60	0.8974	0.8987	0.0396	0.2295	−0.0071	−0.0643	0.1678	0.0429	−0.0349

Maestrichtian, only seven species such as *Bolivinoides draco*, *Buliminella* sp., *Cibicidoides dayi*, *Gyroidinoides quadratus*, *Coryphostoma incrassata*, *Globorotalites conicus*, and *Praebulimina navarroensis* last appear, or become extinct, between Samples 121-752B-13R-1, 40–43 cm, to 121-752B-11R-3, 64–66 cm (358.44–374.40 mbsf) (Fig. 3). The last appearance of *Coryphostoma incrassata* and *Praebulimina navarroensis* is 26 cm above the extinction horizon of the Cretaceous planktonic foraminifers such as *Rugoglobigerina* spp., *Globigerinelloides* spp., and globotruncanids, and 6 cm above the first appearance of the Tertiary nannofossil *Biantholithus sparsus* (Peirce, Weissel, et al., 1989). Among the disappearing species, only two (*Bolivinoi-*

des draco and *Coryphostoma incrassata*) were suggested as becoming extinct at the Cretaceous/Tertiary boundary by van Morkhoven et al. (1983).

Of the 187 taxa that occur in the upper Maestrichtian to Paleocene, 23 taxa (including rare species) disappear at the end of the Maestrichtian. Thus, about 12.3% of the taxa disappeared at the Cretaceous/Tertiary boundary. Thomas (1990b) discussed last appearances of deep-sea benthic foraminifers at the Cretaceous/Tertiary boundary, and estimated that extinction rates fall usually in the range of 10%–25%, in agreement with the 12.3% extinction at Site 752. Furthermore, minor changes in factor loadings reveal that the faunal turnover is slight across the Creta-

Table 4 (continued).

Core, section, interval (cm)	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8
121-752B-									
5R-3, 50–53	0.8843	0.8806	0.0313	0.2784	−0.0045	−0.0453	0.1476	0.0718	−0.0367
6R-1, 44–47	0.9029	0.8867	0.0520	0.2552	0.0058	0.0955	0.0799	0.1770	−0.0443
6R-3, 99–102	0.8938	0.9177	−0.0101	0.1842	0.0118	−0.0662	−0.0380	0.1070	0.0137
7R-1, 82–85	0.9223	0.9288	0.0622	0.1564	0.0194	0.1554	−0.0642	−0.0491	−0.0164
7R-5, 76–78	0.8902	0.9226	0.0218	0.1791	0.0111	−0.0344	0.0210	−0.0689	−0.0006
8R-2, 81–94	0.9085	0.8946	0.0954	0.1693	0.0181	0.2539	−0.0020	0.0375	−0.0646
8R-6, 101–104	0.6769	0.6744	0.1209	0.0812	0.0388	0.4106	−0.1057	−0.1284	−0.0560
9R-1, 42–45	0.8645	0.8333	0.1392	0.0626	0.0313	0.3463	−0.1253	−0.0956	−0.0328
10R-1, 105–108	0.9445	0.9567	0.0207	0.1383	0.0156	0.0639	−0.0462	−0.0562	−0.0035
10R-3, 112–115	0.9560	0.9372	0.0714	0.1415	0.0141	0.1958	−0.0132	−0.1110	−0.0386
10R-4, 79–81	0.9389	0.9333	0.0520	0.1236	0.0229	0.1924	−0.0790	−0.0761	−0.0137
10R-CC	0.8882	0.8932	0.0404	0.0669	0.0310	0.2211	−0.1242	−0.1372	−0.0120
11R-1, 44–47	0.8847	0.9135	0.0497	0.1276	0.0281	0.1452	−0.0876	−0.0430	−0.0005
11R-2, 44–47	0.8069	0.8581	0.0777	0.0767	0.0243	0.1893	−0.0680	−0.1316	−0.0164
11R-3, 38–41	0.8876	0.9183	0.0705	0.1254	0.0198	0.1337	−0.0321	−0.0653	−0.0090
11R-3, 64–66	0.7311	0.8416	0.0625	0.1236	0.0086	0.0374	0.0182	−0.0399	−0.0131
11R-3, 112–114	0.9401	0.9013	0.0142	0.1921	0.0053	−0.0699	0.0013	0.2926	0.0105
12R-1, 104–107	0.9405	0.8939	0.0176	0.1744	0.0120	−0.0370	−0.0094	0.3303	0.0087
12R-3, 10–13	0.9233	0.7857	0.0267	0.2366	0.0136	0.0026	0.0302	0.4977	−0.0206
12R-5, 54–59	0.9612	0.9306	0.0082	0.1970	0.0016	−0.1089	0.0381	0.2070	0.0074
13R-1, 40–43	0.9565	0.9385	−0.0049	0.1830	0.0007	−0.0952	0.0376	0.1779	−0.0012
13R-5, 65–68	0.9518	0.7133	0.0032	0.2360	0.0114	0.0085	0.0407	0.6202	−0.0282
14R-1, 69–72	0.9343	0.8546	−0.0094	0.2012	0.0102	−0.0420	0.0168	0.4015	−0.0089
14R-5, 62–65	0.8796	0.5678	0.0728	0.1926	0.0147	0.0153	0.0221	0.7167	−0.0125
15R-1, 119–122	0.4567	0.3967	0.0020	0.1204	0.0129	0.0578	−0.0233	0.5294	−0.0232
15R-5, 112–115	0.9530	0.8774	0.0773	0.1975	0.0010	−0.0589	0.1206	0.3458	−0.0236
16R-1, 15–18	0.8586	0.7712	−0.0019	0.1845	0.0138	0.0423	−0.0602	0.4734	−0.0045
16R-3, 136–138	0.9478	0.9090	0.0015	0.1919	0.0020	−0.0687	0.0680	0.2738	−0.0197
17R-1, 103–106	0.8625	0.8997	0.0234	0.1572	0.0100	−0.0406	0.0943	0.1310	0.0086
17R-5, 66–69	0.9489	0.8494	0.0042	0.1994	0.0104	−0.0536	0.0000	0.4297	0.0009
19R-1, 42–45	0.6610	0.7248	−0.0101	0.1780	0.0051	−0.0403	0.0265	0.3183	−0.0159
19R-3, 49–52	0.7797	0.6724	−0.0113	0.1877	0.0099	0.0147	0.0184	0.5391	−0.0313
Variance		39.209	8.505	11.861	4.756	5.682	4.334	4.047	4.05
Cumulative variance		39.209	47.714	59.575	64.332	70.014	74.348	78.395	82.445

ceous/Tertiary boundary, although the Maestrichtian *Cibicidoides hyphalus* assemblage explains 4.05% of the original data set (Fig. 6). Results of this study, therefore, are in agreement with previously published results, that there was no major extinction event of benthic foraminifers at the Cretaceous/Tertiary boundary (Beckmann, 1960; Douglas and Woodruff, 1981; Hsü, 1986; Thomas, 1990a, 1990b).

The change in benthic foraminiferal number and planktonic percentage is shown in Figure 8A. The planktonic percentage shows a drastic decrease between Sample 121-752B-11R-3, 112–114 cm (358.92 mbsf), and 121-752B-11R-3, 64–66 cm (358.44 mbsf). The low planktonic percentage continues up to Sample 121-752B-10R-CC (354.8 mbsf), and increases up to 80% in Sample 121-752B-10R-4, 79–81 cm (351.65 mbsf), with some intervals of lower values (Samples 121-752B-10R-5, 124–127 cm, to 121-752B-10R-6, 50–52 cm; 352.34–353.10 mbsf). The total interval of these low planktonic percentages covers 6.1–6.8 m, although a small peak of planktonic percentage (40%–50%) does occur. The benthic foraminiferal number (expressed as the number of individuals/cm^3/m.y.) decreases rapidly between Sample 121-752B-11R-2, 44–47 cm (356.74 mbsf), and Sample 121-752B-11R-1, 44–47 cm (355.24 mbsf), about 2 m above the boundary (corresponding to about 0.11 m.y.). The benthic foraminiferal number increases in Samples 121-752B-10R-7, 41–43 cm, and 121-752B-10R-6, 100–102 cm (353.60–354.51 mbsf), and again decreases just above this interval.

The lower horizon is correlated with a dark green ash layer exhibiting a higher volume magnetic susceptibility variation that relates to ash content (Peirce, Weissel, et al., 1989; Rea et al., 1990a). The composite ash layer above the boundary spans from

352.65 to 358.17 mbsf (Fig. 8B). The highest peaks of ash content (about 355–356 mbsf) correspond to the dramatically lower benthic foraminiferal number per million years. The benthic foraminifers in this interval have a very low species diversity and are badly preserved, with dissolved test walls. Therefore, some chemical effect on foraminifers from the ash layer may occur in this horizon. The influence of the ash layer is also detected in the decrease of carbon isotopic ratio in benthic foraminifers (Fig. 8C). The abrupt decrease of the benthic foraminiferal number/m.y. at about 2 m above the boundary is primarily related to the dissolution of foraminiferal fauna, but preservation of benthic foraminiferal tests is good to moderate in other horizons above the boundary.

DISCUSSION

Cretaceous/Tertiary Boundary

In contrast to the mass extinction of planktonic organisms, minor extinction of deep-sea benthic foraminifers at the Cretaceous/Tertiary boundary event has been documented in various studies as recently reviewed by Thomas (1990a).

Although the percentage of planktonic foraminifers decreases drastically just above the boundary, the benthic foraminiferal number per million years remained unchanged until about 2 m above the Cretaceous/Tertiary boundary at Broken Ridge. The reduced planktonic percentages continue to about 4.2 m above the boundary (within Zone CP1a). This interval falls within the low productivity horizon described in the "Broken Ridge Summary" chapter in Peirce, Weissel, et al. (1989). The reduced benthic foraminiferal number per million years, as well as the near-ab-

Stensioina beccariiformis Assemblge (Factor 1)

Anomalina capitatus/ A. danicus Assemblage (Factor 2)

Cibicidoides cf. *pseudoperlucidus* Assemblage (Factor 3)

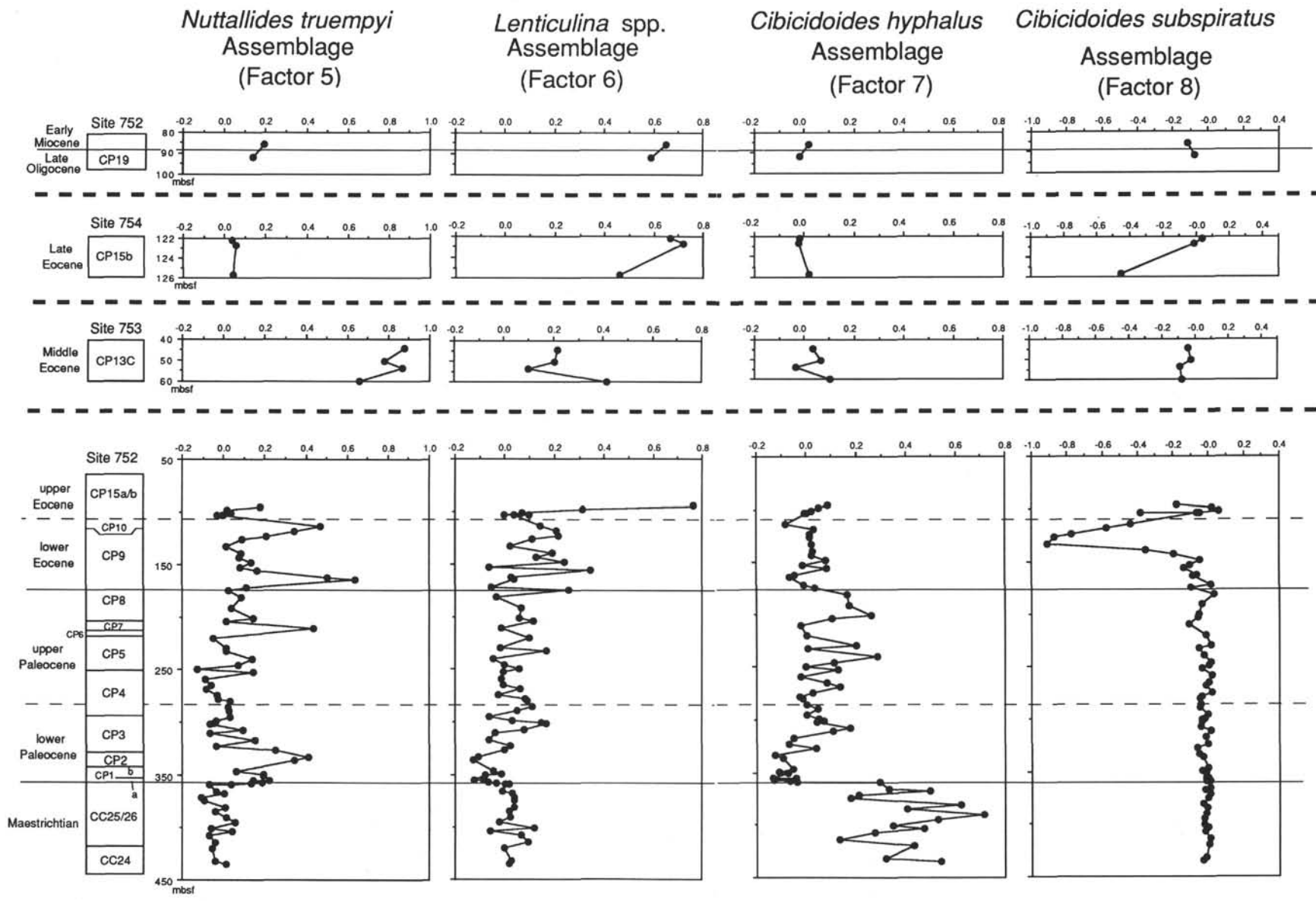*Osangularia* sp. 1 - *Hanzawaia ammophila* Assemblage (Factor 4)
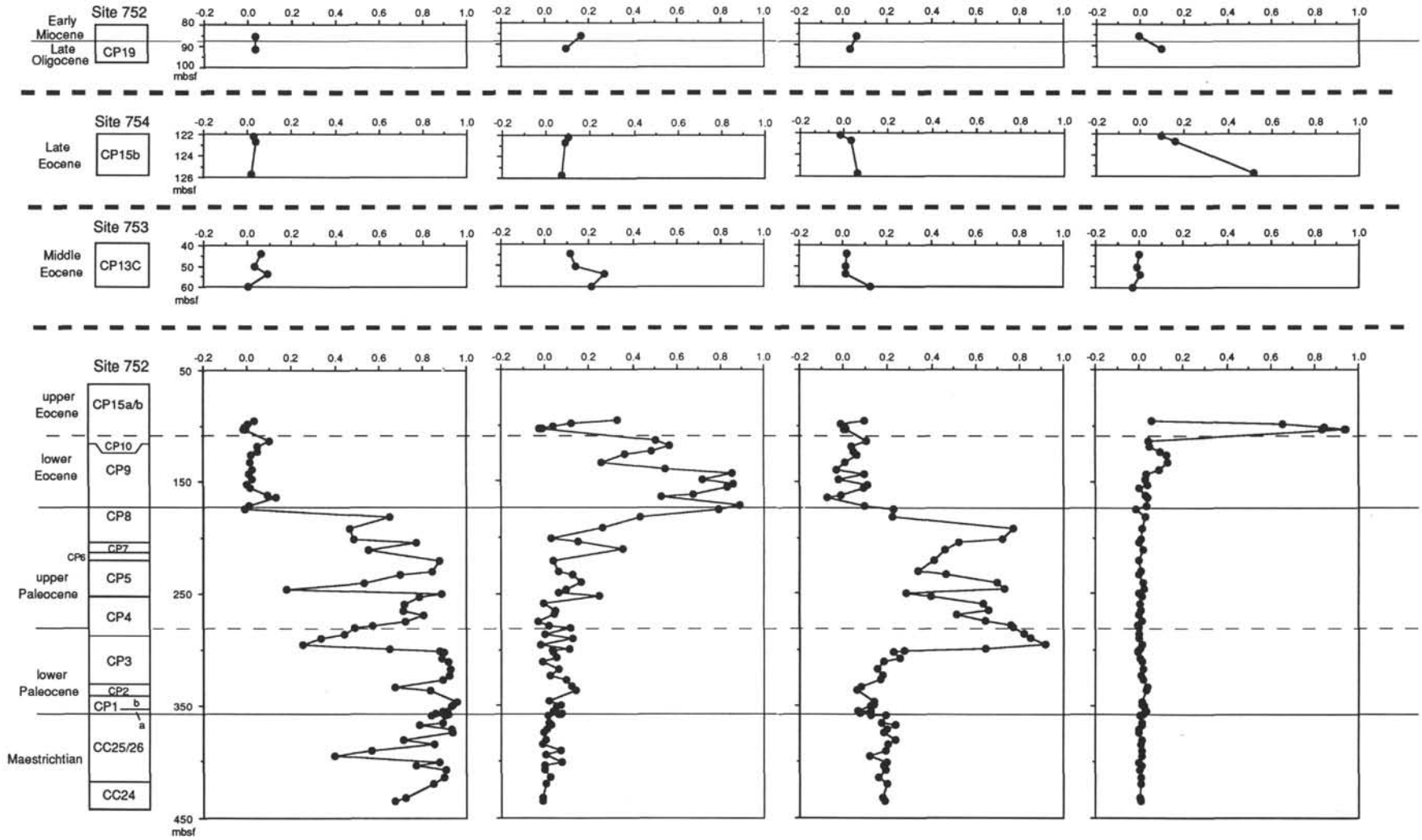
Figure 6. Varimax factor loadings plotted vs. depth and nannofossil zone.

Table 5. Factor score matrix from varimax factor analysis.

Taxa	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8
Alabamina creta	−0.048	−0.005	−0.027	−0.003	0.006	0.002	0.092	−0.005
Alabamina dissonata	−0.003	0.014	−0.008	−0.024	0.003	−0.039	−0.003	−0.328
Ammosphaeroidina sp.	0.014	−0.012	0.050	0.003	0.024	−0.016	−0.043	−0.005
Anomalina praeacuta	0.118	−0.026	0.104	0.005	0.019	−0.022	0.026	−0.005
Anomalinoides spissiformis	−0.010	−0.004	0.001	−0.001	0.111	0.006	0.022	−0.041
Anomalinoides capitatus/danicus	−0.050	0.660	0.136	−0.001	−0.078	−0.136	0.006	0.003
Anomalinoides semicribratus	−0.010	0.072	0.091	0.005	0.003	−0.025	0.025	0.011
Bolivinoides draco	0.001	0.000	−0.008	0.001	0.004	−0.005	0.073	0.001
Bulimina alazanensis	0.001	−0.007	−0.002	−0.011	0.004	0.047	−0.005	−0.002
Bulimina bradburyi	−0.001	0.036	−0.006	0.003	0.013	−0.005	0.001	0.020
Bulimina jarvisi	0.004	0.034	−0.007	0.016	−0.015	−0.012	0.009	−0.021
Bulimina macilenta	0.000	0.030	−0.007	0.010	−0.007	0.003	0.002	−0.006
Bulimina trinitaensis	0.018	0.153	0.231	0.015	−0.008	−0.055	−0.110	0.043
Bulimina tuxpamensis	−0.002	0.108	−0.030	0.055	−0.044	−0.017	0.007	−0.29
Cibicidina walli	−0.008	0.008	0.008	0.363	0.015	−0.058	0.010	0.07
Cibicidoides cf. *alazanensis*	−0.009	−0.027	0.007	−0.007	0.093	0.023	0.022	0.011
Cibicidoides bradyi	0.005	−0.006	−0.009	−0.008	−0.014	0.126	−0.012	0.021
Cibicidoides eocaenus	0.000	0.062	−0.017	0.088	−0.023	0.029	−0.006	−0.132
Cibicidoides mundulus	0.005	−0.023	−0.007	−0.025	0.002	0.166	−0.016	0.01
Cibicidoides laurisae	0.001	0.008	−0.009	0.152	−0.006	0.114	−0.001	0.07
Cibicidoides praemundulus	0.060	−0.019	0.179	0.019	0.065	−0.105	0.809	0.011
Cibicidoides cf. *pseudoperlucidus*	−0.152	−0.085	0.870	0.006	0.048	−0.059	−0.138	−0.004
Cibicidoides subspiratus	−0.005	−0.054	−0.010	0.144	−0.068	−0.078	−0.005	−0.797
Cibicidoides truncanus	0.002	−0.009	−0.007	0.145	−0.013	0.128	−0.008	0.038
Cibicidoides cf. *velascoensis*	0.155	−0.015	−0.068	0.014	0.067	−0.073	0.181	−0.027
Cibicidoides sp. 1	0.005	−0.023	−0.011	0.088	−0.021	0.192	−0.015	0.007
Cibicidoides sp. 6	−0.011	0.346	−0.020	0.018	−0.106	−0.055	0.009	0.107
Cibicidoides sp. 8	0.004	0.231	−0.026	0.032	−0.005	−0.069	0.016	0.136
Cibicidoides sp. 10	0.001	0.076	−0.016	−0.002	−0.039	0.002	0.002	−0.032
Cibicidoides sp. 11	−0.006	0.131	−0.004	0.003	−0.037	−0.009	0.003	0.053
Cibicidoides sp. 12	0.000	0.071	−0.014	0.011	0.055	−0.031	−0.001	0.045
Cibicidoides sp. 13	−0.002	0.036	0.002	−0.001	−0.017	0.004	0.000	0.016
Cibicidoides sp. 18	−0.036	−0.121	0.024	−0.018	0.430	0.062	0.090	0.047
Coryphostoma incrassata	0.038	−0.014	−0.007	0.005	0.038	−0.033	0.141	−0.009
Dentalina spp.	0.037	−0.008	−0.013	0.040	0.075	0.030	0.037	0.012
Gaudryina spp.	0.013	−0.011	0.084	−0.003	0.006	0.004	−0.046	−0.009
Gavelinella sp. 1	0.107	−0.004	−0.073	0.019	0.075	−0.056	−0.168	−0.002
Globocassidulina sp. 2	0.005	−0.020	−0.007	−0.011	0.001	0.131	−0.018	0.011
Globocasssidulina globosa	0.009	−0.033	−0.019	0.085	−0.028	0.244	−0.030	−0.059
Guttulina spp.	0.010	−0.017	0.102	−0.003	0.019	0.012	−0.030	−0.002
Gyroidina orbicularis	0.000	0.040	−0.005	−0.003	−0.010	−0.007	0.001	−0.019
Gyroidina soldanii	−0.009	−0.065	0.060	0.017	0.182	0.163	0.029	0.049
Gyroidinoides globosus	0.019	−0.008	−0.020	0.001	0.008	−0.011	0.144	−0.004
Gyroidinoides planulatus	0.034	−0.016	0.080	−0.003	−0.004	0.003	0.046	−0.005
Gyroidinoides quadratus	0.035	−0.007	−0.049	−0.004	−0.012	0.001	0.221	−0.006
Hanzawaia ammophila	−0.009	0.009	0.006	0.513	0.010	−0.039	0.011	0.096
Lenticulina spp.	0.039	0.194	0.171	−0.041	0.173	0.575	0.056	−0.235
Nonion sp.	0.031	0.001	−0.007	0.005	0.026	−0.021	−0.048	−0.004
Nonion havanensis	0.005	−0.006	0.004	0.000	−0.011	0.069	−0.010	0.011
Nuttallides truempyi (thin type)	0.019	−0.006	−0.034	0.000	0.008	−0.008	0.189	−0.003
Nuttallides truempyi	0.157	0.196	−0.093	0.033	0.727	−0.230	−0.176	−0.063
Oridorsalis sp. 1	0.028	−0.005	0.047	0.000	−0.001	−0.002	0.095	0.003
Oridorsalis umbonatus	0.008	0.433	−0.080	0.001	0.045	0.279	0.112	−0.033
Osangularia mexicana	−0.004	0.036	−0.010	−0.015	0.054	0.105	0.007	0.042
Osangularia sp. 1	−0.008	−0.034	0.007	0.709	−0.005	0.044	−0.006	0.048
Planulina renzi	0.002	−0.010	−0.003	−0.012	0.002	0.069	−0.007	0.003
Planulina costata	−0.019	−0.086	0.010	−0.015	0.248	0.126	0.051	0.051
Pullenia coryelli	0.237	−0.021	−0.004	0.028	0.113	−0.086	−0.155	−0.004
Pullenia quadriloba	−0.006	0.019	−0.002	−0.004	0.067	0.038	0.013	0.016
Pullenia quinqueloba	0.000	0.041	−0.004	−0.006	−0.014	0.029	−0.004	0.010
Stensioina beccariiformis	0.908	−0.012	0.153	−0.005	−0.162	0.039	−0.032	0.024
Stilostomella gracillima	0.002	−0.022	0.007	−0.002	0.023	0.202	−0.021	0.023
Turrilina brevispira	−0.015	−0.034	0.003	−0.014	0.169	0.018	0.044	−0.024
Uvigerina resurgens	0.022	−0.026	−0.032	−0.005	−0.052	0.398	−0.067	0.107

sence of planktonic foraminifers in this interval, is considered to result from dissolution of foraminiferal tests. The differential response of benthic and planktonic foraminifers, however, within 2 m above the Cretaceous/Tertiary boundary probably means that the Cretaceous/Tertiary event occurred in the surface ocean (e.g., Thomas, 1990a, 1990b). The disappearance of some species such as *Coryphostoma incrassata* and *Praebulimina navarroensis* may be related to the collapse of the detritus-feeding food chain, as proposed by Sheehan and Hansen (1986), Arthur et al. (1987), and

Thomas (1990a, 1990b). Arthur et al. (1987) suggested that the rapid decrease of marine primary productivity resulted in selective elimination of organisms dependent on the flux of organic matter as a food source, so detritus and deposit feeders utilizing the organic matter stored within the sediments show fewer extinctions after the Cretaceous/Tertiary event.

The $\delta^{13}C$ values of *Stensioina beccariiformis* increased slightly at 356.74–358.44 mbsf (Seto et al., this volume; Fig. 8C). In general, the benthic $\delta^{13}C$ does not show the significant negative
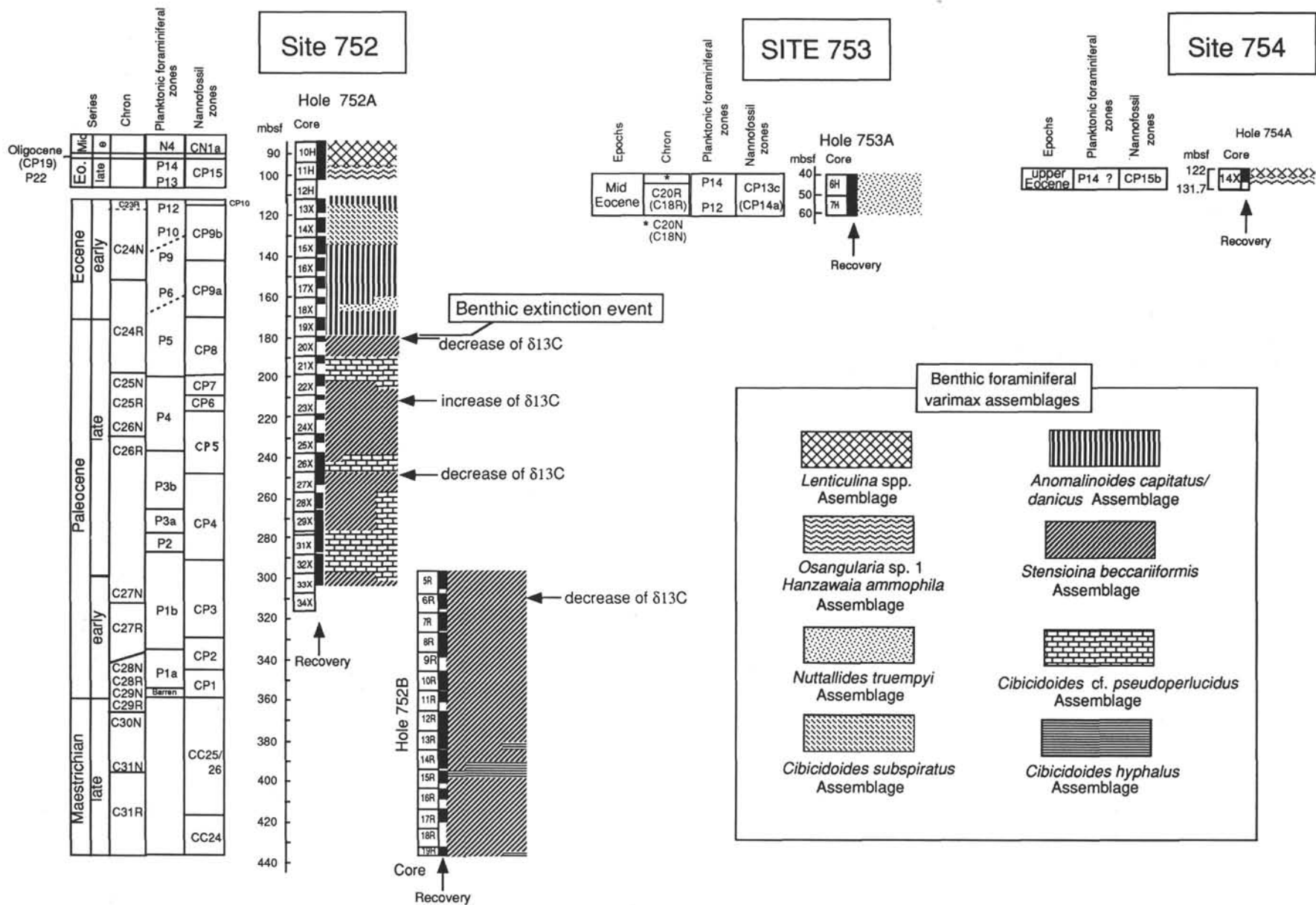
Figure 7. Stratigraphic distribution of varimax assemblages having factor loadings >0.5.
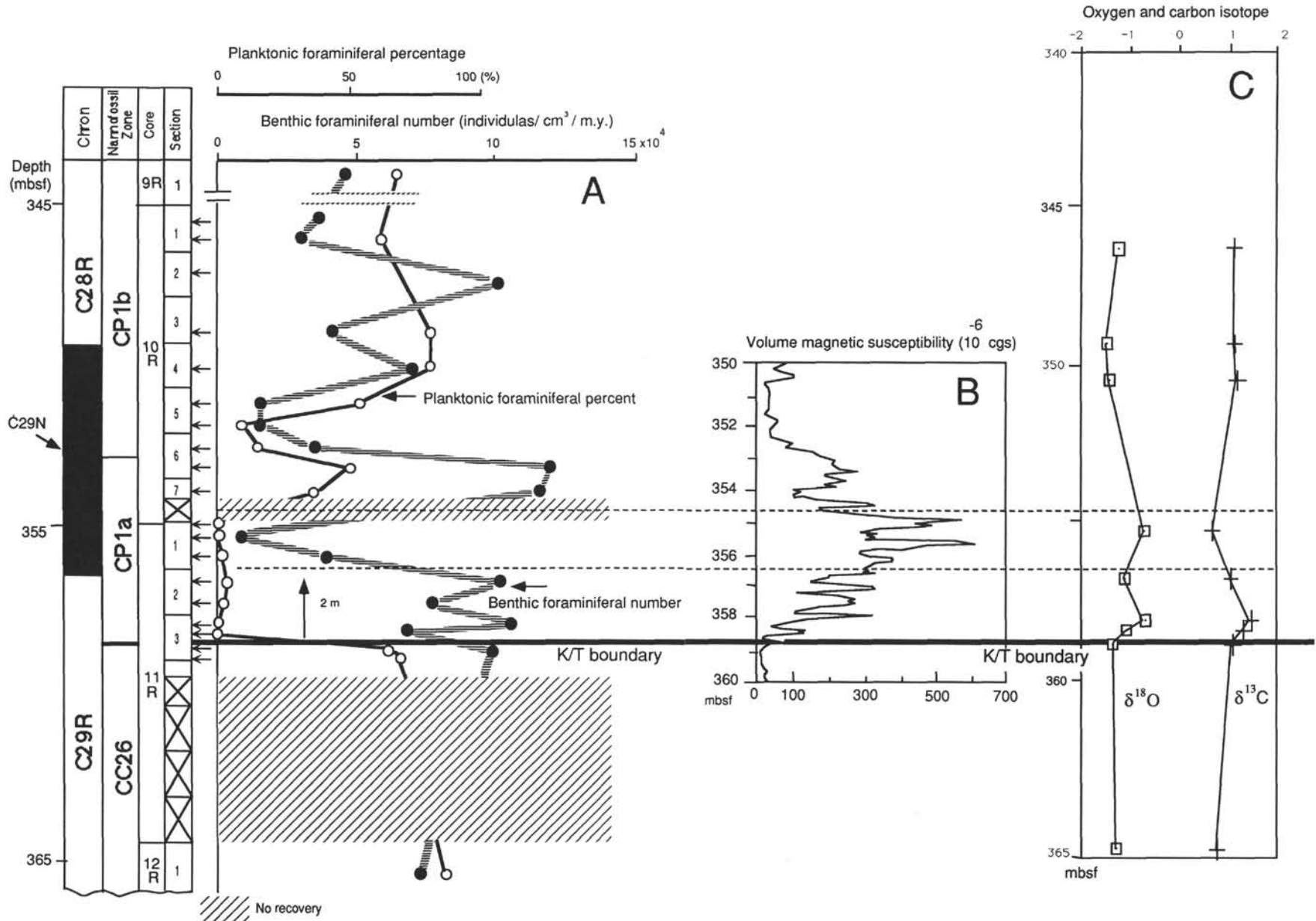
Figure 8. Close-up of the Cretaceous/Tertiary boundary. **A**. Planktonic foraminiferal percentages and benthic foraminiferal number per million years. **B**. Volume magnetic susceptibility. The interval between the two dashed lines has a high ash content. **C**. Oxygen and cargon isotope record based on analysis of 10 individuals of *Stensioina beccariiformis* (Seto et al., this volume).

excursion of $\delta^{13}C$ of planktonic foraminifers (Boersma and Shackleton, 1981; Boersma, 1984; Arthur et al., 1987; Keller, 1989). The positive shift of $\delta^{13}C$ after the Cretaceous/Tertiary boundary event supports the theory of collapse of surface productivity, although the increased values are slight and vary between foraminiferal samples. This may indicate a reduced supply of organic matter to the seafloor environment at Broken Ridge as suggested by Keller (1989). Thomas (1990a, 1990b) reported that epifaunal species at Antarctic Sites 689 and 690 increased just above the Cretaceous/Tertiary boundary, probably as a result of the collapse of surface productivity. The epifaunal species dominate when there is a low amount of organic carbon (Corliss and Chen, 1988). Epifaunal species were not counted in this study, but highly oxygenated bottom water, as well as a low concentration of nutrients just after the Cretaceous/Tertiary event, agrees with the positive shift in $\delta^{13}C$. Hsü (1986) suggested that bottom water was oxygen-deficient after the Cretaceous/Tertiary boundary event, but there is no evidence of such anoxic waters at the Broken Ridge or Maud Rise sites. The decrease of $\delta^{13}C$ in Sample 121-752B-11R-1, 44–47 cm, is correlated with the lowest values of both benthic foraminifers and planktonic foraminiferal percentages. The low value of $\delta^{13}C$ in this interval is correlated with higher amount of ash and may be accounted for by a supply of ^{12}C from volcanic ash. It seems clear that surface productivity did not cause the negative shift of $\delta^{13}C$.

The Late Paleocene Benthic Extinction Event

It remains unclear what caused the extinction of many Paleocene taxa, represented by the *Stensioina beccariiformis* assemblage. The Paleocene and Eocene climate is generally considered to have been warm and stable (Savin, 1977; Oberhänsli and Hsü, 1986), and thermal gradients between low and high latitude were considerably lower than those of today (e.g., Barron, 1987). The exact timing of disappearance varies with species, but the extinction event culminated at the end of the Paleocene and most affected shallower deep-sea taxa (Tjalsma and Lohmann, 1983). According to Thomas (1990b), more than 35% of the Antarctic region species disappeared during the latest Paleocene extinction event that occurred for a short period (about 350,000 yr). At Site 752, about 36.6% of all Paleocene taxa (including rare taxa) disappeared at the end of the Paleocene. Although the paleodepth of Site 752 is slightly shallower than that of the Antarctic sites, the percentage of species that became extinct is similar.

Oberhänsli et al. (1984) and Oberhänsli and Hsü (1986) noted that the late Paleocene positive $\delta^{13}C$ event in surface and bottom waters is related to the benthic faunal turnover. Miller et al. (1987), Thomas (1989), and Katz and Miller (1990) pointed out the correspondence between benthic extinction and bottom-water temperature increase in the late Paleocene. Deep water warmed about 4°C across the Paleocene/Eocene boundary, and minimum deep-water temperatures were 12°C at that time (Katz and Miller, 1990) and ranged up to 17°C (Kennett and Stott, 1990). At Site 752, the bottom-water temperature variation during the Paleocene was small, and the early Eocene temperature was warm, with "spikes" of low benthic $\delta^{18}O$ (Seto et al., this volume; Fig. 9). The Paleocene and lower Eocene $\delta^{18}O$ record from Site 752 is similar to previously described records (Shackleton et al., 1984, 1985; Oberhänsli and Hsü, 1986; Miller et al., 1987; Kennett and Stott, 1990; Katz and Miller, 1990). A detailed examination, however, reveals that the benthic extinction event does not directly correlate with the change in $\delta^{18}O$ variation (Fig. 9), but is more closely related to the changes in $\delta^{13}C$, as demonstrated by Thomas (1989).

Low factor loadings for the *Stensioina beccariiformis* assemblage are closely correlated with the lowering of benthic $\delta^{13}C$ values in upper Zone CP3 (Chron C25N), lower Zone (upper Zone C24R), and upper Zone CP8 (Chron C24R), respectively, al-

though the changes in the *S. beccariiformis* assemblage were slightly later than the drop of $\delta^{13}C$ (Fig. 9). The interval of high benthic $\delta^{13}C$ in the upper Paleocene is coeval with other reported events in the South Atlantic, Pacific, and Antarctic oceans (Shackleton et al., 1984; Shackleton and Hall, 1984; Miller et al., 1987; Kennett and Stott, 1990; Katz and Miller, 1990). Thus, the Indian Ocean stable isotopic results support the conclusion that the late Paleocene oceanographic change occurred globally (Rea et al., 1990b). Kroopnick (1985) showed that $\delta^{13}C$ is controlled mainly by the input of organically produced carbon and subsequent oxidation. Therefore, oxygen-deficient waters show lower $\delta^{13}C$ values (Miller and Fairbanks, 1985; Shackleton, 1986). Woodruff and Savin (1989) commented that low $\delta^{13}C$ is related to aged oceanic water. In addition, the late Paleocene decrease in the surface-to-bottom $\delta^{13}C$ gradient of the Pacific and the South Atlantic oceans was related to a decrease of surface ocean productivity (Shackleton et al., 1984, 1985; Shackleton and Hall, 1984; and Miller et al., 1987). Following these authors' results, the young, nutrient-depleted water developed not only in the middle to lower bathyal waters of the Indian Ocean, but also developed globally in the late Paleocene (CP7–8), and aged, oxygen-depleted water developed in the latest Paleocene and early Eocene. Miller et al. (1987) pointed out three potential source regions of nutrient-depleted bottom waters: the Antarctic region, the North Atlantic/Arctic region, and the Tethys region. In the discussion of faunal change in the Cape Basin, Pacific Ocean Site 577, and the Atlantic sector of the Southern Ocean, Miller et al. (1987) and Katz and Miller (1990) decided that oxygen and carbon isotopic records from the late Paleocene reflect the presence of Antarctic-source bottom water. They further suggested that the short-time elimination of Antarctic-source water, as reflected in the $\delta^{13}C$ record as well as bottom-water warming (a decrease of $\delta^{18}O$ in the latest Paleocene), might have triggered the benthic extinction event.

The extinction event at the end of the Paleocene (Zone CP8) occurred during an abrupt drop of $\delta^{13}C$ values in benthic foraminifers (Fig. 9). In addition, there are two signals (near the Zone CP3/4 and CP4/5 boundaries) of the extinction event that have not been noted previously, though Miller et al. (1987) noted that the decrease of the Paleocene *S. beccariiformis* assemblage began in Zone P3b (CP4–CP5) in the Pacific Ocean (Site 577), and Thomas (1990b) also noted the change of the assemblages 6/7 at the Zone CP4/5 boundary at Maud Rise. At Site 752 (middle to lower bathyal depths, ~1000 m, in the Paleocene; Peirce, Weissel, et al., 1989), the *Stensioina beccariiformis* assemblage belongs to the Velasco-type fauna. The gradual increase in abundance of *Anomalinoides capitatus/A. danicus, Oridorsalis umbonatus, Bulimina tuxpamensis*, and various species of Cibicidoides as represented by the *Anomalinoides capitatus/A. danicus* and *Cibicidoides* cf. *pseudoperlucidus* assemblages in late Paleocene to early Eocene indicates replacement of the Velasco-type fauna by a fauna more similar to the Midway-type fauna, suggesting shelf or upper bathyal depths (Plummer, 1926; Berggren and Aubert, 1975). The timing of the incursion of the Midway-type fauna is closely correlated with the interval of lowered d13C (Fig. 9). The increase of taxa similar to those of the Midway fauna may be explained in two ways: (1) the shallowing of the crest of Broken Ridge up to shelf depths, and (2) depression of a shallower water mass to middle to lower bathyal depths. Rifting and shallowing of Broken Ridge occurred in the middle Eocene, and there is no evidence of shallowing of Broken Ridge during the Paleocene and earliest Eocene (Peirce, Weissel, et al., 1989); thus, it appears that shelf species migrated into this deeper environment. Thomas (1989) noted that the earliest Eocene faunas just after the Paleocene/Eocene boundary event probably migrated into the deep waters. Evidence for depth migration is also presented by Tjalsma and
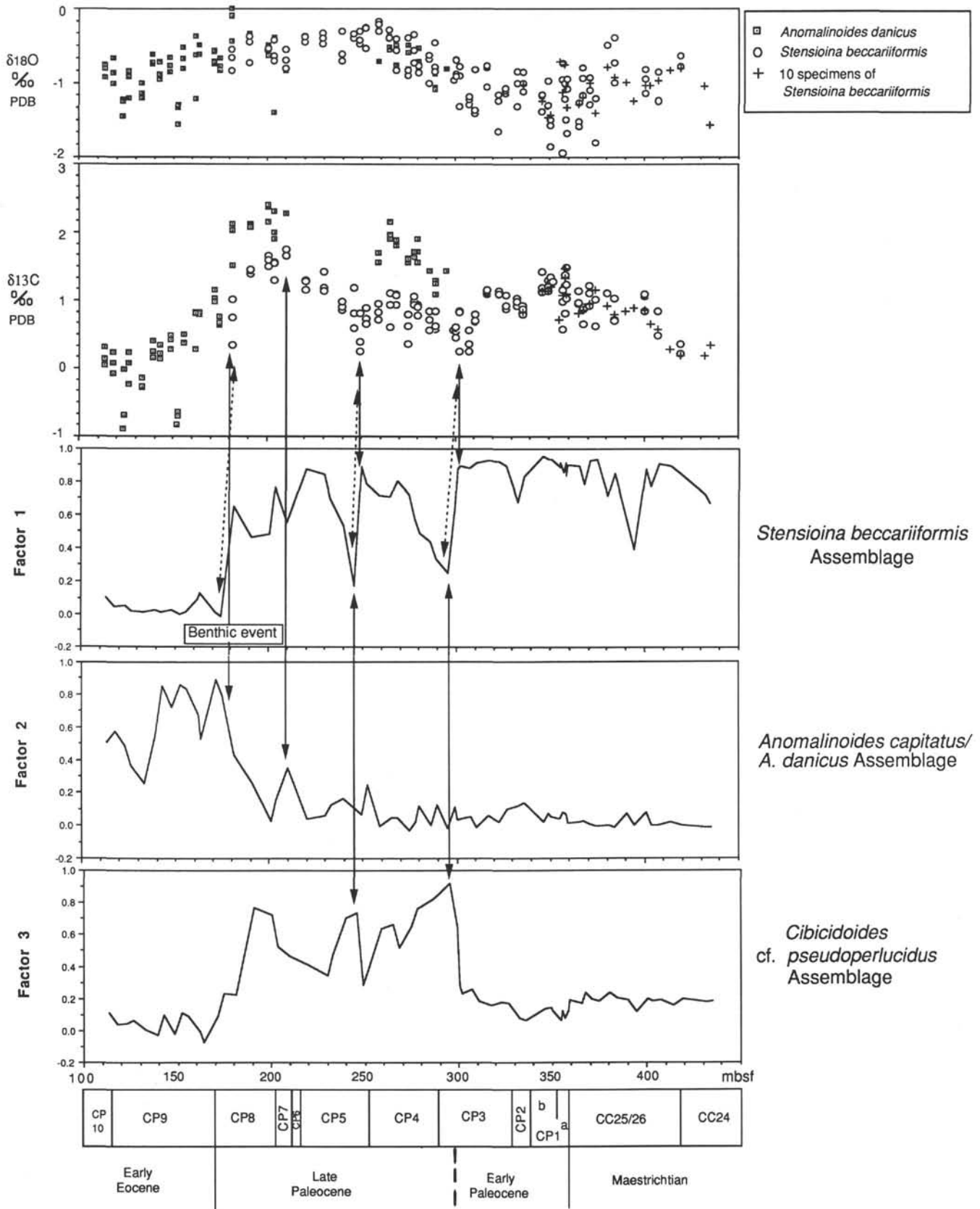
Figure 9. Relationships between oxygen and carbon isotope records (Seto et al., this volume) and benthic foraminiferal assemblages obtained from factor analysis (factors 1–3) from the upper Maestrichtian to lower Eocene. Arrows indicate the correlation between carbon isotope variations and benthic faunal changes, and the correlation between faunal variations. Dotted arrows indicate the correlation between the decreased values of $\delta^{13}C$ and the reduced *Stensioina beccariiformis* assemblage in the Paleocene.

Lohmann (1983); however, they described an upslope migration of Paleocene species that occurred at the latest Paleocene extinction and was followed by a bloom of new species in the early Eocene.

Benthic foraminiferal depth migration might be related to changes in ocean circulation, which may be caused by the reorganization of the ocean and continent configurations. Thomas (1989, 1990a, 1990b) and Katz and Miller (1990) suggested a relation between the extinction event and the production of warm, saline deep waters. Based on the isotopic data of the Antarctic sites, Kennett and Stott (1990) stated, "The ocean during the Eocene, and perhaps the Paleocene, is inferred to have been two-layered, consisting of warm, saline deep waters formed at low latitudes and overlain by cooler waters formed at high latitudes." The source region of such warm, saline deep water is suggested to have been the Tethys. According to Berggren and Aubert (1975), the upper Paleocene sediments surrounding the Tethys Sea in the North African region (LeRoy, 1953; Said and Kenawy, 1956; Berggren, 1974) are characterized by the "Tethyan Carbonate Fauna," shallow-water limestones containing larger foraminifers. The *Cibicidoides-Anomalinoides* assemblage developed as an offshore biofacies of the "Tethyan Carbonate Fauna" on a middle to outer shelf setting, in Zone P5 in the Sirte Basin of Libya (Berggren, 1974). Downslope migration of shallower-dwelling faunas may have been facilitated at this time.

A Proteus Ocean, characterized by halothermal circulation, is in contradiction to the interpretation of Miller et al. (1987) and Katz and Miller (1990) with respect to the source of deep water, although Katz and Miller (1990) suggested that the Antarctic deep-water source was replaced by the short period of warm, saline deep-water formation near the Paleocene/Eocene boundary (58–57 Ma). The warm, saline bottom-water model is based on the notion that more sources of warm, saline water existed during the Late Cretaceous (Brass et al., 1982) and during the Tertiary (Prentice and Matthews, 1989), due to the presence of large marginal seas lying in the net evaporation zone (10°–40° latitude). However, the marginal seas, including the Tethys Sea, contracted in size after the Cretaceous (Barron et al., 1981; Brass et al., 1982), which would correlate with a reduction of the warm, saline deep-water mass (Brass et al., 1982). Carbon isotopes reveal an inflow of young and nutrient-depleted waters in middle to lower bathyal depths at Zones CP7 and lower Zone CP8 (the interval of higher benthic δ^{13}C values), and that warm and aged waters were not only formed during the latest Paleocene to early Eocene, but were also distinctly formed in short periods (near the boundaries of Zones CP3/4 and CP4/5) in the Paleocene at Site 752. The changes in carbon isotopic ratios of *Anomalinoides danicus* and *Stensioina beccariiformis* correlate with changes in *S. beccariiformis*, *A. capitatus/danicus*, and *Cibicidoides* cf. *pseudoperlucidus* assemblages (Fig. 9), which suggests that changes of bottom-water character caused faunal change. Although the deep-water source in the eastern Indian Ocean is not determinable at this site alone, Stott and Kennett (1989) indicated that the Antarctic may not have been a significant source of deep water during the early Paleocene, contrary to Barrera et al. (1987) and Miller et al. (1987). Stott et al. (1990) also suggested that sea-surface temperatures of the oceans surrounding Antarctica were temperate during much of the Paleocene and Eocene. If their conclusions are valid, I consider that the variations of warm, saline water originating from a low-latitude evaporation zone caused the changes in Paleocene and early Eocene benthic fauna. The Paleocene/Eocene extinction event seems to be reflected in the weakened influence of a warm, saline water circulation by the reduction of evaporation area of shallow marginal seas worldwide. This view is not in agreement with the previously mentioned conclusions that extinction resulted from the influence of warm, saline

deep water because it is supposed to have higher δ^{18}O and δ^{13}C values (e.g., Railsback et al., 1989; Railsback, 1990); however, these isotopic values decreased from the late Paleocene to early Eocene.

In conclusion, several hypotheses have been advanced to explain the faunal turnover in relation to water circulation at the end of the Paleocene, such as a decrease of surface ocean productivity, a cessation of the deep-water flow from the Southern Ocean (Antarctic region) (Miller et al., 1987; Katz and Miller, 1990), and a concomitant inflow of warm, saline water from the low latitudes (Thomas, 1989, 1990a, 1990b; Kennett and Stott, 1990). The benthic fauna and their isotopic composition, however, suggest that the weakened influence of the warm, saline water flow from the Tethyan region was critical for the changes in Paleocene deep-sea taxa at Site 752. Aged and oxygen-depleted deep waters would have formed following the weakening circulation influence of the warm, saline water.

The Velasco-type fauna characterized by the *Stensioina beccariiformis* assemblage changed in response to at least three cessations of warm, saline bottom-water flow during the Paleocene. The benthic extinction event at the end of the Paleocene suggests a weakening influence of the warm, saline water on deep-ocean circulation.

ACKNOWLEDGMENTS

SPECIES REFERENCE LIST

Asterisks indicate the taxa that occurred from the Oligocene (Sample 121-752A-10H-5, 70–75 cm) or from the lower Miocene (Sample 121-752A-10H-1, 70–75 cm).

Alabamina creta (Finlay) = *Pulvinulinella creta* Finlay, 1940
Alabamina dissonata (Cushman and Renz) = *Pulvinulinella atlantisae* Cushman var. *dissonata* Cushman and Renz, 1943
Ammodiscus glabratus Cushman and Jarvis, 1928
Anomalina praeacuta Vasilenko, 1950
Anomalinoides capitatus (Gümbel) = *Rotalia capitata* Gümbel, 1868
Anomalinoides danicus (Brotzen) = *Cibicides danica* Brotzen, 1940
**Anomalinoides pseudogrosserugosus* (Colom) = *Anomalina pseudogrosserugosa* Colom, 1945
Anomalinoides semicribratus (Beckmann) = *Anomalina pompilioides* Galloway and Heminway var. *semicribrata* Beckmann, 1953
Anomalinoides spissiformis (Cushman and Stainforth) = *Anomalina alazanensis* Nuttall var. *spissiformis* Cushman and Stainforth, 1945
Anomalinoides undulatus Belford, 1960
Aragonia aragonensis (Nuttall) = *Textularia aragonensis* Nuttall, 1930
**Astrononion stelligerum* (d'Orbigny) = *Nonionina stelligera* d'Orbigny, 1839
*Bolivina cf. *B. silvestrina* Cushman, 1936
*Bolivina cf. *B. thalmanni* Renz, 1948
Bolivinoides delicatulus = *Bolivinoides decorata* (Jones) var. *delicatula* Cushman, 1927
Bolivinoides draco (Marsson) = *Bolivina draco* Marsson, 1878
Bulimina alazanensis Cushman, 1927
Bulimina bradbury Martin, 1943
Bulimina callahani Galloway and Morrey, 1931
Bulimina impendens Parker and Bermúdez, 1937
Bulimina jarvisi Cushman and Parker, 1936
Bulimina macilenta Cushman and Parker, 1939
Bulimina mexicana Cushman = *Bulimina inflata* Seguenza var. *mexicana* Cushman, 1922
Bulimina triangularis Cushman and Parker, 1935
Bulimina trinitatensis Cushman and Jarvis, 1928
Bulimina tuxpamensis Cole, 1928

Buliminella grata Parker and Bermúdez, 1937
Cibicides excavata Brotzen, 1936
Cibicides cf. *C. aknerianus* (d'Orbigny) = *Rotalina akneriana* d'Orbigny, 1846
Cibicides lobatulus (Walker and Jacob) = *Nautilus lobatulus* Walker and Jacob, 1798
Cibicides cf. *C. ribbingi* Brotzen, 1936
Cibicidina walli Bandy, 1949
Cibicidoides cf. *C. alazanensis* (Nuttall) = Cf. *Anomalina alazanensis* Nuttall, 1932
Cibicidoides bradyi (Trauth) = *Truncatulina bradyi* Trauth, 1918
Cibicidoides dayi (White) = *Planulina dayi* White, 1928
Cibicidoides eocaenus (Gümbel) = *Rotalia eocaena* Gümbel, 1868
Cibicidoides grimsdalei (Nuttall) = *Cibicides grimsdalei* Nuttall, 1930
Cibicidoides havanensis (Cushman and Bermúdez) = *Cibicides havanensis* Cushman and Bermúdez, 1937
Cibicidoides hyphalus (Fisher) = *Anomalinoides hyphalus* Fisher, 1969
Cibicidoides cf. *C. incrassatus* (Fichtel and Moll) = Cf. *Nautilus incrassatus* Fichtel and Moll, 1798
Cibicidoides laurisae (Mallory) = *Cibicides laurisae* Mallory, 1959
Cibicidoides mundulus (Brady, Parker, and Jones) = *Truncatulina mundula* Brady, Parker, and Jones, 1888
Cibicidoides cf. *C. pseudoperlucidus* (Bykova) = Cf. *Cibicides (Gamellides) pseudoperlucidus* Bykova,
Cibicidoides subspiratus (Nuttall) = *Cibicides subspiratus* Nuttall, 1930
Cibicidoides truncanus (Gümbel) = *Rotalia truncana* Gümbel, 1868
Cibicidoides tuxpamensis (Cole) = *Cibicides tuxpamensis* Cole, 1928
Cibicidoides velascoensis (Cushman) = *Anomalina velascoenis* Cushman, 1925
Coryphostoma incrassata (Reuss) = *Bolivina incrassata* Reuss, 1851
Coryphostoma midwayensis (Cushman) = *Bolivina midwayensis* Cushman, 1936
Dentalina admodicostata Belford, 1960
Dentalina basiplanata Cushman, 1938
Dentalina colei Cushman and Dusenbury, 1934
Dentalina communis d'Orbigny, 1826
Dentalina cylindroides Reuss, 1860
Dentalina jacksonensis (Cushman and Applin) = *Nodosaria jacksonensis* Cushman and Applin, 1926
Dentalina luma Belford, 1960
Dentalina multilineata Bornemann, 1855
Dentalina obliquata (Batsch) = *Nautilus (Orthoceras) obliquatus* Batsch, 1791
Dentalina pseudoaculeata Olsson, 1960
Dorothia beloides Hillebrandt, 1962
Dorothia bulletta (Carsey) = *Gaudryina bulletta* Carsey, 1926
Dorothia conicula Belford, 1960
Dorothia cf. *D. oxycona* = Cf. *Dorothia oxycona* Reuss, 1860
Dorothia trochoides (Marsson) = *Gaudryina crassa* Marsson var. *trochoides* Marsson, 1878
Ellipsoidella cf. *E. solida* (Brotzen) = Cf. *Nodosarella solida* Brotzen, 1936
Ellipsoidina ellipsoides Seguenza, 1859
Eouvigerina cf. *E. americana* Cushman, 1926
Frondicularia cf. *F. steinekei* Finley, 1939
Frondicularia teuria Finley, 1939
Gaudryina cf. *G. laevigata* Franke, 1914
Gaudryina pyramidata Cushman = *Gaudryina laevigata* Franke var. *pyramidata* Cushman, 1926
Globocassidulina globosa (Hantken) = *Cassidulina globosa* Hantken, 1875
Globocassidulina punctata van Morkhoven, Berggren, and Edwards, 1986
Globorotalites conicus (Carsey) = *Truncatulina refulgens* Montfort var. *conica* Carsey, 1926
Globulina gibba d'Orbigny, 1826
Guttulina problema d'Orbigny, 1826
Guttulina cf. *G. trigonula* (Reuss) = Cf. *Polymorphina trigonula* Reuss, 1845
Gyroidina noda Belford, 1960
Gyroidina orbicularis d'Orbigny, 1826
Gyroidina soldanii d'Orbigny, 1826
Gyroidinoides globosus (Hagenow) = *Nonionina globosa* Von Hagenow, 1842
Gyroidinoides excertus (Belford) = Cf. *Gyroidina excerta* Belford, 1960
Gyroidinoides planulatus (Cushman and Renz) = *Gyroidina planulata* Cushman and Renz, 1941
Gyroidinoides quadratus (Cushman and Church) = *Gyroidina quadrata* Cushman and Church, 1929
Hanzawaia ammophila (Gümbel) = *Rotalia ammophila* Gümbel, 1868
Hemicristellaria fragaria (Gümbel) = *Marginulina fragaria* Gümbel, 1870

Heronallenia sp. "A," Boltovskoy, 1978
Karreriella chapapotensis (Cole) = *Textularia chapapotensis* Cole, 1928
Karreriella subglabra (Gümbel) = *Gaudryina subglabra* Gümbel, 1868
Laticarinina pauperata (Parker and Jones) = *Pulvinulina repanda* var. *menardii* subvar. *pauperata* Parker and Jones, 1865
Lenticulina alato-limbata (Gümbel) = *Robulina alato-limbata* Gümbel, 1868
Lenticulina callifera (Stache) = *Cristellaria callifera* Stache, 1864
Lenticulina caroliniana Cushman, 1933
Lenticulina chambersi Garrett, 1939
Lenticulina convergens (Bornemann) = *Cristellaria convergens* Bornemann, 1855
Lenticulina lucida (Cushman) = *Cristellaria lucida* Cushman, 1923
Lenticulina nuttalli (Cushman and Renz) = *Robulus nuttalli* Cushman and Renz, 1941
Lenticulina occidentalis (Cushman) = *Cristellaria occidentalis* Cushman, 1923
Lenticulina occidentalis torridus (Cushman) = *Cristellaria occidentalis torrida* Cushman, 1923
Lenticulina pseudovortex Cole, 1927
Lenticulina rotulata (Lamarck) = *Lenticulites rotulata* Lamarck, 1806
Lenticulina whitei Tjalsma and Lohmann, 1983
Melonis pompilioides (Fichtel and Moll) = *Nautilus ponpilioides* Fitchel and Moll, 1798
Neoflabellina semireticulata (Cushman and Jarvis) = *Flabellina semireticulata* Cushman and Jarvis, 1928
Nodosarella subnodosa (Guppy) = *Ellipsoidina subnodosa* Guppy, 1891
Nodosaria cf. *N. catenulata* Cushman, 1923
Nodosaria cf. *N. fistuca* Schwager, 1866
Nodosaria hispida Schwager, 1866
Nodosaria limbata d'Orbigny, 1840
Nodosaria pyrula d'Orbigny, 1826
Nodosaria soluta (Reuss) = *Dentalina soluta* Reuss, 1851
Nodosaria vertebralis (Batsch) = *Nautilus (Orthoceras) vertebralis* Batsch, 1791
Nonion havanense Cushman and Bermúdez, 1937
Nuttallides truempyi (Nuttall) = *Eponides truempyi* Nuttall, 1930
Nuttallinella florealis (White) = *Gyroidina florealis* White, 1928
Oridorsalis umbonatus (Reuss) = *Gotalina umbonata* Reuss, 1851
Orthomorphina antillea (Cushman) = *Nodosaria antillea* Cushman, 1923
Orthomorphina challengeriana (Thalmann) = *Nodogenerina challengeriana* Thalmann, 1937
Orthomorphina havanensis (Cushman and Bermúdez) = *Nodogenerina havanensis* Cushman and Bermúdez, 1937
Orthomorphina heterosculpta (Bermúdez) = *Nodogenerina heterosculpta* Bermúdez, 1949
Orthomorphina modesta (Bermúdez) = *Ellipsonodosaria modesta* Bermúdez, 1937
Osangularia cordieriana (d'Orbigny) = *Rotalina cordieriana* d'Orbigny, 1940
Osangularia mexicana (Cole) = *Pulvinulinella culter* (Parker and Jones) var. *mexicana* Cole, 1927
Osangularia velascoensis (Cushman) = *Truncatulina velascoensis* Cushman, 1925
Planulina costata (Hantken) = *Truncatulina costata* Hantken, 1875
Planulina renzi Cushman and Stainforth, 1945
Plectofrondicularia parri Finely, 1939
Pleurostomella acuminata Cushman, 1922
Pleurostomella acuta Hantken, 1875
Pleurostomella alternans Schwager, 1866
Pleurostomella brevis Schwager, 1966
Pleurostomella incrassata Hantken, 1883
Praebulimina navarroensis (Cushman and Parker) = *Bulimina reussi* var. *navarroensis* Cushman and Parker, 1935
Pullenia americana Cushman, 1936
Pullenia bulloides (d'Orbigny) = *Nonionia bulloides* d'Orbigny, 1846
Pullenia coryelli White, 1929
Pullenia cretacea Cushman, 1936
Pullenia eocenica Cushman and Siegfus, 1939
Pullenia osloensis Feyling-Hanssen, 1954
Pullenia quadriloba Reuss = *Pullenia compressiuscula* Reuss var. *quadriloba* Reuss, 1867
Pullenia quinqueloba (Reuss) = *Nonionia quinqueloba* Reuss, 1851
Pullenia reussi Cushman and Todd, 1943
Pullenia subcarinata (d'Orbigny) = *Nonionina subcarinata* d'Orbigny, 1839
Pyramidina rudita (Cushman and Parker) = *Bulimina rudita* Cushman and Parker, 1935

Quadrimorphina allomorphinoides (Reuss) = *Valvulina allomorphinoides* Reuss, 1860

Ramulina globulifera Brady, 1879

Remessella varians (Glaessner) = *Textulaniella? variance* Glaessner, 1937

*Sphaeroidina bulloides d'Orbigny, 1826

Spiroplectammina spectabilis (Grzybowski) = *Spiroplecta spectabilis* Grzybowski, 1898

Stensioina beccariiformis (White) = *Rotalia beccariiformis* White, 1928

Stilostomella aculeata (Cushman and Renz) = *Ellipsonodosaria nuttalli* Cushman and Jarvis var. *aculeata* Cushman and Renz, 1948

Stilostomella annulifera (Cushman and Bermudez) = *Ellipsonodosaria annulifera* Cushman and Bermudez, 1936

*Stilostomella fistuca (Schwager) = *Nodosaria fistuca* Schwager, 1866

Stilostomella gracillima (Cushman and Jarvis) = *Ellipsonodosaria nuttalli* Cushman and Jarvis var. *gracillima* Cushman and Jarvis, 1934

Stilostomella lepidula (Schwager) = *Nodosaria lepidula* Schwager, 1866

Stilostomella modesta (Bermudez) = *Ellipsonodosaria modesta* Bermudez, 1937

Stilostomella subspinosa (Cushman) = *Ellipsonodosaria subspinosa* Cushman, 1943

Trifarina wilcoxensis (Cushman and Ponton) = *Pseudouvigerina wilcoxensis* Cushman and Ponton, 1932

Tritaxia amorpha (Cushman) = *Clavulina amorpha* Cushman, 1926

Tritaxia globulifera (ten Dam and Sigal) = *Pseudoclavulina globulifera* ten Dam and Sigal, 1950

Tritaxia paleocenica Tjalsma and Lohmann, 1983

Turrilina brevispira ten Dam, 1944

Uvigerina elongata Cole, 1927

Uvigerina finelineata Keijzer, 1945

*Uvigerina cf. *mantaensis* Cushman and Edwards, 1938

Uvigerina resurgens Boersma, 1984

Vaginulina mexicana Nuttall, 1932

Vulvulina mexicana Nuttall = *Vulvulina pectinata* Hantken var. *mexicana* Nuttall, 1930

Vulvulina spinosa Cushman, 1927

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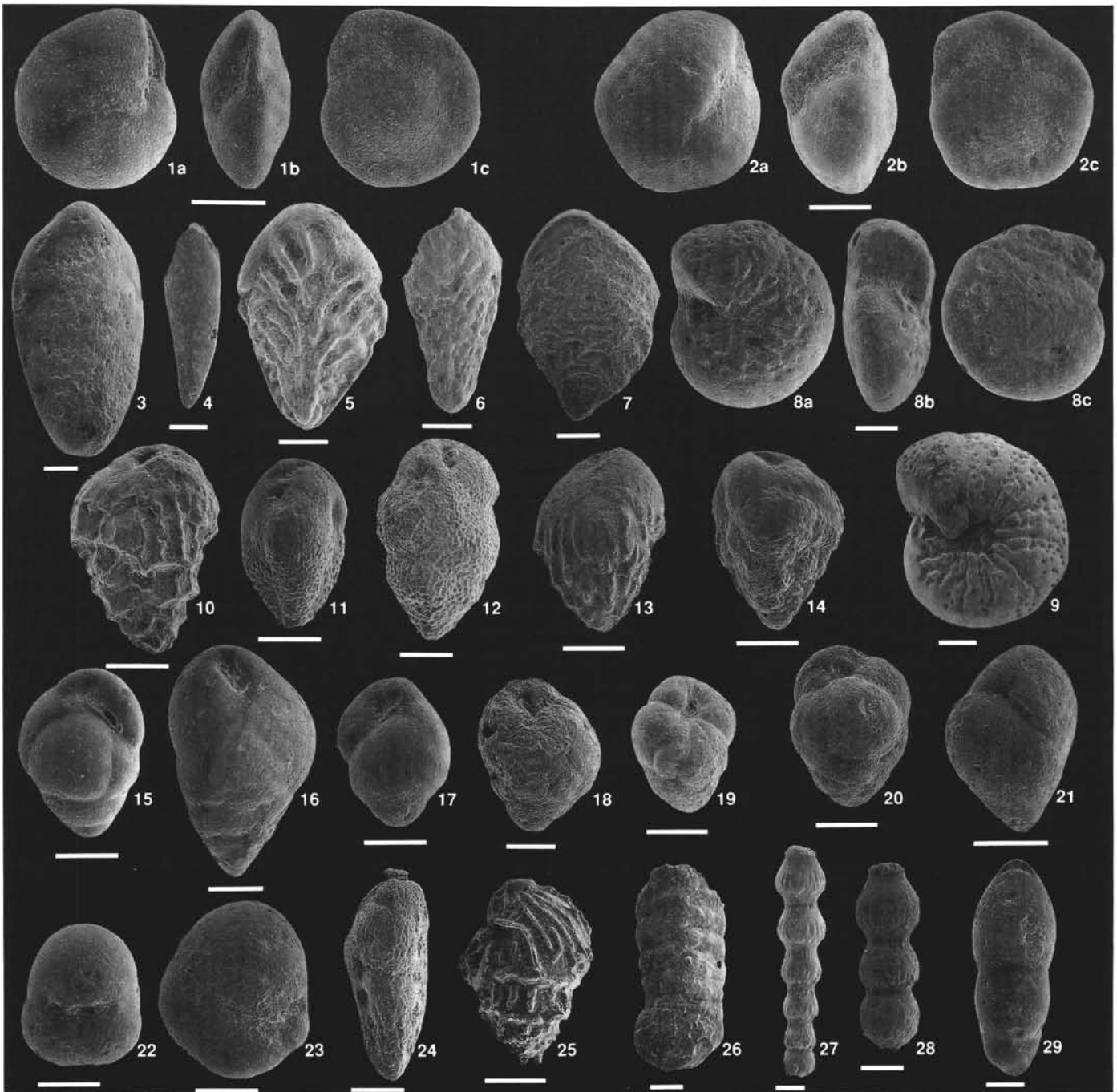
Plate 1. (Scale bar = 100 μm.) **1a–c.** *Alabamina dissonata* (Cushman and Renz). Sample 121-752A-13X-1, 70–75 cm. **2a–c.** *Alabamina creta* (Finlay). Sample 121-752A-33X-1, 68–71 cm. **3.** *Coryphostoma incrassata* (Reuss). Sample 121-752B-11R-1, 44–47 cm. **4.** *Coryphostoma midwayensis* (Cushman). Sample 121-752A-26X-5, 97–100 cm. **5.** *Bolivinoides draco* (Marsson). Sample 121-752B-14R-5, 62–65 cm. **6.** *Bolivinoides delicatulus* (Cushman). Sample 121-753A-21X-1, 70–75 cm. **7.** *Aragonia aragonensis* (Nuttall). Sample 121-752B-8R-6, 101–104 cm. **8a–c, 9.** *Stensioina beccariiformis* (White). Sample 121-752A-27X-1, 70–75 cm. **10.** *Bulimina trinitatensis* Cushman and Jarvis. Sample 121-752A-16X-1, 70–75 cm. **11.** *Bulimina triangularis* Cushman and Parker. Sample 121-752B-19R-3, 49–52 cm. **12.** *Bulimina bradbury* Martin. Sample 121-752B-19R-3, 49–52 cm. **13.** *Bulimina macilenta* Cushman and Parker. Sample 121-752A-15X-5, 70–75 cm. **14.** *Pyramidina* sp. Sample 121-752A-21X-1, 70–75 cm. **15.** *Turrilina brevispira* ten Dam. Sample 121-752A-13X-4, 62–67 cm. **16.** *Praebulimina navarroensis* (Cushman and Parker). Sample 121-752A-21X-1, 70–75 cm. **17.** *Buliminella* sp. 1. Sample 121-752B-11X-3, 112–114 cm. **18.** *Praebulimina* sp. 2. Sample 121-752A-19X-3, 75–79 cm. **19.** *Buliminella grata* (Parker and Bermúdez). Sample 121-752A-22X-3, 70–75 cm. **20.** *Praebulimina* sp. 1. Sample 121-752A-21X-1, 70–75 cm. **21.** *Praebulimina* sp. B. Sample 121-752B-16R-3, 136–138 cm. **22.** *Allomorphina* sp. Sample 121-752B-7R-5, 76–78 cm. **23.** *Quadrimorphina allomorphinoides* (Reuss). Sample 121-752B-7R-1, 82–85 cm. **24.** *Trifarina wilcoxensis* (Cushman and Ponton). Sample 121-752A-11H-1, 70–75 cm. **25.** *Uvigerina* sp. Sample 121-752A-11H-1, 70–75 cm. **26.** *Spiroplectammina spectabilis* (Grzybowski). Sample 121-752A-27X-1, 70–75 cm. **27, 28.** *Stilostomella gracillima* (Cushman and Jarvis). Samples 121-752A-23X-1, 54–56 cm, and 121-752A-26X-5, 97–100 cm. **29.** *Ellipsoidella* sp. A. Sample 121-752B-5R-3, 50–53 cm.
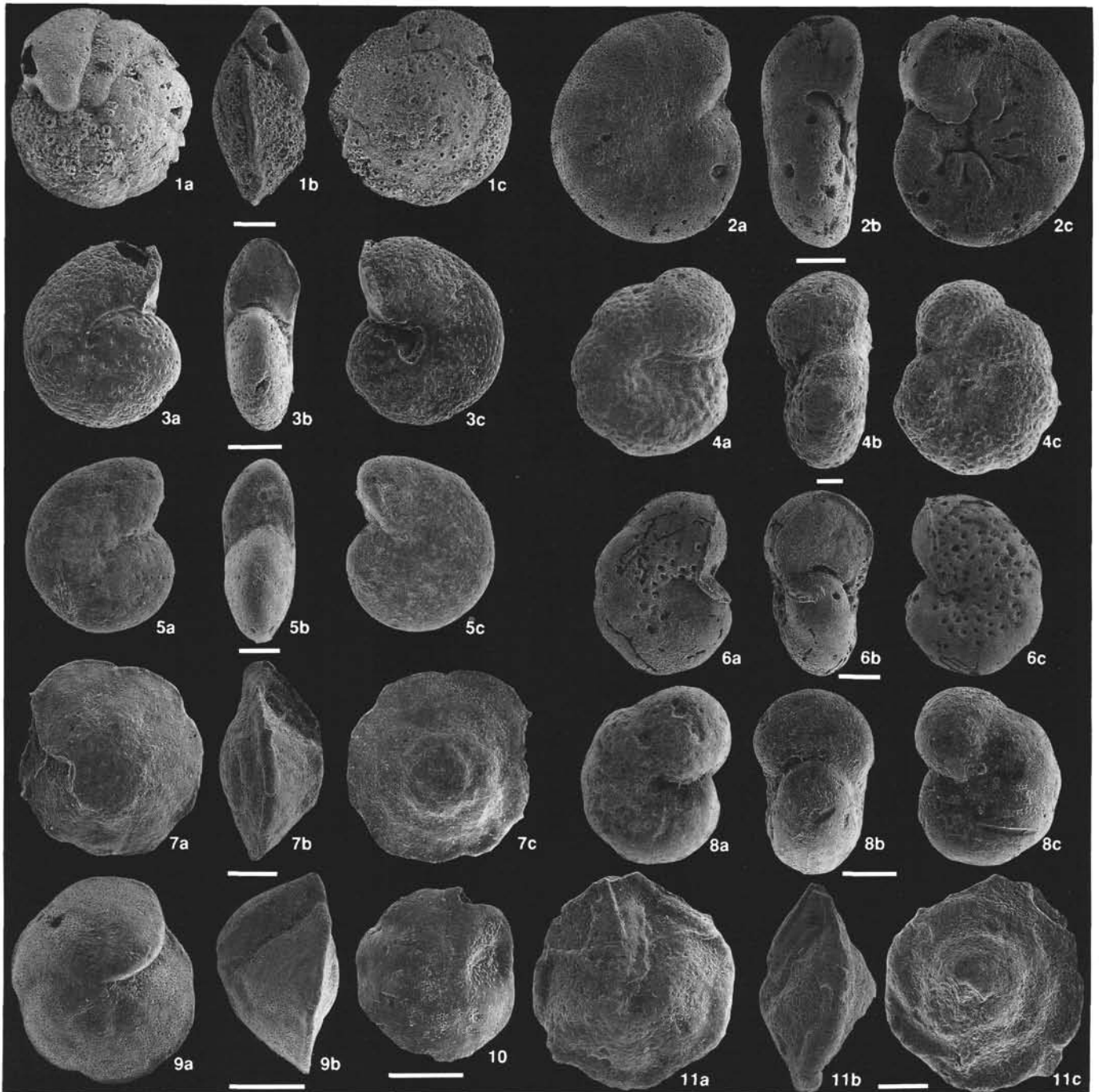
Plate 2. (Scale bar = 100 μm) **1a–c.** *Cibicidoides truncanus* (Gümbel). Sample 121-752A-11H-5, 70–75 cm. **2a–c.** *Hanzawaia ammophila* (Gümbel). Sample 121-742A-11H-5, 70–75 cm. **3a–c.** *Anomalinoides spissiformis* (Cushman and Stainforth). Sample 121-752A-15X-1, 70–75 cm. **4a–c.** *Anomalinoides danicus* (Brotzen). Sample 121-752A-32X-1, 70–75 cm. **5a–c.** *Anomalinoides praeacuta* (Vasilenko). Sample 121-752B-12R-1, 104–107 cm. **6a–c.** *Anomalinoides pseudogrosserugosus* (Colum). Sample 121-752A-10H-1, 70–75 cm. **7a–c, 9a–b, 10.** *Nuttallides truempyi* (Nuttall) with distinct transparent umbilical mass. Sample 121-752A-18X-1, 71–75 cm, *N. truempyi* without umbilical mass. Sample 121-752A-13X-1, 70–75 cm, thin-shaped *N. truempyi*. Sample 121-752A-26X-1, 70–75 cm. **8a–c.** *Anomalinoides semicribratus* (Beckmann). Sample 121-752A-26X-1, 97–100 cm. **11a–c.** *Nuttallinella florealis* (White). Sample 121-752A-19R-3, 49–52 cm.
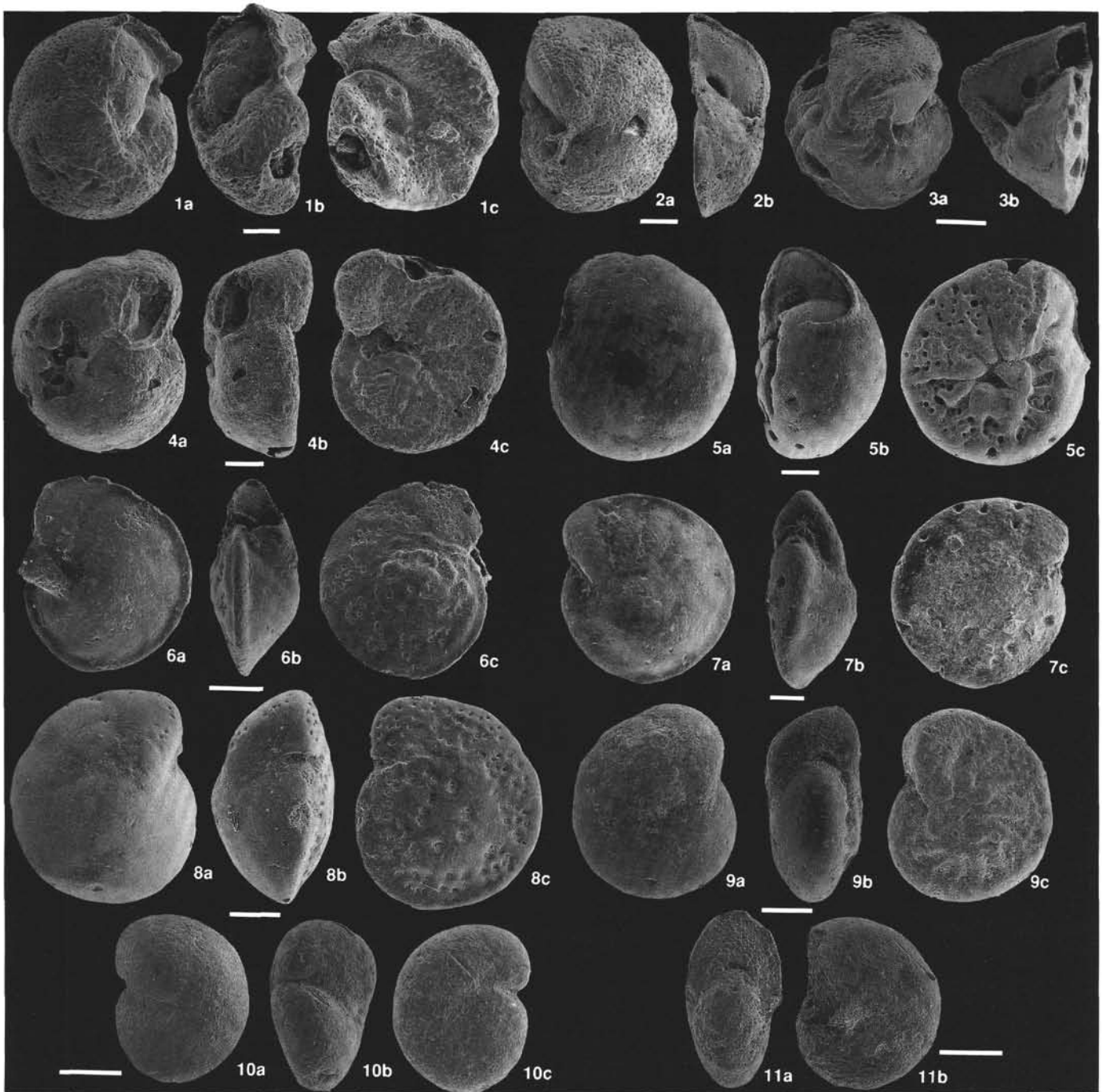
Plate 3. (Scale bar = 100 µm) **1a–c.** *Cibicides* cf. *ribbingi* Brotzen. Sample 121-752B-17R-5, 66–69 cm. **2a–b.** *Cibicidina walli* Bandy. Sample 121-752A-11H-5, 70–75 cm. **3a–b.** *Cibicidoides* cf. *laurisae* (Mallory). Sample 121-752A-11H-5, 70–75 cm. **4a–c.** *Cibicidoides* cf. *grimsdalei* (Nuttall). Sample 121-752A-20X-1, 70–75 cm. **5a–c.** *Cibicidoides velascoensis* (Cushman). Sample 121-752A-22X-1, 70–75 cm. **6a–c.** *Cibicidoides subspiratus* (Nuttall). Sample 121-752A-13X-4, 62–67 cm. **7a–c.** *Cibicidoides* cf. *pseudoperlucidus* Bykova. Sample 121-752A-28X-5, 70–75 cm. **8a–c.** *Cibicidoides eocaenus* (Gümbel). Sample 121-752A-13X-1, 70–75 cm. **9a–c.** *Cibicidoides hyphalus* (Fisher). Sample 121-752A-26X-1, 97–100 cm. **10a–c.** *Gyroidinoides planulatus* (Cushman and Renz). Sample 121-752A-29X-1, 70–73 cm. **11a–b.** *Nonion havanensis* Cushman and Bermúdez. Sample 121-752A-25X-1, 79–84 cm.
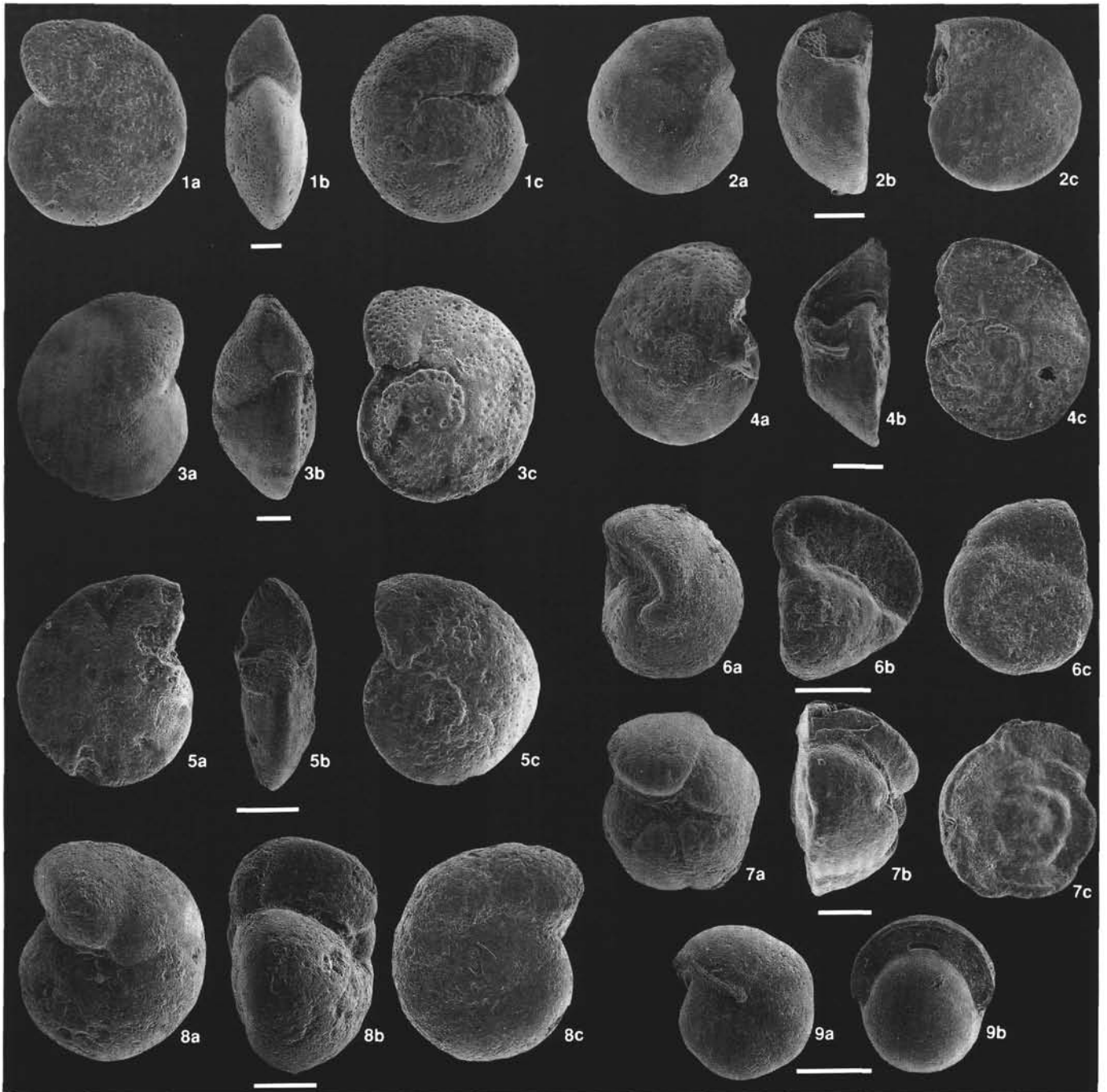
Plate 4. (Scale bar = 100 μm) **1a–c.** *Cibicidoides dayi* (White). Sample 121-752B-14R-1, 69–72 cm. **2a–c.** *Cibididoides* sp. 12. Sample 121-752A-18X-1, 71–75 cm. **3a–c.** *Cibicidoides* sp. 6. Sample 121-752A-18X-1, 71–75 cm. **4a–c.** *Cibicidoides* sp. 5. Sample 121-752A-13X-4, 62–67 cm. **5a–c.** *Gavelinella* sp. Sample 121-752B-7R-5, 76–78 cm. **6a–c.** *Gyroidinoides* sp. 2. Sample 121-752B-7R-5, 76–78 cm. **7a–c.** *Gyroidinoides quadratus* (Cushman and Church). Sample 121-752B-19R-3, 49–52 cm. **8a–c.** *Gyroidinoides globosus* (Hagenow). Sample 121-752A-33X-3, 57–60 cm. **9a–b.** *Pullenia coryelli* White. Sample 121-752A-20X-1, 70–75 cm.
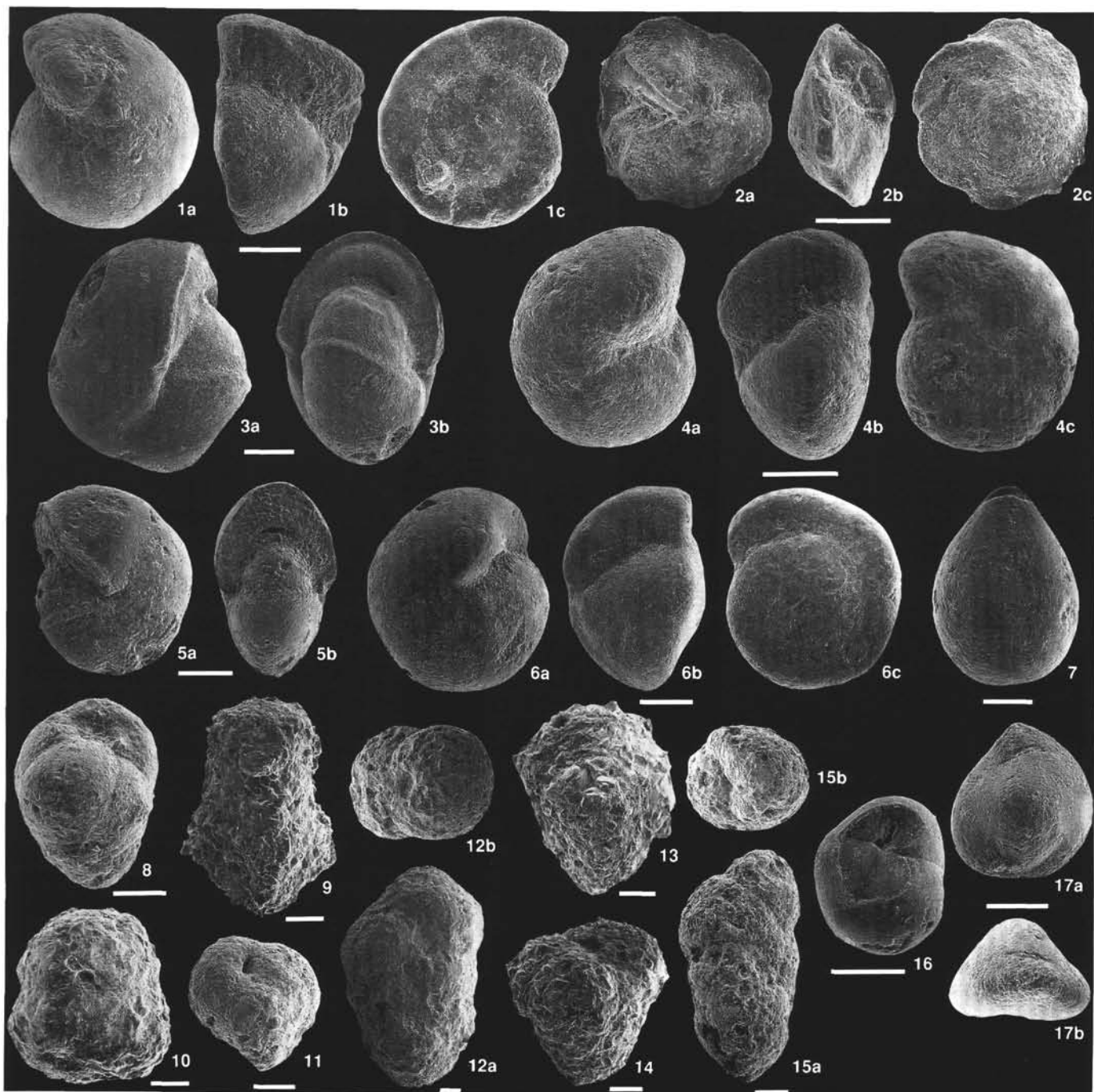
Plate 5. (Scale bar = 100 μm) **1a–c.** *Gyroidina noda* Belford. Sample 121-752B-7R-1, 80–85 cm. **2a–c.** *Globorotalites conicus* Carsey. Sample 121-752B-12R-3, 10–13 cm. **3a–b.** *Pullenia eocenica* Cushman and Siegfus. Sample 121-752A-16X-1, 70–75 cm. **4a–c.** *Gyroidinoides* cf. *excertus* (Belford). Sample 121-752B-10R-4, 79–81 cm. **5a–b.** *Pullenia americana* Cushman. Sample 121-752A-19X-1, 70–75 cm. **6a–c.** *Oridorsalis* sp. 1. Sample 121-752A-29X-1, 70–73 cm. **7.** *Ellipsoidina ellipsoides* Seguenza. Sample 121-752B-10R-1, 105–108 cm. **8.** *Gravelinella* sp. Sample 121-752A-15X-5, 70–75 cm. **9.** *Tritaxia globulifera* (ten Dam and Sigal). Sample 121-752A-26X-5, 97–100 cm. **10.** *Ammosphaeroidina* sp. Sample 121-752A-32X-1, 70–75 cm. **11.** *Gaudryina pyramidata* Cushman. Sample 121-752A-22X-1, 70–75 cm. **12a–b.** *Remesella variance* (Glaesser). Sample 121-752B-8R-6, 101–104 cm. **13.** *Tritaxia paleocenica* Tjalsma and Lohman. Sample 121-752A-26X-1, 97–100 cm. **14.** *Eggerella* sp. Sample 121-752A-27X-1, 70–75 cm. **15a–b.** *Dorothia bulletta* (Carsey). Sample 121-752B-14R-1, 69–72 cm. **16.** *Globocassidulina globosa* (Hantken). Sample 121-752A-15X-5, 112–115 cm. **17a–b.** *Guttulina* cf. *trigonula* (Reuss). Sample 121-752B-7R-1, 82–85 cm.

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