

The Paleocene–Eocene transition in the Antarctic Indian Ocean: Inference from planktic foraminifera

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ABSTRACT

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Isotopic depth stratification and relative abundance studies of planktic foraminifera at ODP Site 738 reveal three major faunal turnovers during the latest Paleocene and early Eocene, reflecting the climatic and structural changes in the Antarctic surface ocean.

Faunal Event 1 occurred near the Paleocene/Eocene boundary and is characterized by a faunal turnover in deep dwellers, decreased relative abundance in intermediate dwellers and increased relative abundance in surface dwellers. This event marks a temporary elimination of the vertical structure in the surface ocean over a period of more than 63,000 years that is apparently associated with the sudden shutdown of the “Antarctic Intermediate Water” production. The appearance of morozovellids before this event suggests that polar warming is the cause for the shutdown in the production of this water mass. At this time warm saline deep water may have formed at low latitudes.

Faunal Event 2 occurred near the AP5a/AP5b Subzonal boundary and is characterized by a faunal turnover in deep dwellers with no apparent change in surface and intermediate dwellers. Increased individual size, wall-thickness and relative abundance in deep dwelling chiloguembelinids suggests the formation of a deep oxygen minima in the Antarctic Oceans during the maximum polar warming possibly as a result of upwelling of nutrient-rich deep water.

Faunal Event 3 occurred in Subzone AP6 and is characterized by a faunal turnover in surface dwellers and a delayed diversification in deep dwellers. This event marks the onset of Antarctic cooling. A drastic decrease in the $\delta^{13}\text{C}/\delta^{18}\text{O}$ values of the deep assemblage in Zone AP7 suggests an intensified thermocline and reduced upwelling following the polar cooling.

Introduction

The latest Maestrichtian to early Paleocene global cooling trend was terminated by a remarkable warming during the latest Paleocene to early Eocene (e.g., Shackleton and Kennett, 1975; Savin et al., 1975). Current studies show that this warming was characterized by: (1) unusual surface warming in high latitudes (Stott et al., 1990; Barrera and Huber, 1991) while low latitude sea surface temperatures remained largely unchanged (Shackleton et al., 1985; Miller et al., 1987); (2) intensive deep water warming in low and high lati-

tudes (Shackleton and Kennett, 1975; Miller et al., 1987; Kennett and Stott, 1990; Barrera and Huber, 1991); (3) a mass extinction in benthic foraminifera in low and high latitudes (Miller et al., 1987; Thomas, 1989, 1990; Kaiho, 1991); and (4) the proliferation of terrestrial thermophilic species into high latitudes (Wolfe, 1978). A significant reduction in both meridional and vertical temperature gradients accompanied this early Eocene warming and is believed to have had a substantial influence on global climate and oceanography (Kennett and Stott, 1990, 1991; Thomas, 1989, 1990, 1991;

Barron, 1987; Barron and Peterson, 1991; Herbert and Sarmiento, 1991).

Within this long-term trend, a distinct short-term event near the Paleocene/Eocene boundary has been observed in benthic foraminiferal studies as well as stable isotopic measurements. This short-term event is characterized by an abrupt negative excursion in $\delta^{13}\text{C}$ values of 5‰ in planktic foraminiferal tests and 3‰ in benthic foraminiferal tests at the Antarctic Atlantic Ocean ODP Site 690 (Kennett and Stott, 1990, 1991). This excursion coincides with a major benthic foraminiferal extinction (Thomas, 1989, 1990, 1991; Kennett and Stott, 1990, 1991). Since the documentation of this $\delta^{13}\text{C}$ excursion by Kennett and Stott (1990, 1991), it has been found elsewhere in the world oceans, including a 3‰ excursion in the Antarctic Indian Ocean ODP Site 738 in both planktic and benthic foraminifera (Barrera and Keller, 1991), a 3‰ excursion in the southern Atlantic Ocean DSDP Sites 525 and 527 of benthic foraminifera and bulk sediments (Thomas, 1991), a 2‰ excursion in the mid-latitude eastern Indian Ocean ODP Site 762 of planktic foraminifera (Kennett, 1991), and a 1‰ excursion in the northern low latitude Pacific Ocean DSDP Site 577 and northern Atlantic Ocean DSDP Site 401 of benthic foraminifera (Pak et al., 1991; Pak and Miller, 1992). The estimated duration for the $\delta^{13}\text{C}$ excursion ranges from 3 kyr (Kennett and Stott, 1991; Stott, 1991) to less than 100 kyr (Miller, 1991) across latitudes.

Low extinction rates of marine plankton during the Paleocene–Eocene transition has led most efforts towards benthos for signals of climatic and oceanographic changes (e.g., Kennett and Stott, 1990, 1991; Thomas, 1989, 1990, 1991). In this paper, however, we show that high resolution relative abundance studies in conjunction with isotopic depth stratification of planktic foraminifera is an efficient approach to separate noise from environmental signals in the surface ocean. By employing this approach at the Antarctic Indian Ocean

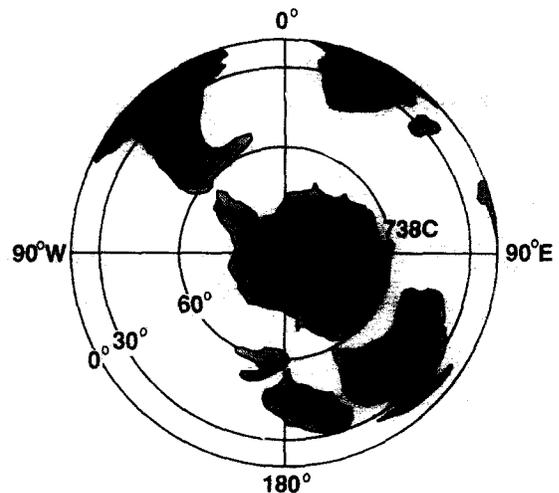


Fig. 1. Late Paleocene (59 Ma) paleogeography of the southern hemisphere with location of ODP Site 738. Dark shading indicates continents above sea level.

ODP Site 738, we found three major faunal turnovers that coincide with major $\delta^{18}\text{O}$ and/or $\delta^{13}\text{C}$ excursions during the latest Paleocene to early Eocene. These faunal turnovers indicate that there are significant oceanographic changes in the surface ocean during the Paleocene–Eocene transition.

Materials and methods

Sediment samples are from the Antarctic Indian Ocean ODP Site 738 located on the southern end of the Kerguelen Plateau (Fig. 1; $62^{\circ}42.54'$ S, $82^{\circ}47.25'$ E) at a present water depth of 2252 m (Barron et al., 1989). This location is north of the modern Antarctic Divergence and near the southern limit of influence of the Antarctic Circumpolar Current. The Polar Front, which separates the cold Antarctic surface water from the warmer Subantarctic surface water, is more than 1500 km to the north. With only a constricted deep water passage separating it from East Antarctica, this site is ideal to monitor the southern high latitude climatic changes and the corresponding fluctuations of the Antarctic water masses. The paleo-latitude of Site 738 is considered un-

Core-section-cm	11R2-002	11R2-009	11R2-020	11R2-031	11R2-040	11R2-044	11R2-052	11R2-059	11R2-061	11R2-074	11R2-100	11R2-143	11R3-015	11RCC	13RCC	14RCC
Mbsf	284.93	285.00	285.11	285.22	285.31	285.35	285.43	285.50	285.52	285.65	285.91	286.34	286.56	286.70	302.75	312.33
Age (Ma)	57.40	57.40	57.41	57.42	57.42	57.43	57.43	57.44	57.44	57.45	57.47	57.50	57.51	57.52	58.68	59.37
<i>Acarinina acarinata</i>	9	30	16	16	25	13	13	7	21	16	25	11	5	11	4	9
<i>A. bullbrooki</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. broedermanni</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. cf. pseudotopilensis</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. collactea</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. decepta</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. esnaensis</i>	3	4	6	11	5	4	-	1	-	-	-	-	1	1	-	-
<i>A. hispidicidaris</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. interposita</i>	5	1	4	5	2	3	-	1	2	2	1	-	2	3	-	-
<i>A. mekannal</i>	-	-	-	-	-	-	-	-	-	2	-	3	1	6	7	-
<i>A. nitida</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. peniacamerata</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. praepeniacameralae</i>	2	1	3	2	3	3	-	3	3	2	3	3	5	1	1	-
<i>A. primitiva</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. pseudotopilensis</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. soldadoensis</i>	4	-	3	2	5	1	1	3	1	4	3	4	5	3	-	-
<i>A. spinulioinflata</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. strabocella</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. subsphaerica</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>A. triplex</i>	5	6	-	2	1	2	-	-	-	-	-	-	-	-	-	-
<i>A. wilcoxensis</i>	2	2	1	1	-	1	1	-	-	-	1	-	-	-	1	2
<i>Chiloguembelina crinita</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>C. morsei</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1
<i>C. sp.</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>C. wilcoxensis</i>	4	1	2	2	1	1	1	2	-	-	-	-	-	-	-	-
" <i>Globigerina</i> " <i>aquiensis</i>	18	8	12	16	13	22	12	12	44	37	22	22	1	12	50	60
" <i>G.</i> " <i>chuscapona</i>	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
" <i>G.</i> " <i>prolata</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
" <i>Globorotalia</i> " <i>reissi</i>	5	6	3	4	3	5	5	-	1	6	10	9	20	10	1	-
" <i>G.</i> " <i>tribulosa</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-
<i>Igorina spiralis</i>	-	-	-	-	-	3	-	1	1	1	-	-	-	1	9	4
<i>Morozovella aequa</i>	2	1	2	2	2	1	-	-	-	-	-	-	-	-	-	-
<i>M. apenthesma</i>	4	2	7	-	3	1	1	-	1	-	-	-	-	-	-	-
" <i>M.</i> " <i>convexa</i>	-	-	2	-	1	5	1	-	2	4	12	14	25	13	-	-
<i>M. gracilis</i>	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-
<i>M. nicoli</i>	-	-	1	1	-	-	-	-	-	-	2	1	3	-	-	-
<i>M. subbotinae</i>	-	4	2	1	-	-	-	-	-	-	-	-	-	-	-	-
<i>Planorotalites</i> sp. 1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>P. sp. 2</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>P. australiformis</i>	1	-	-	1	-	1	-	-	-	-	-	-	-	-	-	-
<i>P. cf. pseudomenardi</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>P. chapmani</i>	1	-	-	2	1	1	-	-	-	-	-	-	-	-	-	-
<i>P. hansbolli</i>	1	-	1	2	1	1	-	-	1	2	1	2	1	3	3	3
<i>P. membranacea</i>	-	1	-	1	1	-	-	-	-	-	-	-	-	-	-	-
<i>P. perclara</i>	1	-	1	1	2	-	-	1	1	1	1	5	3	2	1	4

TABLE 2
Stable isotope measurements of planktic foraminifera in the latest Paleocene and early Eocene, ODP Site 738

Samples	Max. diam (micron)	05R1-078	07R1-145	07R2-104	08R1-132	09R1-026	11R1-015	11R1-060
		$\delta^{18}\text{O}$ $\delta^{13}\text{C}$						
Rounded acarininids								
<i>A. acarinata</i>	420 ± 50				-1.14 2.21	-1.36 2.72	-1.07 2.73	-0.90 2.81
<i>A. interposita</i>	425 ± 50						-0.91 2.54	
<i>A. nitida</i>	440 ± 50						-1.19 2.99	-0.83 2.72
<i>A. soldadoensis</i>	450 ± 50							-0.95 3.23
<i>A. triplex</i>	445 ± 50				-0.97 2.16	-1.20 2.29	-1.15 2.80	-0.74 2.95
Angulate acarininids								
<i>A. bullbrookii</i>	410 ± 30	-0.59 2.34	-0.90 2.25	-0.79 2.25	-1.04 2.31			
<i>A. broedermanni</i>	245 ± 20	-0.79 2.15						
<i>A. cf. pseudotopilensis</i>	385 ± 25	-0.76 2.17	-0.77 1.63	-0.34 1.14				
<i>A. collactea</i>	250 ± 30	-0.54 2.00	-0.50 1.88	-0.72 1.90				
<i>A. hispidicidaris</i>	405 ± 40	-0.48 2.17						
<i>A. pentacamerata</i>	415 ± 30	-0.97 2.61	-0.65 2.03	-0.72 2.12				
<i>A. primitiva</i>	435 ± 40	-1.02 2.71		-1.26 2.81				
<i>A. pseudotopilensis</i>	420 ± 40		-0.81 2.13	-0.70 1.64	-1.01 2.32	-1.29 2.00		
<i>A. wilcoxensis</i>	415 ± 35				-1.00 2.24	-0.91 1.71		
Planorotalitids-pseudohastigerinids								
<i>P. australiformis</i>	265 ± 25	-0.19 1.20	-0.57 1.20	-0.68 1.16				
<i>P. cf. pseudomenardii</i>	280 ± 25	-0.17 1.23	-0.54 1.13					
<i>P. pseudochapmani</i>	300 ± 25	-0.67 1.40						
<i>P. pseudomitata</i>	295 ± 30							
<i>P. pseudomenardii</i>	290 ± 25						-0.35 1.64	-0.43 0.97
<i>P. pseudoscitula</i>	295 ± 25	-0.39 1.13					-0.39 1.51	-0.40 1.29

Subbotinids-"Turborotaliids"										
<i>S. eocaena</i>	585 ± 50	-0.03	1.36							
<i>S. hagni</i>	425 ± 40	-0.13	1.40							
<i>S. hornibrooki</i>	415 ± 50	-0.03	1.45	-0.01	1.24	-0.31	1.25			
<i>S. linaperta</i>	405 ± 30	-0.19	1.35	-0.11	1.19	-0.24	1.29	-0.38	0.98	
<i>S. pseudoocaena</i>	555 ± 50	-0.28	1.07	-0.32	1.18	-0.35	1.22	-0.22	1.34	
<i>S. triangularis</i>	405 ± 40									-0.53 1.82
<i>S. triloculinoides</i>	395 ± 30									-0.31 1.34
"T", cf. <i>praecentralis</i>	350 ± 25	-0.19	1.24							
"T", <i>praecentralis</i>	325 ± 25	0.00	1.27							
Morozovellids										
<i>M. aequa</i>	405 ± 40							-0.92	2.76	
<i>M. gracilis</i>	410 ± 40							-0.96	2.63	
Chilouembelminids										
<i>C. crinita</i>	345 ± 30									-0.14 1.00
<i>C. wilcoxensis</i>	475 ± 40							-0.04	1.10	
"Globigerinids"- "globorotaliids"										
"G", <i>aquiensis</i>	275 ± 25			-0.85	1.65	-0.76	2.16			-0.43 1.88

changed since Cretaceous time (Barron et al., 1989). The estimated depth of this site during the late Paleocene and early Eocene is 1350 m, using normal subsidence rates for oceanic crust (Detrick et al., 1977; Barrera and Huber, 1991).

A total of 67 samples were selected from Site 738 from core 4R to 14R with an average sample interval of 25 cm, and closer sampling across critical intervals. The sediments consist mainly of calcareous nannofossil-foraminiferal chalk with a 20 cm thick clay layer in core 11R. Although sediment recovery was poor, averaging only 30%, three major faunal turnovers are observed within the continued coring intervals.

Samples were disaggregated in water and washed through a 63 μm sieve. This procedure was repeated until foraminifers with clean surface textures were recovered. Preservation of planktic foraminifers is generally excellent. Recrystallization is light. Carbonate dissolution was only found at the base of the clay layer in core 11R which marks a deep-sea hiatus near the Paleocene/Eocene boundary as discussed below.

Population counts are based on random splits (using an Otto microsampler) of 300 or more specimens in the size fraction $> 106 \mu\text{m}$. All specimens were picked, identified and mounted on microslides for a permanent record. Relative abundances of the picked specimens are listed in Table 1. The smaller size fraction (63–106 μm) was also examined, but was found to be impractical for quantitative studies because of the large number of juveniles that could not be identified to species.

The general classification in this study follows the framework discussed by Loeblich and Tappan (1987). Species identification was based on the observations of Subbotina (1953), Bolli (1957), Loeblich and Tappan (1957), Jenkins (1971) and Blow (1979) as well as the southern high latitude studies by Stott and Kennett (1990) and Huber (1991).

Common species are illustrated in Plates I–

V. These plates were assembled by SEM digital images. Raw images were collected by IMIX digital image system connecting to a SEM and then run through some image processing programs that are convenient to the personal computers we worked on. Individual images were sharpened and adjusted in their size, contrast and brightness, and assembled into plates. Digital SEM images are more flexible and provide more control than conventional polaroid photos.

For oxygen and carbon stable isotopic analysis of depth stratification of planktic foraminiferal species, average-sized adult tests for each species were picked with 20–30 individuals per species (Table 2). Measurements were conducted at the Stable Isotope Laboratory of the University of Michigan. Samples were reacted with anhydrous phosphoric acid at 55°C in an on-line gas extraction line coupled to the inlet of a VG602E mass spectrometer, or were reacted individually at 70°C in a Kiel device and analyzed in a Finnigan 261 mass spectrometer. The data are reported in values referenced to PDB through the carbonate standard NBS20. Analytical error was $\pm 0.05\text{‰}$ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$.

Biostratigraphy

Planktic foraminiferal zonal schemes are available for both low and high latitudes. The major low latitude biostratigraphic zonations are those by Berggren (1969), Premoli Silva and Bolli (1973), Stainforth et al. (1975), Blow (1979), Toumarkine and Luterbacher (1985) and Berggren and Miller (1988). Southern high latitude zonations have been proposed by Jenkins (1971) for the Subantarctic Pacific Ocean and by Stott and Kennett for the Antarctic Atlantic Ocean (1990). We found that the Antarctic zonation by Stott and Kennett (1990) was most applicable to Site 738. These zonal schemes including the modifications proposed in this study are illustrated in Fig. 2.

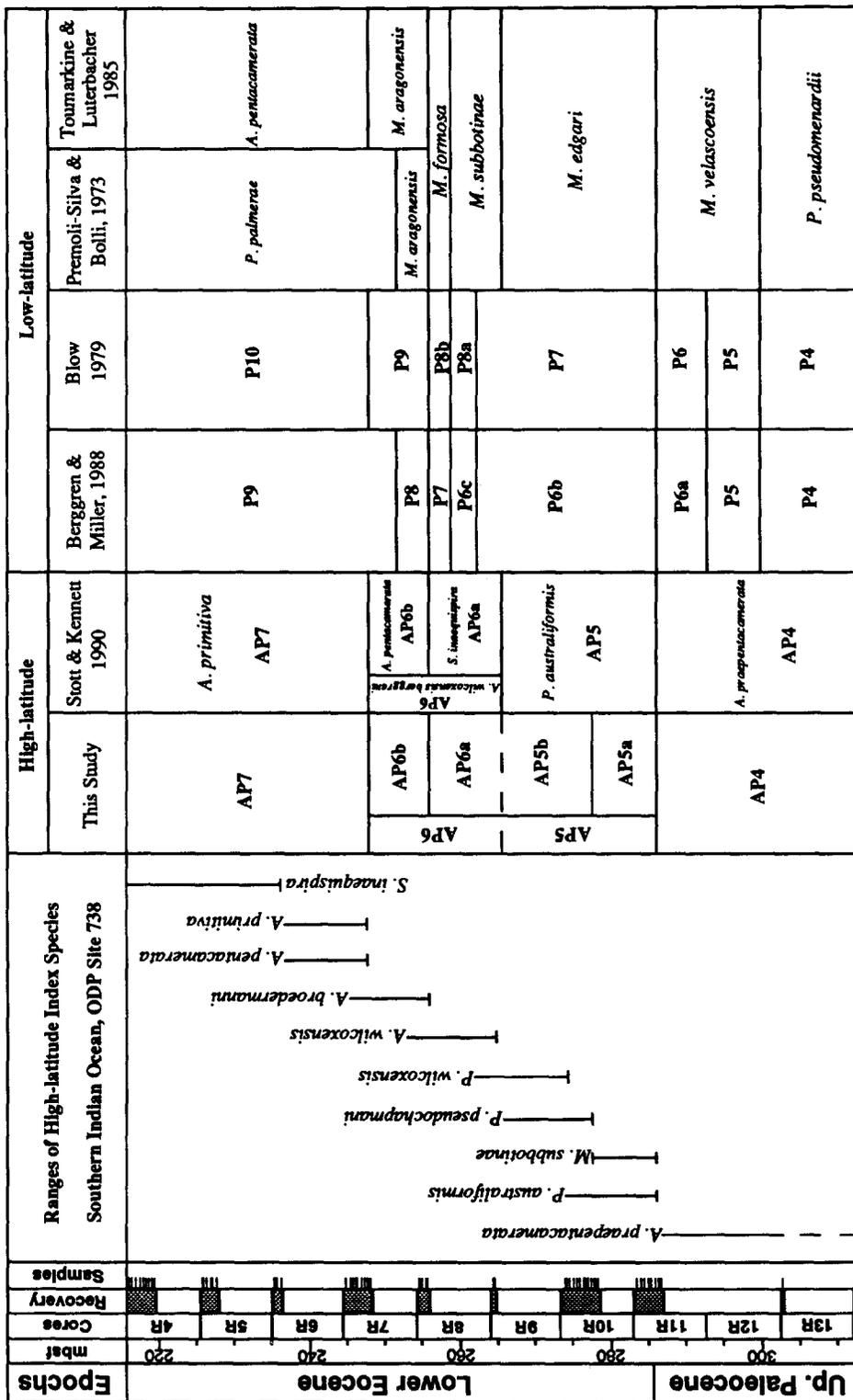


Fig. 2. Biostratigraphic zonation of this study and the correlation with published high and low latitude zonations. Correlation between the low and high latitude zonations is primarily based on Stott and Kennett (1990), short-term isotopic excursion and benthic foraminiferal extinction.

Ranges of planktic foraminiferal species at Site 738 are illustrated in Fig. 3. These species ranges indicate that existing low latitude biostratigraphic zonations can not be applied to Antarctic Ocean sequences because most low latitude index species are either absent or diachronous in their first and last occurrences. In addition, the ranges of major morozovellid and planorotalitid species in the Antarctic region are restricted to the lower part of the lower Eocene and are associated with the southward expansion of subtropical faunas during maximum global warming. Although Stott and Kennett's (1990) Antarctic zonation provides a base for the Antarctic Indian Ocean biostratigraphy, we have found it necessary to modify some zonal boundaries and subdivide some biozones as discussed below and illustrated in Figs. 2 and 3.

High latitude zonation

The upper Paleocene to lower Eocene (AP4 to AP7) biostratigraphic zonation of this study is based on the Antarctic zonation proposed by Stott and Kennett (1990) and modified as described below.

Acarinina praepentacamerata Partial Range Zone (AP4)

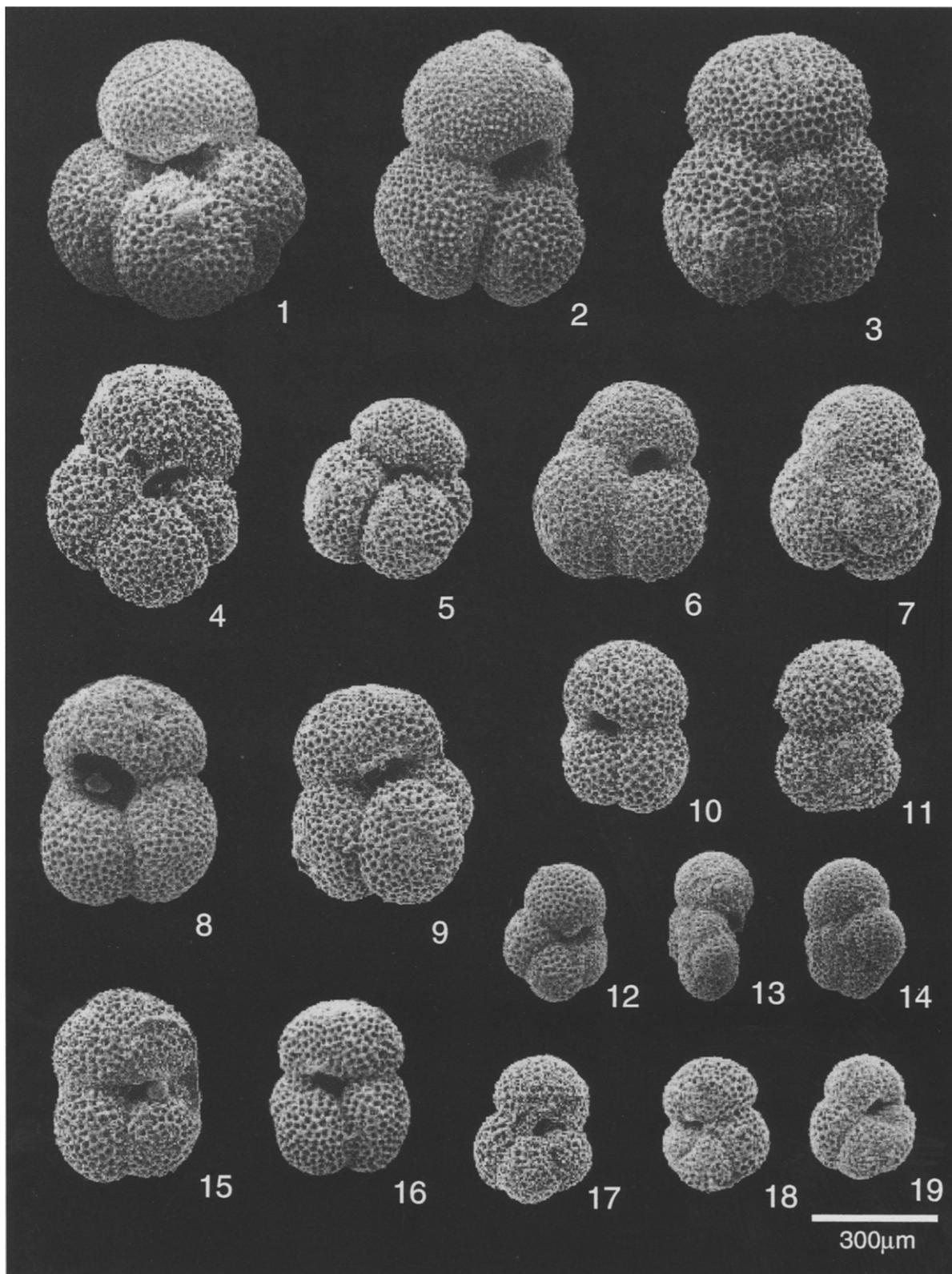
This is the lowermost zone encountered in this study (its lower boundary is below the sample range). The upper zonal boundary is defined by the first appearance datum (FAD) of *Planorotalites australiformis* (Stott and Kennett, 1990; Huber, 1990). At Site 738, the top of Zone AP4 coincides with a hiatus which will be discussed later. The dominant foraminifers within Zone AP4 are subbotinids (e.g., *S. triloculinooides*, *S. triangularis* and *S. varianta*; Plate I, 10, 11 and 17) and rounded acarininids (e.g., *A. acarinata*, *A. soldadoensis*, *A. interposita* and *A. praepentacamerata*; Plate II, 3, 8–13). Planorotalitid taxa (e.g., *P. hansbolli*, *P. perclara* and *P. planoconica*; Plate I,

12–14; Plate IV, 10–11) are present in low relative abundances (<1%), and an influx of "*Morozovella*" *convexa* (Plate III, 16–18) occurs in the uppermost portion of Zone AP4.

Planorotalites australiformis Partial Range Zone (AP5)

The base of this zone is defined by the FAD of *Planorotalites australiformis* and the top by the FAD of *Acarinina wilcoxensis berggreni* (Stott and Kennett, 1990). In this study, however, we found it impractical to separate the subspecies *A. wilcoxensis berggreni* (El Naggari) and *A. wilcoxensis wilcoxensis* Blow. We therefore used the species *A. wilcoxensis* (Cushman and Ponton) instead of the nominate subspecies by Stott and Kennett (1990) to define the top of this zone. At Site 738, the FAD of *A. wilcoxensis* (Plate III, 8) occurs in a unrecovered interval between core 9R and 10R, and the top of Zone AP5 could, therefore, not be determined precisely (Figs. 2 and 3). The most distinct group of planktic foraminifers in this zone are the morozovellid taxa, including the tropical markers *M. subbotinae*, *M. gracilis* and *M. aequa*, which first appear in the uppermost part of Zone AP4 and suddenly disappear in the middle part of Zone AP5 (Fig. 3; Plate IV, 15–19), coeval with the appearance of these taxa observed at Sites 689 and 690 by Stott and Kennett (1990). Zone AP5 is also characterized by a major increase in planorotalitid taxa, including *P. pseudomenardii*, *P. membranacea*, *P. pseudoimitata*, *P. australiformis*, *P. chapmani* and *P. troelseni* which first appear near the lower zonal boundary and increase their relative abundance throughout this zone (Fig. 3; Plate IV, 8–9, 12–13; Plate V, 1–3, 9). Rounded acarininids remain dominant and add some new members, including *A. subsphaerica*, *A. nitida* and *A. triplex* (Plate II, 1–2, 4–7).

The total range of *Planorotalites pseudomenardii* is used to define Zone P4 of the late Paleocene at low latitudes (e.g., Premoli Silva and



Bolli, 1973; Stainforth et al., 1975; Toumarkine and Luterbacher, 1985; Berggren and Miller, 1988). But Blow (1979) has shown that *P. pseudomenardii* could range from P4 (late Paleocene) to P7 (early Eocene) of his zonation (Fig. 2). The *P. pseudomenardii* identified in Subzone AP5a of the early Eocene at Site 738 is almost identical to the type specimen illustrated by Bolli (1957) except for the smaller size, which is true for most high latitude planktic foraminiferal taxa. The appearance of *Morozovella* spp. in Subzone AP5a indicates the proliferation of low latitude species into high latitudes during this period. However, further studies are needed to elucidate whether this taxon is diachronous across latitudes.

The major faunal changes observed within Zone AP5 among morozovellids and planorotalitids provide a basis for subdivision of this zone as discussed below.

Morozovella subbotinae Partial Range Subzone (AP5a)

Definition: Partial range of the nominate taxon between the FAD of *P. australiformis* (base) and the FAD of *Pseudohastigerina pseudochapmani* (top).

Remarks: The most distinct feature of this subzone is the appearance of morozovellid taxa, including the tropical markers *M. aequa*, *M. subbotinae* and *M. gracilis* (Fig. 3). Morozovellids which appear in the uppermost part

of Zone AP4 increase in their relative abundances within Subzone AP5a and disappear near the top of this subzone. Also within this subzone, the planorotalitid group completes its faunal transition from the Paleocene assemblage, represented by low relative abundances of *P. hansbolli*, *P. perclara* and *P. planoconica* in Zone AP4, through a transitional, short-ranged assemblage, represented by high relative abundances of *P. troelseni*, *P. pseudomenardii* and *P. membranacea* in Subzone AP5a and the lowermost part of Subzone AP5b, to the Eocene assemblage, represented by *P. pseudoimitata*, *P. australiformis*, *P. chapmani*, *P. pseudoscitula* and *P. cf. pseudomenardii*. The Eocene assemblage first appears in Subzone AP5a and the lowermost part of Subzone AP5b and dominates in Subzone AP5b. Acariniids and subbotinids show little change in Subzone AP5a whereas chiloguembelinids increase in their relative abundances in Subzone AP5a.

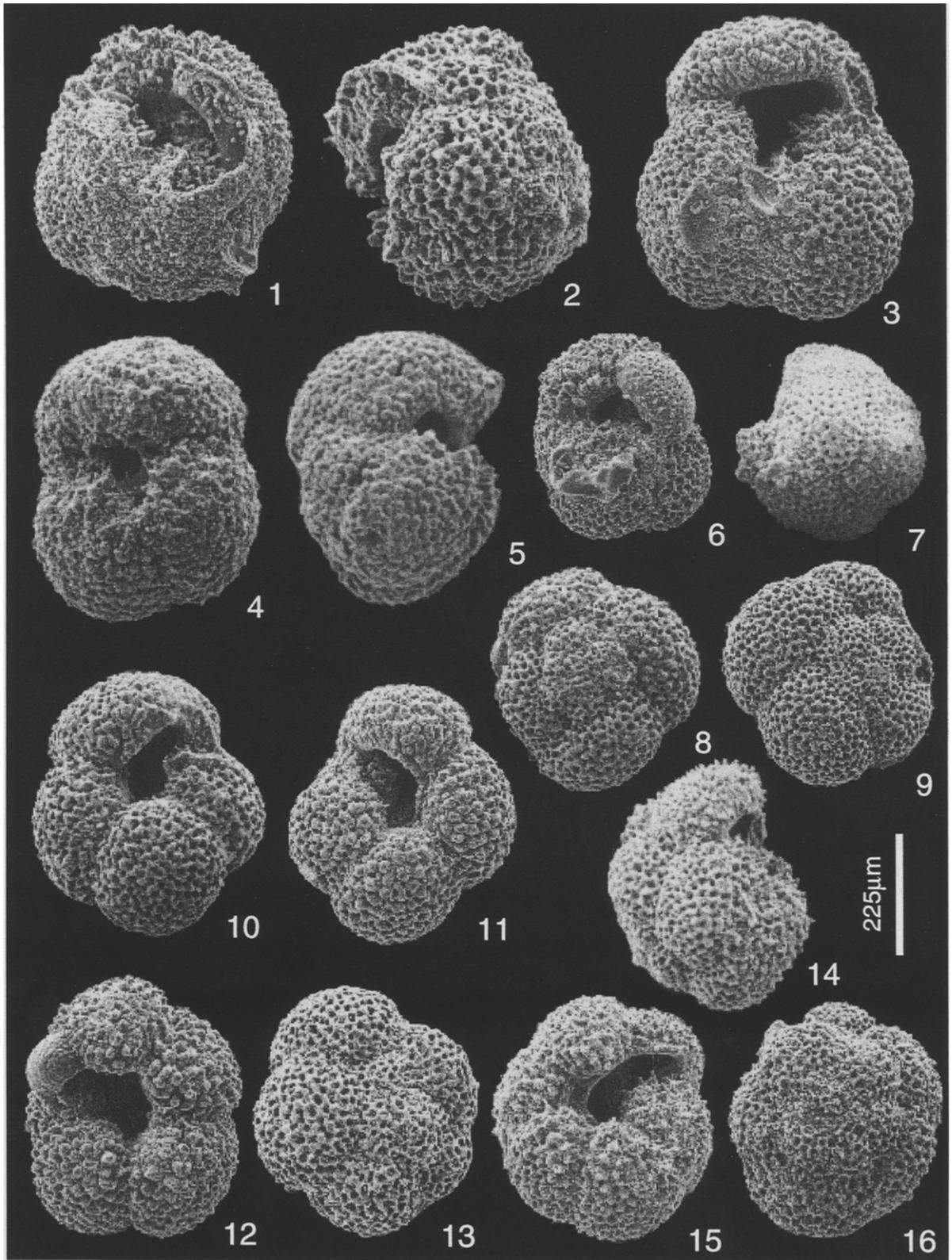
Pseudohastigerina pseudochapmani Partial Range Subzone (AP5b)

Definition: Partial range of the nominate taxon between its FAD (base) and the FAD of *A. wilcoxensis* (top).

Remarks: This interval is marked by the disappearance of morozovellids, the increase in diversity and relative abundance of planorotalitids and pseudohastigerinids, and the maximum relative abundance of chiloguembelinids.

PLATE I

Late Paleocene and early Eocene subbotinids, "turborotaliids" and planorotalitids from ODP Site 738. Scale bar for all figures represents 300 μm . 1. *Subbotina eocaena* (Gumbel), 738C-5R2(57-59). 2-3. *Subbotina pseudoecaena* (Subbotina), 738C-5R2(57-59). 4. *Subbotina inaequispira* (Subbotina), 738C-5R2(57-59). 5. *Subbotina hagni* (Gohrbandt), 738C-5R2(57-59). 6-7. *Subbotina hardingae* (Blow), 738C-9R1(60-62). 8. *Subbotina eocaenica* (Terquem), 738C-9R1(60-62). 9. *Subbotina hornibrooki* (Brönnimann), 738C-9R1(60-62). 10-11. *Subbotina triloculinoides* (Plummer), 738C-13CC(4-6). 12-14. *Planorotalites hansbolli* (Blow), 738C-13CC(4-6). 15. *Subbotina linaperta* (Finlay), 738C-11R1(15-17). 16. "*Turborotalia*" cf. *frontosa* (Subbotina), 738C-5R1(78-80). 17. *Subbotina varianta* (Subbotina), 738C-13CC(4-6). 18. "*Turborotalia*" cf. *praecentralis* (Blow), 738C-5R1(78-80). 19. "*Turborotalia*" *praecentralis* (Blow), 738C-5R1(78-80).



Acarinina wilcoxensis Partial Range Zone (AP6)

The base of this zone is defined by the FAD of *A. wilcoxensis berggreni* (Stott and Kennett, 1990) or *A. wilcoxensis* (Huber, 1991; this study) and the top by the FAD of *Acarinina primitiva* (Stott and Kennett, 1990; Huber, 1991). The zonal interval is characterized by the gradual decrease in relative abundance of rounded acarininids (e.g., *A. acarinata*, *A. soldadoensis*, *A. interposita*, *A. praepentacamerata*, *A. nitida* and *A. triplex*) and the development of angulate acarininids (e.g., *A. strabocella*, *A. wilcoxensis*, *A. pseudotopilensis*, *A. bullbrooki*, *A. broedermanni*, *A. cf. pseudotopilensis* and *A. hispidicidaris*; Plate III, 3–8, 11, 14–15). The replacement of rounded acarininids by angulate acarininids is completed near the upper boundary of this zone.

Stott and Kennett (1990) proposed subdivision of Zone AP6 based on the FAD of *Acarinina pentacamerata*. The first occurrence of this species, however, is diachronous in Site 738 occurring near the base of Zone AP7. We therefore suggest that subdivision of Zone AP6 is based on the FAD of *Acarinina broedermanni*.

Pseudohastigerina wilcoxensis Partial Range Subzone (AP6a)

Definition: Partial range of the nominate taxon between the FAD of *A. wilcoxensis* (base) and the FAD of *Acarinina broedermanni* (top).

Remarks: This subzone is characterized by the replacement of rounded acarininids by angulate acarininids near the upper boundary of

the subzone. The rounded acarininid taxa *A. acarinata*, *A. soldadoensis*, *A. interposita*, *A. praepentacamerata*, *A. nitida* and *A. triplex* decrease in their relative abundances within this interval and disappear at the top. In contrast, angulate acarininid taxa, such as *A. strabocella*, *A. wilcoxensis* and *A. pseudotopilensis*, increase in relative abundance. *Acarinina cf. pseudotopilensis*, *A. hispidicidaris*, *A. bullbrooki* and *A. broedermanni* appear first at/near the top of Subzone AP6a. Chiloguembelids decrease in their relative abundance and essentially disappear within this subzone. Overall Subzone AP6a is characterized by a dramatic decrease in the number of species.

Acarinina broedermanni Partial Range Subzone (AP6b)

Definition: Partial range of the nominate taxon between its FAD (base) and the FAD of *A. primitiva* (top).

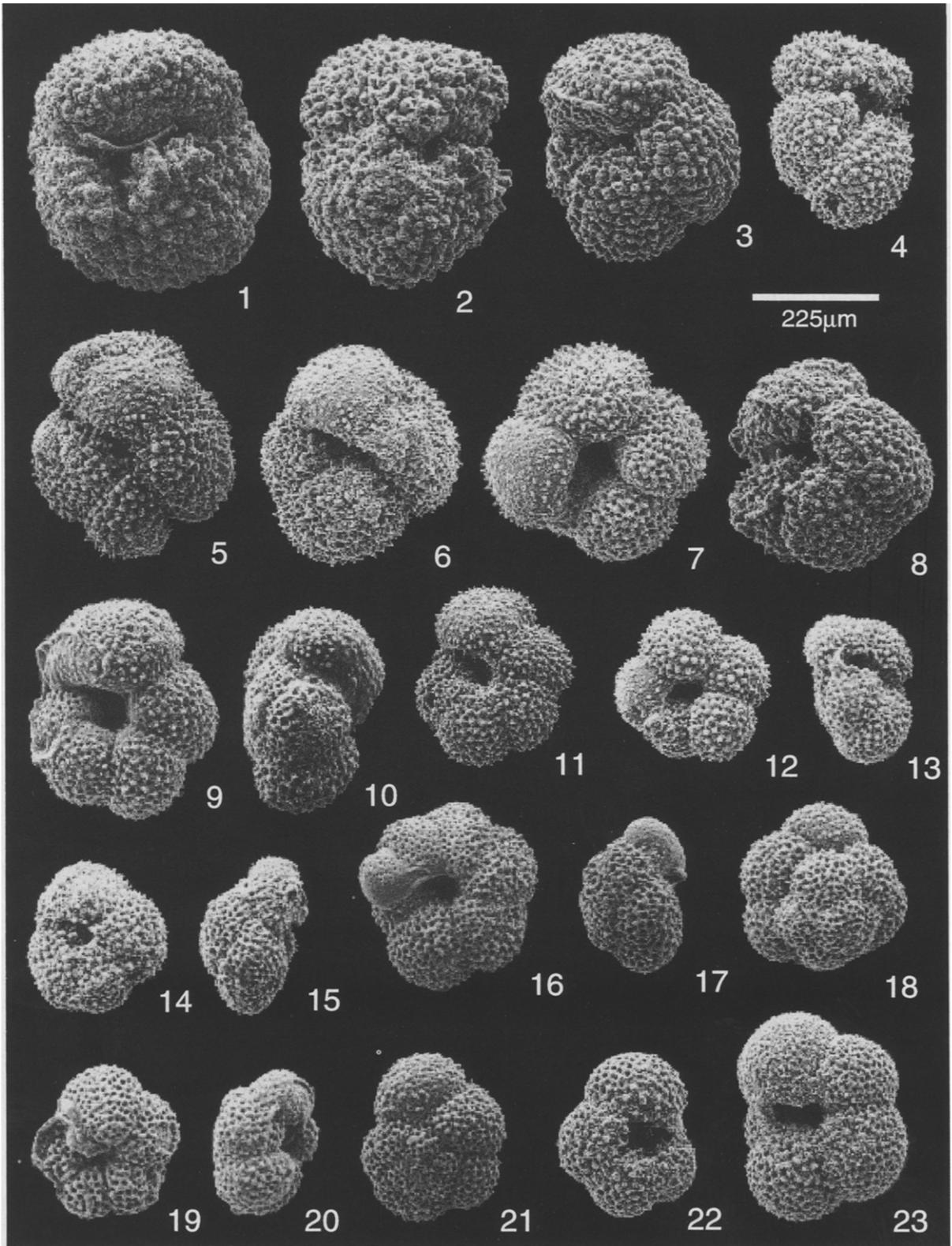
Remarks: This subzone is characterized by the development of angulate acarininids. Other dominant groups are subbotinids and planorotalitids–pseudohastigerinids which show little change across this interval. A new distinct group, “turborotaliids”, first appears within this subzone and becomes important in Zone AP7.

Acarinina primitiva Partial Range Zone (AP7)

Stott and Kennett (1990) defined the base of Zone AP7 by the FAD of *A. primitiva* and the top by the FAD of *A. bullbrooki*. In this study, *A. bullbrooki* appears much earlier in Subzone AP6b. Therefore, this taxon seems inappropriate as the index species to define the

PLATE II

Late Paleocene acarininids from ODP Site 738. Scale bar for all figures represents 225 μm . 1–2. *Acarinina nitida* (Martin), 738C-11R1 (15-17). 3. *Acarinina soldadoensis* (Brönnimann), 738C-11R2 (143-145). 4–5. *Acarinina triplex* Subbotina, 738C-9R1 (60-62). 6–7. *Acarinina subsphaerica* (Subbotina), 738C-11R1 (15-17). 8, 10. *Acarinina acarinata* Subbotina, 738C-11R2 (143-145). 9, 11. *Acarinina interposita* Subbotina, 738C-11R2 (143-145). 12–13. *Acarinina praepentacamerata* (Shutskaya), 738C-11R2 (143-145). 14–16. *Acarinina mckannai* (White), 738C-11RCC (4-6).



top of AP7. Our study interval, however, does not include the top of Zone AP7. At Site 738, this zone is characterized by the first appearance of abundant large subbotinids, including *S. pseudoecaena*, *S. eocaena*, *S. hagni* and *S. inaequispira* (Fig. 3; Plate I, 1–5). The “turborotaliids”, such as “*T*” cf. *praecentralis*, “*T*” cf. *praecentralis*, “*T*” cf. *frontosa* and “*T*” cf. *possagnoensis* (Plate I, 16, 18, 19) become important members of the faunal assemblage. The angulate acarininids continue to increase in diversity and relative abundance whereas planorotalitids decrease gradually in diversity and relative abundance.

Paleocene/Eocene boundary

In low latitude planktic foraminiferal biostratigraphy, the Paleocene/Eocene boundary is identified by the last occurrence of *Morozovella velascoensis* (Berggren, 1969; Premoli Silva and Bolli, 1973; Stainforth et al., 1975; Toumarkine and Luterbacher, 1985; Berggren et al., 1985; Berggren and Miller, 1988) which marks the boundary between Zones P6a and P6b and is dated at 57.7 Ma (Berggren and Miller, 1988). Moreover, the FAD of the first pseudohastigerinid taxon (*P. wilcoxensis*) and the FAD of *Acarinina wilcoxensis berggreni*, which marks the base of Zone P7 in Blow’s scheme (Blow, 1979), are also considered correlative with the last occurrence of *M. velascoensis* and, hence, the Paleocene/Eocene boundary (Jenkins, 1971; Toumarkine and Luterbacher, 1985; Berggren et al., 1985; Berggren and Miller, 1988).

Aubry et al. (1988) suggested that the Paleocene/Eocene boundary was at 57.0 Ma based on revised paleomagnetic calibrations of the low latitude biostratigraphies. The Paleocene/Eocene boundary may thus be higher than the last occurrence of *M. velascoensis*.

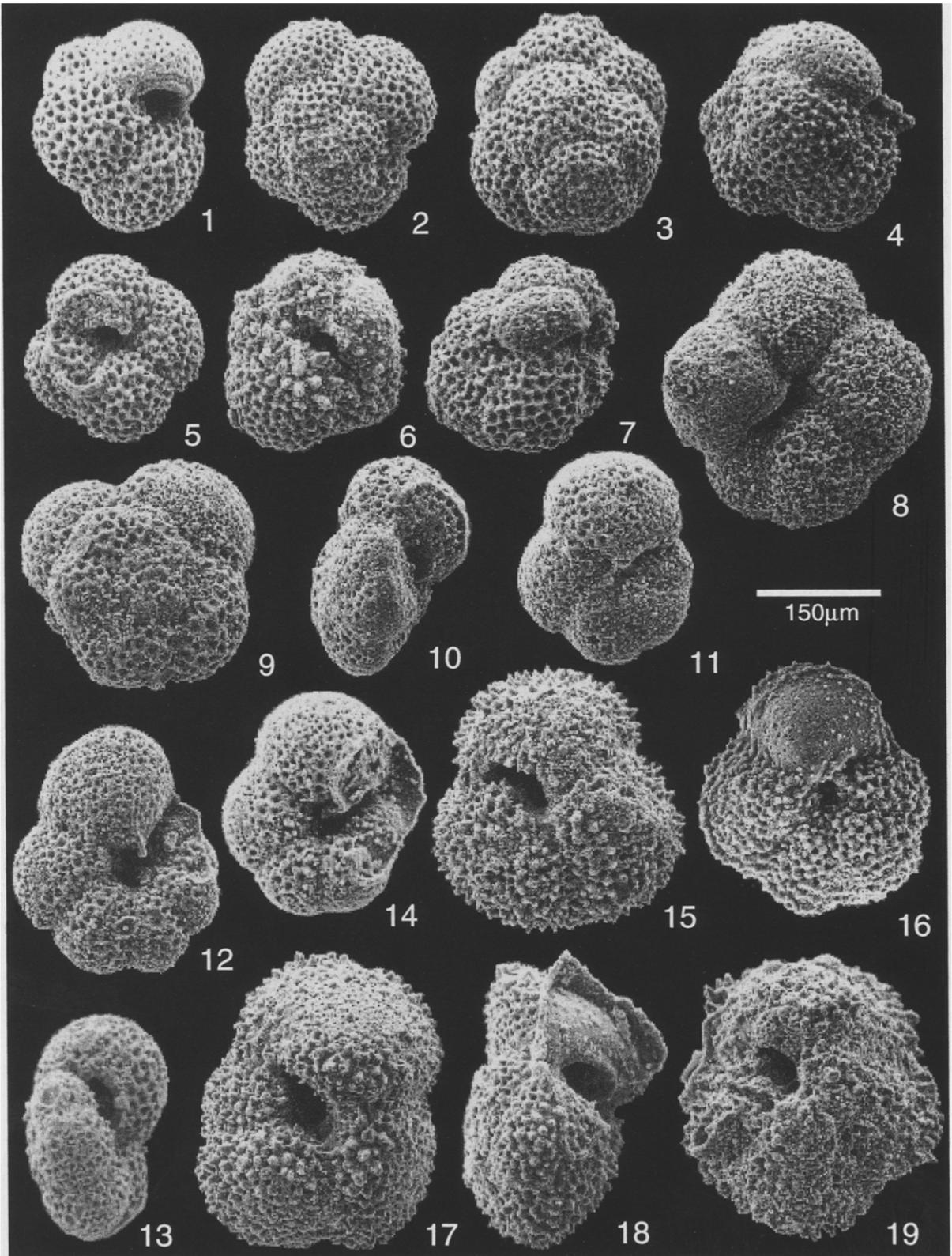
Low latitude index taxa for the Paleocene/Eocene boundary are either absent or diachronous in high latitudes, and high-to-low latitude correlation is difficult. For this reason, Stott and Kennett’s (1990) chronostratigraphic calibration for the Paleocene/Eocene boundary in the Antarctic Atlantic Ocean was based on magnetostratigraphic data. They suggested that the FAD of *Planorotalites australiformis* (which marks the boundary between Zones AP4 and AP5) is close to the magnetostratigraphically defined Paleocene/Eocene boundary in low latitudes. We accept this assessment in this study with further observations on this datum level (the FAD of *P. australiformis*) in the Antarctic Indian Ocean as described below.

Hiatus

The FAD of *P. australiformis* coincides with the base of a 20 cm clay layer at Site 738. The presence of a hiatus at this interval is indicated by (1) the sudden lithologic change from nanofossil–foraminiferal chalk to clay; (2) the strong carbonate dissolution apparent in foraminiferal shells; (3) the suddenly reduced sedimentary carbonate; (4) the sudden increase in the relative abundance of benthic foraminiferal tests (from <5% to >40%) that are more resistant to dissolution than planktic forami-

PLATE III

Late Paleocene and early Eocene acarininids, “globigerinids” and “globorotaliids” from ODP Site 738. Scale bar for all figures represent 225 μm . 1–2. *Acarinina primitiva* (Finlay), 738C-5R2(57-59). 3–4. *Acarinina pseudotopilensis* Subbotina, 738C-9R1(60-62). 5. *Acarinina bullbrooki* (Bolli), 738C-5R2(57-59). 6. *Acarinina spinuloinflata* (Bandy), 738C-5R2(57-59). 7. *Acarinina decepta* (Martin), 738C-5R2(57-59). 8. *Acarinina wilcoxensis* (Cushman and Ponton), 738C-9R1(60-62). 9–10. *Acarinina pentacamerata* Subbotina, 738C-5R1(78-80). 11. *Acarinina hispidicidar* (Loeblich and Tappan), 738C-5R2(57-59). 12–13. *Acarinina collactea* (Finlay), 738C-5R1(78-80). 14–15. *Acarinina broedermanni* (Cushman Bermudez), 738C-5R1(78-80). 16–18. “*Morozovella*” *convexa* (Subbotina), 738C-11R2(143-145). 19–21. *Globorotalia reissi* Loeblich and Tappan, 738C-11R2(143-145). 22. *Globorotalia tribulosa* Loeblich and Tappan, 738C-13RCC(4-6). 23. *Globigerina prolata* Bolli, 738C-5R2(57-59).



niferal tests; and (5) the sudden appearance of abundant (19%) reworked Cretaceous foraminifers. Because of this apparent hiatus, the FAD of *P. australiformis* can not be determined precisely. The length of this hiatus at this time cannot be evaluated, although we suspect it is very short, on the order of thousands of years based on the direct biostratigraphic and stable isotopic correlation with Site 690 (Stott and Kennett, 1990; Kennett and Stott, 1991; Barrera and Keller, 1991). Preliminary studies of mid-to-low latitude Indian Ocean Sites 752 and 215 indicate that this hiatus is widespread in the Indian Ocean.

Faunal change

Major changes in several planktic foraminiferal genera have been observed near the FAD of *P. australiformis*: (1) the first occurrence of major morozovellid taxa, including *M. aequa*, *M. subbotinae* and *M. gracilis*; (2) the first occurrence of the planorotalitid taxa *P. pseudomenardii*, *P. membranacea*, and *P. chapmani* and the decrease in relative abundances of the earlier species *P. hansbolli*, *P. perclara* and *P. planoconica*; and (3) in subbotinids, the last occurrence of the Paleocene species *S. varianta*, the decrease in abundances in *S. triloculinoidea* and *S. triangularis* associated with the first occurrence of the Eocene species *S. linaperta*. The FAD of the *Pseudohastigerina* spp. and angulate *Acarinina* spp., including the low latitude index taxa *P. wilcoxensis* and *A. wilcoxensis*, appear to be later than the FAD of *P. australiformis* and in this study marks the boundaries between Subzones AP5a

and AP5b and between Zones AP5 and AP6, respectively.

Isotopic excursion

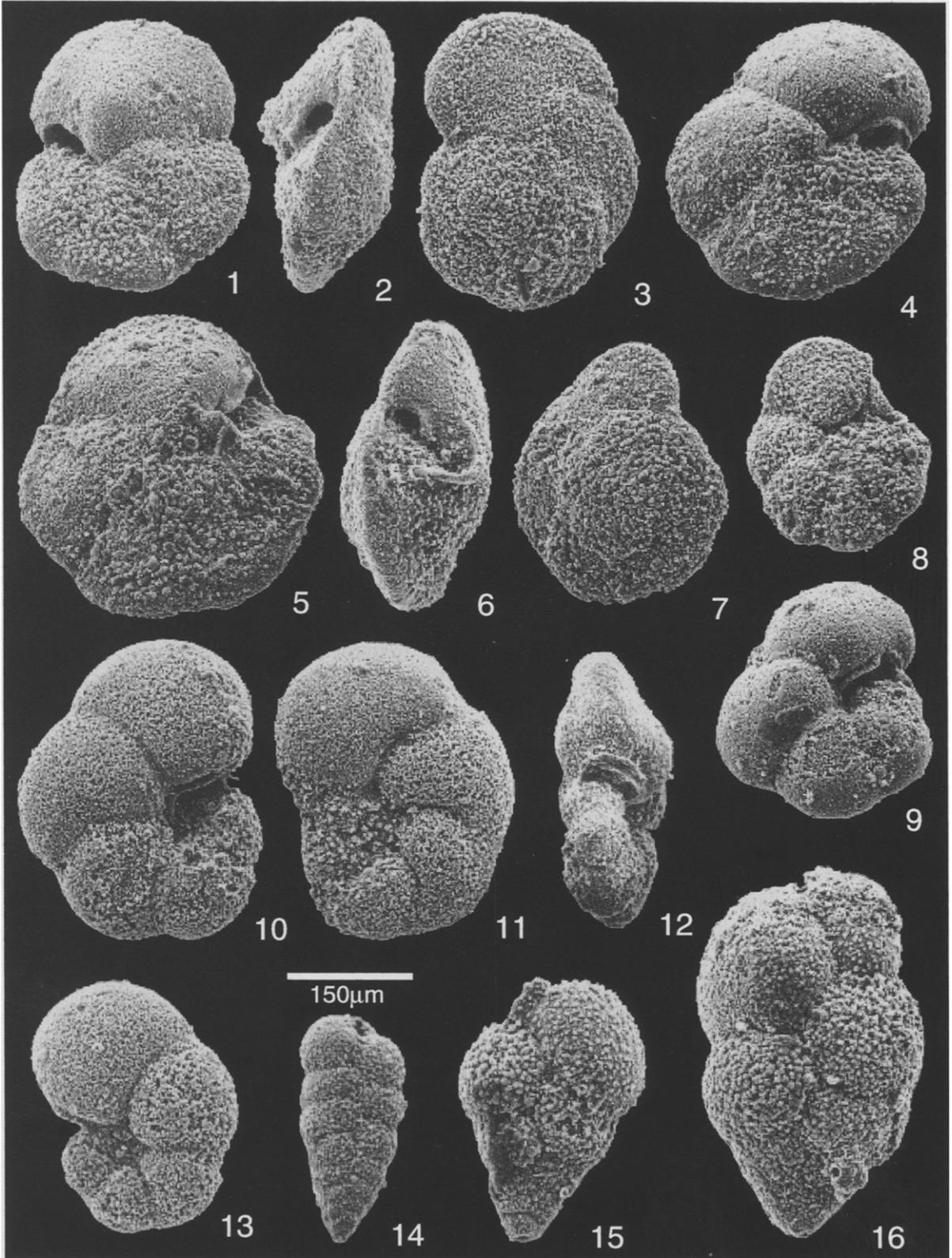
An abrupt negative excursion of 1.5‰ in $\delta^{18}\text{O}$ and 3‰ in $\delta^{13}\text{C}$ was observed near the base of the clay layer (Barrera and Keller, 1991) and coincides with the FAD of *P. australiformis* in Site 738. This excursion has been observed elsewhere in the world oceans (Kennett and Stott, 1991; Stott, 1991; Kennett, 1991; Thomas, 1991; Pak et al., 1991; Pak and Miller, 1992). In the Antarctic Atlantic ODP Sites 689 and 690, this excursion coincides with a benthic foraminiferal extinction, which occurred slightly earlier than the FAD of *P. australiformis* (Kennett and Stott, 1990, 1991; Thomas, 1990, 1991; Stott and Kennett, 1990). In the northern low latitude Pacific DSDP Site 577 and southern and northern mid-latitude Atlantic DSDP Site 525, 527 and 401, this isotopic excursion and the benthic foraminiferal extinction occurred slightly earlier than the last appearance of *M. velascoensis* (Thomas, 1991; Pak et al., 1991; Pak and Miller, 1992).

Depth stratification of planktic foraminifera

Planktic foraminifera live vertically stratified within the upper ocean water column (e.g., Bé, 1977). Stable isotopic measurements have been used to detect the stratification of species in modern oceans (e.g., Emiliani, 1954; Berger et al., 1978; Fairbanks and Wiebe, 1980; Fairbanks et al., 1980, 1982; Spero and William, 1988, 1989) as well as in ancient sediments

PLATE IV

Late Paleocene and early Eocene "globigerinids", planorotalitids and morozovellids from ODP Site 738. Scale bar for all figures represents 150 μm . 1–5. *Globigerina aquiensis* Loeblich and Tappan, 738C-11R2(143-145). 6–7. *Globigerina chascanona* Loeblich and Tappan, 738C-10RCC(4-6). 8–9. *Planorotalites pseudoimitata* Blow, 738C-11R1(15-17). 10–11. *Planorotalites perclara* (Loeblich and Tappan), 738C-11R2(143-145). 12–13. *Planorotalites chapmani* (Parr), 738C-11R1(15-17). 14. *Planorotalites* sp. 2, 738C-9R1(60-62). 15. *Morozovella nicoli* (Martin), 738C-11R1(15-17). 16. *Morozovella apenthesma* (Loeblich and Tappan), 738C-11R1(15-17). 17–18. *Morozovella aequa* (Cushman and Renz), 738C-11R1(15-17). 19. *Morozovella subbotinae* (Morozova), 738C-11R1(15-17).



(e.g., Douglas and Savin, 1978; Poore and Matthews, 1984; Shackleton et al., 1985; Boersma et al., 1987; Corfield et al., 1990). Reviews on methods and problems of stable isotopic depth stratification of planktic foraminiferal species in modern oceans and ancient sediments were given by Wefer and Berger (1991) and Corfield and Cartlidge (1991), respectively. Seasonal and ontogenetic effects are the most extensively discussed factors that may influence sample selection and hence affect the isotopic results and their interpretations.

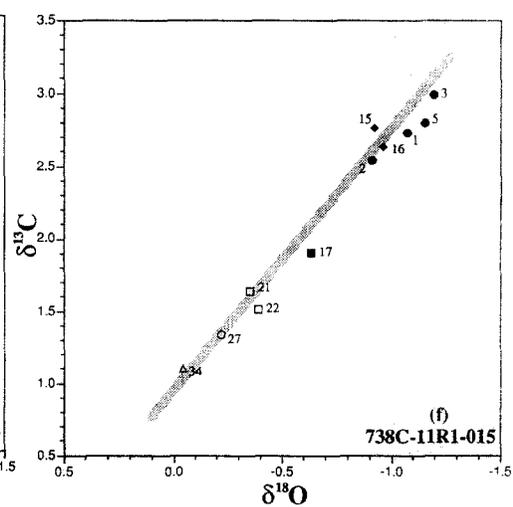
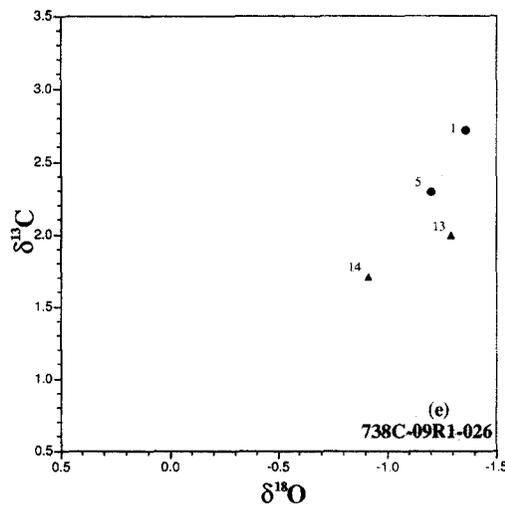
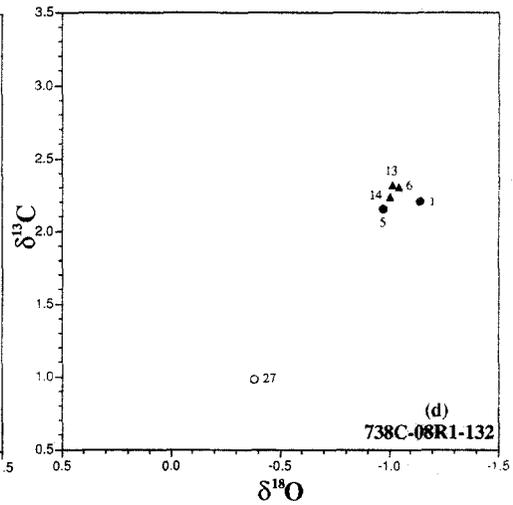
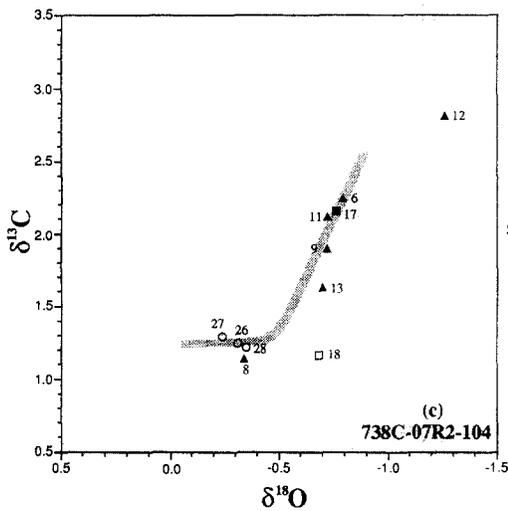
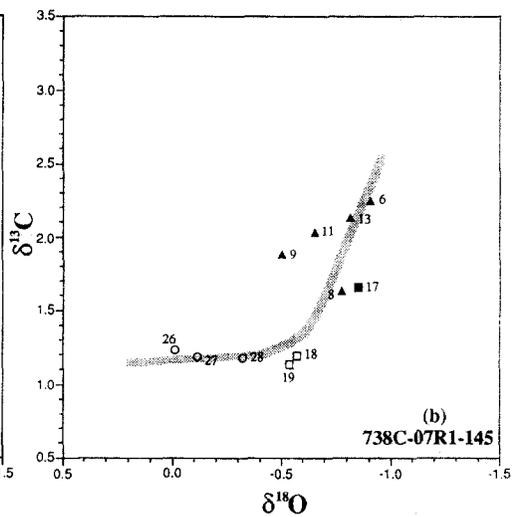
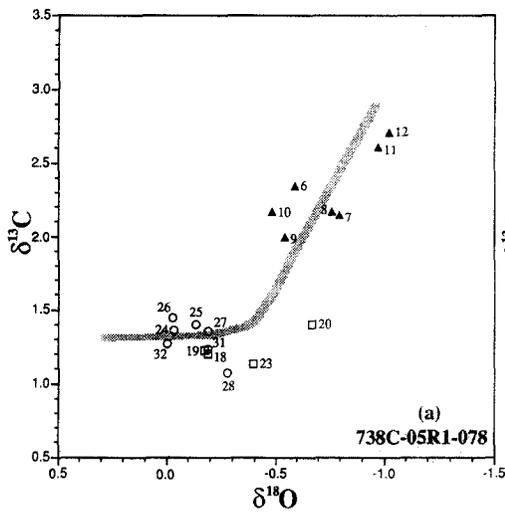
Middle and low latitude planktic foraminifera may change their depth of habitat in the water column as a result of seasonal variations in such parameters as water temperature, irradiance level and depth of chlorophyll maximum (Fairbanks and Wiebe, 1980; Fairbanks et al., 1980, 1982; Spero and Williams, 1988, 1989; Spero et al., 1991). These features have been used to estimate seasonal changes in the euphotic zone in ancient oceans (Spero and Williams, 1989; Spero et al., 1991). However, seasonal effects may result in significant errors when an annual mean value is measured, particularly when small samples (few individuals) are measured. This is normally not a problem for high latitude studies because of the absence of seasonality. However, the drastic polar warming during the Paleocene–Eocene transition may have resulted in seasonal changes in the Antarctic oceans. To minimize seasonal effects, larger samples of 20 to 30 individuals were measured in this study.

Planktic foraminifera may also change their depth of habitat in the water column in differ-

ent ontogenetic stages of their life cycle (e.g., Bé, 1977) and isotopic measurement on different size fractions is the usual approach to detect this ontogenetic effect (e.g., Emiliani, 1954; Berger et al., 1978; Shackleton et al., 1985). However, results show significant differences among species as well as between past and present. Berger et al. (1978) measured oxygen and carbon stable isotopic compositions of modern planktic foraminiferal test from the surface sediments in the West Equatorial Pacific. Their $\delta^{18}\text{O}$ results show a trend towards heavier values with increased size in eight species, a reversed trend in one species and mixed trends in four species. Their $\delta^{13}\text{C}$ results, on the other hand, show a relatively uniform trend towards heavier values with increased size in eleven out of thirteen species. These results were interpreted as (1) ontogenetic change of depth habitat, (2) disequilibrium precipitation of shells with seawater, and (3) environmental change (temperature, nutrients etc.). Shackleton et al. (1985) measured oxygen and carbon stable isotopic compositions of the Paleocene–Eocene planktic foraminiferal test from the western tropical Pacific. Their results show a systematic trend towards heavier values in $\delta^{13}\text{C}$ with increased size and a similar but less significant trend in $\delta^{18}\text{O}$. This trend is much more marked in surface dwelling than in deeper dwelling planktic foraminifera. These results were interpreted as upward migration of planktic foraminifera with shell growth. By comparing the data and interpretations of these two studies, the apparent problem seems to be in the relationships between shell size, ontogenetic age and shell growth. To minimize the

PLATE V

Late Paleocene and early Eocene planorotalitids, pseudohastigerinids and chiloguembelinids from ODP Site 738. Scale bar for all figures represents 150 μm . 1–3. *Planorotalites pseudomenardii* (Bolli), 738C-11R1 (15-17). 4. *Planorotalites* cf. *pseudomenardii* (Bolli), 738C-9R1 (60-62). 5–7. *Planorotalites pseudoscitula* (Glaessner), 738C-9R1 (60-62). 8. *Planorotalites* sp. 1, 738C-9R1 (60-62). 9. *Planorotalites troelseni* (Loeblich and Tappan), 738C-11R1 (15-17). 10–12. *Pseudohastigerina pseudochapmani* (Gohrbandt), 738C-5R2 (57-59). 13. *Pseudohastigerina wilcoxensis* (Cushman and Ponton), 738C-9R1 (60-62). 14. *Chiloguembelina morsei* (Kline), 738C-13RCC (4-6). 15. *Chiloguembelina crinita* (Glaessner), 738C-11R1 (15-17). 16. *Chiloguembelina wilcoxensis* (Cushman and Ponton), 738C-10R2 (106-108).



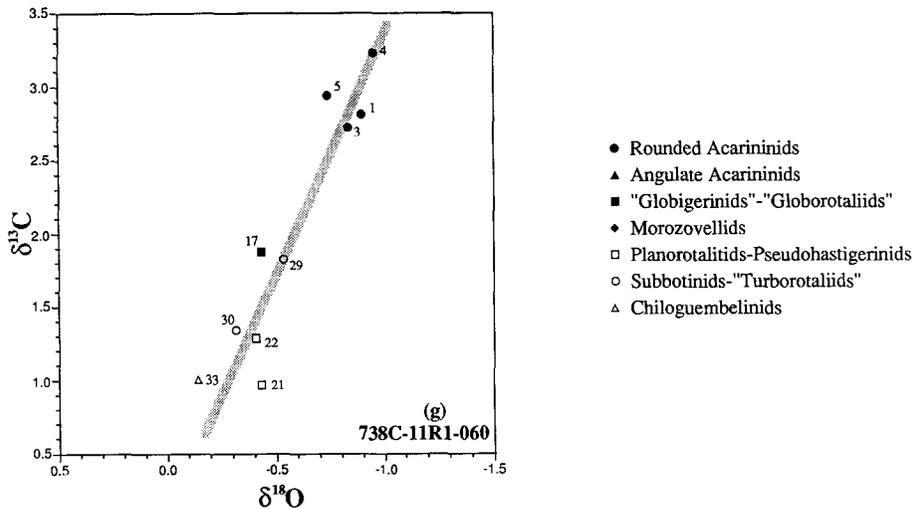


Fig. 4. Depth stratification of major planktic foraminiferal species across the Paleocene–Eocene transition based on carbon and oxygen isotopic measurements. Rounded acarininids, angulate acarininids and morozovellids register more positive $\delta^{13}\text{C}$ and more negative $\delta^{18}\text{O}$ values, indicating a surface habitat. Planorotalitids–pseudohastigerinids, subbotinids–“turborotaliids” and chiliguembelinids register more negative $\delta^{13}\text{C}$ and more positive $\delta^{18}\text{O}$ values, indicating a deep habitat near the thermocline. Isotopic values of “globigerinids” and “globorotaliids” generally fall between these two groups, indicating an intermediate habitat. Species List: Rounded Acarininids: 1=*A. acarinata*; 2=*A. interposita*; 3=*A. nitida*; 4=*A. soldadoensis*; 5=*A. triplex*. Angulate Acarininids: 6=*A. bullbrooki*; 7=*A. broedermanni*; 8=*A. cf. pseudotopilensis*; 9=*A. collactea*; 10=*A. hispidicidaris*; 11=*A. pentacamerata*; 12=*A. primitiva*; 13=*A. pseudotopilensis*; 14=*A. wilcoxensis*. Morozovellids: 15=*M. aequa*; 16=*M. gracilis*. “Globigerinids”–“Globorotaliids”: 17=*G. aquiensis*. Planorotalitids–Pseudohastigerinids: 18=*P. australiformis*; 19=*P. cf. pseudomenardii*; 20=*P. pseudochapmani*; 21=*P. pseudoimitata*; 22=*P. pseudomenardii*; 23=*P. pseudoscitula*. Subbotinids–“Turborotaliids”: 24=*S. eocaena*; 25=*S. hagni*; 26=*S. hornibrooki*; 27=*S. linaperta*; 28=*S. pseudoeocaena*; 29=*S. triangularis*; 30=*S. trilocolinoides*; 31=*T. cf. praecentralis*; 32=*T. praecentralis*. Chiliguembelinids: 33=*C. crinita*; 34=*C. wilcoxensis*.

possible errors caused by these ontogenetic effects, we chose average-sized adult tests for each species to obtain representative stable isotopic measurements for depth stratification (Table 2).

Morphology and isotopic ranking

Planktic foraminifera from Site 738 during the Paleocene–Eocene transition can be morphologically grouped into several assemblages. The coiling mode provides a grouping into three assemblages: (1) the “globorotaliid” assemblage, including morozovellids, rounded acarininids, angulate acarininids, planorotalitids, pseudohastigerinids, “globorotaliids” and “turborotaliids”; (2) the “globigerinid” assemblage, including subbotinids and “globigerinids”; and (3) the biserial assemblage, in-

cluding chiliguembelinids. Surface texture provides also three but different assemblages: (1) taxa with hispid or muricate surface, including morozovellids and both rounded and angulate acarininids; (2) taxa with smooth, pitted or reticulate surface, including subbotinids, planorotalitids, pseudohastigerinids, chiliguembelinids and “turborotaliids”; and (3) taxa with surface textures in between 1 and 2, including “globigerinids” and “globorotaliids”.

Oxygen and carbon stable isotopic compositions of all common species in seven selected intervals across the Paleocene–Eocene transition at Site 738 were measured (Table 2; Fig. 4a–g). The results show that the isotopic rankings of different species are consistent within each morphological group (e.g., within rounded acarininids or subbotinids). These

morphological groups can be further merged into larger assemblages according to their isotopic ranking. Figure 4a–g illustrates that morozovellids, rounded and angulate acarininids consistently registered more positive $\delta^{13}\text{C}$ and more negative $\delta^{18}\text{O}$ values, while planorotalitids–pseudohastigerinids, subbotinids–“turborotaliids” and chiloguembelinids consistently registered more negative $\delta^{13}\text{C}$ and more positive $\delta^{18}\text{O}$ values. Isotopic values of “globigerinids” and “globorotaliids” generally fall between these two groups (see Fig. 4 caption for species list). This indicates that most high latitude planktic foraminifera across the Paleocene–Eocene transition can be grouped into a surface assemblage, including acarininids and morozovellids, and a deep assemblage, including planorotalitids–pseudohastigerinids, subbotinids–“turborotaliids” and chiloguembelinids. Other morphotypes such as “globigerinids” and “globorotaliids” which include few species but with large relative abundance, lived at intermediate depth.

Within the deep assemblage, chiloguembelinids occupied a deeper habitat than any other group and registered lightest $\delta^{13}\text{C}$ values (Fig. 4f–g), which suggests a dwelling depth closer to the deep oxygen minimum zone, as discussed by Boersma and Premoli Silva (1983, 1986, 1987). The relative dwelling depth between planorotalitids–pseudohastigerinids and subbotinids–“turborotaliids” seems to change during the Paleocene–Eocene transition. For instance, near the Paleocene/Eocene boundary (Fig. 4f–g), the relative ranking of these two groups can not be separated by $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values. However, after a drastic change in the $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ slope (see next section) in Zone AP7 (Fig. 4a–c), $\delta^{18}\text{O}$ ranking as a proxy of dwelling depth (e.g., Emiliani, 1954; Berger et al., 1978; Shackleton and Vincent, 1978) suggests that planorotalitids–pseudohastigerinids began to occupy a shallower depth than subbotinids–“turborotaliids”, but registered slightly lighter $\delta^{13}\text{C}$ values. This suggests that, in Zone AP7, the dwelling depth of planorotal-

itids–pseudohastigerinids was closer to the shallow oxygen minimum zone (Shackleton and Vincent, 1978).

In summary, we find that species that are grouped by isotopic ranking are similar to the species grouped according to surface texture, but they differ from the species that are grouped according to coiling mode. Shackleton et al. (1985) and Corfield and Cartledge (1991) correctly showed that morozovellids and acarininids lived in the euphotic zone while subbotinids lived deeper during the Paleocene and Eocene, but they inappropriately claimed that, due to similar coiling modes, “globorotaliid” forms lived in the euphotic zone while “globigerinid” forms lived deeper during that time and concluded that this contrasted with the situation today. During the Paleocene and Eocene, the “globorotaliid” and “globigerinid” forms are composed of several genera that have no direct affinity with the present genera of *Globorotalia* and *Globigerina*. A direct analogy with recent forms is therefore not possible. However, our data suggest that surface texture may be a feature to identify the depth habitat of planktic foraminifera.

Vertical structure change in surface ocean

Isotopic ranking of planktic foraminifera can also reveal the vertical structure of the surface ocean. Near the Paleocene/Eocene boundary at Site 738, the $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ relationship is approximately linear from surface to deep assemblages (Fig. 4f–g). After a transitional period in Zones AP5 and AP6, however, this relationship changes in Zone AP7 (late early Eocene) with the slope in the surface assemblage remaining largely the same while the slope in the deep assemblage decreases drastically (Fig. 4a–c). Assuming that the “vital effects” of planktic foraminifera on oxygen and carbon isotopic fractionation did not change significantly during this period (there is no compelling evidence to suggest otherwise), this change in the $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ relationship reflects a

structural change in the upper ocean water column in the early Eocene. A decreased $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ slope in the deep assemblage can be caused either by an increased temperature gradient or by a decreased nutrient concentration gradient or both. An increased temperature gradient would indicate an intensified thermocline, while a decreased nutrient concentration gradient would indicate reduced upwelling. Both could be the results of the onset of polar cooling that followed the termination of the remarkable deep ocean and high latitude warming during the Paleocene–Eocene transition.

Planktic foraminiferal faunal events

The climatic and oceanographic changes during the Paleocene–Eocene transition affected mainly marine benthos while changes in marine plankton were less significant (Miller et al., 1978; Kennett and Stott, 1990, 1991; Thomas, 1989, 1990, 1991). Although this might be the case in general, in some regions marine plankton also change significantly reflecting special climatic and oceanographic conditions. The Antarctic Indian Ocean is one of these regions. Our study on isotopic ranking and relative abundance of planktic foraminifera at Site 738 reveals three major faunal turnovers during the Paleocene–Eocene transition. These faunal events and their environmental implications are discussed below.

Faunal Event 1: AP4/AP5 boundary (Paleocene/Eocene boundary?)

Faunal Event 1 occurred near the boundary between Zones AP4 and AP5 (Fig. 5) and coincides with a deep-sea hiatus. This faunal turnover resulted in the last appearance of 5 taxa (13%), first appearance of 12 taxa (32%) and major relative abundance changes in 9 taxa (27%). This event thus affected 72% of the planktic foraminiferal assemblage. Species that last appeared at this time are of primarily igo-

rinid morphology (e.g., *I. spiralis*, *A. mckannai* and “*M.* *convexa*”). Species that first appeared at this time include planorotalitids (*P. pseudomenardii*, *P. membranacea*, *P. australiformis* and *P. chapmani*), acarininids (*A. subsphaerica*, *A. nitida* and *A. triplex*), morozovellids (*M. apenthesma*, *M. aequa*, *M. subbotinae* and *M. gracilis*) and one subbotinid taxon (*S. linaperta*). Major relative abundance changes are found in subbotinids (decrease in relative abundance in *S. triloculinoides* and *S. triangularis*), planorotalitids (decrease in relative abundance in *P. hansbolli*, *P. perclara* and *P. planoconica*) and chiloguembelinids (increase in relative abundance in *C. crinita* and *C. wilcoxensis*).

Figure 6 illustrates the faunal change in different depth assemblages at Event 1 based on stable isotopic ranking. Increased diversity in surface dwelling acarininids indicates a steady or slightly “positive” change in the surface environment while a faunal turnover in deep dwelling subbotinids indicates a “negative” change in the intermediate environment. Since surface dwelling acarininids are thermophilic and occupy the mixed layer while deep dwelling subbotinids are cryophilic and occupy the thermocline layer (Shackleton et al., 1985; Corfield and Cartlidge, 1991), both the “positive” environmental change for the thermophilic taxa and the “negative” environmental change for the cryophilic taxa suggest high latitude warming. This warming is also indicated by the poleward proliferation of the low latitude morozovellid taxa (Fig. 6).

Faunal Event 2: AP5a/AP5b boundary

Faunal Event 2 occurred near the AP5a/AP5b Subzone boundary (Fig. 7). This faunal turnover resulted in the last appearance of 13 taxa (35%), first appearance of 7 taxa (19%) and major relative abundance changes in 6 taxa (17%). This event thus affected 71% of the planktic foraminiferal assemblage. Species that last appeared at this time include the Paleo-

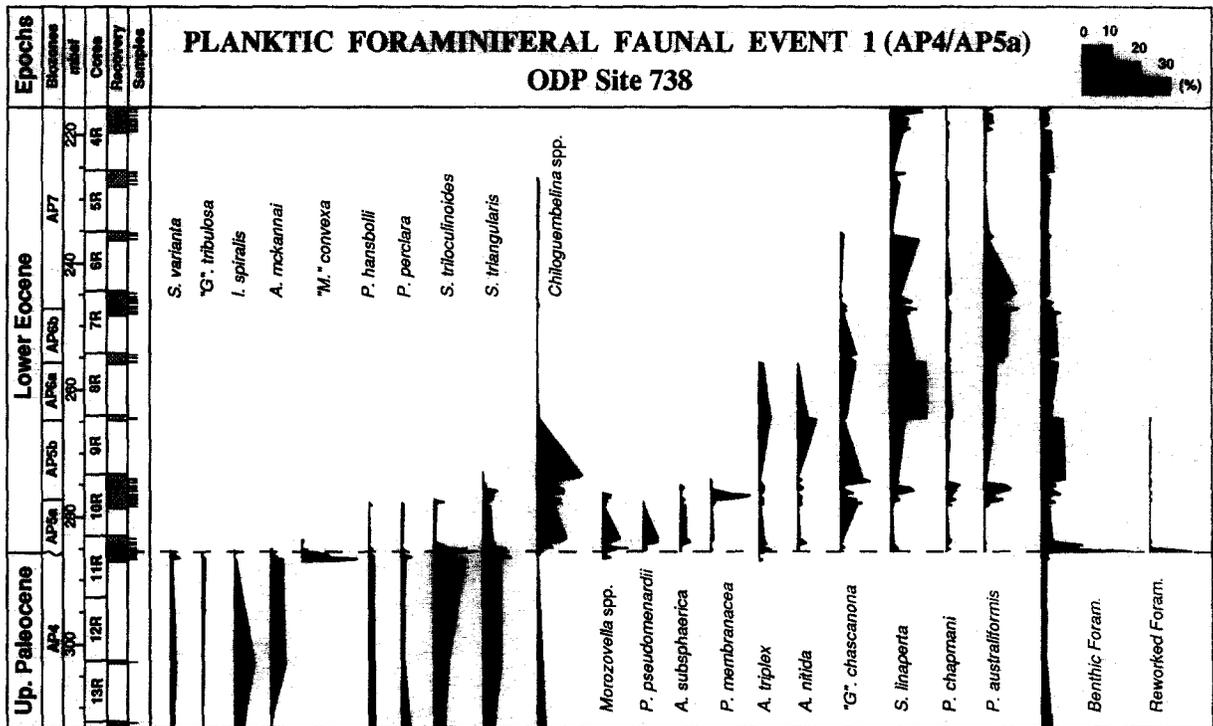


Fig. 5. Relative abundance changes, first and last appearances of planktic foraminifera that characterize Faunal Event 1 near the AP4/AP5 Zonal boundary at Site 738. Note that the sudden disappearance and appearance of many taxa, the major increase in relative abundance of benthic foraminifera and the presence of abundant Cretaceous reworked foraminifera mark a hiatus at the AP4/AP5 Zonal boundary.

cene subbotinid (e.g., *S. triloculinoides* and *S. triangularis*) and planorotalitid species (e.g., *P. hansbolli*, *P. perclara* and *P. planoconica*), the short-ranged transitional planorotalitid species (e.g., *P. pseudomenardii* and *P. membranacea*), and essentially all morozovellid species (*M. nicoli*, *M. apenthesma*, *M. aequa*, *M. subbotinae* and *M. gracilis*). Species that first appeared at this time are planorotalitids (e.g., *P. pseudoscitula* and *P. cf. pseudomenardii*), pseudohastigerinids (e.g., *P. pseudochapmani* and *P. wilcoxensis*) and subbotinids (e.g., *S. eocaenica* and *S. hardingae*). In addition, major relative abundance changes are observed within *Chiloguembelina*, marked by the decrease in relative abundance in *C. crinita* and the sudden increase in relative abundance in *C. wilcoxensis*.

Figure 8 illustrates the faunal changes in different depth assemblages at Event 2. There is

little change among surface dwelling acarininids, but a major faunal turnover occurred among deep dwelling planorotalitids and chiloguembelinids (Fig. 8). Chiloguembelinids are believed to occupy a habitat with low dissolved oxygen concentration (Boersma and Premoli Silva, 1983, 1986, 1987). They may increase in relative abundance, species diversity, individual size and test thickness in response to a well developed oxygen minima (Boersma and Premoli Silva, 1987). Based on these criteria, the relative abundance changes in chiloguembelinids at Site 738 indicate the development of a low oxygen concentration layer in the upper ocean water column at southern high latitudes, as implied by the disappearance of the small thin-walled *C. morsei*, the decreased relative abundance of the mid-sized *C. crinita*, and the increased relative abundance of the large thick-walled *C. wilcox-*

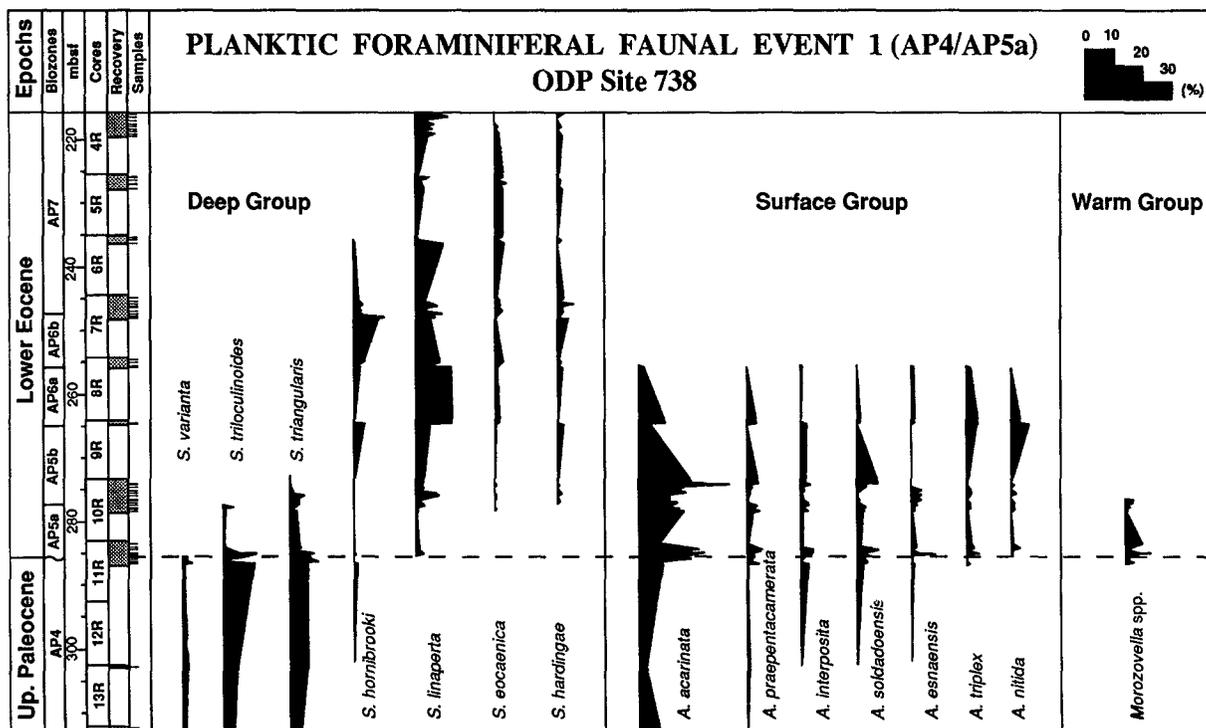


Fig. 6. Faunal turnover of Event 1 near the AP4/AP5 Zonal boundary at Site 738 in surface and deep dwelling foraminifers inferred from stable isotope depth stratification (see Fig. 4 for explanation). Occurrence of low latitude (warm) taxa at this site are also shown. Note that Faunal Event 1 is characterized by faunal turnover in deep dwellers, diversification in surface dwellers and increased relative abundance of low latitude warm water morozovellid taxa.

ensis (Fig. 8). This low oxygen concentration layer might be correlated with the deep oxygen minima as suggested by the depth ranking of chiloguembelinids (Fig. 4f–g).

The relative abundance changes of most species that mark Event 2 begin in Event 1, including the decrease in the relative abundance in *S. triloculinoides*, *S. triangularis*, *P. hansbolli* and *P. perclara*, and the increase in the relative abundance in *C. wilcoxensis*. However, these relative abundance changes and first and last appearances peaked near the AP5a/AP5b Subzonal boundary.

Faunal Event 3: Subzone AP6b

Faunal Event 3 occurred within Subzone AP6b (Fig. 9). This faunal turnover resulted in the last appearance of 12 taxa (29%), first appearance of 16 taxa (38%) and major rela-

tive abundance change in 4 taxa (10%). This event thus affected 77% of the planktic foraminiferal assemblage. Species that last appeared at this time are primarily rounded acarininids, including *A. acarinata*, *A. praepentacamerata*, *A. interposita*, *A. soldadoensis*, *A. esnaensis*, *A. nitida* and *A. triplex*. Species that first appeared are angulate acarininids (e.g., *A. bullbrooki*, *A. hispidicidar*, *A. broedermanni*, *A. cf. pseudotopilensis*, *A. decepta*, *A. collectea*, *A. spinuloinflata*, *A. primitiva* and *A. pentacamerata*), “turborotaliids” (e.g., “*T*”. *praecentralis*, “*T*”. *cf. frontosa* and “*T*”. *cf. possagnoensis*) and large subbotinids (e.g., *S. pseudoeocaena*, *S. hagni*, *S. inaequispira* and *S. eocaena*). In addition, major relative abundance changes occurred in planorotalitid morphotypes, including *P. pseudoscitula*, *P. australiformis* and *P. cf. pseudomenardii*.

Figure 10 illustrates the faunal changes in

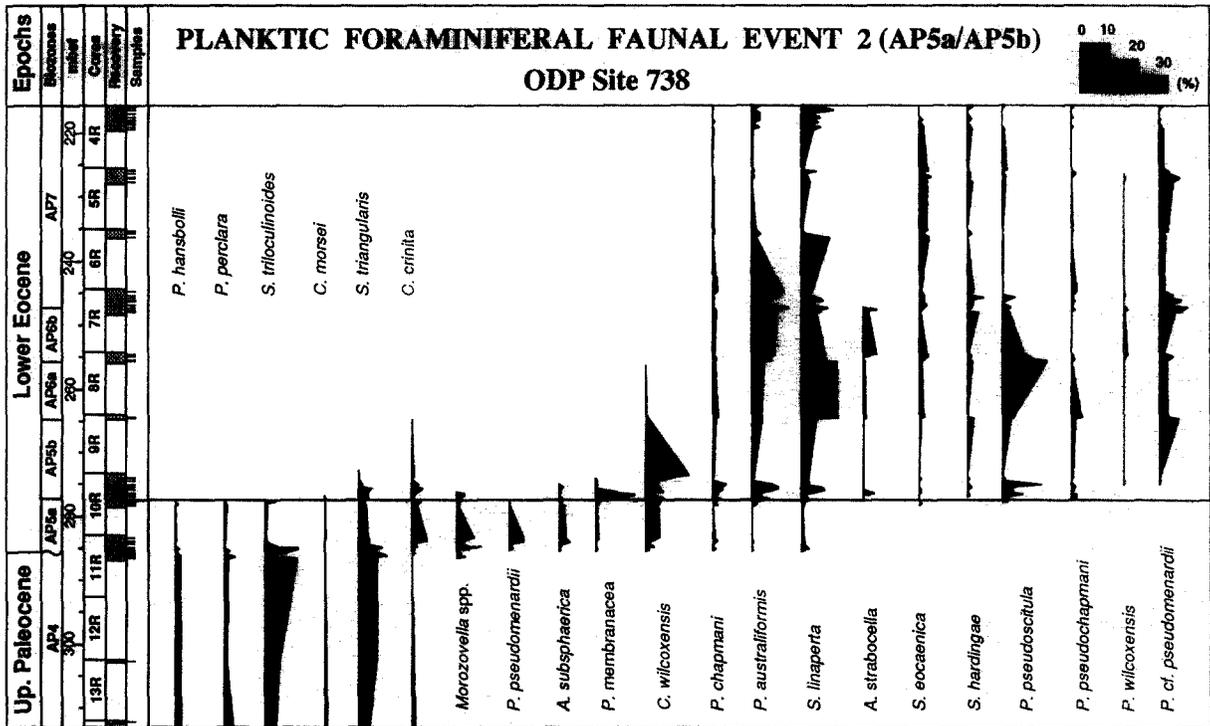


Fig. 7. Relative abundance changes, first and last appearances of planktic foraminifera that characterized Faunal Event 2 near the AP5a/AP5b Subzonal boundary at Site 738.

different depth assemblages at Event 3. Contrary to Events 1 and 2, where the major faunal turnovers occurred in subsurface waters, Event 3 appears to have been primarily a surface water event. Rounded acarininids were replaced by angulate acarininids indicating a “negative” environmental change for thermophilic surface dwellers. A delayed and more gradual diversification occurred in the deep dwelling subbotinids, marked by the appearance of several large species, indicating a “positive” environmental change for the cryophilic deep dwellers. Both changes in surface dwelling acarininids and deep dwelling subbotinids suggest the onset of high latitude cooling. However, there appears to be a time difference between the faunal changes in surface dwellers and that in deep dwellers, suggesting that the surface cooling started earlier in Subzone AP6b whereas sub-surface depth was not influenced until later in Zone AP7.

Climatic and oceanographic implications

Climatic and oceanographic changes during the late Paleocene and early Eocene have been widely discussed (e.g., Shackleton and Kennett, 1975; Savin et al., 1975; Miller et al., 1987; Thomas, 1989, 1990; Kennett and Stott, 1990; Stott et al., 1990; Barrera and Huber, 1991). After the confirmation of the benthic foraminiferal mass extinction (Schnitker, 1979; Tjalsma and Lohmann, 1983) and, especially, the short-term oxygen and carbon isotopic excursion (Kennett and Stott, 1991) near the Paleocene/Eocene boundary, more and more attention has been drawn to the Paleocene–Eocene transition. Most of these investigations, however, concentrate on marine benthos and deep water masses with only a few exceptions, such as Corfield and Shackleton (1988) and Pospichal and Wise (1990). Our knowledge about the behavior of surface ocean

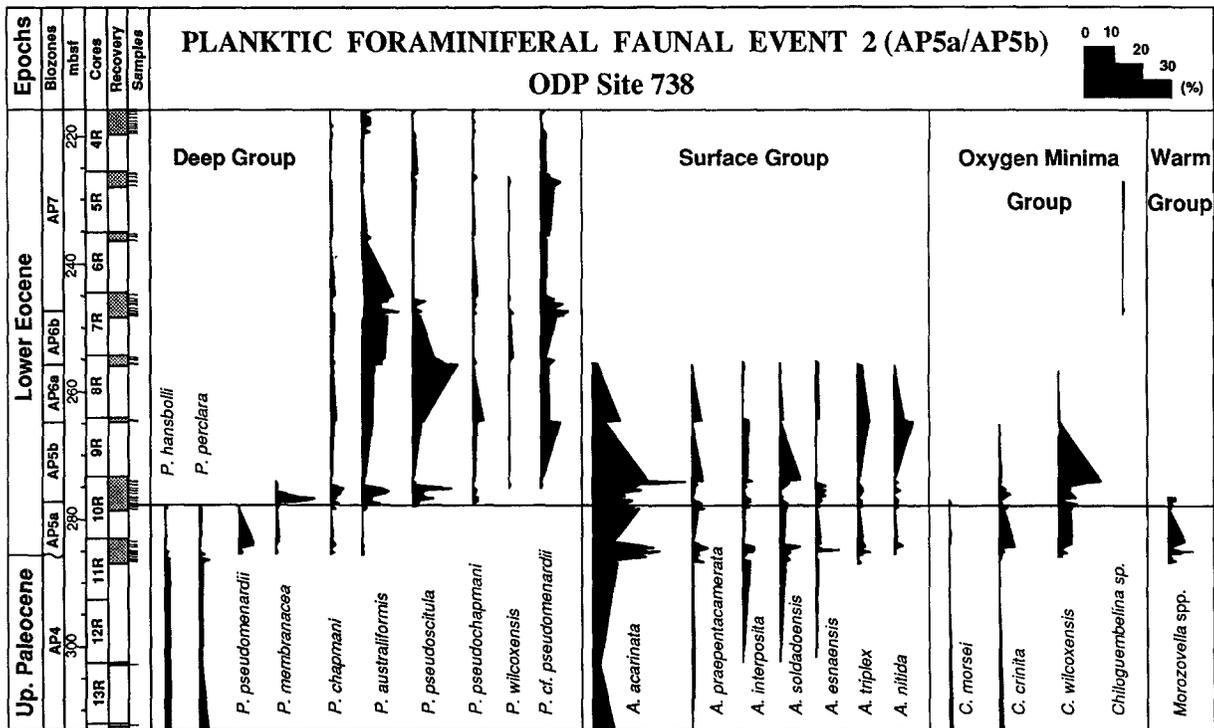


Fig. 8. Faunal turnover of Event 2 near the AP5a/AP5b Subzonal boundary at Site 738 in surface and deep dwellers inferred from stable isotope depth stratification (see Fig. 4 for explanation). Faunal turnover in taxa indicative of low oxygen concentration and occurrence of low latitude (warm) taxa at this site are also shown. Note that Faunal Event 2 is characterized by a faunal turnover in deep dwellers, absence of major change in surface dwellers, disappearance of low latitude taxa and increase in low oxygen tolerant taxa.

water masses corresponding to this global change during the Paleocene–Eocene transition remains poor.

High resolution relative abundance studies and isotopic depth stratification of planktic foraminifera at Site 738 in the Antarctic Indian Ocean provide information of changes in the southern high latitude surface ocean during the Paleocene–Eocene transition. This information is strengthened by $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ time series obtained from surface (*Acarinina* spp.) and deep (*Subbotina* spp.) dwelling planktic foraminifera and benthic foraminifera (*Nuttallides truempyi* and *Cibicidoides* spp.; Fig. 11; isotope data from Barrera and Keller, 1991), and by comparison with the foraminiferal and isotopic studies at Sites 689 and 690, Antarctic Atlantic Ocean (Thomas, 1990; Stott and Kennett, 1990; Stott et al., 1990;

Kennett and Stott, 1990, 1991). We will discuss first a hypothesis that may link the short-term and long-term climatic and oceanographic changes during the late Paleocene and early Eocene.

Warm saline deep water and global warming

The global warming during the latest Paleocene and early Eocene is characterized by a dramatic reduction of the vertical and meridional temperature gradients: deep ocean temperatures increased uniformly about 7.5°C across latitudes, while sea surface temperatures increased 5° – 7.5°C at high latitudes but remained nearly the same at low latitudes (Shackleton, 1984, 1985, 1986, 1987; Miller et al., 1987; Stott and Kennett, 1990, 1991; Stott et al., 1990; Katz and Miller, 1991; Thomas,

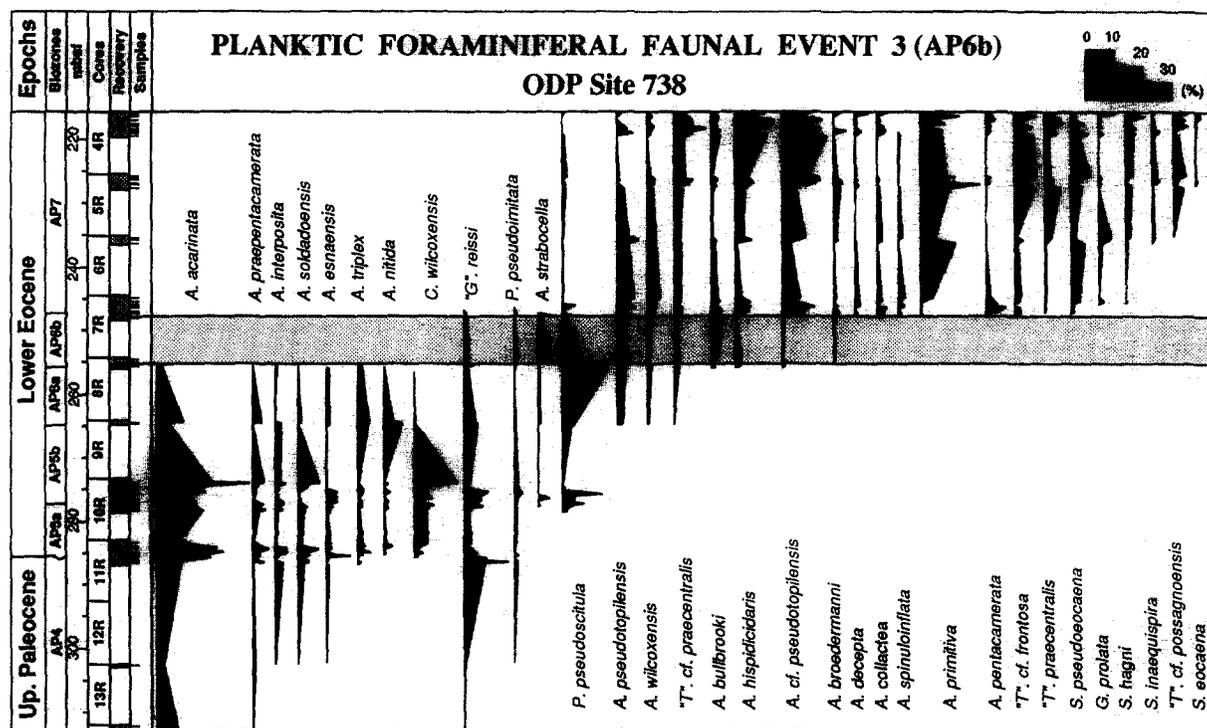


Fig. 9. Relative abundance changes, first and last appearances in planktic foraminifera that characterized Faunal Event 3 in the Subzone AP6b in Site 738. Because of poor core recovery, the precise timing of this faunal event is uncertain (stippled interval). Note that the taxa which disappear at the base of AP6b (Core 8R) and first appear at the top of AP6b (Core 7) could have their last and first appearances in the missing interval.

1991; Pak et al., 1991; Barrera and Huber, 1991; Barrera and Keller, 1991; Pak and Miller, 1992). This unusual global warming led to the revival of Chamberline's (1906) "warm saline deep water (WSDW)" hypothesis. Kennett and Stott (1990, 1991) suggested that, during the latest Paleocene and early Eocene, deep water might have formed at low latitudes (primarily Tethys) instead of high latitudes. Their scenario seems to be supported by faunal and isotopic data of the short-term event during the Paleocene–Eocene transition that will be discussed below.

Similar to the long-term global warming, the short-term event during the Paleocene–Eocene transition is also characterized by a strong vertical and meridional gradient. The benthic faunal change is marked by a mass extinction (e.g., Tjalsma and Lohmann, 1983; Miller et al., 1987; Thomas, 1989, 1990; Pak and Miller,

1992), while the planktic faunal change is marked by diversification (Fig. 11) which seems to continue the radiation process that began after the K/T boundary extinction. This vertical difference in species evolution and extinction indicates that the environmental change in the deep ocean is more severe than in the surface ocean. Moreover, quantitative studies show that, after the benthic mass extinction, southern high latitude benthic foraminifera were dominated by low dissolved oxygen tolerant taxa which is not the case at middle and low latitudes (Thomas, 1989, 1990; Kaiho, 1991). This meridional difference in benthic foraminifera indicates a meridional gradient of dissolved oxygen concentration in deep water, which strongly suggests an influx of deep water from low latitudes during this period.

A clear meridional gradient has been ob-

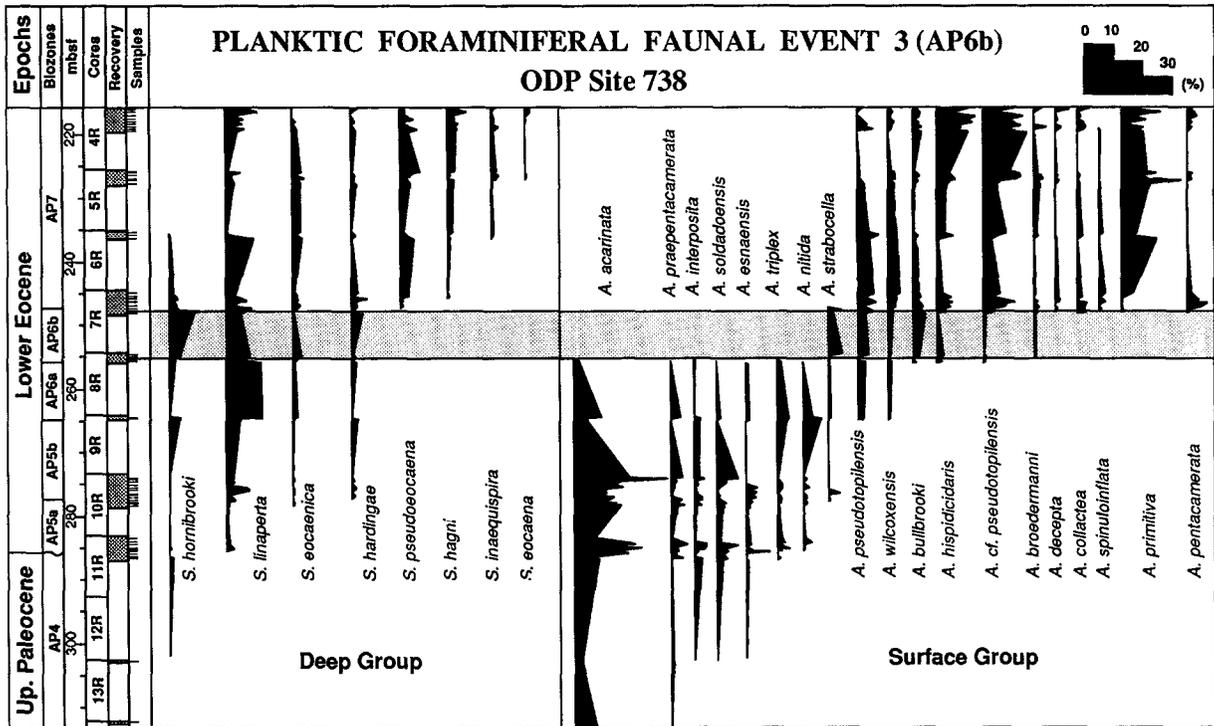


Fig. 10. Faunal turnover of Event 3 in the Subzone AP6b at Site 738 in surface and deep dwelling planktic foraminifers as inferred from stable isotope depth stratification (see Fig. 4 for explanation). Note that a major faunal turnover occurred among surface dwellers with a delayed, more gradual diversification in deep dwellers.

served in the amplitude of the short-term negative excursion in benthic $\delta^{13}\text{C}$ values during the Paleocene–Eocene transition. The amplitudes of this negative excursion are 3–3.5‰ in the Antarctic Indian and Antarctic Atlantic Oceans (Kennett and Stott, 1991; Barrera and Keller, 1991), 2.5–3‰ in the southern Atlantic Ocean (Thomas, 1991), and only 1‰ in the northern low latitude Pacific and the northern mid-latitude Atlantic Oceans (Pak and Miller, 1992). The maximum meridional difference of the excursion is more than 2‰. We note that the maximum difference of $\delta^{13}\text{C}$ values in modern ocean deep waters is about 1.5‰ which are found between the North Atlantic, the source region of modern deep water, and North Pacific where the oldest deep water is present (Arthur et al., 1983). If we assume a similar $\delta^{13}\text{C}$ difference (1.5‰) for the late Paleocene with deep water forming in high latitudes, a more than 2‰ difference in the neg-

ative $\delta^{13}\text{C}$ excursion between high and low latitudes near the Paleocene–Eocene transition would not only reduce but reverse the deep water age gradient. After the excursion, one would find “old” deep water in high latitudes instead of low latitudes. Therefore, the meridional amplitude gradient of the short-term negative excursion in benthic $\delta^{13}\text{C}$ values during the Paleocene–Eocene transition strongly suggest a switch in the deep water source from high to low latitudes.

By a more direct approach, Pak and Miller (1992) compared the benthic $\delta^{13}\text{C}$ values from northern mid-to-low latitude Sites 401 and 577 with those from southern mid-to-high latitude Sites 690 and 702. The results indicate that, during the short-term excursion at about 58 Ma, northern benthic $\delta^{13}\text{C}$ values were about 0.5‰ higher than the Southern Ocean values, suggesting a deep water formed at northern low latitudes.

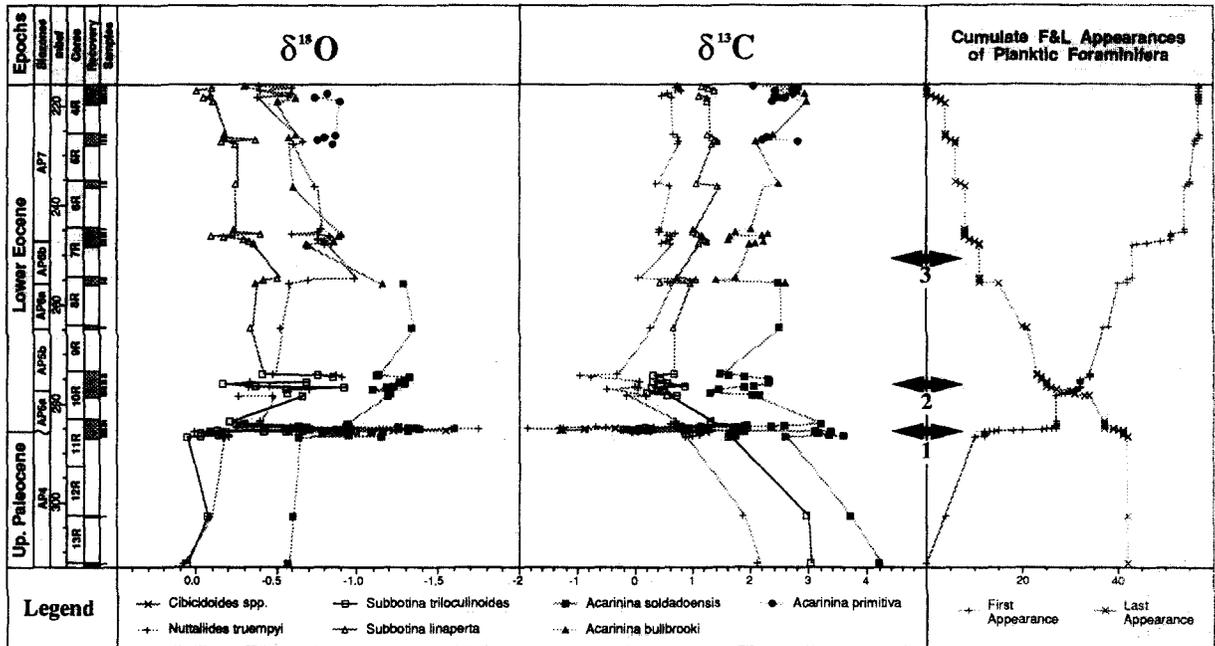


Fig. 11. Oxygen and carbon isotopic trends in benthic foraminifera (*Cibicidoides* spp., *Nuttallides truempyi*) and deep (*Subbotina*) and surface (*Acarinina*) dwelling planktic foraminifera along with the cumulate first and last appearance of planktic foraminifera at Site 738. Arrows indicate the position of the major faunal events. Stable isotopic data are from Barrera and Keller (in prep.).

General Circulation Model studies showed that the polar warming during the Paleocene–Eocene transition was so remarkable that some more efficient mechanisms of poleward heat transport, like through intermediate and/or deep water in the ocean, are needed to account for this warming (e.g., Barron, 1987; Rind and Chandler, 1990; Barron and Peterson, 1991). This led to the suggestion that WSDW during the Paleocene–Eocene transition was not the consequence but the cause of climatic warming (e.g., Lu et al., 1991) which, however, reveals some problems. Firstly, morozovellids, which mark sea surface warming in the Antarctic Oceans, appear earlier than the benthic foraminiferal extinction and isotopic excursion (Figs. 5 and 6; Stott and Kennett, 1990). Secondly, and probably more importantly, even if a sudden switch in the deep water source could account for the observed oceanic $\delta^{18}\text{O}$ change, it is very difficult to explain the huge and rapid $\delta^{13}\text{C}$ change. If a 1‰ negative ex-

ursion in the Pacific could approximate the mean ocean signal (Pak and Miller, 1992), it requires about 1500 gigatons of organic carbon added into the deep ocean over a short period of 3 to less than 100 kyr (Kennett and Stott, 1991; Pak and Miller, 1992) which equals three fourths of the modern biotic and soil organic carbon reservoir. Although the sedimentary organic carbon reservoir is sufficiently large to accommodate this input, it is too slow to respond to a change on the ten-thousand-year scale (Broecker and Peng, 1982). Therefore, the answers may lie in the very deep ocean (paleo-depth > 2000 m), a black-box that remains largely unexplored to date. Possibly the WSDW influenced the very deep ocean, and thus the high latitudes, long before the benthic foraminiferal extinction and isotopic excursion. The extinction and isotopic excursion is the mark of the sudden shutdown of the “Antarctic Intermediate Water” production (Kennett and Stott, 1991; Thomas,

1991; Pak and Miller, 1992) which may have brought the WSDW up to the intermediate depth. Studies of depositional environments below 2000 m depth are still necessary to obtain a more complete history of the oceanographic changes during the Paleocene–Eocene transition.

Surface ocean structure and climate

Because of its huge volume and heat as well as chemical capacity, a change in the deep ocean usually has a great impact on the atmosphere and global climate. This impact, however, has to pass first through the surface ocean which serves as a connection between the deep ocean and the atmosphere. Although not all regions are equally sensitive to changes in the deep ocean, the Antarctic Surface Oceans have a unique advantage in monitoring this connection because of their sensitivity to both the deep water source and climate change (Broecker and Peng, 1982).

This study reveals three major transitions in the structural and climatic changes in the surface Antarctic Indian Ocean which correspond with different stages of the long-term warming cycle during the late Paleocene and early Eocene. These three transitions are marked by planktic foraminiferal turnovers, changes in the $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ slope and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ excursions which are in accordance with the hypothesized WSDW intrusion. A summary of the faunal and isotopic data is shown in Figs. 11 and 12. Figure 11 illustrates that three major faunal turnovers, as shown by the numbers of the first and last appearances, coincide with isotopic excursions. Figure 12 illustrates the variations in the surface, intermediate and deep assemblages of planktic foraminifera at each of the three faunal turnovers. Although there is no apparent change in the relative diversity of the three planktic foraminiferal assemblages, there are major increases in the

number of species in the surface and deep assemblages during the turnovers 1 and 3 (Fig. 12). Moreover, the “old” (Paleocene) assemblages in surface and deep dwellers are gradually replaced by the “new” (Eocene) assemblages whereas the intermediate assemblage remains less affected except for short intervals as discussed below.

1. Structural crisis during the Paleocene–Eocene transition

The late Paleocene planktic foraminiferal fauna at the Site 738 is characterized by the large relative abundance (about 60%) in the intermediate assemblage (Fig. 12). Near the Paleocene/Eocene boundary (Event 1), however, the relative abundance of this assemblage drops to less than 10% which coincides with a pulse of increased relative abundance in the surface assemblage, a turnover in the deep assemblage (Figs. 6 and 12), and a short-term negative excursion in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (Fig. 11). This pulse of faunal and isotopic change lasted about 63,000 years at the Site 738, if we assume a uniform and continuous sedimentation rate during the late Paleocene and early Eocene. However, a longer time duration is indicated by the apparent hiatus and carbonate dissolution.

Detailed observations on the short-term isotopic excursion reveal that the vertical $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ gradients were nearly eliminated (Kennett and Stott, 1991; Barrera and Keller, 1991), marking a structural crisis in the upper ocean water column. This crisis could have changed the habitats of the deep and intermediate dwelling planktic foraminifera drastically and resulted in the observed faunal turnover and relative abundance drop. Isotopic ranking of planktic foraminifera of the samples just after the crisis show that the vertical structure of the surface ocean was quickly restored (Fig. 4f). However, a nutrient-poor water mass that bathed benthic foraminifera

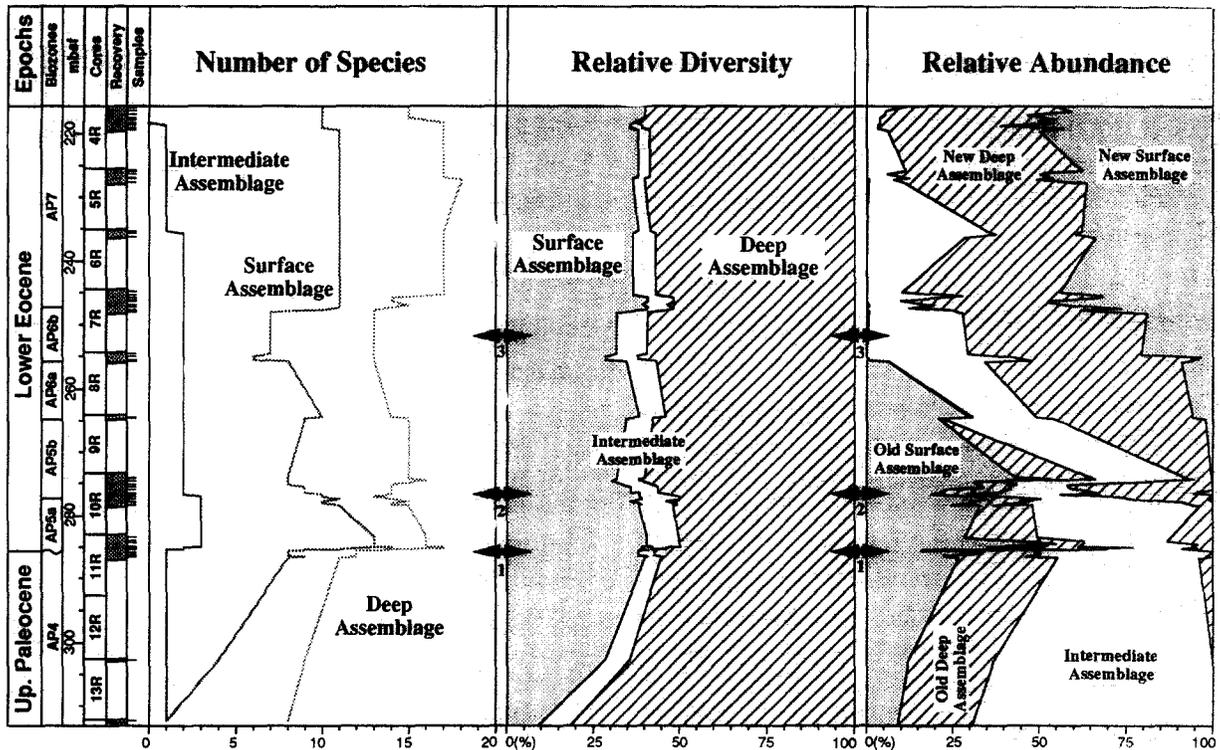


Fig. 12. Planktic foraminiferal assemblages based on isotopic depth stratification at Site 738. From left to right: species richness (number of species) of the surface, intermediate and deep assemblages; relative diversity (percent of species) of the surface, intermediate and deep assemblages; relative abundance (percent of individuals) of the surface, intermediate and deep assemblages. Note that the surface and deep assemblages can be separated into the "old", Paleocene assemblages and the "new", Eocene assemblages, while the intermediate assemblage cannot be separated.

before the crisis was replaced by a nutrient-rich water mass immediately after the crisis at the Site 690 as indicated by a 2‰ difference in the benthic $\delta^{13}\text{C}$ values just before and after the crisis (paleo-depth about 2000 m, Kennett and Stott, 1991) and shortly later at the Site 738 (paleo-depth about 1300 m; Fig. 11).

The appearance of *Morozovella* spp. before the isotopic excursion suggests that the high latitude warming and the hypothesized WSDW formation occurred before the crisis. The crisis seems to reflect the sudden shutdown of the nutrient-poor "Antarctic Intermediate Water" that formerly bathed benthic foraminifera. The formation of a nutrient-rich Intermediate Water possibly by the "recycling" of the WSDW after the crisis could, therefore, restore the vertical structure in the surface ocean.

2. Oxygen minima during the early Eocene maximum warming

The early Eocene maximum warming has been well documented in many $\delta^{18}\text{O}$ measurements, and was coeval with a long-term decrease in benthic $\delta^{13}\text{C}$ values (e.g., Shackleton and Kennett, 1975; Savin et al., 1975; Shackleton, 1984, 1985, 1986, 1987; Miller et al., 1987; Stott et al., 1990; Barrera and Huber, 1991). The planktic foraminiferal turnover near the AP5a/AP5b Subzonal boundary suggests a deep and possibly a shallow oxygen minimum layers developed in the Antarctic Oceans during the maximum polar warming (Fig. 8). Increased individual size, wall-thickness and relative abundance in chiloguembelins suggest the formation of the deep oxygen

minima, as has been discussed by Boersma and Premoli Silva (1983, 1986, 1987) and supported by the isotopic ranking of this study (Fig. 4f–g). Increased relative abundance in planorotalitids, on the other hand, might be associated with the formation of the shallow oxygen minima, although the limited isotopic ranking data can only show that this group dwelled at the shallow oxygen minima depth in Zone AP7 (Fig. 4a–c).

The development of the shallow oxygen minima is mainly a function of sea-surface productivity, while the deep oxygen minima is controlled by both surface productivity and, more importantly, upwelling of the nutrient-rich deep water (Broecker and Peng, 1982). The appearance of the deep oxygen minima, as shown by the large relative abundance of chiloguembelinids (Fig. 8), was restricted within Zone AP5, indicating that the nutrient-rich deep water (WSDW?) upwelled directly to the sub-surface at Site 738 during this period. The possible shallow oxygen minima, as shown by the large relative abundance of planorotalitids (Fig. 8), lasted much longer into the Zone AP7 when the Antarctic surface ocean was cooling.

3. Onset of the high latitude cooling during the late early Eocene

The onset of the late early Eocene southern high latitude cooling has recently been documented by Stott et al. (1990) and Barrera and Huber (1991) at 53–54 Ma. Associated with this cooling is a change in the surface ocean structure (Fig. 4) as well as a faunal turnover in planktic foraminifera (Fig. 10).

A major faunal turnover that affected primarily the surface assemblage occurred in Subzone AP6b, while a diversification in the deep assemblage occurred later in Zone AP7 (Fig. 10), indicating that the cooling started at the surface and propagated downward. The same lag-time is also observed in planktic $\delta^{18}\text{O}$ values which show an initial positive change in surface values in Subzone AP6b followed by a

later positive change in deep values (Fig. 11). Benthic $\delta^{18}\text{O}$ values remained largely unchanged during the same interval suggesting the continued influence of the possible WSDW (Barrera and Huber, 1991; Barrera and Keller, 1991).

Isotopic ranking of planktic foraminifera reveals a major change in $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ slope associated with the onset of the high latitude cooling (Fig. 4). Decreased $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ slope in the deep assemblage indicates either an intensified thermocline or a reduced nutrient concentration gradient or both. Sea-surface cooling could result in an intensified thermocline if the deep ocean was controlled by the WSDW. This thermocline could, in turn, prevent the upwelling of the nutrient-rich WSDW, and reduce the nutrient concentration gradient. This structure change in the Antarctic surface ocean is fundamental. It locally formed a positive feedback that might eventually lead to the formation of a cold, Antarctic deep water mass and the termination of the WSDW.

Conclusions

Isotopic ranking and relative abundance studies of planktic foraminifera at Site 738 reveals three major faunal turnovers during the latest Paleocene and early Eocene, indicating the climatic and structural changes in the Antarctic surface ocean:

(1) A faunal turnover in the deep assemblage, decreased relative abundance in the intermediate assemblage and increased abundance in the surface assemblage near the Paleocene/Eocene boundary indicate a temporary elimination (over 63,000 years or more) of the vertical structure in the surface ocean, associated with the shutdown of the “Antarctic Intermediate Water” production.

(2) A faunal turnover in the deep assemblage and increased abundance in chiloguembelinids near the AP5a/AP5b boundary indicate the formation of a deep oxygen minima in

the Antarctic Oceans during the maximum polar warming.

(3) A faunal turnover in the surface assemblage and a delayed diversification in the deep assemblage during the Subzone AP6b indicate the onset of the Antarctic cooling, as also shown by the $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ slope decrease in the deep assemblage in the Zone AP7.

These climatic and structural changes in the Antarctic surface ocean were associated with the different stages of the global warming cycle during the late Paleocene and early Eocene, which we interpret as the consequence of Warm Saline Deep Water formation at low latitudes.

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