PALEOCEANOGRAPHY, VOL. 10, NO. 4 , PAGES 841-865, AUGUST 1995

Late Paleocene to Eocene paleoceanography of the equatorial Pacific Ocean: Stable isotopes recorded at Ocean Drilling Program Site 865, Allison Guyot

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Abstract. An expanded and largely complete upper Paleocene to upper Eocene section was recovered from the pelagic cap overlying Allison Guyot, Mid-Pacific Mountains at Ocean Drilling Program (ODP) Site 865 (18°26'N, 179°33'W; paleodepth 1300-1500 m). Reconstructions show that the site was within a few degrees of the equator during the Paleogene. Because no other Paleogene sections have been recovered in the Pacific Ocean at such a low latitude, Site 865 provides a unique record of equatorial Pacific paleoceanography. Detailed stable isotopic investigations were conducted on three planktonic foraminiferal taxa (species of *Acarinina, Morozovella,* and *Subbotina*). We studied benthic foraminiferal isotopes at much lower resolution on species of *Cibicidoides* and *Lenticulina, Nuttallides truempyi* and *Gavelinella beccariiformis,* because of their exceptional rarity. The $\delta^{18}O$ and $\delta^{13}C$ stratigraphies from Site 865 are generally similar to those derived from other Paleocene and Eocene sections. The planktonic foraminiferal records at Site 865, however, include significantly less short-term, single-sample variability than those from higher-latitude sites, indicating that this tropical, oligotrophic location had a comparatively stable water column structure with a deep mixed layer and less seasonal variability. Low-amplitude (0.1-0.8‰) oscillations on timescales of 250,000 to 300,000 years correlate between the $\delta^{13}C$ records of all planktonic taxa and may represent fluctuations in the mixing intensity of surface waters. Peak sea surface temperatures of 24°-25°C occurred in the earliest Eocene, followed by a rapid cooling of 3-6°C in the late early Eocene. Temperatures remained cool and stable through the middle Eocene. In the late Eocene, surface water temperatures decreased further. Vertical temperature gradients decreased dramatically in the late Paleocene and were relatively constant through much of the Eocene but increased markedly in the late Eocene. Intermediate waters warmed through the late Paleocene, reaching a maximum temperature of 10°C in the early Eocene. Cooling in the middle and late Eocene paralleled that of surface waters, with latest Eocene temperatures below 5°C. Extinction patterns of benthic foraminifera in the latest Paleocene were similar to those observed at other Pacific sites and were coeval with a short-term, very rapid negative excursion in $\delta^{13}C$ values in planktonic and benthic taxa as at other sites. During this excursion, benthic foraminiferal $\delta^{18}O$ values decreased markedly, indicating warming of 4 to 6°C for tropical intermediate waters, while planktonic taxa show slight warming (1°C) followed by 2°C of cooling. Convergence of $\delta^{18}O$ values of planktonic and benthic foraminifera suggests that thermal gradients in the water column in this tropical location collapsed during the excursion. These data are consistent with the hypothesis that equatorial Pacific surface waters were a potential source of warm, higher salinity waters which filled portions of the deep ocean in the latest Paleocene. Oxygen isotopic data indicate that equator to high southern latitude sea surface thermal gradients decreased to as little as 4°C at the peak of the excursion, suggesting some fundamental change in global heat transport.

Introduction

Paleogene sediments have proven to be elusive targets for high-resolution paleoceanographic studies: they are too young to be widely exposed in mountain belts yet too old to be easily accessible to shallow drilling technology. Most research has thus been done on material recovered by the Deep Sea Drilling

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Paper number 95PA01143.
0883-8305/95/95PA-01143$10.00

Project (DSDP) and Ocean Drilling Program (ODP), especially sediments from high southern latitude sites such as from Maud Rise in the southernmost Atlantic Ocean [*Barker et al.*, 1990] and Kerguelen Plateau in the Indian Ocean [*Wise et al.*, 1992]. These sections have been analyzed at a resolution commonly seen in studies on younger sections [e.g., *Kennett and Stott*, 1990; *Stott and Kennett*, 1990; *Barrera and Huber*, 1991; *Zachos et al.*, 1993; *Thomas and Shackleton*, 1995], demonstrating that Paleogene oceans and climate witnessed a pattern of short-term (10^3-10^4 years) fluctuations in temperature. These short-term excursions are superimposed on long-term (>10^6 years) climatic fluctuations [e.g., *Shackleton and Kennett*, 1975; *Savin*, 1977; *Kennett and Stott*, 1991; *Corfield and Cartlidge*, 1992; *Miller*, 1992]. During the latest Paleocene to earliest Eocene, high-latitude surface waters warmed gradually from 11° to 15°C and deep waters from 9° to 13°C [*Miller et al.*, 1987; *Stott et al.*, 1990; *Zachos et al.*, 1993], but in the middle through late Eocene, high-latitude surface and deep waters cooled to 6°C and 4°C, respectively [e.g., *Zachos et al.*, 1994].

The latest Paleocene rapid climatic change was one of the most dramatic warming events in the geological record. Antarctic surface and deep water temperatures increased from 14°C to 20°C and from 10°C to 18°C, respectively, over less than 10,000 years, so that vertical thermal gradients decreased; they remained at these levels for 50,000 to several hundred thousand years [*Stott et al.*, 1990; *Kennett and Stott*, 1991; *Thomas and Shackleton*, 1995]. Synchronous with the dramatic decrease in $\delta^{18}O$ values was a large negative excursion in the $\delta^{13}C$ records of planktonic and benthic foraminifera. The event is believed to have been associated with a temporary change in dominant deep water sources from high to low latitudes [*Kennett and Stott*, 1991; *Pak and Miller*, 1992; *Thomas*, 1992; *Eldholm and Thomas*, 1993] which could have been the major cause of the associated mass extinction of benthic foraminifera [*Braga et al.*, 1975; *Schnitker*, 1979; *Tjalsma and Lohmann*, 1983] possibly resulting from decreased dissolved oxygen contents of warmer deep waters [e.g., *Kennett and Stott*, 1990; *Thomas*, 1990a, 1992; *Kennett and Stott*, 1991; *Kaiho*, 1991, 1994].

The short-term changes in Eocene sea surface temperatures (SST) are well documented in high-latitude $\delta^{18}O$ records but not in the low latitudes. Low-latitude $\delta^{18}O$ records are essential, however, for reconstructing the low- to high-latitude temperature gradient, especially since inconsistencies exist between faunal and isotopic temperature estimates for the tropics on longer timescales [e.g., *Adams et al.*, 1990]. A knowledge of latitudinal thermal gradients is essential to developing a better understanding of how heat transport by the ocean and atmosphere may have responded to changes in radiative forcing [*Barron*, 1987; *Barron and Washington*, 1982; *Rea et al.*, 1990; *Barron and Peterson*, 1991].

High-resolution deep-sea Paleogene stratigraphic records from low latitudes are rare. Abundant chert occurring in many low-latitude sections of this age has led to reduced core recovery rates [e.g., *Pisciotto*, 1981]. Diagenesis has overprinted isotope values in many deep burial Paleogene sequences. The sequence from Site 577 (Shatsky Rise, paleolatitude 15-20° N) is almost the only proxy for conditions in the Paleogene subtropical Pacific Ocean [*Zachos and Arthur*, 1986; *Miller et al.*, 1987; *Corfield and Cartlidge*, 1992; *Pak and Miller*, 1992]. This section accumulated at low sedimentation rates and contains highly condensed intervals or short-term hiatuses (particularly in the lower Eocene), the middle Eocene is missing, and part of the uppermost Paleocene lies in a core break in two holes. A rotary-drilled record from DSDP Site 47.2 also on the Shatsky Rise has been discussed by *Stott* [1992], but significant drilling disturbance precludes high-resolution studies.

The Paleogene pelagic cap section at Site 865 on Allison Guyot (18° 26' N, 179° 33' W; 1530 m water depth; Figure 1) lies on Cretaceous shallow water limestones targeted on Leg 143. Calculations using the Pacific polar wander path indicate paleolatitudes of about 2° N in the late Paleocene to about 6° N in the late Eocene (R. Larson, oral communication, 1994). Conventional paleodepth back-tracking techniques could not be employed due to the unusual thermal history of the Mid-Pacific Mountains. Depth estimates based on benthic foraminifera are not precise for the bathyal-abyssal range in Paleogene sediments [*Berggren and Miller*, 1989], but detailed comparison between Paleocene/Eocene faunas at Site 865 and those at Sites 762 (Indian Ocean, paleodepth 1000-1500 m), Site 577 (Pacific Ocean, paleodepth about 1500 m), Site 752 (Indian Ocean, paleodepth 500-1000 m), Site 689 (Weddell Sea, paleodepth about 1100 m), and Site 525 (Walvis Ridge, paleodepth about 1600 m) suggests that the paleodepth was in the upper half of the lower bathyal, i.e., between about 1300 and 1500 m [*Thomas and Shackleton*, 1995; E. Thomas, manuscript in preparation, 1995], suggesting little subsidence since the Paleogene. We present the isotopic stratigraphy of the Paleogene section at Site 865 and its general paleoceanographic significance. The paleoclimatic implications of this record are further explored by J. C. Zachos et al. (manuscript in preparation, 1995); the benthic foraminiferal faunal record will be discussed by E. Thomas (manuscript in preparation, 1995).

Methods and Procedures

Sample Selection and Preparation

Samples were analyzed from the upper Paleocene through upper Eocene interval of Hole 865B. Hole 865C was sampled in detail only in the interval close to Paleocene/Eocene boundary because the uppermost Paleocene part of the section in Hole 865B is interrupted by the break between Cores 11 and 12. One to three samples per core section (every 0.5 m to 1.5 m) were selected for isotopic measurement from Hole 865B, with the densest sampling in the upper Paleocene to lower Eocene. A more detailed sample set (one sample every 10 cm) was taken close to the benthic foraminiferal extinction horizon in the upper Paleocene in both holes. One 20 cm^3 sample per section was taken in Hole 865B for benthic foraminiferal faunal analysis. All other samples ranged in volume between 5 and 10 cm^3. Samples for planktonic foraminiferal analyses were split, dried, and washed with pH buffered water through sieves with screen openings of 250, 125, 63, and 38 μm and then oven-dried at 60°C. The >250 μm fraction was dry-split

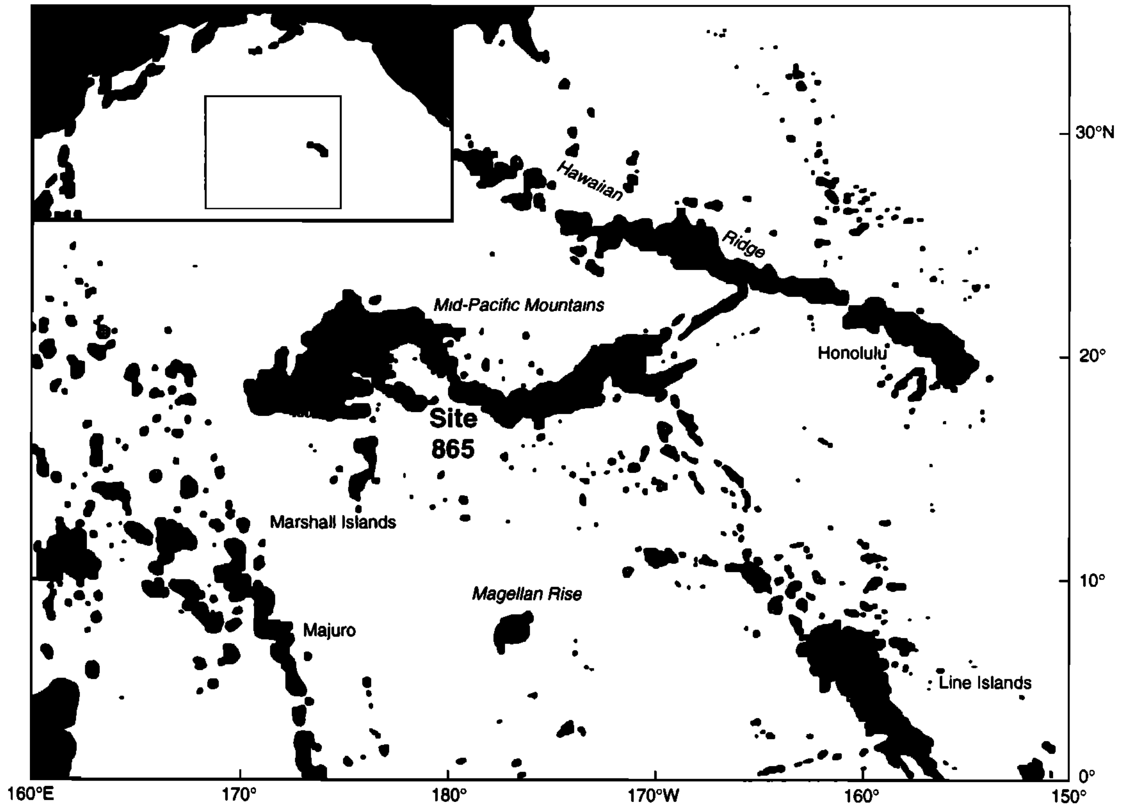

Figure 1. Location of ODP Site 865 on Allison Guyot in the Mid-Pacific Mountains. Inset shows general location of detailed map.

into various size fractions: >400 μm, 355-400 μm, 300-355 μm, and 250-300 μm.

Planktonic Foraminiferal Taxa

Various taxa have been utilized for Paleogene planktonic foraminiferal isotope stratigraphy [e.g., *Shackleton et al.*, 1984; *Boersma et al.*, 1987; *Stott et al.*, 1990; *Pearson et al.*, 1993]. We used species of *Morozovella* and *Acarinina* because of their (1) taxonomic distinctiveness; (2) overlapping stratigraphic ranges spanning the interval of interest; and (3) surface dwelling habitat. We selected *Morozovella velascoensis* (upper Paleocene), *Morozovella subbotinae* (uppermost Paleocene to lower Eocene), *Morozovella aragonensis* (lower to middle Eocene), *Morozovella lehneri* (middle to upper Eocene) (Figure 2), *Acarinina mckannai* (upper Paleocene), *Acarinina soldadoensis* (upper Paleocene to lower Eocene), and *Acarinina* spp. (lower to upper Eocene) (Figure 3). These latter taxa, grouped as *A. bullbrooki* by *Bralower et al.* [1995], include considerable morphological variety, grading from older forms which are compressed and somewhat resemble *A. soldadoensis*, to younger conical forms similar to *A. bullbrooki*, to forms which resemble *Truncorotaloides pseudotopilensis*. We have combined species of *Subbotina* (Figure 3) because of taxonomic uncertainties. Observations of foraminiferal preservation were made in a Leica Stereoscan 440 Scanning Electron Microscope in the Geology Department at the University of North Carolina-Chapel Hill. To reduce ontogenetic and other vital effects on the interpretation of stable isotopic results [e.g., *Shackleton et al.*, 1985a; *Corfield and Cartlidge*, 1991; *Pearson et al.*, 1993], almost all of our isotopic investigations were performed on the 300-355 μm fraction. Initially, 25 specimens of each species were picked; however, the eight to 10 best-preserved specimens were selected for isotopic measurement.

Benthic Foraminiferal Taxa

Stable isotopic analyses have been conducted on *Nuttallides truempyi* and species of *Cibicidoides* (large *C. praemundulus*) throughout the section and *Gavelinella beccariiformis* and species of *Lenticulina* in samples from the uppermost Paleocene. Depending on size, between five and 20 benthic foraminifera were picked for isotopic measurement; all specimens were larger than 125 μm in diameter.

Isotopic Analyses

Isotopic analyses were performed in the Stable Isotope laboratory at the University of Michigan. Individual foraminifera were sonicated in distilled water to remove adhering particles and roasted in vacuo at 380° C. The specimens were processed in a Kiel automated carbonate digestion device. Each sample was reacted in an individual vessel with three drops of phosphoric acid at 75° C. The resulting CO_2 was isolated in a single-step distillation and

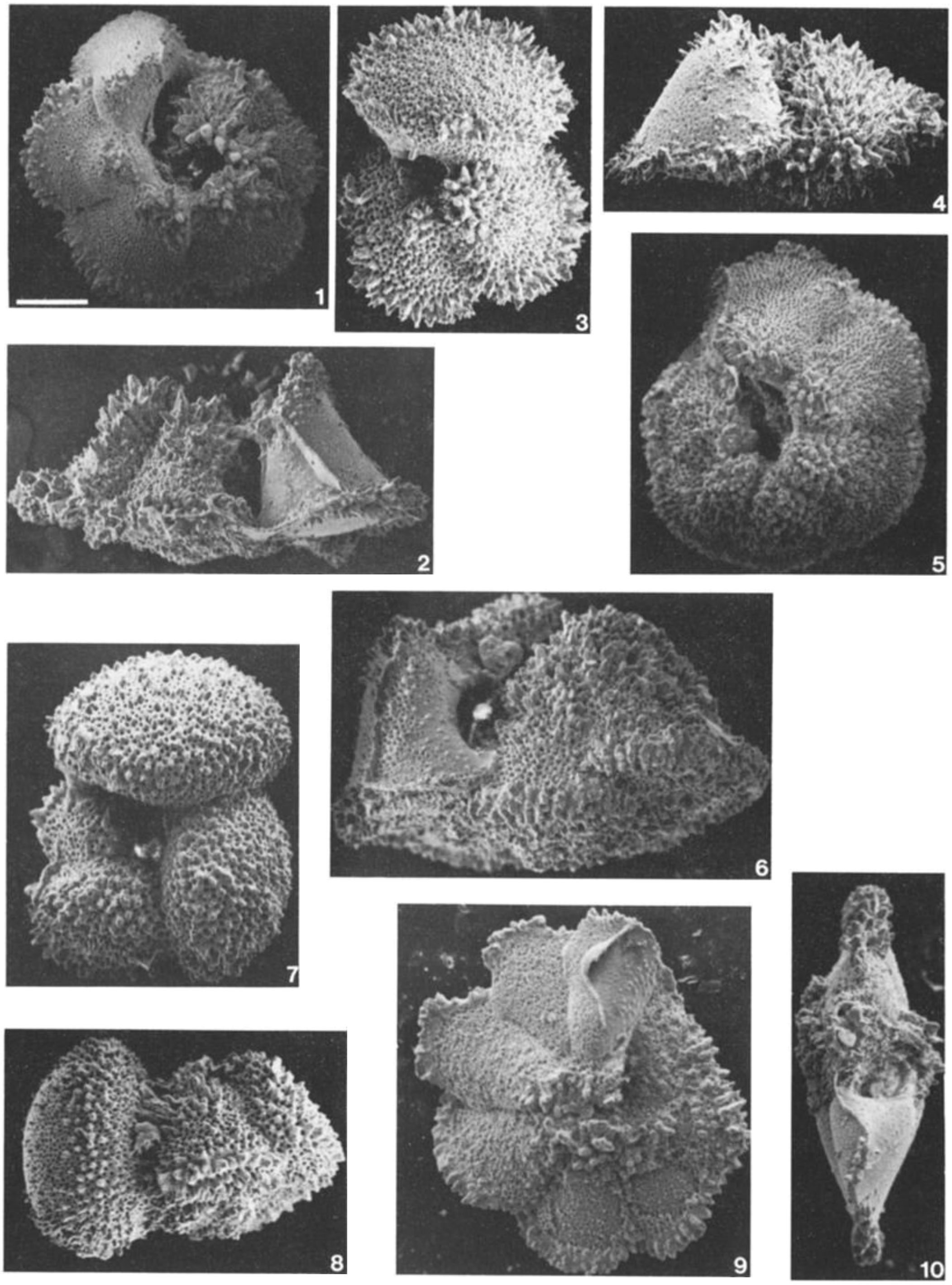

Figure 2. Typical specimens of planktonic foraminifera from Site 865. Specimens 1 and 2 are *Morozovella velascoensis*, specimen 1 is the umbilical view and specimen 2 is the side view; Sample 865C-12H-4, 10-12 cm. Specimens 3 and 4 are *M. subbotinae*, specimen 3 is the umbilical view and specimen 4 is the side view; Sample 865C-12H-4, 10-12 cm. Specimens 5 and 6 are *M. aragonensis*; specimen 5 is the umbilical view and specimen 6 is the side view; Sample 865B-10H-2, 4-6 cm. Specimens 7 and 8 are *M. quetra*, specimen 7 is the umbilical view and specimen 8 is the side view; Sample 865B-10H-2, 60-62 cm. Specimens 9 and 10 are *M. lehneri*, specimen 9 is the umbilical view and specimen 10 is the side view; Sample 865B-4H-6, 20-22 cm. Scale bar represents 100 microns.

introduced directly to the MAT-251 mass spectrometer for measurement. National Bureau of Standards (NBS)-18, -19, and -20 as well as an in-house standard LV-2 were measured on a daily basis to monitor instrument calibration and analytical accuracy. Average precision determined from 40 replicate analyses of planktonic foraminifera was better than ±0.1 for both $\delta^{18}O$ and $\delta^{13}C$ values but significantly lower for benthic foraminifera [*Bralower et al.*, 1995].

In order to calculate paleotemperatures, we used the equation of *Erez and Luz* [1983] and a $\delta^{18}O_{SW}$ value of -0.98‰ for seawater assuming an ice-free earth [*Zachos et al.*, 1994] corrected relative to the Pee Dee belemnite (PDB) standard by subtracting 0.27‰ [*Hut*, 1985]. In addition, to adjust for systematic changes in salinity as a function of latitude, we applied the equation proposed by *Zachos et al.* [1994] to our calculation of SST. This equation is based on the assumption that sea surface salinities were high in the subtropics and low in higher latitudes throughout the Cenozoic as today. While it is possible that the latitudinal salinity gradient has changed through time, there is no evidence to suggest that the pattern or magnitude of this gradient was substantially different than present.

Biostratigraphy and Timescale

Stratigraphic control is largely based on calcareous nannofossil biostratigraphy [*Bralower and Mutterlose*, 1995], indicating that the sequence is largely complete, with apparent unconformities correlating to lower Eocene nannofossil Zone NP13 and an interval around the Eocene/Oligocene boundary. Assemblages are characterized by only minor apparent redeposition concentrated at the top of cores, much of which might have resulted from the soupy nature of the sediments when cored [*Bralower and Mutterlose*, 1995]. Preliminary planktonic foraminiferal biostratigraphy focused on determining the precise location of zonal and subzonal boundaries (I. Premoli Silva and W. V. Sliter, unpublished data, 1994). No magnetostratigraphic control is available. As is standard in low-latitude deep-sea sequences [e.g., *Berggren et al.*, 1985; *Aubry et al.*, 1988; *Berggren et al.*, 1995], we use the last occurrence of the planktonic foraminifer, *Morozovella velascoensis*, to recognize the Paleocene/Eocene boundary. Nannofossil events which have been used to correlate this boundary, the first occurrences of *Tribrachiatus bramlettei* and *Discoaster diastypus* [e.g., *Perch-Nielsen*, 1985], cannot be determined with confidence in Site 865 [*Bralower and Mutterlose*, 1995], although the last occurrence of *Fasciculithus* can be determined precisely. The highest sample analyzed is from the uppermost Eocene based on the occurrences of *Discoaster barbadiensis* and *D. saipanensis*.

Paleogene time scales are currently in a state of flux [*Berggren et al.*, 1992; *Berggren and Aubry*, 1995; *Berggren et al.*, 1995]. The age of the Paleocene/Eocene boundary has commonly been placed at 57.8 Ma [*Berggren et al.*, 1985] or 57 Ma [*Aubry et al.*, 1988], but this value is almost certainly too high in view of newly obtained radiometric dates [*Wing et al.*, 1991; *Berggren et al.*, 1995]. *Cande and Kent* [1992] used a value of 55 Ma in constructing a geomagnetic polarity timescale. Because of inevitable changes in the timescale [e.g., *Berggren et al.*, 1995], we present the isotopic data from Site 865 in plots versus depth (Figures 4-11). In order to compare data from different sites, however, these depths need to be converted to a common reference. Because many sites have magnetostratigraphic control, we utilize the geomagnetic polarity timescale of *Cande and Kent* [1992] as a reference. We have selected several nannofossil and planktonic foraminiferal datums which can be placed reliably in a variety of sites, including Site 865 and which have been correlated to the geomagnetic polarity timescale [e.g., *Berggren et al.*, 1985; *Wei and Wise*, 1989]. The numerical ages of these datums were determined by estimating their average relative positions within the chrons (Table 1), assuming constant sedimentation rates between tie points. For comparison, we include the ages of the same datums taken from *Berggren et al.* [1985] and *Wei and Wise* [1989]. In addition, we include the age of the latest Paleocene benthic foraminiferal extinction following *Pak and Miller* [1992] and *Eldholm and Thomas* [1993] (58 Ma from *Aubry et al.* [1988]; 55.7 Ma from *Cande and Kent,* [1992]).

Results

Observations indicate high current velocities, winnowing, and redeposition on top of Horizon Guyot [*Lonsdale et al.*, 1972]. Similar activity on Allison Guyot as it subsided should have led to pervasive unconformities and condensed sections. Anomalous enrichments of planktonic foraminifera over smaller particles, including calcareous nannofossils, in sediments from Site 865 indicate winnowing. The shallow burial depths (15-135 meters below sea floor (mbsf)) of the Paleogene section at Site 865 resulted in excellent microfossil preservation, particularly among the foraminifera. Some samples contain yellowed, corroded benthic foraminifera that were probably reworked from older materials (these specimens were not used in isotopic and faunal analysis). Benthic foraminiferal specimens are extremely rare in all samples, even for deep-sea benthic foraminifera; about 10-100 times fewer specimens per gram occurred at Site 865 than in samples of similar age and paleodepth from Maud Rise (Weddell Sea, Antarctica [*Thomas*, 1990b]), and Walvis Ridge (S. Atlantic Ocean [*Thomas and Shackleton*, 1995]). Benthic foraminifera occurred at less than 500 per gram in the Paleocene through lower Eocene (below the unconformity at 79 mbsf in Hole 865B), increased to slightly more than 1000 per gram in the first half of the middle Eocene (between 57 and 79 mbsf), decreased to 500-1000 per gram in the upper middle Eocene (57 to 35 mbsf), and increased considerably (1500-2000 per gram) in the uppermost middle Eocene (above 35 mbsf). These extremely low values for benthic foraminiferal abundance, as well as benthic foraminiferal accumulation rates in the Paleocene through middle Eocene, indicate a very low transport of organic matter to the seafloor [*Berger et al.*, 1994], probably as a result of very low primary productivity. The extremely low abundance makes isotopic analyses very time consuming. Stable isotopic data are compiled by *Bralower et al.* [1995] and Table 2, summarized in Table 3, and plotted in Figures 4-14 with more positive $\delta^{18}O$ values to the right in all figures except Figure 12 (versus general convention).

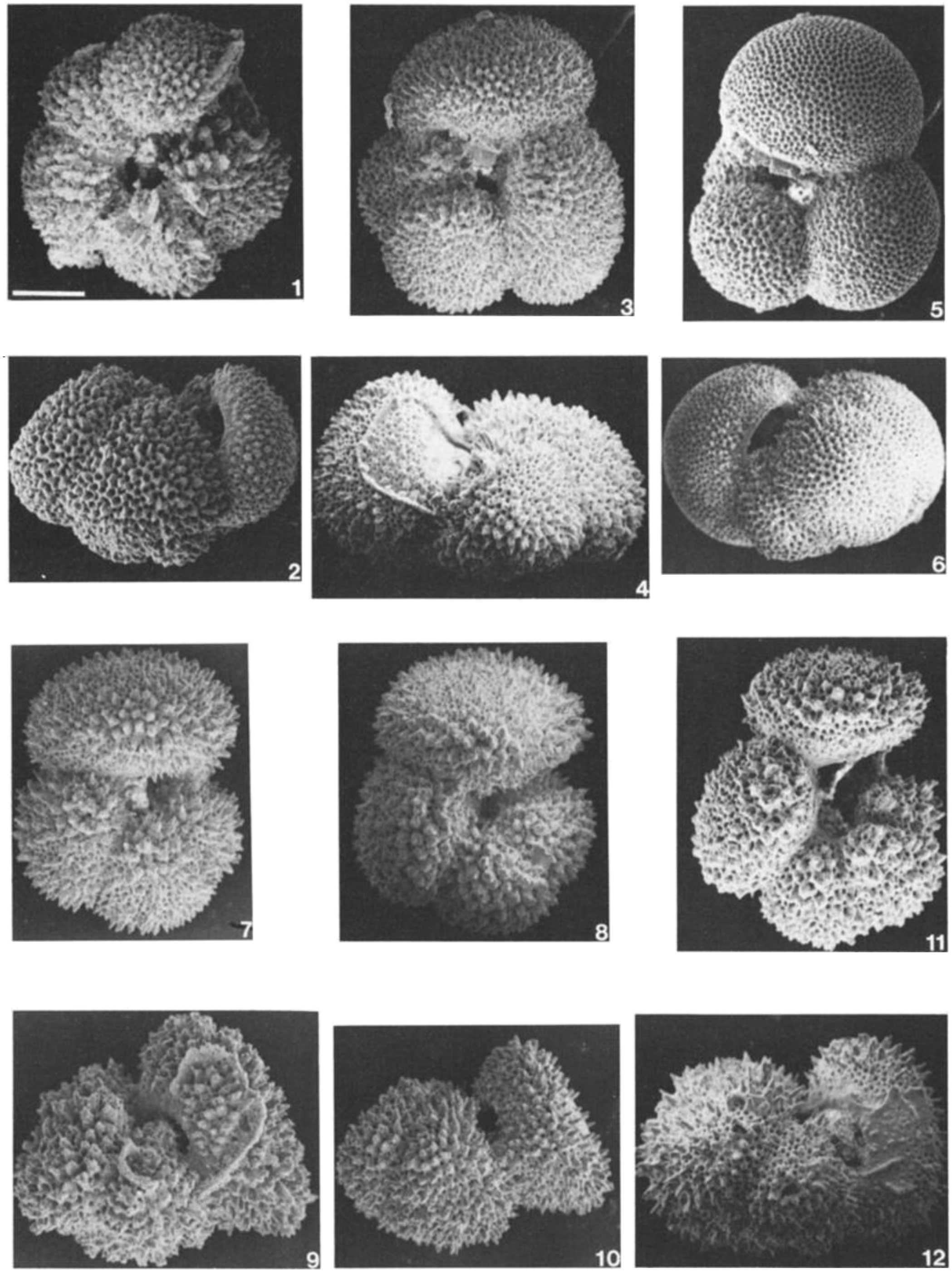

Figure 3. Typical specimens of planktonic foraminifera from Site 865. Specimens 1 and 2 are *Acarinina mckannai*, specimen 1 is the umbilical view and specimen 2 is the side view; Sample 865C-12H-4, 10-12 cm. Specimens 3 and 4 are *A. soldadoensis*; specimen 3 is the umbilical view and specimen 4 is the side view; Sample 865C-10H-4, 60-62 cm. Specimens 5 and 6 are *Subbotina* spp., specimen 5 is the umbilical view and specimen 6 is the side view; Sample 865B-12H-4, 70-72 cm. Specimens 7-10 are *Acarinina* spp., specimens 7 and 8 are umbilical views and specimens 9 and 10 are side views; Sample 865B-7H-1,118-120 cm. Specimens 11 and 12 are *Truncorotaloides rohri*; specimen 11 is the umbilical view, specimen 12 is the side view; Sample 865B-5H-5, 50-72 cm. Scale bar represents 100 microns.

Table 1. Datums Used in the Estimation of Ages for Intersite Comparison

Datum	Polarity Chron[*]	Age (CK92), Ma	Age (BKF85), Ma[†]	Depth 865B[‡]	Depth 865C[‡]
LO *D. barbadiensis*	C13r.0.50	34.11	36.7	18.70	
LO *C. grandis*	C17n.1n.0.20	37.32	40.0	19.32	
LO *C. solitus*	C17r.0.00	38.50	41.3	29.40	
FO *R. umbilicus*	C19r.0.25	42.38	44.6	47.31	
FO *C. gigas*	C20r.0.50	45.08	47.4	67.70	
FO *D. sublodoensis*	C22r.0.00	49.60	52.6	79.60	
LO *T. orthostylus*	C23n.1.0.50	50.73	53.6	79.60	
FO *D. lodoensis*	C24n.1n.0.50	52.39	55.2	89.60	
LO *M. velascoensis*	C24r.0.35	55.00	57.8	100.90	98.30
Benthic foram. extinction		55.70	58.0	102.53-103.50[§]	102.95
FO. *D. multiradiatus*	C25n.0.50	56.26	59.2	116.21	114.60
FO *D. mohleri*	C26n.0.80	58.12	60.5	125.75	
FO *F. tympaniformis*	C26r.0.40	60.21	62.0	132.20	

[*] Terminology is taken from *Cande and Kent* [1992]. Numerical suffix refers to relative position in chron at several sites with base at 0.00 and top at 1.00.

[†] Ages are taken from *Berggren et al.* [1985] and *Wei and Wise* [1989].

[‡] All depths are meters below sea floor.

[§] This depth is between Cores 11 and 12.

Planktonic foraminifera

***Acarinina*: Oxygen isotopes (Figures 4-7).** Oxygen isotopic values show a long-term decrease from -1.8‰ in the uppermost Paleocene (~115 mbsf; nannofossil Zone CP8) to -2.1‰ in the lowermost lower Eocene (~102 mbsf; Zone CP9) and are relatively constant through the lower lower Eocene (~102-84 mbsf; Zones CP9 and CP10) (Figure 4 and Table 3). A sharp 1.0‰ increase in average $\delta^{18}O$ values occurs in the upper lower Eocene (~84-82 mbsf; upper part of Zone CP10 and Zone CP11), followed by an interval of fluctuating values without long-term trend in the uppermost lower Eocene (~82-71 mbsf; Zone CP12). Average $\delta^{18}O$ values in the middle and upper Eocene (Zones CP13 to CP15) show a long-term increase from -1.2‰ to 0.2‰ (~69-20 mbsf; Figure 4). There is little difference between $\delta^{18}O$ values of *A. mckannai* and *A. soldadoensis* measured in the same samples (Figure 5). Oxygen isotopic values of *A. soldadoensis* and *Acarinina* spp. differ to a greater extent (Figure 5).

***Acarinina*: Carbon isotopes (Figures 8-11).** Carbon isotopic values show a steady decrease from average values of about 4.7‰ in the upper Paleocene (~115 mbsf; nannofossil Zone CP8) to an average of 2.6‰ in the lower Eocene (~88-80 mbsf; Zones CP10 and CP11) (Figures 8 and 9 and Table 3). A slight increase to average values close to 3.0‰ occurs in Zones CP12 and CP13 (~80-50 mbsf). The $\delta^{13}C$ values of *A. mckannai* and *A. soldadoensis* are similar, but values for *A. soldadoensis* and *Acarinina* spp. in the lower Eocene are up to 0.6‰ different (Figure 9).

***Morozovella*: Oxygen isotopes (Figures 4-7).** Oxygen isotopic values for *Morozovella* from Hole 865B show similar patterns to those of *Acarinina* but cover a longer stratigraphic interval (Figure 4 and Table 3). Two long-term trends are clear: (1) a decrease from an average of ~-1.4‰ in the lower upper Paleocene (~130-124 mbsf; nannofossil Zone CP4 to the lower part of Zone CP6) to an average of -2.0‰ in the lowermost Eocene (~102-84 mbsf; Zones CP9 and CP10), followed by (2) an increase to -0.3‰ in the upper Eocene (~20 mbsf; Zone CP15). As in the record of *Acarinina*, a rapid 1.0‰ decrease in $\delta^{18}O$ values occurs in lower Eocene Zones CP10 and CP11 (~86-81 mbsf; Figure 5), and an interval with fluctuating values occurs in Zone CP11 to the lower part of Zone CP13 (~81-68 mbsf).

Oxygen isotopic values of *M. subbotinae* are up to 0.2‰ heavier than those of *M. velascoensis* and between 0.1‰ heavier and 0.2‰ lighter than those of *M. aragonensis* (Figure 5). Oxygen isotopic values of *M. aragonensis* are between 0.2 and 0.4‰ lighter than those of *M. lehneri* (Figure 6).

***Morozovella*: Carbon isotopes (Figures 8-11).** Carbon isotopic values show similar trends to those of *Acarinina* (Figures 8-10 and Table 3). Values increase from 3.8‰ in the lower upper Paleocene (~130 mbsf; nannofossil Zone CP5) to 5.1‰ in the middle upper Paleocene (~118 mbsf; Zone CP7), then decrease through the uppermost Paleocene and lower Eocene (~118-80 mbsf; Zones CP8 to CP11) to an average of 2.5‰, followed by a gradual increase to an average of 3.0‰ in the lower middle Eocene (~74-61 mbsf; Zone CP13). Upper middle and upper Eocene $\delta^{13}C$ values show a gradual decline to 2.6‰ (~20 mbsf; Zone CP15). Overlapping records illustrate slightly different $\delta^{13}C$ values for different species of *Morozovella*: *M. subbotinae* is up to 0.2‰ heavier than *M. velascoensis* and up to 0.5‰ heavier than *M. aragonensis* (Figure 9). Values of *M. aragonensis* in turn are up to 0.2‰ lighter than those of *M. lehneri* (Figure 10).

***Subbotina*: Oxygen isotopes (Figures 4-7).** Oxygen isotopic values of *Subbotina* show more variability than those of the other planktonic genera (Figure 4 and Table 3); average values decrease from about 0.0‰ in the lower upper Paleocene (~128-124 mbsf; top of Zone CP5 and bottom of Zone CP6) to ~-1.3‰ in the uppermost Paleocene (~117-103

Table 2. Additional Stable Isotopic Data for Site 865

Hole-Core	Sec.	Interval, cm	mbsf	Taxon	Size, µm	δ13C, ‰	δ18O, ‰
B-13H	1	21-23	113.21	*Subbotina* spp	300-355	2.77	-1.28
B-12H	4	70-72	108.70	*Subbotina* spp	300-355	2.77	-1.39
B-12H	3	20-22	106.70	*Subbotina* spp	300-355	2.67	-1.26
C-12H	4	20-22	103.00	*A. soldadoensis*	300-355	4.05	-2.18
C-12H	4	20-22D	103.00	*A. soldadoensis*	300-355	4.26	-1.97
C-12H	4	30-32	103.10	*A. soldadoensis*	300-355	4.28	-1.96
C-12H	4	40-42	103.20	*A. soldadoensis*	300-355	4.05	-2.03
C-11H	6	52-54	96.82	*Subbotina* spp.	300-355	1.74	-0.97
C-12H	1	10-12	98.40	*Subbotina* spp.	300-355	1.68	-0.96
C-12H	1	60-62	98.90	*Subbotina* spp.	250-300	1.81	-1.06
C-12H	2	70-72	100.50	*Subbotina* spp.	300-355	2.00	-1.02
C-12H	2	70-72	100.50	*Subbotina* spp.	300-355	2.06	-1.50
C-12H	3	00-02	101.30	*Subbotina* spp.	250-300	2.07	-1.39
C-12H	3	10-12	101.40	*Subbotina* spp.	250-300	1.82	-1.47
C-12H	3	30-32	101.60	*Subbotina* spp.	300-355	2.00	-1.47
C-12H	3	50-52	101.80	*Subbotina* spp.	300-355	1.83	-1.32
C-12H	3	60-62	101.90	*Subbotina* spp.	300-355	1.81	-1.16
C-12H	3	70-72	102.00	*Subbotina* spp.	300-355	1.78	-1.06
C-12H	3	80-82	102.10	*Subbotina* spp.	300-355	1.79	-1.18
C-12H	3	90-92	102.20	*Subbotina* spp.	300-355	1.66	-0.78
C-12H	3	110-112	102.40	*Subbotina* spp.	250-300	1.76	-1.04
C-12H	3	120-122	102.50	*Subbotina* spp.	300-355	1.45	-0.88
C-12H	3	130-132	102.60	*Subbotina* spp.	300-355	1.47	-0.80
C-12H	3	140-142	102.70	*Subbotina* spp.	300-355	2.01	-0.76
C-12H	3	140-142D	102.70	*Subbotina* spp.	300-355	1.93	-1.31
C-12H	4	10-12	102.90	*Subbotina* spp.	300-355	1.53	-1.64
C-12H	4	20-22	103.00	*Subbotina* spp.	300-355	2.26	-1.56
C-12H	4	20-22D	103.00	*Subbotina* spp.	300-355	2.22	-1.28
C-12H	4	30-32	103.10	*Subbotina* spp.	300-355	2.39	-1.26
C-12H	4	40-42	103.20	*Subbotina* spp.	300-355	2.14	-0.80
C-12H	4	50-52	103.30	*Subbotina* spp.	300-355	2.61	-1.48
C-12H	4	60-62	103.40	*Subbotina* spp.	300-355	2.17	-0.90
C-12H	4	70-72	103.50	*Subbotina* spp.	300-355	2.01	-0.42
C-12H	4	80-82	103.60	*Subbotina* spp.	300-355	2.55	-1.29
C-12H	4	90-92	103.70	*Subbotina* spp.	300-355	3.72	-1.55
C-12H	4	110-112	103.90	*Subbotina* spp.	300-355	2.77	-1.50
C-12H	4	120-122	104.00	*Subbotina* spp.	300-355	2.77	-1.51
C-12H	4	130-132	104.10	*Subbotina* spp.	300-355	2.54	-1.26
C-12H	4	140-142	104.20	*Subbotina* spp.	300-355	2.55	-1.35
C-12H	5	00-02	104.30	*Subbotina* spp.	300-355	2.60	-1.51
C-12H	5	70-72	105.00	*Subbotina* spp.	300-355	2.75	-1.10
C-12H	5	70-72D	105.00	*Subbotina* spp.	300-355	2.67	-1.28
C-12H	5	130-132	105.60	*Subbotina* spp.	300-355	2.30	-0.76

D after centimeter interval refers to duplicate analysis. All analyses are reported with respect to Pee Dee belemnite (PDB) standard. Sec. is section. mbsf is meters below sea floor.

mbsf; Zone CP8) and increase steadily to ~0.8 ‰ in the upper Eocene (~29-20 mbsf; Subzone CP14b and Zone CP15). Short-term decreases of up to -1.2‰ and 0.6‰ in $\delta^{18}O$ values occur between 91 and 85 mbsf and between 60 and 70 mbsf, respectively.

***Subbotina*: Carbon isotopes (Figures 8-11).** The $\delta^{13}C$ record of *Subbotina* resembles those of the other two genera (Figure 8 and Table 3). Carbon isotopic values increase from ~1.8‰ in the lower upper Paleocene (~133 mbsf; nannofossil Zone CP5) to ~3.0‰ in the middle part of the upper Paleocene (~118 mbsf; Zone CP7) then decrease to ~1.0‰ in the lower Eocene (~91 mbsf; Zone CP9) (Figure 9). Values fluctuate between 1.0‰ and 2.0‰ throughout the remainder of the Eocene (~91-20 mbsf).

Benthic foraminifera

Oxygen isotopes (Figures 4-7). Benthic foraminiferal measurements could not be conducted at a similar resolution as that of the planktonic foraminifera because of the extreme and unusual rarity of benthic foraminifera. We chose to include the incomplete record in order to demonstrate at least to some degree the intermediate water developments. Replicate measurements of benthic foraminifera yield greater variability than those of planktonic foraminifera [*Bralower et al.*, 1995]. This difference averages 0.93‰ (s=0.92; n=5) for $\delta^{18}O$ values and 0.53‰ for $\delta^{13}C$ values (s=0.38; n=5). We do not think that this larger variability results from "vital effects" (either size or microhabitat related), because the variability in $\delta^{18}O$ values is larger than that in $\delta^{13}C$ values, while it has been well

Table 3. Mean Carbon and Oxygen Isotopic Values of Planktonic and Benthic Foraminifer Taxa in Individual Nannofossil Zones

	Acarinina			*Morozovella*			*Subbotina*			*Cibicidoides*			*N. truempyi*			*Gavelinella*		
	X	σ	n	X	σ	n	X	σ	n	X	σ	n	X	σ	n	X	σ	n
							$\delta^{13}C$ values (‰ versus PDB)											
CP15	1.48		1	2.60		1	1.32		1									
CP14	2.29	0.66	19	2.80	0.13	20	1.48	0.15	20	0.66	0.21	7	0.14	0.14	7			
CP13	3.02	0.35	20	3.06	0.20	16	1.68	0.21	20	0.50	0.08	5	0.16	0.21	10			
CP12	2.89	0.16	9	2.71	0.20	8	1.78	0.17	7	1.10		1	0.59		1			
CP11	2.58	0.34	14	2.46	0.36	10	1.68	0.17	10	0.78		1	0.30	0.45	2			
CP10	2.71	0.28	12	2.71	0.20	13	1.50	0.33	11	0.03		1	-0.17		1			
CP9	3.30	0.31	23	3.47	0.38	21	1.55	0.31	15	0.75	0.23	4	0.39	0.64	3			
CP8	4.06	0.66	40	4.27	0.52	49	2.42	0.32	29	0.88	0.76	6	1.11	0.59	4	1.73	0.03	2
CP7				4.74	0.26	11	2.73	0.13	10									
CP6				4.35	0.10	6	2.35	0.13	3							1.87		1
CP5				4.12	0.19	7	2.31	0.14	4									
CP4				3.77		1	2.04	0.17	4									
CP3													0.27		1	0.59	0.13	2
							$\delta^{18}O$ values (‰ versus PDB)											
CP15	0.20		1	-0.30		1	0.82		1									
CP14	-0.35	0.31	19	-0.56	0.13	20	0.36	0.41	20	0.78	0.24	7	0.75	0.16	7			
CP13	-0.88	0.30	20	-1.11	0.35	16	-0.11	0.23	20	0.36	0.21	5	0.24	0.32	10			
CP12	-1.16	0.14	9	-1.55	0.17	8	-0.38	0.11	7	-0.35		1	-0.55		1			
CP11	-1.29	0.24	14	-1.56	0.22	10	-0.54	0.22	10	-0.12		1	-0.56	0.00	2			
CP10	-1.98	0.13	12	-2.00	0.14	13	-1.07	0.42	11	-0.53		1	-0.45		1			
CP9	-2.10	0.12	23	-1.96	0.13	21	-1.05	0.30	15	-0.26	0.12	4	-0.26	0.16	3			
CP8	-1.92	0.13	40	-1.86	0.14	49	-1.32	0.58	29	-0.09	0.27	6	-0.03	0.28	4	0.06	0.11	2
CP7				-1.69	0.14	11	-0.85	0.29	10									
CP6				-1.48	0.14	6	0.18	0.13	3							0.25		1
CP5				-1.36	0.15	7	-0.15	0.49	4									
CP4				-1.42		1	-0.44	0.25	4									
CP3													-0.64		1	0.10	0.33	2

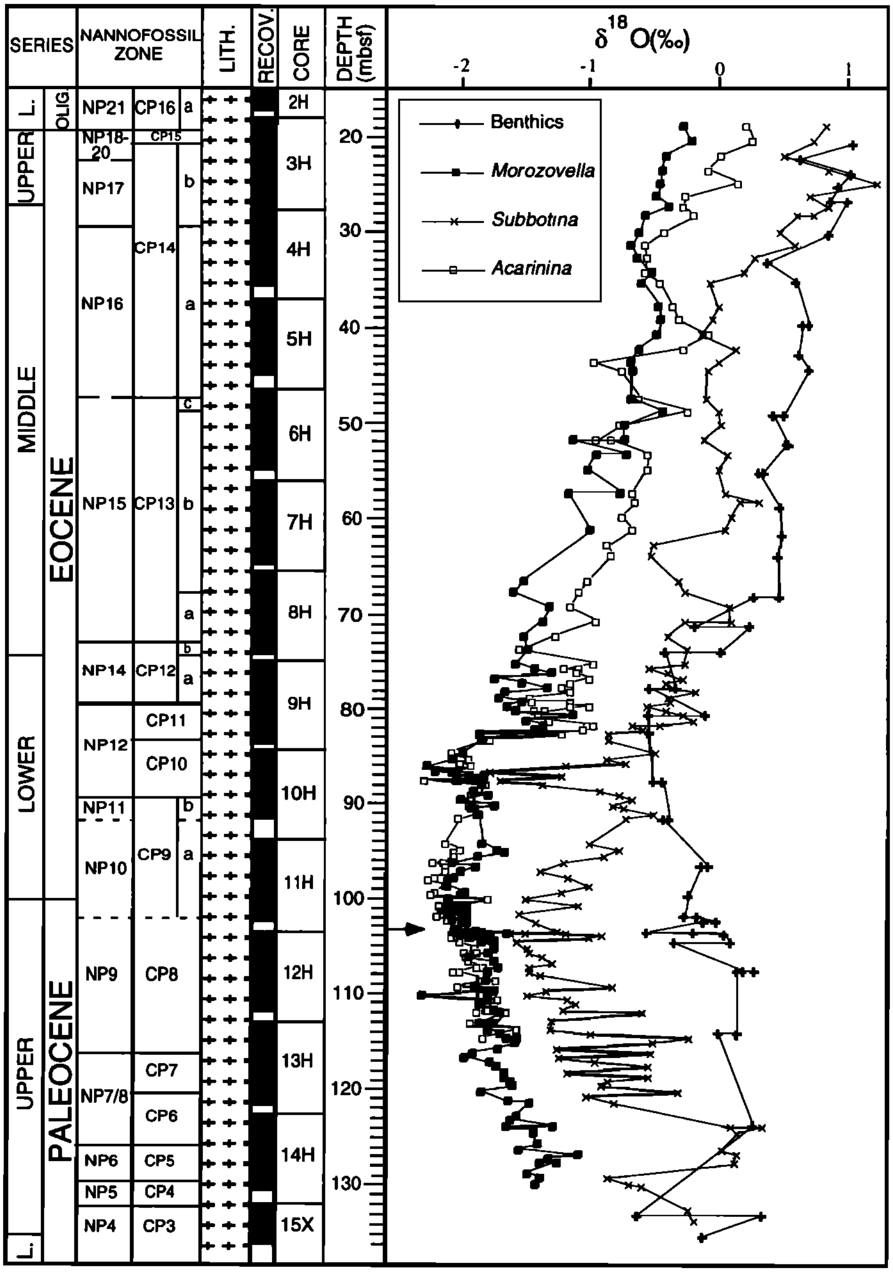

Figure 4. Planktonic and benthic foraminifer $\delta^{18}O$ (‰ versus Pee Dee belemnite (PDB)) records of the upper Paleocene to upper Eocene of Hole 865B. Planktonic taxa are grouped into genera, and benthic taxa are combined. Calcareous nannofossil zones of *Martini* [1971] and *Bukry* [1973, 1975] (using terminology of *Okada and Bukry* [1980]) are shown at left. Arrow indicates position of benthic foraminiferal extinction.

documented that microhabitat variability very strongly influences $\delta^{13}C$ values but not $\delta^{18}O$ values [e.g., *McCorkle et al.*, 1990; *Woodruff and Savin*, 1985]. We think that the benthic variability is so much larger than that of the planktonics because the benthic samples were larger (thus representing a longer time), and the specimens are extremely rare and thus represent the full sample thickness (representing 3000 to 7500 years throughout most of the section). More data are being collected to evaluate this problem fully.

Analyses of separate taxa from the same samples mostly differ by small amounts (0.1-0.3‰) with one exception (Sample 865B-15X-1, 120-125 cm) in which $\delta^{18}O$ values in *G. beccariiformis* and *N. truempyi* differ by close to 1.0‰ (Figure 5). There appear to be no consistent offsets between *Cibicidoides* spp. and *N. truempyi* [*Shackleton and Hall*, 1984; *Katz and Miller*, 1991; *Pak and Miller*, 1992]. The $\delta^{18}O$ record for benthic foraminifera shows the same general trends as those for the planktonic foraminiferal taxa (Figure 4). Oxygen isotopic values in the upper Paleocene (~135-108 mbsf; nannofossil Zones CP3 to CP8) average close to 0.0‰. Average values decrease steadily in the upper Paleocene-lower Eocene (~108-92 mbsf; Zones CP8 to CP9) to ~-0.5‰ in Zones

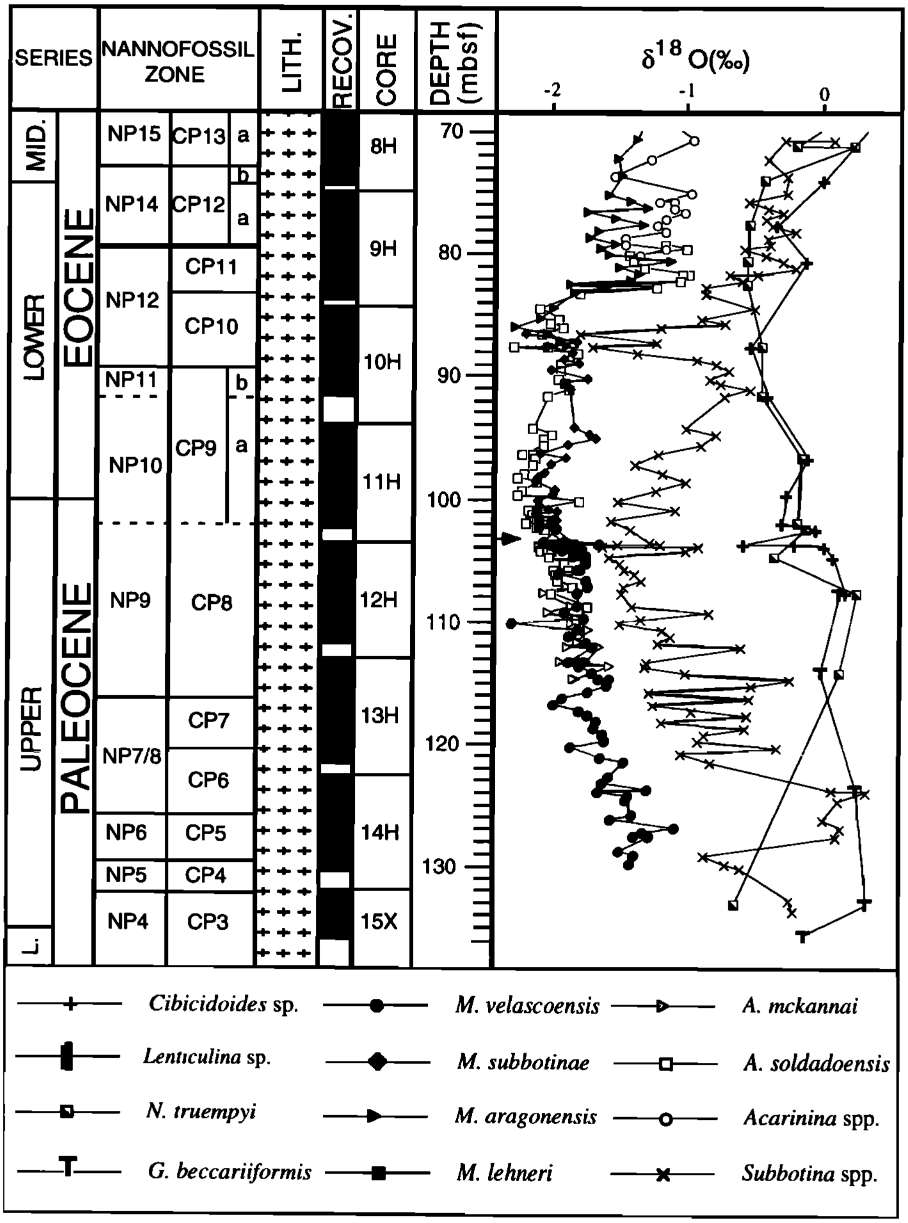

Figure 5. Planktonic and benthic foraminifer $\delta^{18}O$ (‰ versus PDB) records of the upper Paleocene to lowermost Eocene of Hole 865B. Planktonic taxa are separated into species, and benthic taxa are differentiated. See key below for symbols. Arrow indicates position of benthic foraminiferal extinction.

CP10 to CP12 (~90-74 mbsf; Figure 5 and Table 2). Average $\delta^{18}O$ values increase markedly in the lower part of the middle Eocene (~74-68 mbsf; Subzones CP12b and CP13a) to ~0.3‰. For the remainder of the Eocene, values increase steadily, attaining an average of ~0.8‰ in the upper middle and lower upper Eocene (~30-20 mbsf; top of Zone CP14 and Zone CP15) (Figure 6). In the upper Paleocene, $\delta^{18}O$ values measured on benthic foraminifera are up to 2.0‰ heavier than those measured on planktonic foraminifera in the same samples. This difference decreases to less than 1.0‰ in the upper lower and middle Eocene (Figures 5 and 6).

Carbon isotopes (Figures 8-11). Measurements on *G. beccariiformis*, *Cibicidoides* spp., and *N. truempyi* show a fairly consistent offset, with the latter species recording average $\delta^{13}C$ values 0.3-0.5‰ lighter than the former two taxa for most of the interval analyzed (Table 3 [e.g., *Pak and Miller*, 1992]). The *N. truempyi* record and the combined *G. beccariiformis* and *Cibicidoides* spp. record show similar trends with an increase in average values of about 0.9 to 1.1‰ in the upper Paleocene (~135-104 mbsf; nannofossil Zones CP3 to CP8), a decrease to ~0.0‰ in the lowermost Eocene (~91-83 mbsf; Zones CP9 to CP10), stable values through much of the lower and middle Eocene (~91-27 mbsf; Zone CP10 to Subzone CP14b), and the beginning of an increase in the upper Eocene (27-21 mbsf; Subzone CP14b) (Figures 9 and 10).

A negative $\delta^{13}C$ excursion of about 1.4‰ occurs in the *Cibicidoides* spp. record between Samples 865B-12H-1, 40-42

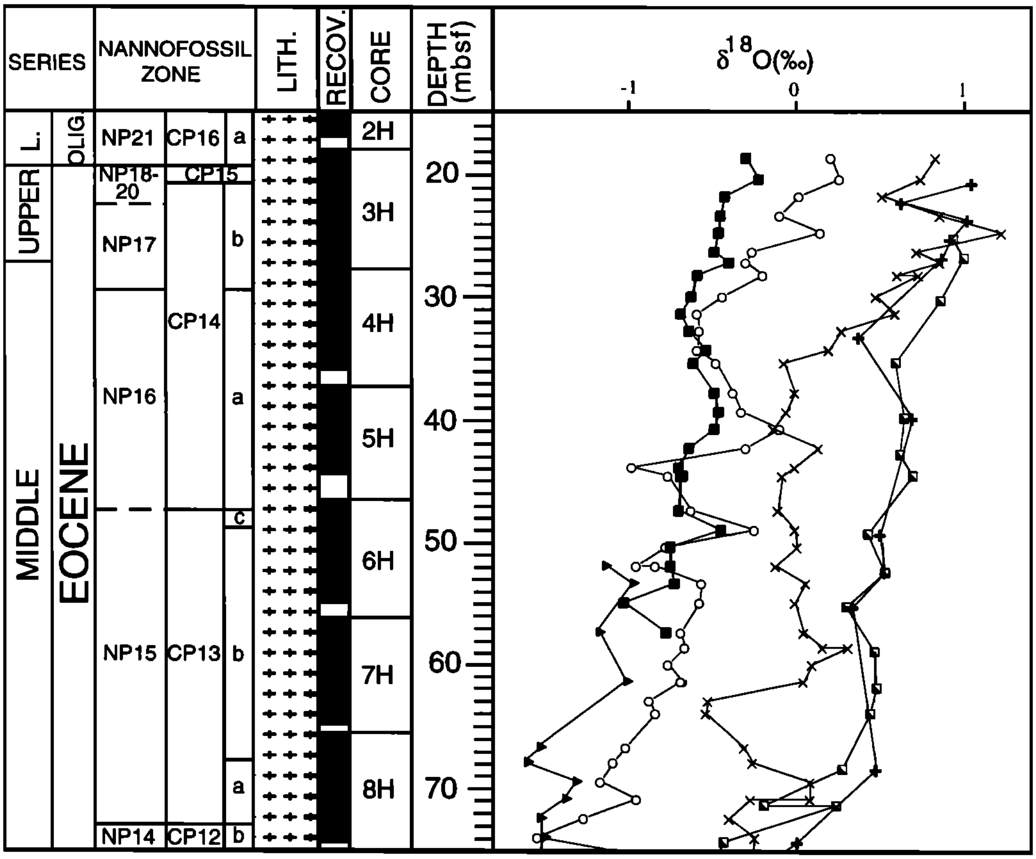

Figure 6. Planktonic and benthic foraminifer $\delta^{18}O$ (‰ versus PDB) records of the lower to upper Eocene of Hole 865B. Planktonic taxa are separated into species, and benthic taxa are differentiated. See key in Figure 5 for symbols.

cm and -12H-1, 10-12 cm (103.9-103.6 mbsf; Figure 9). The *N. truempyi* record shows the same general trend based on a coarser set of samples.

In Hole 865C, carbon isotopic measurements on *Cibicidoides* spp. show a marked negative excursion of approximately 2.0‰ in the uppermost Paleocene from near 1.5‰ to -0.8‰ (102.9-102.7 mbsf; Figure 11). Values are offset consistently from those of the planktonic taxa, with the exception of one sample (865C-12H-4, 10 cm; 102.9 mbsf). The excursion in $\delta^{13}C$ measured on four samples of *Lenticulina* is offset downward by 20 cm from that of *Cibicidoides* spp.

Discussion

Relative Isotopic Values of Different Planktonic Genera

Previous studies have demonstrated the systematic differences (hereafter termed offsets) between $\delta^{18}O$ and $\delta^{13}C$ values for *Morozovella* and *Subbotina* [*Boersma et al.*, 1979; *Shackleton et al.* 1985a; *Corfield and Cartlidge*, 1991; *Pearson et al.*, 1993; *D'Hondt et al.*, 1994]. Lower $\delta^{18}O$ and higher $\delta^{13}C$ values for *Morozovella* indicate that it probably lived within the mixed layer, whereas higher $\delta^{18}O$ and lower $\delta^{13}C$ values for *Subbotina* suggest a habitat within or below the thermocline [e.g., *Stott et al.*, 1990; *Pearson et al.*, 1993; *D'Hondt et al.*, 1994]. Data from Site 865 agree with these established patterns. Differences between isotopic values of deep-dwelling *Subbotina* and the two surface-dwelling genera are between 0.5 and 1.5‰ for $\delta^{18}O$ and 1.0 and 2.0‰ for $\delta^{13}C$ (Figures 4 and 8), similar to values from high-latitude sites [e.g., *Stott et al.*, 1990]. Records of $\delta^{18}O$ and $\delta^{13}C$ values of *Subbotina* contain considerably more short-term variability than the records for the other two genera, reflecting either greater (1) habitat variability of this taxon, (2) environmental heterogeneity of deeper surface waters, or (3) interspecific variability within *Subbotina* compared to monospecific analyses of the other planktonic genera.

Some intervals in the Eocene are characterized by convergence in the $\delta^{13}C$ values of *Acarinina* spp. and *Subbotina* spp. (Figures 9 and 10). In only one of eight samples in which $\delta^{13}C$ values for the two taxa converge, however, are $\delta^{18}O$ values similar (Figures 5 and 6). If depth habitat was responsible for the convergence of *Subbotina* spp. and the surface water species, we would expect both $\delta^{13}C$ and $\delta^{18}O$ values to converge. Therefore we postulate that the variability in the middle-upper Eocene *Acarinina* record is a result of changes in vital processes over time. It is possible that *Acarinina* increased its depth habitat but not to the depth at which *Subbotina* reside.

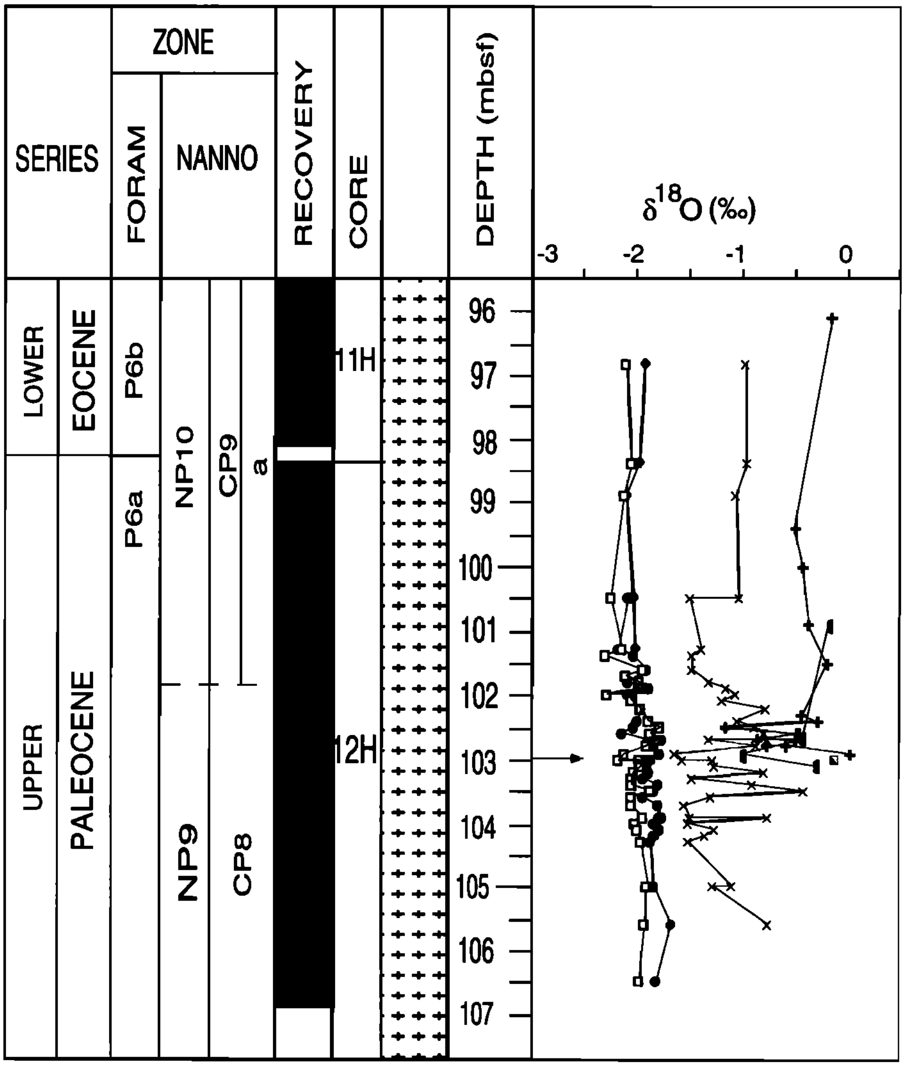

Figure 7. Planktonic and benthic foraminifer δ^{18}O (‰ versus PDB) records of the uppermost Paleocene and lowermost Eocene of Hole 865C. Planktonic taxa are separated into species, and benthic taxa are differentiated. See key in Figure 5 for symbols. Calcareous nannofossil zones of *Martini* [1971] and *Bukry* [1973, 1975] are shown at left. Planktonic foraminifer subzones of *Berggren and Miller* [1988] as determined by D. C. Kelly are indicated. Arrow indicates position of benthic foraminiferal extinction.

Although *Acarinina* is inferred to have been a surface dweller [e.g., *Pearson et al.*, 1993], previous comparisons of its isotopic values with *Morozovella* have been mostly inconsistent. Distinguishable offsets between *Acarinina* and *Morozovella* exist at Site 865. Below 96 mbsf at Site 865, *A. mckannai* and *A. soldadoensis* give δ^{13}C values consistently 0.1 to 0.2‰ lighter than species of *Morozovella* including *M. velascoensis* and *M. subbotinae* (Figure 9). *A. soldadoensis* δ^{18}O values are consistently lighter by 0.1 to 0.2‰ than those of *Morozovella* species through the uppermost Paleocene and lower Eocene (Figure 5), except near the Paleocene/Eocene boundary. In the upper lower Eocene to upper Eocene interval, species of *Acarinina* (mostly *Acarinina* spp.) contain consistently higher δ^{18}O values by 0.1 to 0.5‰ than those of *Morozovella* (*M. aragonensis* and *M. lehneri*), but there is no consistent offset in δ^{13}C. The smaller (0.1‰) offsets are not statistically significant, but offsets larger than 0.2‰ are. Analyses of *Acarinina* and *Morozovella* were mostly performed separately several months apart and have been corrected for long-term "machine drift" [*Bralower et al.*, 1995]. The fact that the offset between *Acarinina* and *Morozovella* in the upper Paleocene-lower Eocene is opposite from that in the lower-upper Eocene intervals suggests that this phenomenon is a result of factors other than "machine drift."

Consistent offsets between *Acarinina* and *Morozovella* have been observed only in two other data sets. Similar offsets to those observed at Site 865 were recorded between combined species of *Morozovella* and *Acarinina* in the upper Paleocene-lower Eocene of South Atlantic Site 524 [*Oberhänsli and Tourmarkine*, 1985]. In a study of various size fractions of late Paleocene planktonic foraminifera, *Acarinina nitida* was found to record lower δ^{13}C values than *Morozovella subbotinae* and *M. velascoensis* [*D'Hondt et al.*, 1994]. No reasons were

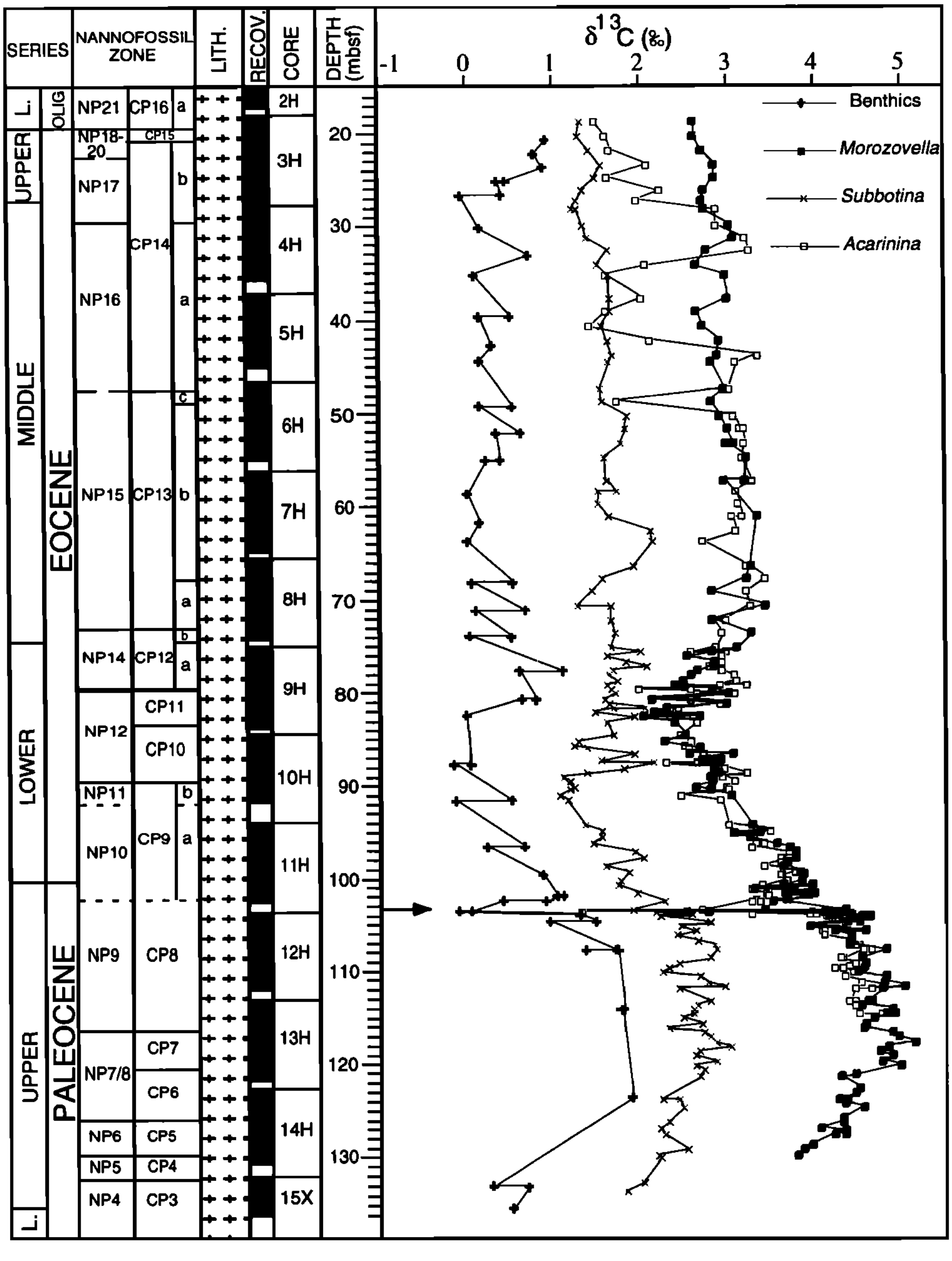

Figure 8. Planktonic and benthic foraminifer δ^{13}C (‰ versus PDB) records of the upper Paleocene to upper Eocene of Hole 865B. Planktonic taxa are grouped into genera, and benthic taxa are combined. Calcareous nannofossil zones of *Martini* [1971] and *Bukry* [1973, 1975] are shown at left. Arrow indicates position of benthic foraminiferal extinction.

given for the offsets in either study. Small but consistent offsets between species may be the result of differences in depth habitat, season of growth, or vital effects. Without ontogenetic information, distinguishing between these two possibilities [e.g., *D'Hondt and Zachos*, 1993] is difficult. When both δ^{18}O and δ^{13}C values are offset consistently, as in the upper Paleocene-lower Eocene, it is likely that paleohabitat depth is a factor. On the basis of present-day profiles in δ^{13}C [e.g., *Kroopnick et al.*, 1977], the 0.2‰ offset can be explained by minor (<100 m) differences in depth. Where only δ^{18}O values are offset, as in the middle and upper Eocene, paleohabitat depth difference is less likely, and vital effects are more probable.

In most other sections where joint measurements of *Acarinina* and *Morozovella* have been made, consistent offsets have not been observed. *Boersma et al.* [1979] showed in samples with joint δ^{18}O analyses that in five of seven cases values of *Acarinina* are lower than those of *Morozovella*. *Pearson et al.* [1993] concluded that relative isotopic values between the two genera, and between individual species of

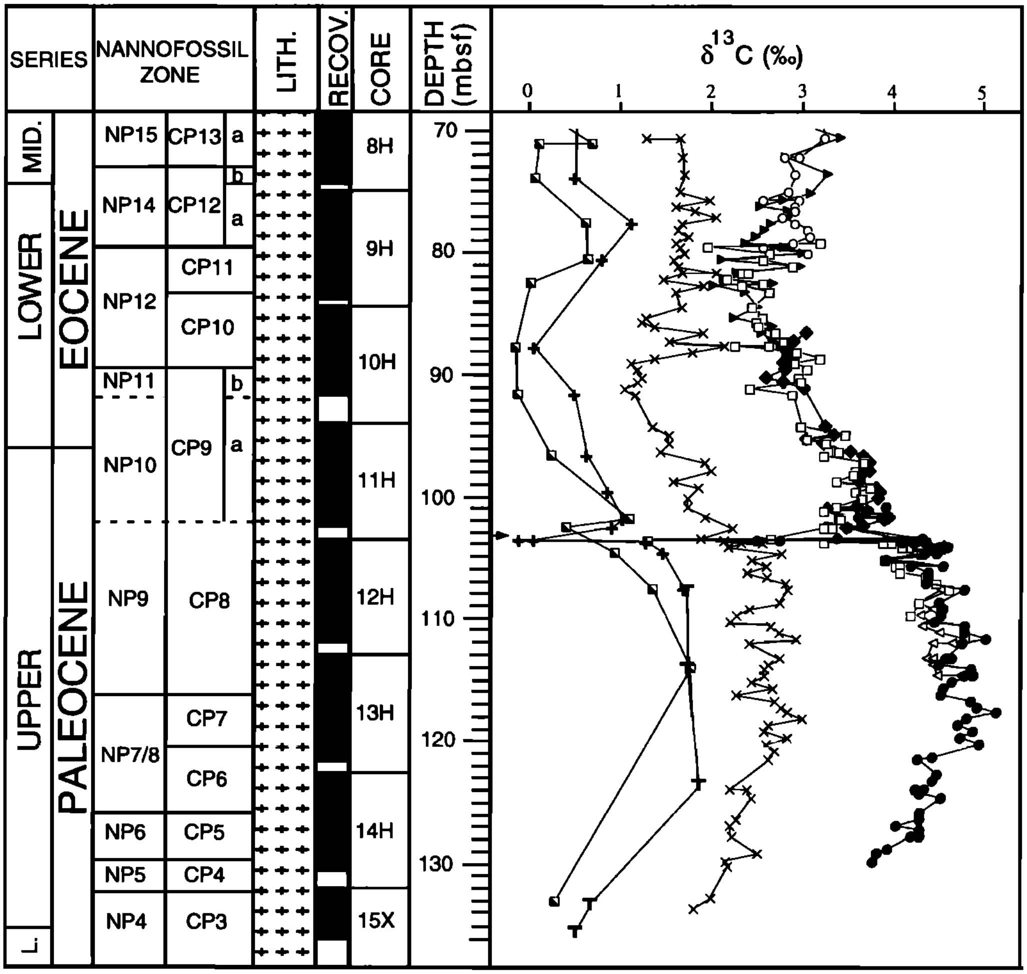

Figure 9. Planktonic and benthic foraminifer $\delta^{13}C$ (‰ versus PDB) records of the upper Paleocene to lowermost Eocene of Hole 865B. Planktonic taxa are separated into species, and benthic taxa are differentiated. See key in Figure 5 for symbols. Arrow indicates position of benthic foraminiferal extinction.

them, are variable in middle Eocene samples. The apparent lack of offsets between these genera at other sites may result from slight diagenetic overprinting which may tend to homogenize sample isotope ratios. Alternatively, the equatorial water column at Site 865 with a steeper thermal gradient may have had more distinct habitat separation.

Long-Term Isotopic Trends and Short-Term Variability: Comparison With Other Sites

The record of upper Paleocene to upper Eocene planktonic and benthic $\delta^{18}O$ and $\delta^{13}C$ values for Hole 865B is similar to records from other sites [e.g., *Shackleton and Boersma*, 1981; *Oberhänsli et al.*, 1984; *Shackleton et al.*, 1984; *Keigwin and Corliss*, 1986; *Shackleton*, 1986; *Miller et al.*, 1987; *Kennett and Stott*, 1990; *Stott et al.*, 1990; *Barrera and Huber*, 1991; *Corfield and Cartlidge*, 1992; *Corfield et al.*, 1992; *Pak and Miller*, 1992; *Zachos et al.*, 1992a, b; *Lu and Keller*, 1993]. Our data set is the only one from equatorial Pacific waters and contains detailed measurements of three planktonic genera (*Acarinina*, *Morozovella*, and *Subbotina*) through most of the interval of interest. In high-latitude sites [e.g., *Stott et al.*, 1990; *Barrera and Huber*, 1991; *Lu and Keller*, 1993], large, ornate morozovellids that typify tropical assemblages are absent or very rare. In temperate and low-latitude records, published long-term $\delta^{18}O$ records are mostly based on one or two genera [e.g., *Shackleton et al.*, 1984; *Corfield and Cartlidge*, 1992]. Analysis of three different low-latitude genera has been performed on short stratigraphic intervals only [e.g., *Shackleton et al.*, 1985a] or in single-sample comparisons [e.g., *Boersma et al.*, 1979; *Boersma et al.*, 1987]. Because the three genera were thought to inhabit variable water depths [e.g., *Boersma et al.*, 1987], we can use their $\delta^{18}O$ and $\delta^{13}C$ values to interpret the structure of surface waters through time in terms of thermal and nutrient gradients.

Carbon isotopic values of planktonic foraminifera increase in the upper Paleocene, reach a peak in its uppermost part, and then decrease gradually across the Paleocene/Eocene boundary into the lower Eocene as in other sites [e.g., *Shackleton and Hall*, 1984; *Shackleton et al.*, 1985b; *Corfield and Cartlidge*, 1992] (Figure 8). Our data exhibit a slight increase in $\delta^{13}C$ values in all three genera from the lower to the middle Eocene,

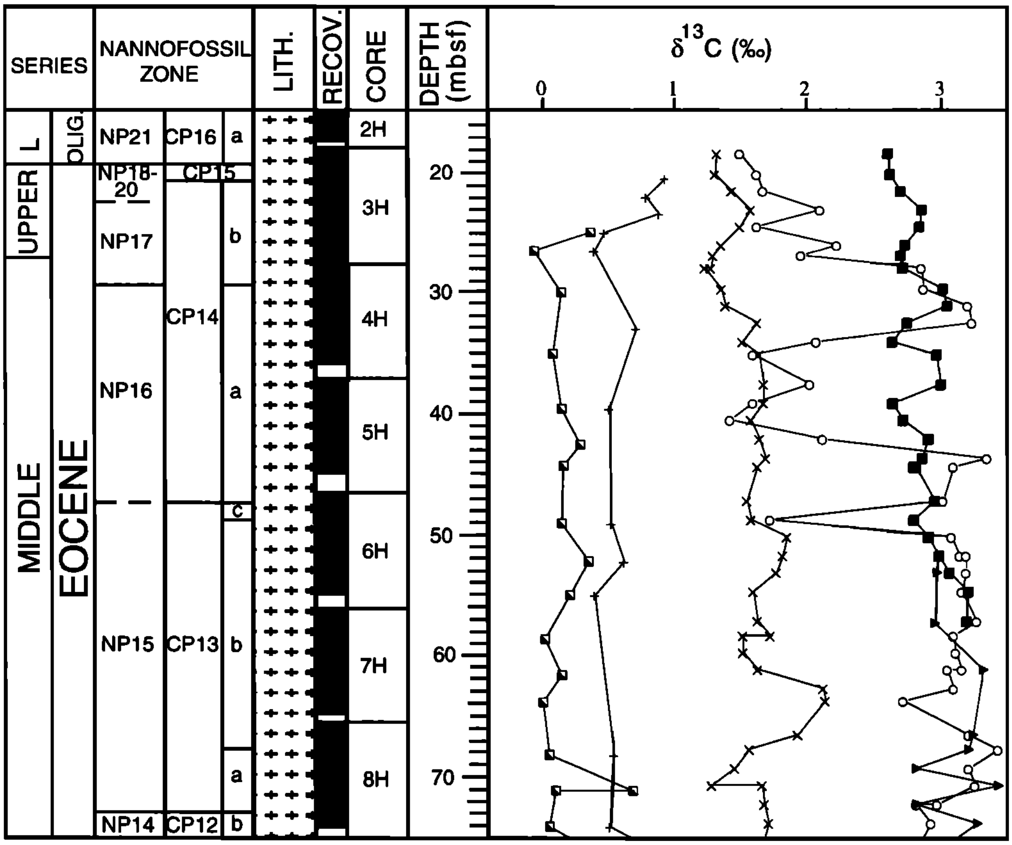

Figure 10. Planktonic and benthic foraminifer $\delta^{13}C$ (‰ versus PDB) records of the lower to upper Eocene of Hole 865B. Planktonic taxa are separated into species, and benthic taxa are differentiated. See key in Figure 5 for symbols.

similar to published reports. Middle and upper Eocene $\delta^{13}C$ values are fairly constant for all the planktonic and benthic taxa, similar to trends from other sites [e.g., *Keigwin and Corliss*, 1986; *Stott et al.*, 1990; *Kennett and Stott*, 1990; *Pak and Miller*, 1995].

Although the stratigraphic trends appear similar, $\delta^{13}C$ records from other sites have different average values. Some differences in $\delta^{13}C$ values between sites are probably real, reflecting regional differences in sea surface $\delta^{13}C$ and nutrient levels, while other differences might be artifacts of differences in the sampling strategies used to construct each record. For example, minor isotopic variability can be ascribed to disparities in the taxonomy and size ranges of the foraminifera measured [e.g., *Shackleton et al.*, 1985a; *Corfield and Cartlidge*, 1991].

The planktonic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ records also show less high-amplitude (0.5-1.0‰) single sample variability than other records [e.g., *Shackleton and Hall*, 1984; *Stott et al.*, 1990]. This may be a result of a number of factors. First, our record is more detailed than several others (e.g., Site 738 [*Barrera and Huber*, 1991] (0.5-1 m.y. between points); Site 577 [*Corfield and Cartlidge*, 1992] (>0.3 m.y. between points)). Because generally less time (average of 0.15 m.y.) is represented between our data points, they may record less short-term variability. Second, the lower intersample variability in our record may result from the generally better preservation of the planktonic foraminifera in Site 865 than in several other sections (e.g., South Atlantic Sites 525-529 contain several intervals with poor to moderate preservation [*Boersma*, 1984]). The greater variability of the record at high-latitude sites with good preservation (e.g., Site 690) may result from large seasonal fluctuations in temperature, depth to the thermocline, mixing intensity, upwelling, and productivity [e.g., *Stott et al.*, 1990]. Tropical, oligotrophic locations today are characterized by comparatively stable water column structures with a deep mixed layer and less seasonal variability than high-latitude settings.

Carbon isotopic values from Hole 865B appear to show correlated short-term (1-3m) multisample fluctuations between the different planktonic genera (Figure 9). To substantiate these correlations, we have normalized all $\delta^{13}C$ values to the mean value for each genus for the intervals between 94.0 and 130.0 mbsf then carried out a cross-correlation analysis. We have excluded the abnormal interval around the benthic foraminiferal extinction. Minor (0.1 to 0.8‰) fluctuations in $\delta^{13}C$ values measured in all three taxa are similar with Pearson correlation coefficients significant at the 99% interval of confidence and a significant decrease in correlation coefficients when curves are offset upward or downward by one or more sample. The lower-amplitude fluctuations (~0.1‰) are close to precision levels, but the higher-amplitude fluctuations which show significant correlation between different genera are

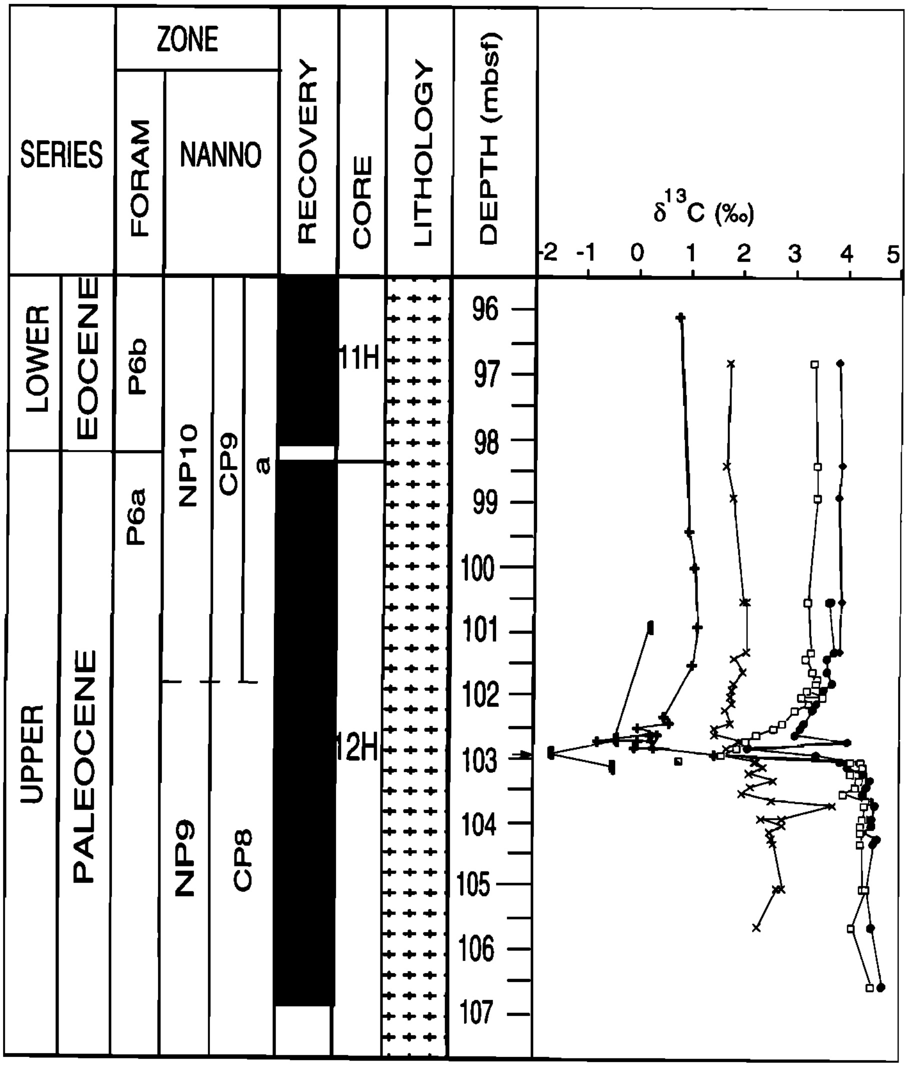

Figure 11. Planktonic and benthic foraminifer $\delta^{13}C$ (‰ versus PDB) records of the uppermost Paleocene and lowermost Eocene of Hole 865C. Planktonic taxa are separated into species, and benthic taxa are differentiated. See key in Figure 5 for symbols. Calcareous nannofossil zones of *Martini* [1971] and *Bukry* [1973, 1975] are shown at left. Planktonic foraminifer subzones of *Berggren and Miller* [1988] as determined by D. C. Kelly are indicated. Arrow indicates position of benthic foraminiferal extinction.

probably not an artifact of ontogenetic, sedimentologic, or analytical factors.

Fluctuations in upper Paleocene planktonic foraminifera $\delta^{13}C$ values suggest oscillating oceanographic conditions. Given the stratigraphic resolution available, we cannot say whether these fluctuations are truly rhythmic, but they have an average frequency of about 2-3 m (250,000-300,000 years at a sedimentation rate of 6-8 m/m.y. [*Bralower and Mutterlose*, 1995]). Covariance of short-term $\delta^{13}C$ fluctuations in planktonic taxa living at different depths indicates that the variations may reflect changes in either surface water conditions (productivity, nutrient levels) or the mean carbon isotopic composition of seawater. If the latter is the source of these variations, one would expect to see similar variations at other sites. Unfortunately, most other pelagic records lack the resolution to resolve such cycles. One exception is Site 690 on Maud Rise, which does not show similar cycles in its carbon isotope record. Any global small amplitude short-term variability, however, may be masked by the larger amplitude variability associated with seasonal environmental variations. Thus it is possible that these cycles are reflecting short-term variations in the mean carbon isotopic composition of seawater. Lower correlation coefficients observed between the $\delta^{18}O$ records of the different genera and between $\delta^{18}O$ and $\delta^{13}C$ would tend to support this inference. These fluctuations disappear in the middle and upper Eocene interval, possibly as a result of lower sample resolution or unidentified minor unconformities.

Paleogene Tropical Ocean Thermal History

Site 865 contains the only available late Paleocene to late Eocene $\delta^{18}O$ record from an equatorial location and thus provides a potentially important record of sea surface temperature. Stratigraphic trends in the record of $\delta^{18}O$ values of planktonic foraminifera from Site 865 are similar to those from other sites [*Shackleton et al.*, 1984; *Keigwin and Corliss*, 1986; *Boersma et al.*, 1987; *Stott et al.*, 1990; *Barrera and Huber*, 1991; *Corfield and Cartlidge*, 1992; *Zachos et al.*, 1994]. Oxygen isotope values gradually decreased during the late Paleocene reaching a minimum in the earliest Eocene (Figure 4). The lower Eocene $\delta^{18}O$ values of surface-dwelling species at Site 865 are among the lowest recorded; $\delta^{18}O$ values for *Acarinina* and *Morozovella* peak at -2.3‰, which indicates the warmest oceanic temperatures of the last 65 m.y. [e.g., *Shackleton and Kennett*, 1975; *Savin*, 1977]. These values are similar to those obtained from Site 171 on Horizon Guyot at a comparable latitude in the central Pacific but slightly lower than values from Site 144 on Demerara Rise in the equatorial Atlantic [*Shackleton and Boersma*, 1981]. Planktonic foraminifera from tropical Sites 144 and 171, however, appear to have been altered by burial diagenesis which may have lowered $\delta^{18}O$ values [e.g., *Anderson and Arthur*, 1983]. The lowest consistently recorded lower Eocene $\delta^{18}O$ values at Antarctic Site 690 and subantarctic Site 738 are about -1.0‰ and -1.3‰, respectively [*Stott et al.*, 1990; *Lu and Keller*, 1993], and subtropical-temperate South Atlantic Sites 525 and 527 record values close to -1.2‰ [*Shackleton et al.*, 1984]. Subtropical Pacific Sites 47.2 and 577 reach minima of -1.5‰ and -1.25‰, respectively, the former in the upper Paleocene and the latter in the lower Eocene [*Shackleton et al.*, 1985a; *Corfield and Cartlidge*, 1992; *Stott*, 1992].

Our data suggest that maximum sea surface temperatures of 24-25°C were attained in the early Eocene in the equatorial Pacific (Figure 12) while coeval paleotemperatures elsewhere ranged from 14°C (subantarctic) to 26°C (equatorial Atlantic) [*Zachos et al.*, 1994]. Oxygen isotopic values from Pacific Sites 865, 577 and 47.2 indicate thermal gradients of some 4-5°C within the low latitudes.

At Site 865, $\delta^{18}O$ values for *Morozovella* show two lower Eocene peaks (100-96 mbsf and 86 mbsf) separated by an interval of slightly higher values (Figures 5 and 12). The second peak includes the lowest values (-2.28‰) recorded for this genus and separates short-term warming and cooling events. The warming event begins at 88 mbsf and is clearest in measurements of *M. aragonensis* but is also seen at a slightly lower stratigraphic level in the *Subbotina* record; the 0.45‰ decrease in $\delta^{18}O$ values for *Morozovella* represents a temperature change of just over 2°C. The cooling event between 86 and 80.7 mbsf includes an increase in $\delta^{18}O$ values of over 1.10‰ indicating at least 4°C of cooling over a short interval of time. Steady cooling into the middle Eocene is shown by $\delta^{18}O$ values (Figures 6 and 12). Overall, the early and part of the middle Eocene witnessed some 6°C of cooling, comparable with other sites [e.g., *Shackleton et al.*, 1984].

Temperature changed little over much of the late middle Eocene, but cooling again commenced in the latest middle Eocene and continued into the late Eocene (Figure 12), for an overall 2-3°C of cooling. Oxygen isotopic values from subtropical and temperate sites suggest rather similar surface water cooling histories for much of the middle and late Eocene, although these sites were characterized by colder waters (at least 0.5-1.0‰, representing ~2°C) throughout this interval [e.g., *Shackleton and Kennett*, 1975; *Shackleton et al.*, 1984; *Keigwin and Corliss*, 1986; *Zachos et al.*, 1994]. Sparse data indicate comparable temperatures in other equatorial Pacific (Sites 167 and 171) and Indian Ocean (Site 219) locations but slightly higher temperatures in the equatorial Atlantic (Site 366) [e.g., *Keigwin and Corliss*, 1986; *Zachos et al.*, 1994]. High-latitude sites, on the other hand, witnessed constant cooling throughout the middle and late Eocene [e.g., *Stott et al.*, 1990; *Barrera and Huber*, 1991; *Miller*, 1992; *Mackensen and Ehrmann*, 1992; *Zachos et al.*, 1992a].

Comparison of relative isotopic values of *Acarinina* and *Morozovella* with those of *Subbotina* reveals some interesting trends (Figure 4), suggesting that different parts of the surface water layer did not experience an identical temperature history and possibly that the depth to the thermocline changed through time. The difference between these groups decreased throughout the late Paleocene and reached a minimum in the latest part of this epoch (Figures 5 and 7) before increasing in the early Eocene. This late Paleocene minimum occurred prior to the early Eocene interval of maximum warmth and suggests that water column thermal gradients were at a minimum. Carbon isotopic value gradients narrowed but not as significantly (Figure 9). For much of the early Eocene and the

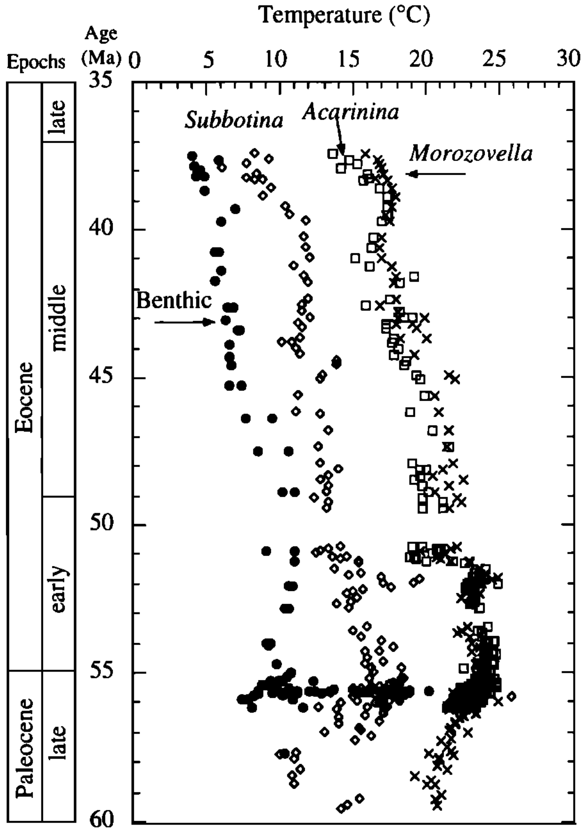

Figure 12. Paleogene paleotemperature history of surface and intermediate waters at Site 865 based on $\delta^{18}O$ values of planktonic and benthic foraminifera (see text for discussion). Note that temperature scale is inverted relative to other figures.

early part of the middle Eocene, the difference between $\delta^{18}O$ values of *Subbotina* and the surface-dwelling taxa remained constant, with two brief intervals where gradients appeared to diminish briefly, in the middle part of the early Eocene and in the early part of the middle Eocene (Figure 4). Surface water thermal gradients lessened gradually through the middle part of the middle Eocene, reaching a minimum in Subbiochron CP14a (35-40 mbsf). Thereafter, the deeper part of the surface water layer cooled dramatically as indicated by an increase in $\delta^{18}O$ values of *Subbotina* toward benthic values, whereas the upper part of the surface water layer cooled more gradually. Thus this pattern indicates a steeper, more shallow thermocline. Benthic foraminiferal accumulation rates suggest that surface productivity increased at this time.

The combined planktonic $\delta^{18}O$ record from Hole 865B (Figures 4-6) suggests that after the gradual late Paleocene to early Eocene warming, cooling occurred from the late early Eocene to late Eocene in a series of steps. Intervals of rising or of constant surface water temperatures were accompanied by reduction of surface water thermal gradients while periods of cooling were accompanied by increased thermal gradients (i.e., the increases were larger in *Subbotina*). The fact that equatorial Pacific temperatures at this time of dramatically reduced latitudinal thermal gradients were slightly cooler than those of today (mean temperatures are 27-28°C; $\delta^{18}O$ values are 0.5‰) is unexpected. This result is consistent with other supposed indices of tropical temperature [*Adams et al.*, 1990] but is extremely difficult to explain in climate modeling efforts [e.g., *Sloan et al.*, 1995]. Is it possible that our temperature estimates are biased toward cooler temperature because we have underestimated the $\delta^{18}O$ composition of tropical surface seawater? There are potentially two ways this could be achieved. The first requires that sea surface salinity and tropical sea surface $\delta^{18}O$ values were much higher than present. Increasing salinity by one part per thousand (ppt) over typical equatorial values today would lead to a decrease in calculated paleotemperature of roughly 1-2°C (assuming 0.35‰/ppt). It is very difficult to envisage why the salinity would be so high, however, since climate models consistently show higher precipitation than evaporation in the equatorial belt [e.g., *Sloan and Barron*, 1992; *Sloan et al.*, 1995].

Another possibility is that the assumed value of -0.98‰ for $\delta^{18}O_{SW}$ is lower than the actual value for an ice-free Earth or that the Earth was in fact not ice-free during the Eocene. The value used here, however, is the most conservative of available estimates for mean $\delta^{18}O_{SW}$ of an ice-free Earth. All other estimates are lower (e.g., -1.2‰ [*Shackleton and Kennett*, 1975]), which would only decrease the computed temperatures by another 1°C. As for ice volume, underestimating ice would also tend to bias temperature estimates toward cooler values. There is some physical evidence for ice sheets appearing in the late Eocene but not in the early Eocene [*Wise et al.*, 1991]. Thus, if we assume these extreme conditions in the late middle Eocene, sea surface salinity 2 ppt higher (+0.7‰), and ice volume 50% of present day (+0.5‰), these effects combined would increase the value for $\delta^{18}O_{SW}$ by 1.2‰ adding a total of 5°C to the computed temperatures, resulting in a maximum value of less than 25°C for the late middle Eocene. For the early Eocene, assuming just the salinity effect, the maximum SST value would increase by 3°C. In either case SST would still not exceed present day at this latitude.

Tropical Intermediate Water Evolution

Oxygen isotopic values of *Cibicidoides* spp. and *Nuttallides truempyi* decrease through the upper Paleocene and reach their lowest levels (-0.5‰) in the lower Eocene (Zones CP10 to CP12; Figure 5), but these values are slightly higher than those measured on the same taxa from several other sites including Sites 401 (Bay of Biscay), 524 (Cape Basin), 577 (Shatsky Rise; paleodepth about 1500 m)), and 738 (Kerguelen Plateau; paleodepth about 1600 m) [*Oberhänsli et al.*, 1984; *Oberhänsli and Tourmarkine*, 1985; *Miller et al.*, 1987; *Barrera and Huber*, 1991; *Pak and Miller*, 1992; *Zachos et al.*, 1993]. All of these sites possess values between -0.7 and -1.2‰ in this interval. The fact that the values are lighter at the other sites, all of which are from higher latitudes and most of which are from greater water depths, is puzzling. One viable explanation is that the low $\delta^{18}O$ interval is simply not represented at Site 865 due to a combination of factors including: (1) inadequate sampling resolution and (2) the presence of a brief hiatus in Zone NP13. Alternatively, the differences in $\delta^{18}O$ values may be reflecting differences in the temperature and salinity of water masses. The lower Site 865 $\delta^{18}O$ values may result from a mixture of cool and warmer but more saline waters [e.g., *Kennett and Stott*, 1991]. Oxygen isotopic data combined from *Cibicidoides* spp. and *Nuttallides truempyi* indicate that about 4°C of warming of intermediate waters took place in the late Paleocene-early Eocene and that maximum temperatures were close to 11°C (Figure 12). Cooling of intermediate waters at Site 865 in the late early Eocene to late Eocene occurred at similar rates to other sites suggesting a similar source or sources of deep water [*Pak and Miller*, 1992; 1995]. The latest Eocene intermediate water temperatures at Site 865 were around 5°C (Figure 12).

Carbon isotopic values for *Nuttallides truempyi* and many *Cibicidoides* spp. are lighter (between 0.1 and 0.5‰) at Site 865 than at most other sites at comparable depths. This difference suggests that deep waters at Site 865 were older than those at these other locations. The lowest Eocene benthic $\delta^{13}C$ values, however, have been measured at Pacific Site 577 [*Pak and Miller*, 1992], where the oldest deep waters would be expected if circulation went from high to low latitudes.

Isotopic Excursions and Events in the Latest Paleocene

The latest Paleocene decrease in the meridional thermal gradient preceded one of the most rapid intervals of warming observed in the geologic record, the late Paleocene thermal maximum, [*Zachos et al.*, 1993] toward the end of the late Paleocene long-term warming episode. Substantial decreases in $\delta^{18}O$ values of benthic foraminifera at sites at different depths in different oceans indicate widespread long-term warming of deep waters to close to 16°C [e.g., *Kennett and Stott*, 1991; *Corfield and Cartlidge*, 1992; *Hovan and Rea*, 1992; *Pak and Miller*, 1992]. Correlative with the short-term

$\delta^{18}O$ excursion is a marked decrease in $\delta^{13}C$ values and the most dramatic extinction of deep-sea benthic foraminifera since the Cenomanian/Turonian boundary (Late Cretaceous) [e.g., *Tjalsma and Lohmann*, 1983; *Thomas*, 1990a, 1992; *Kaiho*, 1991, 1994]. These data have been interpreted in terms of short-term warming of high latitudes and possibly a change in the source of deep waters from high to low latitudes [e.g., *Thomas*, 1990a; *Katz and Miller*, 1991; *Kennett and Stott*, 1991; *Eldholm and Thomas*, 1993], although local productivity changes may have played a role in the extinctions [*Thomas and Shackleton*, 1995]. Consequent changes in deep water chemistry, particularly oxygen capacity, may have led to a mass extinction of benthic foraminifera in all oceans.

Compared to the abundant benthic isotopic data across this event, planktonic data are relatively sparse. *Kennett and Stott* [1991] discussed the records for *Acarinina prepentacamerata* and *Subbotina* spp. from Site 690, which show close to 2.0‰ decrease in $\delta^{18}O$ values in this time period (Figure 13a). A single value of -2.2‰ for the former genus represents a surface water temperature of close to 19°C, and a few values for *Morozovella convexa* at Sites 689 and 690 range from -2.05 to -2.15‰ [*Thomas and Shackleton*, 1995]. Oxygen isotopic values measured on *A. soldadoensis* decrease by 1.0‰ at Site 738 [*Lu and Keller*, 1993] to a minimum value of -1.6‰ (16°C). The record of *Morozovella velascoensis* from Site 47.2 from the Shatsky Rise showed virtually no change in $\delta^{18}O$ values in this interval, maintaining values close to -1.5‰ (19.5°C [*Stott*, 1992]). The $\delta^{18}O$ data suggest similar temperatures in these locations in the Antarctic and tropical Pacific separated by some 50° of latitude. Severe drilling disturbance at Site 47.2 raises the chance that the stratigraphic record is not entirely complete, even though $\delta^{13}C$ values clearly record the negative excursion. Thus oxygen isotopic data from planktonic foraminifera from Site 865, which occupied an equatorial latitude at this time, are critical in establishing changes in low-latitude SST during this event.

A recent biostratigraphic study by *Aubry et al.* [1995] has thrown into doubt the stratigraphic completeness of the uppermost Paleocene in all sequences, including Site 690 where the record appears to be the most expanded across the benthic extinction but where there appears to be a hiatus across paleomagnetic chron C24r-1, higher in the section. At Site 690, the last occurrence (LO) of the late Paleocene fasciculith nannofossils lies 23 m above the level of the benthic extinction and $\delta^{13}C$ shift [*Pospichal and Wise*, 1990; *Thomas*, 1990b; *Thomas et al.*, 1990; *Kennett and Stott*, 1991]. At Site 865, and at many other sections (e.g., Sites 577 and 527 [*Backman*, 1986]), these events almost correlate. Although there is potential that reworking at Site 690 [e.g., *Pospichal and Wise*, 1990] could have raised the level of the LO of the fasciculiths or that diachrony occurs in the ranges of taxa between high and low latitudes, the possibility exists that a

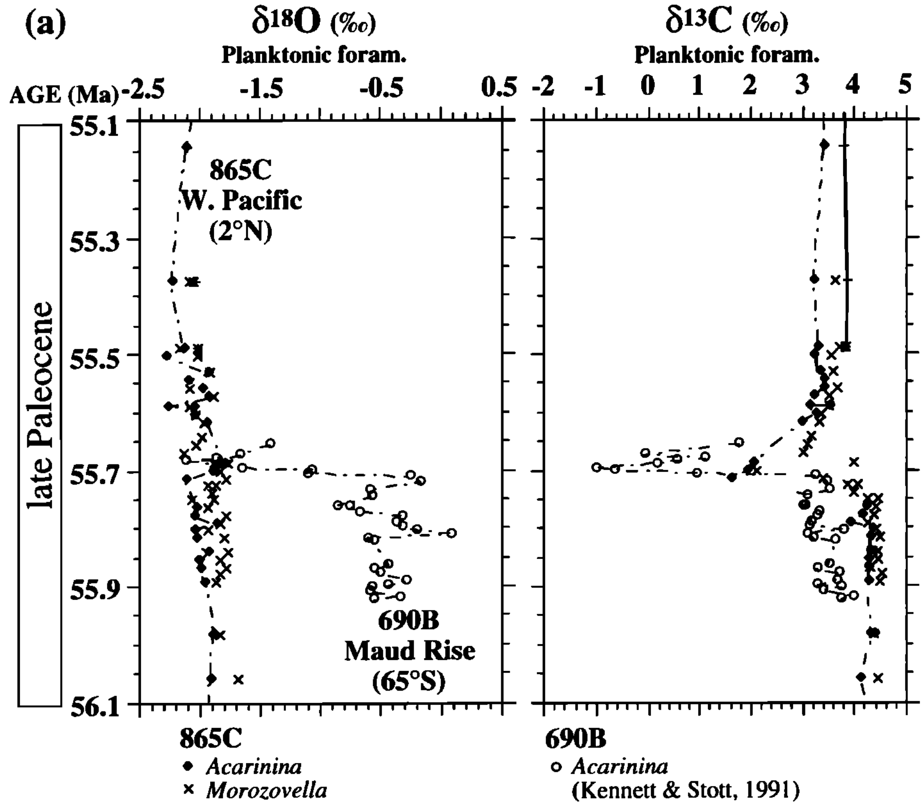

Figure 13. (a) Planktonic and (b) benthic stable isotopic records of the latest Paleocene interval in Hole 865C compared to records from other sites including Site 527 in the South Atlantic [*Thomas and Shackleton*, 1995; J. C. Zachos and D. K. Rea, unpublished data, 1994] and Site 690 on Maud Rise [*Kennett and Stott*, 1991].

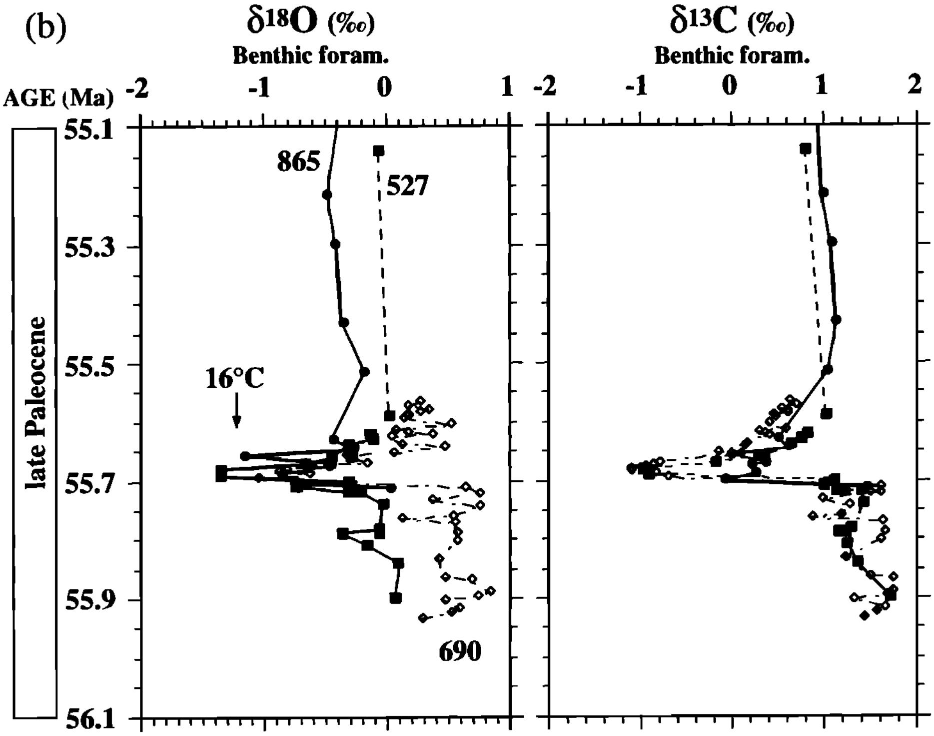

Figure 13. (continued)

minor unconformity lies right above the benthic extinction level in many sections. The interval in which benthic foraminiferal faunas have abnormally low diversity after the extinction is considerably thicker at Site 690 than at Site 865, supporting the idea that a minor unconformity or condensed interval occurs just above the extinction level.

The planktonic foraminiferal isotopic record from the Paleocene/Eocene boundary interval of Hole 865C is of sufficiently high resolution to identify a warming event some several tens of thousands of years in duration or greater (Figures 13 and 14). Unfortunately, the benthic foraminiferal isotopic record is less detailed because specimens are extremely rare and their collection is time-intensive. A negative $\delta^{13}C$ excursion measured on both benthic (2.2‰) and planktonic foraminifera (2.4-2.7‰) indicates that the Paleocene/Eocene boundary event is recorded at Site 865 over a relatively thin stratigraphic interval (~20 cm). The condensed interval may have been caused by a reduction in carbonate accumulation rates which would occur if there had been a regional decline in productivity or increased dissolution [*Zachos et al.*, 1993; *Thomas*, 1992; *Thomas and Shackleton*, 1995] or by a brief hiatus.

The $\delta^{13}C$ excursion measured on planktonic foraminifera at Site 865 is smaller in magnitude (1.9‰) than in other sites (Figure 13a). At Sites 689 and 690, the $\delta^{13}C$ excursion for *Acarinina* measures close to 4.0‰ [*Kennett and Stott*, 1991; *Thomas and Shackleton*, 1995]; values for *Morozovella* at Site 47.2 decrease by more than 3.0‰ [*Stott*, 1992]. At Sites 689 and 690, however, the excursion was much smaller in the benthic foraminifera (about 2‰) than in the planktonics and $\delta^{13}C$ gradients decreased strongly, suggesting that the effects of local productivity changes are superimposed on the global $\delta^{13}C$ shift [*Thomas and Shackleton*, 1995]. In addition, it is extremely difficult to compare the maximum magnitude of such a short-lived excursion, because isotope values changed extremely rapidly and even very minor unconformities or differences in sampling resolution can cause comparison of noncoeval data.

In the latest Paleocene interval there was also a 1.5‰ decrease in $\delta^{18}O$ values in benthic foraminifera (Figures 13b and 14), illustrating that low-latitude intermediate waters warmed by 4 to 6°C, with one sample reaching a value of roughly 16°C. Oxygen isotopic changes in planktonic foraminifera are far more subtle (Figures 13a and 14), suggesting that surface water stratification, as indicated by differences in the isotopic values between *Acarinina* and *Morozovella*, disappeared for a short (~10^5 years) period of time. The *Morozovella* record shows a 0.4‰ decrease in $\delta^{18}O$ values (just over 1°C warming), whereas the *Acarinina* record exhibits an increase in $\delta^{18}O$ values, indicating a similar amount of cooling. These changes are insignificant compared to the 8°C of warming that occurred in high-latitude surface waters [e.g., *Kennett and Stott*, 1991; *Thomas and Shackleton*, 1995]. The lowest $\delta^{18}O$ values of *Acarinina* from Site 690 are -2.2‰ (19°C), compared to -2.3‰ (25°C; both of the temperature values have been corrected [*Zachos et al.*, 1994]) for this genus at Site 865 (Figure 13a). In the absence of exceptional changes in the physical properties of the water accompanying this dramatic event, these relative values

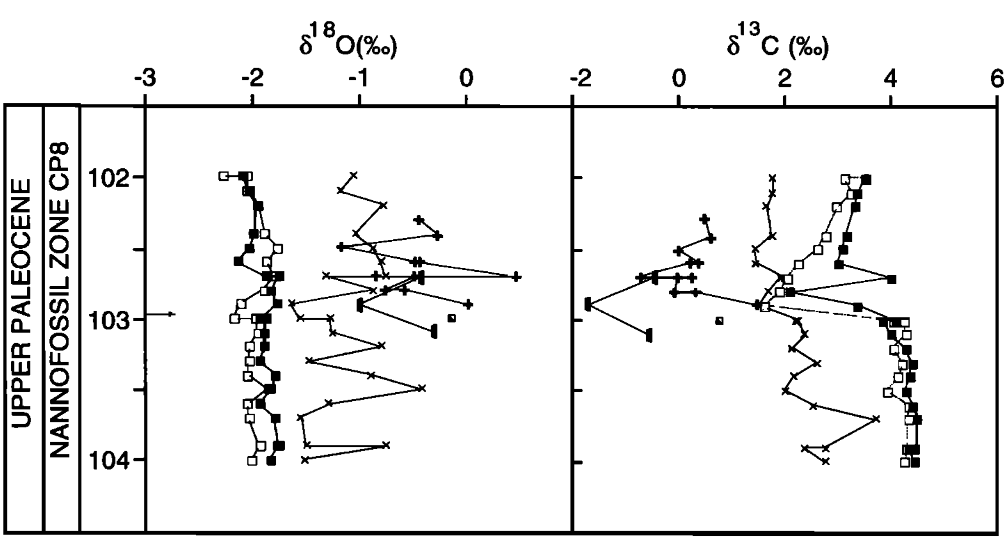

Figure 14. Planktonic and benthic foraminifer $\delta^{13}C$ and $\delta^{18}O$ records (‰ versus PDB) of the uppermost Paleocene of Hole 865C. Scale is meters below sea floor. Planktonic taxa are separated into species, and benthic taxa are differentiated. See key in Figure 5 for symbols. Arrow indicates position of benthic foraminiferal extinction.

indicate that equator-to-pole temperature gradient was substantially diminished.

The finding that temperatures at Site 865 were either similar to or cooler than present during all of the late Paleocene and Eocene, including during the brief warming in the latest Paleocene, is significant. These data suggest that in the past the ocean/atmosphere system operated in such a manner as to maintain cool tropics while allowing high-latitude temperatures to vary substantially. However, no climate models have been able to produce the low gradients suggested by these isotopic data: increased heat transport by oceans and atmosphere is difficult to accomplish at low temperature gradients [*Barron*, 1987; *Rea*, 1994; *Sloan and Rea*, 1995].

How good a source for deep waters was the surface water in the equatorial Pacific? Although the magnitude of the $\delta^{13}C$ excursion measured on benthic foraminifera is similar at numerous sites, values at the peak of the $\delta^{13}C$ excursion are slightly different (Figure 13b). The significance of such differences, however, is hard to evaluate for such a short-term event: parts of the record represented in data from different sites may represent events occurring at different times, especially because hiatuses may occur at many locations [*Aubry et al.*, 1995]. The problem is exacerbated because at Southern Ocean and Pacific sites (including 690 and 865) *N. truempyi* is absent for a short interval just at the extinction. The lowest $\delta^{13}C$ values measured on *N. truempyi* are as follows: Site 525: -1.47‰, Site 527: -1.53‰ [*Thomas and Shackleton*, 1995]; Site 577 (where a short unconformity almost certainly is present): 0.15‰ [*Pak and Miller*, 1992]; Site 690: -1.25‰ [*Kennett and Stott*, 1991]; Site 865: 0.39‰ (Sample 865B-11H-CC). For *Lenticulina* spp. the lowest value at Site 690 is -1.89‰, for Site 689 -1.23‰ [*Thomas and Shackleton*, 1995], compared to -1.7‰ at Site 865 (Sample 865C-12H-4, 10-12cm).

Although the benthic carbon isotopic values thus cannot help in determining the aging patterns of deep and intermediate water flow, the notion that dense surface waters might have been sinking in the equatorial Pacific is compatible with (1) the observation that $\delta^{18}O$ values of *Acarinina*, and especially *Subbotina*, actually increase during the excursion (the latter approaching values from benthic foraminifera (Figure 14)) indicating cooling of about 2°C for waters close to the thermocline (or slightly increased salinity), and (2) the convergence of $\delta^{13}C$ values of shallow and deep planktonic foraminiferal genera (Figure 14). Although it is difficult to estimate the buoyancy of surface waters, the convergence of $\delta^{18}O$ values of *Subbotina* and benthic foraminifera over a 50-cm interval (Figure 14) indicates that surface waters may have been dense (saline) enough to sink at least to intermediate water depths. If surface waters indeed were sinking, the physical properties of the deeper part of this layer where *Subbotina* lived would be expected to change more drastically than the shallower part. The isotopic record of *Subbotina* is intriguing in its potential bearing on surface water stability; however, convergence of $\delta^{18}O$ values of *Subbotina* and benthic foraminifera can also be explained by a short-term hiatus in the upper part of the excursion interval, possibly leading to bioturbation of postexcursion *Subbotina* which have higher $\delta^{18}O$ values into the excursion interval.

Conclusions

1. Long-term late Paleocene-Eocene $\delta^{18}O$ and $\delta^{13}C$ records at Site 865 are similar to those at other sites. However, the planktonic record at Site 865 includes significantly less short-term, single-sample variability than those at higher-latitude sites, suggesting a comparatively stable water column structure with a deep mixed layer and less seasonal variability. Small-scale (0.1-0.8‰) multisample oscillations are observed in the $\delta^{13}C$ records of all planktonic genera.

2. The $\delta^{18}O$ and $\delta^{13}C$ values for genera (*Acarinina* and

Morozovella) living within the mixed layer are consistently offset from those measured on *Subbotina*, which lived deeper in the water column. The $\delta^{18}O$ and $\delta^{13}C$ values of *Acarinina* and *Morozovella* are slightly offset from one another for large stratigraphic intervals as a result of depth-of-habitat or vital processes.

3. Peak sea surface temperatures of 24-25°C are recorded in the lowermost Eocene; this interval of dramatically reduced latitudinal thermal gradients was not accompanied by substantially higher equatorial SSTs as inferred from oxygen isotopes. This warm interval was terminated by a sharp cooling event of 4°C in the latest middle Eocene. Vertical thermal gradients decreased dramatically in the late Paleocene and reached a minimum in the latest part of this period.

4. A short-term, strong, negative excursion in $\delta^{13}C$ values occurred in planktonic and benthic taxa at the time of the latest Paleocene benthic foraminiferal extinction, but $\delta^{18}O$ data indicate that only intermediate waters warmed (4 to 6°C). Increase in $\delta^{18}O$ values of certain planktonic foraminiferal genera suggests cooling or an increase in salinity in this interval; convergence of $\delta^{18}O$ values for planktonics and benthics suggests that the thermocline in this tropical location weakened strongly. This collapse of thermal gradients may have been coincident with sinking of these low-latitude surface waters to at least intermediate depths.

5. The finding that temperatures at Site 865 were either similar to or cooler than present during all of the late Paleocene and Eocene, including during the brief warming in the latest Paleocene, is significant. These data suggest that in the past the ocean/atmosphere system operated in such a manner as to maintain cool tropics while allowing the high-latitude temperatures to vary substantially.

Acknowledgments. We gratefully acknowledge discussions with S. D'Hondt and U. Rohl and critical reviews by R. Corfield, K. Miller, D. Pak, L. Stott, J. Winterer, and an anonymous reviewer. Research supported by JOI-USSAC and NSF EAR-9405784 awards to Bralower and EAR-9406099 award to Zachos and Thomas.

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(Received October 20, 1994; revised March 29, 1995;
accepted April 6, 1995.)