30. PALEOCEANOGRAPHIC IMPLICATIONS OF A 17-M.Y.-LONG RECORD OF HIGH-LATITUDE MIOCENE CALCAREOUS NANNOPLANKTON FLUCTUATIONS[1]

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ABSTRACT

A record based on counts of the relative abundance of the dominant calcareous nannofossil taxa *Coccolithus pelagicus* and *Reticulofenestra* spp. in sediments recovered from Ocean Drilling Program Hole 747A (Kerguelen Plateau, Southern Indian Ocean) is established in this paper. This record (17 m.y. long) virtually spans the entire Miocene. Broad, steplike variations in the abundance of *C. pelagicus* range between 0% and 96%. Based on these variations, five stratigraphic units characterized by high abundance in *C. pelagicus* are delineated. We suggest that these variations are caused by water-mass movements (such as the north/south shifting of a front). This pronounced signal is compared with paleoceanographic events revealed by isotopic ($\delta^{18}O$ and $\delta^{13}C$) studies. The five defined units are tentatively correlated to well-known global isotopic events. In particular, Units A and D correlate respectively with the Oligocene/Miocene boundary glaciation and the middle Miocene cooling event. Time-series analysis indicates the presence of the three main periodic components of the eccentricity of the Earth's orbit. A 200-k.y. cycle is also present. The stratigraphic and paleoceanographic significance of this record is discussed.

INTRODUCTION

The Antarctic Ocean ecosystem is subject to extreme conditions that control the nature and distribution of the phytoplankton community (e.g., Priddle et al., 1986). In this ecosystem, the most influential ecologic factors are temperature, irradiance, concentration of nutrients, and depth of the mixed layer (Priddle et al., 1986). One can expect to retrace the history of the Antarctic paleoecosystem through the study of its fossil phytoplankton, in relation to the development of severe climate conditions as Antarctica became glaciated (i.e., at least since the early Oligocene; Miller and Fairbanks, 1985; Zachos et al., this volume),

At Ocean Drilling Program (ODP) Sites 747, 748, and 751, the Miocene calcareous nannofossil assemblages are poorly diversified. *Coccolithus pelagicus* and species of the genus *Reticulofenestra* (*R. minutula-pseudoumbilica* group, *R. perplexa*, and *R. floridanus* [in the lower Miocene]) represent at least 95% of the calcareous nannoflora. Other taxa are *Sphenolithus* sp. cf. *S. moriformis*, *Calcidiscus macintyrei*, and *Helicosphaera* sp. cf. *H. granulata*. Because these latter are so few, the abundance of *C. pelagicus* vs. *Reticulofenestra* spp. approximates the abundance of *C. pelagicus* in the whole nannoflora. It is instructive to count the abundance of *C. pelagicus* because it is often regarded as a cool-water species and, therefore, can be a good tracer of water masses. Site 747 has been selected for this study because its relative stratigraphic continuity permits a long, detailed, and continuous record of the variations of the abundance of *C. pelagicus*.

SITE AND METHOD

Hole 747A, drilled on the Kerguelen Plateau (Southern Indian Ocean, 54°49'S, 76°48'E) (Fig. 1), provides an almost continuous section throughout the Neogene. A good magnetostratigraphic control is available from the Oligocene/Mio-

cene boundary to the lower upper Miocene (Heider et al., this volume). The average sedimentation rate of the mainly uniform nannofossil ooze is about 5 m/m.y. (Shipboard Scientific Party, 1989).

To establish a sufficiently detailed record, smear slides were prepared from samples taken every 10 cm in an interval from 42 to 132 mbsf (Samples 120-747A-5H-4, 5 cm, to -14H-7, 50 cm). About 900 samples were analyzed. The first 200 placoliths encountered while scanning a slide were recorded and the percentage of *C. pelagicus* vs. *Reticulofenestra* spp. was calculated as follows: (number of *C. pelagicus*/[number of *R. pseudoumbilica* + number of *C. pelagicus*]) × 100.

Using this methodology, the percentage varies solely with processes (ecologic and/or taphonomic) exclusively controlling the abundance of the two species. It does not vary, in particular, with fluctuations in the flux of terrigenous material. Coccoliths in both groups are of about the same size and shape. They are placoliths, a kind of coccolith most resistant to dissolution. The relative frequencies between the two species are unlikely to be biased by differential (e.g., winnowing) or chemical (e.g., dissolution) processes. The coccoliths are transported to the abyss by means of fecal pellets, and it is thought that the composition of these latter reflect faithfully the original nannoplankton community (Honjo, 1976). For these reasons, we assume that the percentages established are not biased to a significant degree by taphonomic processes in relation to the original percentages in the phytoplankton. Therefore, they probably reflect the state of the ecologic environment in which the organisms lived.

STRATIGRAPHY AND CHRONOLOGY

The stratigraphic and chronologic framework on which this study is based results from an integration of the magnetobiostratigraphic data with the global polarity time scale of Berggren et al. (1985) (Shipboard Scientific Party, 1989; Heider et al., this volume). In the interval from 42 to 132 mbsf, 43 reversals were identified. Isotope stratigraphy (Wright and Miller, this volume) essentially confirms the interpretation of the magnetostratigraphy (Heider et al., this volume), and only a few problems remain relative to the interpretation of the upper Miocene record. Following Heider et al. (this volume),
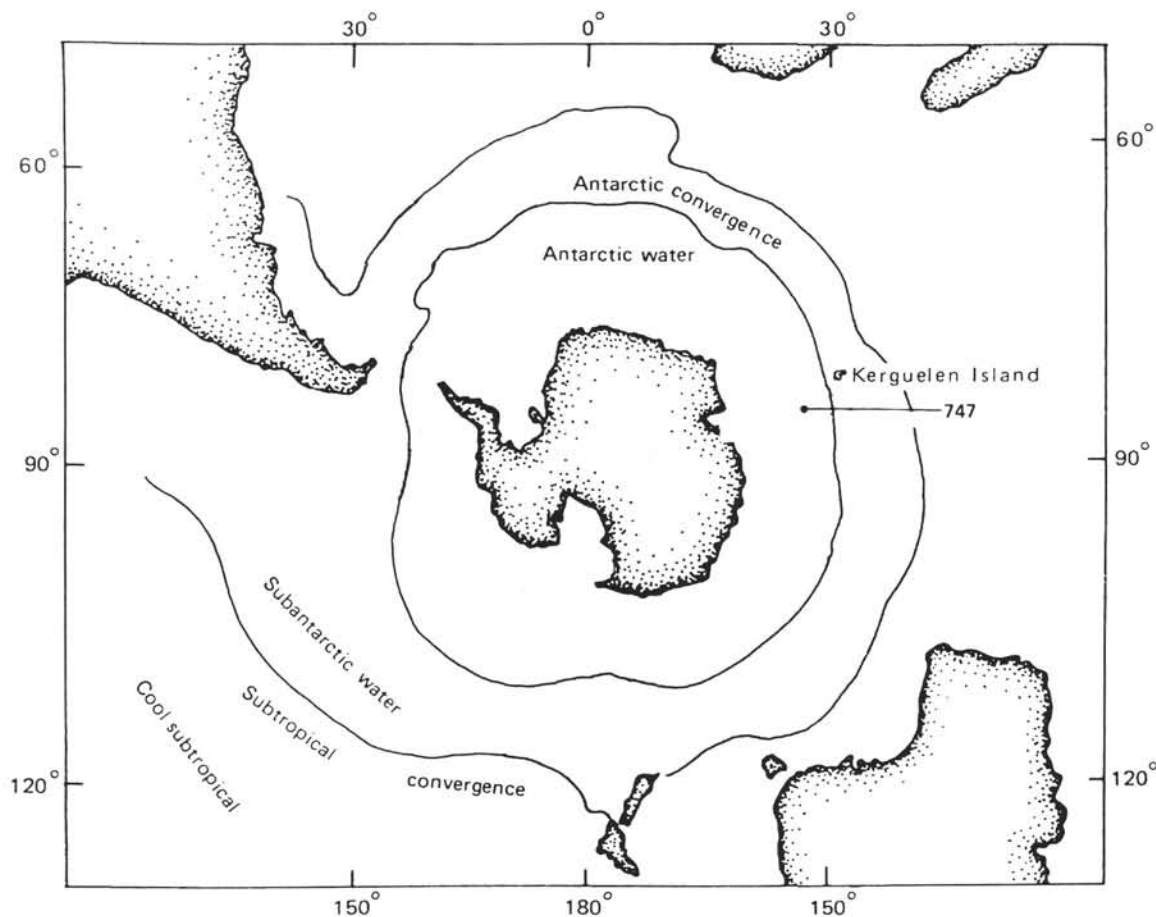
Figure 1. Location of Hole 747A, Leg 120.

the short normal event present in Core 120-747A-5H (42.3–43.05 mbsf) is interpreted in this study as the lower normal part of Subchron 4A. It bears an age of 8.41 Ma. An unconformity at ≈41 mbsf prevented us from precisely dating Miocene calcareous nannofossil assemblages younger than about 8.4 Ma.

The sedimentation rate in the Miocene interval studied (42–127.5 mbsf) averages 5.5 m/m.y. As samples were taken at 10-cm intervals, the time span between consecutive samples is on the order of 18 k.y. The age model used in this study is based on the linear interpolation between the ages of the 43 reversals and provides a calibration point roughly every 400 k.y. This age model is well constrained with respect to the sampling interval.

FLUCTUATION OF THE PERCENTAGE OF *COCCOLITHUS PELAGICUS/RETICULOFENESTRA* SPP.

Analysis

The results of the counting are shown in Figures 2 and 3 and in Table 1. The percentage of *C. pelagicus* shows extremely broad variations ranging from 0% to 96% (Figs. 1 and 2). Long periods dominated by *C. pelagicus* alternate with long intervals during which this species is a marginal component of the assemblages. The average percentage of *C. pelagicus* is 34%. The units are defined as corresponding to intervals at least 1 m thick, where the percentage of *C. pelagicus* is higher than the average. Five intervals fit this criterion and are labeled by capital letters (Figs. 2 and 3; Table 2).

Discussion

The present distribution of *Coccolithus pelagicus* reflects an affinity for cool water. This species is restricted to high latitudes where it is known in the North Atlantic (McIntyre and Bé, 1967), the North Pacific (Geitzenauer et al., 1976), and the South Pacific (Nishida, 1979). Okada and McIntyre (1979) indicate that *Coccolithus pelagicus* is a stenothermal species adapted to water temperatures from 0° to 15°C (with optimum abundance between 2° and 12°C). Large fluxes of *C. pelagicus* in samples collected during winter and spring in the Arctic Sea, where the temperature is around –1.75°C (Honjo, in press), reflect the adaptability of *C. pelagicus* to cold waters. The latitudinal distribution of *C. pelagicus* throughout the entire Neogene suggests that *C. pelagicus* did not change its ecological affinity since the beginning of the Miocene (Haq, 1980). Bukry (1980) showed that the abundance pattern of *C. pelagicus* does not exactly follow a latitudinal gradient in the South Pacific but has been linked to the paths of cold-water currents at least since the late Miocene.

On the contrary, the extinct species *R. pseudoumbilica* and other related species seem to have no distinct ecologic preferences. It is often regarded as cosmopolitan (e.g., Bukry, 1972, 1976). In the North Atlantic, during the Neogene, *R. pseudoumbilica* was most abundant at mid and low latitudes (Haq, 1980).

The extreme minimal and maximal values that the percentage between the two species reaches at Site 747 indicate that the two species had opposite ecological affinities during the
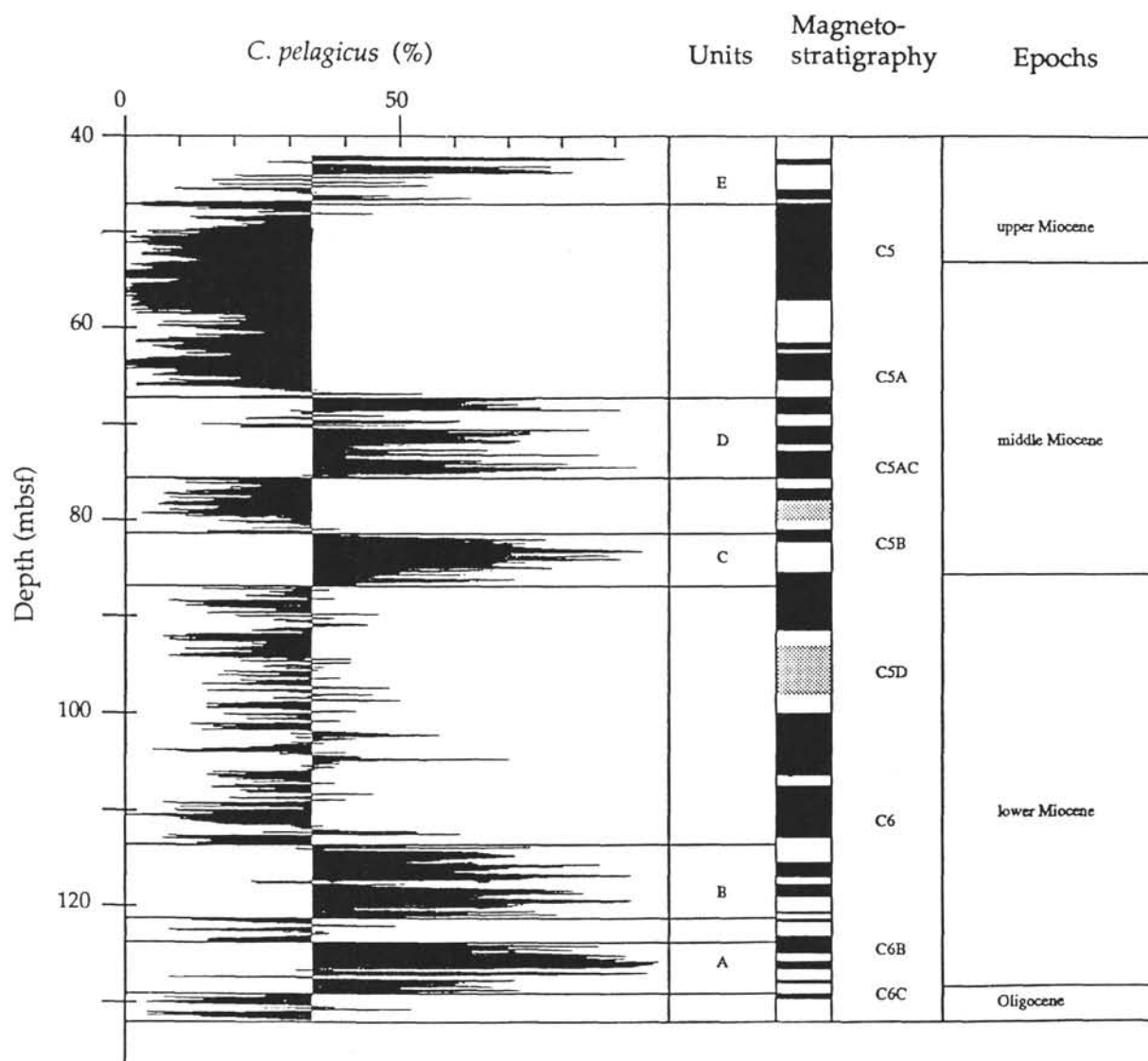
Figure 2. Stratigraphic abundance of *Coccolithus pelagicus* vs. *Reticulofenestra* spp. at Hole 747A. The vertical line at 34% represents the average of the abundance. The shaded area in the magnetostratigraphic column indicates uninterpretable data or the absence of data.

Miocene. The fact that periods with equal abundance between the two species are rare and correspond only to short transitions between the two types of assemblages suggests that two distinct surface-water masses migrated back and forth over Site 747 throughout the Miocene. It is likely that a front between these two water masses existed during most of the Miocene at the latitude of the Kerguelen Plateau. Hays et al. (1976a) showed that 18,000 yr ago the Antarctic polar front was about 7° north of its actual position. Although not yet clearly understood, north/south movements of this front have undoubtedly occurred. Site 747 is located about 6°S of the Antarctic convergence and about 22°S of the subtropical convergence (Fig. 1). Kemp et al. (1975) and Kemp (1978) have suggested that the Miocene polar front was located 10°S of its present location, which is south of Site 747, therefore. If the Miocene path of water masses corresponded to the present oceanographic pattern as Kennett et al. (1975) or Kemp (1978) suggested, the Antarctic convergence or the subtropical convergence may have been located around the latitude of Site 747. Another possibility is that instead of a juxtaposition between two water masses, a given water mass experienced

successive chemical and/or physical changes (like the presence or absence of upwellings). Although small shifts of a front would easily produce strong local variations in the composition of the phytoplankton, such variations would require very pronounced changes in the quality of a single water mass.

HIGH ABUNDANCE IN *COCCOLITHUS PELAGICUS* AND THE ISOTOPIC RECORD

Comparison with the δ¹⁸O

A strong correlation (same pattern in the records) between the abundance of *C. pelagicus* and isotopic composition ($\delta^{18}O$ and $\delta^{13}C$) of benthic foraminifers is not expected because deep oceanic circulation does not necessary reflect surface circulation (at the Kerguelen Plateau, today's deep-water masses and the surface-water masses are entirely different in nature and in origin; see Gambéroni, 1979). Yet it is interesting to compare such records so as to depict time correlations between events, that is, a link between global events (isotopic records) and local events (abundance of *C. pelagicus*). To have a more
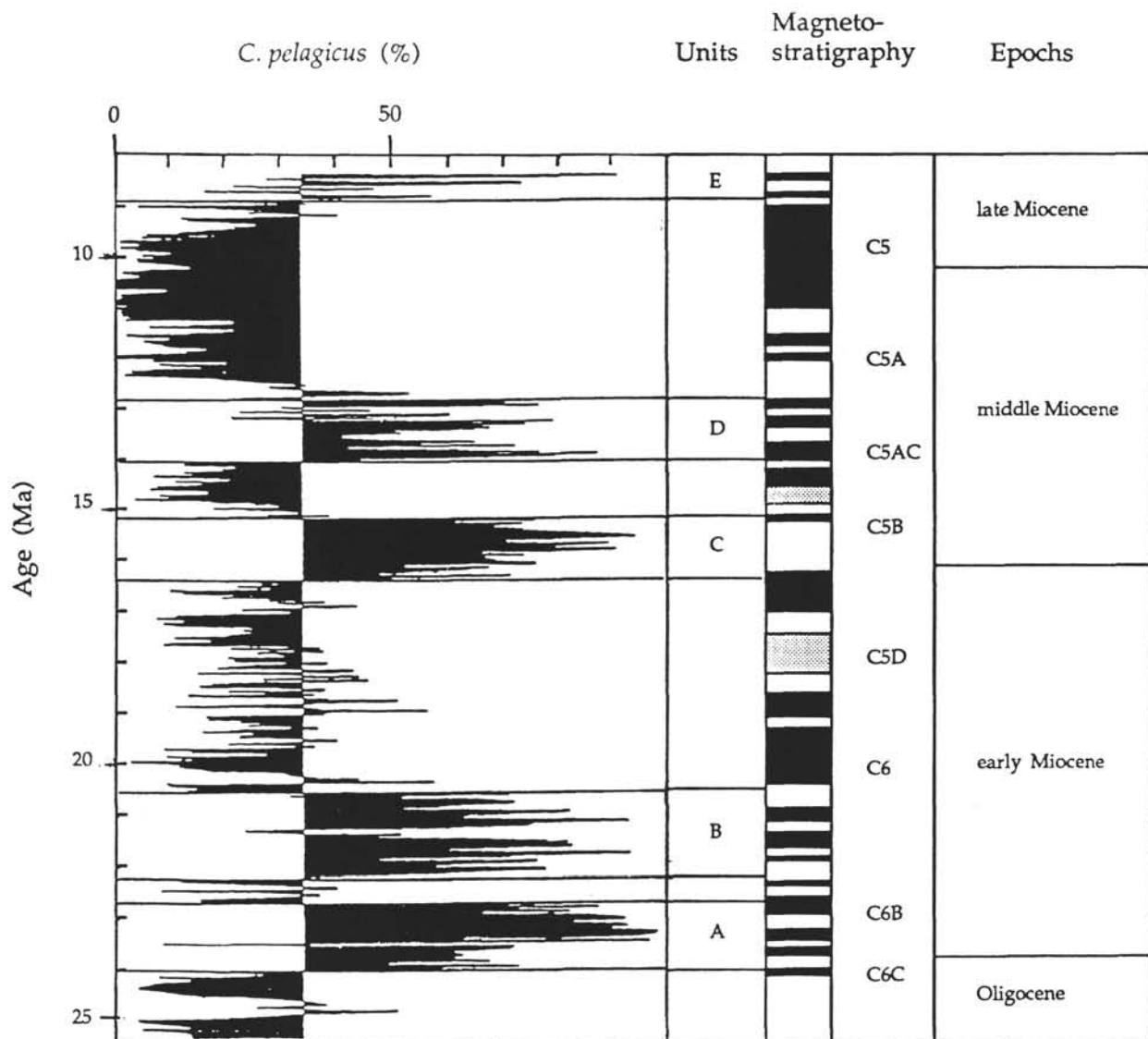
Figure 3. Temporal abundance of *Coccolithus pelagicus* vs. *Reticulofenestra* spp. at Hole 747A. The vertical line at 34% represents the average of the abundance. The shaded area in the magnetostratigraphic column indicates uninterpretable data or the absence of data.

comprehensive history of the global $\delta^{18}O$ events, records from other sites are used in the comparison.

No isotopic studies on planktonic foraminifers are yet available for the Miocene sediment recovered from Site 747, but Wright and Miller (this volume) have analyzed the isotopic composition of the benthic foraminifers (Fig. 4).

The most dominant feature in the Miocene benthic foraminifers $\delta^{18}O$ records are (1) heavy values following the Oligocene/Miocene boundary (Shackleton and Kennett, 1975; Miller and Fairbanks, 1985), (2) late early Miocene minimum values (Vincent et al., 1985), and (3) a middle Miocene steplike increase (Vincent et al., 1985) (Fig. 5).

At Site 747, a sharp increase in the percentage of *C. pelagicus* (at the top of Unit A) was observed at the Oligocene/Miocene boundary; this increase correlates to the $\delta^{18}O$ increase reported from several DSDP and ODP sites, that is, DSDP Sites 277 (Shackleton and Kennett, 1975), 563 and 558 (Miller and Fairbanks, 1985), 522 (Miller et al., 1988), and 366 (Miller et al., 1989), and ODP Site 667 (Miller et al., 1989).

Miller and Fairbanks (1985) interpreted this increase as reflecting a glacial event.

The top of Unit C corresponds to the minimum oxygen event at 16.5 Ma described by Vincent et al. (1985). In the benthic foraminifer record from Hole 747A (Wright and Miller, this volume, fig. 3), this isotopic event occurs between 90 and 86 mbsf (Fig. 4), whereas Unit C ends at 86.4 mbsf.

The prominent middle Miocene cooling event corresponds to an increase of the isotopic values from 1‰ to 1.5‰ between 14.6 and 12.6 Ma (Vincent et al., 1985). Most authors (Shackleton and Kennett, 1975; Savin et al., 1975; Woodruff et al., 1981; Vincent and Berger, 1985; Miller et al., 1988; among others) explain this event as reflecting first the growth of Antarctica's ice sheet and, second, a deepwater cooling (but see Matthews and Poore, 1980). The $\delta^{18}O$ record from Hole 747A (Wright and Miller, this volume) shows this increase particularly well between 81 and 63 mbsf (Fig. 4). It is during this important isotopic event that Unit D was deposited.

For the remainder of the Miocene, the $\delta^{18}O$ values on benthic foraminifers remain high but fluctuated irregularly (Woodruff and Savin, 1989), whereas the planktonic foraminifer $\delta^{18}O$ values decreased significantly after 12.6 Ma (Vincent et al., 1985), which correlates exactly with the end of Unit D. The explanation of this drop in the $\delta^{18}O$ of the planktonic foraminifers is not yet fully understood (cf. Shackleton and Kennett, 1975; Matthews and Poore, 1980; Vincent et al., 1985; Woodruff and Savin, 1989), possibly in part because of the lack of data (few planktonic isotopic records are available for this time interval). At this time, we can only point out this correlation.

Comparison with the $\delta^{13}C$ Record

A maximum was observed in every middle Miocene benthic carbon isotope records around 16 Ma (Loutit et al., 1978; Woodruff and Savin, 1985; Vincent et al., 1985; Miller et al., 1989). At Site 747, it occurs at 84 m (Wright et al., this volume) (Fig. 4). The significance of this event is still a point of discussion, and several explanations have been proposed (cf. Vincent and Berger, 1985; Woodruff and Savin, 1989). Unit C is tentatively correlated to this event.

Vincent et al. (1985) described two other $\delta^{13}C$ events in the planktonic foraminifers that correspond to an increase in the $\delta^{13}C$ around 22.7 Ma, followed by a decrease in values around 20.7 Ma. These events correlate with the boundaries of Unit B (Fig. 5).

Oceanographic studies in the Kerguelen area reveal a strong chemical and physical contrast between the surface-water masses on both sides of a front (Jacques, 1978). Temperature, depth of the mixing layer, salinity, and concentration of nutrients are extremely different (Jacques, 1978). As phytoplanktonic communities are well adapted to the various ecologic factors of their living environment, not only to its temperature, it is suspected that the correlation observed between abundance in *C. pelagicus* and $\delta^{13}C$ events at Site 747 reflects intricate relations between water masses and the composition of their phytoplankton.

TIME-SERIES ANALYSIS

The abrupt variations in the abundance of *C. pelagicus* at Site 747 correlate with important paleoceanographic events as revealed by isotopic studies supports the hypothesis that variations in abundance in *C. pelagicus* reflect water-mass movements. Hays et al. (1976a) showed that the latitudinal position of the Antarctic Polar Front during the Pleistocene was dependent upon climatic fluctuations. The Milankovitch theory of climate, which predicts that global ice volume varies as a function of cycles inherent to the Earth orbital parameters, has been well documented in the last two decades (e.g., Hays et al., 1976b; Imbrie et al., 1984). If the signals observed in the calcareous nannofossil record at Hole 747A are linked to climatic variations, an orbital imprint should be detected by a time-series analysis.

The chronologic resolution (with an average of one stratigraphic tie point every 400 k.y.), the sampling density (18 k.y. on average), and the length of the record (17 m.y.) allow a resolution of cyclicity in a period range of 80 to 5000 k.y. Hence, it is possible to test the presence of eccentricity cycles (95, 126, and 413 k.y.). The sampling interval is too broad to study frequencies higher than about 80 k.y. Also, the presence of obliquity cycles (41 k.y.) or precession cycles (23 and 19 k.y.) cannot be tested in this series.

Method

The data were first linearly interpolated to produce a new series equally spaced in time (20 k.y.) (program TIMER of

SPECMAP). A Fast Fourier Transform (Blackman-Tukey spectral analysis) was performed, using a Hamming window and a prewhitening constant of 0.8 (allowing the removal of the low-frequency components in the data) (POWER, the program used, was written by N. Pisias and has been used by the SPECMAP group).

Results

The entire series was first analyzed (Fig. 6). The prewhitening method does not remove entirely a large peak centered on 2653 k.y. that dominates the spectrum (on Fig. 6, it was intentionally truncated so as to examine in greater detail the frequency band of interest). The spectrum shows large peaks at 995, 444, 300, 200, and around 100 k.y. Several peaks are centered on 130 k.y. (144–115 k.y.) and 95 k.y. (102–87 k.y.). It is noteworthy that 130 k.y. and 95 k.y. are close to the two principal terms of the eccentricity cycles, that is, to 123 and 95 k.y. (Berger, 1977). Also, 444 k.y. is close to the 413-k.y. period predicted for the eccentricity. With such a long series, it is possible to check with sufficient accuracy the presence of these periods in a different part of the series. The series was split into four parts, each 5 m.y. long, with overlaps of 1 m.y. The four resulting spectra show peaks in the same frequency range (200, 125, and 95 k.y.) (Fig. 7). The small variations of the periods can easily be explained by imperfections in the chronologic model used (linear interpolation between tie points, for example).

Periods close to the predicted eccentricity cycles are significant and stable in the series. The period close to 413 k.y. found in the spectrum of the entire series shows some variability; in the second subseries, it does not show clear power. Even though the prewhitening technique may have artificially diminished power around 413 k.y., the occurrence of this period in the series cannot be confirmed. A stable and significant component of the five spectra is a 200-k.y. peak. It is not explained by the Milankovitch theory, but it is found in other pre-Pliocene series. For instance, Herbert and Fischer (1986) reported a 225-k.y. cycle from a Cretaceous $CaCO_3$ series; and the Walsh spectra of long isotopic records from Miocene benthic foraminifers show strong 185-k.y. ($\delta^{13}C$) and 227-k.y. ($\delta^{18}O$) peaks (Tiwary, 1987, fig. 3).

The presence of significant power close to the eccentricity cycle suggests that the percentage of *C. pelagicus* in the Miocene sediments of the Kerguelen Plateau varied, at least in part, as a function of climatic variations. The frequencies that correspond to the eccentricity, however, are minor compared with a low-frequency component that virtually dominates the spectrum and is not directly explained by orbital forcing.

CONCLUSIONS

The abundance of *Coccolithus pelagicus* in the Southern Indian Ocean varied broadly during the Miocene; therefore, the ecological parameters controlling its distribution did as well. Correlation of the abundance record of this cool-water species with global climatic events as indicated by stable isotope studies suggests that important changes in the ecological parameters in the Southern Indian Ocean occurred at times of global climatic and oceanographic changes. The cause of variation, however, is not really understood yet. Until further studies, variation in the composition of the calcareous nannoplankton as a function of water-mass movement represents the best hypothesis. First-order variations observed in this calcareous nannofossil record correspond to time intervals a few million years long dominated by *C. pelagicus* alternating with periods when it was a minor component of the calcareous nannofossil assemblages. A second order of variation (period < 1 m.y.) are periodic fluctuations

Table 1. Percentage of *Coccolithus pelagicus* vs. *Reticulofenestra* spp.

Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %
42.05	44	49.80	15	57.90	4	65.50	10	73.30	48	81.63	15	89.30	26	97.20	27	104.50	43
42.10	49	49.90	4	58.00	5	65.55	20	73.40	35	81.79	19	89.40	30	97.30	42	104.60	34
42.20	77	50.00	25	58.10	3	65.60	8	73.60	50	81.87	22	89.60	18	97.40	48	104.70	70
42.30	88	50.10	5	58.20	2	65.65	7	73.70	62	81.94	39	89.70	15	97.55	26	104.80	56
42.40	92	50.20	5	58.30	16	65.70	6	73.80	65	82.02	39	89.80	46	97.60	19	104.90	39
42.50	86	50.30	17	58.40	3	65.75	2	73.90	58	82.10	48	89.90	32	97.70	15	105.00	39
42.60	47	50.40	6	58.50	2	65.80	5	74.00	67	82.18	61	90.00	20	97.80	29	105.10	36
42.70	26	50.50	1	58.60	7	65.85	5	74.10	81	82.26	67	90.10	34	97.90	30	105.20	39
42.80	31	50.60	1	58.70	22	65.90	2	74.20	72	82.34	77	90.20	38	98.00	35	105.30	36
42.90	45	50.70	3	58.80	22	65.95	2	74.30	49	82.41	75	90.30	37	98.10	45	105.40	32
43.00	43	50.80	6	58.90	21	66.10	18	74.40	75	82.49	51	90.40	27	98.20	33	105.55	38
43.10	65	50.90	3	59.00	17	66.20	21	74.50	94	82.57	68	90.50	32	98.30	36	105.60	36
43.20	78	51.00	6	59.10	26	66.30	26	74.60	76	82.96	73	90.60	29	98.40	27	105.70	33
43.30	61	51.10	0	59.20	18	66.40	35	74.70	79	83.04	68	90.70	35	98.50	27	105.80	35
43.40	73	51.20	4	59.30	21	66.50	28	74.80	79	83.12	68	90.80	43	98.60	45	105.90	31
43.50	73	51.30	4	59.40	7	66.60	30	74.90	69	83.20	73	90.90	44	98.70	50	106.00	16
43.60	78	51.40	4	59.50	25	66.70	44	75.00	63	88.27	73	91.10	35	98.80	23	106.10	24
43.70	72	51.50	7	59.60	18	66.80	54	75.10	68	88.35	78	91.20	28	98.90	22	106.20	22
43.80	82	51.60	10	59.70	9	66.90	48	75.20	54	88.43	88	91.30	27	99.05	15	106.30	15
43.90	76	51.70	11	59.80	6	67.00	21	75.30	32	83.51	90	91.40	25	99.10	19	106.40	20
44.00	47	51.80	5	59.90	11	67.10	23	75.40	38	83.59	93	91.50	23	99.20	17	106.50	18
44.10	20	51.90	5	60.00	14	67.20	35	75.50	53	88.67	95	91.60	33	99.30	18	106.60	17
44.20	22	52.00	10	60.10	13	67.30	75	75.60	37	83.74	86	91.70	32	99.40	15	106.70	25
44.30	56	52.10	6	60.20	17	67.40	75	77.10	12	83.82	69	91.80	12	99.50	15	106.80	20
44.40	36	52.20	3	60.30	17	67.60	63	77.17	9	83.90	71	91.90	11	99.60	30	106.90	31
44.50	22	52.30	6	60.40	23	67.70	60	77.25	19	88.98	89	92.00	12	99.70	28	107.05	23
44.60	16	52.40	3	60.50	27	67.80	70	77.33	24	84.13	84	92.10	7	99.80	42	107.10	32
44.70	31	52.50	3	60.60	20	67.90	72	77.41	11	84.21	79	92.20	13	99.90	35	107.20	38
44.80	51	52.60	9	60.70	13	68.00	67	77.49	15	84.29	78	92.30	13	100.00	28	107.30	20
44.90	47	53.00	15	60.80	15	68.10	65	77.56	22	84.37	91	92.40	8	100.10	18	107.40	25
45.00	17	53.10	7	60.90	20	68.20	76	77.64	27	84.45	82	92.60	12	100.20	23	107.50	16
45.10	18	53.20	5	61.00	8	68.30	75	77.72	19	84.53	60	92.70	28	100.30	30	107.60	16
45.20	55	53.30	4	61.10	10	68.40	72	77.80	19	84.60	75	92.80	23	100.40	33	107.70	31
45.30	40	53.40	1	61.20	5	68.50	91	77.88	23	84.68	66	92.90	23	100.55	22	107.80	26
45.40	10	53.50	4	61.30	2	68.60	30	77.96	15	84.76	66	93.00	26	100.60	25	107.90	21
45.50	9	53.60	3	61.40	5	68.70	39	78.03	14	84.84	68	93.10	22	100.70	30	108.00	24
45.60	14	53.70	5	61.50	2	68.80	32	78.11	11	84.92	68	93.20	20	100.80	39	108.10	22
45.70	30	53.80	5	61.60	13	68.90	32	78.27	19	85.00	78	93.30	11	100.90	35	108.20	23
45.80	27	53.90	3	61.70	10	69.10	47	78.35	8	85.10	41	93.40	11	101.00	22	108.30	45
45.90	35	54.00	0	61.80	9	69.20	30	78.42	7	85.20	67	93.50	18	101.10	12	108.40	35
46.00	31	54.10	0	61.90	5	69.30	23	78.50	9	85.30	63	93.60	26	101.20	17	108.55	31
46.10	33	54.20	0	62.00	7	69.40	22	78.58	19	85.40	62	93.70	16	101.30	25	108.60	28
46.20	48	54.30	0	62.10	7	69.50	41	78.66	27	85.50	48	93.80	13	101.40	16	108.70	19
46.30	44	54.40	1	62.20	9	69.60	61	78.74	8	85.60	50	93.90	10	101.50	19	108.80	22
46.40	40	54.50	0	62.30	9	69.70	60	78.82	17	85.70	62	94.05	11	101.60	31	108.90	40
46.50	63	54.60	0	62.40	18	69.80	58	78.89	16	85.80	47	94.17	8	101.70	14	109.00	32
46.60	57	54.70	0	62.50	13	69.90	44	78.97	15	85.90	42	94.24	12	101.80	35	109.10	26
46.70	51	54.80	0	62.60	11	70.00	14	79.05	9	86.00	50	94.31	20	101.90	40	109.20	7
46.80	15	54.90	1	62.70	13	70.10	51	79.13	7	86.10	61	94.38	41	102.05	48	109.30	11
46.90	3	55.00	12	62.80	29	70.20	22	79.21	11	86.20	71	94.45	41	102.10	30	109.40	19
47.00	28	55.10	9	62.90	10	70.30	21	79.29	6	86.30	57	94.55	22	102.20	57	109.50	18
47.10	36	55.20	8	63.00	12	70.40	51	79.44	8	86.40	65	94.60	21	102.30	53	109.60	10
47.20	10	55.30	3	63.10	4	70.60	85	79.52	19	86.60	42	94.70	25	102.40	48	109.70	32
47.30	3	55.40	1	63.20	4	70.70	51	79.60	16	86.70	42	94.80	41	102.50	31	109.80	33
47.40	5	55.50	1	63.30	1	70.80	74	79.68	18	86.80	40	94.90	35	102.60	42	109.90	9
47.50	27	55.60	2	63.40	0	70.90	67	79.75	8	86.90	30	95.00	27	102.70	40	110.05	10
47.60	13	55.70	1	63.50	0	71.00	74	79.88	8	87.00	29	95.10	26	102.80	37	110.10	11
47.70	31	55.80	1	63.60	0	71.10	72	79.91	14	87.10	33	95.20	25	102.90	34	110.20	16
47.80	26	55.90	0	63.70	0	71.20	69	79.99	11	87.20	14	95.30	36	103.00	30	110.30	16
47.90	24	56.00	2	63.80	0	71.30	67	80.07	3	87.30	37	95.40	27	103.10	36	110.40	6
48.00	25	56.10	0	63.90	0	71.40	58	80.15	6	87.40	27	95.50	34	103.20	27	110.50	0
48.10	45	56.20	0	64.00	3	71.50	66	80.22	25	87.50	36	95.60	35	103.30	31	110.60	7
48.20	25	56.30	1	64.10	2	71.60	64	80.30	11	87.60	28	95.70	18	103.40	23	110.70	9
48.30	28	56.40	0	64.20	0	71.70	72	80.38	33	87.70	30	95.80	22	103.55	22	110.80	15
48.40	12	56.50	3	64.30	9	71.80	56	80.46	24	87.80	22	95.90	28	103.60	16	110.90	10
48.50	20	56.60	1	64.40	9	71.90	71	80.61	33	87.90	22	96.05	28	103.65	14	111.00	13
48.60	13	56.70	0	64.50	10	72.10	43	80.69	28	88.10	28	96.10	17	103.70	28	111.10	12
48.70	17	56.80	1	64.60	9	72.20	52	80.77	17	88.20	38	96.20	26	103.75	10	111.25	16
48.80	23	56.90	2	64.70	7	72.30	42	80.85	26	88.30	19	96.30	22	103.80	5	111.30	16
48.90	20	57.00	1	64.80	7	72.40	41	80.93	22	88.40	8	96.40	39	103.85	16	111.40	17
49.00	30	57.10	1	64.90	5	72.50	43	81.01	30	88.50	12	96.50	29	103.90	11	111.50	19
49.10	22	57.20	1	65.00	10	72.60	60	81.08	33	88.60	11	96.60	21	103.95	10	111.60	36
49.20	21	57.30	3	65.10	17	72.70	66	81.16	34	88.70	16	96.70	26	104.00	12	111.70	30
49.30	26	57.40	4	65.20	30	72.80	51	81.24	32	88.80	14	96.80	23	104.05	40	111.80	32
49.40	16	57.50	2	65.30	24	72.90	46	81.32	23	88.90	11	96.90	22	104.10	31	111.90	32
49.50	18	57.60	1	65.35	8	73.00	50	81.40	39	89.00	15	97.00	14	104.20	28	112.00	39
49.60	14	57.70	2	65.40	8	73.10	68	81.48	37	89.10	15	97.10	22	104.30	36	112.10	34
49.70	11	57.80	1	65.45	11	73.20	87	81.55	15	89.20	21			104.40	42	112.20	53

Table 1 (continued).

Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %	Depth (mbsf)	C %
112.30	25	114.50	67	116.80	93	118.90	70	121.10	55	123.20	24	125.30	79	127.40	8	129.60	11
112.40	52	114.60	69	116.90	92	119.00	53	121.20	36	123.30	17	125.40	90	127.60 ·	60	129.70	16
112.50	61	114.70	71	117.00	75	119.10	67	121.30	31	123.40	15	125.50	92	127.70	71	129.80	8
112.60	8	114.80	71	117.10	74	119.20	70	121.40	21	123.50	16	125.60	87	127.80	70	129.90	6
112.70	11	115.10	62	117.20	73	119.30	84	121.50	12	123.60	15	125.70	94	127.90	59	130.00	4
112.80	13	115.20	56	117.30	62	119.40	93	121.60	17	123.70	23	125.80	98	128.00	62	130.10	9
112.90	7	115.30	58	117.40	23	119.60	92	121.70	24	123.80	40	125.90	97	128.10	60	130.20	13
113.00	14	115.40	44	117.50	24	119.70	76	121.80	23	123.90	48	126.10	97	128.20	60	130.30	25
113.10	16	115.50	64	117.60	24	119.80	68	121.90	32	124.00	68	126.20	95	128.30	64	130.40	35
113.20	16	115.60	58	117.70	51	119.90	73	122.00	37	124.10	79	126.30	94	128.40	67	130.50	38
113.30	13	115.70	87	117.80	43	120.00	70	122.10	49	124.20	87	126.40	93	128.50	38	130.60	25
113.40	15	115.80	74	117.90	46	120.10	71	122.20	29	124.30	63	126.50	88	128.60	64	130.70	52
113.60	34	115.90	80	118.10	66	120.20	62	122.30	25	124.40	75	126.60	46	128.70	70	130.80	34
113.70	51	116.00	68	118.20	77	120.30	36	122.40	13	124.60	82	126.70	31	128.80	72	130.90	22
113.80	36	116.10	70	118.30	75	120.40	50	122.50	8	124.70	56	126.80	78	128.90	60	131.00	4
113.90	74	116.20	65	118.40	82	120.50	61	122.60	10	124.80	68	126.90	91	129.10	31	131.10	6
114.00	31	116.30	67	118.50	72	120.60	75	122.70	36	124.90	82	127.00	96	129.20	12	131.25	15
114.10	37	116.40	57	118.60	80	120.70	68	122.80	28	125.00	86	127.10	88	129.30	29	131.30	4
114.20	59	116.60	72	118.70	84	120.80	52	122.90	37	125.10	90	127.20	70	129.40	25	131.40	13
114.30	64	116.70	86	118.80	70	120.90	79	123.10	31	125.20	92	127.30	18	129.50	7	131.50	14
114.40	66																

Table 2. Name, depth, and estimated ages of the units described from the abundance of *Coccolithus pelagicus*.

		Sample	Depth (mbsf)	Chron	Estimated ages (MA)
Unit A	Bottom	14H-5, 10	129.1	top C6CN1	24.04
	Top	14H-1, 80	123.8	in C 6B	22.72
Unit B	Bottom	13H-6, 30	121.3	top C6AAN2	22.25
	Top	10H-2, 40	113.6	in C6R	20.57
Unit C	Bottom	10H-1, 30	86.9	in C5CN1	16.41
	Top	9H-5, 140	81.4	in C5BN2	15.2
Unit D	Bottom	9H-1, 10	75.6	in C5ACN	14.07
	Top	8H-1, 120	67.2	top C5AAN	12.84
Unit E	Bottom	6H-1, 10	47.1	top C5	8.92

Note: Taken from percentages greater than the average (34%).

with frequencies close to those of orbital cycles 123 and 95 k.y and perhaps 413 k.y. Frequency not explained by the Milankovitch theory of climate is also present (200 k.y.). An orbital forcing in the series expresses the influence of climate variations on the phytoplankton of the Kerguelen Plateau during the Miocene. Most of the variations recorded by the calcareous nannoplankton at Kerguelen Plateau are of a longer scale, however.

This study essentially demonstrates the great potential that quantitative studies of calcareous nannofossil assemblages have for delineating the paleoceanographic and paleoclimatic evolution of the Miocene of the southern oceans.

ACKNOWLEDGMENTS

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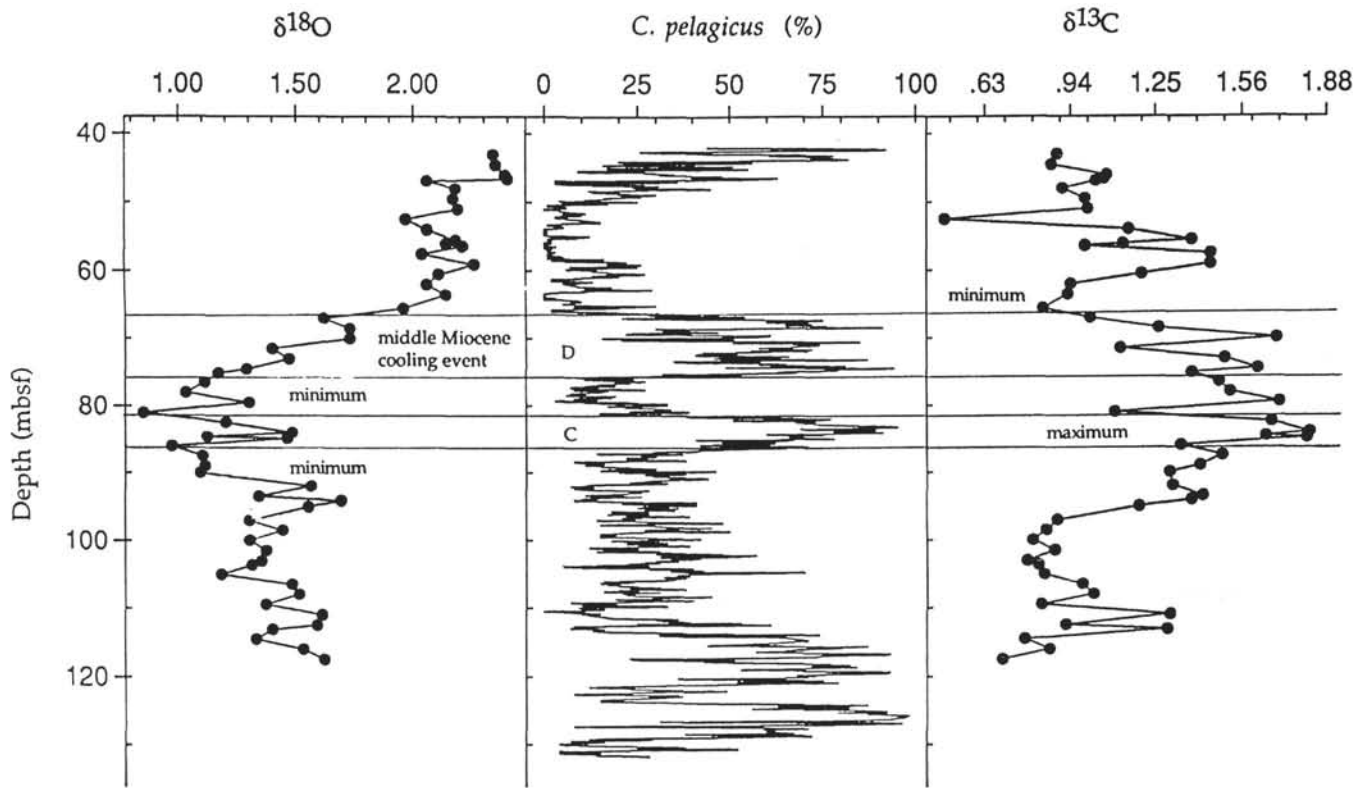
Figure 4. Comparison of the abundance of *Coccolithus pelagicus* and the stable isotope values from benthic foraminifers, Hole 747A.

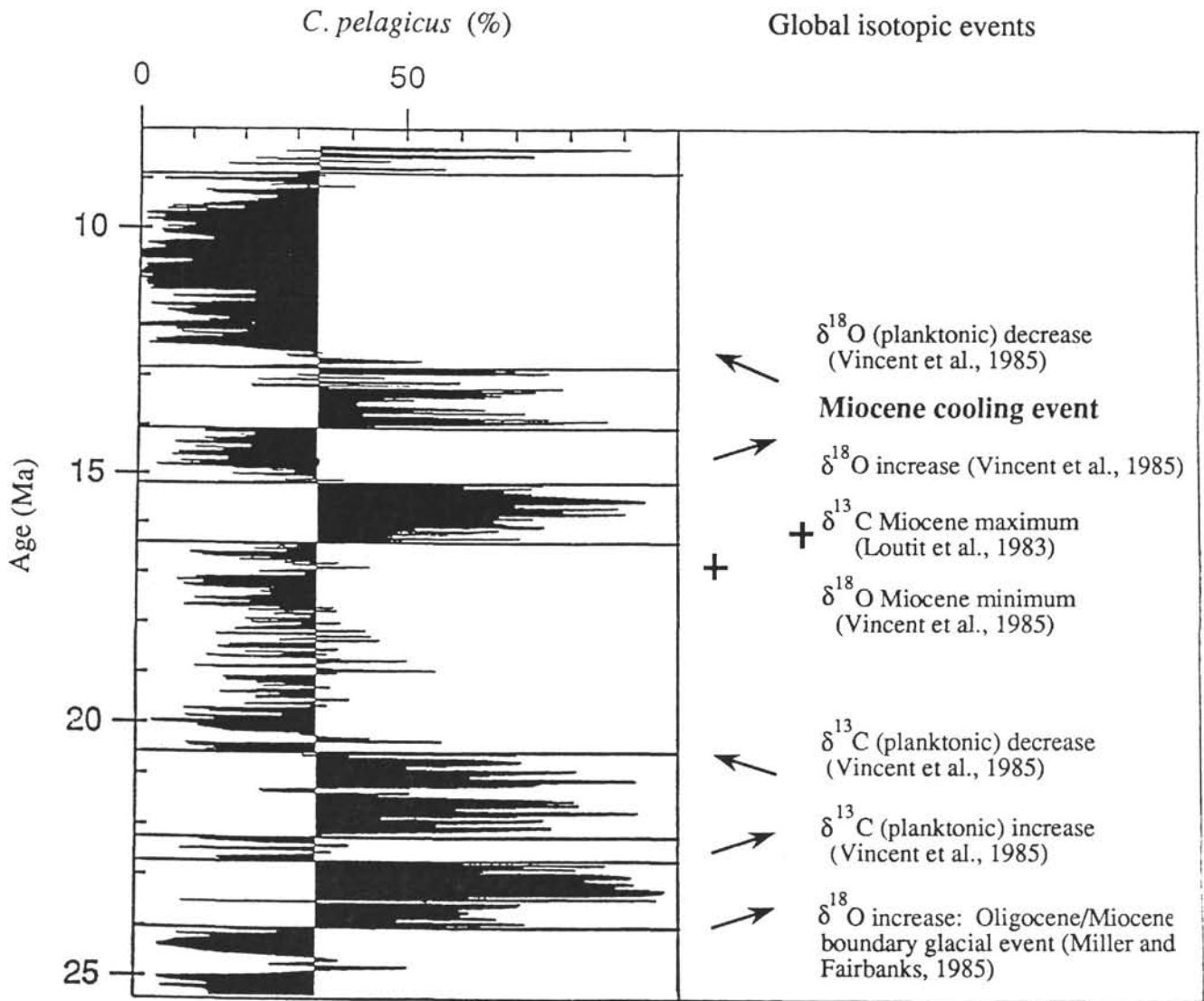C. pelagicus (%)　　　　　　　Global isotopic events

Figure 5. Correlation of the *Coccolithus pelagicus* units of Site 747 with global isotopic events (data from Wright and Miller, this volume).
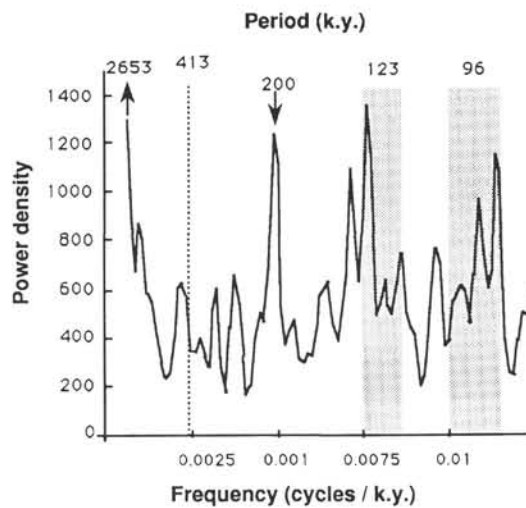

Figure 6. Spectra for the entire *C. pelagicus series*; the shaded areas correspond to the expected position of the eccentricity cycles (±7 k.y.), bandwidth = 0.003.
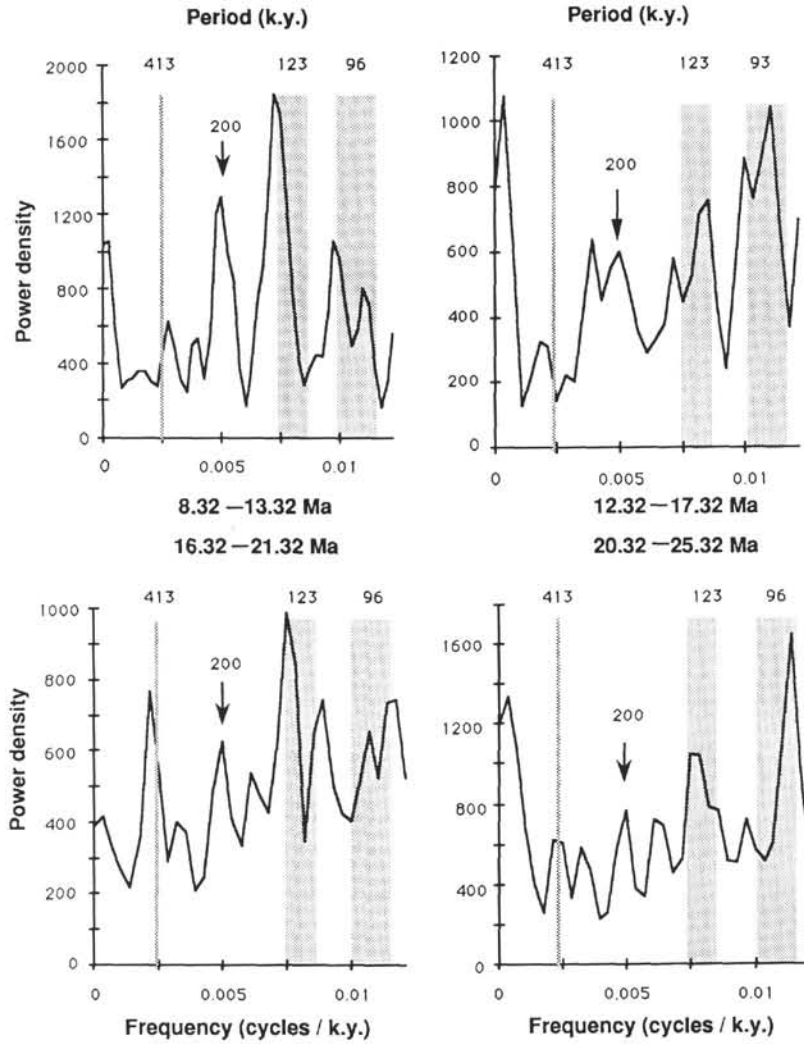
Figure 7. Spectra of four different parts of the *C. pelagicus* series; the shaded areas correspond to the expected frequency values of the eccentricity cycles (±7 k.y.), bandwidth = 0.007.