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42. PLIOCENE–PLEISTOCENE PALEOCLIMATIC AND PALEOCEANOGRAPHIC HISTORY OF SITE 959, EASTERN EQUATORIAL ATLANTIC OCEAN[1]

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ABSTRACT

Pliocene–Pleistocene paleoclimatic and paleoceanographic variables were examined based on the number (in 20 view fields) and relative abundances of calcareous nannofossil *F. profunda*, number of discoasters in 20 view fields, relative abundances of warm- and cool-water indicator calcareous nannofossils, and the species diversity indices *S*, *H(S)*, and *E*. The early Pliocene is characterized by relatively shallow nutricline (by proxy, thermocline) compared to the late Pliocene as evidenced by lower relative abundances of *F. profunda.* The early Pliocene contains a higher abundance of discoasters, warm-water indicator calcareous nannofossils, and the species diversity indices *S*, *H(S)*, and *E* all suggest warm and stable surface-water conditions. The late Pliocene contains the highest relative abundance of *F. profunda*, indicating the deepest nutricline and, by proxy, thermocline. Climatic shift and changes in nutricline/thermocline occurred between 2.82 and 3.03 Ma. The surface-water temperature became cool, the thermocline/nutricline depth became shallower, and the primary productivity began to get higher starting from the early late Pliocene (2.82 Ma) to the latest Pleistocene. These paleoceanographic events are shown by significant changes in both number and relative abundances of *F. profunda*, relative abundances of warm-water indicator calcareous nannofossils, and by the species diversity indices from the early late Pliocene (upper part of Subzone CN 12a; 2.82 Ma) through the latest Pleistocene. The early Pleistocene shows greater variations of the relative abundances of *F. profunda* and warm-water nannofossils, suggesting unstable and great fluctuation of surface-water temperature and nutricline/thermocline depth. Another climatic cooling starting approximately 2.4 Ma, also shown by the decreasing relative abundances of *F. profunda*, by warm-water indicator nannofossils, and by the species diversity indices for the younger sediment. The middle and late Pleistocene contain the lowest relative abundances of *F. profunda*, suggesting the shallowest thermocline/nutricline.

INTRODUCTION

The purpose of this paper is to investigate the paleoclimatic and paleoceanographic history of the Pliocene to Pleistocene sediment of Hole 959C based on the calcareous nannofossils in the equatorial Atlantic Ocean. Four sites were drilled during Leg 159 (Sites 959–962) on the Marginal Ridge of the Côte d'Ivoire-Ghana Transform Margin (CIGTM) in the eastern Equatorial Atlantic. Four holes were drilled at Site 959: Holes 959A, 959B, 959C, and 959D. Site 959 lies within intermediate and uppermost deep waters. Site 959 is located on a small plateau that extends just north of the top of the Côte d'Ivoire-Ghana Marginal Ridge (CIGMR) on the southern shoulder of the Deep Ivorian Basin (Shipboard Scientific Party, 1996). Pliocene to Pleistocene sediments from Hole 959C are composed of nannofossil ooze with foraminifers. Hole 959C is at 3°37.669′N, 2°44.116′W and has a water depth of 2090 m (Fig. 1). Hole 959C was drilled using advanced hydraulic piston coring (APC), until refusal at 179.6 mbsf.

Core recovery from Hole 959C was complete, and contains well-preserved abundant calcareous nannofossils. Therefore, Hole 959C is an ideal site for the study of calcareous nannofossil paleoceanography.

METHODS

Conventionally, the smear slide method is used by calcareous nannofossil paleontologists for the paleoceanography and quantitative study of calcareous nannofossils. However, size fractionation on smear slides has been observed as a result of toothpick action on a slide (Wei, 1988). Beaufort (1991; p. 415) stressed that "a count of relative abundance using smear slides is accurate only for species of similar size unless a large number of view fields are examined." To avoid the size fractionation of calcareous nannofossils during the preparation of smear slides, the settling method developed by Beaufort (1991) and Ehrendorfer (1993) is used for the study of paleoceanography.

Neogene zonation of Okada and Bukry (1980) was used for the biostratigraphy. The age assignments of marker species were followed Berggren et al. (1985, 1995). Neogene (Pliocene to Pleistocene) samples totaling 371 from interval 159-959C-1H to 8H were selected, using 20-cm sampling intervals. Calcareous nannofossil *Florisphaera profunda* was counted in 20 view fields at 1000× mag-

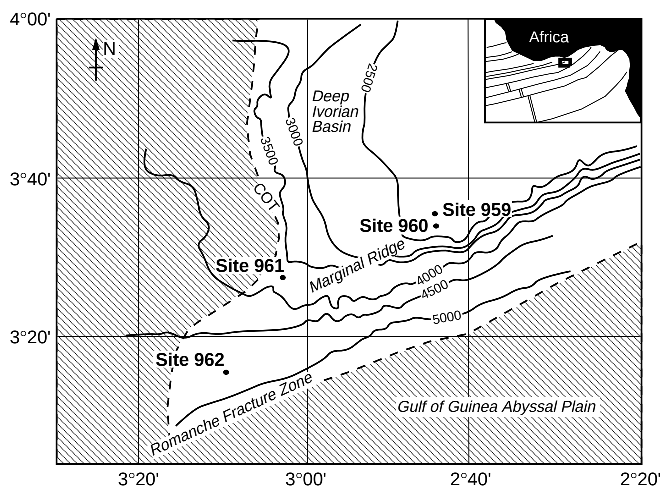

Figure 1. Location map of Site 959 and the other Leg 159 sites.

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nification (Table 1). Relative abundances of calcareous nannoplankton species per section (1.5-m intervals) are reported based on 500 countings from the settled slide (Shin et al., Chap. 39, this volume). Relative abundances of *F. profunda* in each section (1.5-m intervals) are used to study the nutricline/thermocline depth variations.

The species diversity indices of calcareous nannofossils were calculated based on the percentage data in terms of species richness, *S*, Shannon-Wiener information function *H(S)*, and equitability (*E*) (Table 2). Richness was estimated by the number of species per settled slide, using a count of 500 specimens. The Shannon-Wiener information function, derived from information theory, is defined as $H(S) = -\Sigma P_i \times \ln P_i$, where *S* is the number of species in the sample and P_i is the proportion of the i_{th} species in the sample. One advantage of this information function is the minimization of problems related to sample size. This information function is little affected by rare and extremely abundant species and is affected mostly by species with common abundances (Gibson and Buzas, 1973). Theoretically, the maximum value of *H(S)* occurs when all species are equally distributed.

Equitability (*E*), used here, is the Buzas and Gibson equation (1969). It is defined as $E = e^{H(S)}/S$ where *H(S)* is the Shannon-Wiener index for the sample and *S* is the number of species in the sample. Values of *E* are always less than one and measure how far the sample departs from complete equitability. When all species are equally distributed, *E* = 1.0. A low value for *E* indicates greater deviation from a sample of equally proportioned species. In this study, the species diversity indices were used as a proxy measure of the surface-water temperatures and the stability of the surface-water mass conditions.

The variations in relative abundance of cool- and warm-water calcareous nannofossil species also were used as a measure of surface-water paleotemperature conditions. The cool-water indicator calcareous nannofossil species used in this study are *Coccolithus pelagicus, Discoaster asymmetricus, Emiliania huxleyi,* and *Gephyrocapsa caribbeanica.* The warm-water indicator nannofossil species used in this study are *Calcidiscus leptoporus*, different species of *Discoaster* (except *D. asymmetricus*), *Florisphaera profunda, Gephyrocapsa oceanica, Sphenolithus abies, S. neoabies,* and *Umbellosphaera irregularis.* The following references were used for the selection of warm- and cool-water indicator calcareous nannofossils (McIntyre et al., 1970; Okada and Honjo, 1973, 1975; Bukry, 1978; Decima et al., 1978; Haq et al., 1977; Haq and Lohmann, 1976; Honjo, 1977; Schneidermann, 1977; Okada and McIntyre, 1979; Backman and Shackleton, 1983; Manivit, 1989; Chepstow-Lusty et al., 1989; Rio et al., 1990; Spaulding, 1991). The number of *Discoaster* in 20 view fields at 1000× magnification was counted to know the surface-water temperature variations (Table 2).

RESULTS AND DISCUSSION

Paleoclimatic and Paleoceanographic History of Hole 959C

The number of *F. profunda* in 20 view fields in each 20-cm interval ranges from 74 to 1664 individuals (Fig. 2; Table 1). Figures 3 and 4 show the downcore distribution patterns of the numbers and relative abundances of *F. profunda* in each 1.5-m interval (1 sample/section). *Florisphaera profunda* was first described from the Pacific Ocean by Okada and Honjo (1973). This species is easy to recognize and is well preserved in oceanic sediments (Okada and Honjo, 1973). It lives only in the lower photic layer (150–200 m) and prefers low light and high nutrients (Honjo, 1977; Okada and Honjo, 1973; Honjo and Okada, 1974; Molfino and McIntyre, 1990a). The variations of this species were interpreted as changes in water depth, nutricline (by proxy, thermocline) depth, and water transparency and turbidity (Okada and Honjo, 1973; Honjo and Okada, 1974; Honjo, 1977; Okada and McIntyre, 1977, 1979; Reid, 1980; Okada, 1984, 1990; Molfino and McIntyre, 1990a, 1990b; Ahagon et al., 1993).

Climate control of nutricline/thermocline depth can be monitored by variations of *F. profunda* (Molfino and McIntyre, 1990a, 1990b). Molfino and McIntyre (1990a, 1990b) suggested that the high relative abundances (%) of *F. profunda* indicate a deep nutricline and warm surface-water temperatures associated with wind strength, divergence, and primary productivity minima. A deep nutricline means the upper euphotic zone is nutrient depleted. Nutricline depth is defined by a level of PO_4 of 1.0 µmol/liter, and it varies between 50 and 200 m (Molfino and McIntyre, 1990b). Therefore, there is a close relationship between the relative abundances of *F. profunda* and the nutrient content in the euphotic water column (Molfino and McIntyre, 1990a, 1990b; Ahagon et al., 1993). When the nutricline (by proxy, thermocline) becomes deep, the production of *F. profunda* in the upper euphotic layer is greater than the production of coccolithophorids (Molfino and McIntyre, 1990a, 1990b). On the other hand, lower relative abundances of *F. profunda* are associated with shallow nutricline/thermocline and low sea-surface temperatures because of wind strength, divergence, and primary productivity maxima (Molfino and McIntyre, 1990a, 1990b).

The early Pliocene in Hole 959C is characterized by lower relative abundances of *F. profunda* compared to late Pliocene (Fig. 4). This suggests that the nutricline/thermocline is relatively shallower in the early Pliocene than that in the late Pliocene. Figure 5 shows the number of *Discoasters* in 20 view fields. *Discoaster* spp. have an ecological preference for warm waters (Haq and Lohmann, 1976; Haq et al., 1977; Backman and Shackleton, 1983) and are resistant to dissolution (Bukry, 1971; Roth, 1973; Lohmann and Carlson, 1981; Manivit, 1989). Total *Discoaster* abundance is sensitive to temperature changes (Haq and Lohmann, 1976; Chepstow-Lusty et al., 1989). The plot of the number of *Discoaster* spp. does not show exactly the same trend as the relative abundances and number of *F. profunda* (Figs. 3–5). However, the number of *Discoaster* spp. shows a rough decreasing trend from the early Pliocene through the latest Pliocene, suggesting that surface-water temperatures became cooler from the early Pliocene through the latest Pliocene (Fig. 5). The *Discoaster* accumulation rate during the early Pliocene is four times higher than the late Pliocene in the North Atlantic according to Backman et al., (1986). They interpreted this as warmer surface water during the early Pliocene compared to the late Pliocene. This study also shows significantly higher numbers of *Discoaster* during the early Pliocene than the late Pliocene. Higher numbers of *Discoaster*, higher relative abundances of warm-water calcareous nannofossils, and greater values and smaller fluctuations of species diversity indices *S, H(S),* and *E* during the early Pliocene suggest warm and stable surface-water conditions (Figs. 5–7).

Backman and Pestiaux (1987) demonstrated that surface water shows continuous decreasing temperature from 3.5 Ma to the younger sediment based on *Discoaster* accumulation rate in the North Atlantic. This study shows a decreasing trend of the number of *Discoaster* spp. from 3.65 Ma to the younger sediment (Fig. 5).

Calcareous nannofossil richness declines during climatic cooling in the Cenozoic (Wise, 1988). Huber and Watkins (1992) also interpreted the lower number of species as an indication of cool climate during the Maastrichtian. Honjo and Okada (1974) showed that modern day coccolith richness is highest in the equatorial zone. Winter et al. (1979) demonstrated that high species richness in modern nannoplankton communities is correlated with high water temperatures, and low diversity is characteristic of relatively cool periods. Haq (1971) showed greater calcareous nannofossil species richness at climatic warming during the Paleogene period. Schneidermann (1977) reported richness decreases toward polar regions. Winter et al. (1979) found higher richness can correlate with high water temperature (summer) and low richness in cool winter period. Okada and McIntyre (1979) also reported higher diversity in late summer or autumn in the North Atlantic Ocean. From this study, the species richness (S) shows moderate positive correlation to the sum of warm ($r = 0.65$) and cool ($r = -0.55$) water indicator calcareous nannofossils. This suggests that higher richness (S) occurs in warm water. Pliocene sediments have higher richness values than those of the cool Pleistocene (Fig. 7). Manivit (1989) also reported lower species richness in the

Table 1. List of the number of calcareous nannofossil species *F. profunda* and its biostratigraphic zone in each 20-cm interval.

Core, section, interval (cm)	Depth (mbsf)	*F. profunda*	Zone
159-959C-			
1H-1, 0-2.5	0.01	393	CN15-CN14b
1H-1, 20-22.5	0.21	410	CN15-CN14b
1H-1, 40-42.5	0.41	681	CN15-CN14b
1H-1, 60-62.5	0.61	175	CN15-CN14b
1H-1, 80-82.5	0.81	308	CN15-CN14b
1H-1, 100-102.5	1.01	328	CN15-CN14b
1H-1, 120-122.5	1.21	238	CN15-CN14b
1H-1, 140-142.5	1.41	220	CN15-CN14b
1H-2, 0-2.5	1.51	298	CN15-CN14b
1H-2, 20-22.5	1.71	272	CN15-CN14b
1H-2, 40-42.5	1.91	448	CN15-CN14b
1H-2, 60-62.5	2.11	213	CN15-CN14b
2H-1, 0-2.5	2.31	178	CN15-CN14b
2H-1, 20-22.5	2.51	265	CN15-CN14b
2H-1, 40-42.5	2.71	166	CN15-CN14b
2H-1, 60-62.5	2.91	178	CN15-CN14b
2H-1, 80-82.5	3.11	178	CN15-CN14b
2H-1, 100-102.5	3.31	212	CN15-CN14b
2H-1, 120-122.5	3.51	170	CN15-CN14b
2H-1, 140-142.5	3.71	170	CN15-CN14b
2H-2, 0-2.5	3.81	117	CN15-CN14b
2H-2, 20-22.5	4.01	111	CN15-CN14b
2H-2, 40-42.5	4.21	118	CN15-CN14b
2H-2, 60-62.5	4.41	169	CN15-CN14b
2H-2, 80-82.5	4.61	107	CN15-CN14b
2H-2, 100-102.5	4.81	159	CN14a
2H-2, 120-122.5	5.01	269	CN14a
2H-2, 140-142.5	5.21	85	CN14a
2H-3, 0-2.5	5.31	80	CN14a
2H-3, 20-22.5	5.51	258	CN14a
2H-3, 40-42.5	5.71	270	CN14a
2H-3, 60-62.5	5.91	170	CN14a
2H-3, 80-82.5	6.11	257	CN14a
2H-3, 100-102.5	6.31	307	CN14a
2H-3, 120-122.5	6.51	371	CN14a
2H-3, 140-142.5	6.71	151	CN14a
2H-4, 0-2.5	6.81	254	CN14a
2H-4, 20-22.5	7.01	198	CN14a
2H-4, 40-42.5	7.21	206	CN14a
2H-4, 60-62.5	7.41	197	CN14a
2H-4, 80-82.5	7.61	361	CN14a
2H-4, 100-102.5	7.81	363	CN14a
2H-4, 120-122.5	8.01	380	CN14a
2H-4, 140-142.5	8.21	260	CN14a
2H-5, 0-2.5	8.31	233	CN14a
2H-5, 20-22.5	8.51	360	CN14a
2H-5, 40-42.5	8.71	314	CN14a
2H-5, 60-62.5	8.91	296	CN14a
2H-5, 80-82.5	9.11	960	CN14a
2H-5, 100-102.5	9.31	373	CN14a
2H-5, 120-122.5	9.51	386	CN14a
2H-5, 140-142.5	9.71	151	CN14a
2H-6, 0-2.5	9.81	316	CN14a
2H-6, 20-22.5	10.01	145	CN14a
2H-6, 40-42.5	10.21	233	CN14a
2H-6, 60-62.5	10.41	265	CN14a
2H-6, 80-82.5	10.61	356	CN14a
2H-6, 100-102.5	10.81	385	CN14a
2H-6, 120-122.5	11.01	165	CN14a
2H-6, 140-142.5	11.21	255	CN14a
2H-7, 0-2.5	11.31	254	CN14a
2H-7, 20-22.5	11.51	291	CN14a
2H-7, 40-42.5	11.71	416	CN14a
2H-7, 60-62.5	11.80	233	CN14a
3H-1, 0-2.5	11.81	416	CN14a
3H-1, 20-22.5	12.01	251	CN14a
3H-1, 40-42.5	12.21	392	CN14a
3H-1, 60-62.5	12.41	488	CN14a
3H-1, 80-82.5	12.61	219	CN14a
3H-1, 100-102.5	12.81	218	CN13a
3H-1, 120-122.5	13.01	293	CN13a
3H-1, 140-142.5	13.21	220	CN13a
3H-2, 0-2.5	13.31	183	CN13a
3H-2, 20-22.5	13.51	188	CN13a
3H-2, 40-42.5	13.71	75	CN13a
3H-2, 60-62.5	13.91	126	CN13a
3H-2, 80-82.5	14.11	257	CN13a
3H-2, 100-102.5	14.31	235	CN13a
3H-2, 120-122.5	14.51	271	CN13a
3H-2, 140-142.5	14.71	309	CN13a
3H-3, 0-2.5	14.81	201	CN13a
3H-3, 20-22.5	15.01	322	CN13b
3H-3, 40-42.5	15.21	338	CN13b
3H-3, 60-62.5	15.41	177	CN13b
3H-3, 80-82.5	15.61	424	CN13b
3H-3, 100-102.5	15.81	388	CN13b
3H-3, 120-122.5	16.01	317	CN13b
3H-3, 140-142.5	16.21	586	CN13b
3H-4, 0-2.5	16.31	270	CN13b
3H-4, 20-22.5	16.51	372	CN13b
3H-4, 40-42.5	16.71	210	CN13b
3H-4, 60-62.5	16.91	319	CN13b
3H-4, 80-82.5	17.11	371	CN13b
3H-4, 100-102.5	17.31	398	CN13b
3H-4, 120-122.5	17.51	339	CN13b
3H-4, 140-142.5	17.71	173	CN13b
3H-5, 0-2.5	17.81	536	CN13b
3H-5, 20-22.5	18.01	532	CN13b
3H-5, 40-42.5	18.21	541	CN13b
3H-5, 60-62.5	18.41	508	CN13b
3H-5, 80-82.5	18.61	416	CN13b
3H-5, 100-102.5	18.81	373	CN13b
3H-5, 120-122.5	19.01	84	CN13b
3H-5, 140-142.5	19.21	348	CN13b
3H-6, 0-2.5	19.31	380	CN13b
3H-6, 20-22.5	19.51	293	CN13b
3H-6, 40-42.5	19.71	256	CN13b
3H-6, 80-82.5	20.11	487	CN13b
3H-6, 100-102.5	20.31	350	CN13b
3H-6, 120-122.5	20.51	258	CN13b
3H-6, 140-142.5	20.71	283	CN13b
3H-7, 0-2.5	20.81	457	CN13a
3H-7, 20-22.5	21.01	240	CN13a
3H-7, 40-42.5	21.21	227	CN13a
4H-1, 0-2.5	21.31	74	CN13a
4H-1, 20-22.5	21.51	293	CN13a
4H-1, 40-42.5	21.71	270	CN13a
4H-1, 60-62.5	21.91	65	CN13a
4H-1, 80-82.5	22.11	277	CN13a
4H-1, 100-102.5	22.31	160	CN13a
4H-1, 120-122.5	22.51	138	CN13a
4H-1, 140-142.5	22.71	122	CN13a
4H-2, 0-2.5	22.81	177	CN13a
4H-2, 20-22.5	23.01	181	CN13a
4H-2, 40-42.5	23.21	333	CN13a
4H-2, 60-62.5	23.41	169	CN13a
4H-2, 80-82.5	23.61	240	CN13a
4H-2, 100-102.5	23.81	125	CN13a
4H-2, 120-122.5	24.01	218	CN13a
4H-2, 140-142.5	24.21	390	CN13a
4H-3, 0-2.5	24.31	370	CN13a
4H-3, 40-42.5	24.71	472	CN13a
4H-3, 60-62.5	24.91	395	CN13a
4H-3, 80-82.5	25.11	413	CN12d
4H-3, 100-102.5	25.31	395	CN12d
4H-3, 120-122.5	25.51	274	CN12d
4H-3, 140-142.5	25.71	182	CN12d
4H-4, 0-2.5	25.81	231	CN12d
4H-4, 20-22.5	26.01	345	CN12d
4H-4, 40-42.5	26.21	190	CN12d
4H-4, 60-62.5	26.41	288	CN12d
4H-4, 80-82.5	26.61	487	CN12d
4H-4, 100-102.5	26.81	228	CN12d
4H-4, 120-122.5	27.01	418	CN12d
4H-4, 140-142.5	27.21	283	CN12d
4H-5, 0-2.5	27.31	269	CN12d
4H-5, 20-22.5	27.51	225	CN12d
4H-5, 40-42.5	27.71	413	CN12d
4H-5, 60-62.5	27.91	432	CN12d
4H-5, 80-82.5	28.11	264	CN12d
4H-5, 100-102.5	28.31	265	CN12d
4H-5, 120-122.5	28.51	440	CN12d
4H-5, 140-142.5	28.71	511	CN12d
4H-6, 0-2.5	28.81	505	CN12c
4H-6, 20-22.5	29.01	196	CN12c
4H-6, 40-42.5	29.21	472	CN12c
4H-6, 60-62.5	29.41	358	CN12c
4H-6, 80-82.5	29.61	507	CN12c
4H-6, 100-102.5	29.81	531	CN12c
4H-6, 120-122.5	30.01	592	CN12c
4H-6, 140-142.5	30.21	490	CN12c
4H-7, 0-2.5	30.31	300	CN12c
4H-7, 20-22.5	30.51	208	CN12c
4H-7, 40-42.5	30.71	329	CN12c
4H-7, 60-62.5	30.80	522	CN12c
5H-1, 0-2.5	30.81	523	CN12c
5H-1, 20-22.5	31.01	448	CN12c
5H-1, 40-42.5	31.21	531	CN12c
5H-1, 60-62.5	31.41	218	CN12c
5H-1, 80-82.5	31.61	871	CN12c
5H-1, 100-102.5	31.81	336	CN12c
5H-1, 120-122.5	32.01	731	CN12c
5H-1, 140-142.5	32.21	441	CN12c
5H-2, 0-2.5	32.31	670	CN12c
5H-2, 20-22.5	32.51	790	CN12c
5H-2, 40-42.5	32.71	990	CN12c
5H-2, 60-62.5	32.91	333	CN12c
5H-2, 80-82.5	33.11	752	CN12c
5H-2, 100-102.5	33.31	517	CN12c
5H-2, 120-122.5	33.51	832	CN12c

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	*F. profunda*	Zone
159-959C-			
5H-2, 140-142.5	33.71	975	CN12c
5H-3, 0-2.5	34.01	942	CN12c
5H-3, 20-22.5	34.01	942	CN12c
5H-3, 40-42.5	34.21	693	CN12c
5H-3, 60-62.5	34.41	725	CN12c
5H-3, 80-82.5	34.61	1081	CN12c
5H-3, 100-102.5	34.81	1065	CN12c
5H-3, 120-122.5	35.01	196	CN12c
5H-3, 140-142.5	35.21	583	CN12c
5H-4, 0-2.5	35.31	748	CN12c
5H-4, 20-22.5	35.51	687	CN12c
5H-4, 40-42.5	35.71	626	CN12c
5H-4, 60-62.5	35.91	394	CN12c
5H-4, 80-82.5	36.11	953	CN12c
5H-4, 100-102.5	36.31	827	CN12c
5H-4, 120-122.5	36.51	653	CN12c
5H-4, 140-142.5	36.71	607	CN12c
5H-5, 0-2.5	36.81	551	CN12c
5H-5, 20-22.5	37.01	853	CN12c
5H-5, 40-42.5	37.21	528	CN12c
5H-5, 60-62.5	37.41	525	CN12c
5H-5, 80-82.5	37.61	614	CN12c
5H-5, 100-102.5	37.81	820	CN12c
5H-5, 120-122.5	38.01	226	CN12c
5H-5, 140-142.5	38.21	445	CN12c
5H-6, 0-2.5	38.31	565	CN12c
5H-6, 20-22.5	38.51	681	CN12c
5H-6, 40-42.5	38.71	1100	CN12c
5H-6, 60-62.5	38.91	603	CN12c
5H-6, 80-82.5	39.11	890	CN12c
5H-6, 100-102.5	39.31	745	CN12c
5H-6, 120-122.5	39.51	745	CN12c
5H-6, 140-142.5	39.71	421	CN12c
5H-7, 0-2.5	39.81	292	CN12c
5H-7, 20-22.5	40.01	606	CN12c
5H-7, 40-42.5	40.21	650	CN12c
5H-7, 60-62.5	40.30	558	CN12b
6H-1, 0-2.5	40.31	850	CN12b
6H-1, 20-22.5	40.51	596	CN12b
6H-1, 40-42.5	40.71	803	CN12b
6H-1, 60-62.5	40.91	586	CN12b
6H-1, 80-82.5	41.11	1050	CN12b
6H-1, 100-102.5	41.31	1100	upper CN12a
6H-1, 120-122.5	41.51	903	upper CN12a
6H-1, 140-142.5	41.71	522	upper CN12a
6H-2, 0-2.5	41.81	773	upper CN12a
6H-2, 20-22.5	42.01	457	upper CN12a
6H-2, 40-42.5	42.21	736	upper CN12a
6H-2, 60-62.5	42.41	657	upper CN12a
6H-2, 80-82.5	42.61	1042	upper CN12a
6H-2, 100-102.5	42.81	536	upper CN12a
6H-2, 120-122.5	43.01	394	upper CN12a
6H-2, 140-142.5	43.21	585	upper CN12a
6H-3, 0-2.5	43.31	580	upper CN12a
6H-3, 20-22.5	43.51	820	upper CN12a
6H-3, 40-42.5	43.71	634	upper CN12a
6H-3, 60-62.5	43.91	829	upper CN12a
6H-3, 80-82.5	44.11	681	upper CN12a
6H-3, 100-102.5	44.31	501	upper CN12a
6H-3, 120-122.5	44.51	485	upper CN12a
6H-3, 140-142.5	44.71	745	upper CN12a
6H-4, 0-2.5	44.81	611	upper CN12a
6H-4, 20-22.5	45.01	926	upper CN12a
6H-4, 40-42.5	45.21	712	upper CN12a
6H-4, 60-62.5	45.41	823	upper CN12a
6H-4, 80-82.5	45.61	623	upper CN12a
6H-4, 100-102.5	45.81	682	upper CN12a
6H-4, 120-122.5	46.01	400	upper CN12a
6H-4, 140-142.5	46.21	641	upper CN12a
6H-5, 0-2.5	46.31	853	lower CN12a
6H-5, 20-22.5	46.51	432	lower CN12a
6H-5, 40-42.5	46.71	478	lower CN12a
6H-5, 60-62.5	46.91	712	lower CN12a
6H-5, 80-82.5	47.11	901	lower CN12a
6H-5, 100-102.5	47.31	932	lower CN12a
6H-5, 120-122.5	47.51	703	lower CN12a
6H-5, 140-142.5	47.71	616	lower CN12a
6H-6, 0-2.5	47.81	658	lower CN12a
6H-6, 20-22.5	48.01	415	lower CN12a
6H-6, 40-42.5	48.21	337	lower CN12a
6H-6, 60-62.5	48.41	553	lower CN12a
6H-6, 80-82.5	48.61	918	lower CN12a
6H-6, 100-102.5	48.81	534	lower CN12a
6H-6, 120-122.5	49.01	547	upper CN11b
6H-6, 140-142.5	49.21	712	upper CN11b
6H-7, 0-2.5	49.31	708	upper CN11b
6H-7, 20-22.5	49.51	638	upper CN11b
6H-7, 40-42.5	49.71	866	upper CN11b
6H-7, 60-62.5	49.80	730	upper CN11b
7H-1, 0-2.5	49.81	931	upper CN11b
7H-1, 20-22.5	50.01	440	upper CN11b
7H-1, 40-42.5	50.21	797	upper CN11b
7H-1, 60-62.5	50.41	623	upper CN11b
7H-1, 80-82.5	50.61	838	upper CN11b
7H-1, 100-102.5	50.81	618	upper CN11b
7H-1, 120-122.5	51.01	610	upper CN11b
7H-1, 140-142.5	51.21	720	upper CN11b
7H-2, 0-2.5	51.31	1185	upper CN11b
7H-2, 20-22.5	51.51	630	upper CN11b
7H-2, 40-42.5	51.71	647	upper CN11b
7H-2, 60-62.5	51.91	802	upper CN11b
7H-2, 80-82.5	52.11	1264	upper CN11b
7H-2, 100-102.5	52.31	1019	upper CN11b
7H-2, 120-122.5	52.51	1072	upper CN11b
7H-2, 140-142.5	52.71	986	upper CN11b
7H-3, 0-2.5	52.81	1284	upper CN11b
7H-3, 20-22.5	53.01	1144	upper CN11b
7H-3, 40-42.5	53.21	1476	upper CN11b
7H-3, 60-62.5	53.41	1020	upper CN11b
7H-3, 80-82.5	53.61	977	upper CN11b
7H-3, 120-122.5	54.01	1046	upper CN11b
7H-3, 140-142.5	54.21	1192	upper CN11b
7H-4, 0-2.5	54.31	1105	upper CN11b
7H-4, 20-22.5	54.51	1020	upper CN11b
7H-4, 40-42.5	54.71	1050	upper CN11b
7H-4, 60-62.5	54.91	1376	upper CN11b
7H-4, 80-82.5	55.11	1512	upper CN11b
7H-4, 100-102.5	55.31	1104	upper CN11b
7H-4, 120-122.5	55.51	1173	upper CN11b
7H-4, 140-142.5	55.71	977	upper CN11b
7H-5, 0-2.5	55.81	1113	upper CN11b
7H-5, 20-22.5	56.01	1236	upper CN11b
7H-5, 40-42.5	56.21	714	upper CN11b
7H-5, 60-62.5	56.41	1125	upper CN11b
7H-5, 80-82.5	56.61	1166	upper CN11b
7H-5, 100-102.5	56.81	1401	upper CN11b
7H-5, 120-122.5	57.01	1285	upper CN11b
7H-5, 140-142.5	57.21	1055	upper CN11b
7H-6, 0-2.5	57.31	631	upper CN11b
7H-6, 20-22.5	57.51	1077	upper CN11b
7H-6, 40-42.5	57.71	740	upper CN11b
7H-6, 60-62.5	57.91	1114	upper CN11b
7H-6, 80-82.5	58.11	982	upper CN11b
7H-6, 100-102.5	58.31	1664	upper CN11b
7H-6, 120-122.5	58.51	1545	upper CN11b
7H-6, 140-142.5	58.71	1387	upper CN11b
7H-7, 0-2.5	58.81	1280	upper CN11b
7H-7, 20-22.5	59.01	1168	upper CN11b
7H-7, 40-42.5	59.21	808	upper CN11b
7H-7, 60-62.5	59.30	958	upper CN11b
8H-1, 0-2.5	59.31	1240	upper CN11b
8H-1, 20-22.5	59.51	1285	upper CN11b
8H-1, 40-42.5	59.71	1034	upper CN11b
8H-1, 80-82.5	60.11	1293	upper CN11b
8H-1, 100-102.5	60.31	1048	upper CN 11b
8H-1, 120-122.5	60.51	576	lower CN11
8H-1, 140-142.5	60.71	973	lower CN11
8H-2, 0-2.5	60.81	930	lower CN11
8H-2, 20-22.5	61.01	996	lower CN11
8H-2, 40-42.5	61.21	1076	lower CN11
8H-2, 60-62.5	61.41	1108	lower CN11
8H-2, 80-82.5	61.61	1213	lower CN11
8H-2, 100-102.5	61.81	1136	lower CN11
8H-2, 120-122.5	62.01	754	lower CN11
8H-2, 140-142.5	62.21	921	lower CN11
8H-3, 0-2.5	62.31	742	lower CN11
8H-3, 20-22.5	62.51	1588	lower CN11
8H-3, 40-42.5	62.71	1150	lower CN11
8H-3, 60-62.5	62.91	1411	lower CN11
8H-3, 80-82.5	63.11	1322	lower CN11
8H-3, 100-102.5	63.31	1080	lower CN11
8H-3, 120-122.5	63.51	976	lower CN11
8H-3, 140-142.5	63.71	971	lower CN11
8H-4, 0-2.5	63.81	851	lower CN11
8H-4, 20-22.5	64.01	1135	lower CN11
8H-4, 40-42.5	64.21	432	lower CN11
8H-4, 60-62.5	64.41	1054	lower CN11
8H-4, 80-82.5	64.61	600	lower CN11
8H-4, 100-102.5	64.81	1230	lower CN11
8H-4, 120-122.5	65.01	733	lower CN11
8H-4, 140-142.5	65.21	415	lower CN11
8H-5, 0-2.5	65.31	645	lower CN11
8H-5, 20-22.5	65.51	950	lower CN11
8H-5, 40-42.5	65.71	954	lower CN11
8H-5, 60-62.5	65.91	1176	lower CN11
8H-5, 80-82.5	66.11	1187	lower CN11
8H-5, 100-102.5	66.31	755	lower CN11
8H-5, 120-122.5	66.51	600	lower CN11
8H-5, 140-142.5	66.71	940	lower CN11

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	*F. profunda*	Zone
159-959C-			
8H-6, 0-2.5	66.81	781	lower CN11
8H-6, 20-22.5	67.01	750	lower CN11
8H-6, 40-42.5	67.21	648	lower CN11
8H-6, 60-62.5	67.41	666	lower CN11
8H-6, 80-82.5	67.61	709	lower CN11
8H-6, 100-102.5	67.81	540	lower CN11
8H-6, 120-122.5	68.01	681	lower CN11
8H-6, 140-142.5	68.21	711	lower CN11
8H-7, 0-2.5	68.31	680	lower CN11
8H-7, 20-22.5	68.51	901	lower CN11
8H-7, 40-42.5	68.71	965	CN 10d
8H-7, 60-62.5	68.80	967	CN 10d

Pleistocene than the Pliocene, where warm-water *Discoaster* spp. are abundant.

The late Pliocene has the highest relative abundances of *F. profunda,* suggesting the deepest nutricline/thermocline depth, warm surface-water temperature, and low primary productivity in the upper euphotic water column because of the wind strength and divergence minima (Fig. 4). There is a significant change of both number (numbers/20 view fields) and relative abundances (%) of *F. profunda* in the lower upper Pliocene (Sample 159-959C-6H-2, 80–82.5 cm; 42.61 mbsf) (Figs. 3, 4). Both the number and relative abundances of *F. profunda* gradually decrease from lower upper Pliocene (Sample 159-959C-6H-2, 80–82.5 cm; 42.61 mbsf) through the uppermost Pleistocene (Figs. 3, 4). This suggests that the nutricline/thermocline depth is gradually getting shallower from the lower upper Pliocene (Sample 159-959C-6H-2, 80–82.5 cm; 42.61 mbsf) through the uppermost Pleistocene. A decreasing trend of *F. profunda* from lower upper Pliocene (Sample 159-959C-6H-2, 80–82.5 cm; 42.61 mbsf) to the uppermost Pleistocene also suggests that the surface water cooled and productivity in the upper euphotic water column increased from the lower upper Pliocene through the uppermost Pleistocene (Fig. 4). The age of the sediments at 42.61 mbsf is ~2.82 Ma, by the assumption of a linear sediment accumulation rate between 2.73 and 3.65 Ma. The sum of the relative abundances of warm-water species also shows climatic cooling starting at the lower upper Pliocene (upper part of Subzone 12a; near 2.82 Ma) (Fig. 6). Species richness (*S*) also shows a decreasing trend from the upper part of Subzone 12a (lower upper Pliocene) through the uppermost Pleistocene (Fig. 7).

Whitman and Berger (1993) reported climatic cooling at 2.87 Ma based on the oxygen isotope record of foraminifers at the Pacific Site 586. The results of this study agrees well with that of the Whitman and Berger (1993).

The relative abundances of *F. profunda* decrease with decreased transparency in the euphotic water column at the northwestern margin of the Pacific (Ahagon et al., 1993). Gradual increases in water turbidity caused by increased particle and nutrient supplies from more exposed land areas, caused by lowering sea level, may be responsible for the decreasing trend of *F. profunda* starting from the lower upper Pliocene (Sample 159-959C-6H-2, 80–82.5 cm; 42.61 mbsf; 2.82 Ma) through uppermost Pleistocene. There is an abrupt fall of sea level shortly after 3 Ma (Haq et al., 1987). As previously mentioned, the progressive productivity increase from lower upper Pliocene through uppermost Pleistocene matches well with the increased particles and nutrients at the same interval. Molfino and McIntyre (1990b) also reported that the rapid change of the relative abundance of *F. profunda* is associated with the boundary between high values of phosphate and low values of phosphate in the euphotic zone. Relatively greater sedimentation rate of the above time interval may support a great amount of terrigenous sediment input from nearby land areas (Shin et al., Chap. 39, this volume).

There is a significant shift in the relative abundance of *F. profunda* in the lowermost part of upper Pliocene (Sample 159-959C-6H-4, 80–82.5 cm; 45.61 mbsf). The age of this depth is ~3.03 Ma, based on the assumption of linear sediment accumulation rate between 2.73 and 3.65 Ma. Backman et al. (1986) reported changes in sediment accumulation rate in the North Atlantic at 3.2 Ma. There was a higher abyssal current velocity and an increase in the production of deep and bottom water at 3.2 Ma in the high-latitude North Atlantic (Backman et al., 1986). This study also shows sedimentation rate changes (Shin et al., Chap. 39, this volume), relative abundances of warm-water indicator calcareous nannofossils, and species diversity indices. Early late Pliocene (3.0 Ma) is a time of deepening of the carbonate compensation depth (CCD) to the present-day values (Rio et al., 1990). This CCD change corresponds with a climatic deterioration (Prell, 1984; Keigwin, 1982, 1987) and preceded the onset of the Northern Hemisphere glaciation that occurred at 2.5 Ma (Shackleton et al., 1984). Shackleton et al. (1984) also reported that a considerable climatic variability existed from 2.4 to 3.5 Ma, before the initial glacial event. A significant climatic shift together with nutricline/thermocline depth change occurred between Sample 159-959C-6H-2, 80–82.5 cm (42.61 mbsf) and Sample 6H-4, 80–82.5 cm (45.61 mbsf). The duration of this 3-m core is 0.21 Ma (3.03–2.82 Ma).

The relative abundances of *F. profunda* show a significant decreasing trend from the late late Pliocene (around 2.4 Ma) through the latest Pleistocene (Fig. 4). The percentages of warm-water indicator calcareous nannofossil species also show a decreasing trend from ~2.4 Ma through the Pleistocene (Fig. 6). Cool-water indicator calcareous nannofossils also show an increasing trend near the same time interval (Fig. 6). Lower abundances of *Discoaster* also occur at 2.4 Ma compared to the older sediment (Fig. 5). Species diversity indices *S* and *H(S)* also show decreasing trends from ~2.4 Ma to the core top (Fig. 7). All of these trends indicate climatic cooling from near 2.4 Ma to the younger sediments. First Pliocene glaciation is close to 2.4 Ma (Shackleton et al., 1984). Rapid cooling started at 2.4 Ma in the North Atlantic (Shackleton et al., 1984). Backman and Pestiaux (1987) also reported low *Discoaster* accumulation rates at 2.4 Ma in the North Atlantic, indicating cool surface temperature conditions.

The middle and upper Pleistocene (Zone CN15–CN14b) is characterized by the lowest relative abundances of *F. profunda* indicating the shallowest nutricline/thermocline depth and the coolest surface-water temperatures caused by the maximum divergence and wind strength (Fig. 4). Pleistocene shallowing of the nutricline/thermocline were also reported in the Equatorial Atlantic as evidenced by the low relative abundances of *F. profunda* (Molfino and McIntyre, 1990a).

Species diversity of planktonic organisms shows an increasing trend in more stable marine conditions (Gibson, 1966; Gibson and Buzas, 1973). Watkins (1989) also observed that the higher *H(S)* values of calcareous nannofossils indicate more stable surface-water conditions. Species diversity represents an inverse relationship to environmental stress (Sanders, 1968; Abele and Walters, 1979). The lower Pliocene is characterized by greater species diversity values. This suggests more stable surface-water conditions than the upper Pliocene and Pleistocene. Generally, the whole part of the core studied (Pliocene to Pleistocene) shows smaller fluctuations of the species diversity indices *S, H(S),* and *E,* suggesting stable surface-water conditions during the deposition (Fig. 7).

SUMMARY AND CONCLUSIONS

The nutricline/thermocline depth fluctuated several times during the Pliocene to Pleistocene. The early Pliocene is characterized by a relatively shallow nutricline/thermocline and stable surface-water conditions compared to the late Pliocene. The late Pliocene has the

Table 2. List of the discoasters (20 view fields), species diversity indices (*S*, *H[S]*, *E*), and sum of the relative abundances of cool- and warm-water indicator calcareous nannofossil species.

Age	Nannofossil zone	Core, section, interval (cm)	Depth (mbsf)	Discoasters (20 view fields)	*S*	*H(S)*	*E*	Cool-water species (%)	Warm-water species (%)
late/middle Pleistocene	*E. huxleyi*/ *C. cristatus* (CN15/CN14b)	1H-1, 0-2.5	0.01	0	9	1.81	0.68	29.44	42.17
		1H-1, 80-82.5	0.81	0	14	1.76	0.42	30.55	43.93
		2H-1, 80-82.5	3.11	0	8	1.1	0.38	29.04	8.32
		2H-2, 80-82.5	4.61	0	9	1.41	0.46	35.95	6.86
early Pleistocene	*E. ovata* (CN14a)	2H-3, 80-82.5	6.11	0	7	1.08	0.42	16.72	22.45
		2H-4, 80-82.5	7.61	0	10	1.34	0.38	8.09	43.63
		2H-5, 80-82.5	9.11	0	11	1.2	0.3	3.46	58.50
		2H-6, 80-82.5	10.61	0	11	1.36	0.35	4.80	34.50
		3H-1, 80-82.5	12.61	0	12	1.62	0.42	0.00	38.36
	G. caribbeanica (CN13b)	3H-2, 80-82.5	14.11	0	10	0.89	0.24	0.00	17.59
		3H-3, 80-82.5	15.61	0	8	0.69	0.25	0.17	18.53
		3H-4, 80-82.5	17.11	0	14	1.7	0.39	4.27	25.30
		3H-5, 80-82.5	18.61	0	12	1.77	0.49	11.64	29.97
		3H-6, 80-82.5	20.11	0	14	1.44	0.3	5.81	40.68
	E. annula (CN13a)	4H-1, 80-82.5	22.11	0	14	1.59	0.35	1.00	57.40
		4H-2, 80-82.5	23.61	0	16	1.62	0.32	1.01	58.87
late Pliocene	*C. macintyrei* (CN12d)	4H-3, 80-82.5	25.11	8	17	1.65	0.31	0.40	45.80
		4H-4, 80-82.5	26.61	9	18	1.24	0.19	1.40	66.80
		4H-5, 80-82.5	28.11	0	13	1.26	0.27	0.00	43.80
	D. pentaradiatus (CN12c)	4H-6, 80-82.5	29.61	0	15	1.41	0.27	0.40	48.60
		5H-1, 80-82.5	31.61	7	14	1.25	0.25	0.00	59.90
		5H-2, 80-82.5	33.11	0	15	1.35	0.26	0.00	56.60
		5H-3, 80-82.5	34.61	1	13	1.21	0.26	0.00	58.80
		5H-4, 80-82.5	36.11	6	13	0.98	0.2	0.00	71.14
		5H-5, 80-82.5	37.61	6	17	1.39	0.24	0.00	57.20
		5H-6, 80-82.5	39.11	12	16	1.25	0.22	0.00	64.40
	D. sur. (CN12b)	6H-1, 80-82.5	41.11	41	15	1.33	0.25	0.40	62.43
	D. tamalis upper CN12a	6H-2, 80-82.5	42.61	21	18	1.03	0.16	0.20	77.10
		6H-3, 80-82.5	44.11	23	17	1.66	0.31	0.20	44.54
		6H-4, 80-82.5	45.61	23	11	1.17	0.29	0.00	28.75
	D. tamalis lower CN12a	6H-5, 80-82.5	47.11	35	15	1.35	0.26	0.00	39.58
		6H-6, 80-82.5	48.61	39	13	1.5	0.34	0.00	44.80
early Pliocene	*D. asymmetricus* upper CN11b	7H-1, 80-82.5	50.61	29	18	1.92	0.38	0.00	42.40
		7H-2, 80-82.5	52.11	100	17	1.71	0.33	0.00	69.26
		7H-3, 80-82.5	53.61	59	16	2	0.46	0.20	58.00
		7H-4, 80-82.5	55.11	32	14	1.62	0.36	0.00	62.05
		7H-5, 80-82.5	56.61	27	16	1.78	0.37	0.00	60.60
		7H-6, 80-82.5	58.11	42	17	1.79	0.35	0.20	62.00
		8H-1, 80-82.5	60.11	62	13	1.67	0.41	0.00	60.72
	D. asymmetricus lower CN11	8H-2, 80-82.5	61.61	136	15	1.69	0.36	0.00	50.80
		8H-3, 80-82.5	63.11	134	16	1.9	0.42	0.00	48.88
		8H-4, 80-82.5	64.61	63	19	2.16	0.46	0.20	44.60
		8H-5, 80-82.5	66.11	84	16	1.64	0.32	0.00	44.00
		8H-6, 80-82.5	67.61	107	16	1.94	0.43	0.00	33.80

deepest nutricline/thermocline within the Pliocene to Pleistocene. A significant climatic and paleoceanographic shift occurred between 3.03 and 2.82 Ma (early late Pliocene). The nutricline/thermocline depth becomes shallower from 2.82 Ma through the younger sediment. The surface-water temperature becomes cooler and surface water (upper euphotic water) primary productivity becomes higher starting from 2.82 Ma through the latest Pleistocene. The transition between deep and shallow nutricline/thermocline occurred at 3.03 Ma (early late Pliocene). The nutricline/thermocline depth younger than 3.03 Ma is deeper than that of older than 3.03 Ma within Pliocene. The early Pleistocene shows great fluctuations of nutricline and thermocline depth. The middle and late Pleistocene is characterized by shallowest nutricline/thermocline.

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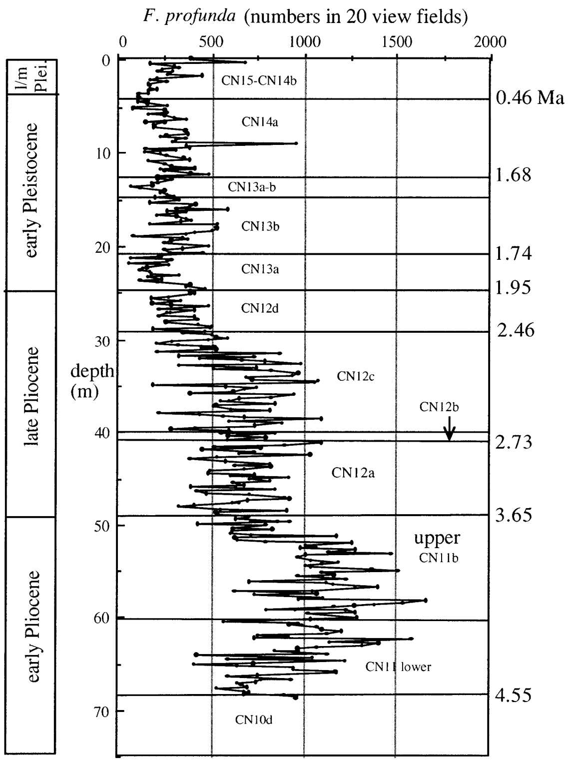

Figure 2. Depth-distribution patterns of calcareous nannofossil species *F. profunda* in 20 view fields at 20-cm intervals (magnification 1000×).

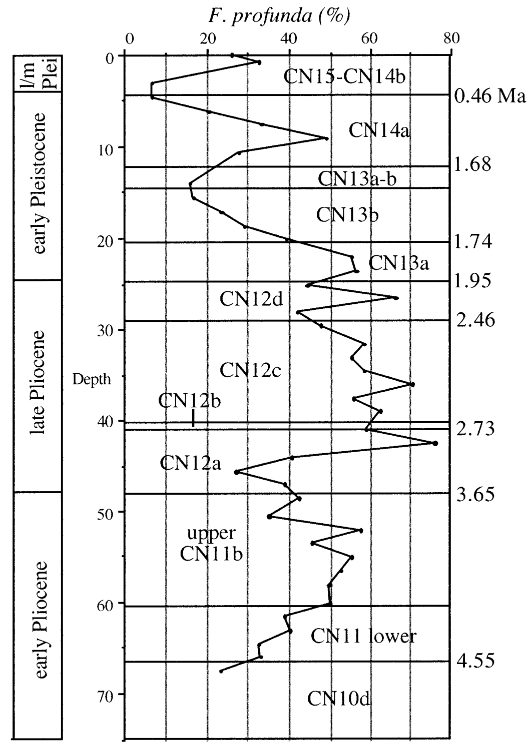

Figure 4. Depth-distribution patterns of the relative percentages of *F. profunda* in each section.

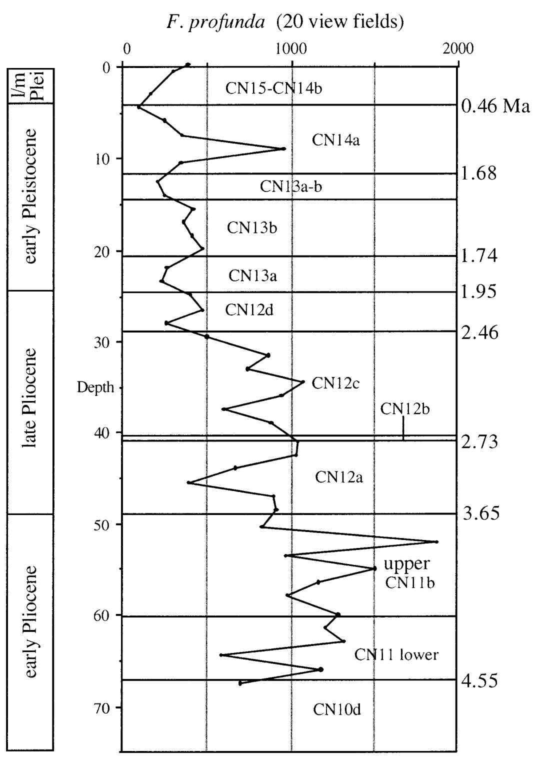

Figure 3. Depth-distribution patterns of the numbers (20 view fields) of *F. profunda* in each section.

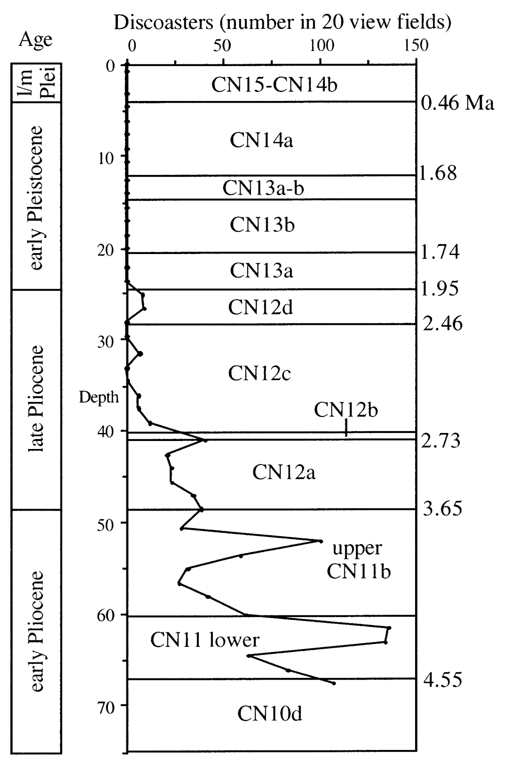

Figure 5. Depth-distribution patterns of the number of *Discoasters* in each section (magnification 1000×).

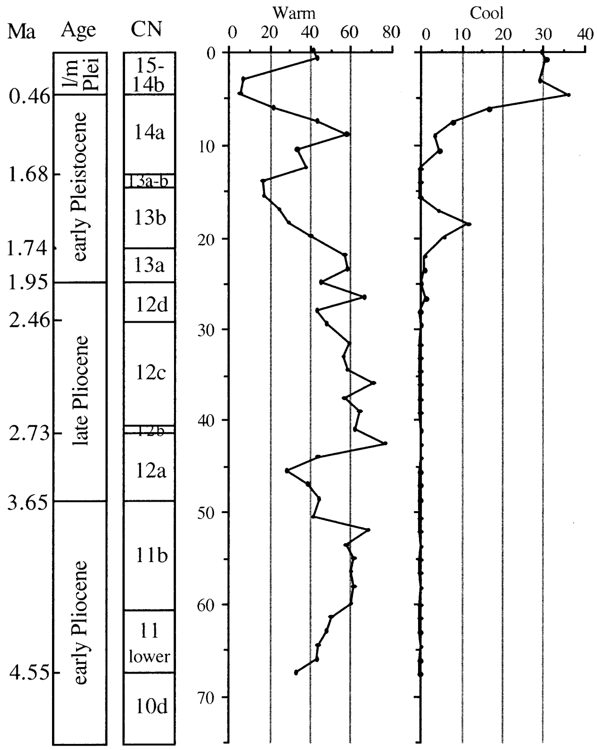

Figure 6. Relative abundances of warm- and cool-water indicator calcareous nannofossil species in each section.

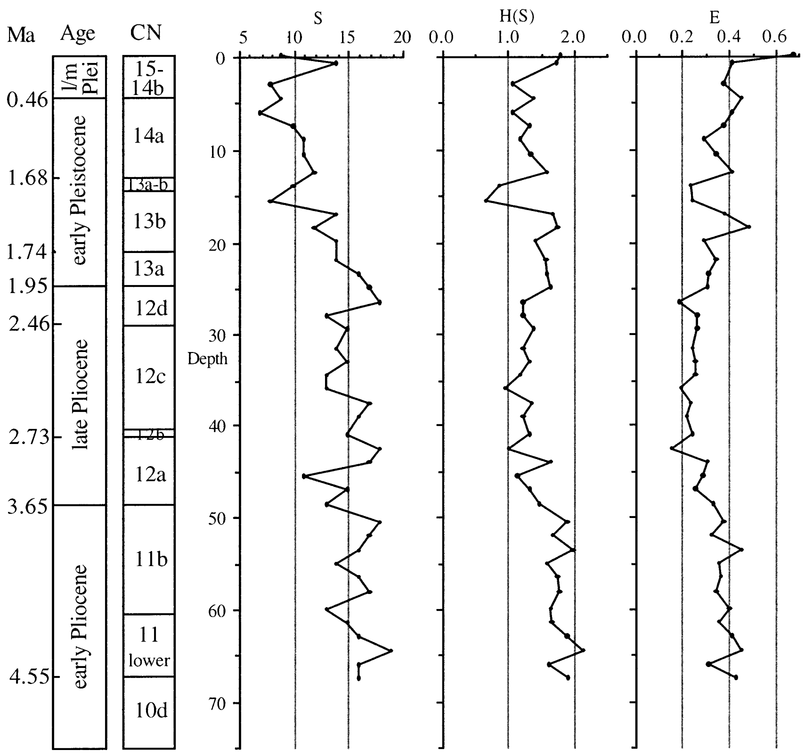

Figure 7. Species diversity indices *S*, *H(S)*, and *E* in each section.