

## 2. NEOGENE CALCAREOUS NANNOFOSSILS FROM SITES 811 AND 819 THROUGH 825, OFFSHORE NORTHEASTERN AUSTRALIA<sup>1</sup>

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### ABSTRACT

Calcareous nannofossils are generally abundant at the Queensland Trough transect sites (811 and 819 through 825) of Leg 133, and they provide the primary means of dating the Neogene sediments. Sites 819 through 821 to the east of the Great Barrier Reef yielded abundant, moderately preserved Pleistocene nannofossils. The sections are biostratigraphically complete, except for a very condensed interval or a hiatus in the middle Pleistocene section at Site 819. A similar hiatus has been identified at Site 822, where abundant, well-preserved upper Pliocene through Holocene nannofossils were recovered. Abundant and well-preserved nannofossils at Site 823 provide a fairly high-resolution biostratigraphy for the upper Miocene–Holocene sediments recovered, which is remarkable for this turbidite-ridden sequence. Calcareous nannofossils diminish as preservation deteriorates abruptly downhole at Sites 811, 824, and 825 on the Queensland Plateau, and the nannofossil biostratigraphy for the Pliocene and Miocene intervals is only marginally useful.

Preservation of calcareous nannofossils varies greatly among different sites and is controlled by the amount of clay and bank-derived metastable aragonite and high-magnesium calcite in the sediments. Strong dissolution of upper Pleistocene calcareous nannofossils deposited in relatively shallow water and buried at shallow depth is documented for the first time.

### INTRODUCTION

During Ocean Drilling Program (ODP) Leg 133, drilling was performed at 16 sites in the carbonate platform and troughs off the shore of northeastern Australia (Fig. 1) to understand the evolution of these large carbonate platforms and the adjoining basin and to investigate the effects of climate and sea level on their development through time. Calcareous nannofossils are generally abundant at all sites, and they provide the primary means of dating the sediments, particularly for the Pliocene–Pleistocene intervals. For the Miocene and upper Paleogene, where calcareous nannofossils are rare and poorly preserved, larger benthic foraminifers offer the most useful age information (Betzler, this volume). No useful magnetostratigraphic information could be extracted from Leg 133 cores because the original magnetic signals have been severely altered by diagenesis of the magnetic minerals (Omarzai, this volume).

This chapter presents the nannofossil biostratigraphy for Sites 811 and 819 through 825 on the Queensland Trough transect (Fig. 2). Major biostratigraphic results for these sites are summarized in Table 1 and discussed in detail below. Nannofossil biostratigraphy for Sites 812 through 818 and 826 on the Townsville Trough transect is provided in Gartner et al. (this volume).

In addition, this study discusses the effect of diagenesis on calcareous nannofossil preservation in sediments from the Queensland Trough transect sites and Deep Sea Drilling Project Site 209 (Fig. 1). Previously diagenesis of calcareous nannofossils was investigated by Schlanger and Douglas (1974), Neugebauer (1974), Matter et al. (1975), Wise (1977), and others. All these studies were concerned mainly with relatively deep water and deeply buried sediments of pre-Quaternary age. Roth and Berger (1975) reported dissolution and overgrowth on calcareous nannofossils from surface sediments taken mostly from depths ranging from 3500 to 4800 m in the South and Central Pacific Ocean. Winter (1982) showed calcite overgrowth in *Emiliania huxleyi* and *Umbellosphaera irregularis* in upper Pleisto-

cene sediments from the Red Sea. Here we show that strong dissolution of upper Pleistocene calcareous nannofossils can occur along with calcite overgrowth in sediments deposited in relatively shallow water and buried at shallow depth.

### METHODS

One sample was taken from each core section aboard the ship. Smear slides were made directly from unprocessed samples and examined with a light microscope at a magnification of about 1250×. The abundance of calcareous nannofossils on each slide was estimated using the following criteria: V = very abundant, more than 10 specimens per field of view; A = abundant, 1–10 specimens per field of view; C = common, 1 specimen per 2–10 fields of view; F = few, 1 specimen per 11–50 fields of view; R = rare, 1 specimen per 51–200 fields of view; B = barren, no specimen was found in 200 fields of view. For preservation of nannofossil assemblages, the following notations are used: G = good, little evidence of etching or overgrowth; M = moderate, etching or overgrowth is apparent; P = poor, there is significant etching or overgrowth and identification of some species is impaired.

The calcareous nannofossil zonation of Okada and Bukry (1980) is used in this study (Fig. 3); however, a number of nannofossil datums not used in their zonation have been documented in this study. These include the beginning of the acme of *Emiliania huxleyi*, the last occurrence of *Reticulofenestra* sp. A Takayama and Sato (1987), the first occurrence of *Gephyrocapsa* spp. C-D Matsuoka and Okada (1990), the last occurrence of *Gephyrocapsa* spp. A-B Matsuoka and Okada (1990), the last occurrence of *Helicosphaera sellii*, the first and last occurrences of *Amaurolithus amplificus*, and the last occurrence of *Catinaster calyculus*. These additional datums allow higher biostratigraphic resolution than is possible with the formal zonation alone. The numerical ages for the nannofossil datums are taken mostly from the compilation of Berggren et al. (1985; see Fig. 3). Some were modified slightly, based on more recent studies (e.g., Gartner, 1992, unpubl. data).

Calcareous nannofossil species observed in this study are listed alphabetically by generic epithets in the appendix; the bibliographic references of these species can be found in Loeblich and Tappan (1966, 1968, 1969, 1970a, 1970b, 1971, 1973), van Heck (1979a, 1979b, 1980a, 1980b, 1981a, 1981b, 1982a, 1982b, 1983), and Steinmetz

<sup>1</sup> McKenzie, J.A., Davies, P.J., Palmer-Julson, A., et al., 1993. *Proc. ODP, Sci. Results*, 133: College Station, TX (Ocean Drilling Program).

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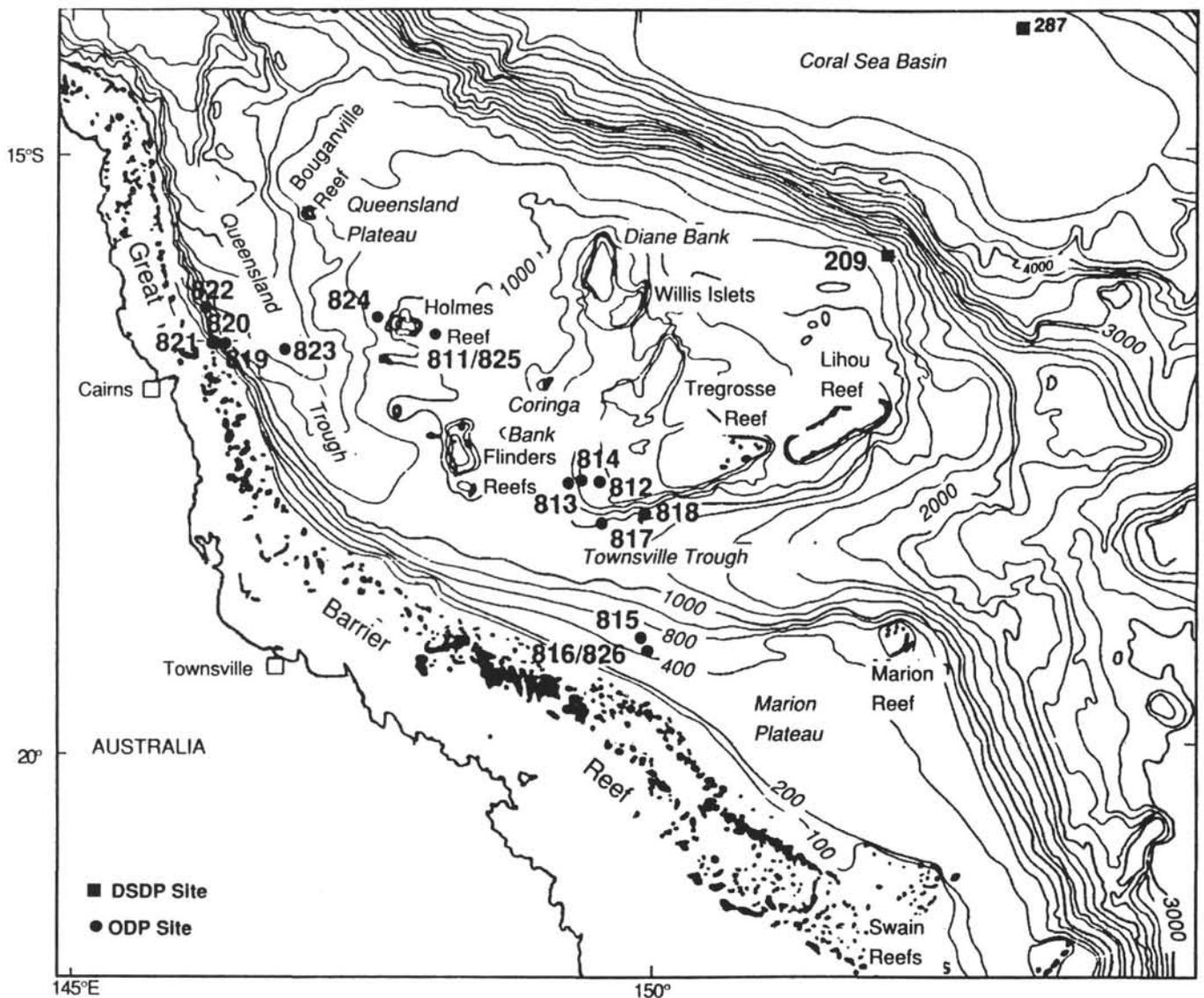


Figure 1. Map of northeastern Australian margin showing Leg 133 drill sites. Bathymetry in meters.

(1985a, 1985b, 1986, 1987a, 1987b, 1988a, 1988b, 1989). Selected nanofossil species are illustrated in Plates 1 and 2.

Diagenesis of calcareous nanofossils was investigated using a light microscope and a scanning electron microscope (SEM). Samples examined with the SEM were mounted on a cover glass glued to a specimen stub and coated with a thin film of gold-platinum alloy in a vacuum sputterer.

## NANNOFOSSIL BIOSTRATIGRAPHY

### Site 811

Calcareous nanofossils are abundant in the upper 170 m of the sequence recovered at Site 811. Preservation of nanofossils deteriorates rapidly downhole; consequently, the resolution of the nanofossil biostratigraphy (Fig. 4) also deteriorates downhole and the 170- to 380-mbsf interval is practically unzonable by nanofossils.

Hole 811A extends from 0 to 214.5 mbsf and core recovery was nearly 100%. Samples 133-811A-1H-CC through -2H-2, 112 cm, contain *Gephyrocapsa caribbeanica* and other Pleistocene taxa, but no *Emiliania huxleyi* or *Pseudoemiliania lacunosa*, which constrains this interval to Subzone CN14b (0.275 to 0.465 Ma). Rare *P. lacunosa*

were observed from Sample 133-811A-2H-3, 112 cm, downward. The last occurrence of *P. lacunosa* (placed between Samples 133-811A-2H-2, 112 cm, and -2H-3, 112 cm) defines the CN14a/CN14b boundary, which has an age of 0.465 Ma. Few *Calcidiscus macintyreii* and common *Discoaster brouweri* were first encountered in Sample 133-811A-3H-6, 112 cm. This suggests that the sample is in Subzone CN12d (1.48 to 1.88 Ma). This also suggests that the stratigraphic range of *C. macintyreii* is truncated, and an unconformity (>0.4 m.y.) is present between Samples 133-811A-3H-5, 112 cm, and -3H-6, 112 cm. This unconformity separates Pliocene and Pleistocene sediments.

The last occurrence of *Discoaster pentaradiatus* was determined between Samples 133-811A-4H-3, 112 cm, and -4H-4, 112 cm, where the species is rare. This datum marks the CN12c/CN12d subzonal boundary (2.29 Ma). The next datum recognized is the last occurrence of *Discoaster tamalis* in Sample 133-811A-5H-3, 112 cm, which defines the CN12b/CN12a subzonal boundary. The last occurrence of *Discoaster surculus* could not be used at this site because of poor preservation of the nanofossil assemblages in the Pliocene.

Rare specimens of *Sphenolithus abies* were found in Sample 133-811A-8H-CC. The last occurrence of *Reticulofenestra pseudoumbilicus* is in Sample 133-811A-9H-1, 114 cm, where the species is abun-

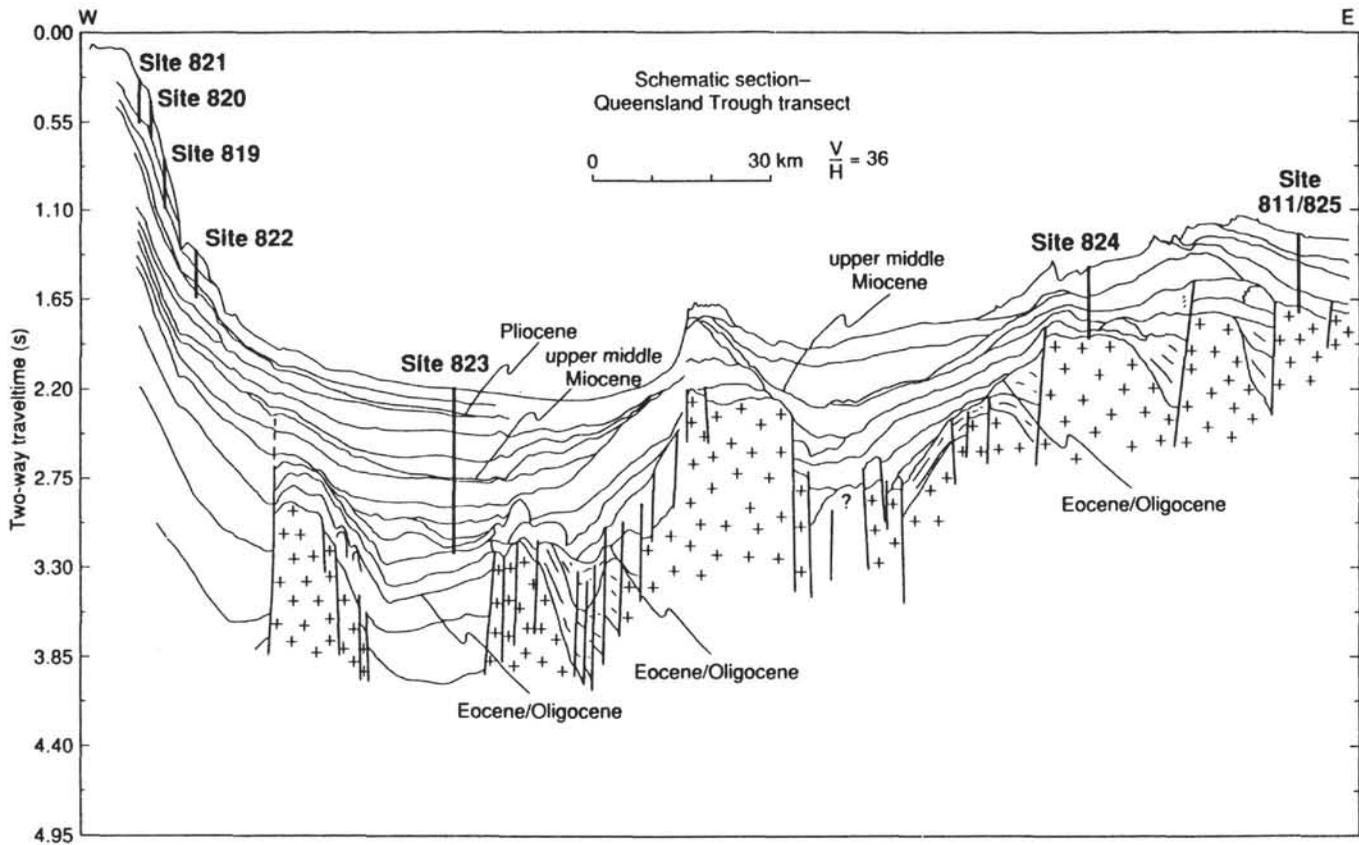


Figure 2. Schematic transect across the Queensland Trough.

tant. This datum has an age of 3.51 Ma and marks the lower Pliocene/upper Pliocene boundary. Samples 133-811A-9H-4 and -9H-CC contain rare specimens of *Amaurolithus tricorniculatus*, and these samples are placed in Zone CN10. Zone CN11 is thus condensed (Fig. 4) and may contain an unconformity.

The last occurrence of *Discoaster quinqueramus*, which defines the Miocene/Pliocene boundary in terms of nannofossil biostratigraphy, is drawn between Samples 133-811A-10H-CC and -11H-1, 113 cm. One specimen of *Amaurolithus amplificus* was found in Sample 133-811A-11H-CC, and that level is dated as the lower part of Subzone CN9b (5.6–5.9 Ma, see Fig. 3). Rare specimens of *Amaurolithus* are present in Samples 133-811A-11H-CC and -12H-CC, indicating an age younger than 6.74 Ma for these samples. Species of *Amaurolithus* are absent, whereas *Discoaster quinqueramus* is still present in Cores 133-811A-13H and -14H. The first occurrence of *D. quinqueramus* is tentatively placed between Samples 133-811A-15H-2, 113 cm, and -15H-3, 113 cm, because it is difficult to determine the first occurrence of this species in the presence of transitional forms between this species and an earlier one, *Discoaster bellus*. The lowest datum identified in Hole 811A is the last occurrence of *Discoaster hamatus* in Core 811A-19H. Rare specimens of *D. hamatus* were found in Samples 133-811A-19H-5, 113 cm, and -19H-CC. The species is absent in or above Sample 133-811A-19H-3, 113 cm. Sample 133-811A-19H-4, 113 cm, is virtually barren of calcareous nannofossils because of strong dissolution and reprecipitation. Consequently, the last occurrence of *D. hamatus*, which defines the CN7/CN8 zonal boundary, is drawn between Samples 133-811A-19H-3, 113 cm, and -19H-5, 113 cm.

Hole 811B was cored from 193.2 to 392.5 mbsf. Core recovery was very poor (<8%) throughout the hole, with no sediment recovered from Cores 133-811B-1X, -5X, -6X, -11X, -13X, -14X, and -22X through -24X. Calcareous nannofossils are generally rare and poorly preserved in this hole. Sample 133-811B-8V-CC contains *Calcidiscus premaxin-*

*tyrei*. The range of this species has been correlated with magnetostratigraphy in the North Atlantic at 12.3 to 14.1 Ma (Gartner, 1992). Samples 133-811B-10V-CC, -12X-CC, and -15X-CC are barren of nannofossils. Core-catcher samples from Cores 133-811B-16X through -21X contain rare or few specimens of *Cyclicargolithus floridanus* and, sporadically, rare specimens of *Sphenolithus moriformis* and *Coccolithus pelagicus*. An age range of middle Eocene–middle Miocene can be assigned to these samples based on the occurrence of *C. floridanus*.

### Site 819

One hole was drilled at Site 819, and an expanded Pleistocene section (400 m) was recovered. Calcareous nannofossils are abundant and generally moderately well preserved in most of the samples examined. Nannofossil biostratigraphy is summarized graphically in Figure 5.

*Emiliana huxleyi* is abundant in Samples 133-819A-1H-1, 112 cm, through -1H-5, 112 cm; common in Sample 133-819A-2H-1, 112 cm; few or rare in Samples 133-819A-22H-3, 112 cm, through -4H-1, 112 cm; and absent in and below Sample 133-819A-4H-2, 112 cm. The lower boundary of the *Emiliana huxleyi* Acme Zone (0.075 Ma) is between Samples 133-819A-1H-5, 112 cm, and -2H-1, 112 cm; the first occurrence of *E. huxleyi* (0.275 Ma), which defines the CN14b/CN15 zonal boundary, is between Samples 133-819A-4H-1, 112 cm, and -4H-2, 112 cm. Samples 133-819A-4H-2, 112 cm, and -4H-3, 112 cm, contain abundant *Gephyrocapsa oceanica* and small *Gephyrocapsa* but no *E. huxleyi* or *Pseudoemiliana lacunosa*, and thus have been assigned to Subzone CN14b (0.275–0.465 Ma). *Pseudoemiliana lacunosa* occurs from Sample 133-819A-4H-4, 112 cm, where it is abundant, downward throughout the hole. The lower boundary of Subzone CN14b defined by the last occurrence of *P. lacunosa* has been placed between Samples 133-819A-4H-3, 112 cm,

Table 1. Summary of age–mean depth (mbsf) information for the Queensland Trough transect sites.

Datum	Age (Ma)	Site 811 depth	Site 819 depth	Site 820 depth	Site 821 depth	Site 822 depth	Site 823 depth	Site 824 depth	Site 825 depth
FO <i>E. huxleyi</i> acme	0.075		8.4	12.1					
FO <i>E. huxleyi</i>	0.275		29.4	35.8	39.3	21.8	12.2		
LO <i>P. lacunosa</i>	0.465	8.9	32.4	107.1	123.1	21.8	32.0	47.8	
LO <i>R. sp. A</i>	0.81					54.8			
FO <i>G. spp. C-D</i>	0.92		56.1	163.6	176.8	77.8	80.2		
LO <i>G. spp. A-B</i>	1.10		166.9	260.3	270.1	125.6	95.5		
LO <i>H. sellii</i>	1.27		189.2	271.7	279.2	220.0	105.7		
LO <i>C. macintyreii</i>	1.48	22.9	>400	>400	>400	301.5	150.9	92.8	
LO <i>D. brouweri</i>	1.88	22.9				333.4	163.0		
LO <i>D. pentaradiatus</i>	2.29	29.4				399.3	222.3		
LO <i>D. surculus</i>	2.42					411.0	236.2		
LO <i>D. tamalis</i>	2.60	38.9				419.0	244.3		
LO <i>R. pseudoumbilicus</i>	3.51	72.6					359.3		
FO <i>D. asymmetricus</i> ac.	3.88						435.5		
LO <i>A. tricorniculatus</i>	4.24	76.9					521.6		
LO <i>C. armatus</i>	4.60						602.0		
LO <i>D. quinqueramus</i>	5.26	91.6					653.0		
LO <i>A. amplificus</i>	5.6						733.1		
FO <i>A. amplificus</i>	5.9						767.6		
FO <i>D. quinqueramus</i>	8.2	132.6					967.4		
LO <i>C. calyculus</i>	8.75						971.9		
LO <i>D. hamatus</i>	8.85	172.6							
LO <i>C. coalitus</i>	9.0						989.8		
FO <i>C. coalitus</i>	10.8						1009.1		
LO <i>C. floridanus</i>	11.0								214.3

Note: LO = last occurrence; FO = first occurrence.

and -4H-4, 112 cm. Subzone CN14b is very thin, and a significant amount of sediment appears to be missing.

*Gephyrocapsa* spp. C-D Matsuoka and Okada (1990) are common or abundant in Cores 133-819A-1H through -6H. The first occurrence of these taxa (0.92 Ma) is between Samples 133-819A-6H-6, 112 cm, and -7H-1, 112 cm. *Gephyrocapsa* spp. A-B Matsuoka and Okada (1990) occur from Sample 133-819A-20X-1, 112 cm, downward. Because preservation of nannofossils is generally poor in Cores 133-819A-15X through -21X, the bridge in some of the *Gephyrocapsa* spp. A-B specimens may have been destroyed, rendering these specimens indistinguishable from small specimens of *Reticulofenestra*. Consequently, the last occurrence of *Gephyrocapsa* spp. A-B drawn between Samples 133-819A-19X-3, 112 cm, and -21X-1, 112 cm, is considered less reliable.

No sediment was recovered from Core 133-819A-22X. The last occurrence of *Helicosphaera sellii* was found in Sample 133-819A-23X-CC. Rare to few specimens of this species also were found in Samples 133-819A-24X-CC, -26X-CC, -27X-CC, -33X-CC, -42X-CC, -43X-CC, and -44X-CC. Based on the presence of this species in the absence of *Calcidiscus macintyreii* in Cores 133-819A-23X through -44X-CC, this interval is dated as 1.27–1.48 Ma.

### Site 820

Two holes were drilled at Site 820; Hole 820A extends from 0 to 144 mbsf, and Hole 820B extends from 0 to 400 mbsf. As at Site 819, an expanded Pleistocene section (400 m) was recovered at Site 820. The sediments are rich in calcareous nannofossils. Preservation of nannofossils is generally good for the upper 40 m and moderate to poor for the lower sequence. A summary of the nannofossil biostratigraphic results is presented in Figure 6.

*Emiliana huxleyi* is abundant in Samples 133-820A-1H-1, 112 cm, through -2H-3, 112 cm; few or rare in Samples 133-820A-2H-4, 112 cm, through -4H-6, 112 cm; and absent from Sample 133-820A-5H-1, 112 cm, downward. The lower boundary of the *Emiliana huxleyi* Acme Zone (0.075 Ma) is drawn between Samples 133-820A-2H-3, 112 cm, and -2H-4, 112 cm; the lower boundary of Zone CN15 (the first occurrence of *E. huxleyi*, 0.275 Ma) is placed between

Samples 133-820A-4H-6, 112 cm, and -5H-1, 112 cm. Species present in these four cores include rare *Calcidiscus leptoporus*, abundant *Gephyrocapsa oceanica* and *Gephyrocapsa* spp. (small), few-to-rare *Helicosphaera carteri*, *Scapholithus fossilis*, *Syrocosphaera pulchra*, and *Umbellosphaera irregularis*.

Rare specimens of *Pseudoemiliana lacunosa* were first encountered in Sample 133-820A-12H-4, 110 cm; medium- to large-sized *Gephyrocapsa* (*Gephyrocapsa* spp. C-D Matsuoka and Okada, 1990) are common in this sample through Sample 133-820A-15H-4, 110 cm. Thus, the interval from Samples 133-820A-12H-4, 110 cm, to -15H-4, 110 cm, is dated as 0.465 to 0.92 Ma. Samples 133-820B-18H-3, 112 cm, through -28X-6, 112 cm, contain abundant small *Gephyrocapsa*, although large- or medium-sized *Gephyrocapsa* are virtually absent. This interval has an age of 0.92–1.10 Ma.

*Gephyrocapsa* spp. A-B Matsuoka and Okada (1990) occur from Sample 133-820B-28X-CC downward to the bottom of the hole. The last occurrence of *Gephyrocapsa* spp. A-B (1.10 Ma) is placed between Samples 133-820B-28X-6, 112 cm, and -28X-CC.

The last occurrence of *Helicosphaera sellii* (1.27 Ma) is placed between Samples 133-820B-29X-CC and -30X-2, 110 cm, based on the absence of the species in and above Sample 133-820B-29X-CC and the rare occurrences of this species in Samples 133-820B-30X-2, 110 cm, and -30X-CC, and in several samples further downhole. The next lower biostratigraphic marker, the last occurrence of *Calcidiscus macintyreii* (1.48 Ma), was not encountered in the hole. This suggests that the bottom of the hole (Sample 133-820B-44X-CC) did not penetrate into the lowermost Pleistocene and is younger than 1.48 Ma.

### Site 821

Site 821 is the shallowest of the three sites on the slope transect (Fig. 2) to the east of the Great Barrier Reef. At Site 821, as at the other two sites (819 and 820) on the slope, an expanded Pleistocene section was recovered (Fig. 7). Calcareous nannofossils are abundant, and preservation is moderate to poor except in some clayey intervals where preservation is excellent.

*Emiliana huxleyi* are present in Samples 133-821A-1H-1, 112 cm, through -3H-1, 111 cm. This species is rare in Samples 133-821A-3H-2,

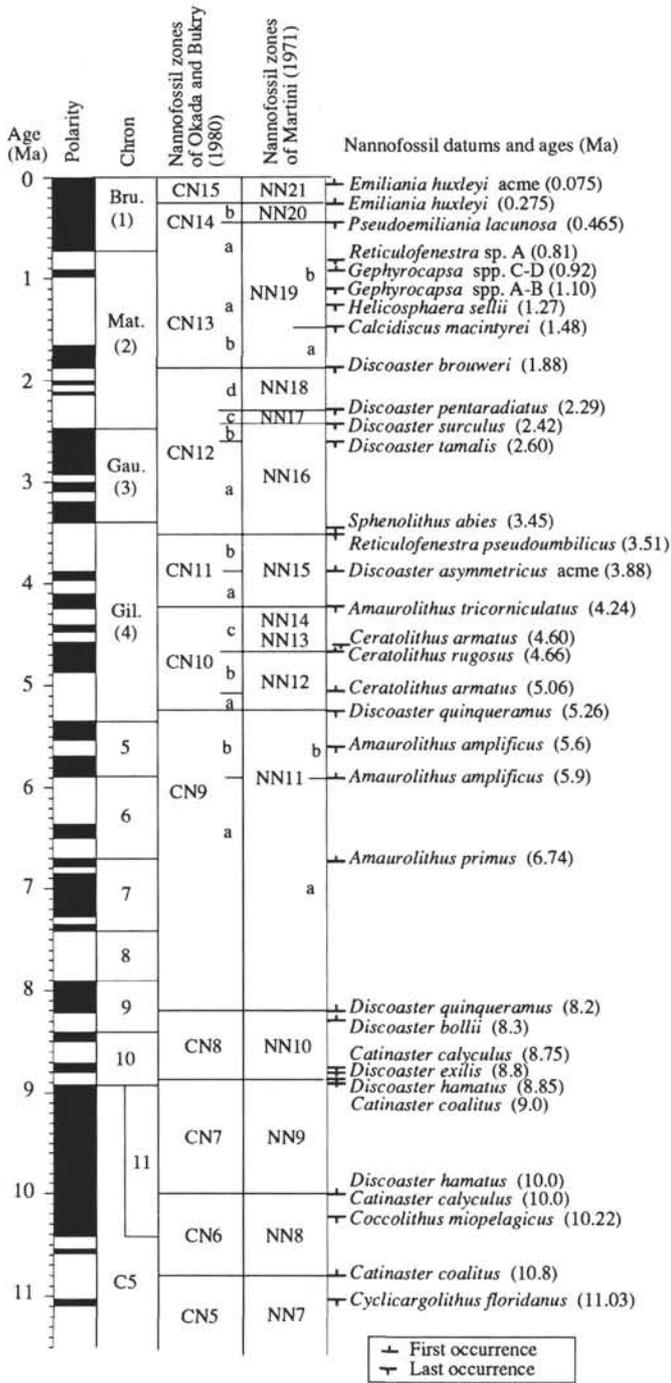


Figure 3. Calcareous nannofossil zonation and datums used here and their ages as calibrated with the geomagnetic polarity time scale of Berggren et al. (1985).

111 cm, through -5H-4, 111 cm, and absent from Sample 133-821A-5H-5, 111 cm, downward. The *Emiliana huxleyi* Acme Zone cannot be identified in this section because of the generally low abundance of this species. The first occurrence of *E. huxleyi* (0.275 Ma) is between Samples 133-821A-5H-4, 111 cm, and -5H-5, 111 cm. The last occurrence of *Pseudoemiliana lacunosa* is in Sample 133-821A-14H-4, 112 cm, and the interval between this datum and the previous one is assigned to Subzone CN14b, with an age range of 0.275–0.465 Ma.

*Gephyrocapsa* spp. C-D Matsuoka and Okada (1990) are common or abundant down to Sample 133-821A-20X-1, 112 cm, and are rare or absent from Sample 133-821A-20X-2, 112 cm, downward. An age

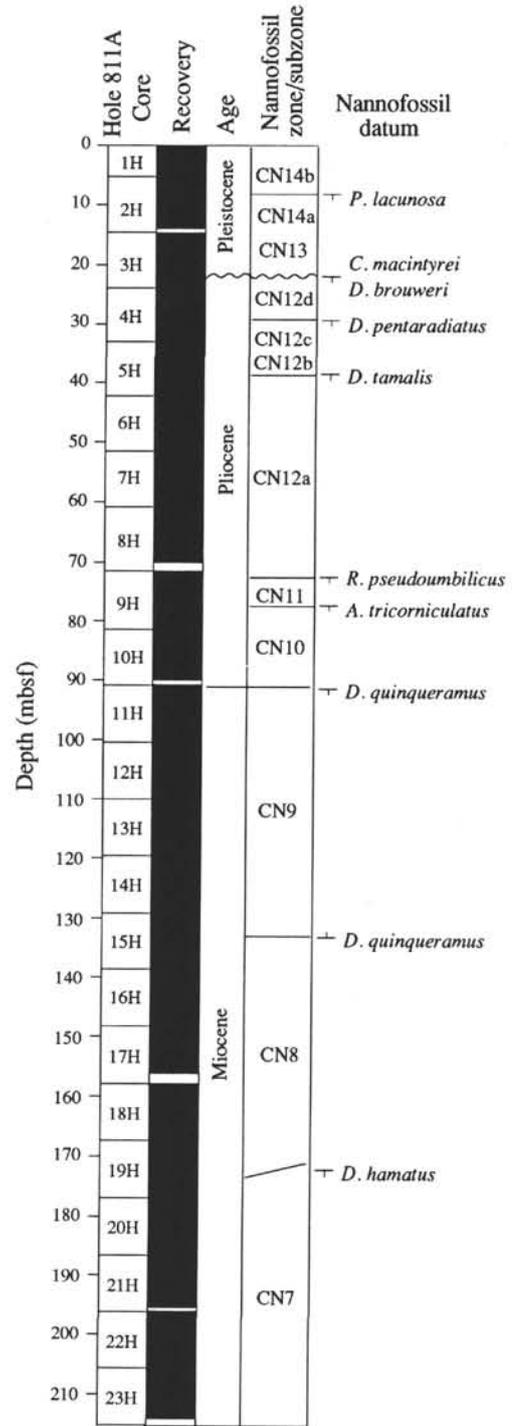


Figure 4. Calcareous nannofossil biostratigraphy, Hole 811A.

of 0.92 Ma can be assigned between Samples 133-821A-20X-1, 112 cm, and -20X-2, 112 cm, based on the first occurrence of *Gephyrocapsa* spp. C-D there. The interval from Samples 133-821A-20X-2, 112 cm, to -29X-5, 116 cm, contains dominantly small *Gephyrocapsa* (mostly 2–3 mm) with a virtual absence of large- or medium-sized *Gephyrocapsa*. The last occurrence of *Gephyrocapsa* spp. A-B Matsuoka and Okada (1990) is in Sample 133-821A-30X-1, 112 cm, which has an age of 1.10 Ma. The next lower datum is the highest occurrence of *Helicosphaera sellii* between Samples 133-821A-30X-5, 112 cm, and -30X-CC, and this level has an age of 1.27 Ma. The last occurrence

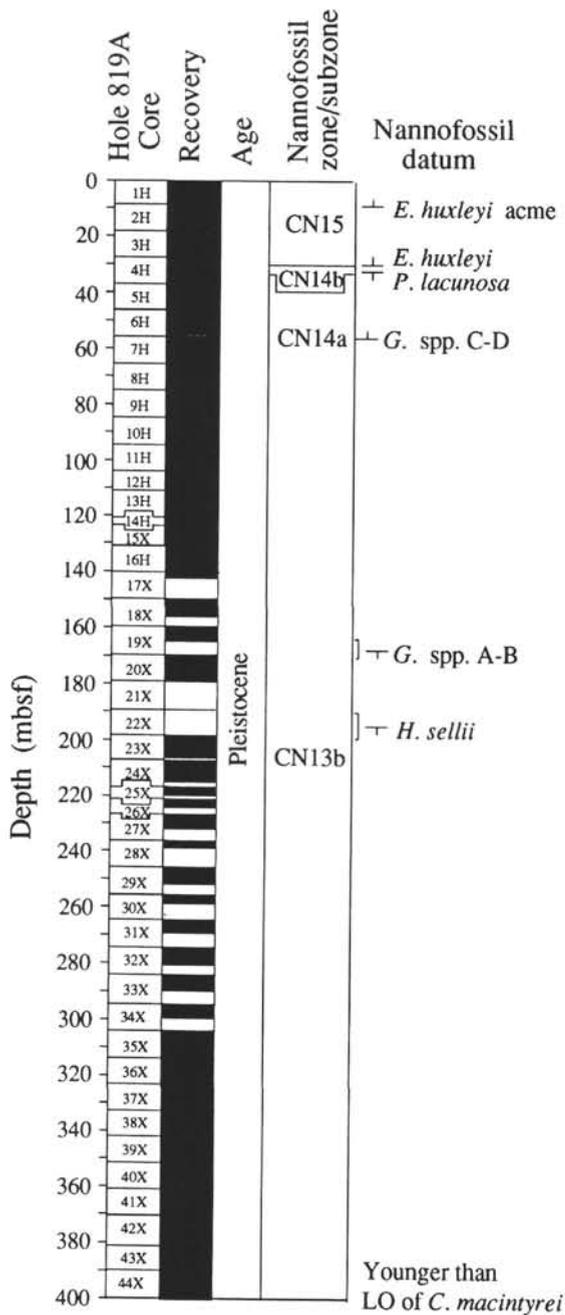


Figure 5. Calcareous nannofossil biostratigraphy, Hole 819A.

of *Calcidiscus macintyreii* (1.48 Ma) was not observed in the oldest sediment recovered at Site 821, and this indicates an age between 1.27 and 1.48 Ma.

### Site 822

Site 822 penetrated 434 m of sediments and recovered an expanded Holocene to upper Pliocene section of hemipelagic sediments. Calcareous nannofossils are generally abundant and well preserved throughout the sequence. The distribution of nannofossil taxa at Site 822 is documented in Table 2.

*Emiliania huxleyi* occurs from Samples 133-822A-1H-CC to -4H-1, 113 cm; this interval is assigned to the *Emiliania huxleyi* Zone (CN15, 0-0.275 Ma). The abundance of *E. huxleyi* fluctuates greatly in this

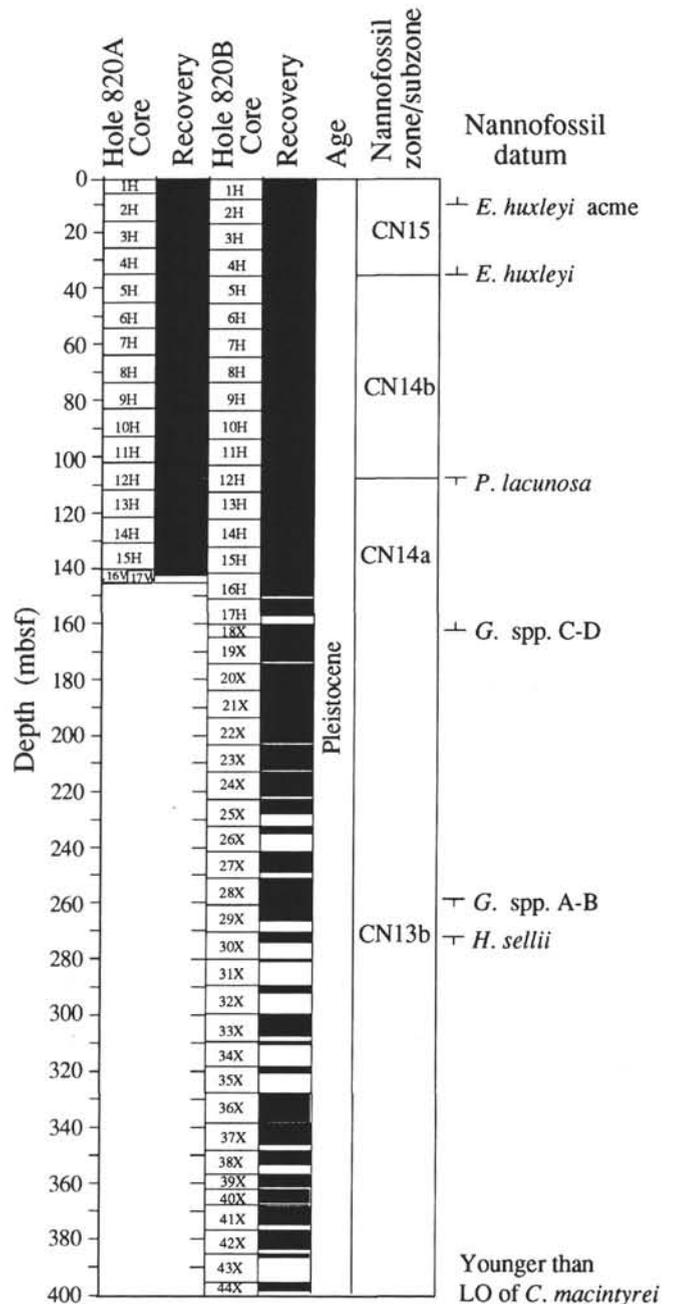


Figure 6. Calcareous nannofossil biostratigraphy, Site 820.

interval, and it is not possible to identify the *Emiliania huxleyi* Acme Zone. The absence of this species in Sample 133-822A-2H-1, 112 cm, is unusual, and it may be because of a sediment slump of Subzone CN14b from upslope. A slump of sediment of other ages would have yielded a different assemblage easily detectable by our analysis. The highest occurrence of *Pseudoemiliania lacunosa* is in Sample 133-822A-4H-2, 113 cm. This suggests that Subzone CN14b (0.275 to 0.465 Ma) is missing because of an unconformity.

The next lower datum recognized is the last occurrence of *Reticulofenestra* sp. A (see Pl. 2, Figs. 3, 8, and 9) Takayama and Sato (1987) in Sample 133-822A-7H-5, 113 cm. This datum has an age of about 0.81 Ma as calibrated with magnetostratigraphy (Takayama and Sato, 1987; Matsuoka and Okada, 1989) and oxygen isotope stratigraphy at a number of sites (W. Wei, unpubl. data). The first occurrence of *Gephyrocapsa* spp. C-D Matsuoka and Okada (1990), which has an

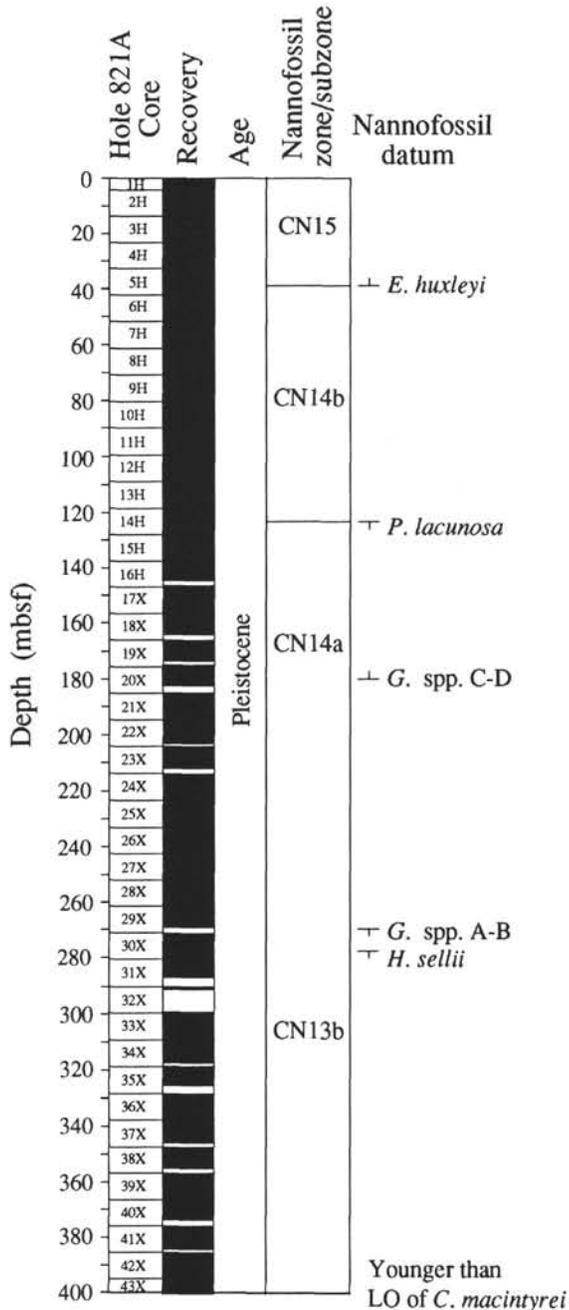


Figure 7. Calcareous nannofossil biostratigraphy, Hole 821A.

age of 0.92 Ma, is in Sample 133-822A-9H-CC, where the species is abundant. *Gephyrocapsa protohuxleyi* is very abundant (50%–80% of the assemblage) in Samples 133-822A-10H-2, 113 cm, through -13H-CC, and this species was verified by SEM (see Pl. 1, Figs. 4 and 5). Apparently, an acme of this species occurred at about 1.0 Ma. This finding is at variance with that of Matsuoka and Okada (1989, 1990), who correlated the event to the Brunhes/Matuyama boundary at about 0.73 Ma. The first occurrence of *Reticulofenestra* sp. A Takayama and Sato (1987) is in Sample 133-822A-11H-3, 111 cm. *Reticulofenestra asanoi*, a circular variant of *R. sp. A*, was found in only one sample (133-822A-10H-2, 114 cm, Pl. 2, Fig. 4), although this species is common in the Arabian Sea and was used there as an index fossil (Sato et al., 1991).

The last occurrence of *Gephyrocapsa* spp. A-B Matsuoka and Okada (1990) is in Sample 133-822A-15X-1, 112 cm; this sample has an age of 1.10 Ma. Rare specimens of *Helicosphaera sellii* are present

in Sample 133-822A-25X-1, 37 cm, and in a number of samples down-hole. An age of 1.27 Ma can be assigned to Sample 133-822A-15X-1, 112 cm. The next lower datum, the last occurrence of *Calcidiscus macintyreii* (1.48 Ma) is between Samples 133-822A-33X-2, 112 cm, and -33X-3, 112 cm. This datum is followed by the last occurrence of *Discoaster brouweri* (1.88 Ma) in Sample 133-822A-36X-5, 110 cm, where the species is common. The last occurrence of *Discoaster pentaradiatus* (2.29 Ma) is in Sample 133-822A-43X-CC, followed by the last occurrence of *Discoaster surculus* (2.42 Ma) in Sample 133-822A-45X-5, 112 cm. The last datum encountered is the last occurrence of *Discoaster tamalis* (2.60 Ma) in Sample 133-822A-45X-CC. The oldest sediment from Site 822 has an age of older than 2.60 Ma but younger than 3.45 Ma, based on the presence of *D. tamalis* in the absence of *Sphenolithus abies* and *Reticulofenestra pseudoumbilicus*.

### Site 823

Three holes were drilled at Site 823; Hole 823A extends from 0 to 120 mbsf; Hole 823B duplicates Hole 823A for the upper 120 m and extends to 805 mbsf; Hole 823C cored from 784 to 1011 mbsf (Fig. 8). Calcareous nannofossils are generally abundant and well preserved in the Holocene through upper Miocene sediments recovered at Site 823. Virtually all of the conventional nannofossil markers for the interval were found, which enables a fairly high-resolution biostratigraphy (Fig. 8).

The first occurrence of *Emiliania huxleyi* is in Sample 133-823A-2H-4, 115 cm; this datum defines the lower boundary of Zone CN15 (0.275 Ma). *Emiliania huxleyi* is generally rare in this interval, except in Samples 133-823A-1H-1, 113 cm, and -2H-2, 115 cm, where it is common to abundant. Consequently, it is not possible to identify the *Emiliania huxleyi* Acme Zone. *Florisphaera profunda* is most conspicuous in Zone CN15 at Site 823, because it constitutes 70%–90% of the nannofossil assemblages. The last occurrence of *Pseudoemiliania lacunosa* is between Samples 133-823A-4H-4, 115 cm, and -4H-6, 115 cm. Rare specimens of this species were found in Samples 133-823A-3H-3, 115 cm, and -4H-2, 115 cm, and these rare and sporadic occurrences are considered reworked. The first occurrence of *Gephyrocapsa* spp. C-D (0.92 Ma) is in Sample 133-823A-9H-5, 115 cm, where the species is common. The interval from Samples 133-823A-9H-6, 115 cm, to 11H-2, 116 cm, contains mainly small *Gephyrocapsa*, with a virtual absence of large- or medium-sized *Gephyrocapsa*, and can be dated as 0.92 to 1.10 Ma. The highest occurrence of *Gephyrocapsa* spp. A-B (1.10 Ma) is in Sample 133-823C-11H-4, 116 cm. The next datum recognized is the last occurrence of *Helicosphaera sellii* (1.27 Ma) in Sample 133-823C-12H-4, 116 cm. Rare specimens of this species also were found in the next several samples (133-823A-12H-4, 116 cm; -12H-5, 116 cm; -12H-CC; -13H-2, 115 cm; and -13H-CC). Rare specimens of *Calcidiscus macintyreii* were first encountered in Sample 133-823B-16X-CC. The CN13a/CN13b subzonal boundary (1.48 Ma) thus can be drawn between Samples 133-823B-16H-6, 116 cm, and -16H-CC.

The highest Pliocene nannofossil datum, the last occurrence of *Discoaster brouweri* (1.88 Ma), is placed between Samples 133-823B-18X-1, 115 cm, and -18X-2, 115 cm. A succession of last occurrences of *Discoaster pentaradiatus* (2.29 Ma), *Discoaster surculus* (2.42 Ma), and *Discoaster tamalis* (2.6 Ma) occurs in Samples 133-823B-24X-3, 137 cm, -25X-6, 144 cm, and -26X-5, 136 cm, respectively. The last occurrence of *Reticulofenestra pseudoumbilicus* (3.51 Ma) lies in Sample 133-823B-38X-5, 126 cm, where the species is represented by few specimens. This datum defines the CN11/CN12 zonal boundary, which corresponds to the lower Pliocene/upper Pliocene boundary.

The beginning of the acme of *Discoaster asymmetricus* (3.88 Ma) occurs in Sample 133-823B-45X-CC; this datum further divides Zone CN11 into Subzone CN11a and CN11b (Fig. 8). Rare specimens of *Amaurolithus tricorniculatus* were found in Sample 133-823B-55X-CC, thus the CN11/CN12 zonal boundary (4.24 Ma) can be placed



Table 2 (continued).

Age	Nannofossil zone/subzone	Hole 822A Sample	Depth (mbsf)	Abundance	Preservation	<i>Braarudosphaera bigelowii</i>	<i>Calcidiscus leptoporus</i>	<i>Calcidiscus macintyreii</i>	<i>Ceratolithus cristatus</i>	<i>Ceratolithus telesmus</i>	<i>Coccolithus pelagicus</i>	<i>Discoaster brouweri</i>	<i>Discoaster pentaradiatus</i>	<i>Discoaster surcutulus</i>	<i>Discoaster tamalis</i>	<i>Discoaster triradiatus</i>	<i>Emiliana huxleyi</i>	<i>Gephyrocapsa</i> spp. A-B	<i>Gephyrocapsa</i> spp. C-D	<i>Gephyrocapsa</i> spp. (<4 µm)	<i>Helicosphaera carteri</i>	<i>Helicosphaera sellii</i>	<i>Oolithon fragilis</i>	<i>Pontosphaera multipora</i>	<i>Pontosphaera</i> spp.	<i>Pseudoemiliana lacunosa</i> (elliptical)	<i>Pseudoemiliana lacunosa</i> (round)	<i>Reticulofenestra asanoi</i>	<i>Reticulofenestra</i> sp. A	<i>Reticulofenestra</i> spp. (<5 µm)	<i>Rhabdosphaera clavigera</i>	<i>Scapholithus fossilis</i>	<i>Syracosphaera pulchra</i>	<i>Umbilicosphaera sibogae</i>			
Pleistocene	CN13b	29X-CC	268.19	A	G	.	R	.	.	.	.	.	.	.	.	.	.	F	A	F	R	.	.	R	C	.	.	.	.	.	.	.	.	F			
		30X-CC	278.80	A	G	.	F	.	.	.	.	.	.	.	.	.	.	.	C	A	F	.	.	.	.	C	.	.	.	.	.	.	F	R			
		31X-5, 112-113	284.94	A	G	.	R	.	.	.	.	.	.	.	.	.	.	.	C	A	F	.	.	R	R	A	R	.	.	.	.	.	.	R			
		31X-6, 112-113	286.48	A	G	.	R	.	.	.	.	.	.	.	.	.	.	.	.	C	A	F	.	.	R	R	C	R	.	.	.	.	.	.	R		
		31X-CC	288.40	A	G	.	R	.	.	.	.	.	.	.	.	.	.	.	.	C	A	F	R	.	R	.	C	.	.	.	.	.	F	F			
		32X-CC	296.18	A	G	.	R	.	R	.	.	.	.	.	.	.	.	.	.	F	C	F	R	.	.	.	C	.	.	.	.	.	.	.	.		
		33X-2, 112-113	300.72	A	G	.	R	.	.	.	.	.	.	.	.	.	.	.	.	F	A	F	R	.	R	R	A	F	.	.	.	.	.	.	R		
	CN13a	33X-3, 112-113	302.22	A	G	.	R	R	.	.	.	.	.	.	.	.	.	.	F	A	F	.	.	R	R	A	C	.	.	.	.	R	R	.	R		
		33X-5, 116-117	305.26	A	G	.	F	R	.	.	.	.	.	.	.	.	.	.	F	C	C	.	.	.	R	A	.	.	.	.	.	.	.	.	.	.	
		33X-6, 112-113	306.72	A	G	.	F	F	.	.	.	.	.	.	.	.	.	.	F	A	F	.	.	.	.	C	.	.	.	.	.	.	.	.	.	.	
		33X-CC	307.80	A	G	.	F	R	.	.	.	.	.	.	.	.	.	.	.	C	C	.	.	.	R	A	.	.	.	.	.	.	.	.	.	.	
		34X-CC	312.94	A	G	.	F	F	.	.	.	.	.	.	.	.	.	.	.	A	F	.	.	.	.	C	.	.	.	.	.	.	.	.	.	.	
		35X-CC	324.79	A	G	.	F	F	R	.	R	.	.	.	.	.	.	.	.	A	F	R	.	.	R	C	.	.	.	.	.	.	R	.	.	.	
		36X-4, 111-112	332.61	A	G	.	F	F	R	.	R	.	.	.	.	.	.	.	.	A	F	.	.	.	F	A	C	.	.	.	.	.	.	.	.	.	
Pliocene	CN12d	36X-5, 110-111	334.10	A	G	.	F	C	R	.	C	C	.	.	F	.	.	A	C	.	.	R	R	A	F	.	.	.	.	.	.	.	.	.	.		
		36X-CC	335.64	A	G	.	C	C	R	.	F	F	.	.	.	.	.	.	C	C	.	.	.	R	A	.	.	.	.	.	.	.	.	.	.	.	
		37X-CC	346.30	A	G	.	C	F	R	.	R	R	.	.	R	.	.	.	C	F	.	.	.	.	C	.	.	.	.	.	.	.	.	.	.	.	
		38X-CC	355.09	A	G	.	C	F	.	.	F	C	.	.	R	.	.	.	A	F	R	.	.	R	C	.	.	.	.	.	.	.	.	.	.	.	
		39X-CC	363.04	A	G	.	C	F	R	.	C	C	.	.	R	.	.	.	C	C	R	.	.	.	A	.	.	.	.	.	.	.	.	.	.	.	.
		40X-CC	373.94	A	G	.	C	R	.	.	C	C	.	.	R	.	.	.	C	C	.	.	.	A	.	.	.	.	.	.	.	.	.	.	.	.	.
		41X-CC	381.88	A	G	.	F	F	.	.	F	C	.	.	.	.	.	.	.	A	F	.	.	R	A	.	.	.	.	R	.	R	.	.	.	.	
	42X-CC	394.24	A	G	.	F	F	.	.	R	F	.	.	.	.	.	.	.	C	F	R	.	.	A	.	.	.	.	.	.	.	.	.	.	.		
	43X-3, 112-113	398.62	A	G	.	F	F	.	.	R	F	.	.	.	.	.	.	.	F	R	.	.	.	A	R	.	.	.	.	.	.	.	.	R	.	.	
	CN12c	43X-CC	400.00	C	G	.	F	F	.	.	F	F	R	.	.	.	.	.	R	.	.	.	.	C	.	.	.	.	R	.	.	.	.	.	.	C	
		44X-CC	404.90	C	G	.	F	F	.	.	F	R	F	.	.	.	.	.	.	F	.	.	.	.	C	.	.	.	.	.	.	.	.	.	.	.	
		45X-4, 112-113	410.25	C	G	.	R	R	.	.	F	C	C	.	.	.	.	.	.	C	R	.	R	R	A	F	.	.	.	.	.	.	.	.	R		
	CN12b	45X-5, 112-113	411.75	A	G	.	F	F	.	.	F	C	F	F	.	.	.	.	.	C	R	.	.	A	.	.	.	.	.	.	.	.	.	.	R		
		45X-6, 112-113	413.25	A	G	.	F	F	.	.	F	C	F	F	.	.	.	.	.	C	R	.	.	A	.	.	.	.	.	.	.	.	.	R			
CN12a	45X-CC	414.60	C	G	.	C	F	R	.	F	C	F	R	R	.	.	.	.	F	R	.	.	C	.	.	.	.	.	.	.	.	.	.	.	.		
	46X-CC	424.30	A	G	.	F	F	.	.	F	C	C	F	R	.	.	.	.	F	.	.	.	C	.	.	.	A	.	.	.	.	.	.	.	.		
	47X-CC	433.90	A	G	.	F	F	.	.	F	C	C	R	R	.	.	.	.	F	R	.	.	C	.	.	.	A	.	.	.	.	.	.	.	.		

between Samples 133-823B-54X-CC and -55X-CC. However, this zonal boundary is considered very tentative because *Amaurolithus tricorniculatus* is very rare at Site 823 and was found in only one sample. The last occurrence of *Ceratolithus armatus* (4.6 Ma) is between Samples 133-823B-63X-5, 125 cm, and -63X-CC, and the first occurrence of this species (5.06 Ma) is between Samples 133-823B-66X-CC and -67X-1, 134 cm.

The last occurrence of *Discoaster quinqueramus* (5.26 Ma), which corresponds to the Miocene/Pliocene boundary, occurs between Samples 133-823B-69X-1, 135 cm, and -69X-2, 135 cm. Very rare specimens of *Amaurolithus amplificus* occur in Samples 133-823B-77X-CC, -78X-CC, -80X-3, 125 cm, and -80X-CC. This suggests an age of lower Subzone CN9b (5.6 to 5.9 Ma) for these samples. *Amaurolithus delicatus/Amaurolithus primus* is very rare and its occurrence is very sporadic. It is not possible to use its first occurrence to subdivide Zone CN9 into CN9a and CN9b at Site 823.

The first occurrence of *Discoaster quinqueramus/Discoaster bergrenii* (8.2 Ma) is placed between Samples 133-823C-19R-CC and -20R-1, 118 cm. Rare specimens of *Catinaster calyculus* occur in Sam-

ples 133-823C-20R-5, 117 cm, through -22R-4, 128 cm; ages of 8.75 Ma and 10.0 Ma are assigned to these two samples respectively. Rare to few specimens of *Catinaster coalitus* occur from Samples 133-823C-22R-3, 137 cm, through -24R-2, 125 cm; this suggests an age range of 9.0 to 10.8 Ma for this stratigraphic interval. The lowest two samples from Site 823 (Samples 133-823C-24R-2, 125 cm, and -24R-CC) contain poorly preserved nannofossils, which include *Calcidiscus macintyreii*, *Coccolithus pelagicus*, *Discoaster brouweri*, *Helicosphaera* sp., *Reticulofenestra pseudoumbilicus*, and *Reticulofenestra minuta/Reticulofenestra minuta*. These samples are probably younger than 11.0 Ma, based on the absence of *Cyclicargolithus floridanus*, a common species in middle Eocene-middle Miocene sediments.

A most remarkable feature of Site 823 sediments is that, although the sequence contains more than 1860 gravity flows (Davies, McKenzie, Palmer-Julson, et al., 1991), the succession of the nannofossil datums is still in order, and reworking of nannofossils is undetectable in virtually all the samples examined. This suggests that the gravity flow was a penecontemporaneous redeposition process, which did not involve sediments of markedly older ages.

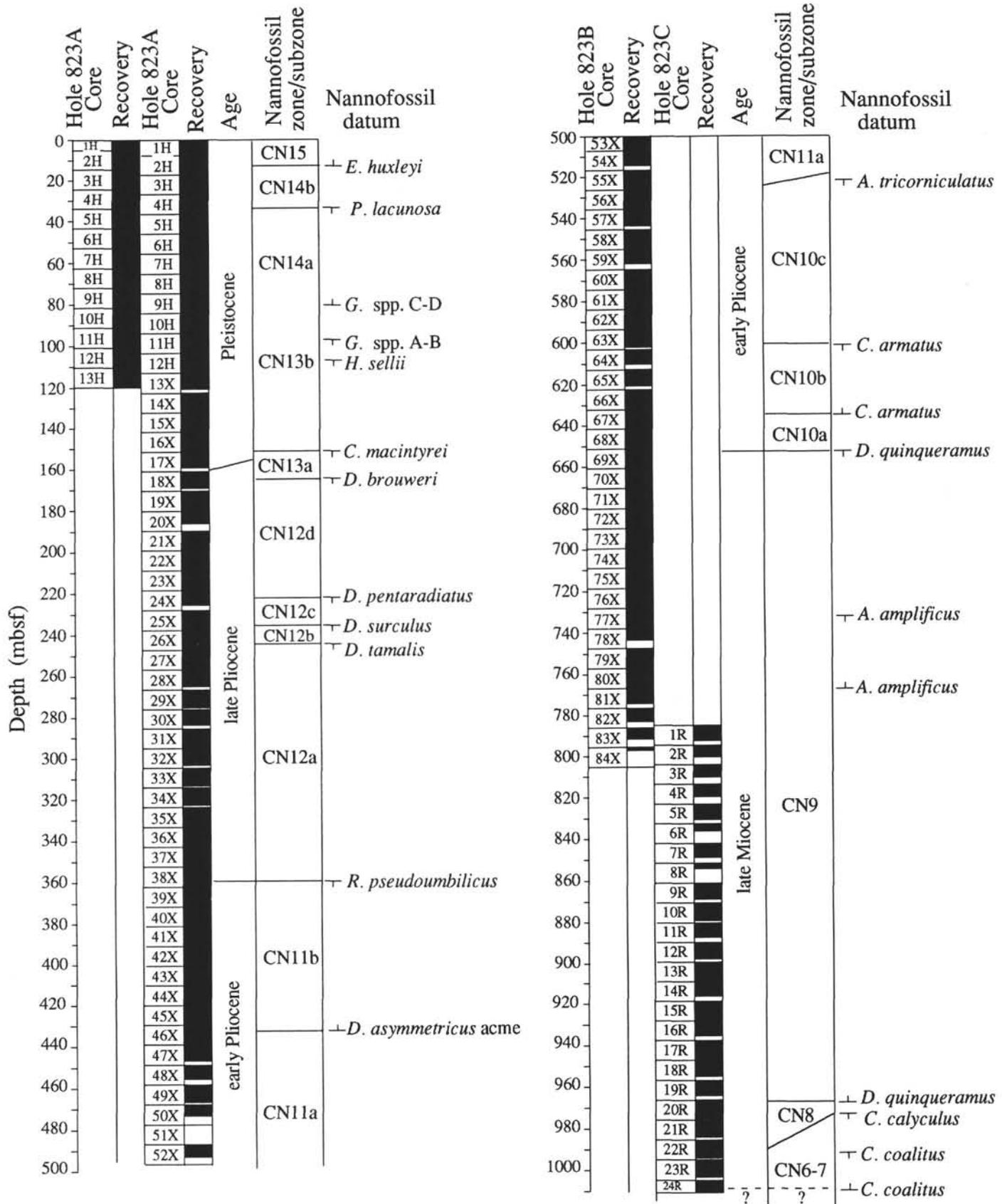


Figure 8. Calcareous nannofossil biostratigraphy, Site 823.

### Site 824

Four holes were drilled at Site 824. Calcareous nannofossils are generally rare and poorly preserved at this site and are marginally useful for dating the upper Pleistocene to the middle Miocene sediments (Fig. 9).

Both *Emiliania huxleyi* and *Pseudoemiliania lacunosa* are absent in Samples 133-824B-1H-CC through -5H-CC; this interval is therefore assigned to Subzone CN14b. Rare specimens of *P. lacunosa* were first observed in Sample 133-824B-6H-CC, and this sample is older than 0.465 Ma. The true last occurrence of *P. lacunosa* may be stratigraphically higher but cannot be identified because nannofossils are scarce and preservation is poor. The next datum recognized is the last occurrence of *Calcidiscus macintyreii* (1.48 Ma) in Sample 133-824A-5H-CC. Sample 133-824A-6H-CC contains *Discoaster pentaradiatus* and is older than 2.29 Ma. Common *Discoaster quinqueramus* occur in Sample 133-824A-4H-CC; this sample has a minimum age of 5.26 Ma. Common *Cyclicargolithus floridanus* were found in Sample 133-824A-32X-CC. As no sediment was recovered in the seven cores above this level, the stratigraphic level for the last occurrence of *C. floridanus* (11.0 Ma) is unknown. No datable nannofossil assemblages were recovered below Core 824A-32X.

### Site 825

Site 825 was intended to occupy the same position as Site 811 to penetrate the basement rock that Site 811 did not reach. Two holes were drilled at Site 825. Calcareous nannofossils are few to rare and poorly preserved in the sediments recovered, except for Core 133-825A-1H. Biostratigraphic resolution is poor (Fig. 10) owing to a low species diversity and the general absence of age-diagnostic species.

Sample 133-825A-1H-1 yielded a Pleistocene assemblage, which includes abundant *Gephyrocapsa caribbeanica*. Both *Emiliania huxleyi* and *Pseudoemiliania lacunosa* are absent. This suggests an age of Subzone CN14b (0.275–0.465 Ma).

Specimens of *Sphenolithus* are present from Samples 133-825A-5H-CC through -12X-CC. This indicates that these samples are older than 3.45 Ma (Zone CN11). *Cyclicargolithus floridanus* is present in Sample 133-825A-6H-CC, which should be older than CN6. *Calcidiscus premacintyreii* occurs in Sample 133-825A-11X-CC. The presence of this species constrains the sample to an age range of 12.2–14.1 Ma (CN4–CN5).

No sediment was recovered from Cores 133-825A-13X through -825B-4R (Fig. 10). Samples from Hole 825B contain virtually no age-diagnostic taxa. The presence of *Cyclicargolithus floridanus* in the samples, including Sample 133-825B-9R-1, 1 cm, immediately above the metamorphic basement rock, indicates a broad age range of middle Eocene to middle Miocene.

### DIAGENESIS OF CALCAREOUS NANNOFOSSILS

Preservation of calcareous nannofossils is generally good at Sites 209, 822, and 823; moderate at Sites 819 through 821; and poor at Sites 811, 824, and 825. Examples of relatively well-preserved calcareous nannofossils from Site 822 can be seen in Plates 1 and 2. Poorly preserved assemblages (Pl. 3) exhibit distinct calcite overgrowth and dissolution on most specimens. To better understand the diagenesis of calcareous nannofossils in the Great Barrier Reef–Queensland Plateau transect sites, the mineralogical composition and calcium carbonate content at Sites 821 through 824 and 209 are compared (Fig. 11). Results from Sites 819 and 820 are similar to those from Site 821, and results from Sites 811 and 825 are similar to those from Site 824. For simplicity, data from Sites 819, 820, 811, and 825 are not presented in Figure 11.

A distinct feature in these periplatform carbonate sediments is that they contain a large amount of aragonite (Fig. 11) and high-magnesium calcite (see Davies, McKenzie, Palmer-Julson, et al., 1991),

which is mostly derived from the carbonate platforms. Because aragonite and high-magnesium calcite are metastable, the sediments possess a high diagenetic potential (Schlanger and Douglas, 1974). Site 209 on the margin of the Queensland Plateau apparently received very little bank-derived material, and the sediments consist mainly of low-magnesium calcite contributed by calcareous nannofossils and foraminifers (Burns, Andrews, et al., 1973).

Figure 11 shows that the mineral compositions at Sites 821, 822, and 823 are generally similar except that the carbonate contents are slightly higher and noncarbonate (predominantly clay) contents are lower at Site 821. It has long been recognized empirically that nannofossil specimens in samples with high clay content are generally better preserved than those in carbonate oozes. The clay particles presumably have insulation effects on nannofossil specimens, inhibiting the diffusion necessary for the dissolution-diffusion-reprecipitation. The higher clay contents at Sites 822 and 823 thus contribute to the better preservation of the nannofossils there. Water depth is another factor that affects preservation. The most unstable minerals and least dissolution-resistant foraminifers and coccoliths are dissolved before burial at the relatively deep-water sites (209, 822, and 823). The assemblages thus have lower diagenetic potential. Besides water depth, the lack of bank-derived, metastable sediments at Site 209 accounts for the good preservation of nannofossils.

Sites 811, 824, and 825 differ significantly from Sites 819 through 823 in that they show consistently higher calcium carbonate contents (around 97% at Site 824, Fig. 11). This suggests that very little terrestrial material (clay and quartz) reached the Queensland Plateau. The lower silicate contents and abundant metastable minerals account for the poor preservation of nannofossils at these plateau sites.

Dissolution of aragonite and high-magnesium calcite and its consequent reprecipitation as low-magnesium calcite is relatively well known. Dissolution of low-magnesium calcite in shallow-water, shallow-burial carbonate sediments, however, is documented for the first time here (see Pl. 3) and discussed below.

The mineralogy of calcareous nannofossils has long been known as low-magnesium calcite (Siesser, 1977). The dissolution features of calcareous nannofossils thus are helpful for recognizing the dissolution of calcite, which otherwise would be difficult to recognize.

The species diversity and the abundance of calcareous nannofossils at Sites 811, 824, and 825 are very low. We ascribe this to the strong dissolution and overgrowth of the nannofossils. Both intense dissolution and overgrowth can be seen in Sample 133-824B-2H-1, 112 cm (Pl. 3), which is from 6.12 mbsf and is of late Pleistocene age (0.28–0.47 Ma). This sample still contains abundant calcareous nannofossils and has far better preservation than samples farther downhole. Dissolution of calcite (indicated by arrow in Pl. 3) has caused fragmentation of many nannofossil specimens. This is surprising as aragonite needles are abundant in the sample (Pl. 3). Aragonite needles are less stable than low-magnesium calcite and would be expected to dissolve before calcareous nannofossils.

The dissolved carbonate reprecipitates as secondary overgrowth on calcareous microfossils, including calcareous nannofossils. This process alters the appearance of nannofossils and, in extreme cases, makes identification of species impossible. For instance, the coccolith in Figure 2 (upper center) of Plate 3, the three coccoliths in Figure 3 of Plate 3, and the two coccoliths in Figure 4 of Plate 3 are so heavily overgrown that it is not possible to identify them even at the genus level.

### SUMMARY AND CONCLUSIONS

Calcareous nannofossils are generally abundant in all Leg 133 sites, and they have provided the primary means of dating the sediments, particularly for the Pliocene–Pleistocene intervals.

Site 811 yielded abundant, moderately to poorly preserved nannofossils in the upper 230 m section. Ten nannofossil datums are useful for dating this middle Miocene through Pleistocene interval, and they





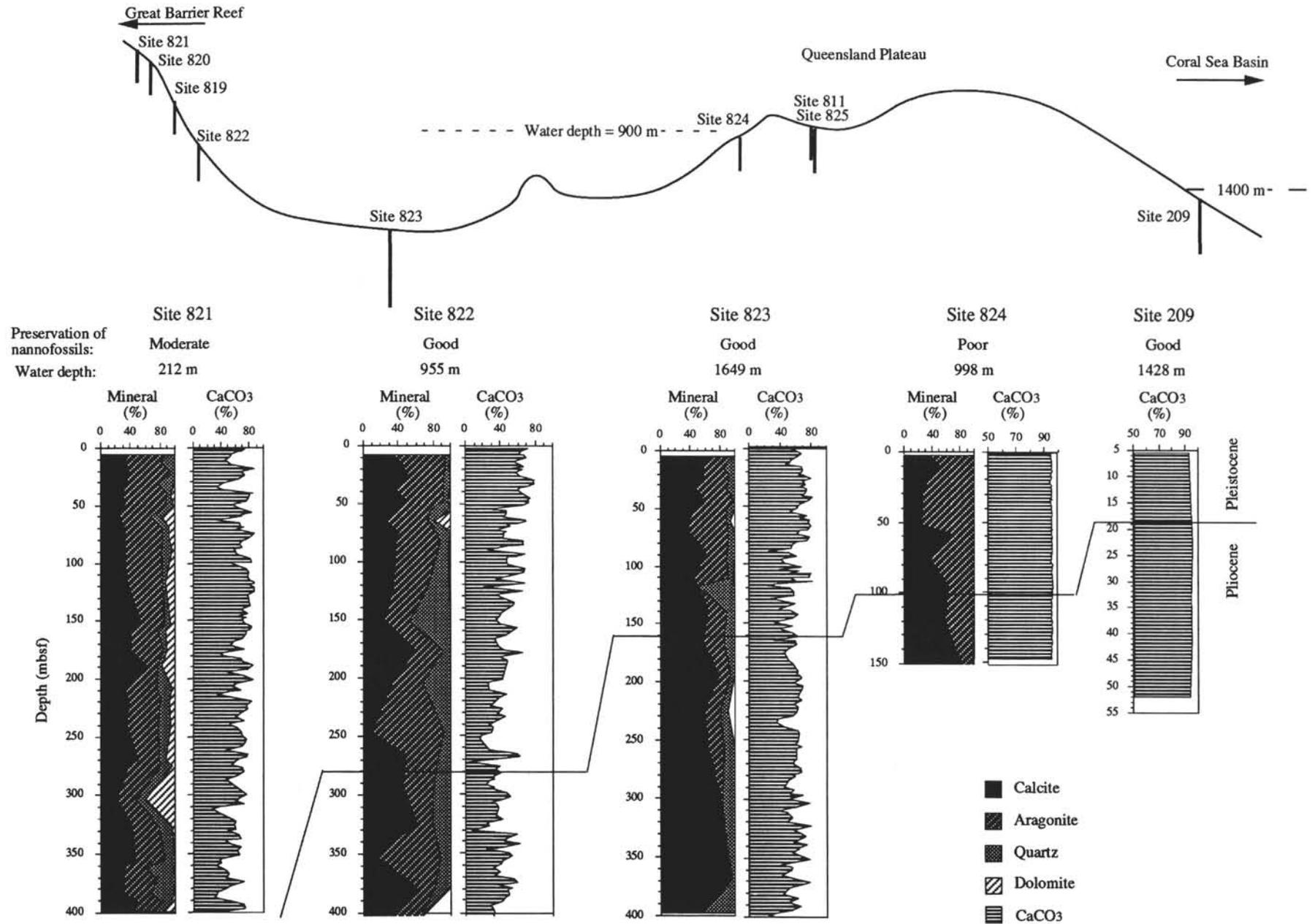


Figure 11. Schematic cross section showing sites investigated for diagenesis of calcareous nanfossils (upper panel); mineralogical composition (clays not included) and carbonate content for Sites 821 through 824 and 209 are shown in the lower panel (data from Davies, McKenzie, Palmer-Julson, et al., 1991; Burns, Andrews, et al., 1973).

Strong dissolution of upper Pleistocene calcareous nannofossils deposited in relatively shallow water and buried at shallow depth is documented for the first time.

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## APPENDIX

List of species mentioned in the text, arranged in alphabetical order by generic epithets.

- Amaurolithus amplificus* (Bukry and Percival) Gartner and Bukry, 1975  
*Amaurolithus delicatus* Gartner and Bukry, 1975  
*Amaurolithus primus* (Bukry and Percival) Gartner and Bukry, 1975  
*Amaurolithus tricorniculatus* (Gartner) Gartner and Bukry, 1975  
*Braarudosphaera bigelowii* (Gran and Braarud) Deflandre, 1947  
*Calcidiscus leptoporus* (Murray and Blackman) Loeblich and Tappan, 1978  
*Calcidiscus premacintyreii* Theodorides, 1984  
*Calcidiscus macintyreii* (Bukry and Bramlette) Loeblich and Tappan, 1978  
*Catinaster calyculus* Martini and Bramlette, 1963  
*Catinaster coalitus* Martini and Bramlette, 1963  
*Ceratolithus armatus* Müller, 1974  
*Ceratolithus cristatus* Kamptner, 1950  
*Ceratolithus telesmus* Norris, 1965  
*Coccolithus pelagicus* (Wallich) Schiller, 1930

\* Abbreviations for names of organizations and publications in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).

- Cyclicargolithus floridanus* (Roth and Hay) Bukry, 1971  
*Discoaster asymmetricus* Gartner, 1969  
*Discoaster bellus* Bukry and Percival, 1971  
*Discoaster berggrenii* Bukry, 1971  
*Discoaster brouweri* Tan emend. Bramlette and Riedel, 1954  
*Discoaster hamatus* Martini and Bramlette, 1963  
*Discoaster pentaradiatus* Tan emend. Bramlette and Riedel, 1954  
*Discoaster quinquerramus* Gartner, 1969  
*Discoaster surculus* Martini and Bramlette, 1963  
*Discoaster tamalis* Kamptner, 1967  
*Discoaster triradiatus* Tan, 1927  
*Discosphaera tubifer* (Murray and Blackman) Ostenfeld, 1900  
*Emiliana huxleyi* (Lohmann) Hay and Mohleri in Hay et al., 1967  
*Florisphaera profunda* Okada and Honjo, 1973  
*Gephyrocapsa caribbeanica* Boudreaux and Hay, 1969  
*Gephyrocapsa oceanica* Kamptner, 1943  
*Gephyrocapsa protohuxleyi* McIntyre, 1970  
*Helicosphaera carteri* (Wallich) Kamptner, 1954  
*Helicosphaera sellii* Bukry and Bramlette, 1969  
*Oolithotus fragilis* Bramlette and Reinhardt, 1968  
*Pontosphaera multipora* (Kamptner) Roth, 1970  
*Pseudoemiliana lacunosa* (Kamptner) Gartner, 1969  
*Reticulofenestra asanoi* Sato and Takayama, 1992  
*Reticulofenestra minuta* Roth, 1970  
*Reticulofenestra minutula* (Gartner) Haq and Berggren, 1978  
*Reticulofenestra pseudoumbilicus* (Gartner) Gartner, 1969  
*Rhabdosphaera clavigera* Murray and Blackman, 1898  
*Scapholithus fossilis* Deflandre in Deflandre and Fert, 1954  
*Sphenolithus abies* Deflandre in Deflandre and Fert, 1954  
*Sphenolithus moriformis* (Brönnimann and Stradner) Bramlette and Wilcoxon, 1967  
*Syracosphaera pulchra* Lohmann, 1902  
*Umbellosphaera irregularis* Paache in Markali and Paasche, 1955  
*Umbilicosphaera sibogae* (Weber-van Bosse) Gaarder, 1970

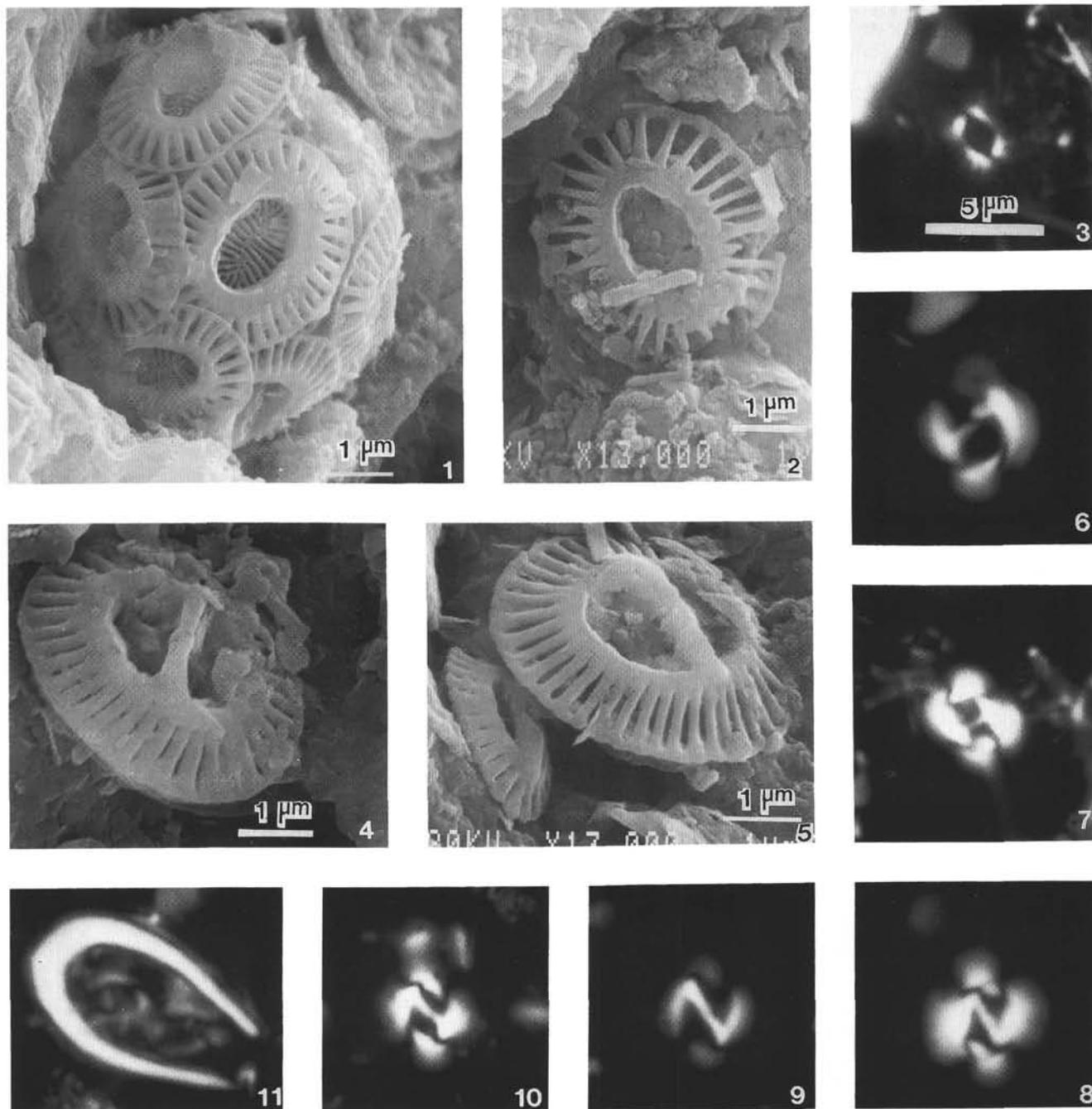


Plate 1. All light micrographs (3–11) are at the same magnification. 1–3. *Emiliania huxleyi*, Sample 133-822A-1H-CC. 4–5. *Gephyrocapsa protohuxleyi*, (4) Sample 133-822A-10H-2, 114 cm, (5) Sample 133-822A-11H-5, 111 cm. 6–7. *Gephyrocapsa* sp. C Matsuoka and Okada (1990), Sample 133-822A-7H-5, 113 cm. 8–10. *Gephyrocapsa* spp. A-B Matsuoka and Okada (1990). 11. *Ceratolithus cristatus*, Sample 133-822A-11H-5, 111 cm.

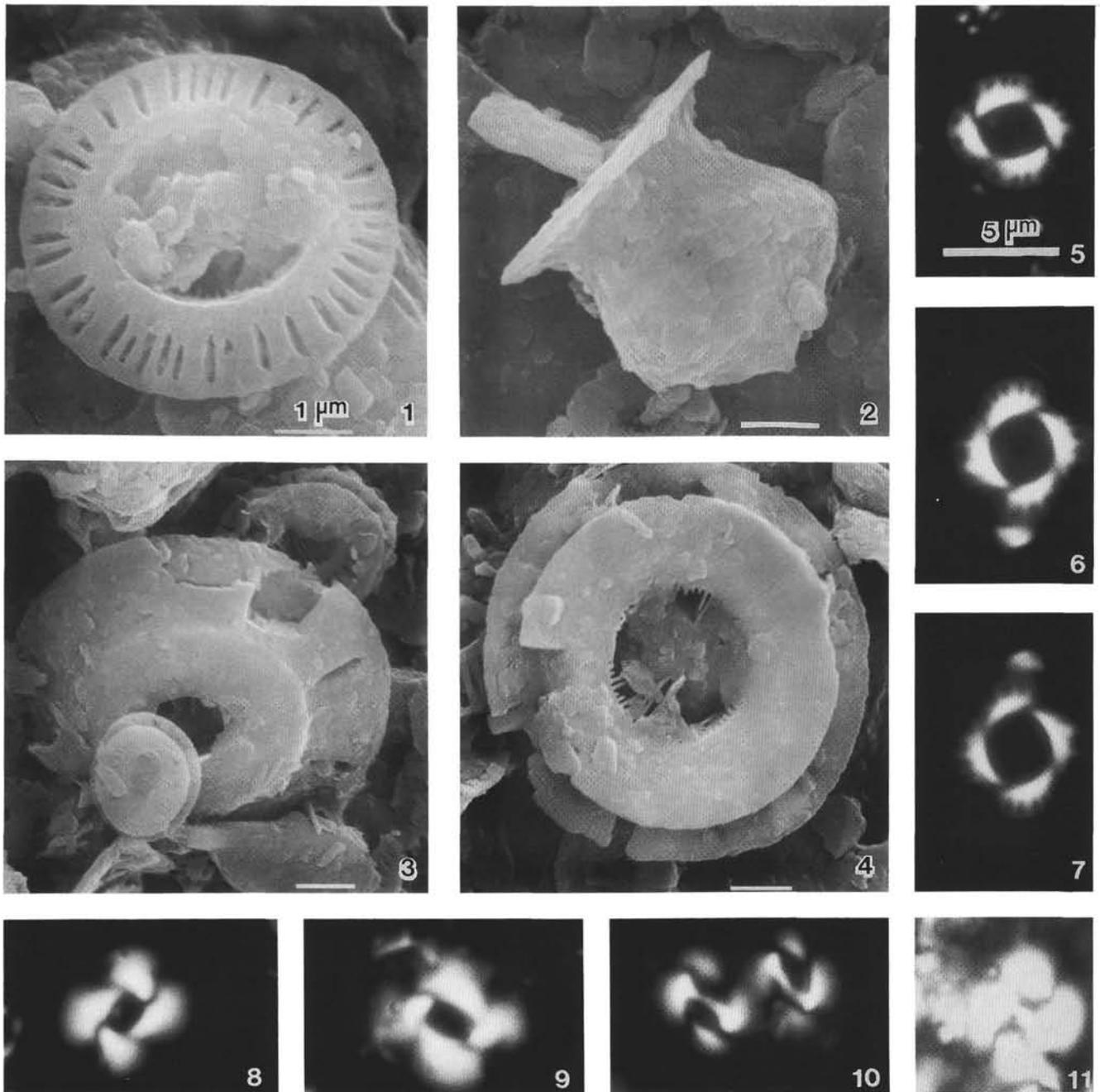


Plate 2. The scale bar for the SEM micrographs indicates 1  $\mu\text{m}$ . All light micrographs are at the same magnification. **1, 5.** *Pseudoemiliana lacunosa* (elliptical type), Sample 133-822A-10H-2, 114 cm. **2.** *Discosphaera tubifer*, Sample 133-822A-10H-4, 114 cm. **3, 8, 9.** *Reticulofenestra* sp. A Takayama and Sato (1987), Sample 133-822A-10H-2, 114 cm. **4.** *Reticulofenestra asanoi*, Sample 133-822A-10H-2, 114 cm. **6-7.** *Pseudoemiliana lacunosa* (round type), Sample 133-822A-10H-2, 114 cm. **10.** *Gephyrocapsa* sp. B Matsuoka and Okada (1990), Sample 133-822A-24X-CC. **11.** *Gephyrocapsa* sp. C Matsuoka and Okada (1990), Sample 133-822A-7H-5, 113 cm.

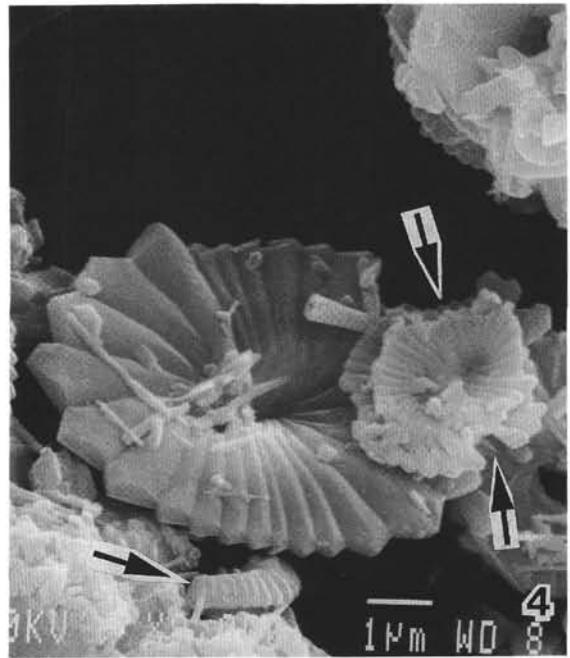
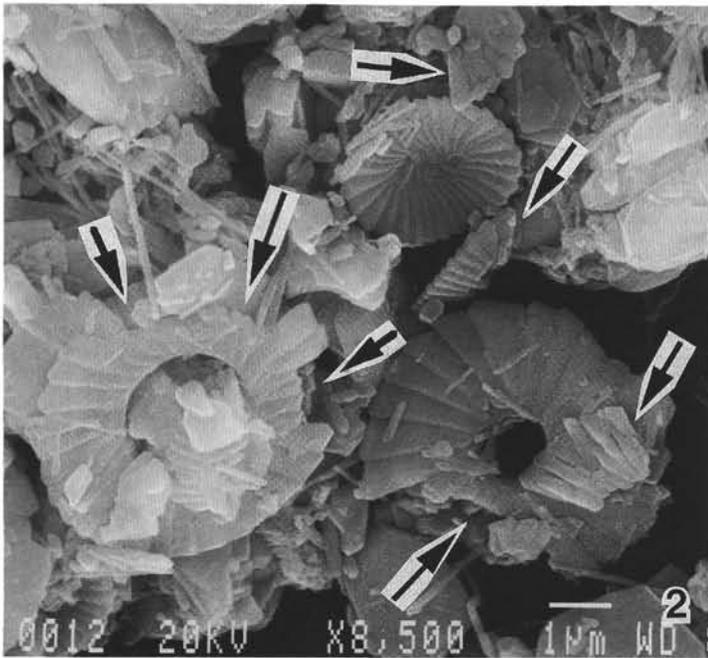
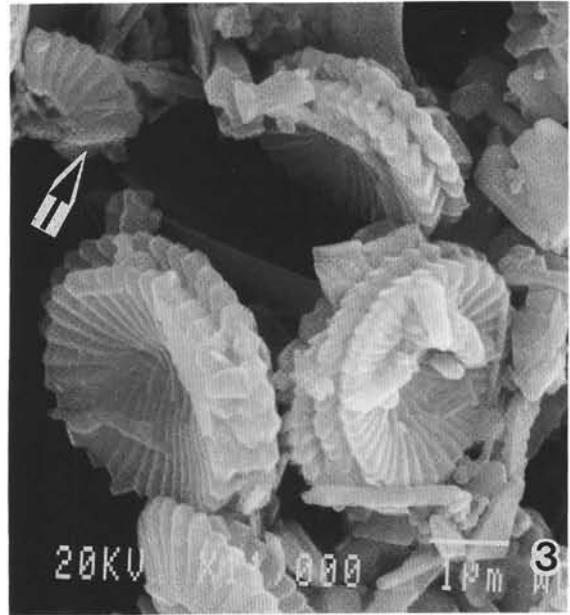
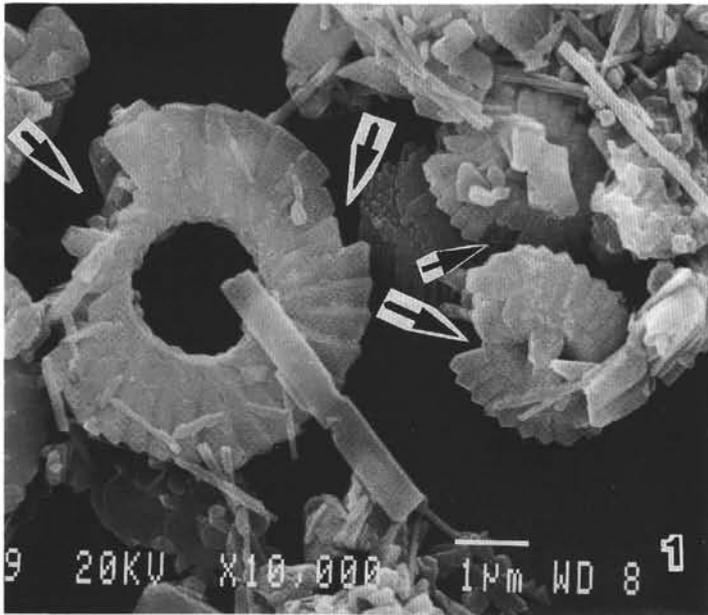


Plate 3. A nannofossil assemblage that shows strong dissolution (indicated by arrows) and overgrowth, Sample 133-824B-2H-1, 112 cm. Note that aragonite needles are abundant.