

1. NEOGENE CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY AT SITES 812 THROUGH 818, NORTHEASTERN AUSTRALIAN MARGIN¹

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ABSTRACT

Two major transects were drilled across the northeastern Australian margin during Leg 133. The southern transect, consisting of Sites 812 through 818 (and 826), extends from the northern edge of Marion Plateau north to the southern edge of Queensland Plateau. Hemipelagic and pelagic sediments were recovered at all sites from the Holocene back to the upper Miocene sections. Calcareous nannofossils are a major constituent of these sediments. Nearly all of the low-latitude nannofossil biohorizons can be identified in the Pliocene and Pleistocene, which makes it possible to construct a reasonably accurate biochronology for each site. Sites 813 and 814 are similar in sedimentation rate and succession of biohorizons, and both have a hiatus (nondeposition) that straddles the Miocene/Pliocene boundary; much of the lower Pliocene is missing. Site 812 is also similar to the last two, but its biostratigraphic resolution is reduced because of poorer preservation in critical intervals. Sites 815 and 816 are broadly similar in that both have excellent biostratigraphic resolution in the Pleistocene and uppermost Pliocene intervals, even though the sedimentation rate for the two is different. Both sites have an expanded mid-Pliocene section. At Site 815 the expanded Pliocene section has been identified as a contourite; however, there is no evidence in the nannofossils for significant redeposition. Site 815 also has exceptionally good biostratigraphic resolution into the upper Miocene section. The ranges of *Amaurolithus tricorniculatus* and *Amaurolithus amplificus* were clearly identified at this site, although the lack of a magnetostratigraphy prevents assigning precise ages to them. Sites 817 and 818 also are similar, although Site 818 is more expanded. Both sites have a hiatus at the Pliocene/Pleistocene boundary.

INTRODUCTION

During Leg 133 the northeastern Australian margin was explored from just seaward of the Great Barrier Reef to the landward side of the Queensland Plateau (Fig. 1). Holes were drilled and cored along two transects, one an east-west transect across the Queensland Trough, roughly at the latitude of Cairns—the northern transect; the other a north-south transect across Townsville Trough, with the southern end of the transect at about the latitude of Townsville—the southern transect. This study is concerned with the southern transect, which includes Sites 812 through 818 (Fig. 2). Site 826 is a depth extension of Site 816, but as it yielded no nannofossils, it has not been considered further.

The sediments recovered at all sites of the southern transect are highly calcareous, approaching near 100% carbonate at some levels. The noncarbonate fraction—clays and other siliciclastics—is most abundant at the southern end of the transect (e.g., Site 815), which is just beyond the Great Barrier Reef. The carbonate fraction consists of detrital carbonate derived from nearby reefs and banks, and of the remains of pelagic organisms, prominent among them calcareous nannofossils and planktonic foraminifers.

The biostratigraphy of the holes drilled during Leg 133 is based principally on calcareous nannofossils, and this study is a detailed documentation of the biostratigraphy of Sites 812 through 818. Abundant planktonic calcareous micro- and nannofossils were recovered from the sediment surface into the upper Miocene, beyond which pelagic micro- and nannofossils are extremely rare. This is true in some instances because deposition occurred in shallow water, in others because nannofossils may have been destroyed by diagenesis and lithification. Some nannofossils were found in these shallow-water carbonates and chalky limestones, but they are poorly preserved

and sporadic, and, consequently, a precise biochronology cannot be constructed from them.

Preservation of the calcareous nannofossils is highly variable. Rarely, nannofossils are pristine as at the water/sediment interface; more often, they are overgrown and fragmented.

METHODS

Nannofossil studies on board the *JOIDES Resolution*, as well as those done subsequently on land, were made on smear slides prepared from unprocessed sample material. All determinations were made with a light microscope. Total coccolith abundances were estimated and represent an impression of the proportion of the sediment that is nannofossils. This estimate, although useful, is inherently subjective and should be regarded with some caution. It is most valid as a relative measure for adjacent samples. Even so, the small sample used in the preparation of the smear slides may not be entirely representative of the bulk sediments at any level in a core. Abundances of individual species were recorded in six (semi-quantitative) categories that range from very rare (V) through very abundant (W) and have roughly the following numerical equivalents:

V (very rare) = <1 specimen per 50 fields (<0.04%)
R (rare) = 1 specimen per 11–50 fields (~0.04%–0.2%)
F (few) = 1 specimen per 2–10 fields (~0.2%–1%)
C (common) = 1–5 specimens per field (~1%–5%)
A (abundant) = 6–25 specimens per field (~5%–25%)
W (very abundant) = >25 specimens per field (>25%)

This abundance ranking approximates a geometric progression where each category is roughly five times the preceding category.

All nannofossil biohorizons were determined to within 150 cm, that is, to within one section, even where the checklist shows a larger sample spacing for the total assemblage determination (i.e., Hole 815A, Cores 13H to 48X). Thus, the actual highest occurrence of a marker species may be anywhere within the 150-cm interval above the designated highest occurrence; the actual lowest occurrence may be anywhere within 150 cm below the designated lowest occurrence.

¹ 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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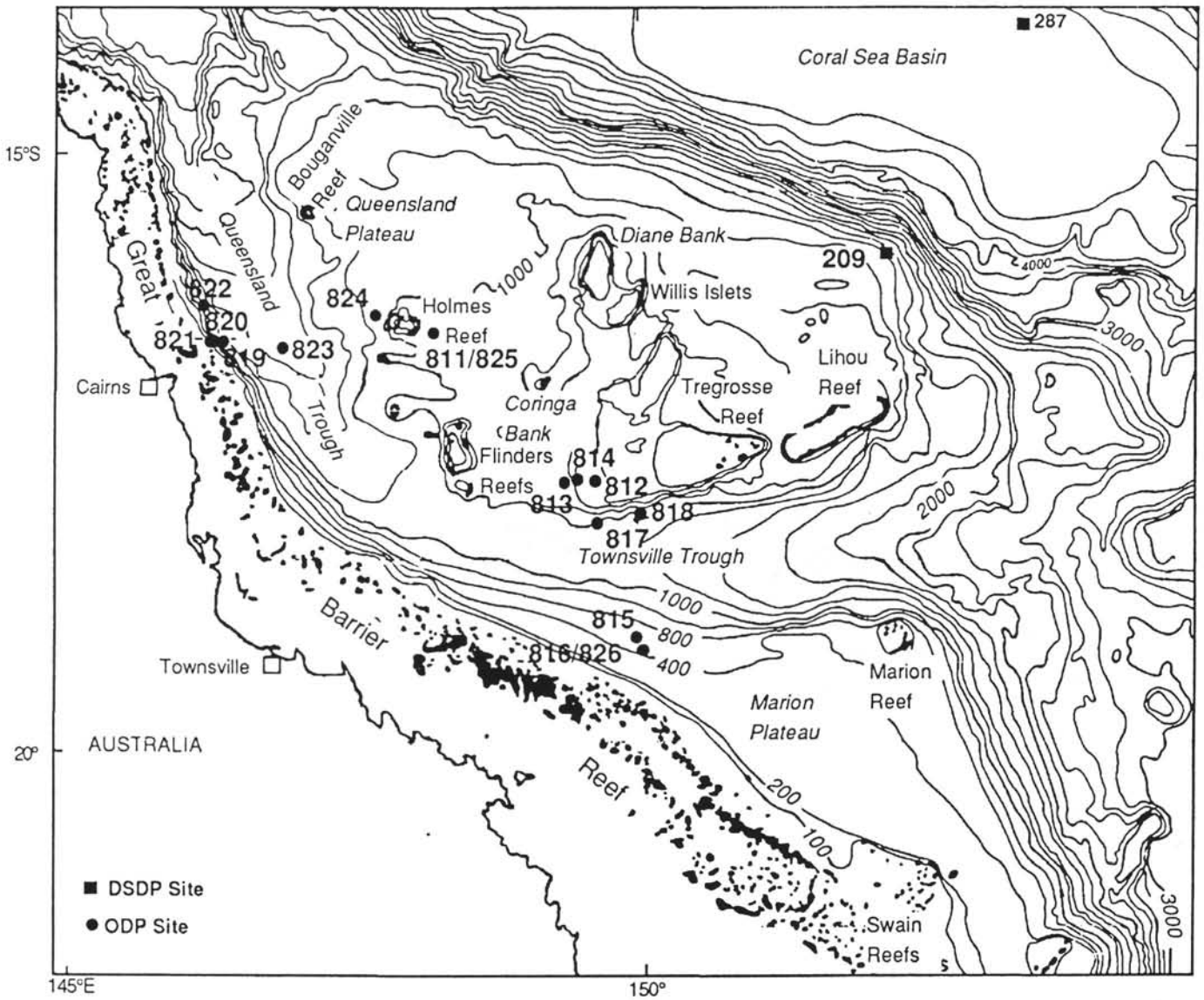


Figure 1. Location of Leg 133 sites on the northeastern Australian margin. Bathymetry in meters.

DESCRIPTION OF FRAMEWORK

The basic biostratigraphic framework for this study is the succession of calcareous nannofossil biohorizons given in Figure 3. The magnetic polarity time scale for the nannofossil biohorizons is from Berggren et al. (1985), with further revisions mainly from Baldauf et al. (1987). For reference purposes, both the nannofossil zonations of Okada and Bukry (1980) and of Martini (1971) are included. For the individual site overview, only the zonation of Okada and Bukry (1980) is given. Additional biohorizons have been included where sufficient documentation is available for their age or relative position. The biohorizons are inherently more accurate and precise, and, therefore, should be emphasized over zones and zonations. Among the added biohorizons are the lowest occurrence of *Pseudoemiliania lacunosa* and the lowest occurrence of *Amaurolithus tricorniculatus*, both in the lower Pliocene. Neither of these two can be considered an entirely dependable marker. The former species, although common, is mostly very small and altogether undistinguished at the lower limit of its occurrence; the latter is distinctive, but always rare or very rare. Nevertheless, the ages here assigned to these biohorizons are considered reliable and useful. In addition to the Leg 133 sites, these two

biohorizons have been documented at the same relative position in Gulf of Mexico sediments (unpublished data).

The several upper Miocene biohorizons inserted in Figure 3 are from the North Atlantic Site 608 and are documented elsewhere (Gartner, 1992). The sites drilled during Leg 133 did not yield sufficient pelagic sections over this interval to materially test the utility of all of these biohorizons in the western Pacific Ocean, but they did prove useful for dating some sparsely fossiliferous intervals.

The Leg 133 sites did not yield a usable magnetostratigraphy, and the correlation of nannofossil biohorizons with the magnetic polarity time scale cannot be checked or improved with data from these sites. Moreover, the sedimentation rate at the Leg 133 sites is extremely variable, temporally and spatially, and any age estimates made by interpolation or extrapolation might have extremely large errors and, therefore, should be approached cautiously.

In the following site by site discussion, the biostratigraphy is presented primarily in terms of the depth (mbsf = meters below seafloor) of occurrence of relevant nannofossil biohorizons. Age assignments for each site are given graphically in the summary charts, along with nannofossil zonal assignments and the position of all identified nannofossil biohorizons. The ages for these biohorizons

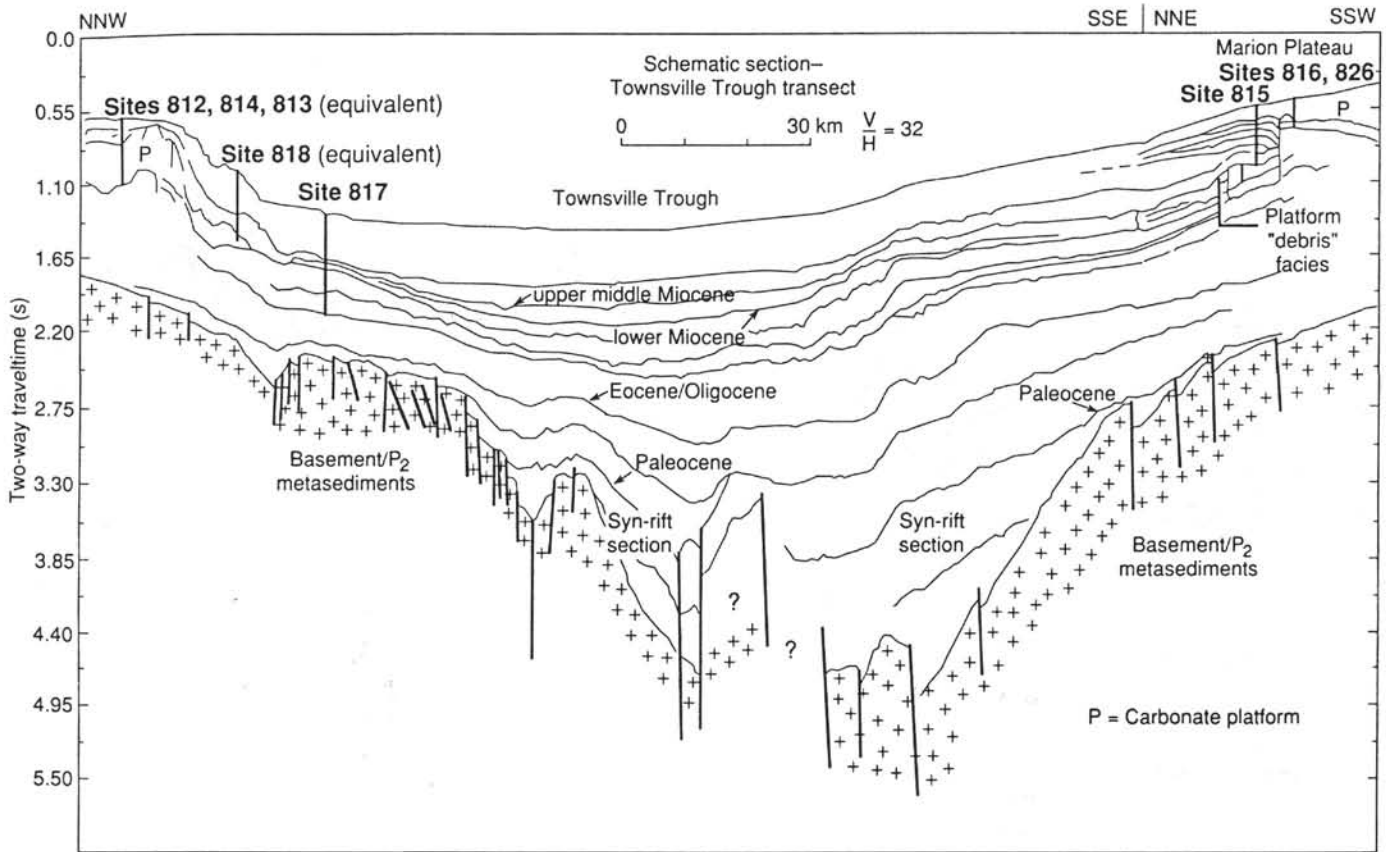


Figure 2. Schematic cross section of Townsville Trough, with location of Sites 812 through 818 (projected onto interpreted structural section).

(best current estimate) can be obtained from the chronological framework given in Figure 3. This format for the presentation was chosen to separate data and interpretation clearly so that future improvements to the chronology of nannofossil biohorizons can be readily applied to the data presented here.

SITE REPORTS

Site 812

Calcareous nannofossils are abundant in the uppermost 30 m of the section cored at this site and may constitute 10% to 20% of the sediments, which are almost entirely carbonate. Hole 812A yielded poor recovery below about 20 m (Core 3H), and the biostratigraphy of the site has been augmented with data from Hole 812C, in which recovery was reasonably good to about 115 m (Core 13H). The nannofossil biostratigraphy for Site 812 is summarized in Figure 4.

The youngest biohorizon recognized was the lowest occurrence of *Emiliana huxleyi* at 1.87 mbsf (812A-1H-2, 37 cm). That is followed by the highest occurrence of *Pseudoemiliana lacunosa* at 8.27 mbsf (812A-2H-3, 37 cm), and the top of the interval of dominance of small *Gephyrocapsa* at 17.77 mbsf (812A-3H-3, 37 cm). This last species marks approximately the midpoint of the Pleistocene. *Calcidiscus macintyreii* has its highest occurrence at 23.9 mbsf in Hole 812A (812A-3H-CC) and at 24.4 mbsf in Hole 812C (812C-36X-6, 0 cm). The slightly different depths of this datum in these two holes can be accounted for by sample spacing or incomplete recovery. The more complete core recovery in Hole 812C suggests that the 24.4-mbsf depth of the datum may be more nearly correct.

The highest occurrence of *Discoaster brouweri* was documented only in Hole 812C, where it occurs at 25.9 mbsf (812C-3H-7, 0 cm), and the highest occurrence of *Discoaster pentaradiatus* was documented in Hole 812A at 27.9 mbsf (812A-4H-CC). Immediately below this level in both holes is the highest occurrence of *Spheno-*

lithus abies, which in Hole 812C can be placed fairly precisely at 29.86 mbsf (812C-5H-1, 36 cm).

The interval from the highest occurrence of *Calcidiscus macintyreii* to the highest occurrence of *Sphenolithus abies* clearly represents an attenuated section, while the lowermost part of the interval from the highest occurrence of *Discoaster pentaradiatus* to the highest occurrence of *Sphenolithus abies* almost certainly must contain a major hiatus that encompasses much of the late Pliocene interval. The poor core recovery in Core 4H of each of the two holes may be related to this hiatus and to the greatly attenuated section above it, because this interval of poor recovery is much too thin to account for the missing time interval.

The remaining section yielded far fewer nannofossils—from less than 1% to perhaps as much as 1% to 2%—that consisted of a poorly preserved, low-diversity assemblage only marginally usable for biostratigraphy. Useful biohorizons are the highest occurrence of *Reticulofenestra pseudumbilicus* at 58.36 mbsf (812C-8H-1, 36 cm), which marks the early Pliocene to late Pliocene transition, and the highest occurrence of *Discoaster quinquerramus* at 86.36 mbsf (812C-10-6H, 36 cm), which marks the Miocene/Pliocene boundary. Below this level no further datable nannofossil assemblages were recovered, and from Core 133-812C-12H downward, nannofossil yield approaches zero.

Site 813

Site 813 is located to the west of Site 812 and in slightly deeper water as well (see Fig. 1). The upper Neogene sediments recovered at this site have a strongly pelagic aspect, and calcareous nannofossils constitute from 20% to 80% of the sediments. Preservation is only moderate in the upper part of the section and deteriorates to poor below about 100 mbsf, which corresponds approximately to the Miocene/Pliocene boundary. Nevertheless, the biostratigraphy for the Pleistocene and upper Pliocene sections is good, with adequate biohorizons represented to permit reasonably accurate dating (Fig. 5).

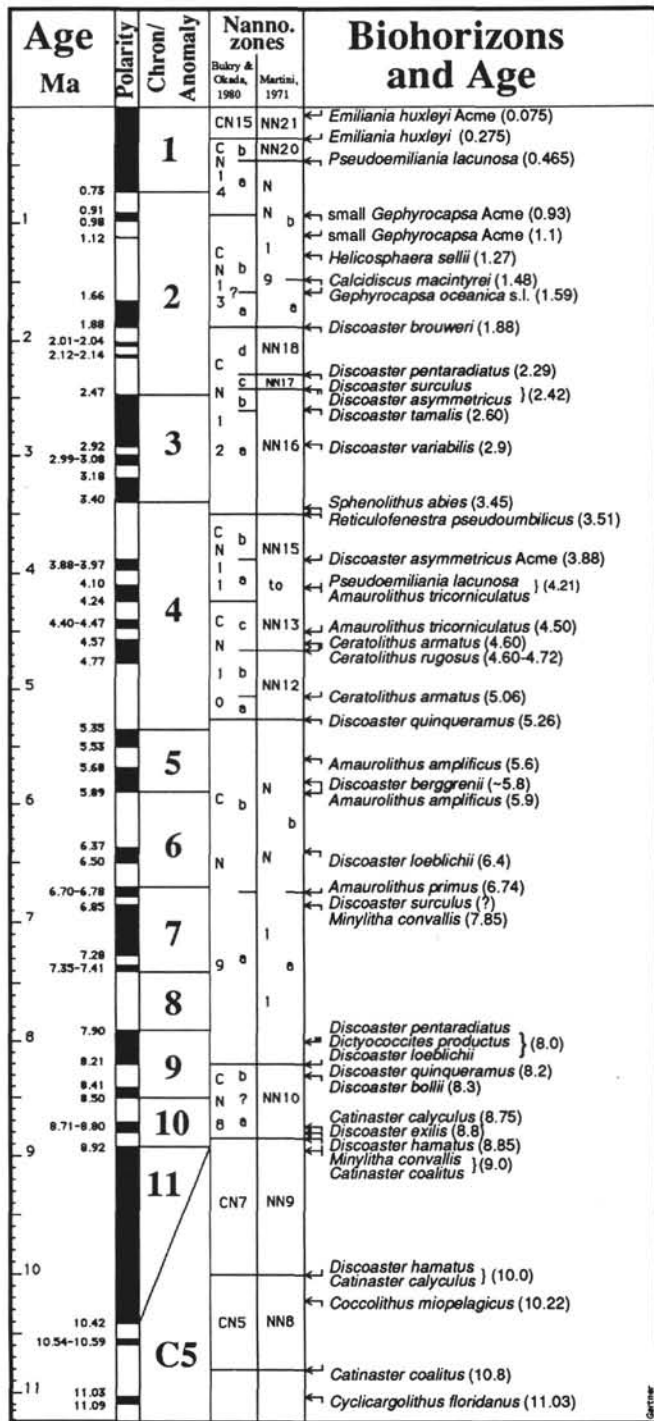


Figure 3. Biochronologic framework of calcareous nannofossil biohorizons and magnetostratigraphy compiled mainly from Berggren et al. (1985) and Baldauf et al. (1987).

The youngest biohorizon is the lowest occurrence of *Emiliana huxleyi* at 1.88 mbsf (813A-1H-2, 38 cm), followed by the highest occurrence of *Pseudoemiliana lacunosa* at 10.58 mbsf (813A-2H-4, 38 cm), and by the top of the small *Gephyrocapsa* dominance interval at 24.57 mbsf (813A-3H-7, 38 cm). This last datum has an age of about 0.93 Ma and approximately marks the midpoint of the Pleistocene. The *Helicosphaera sellii* datum could not be identified at this site, and the next lower datum is the highest occurrence of *Calcidiscus*

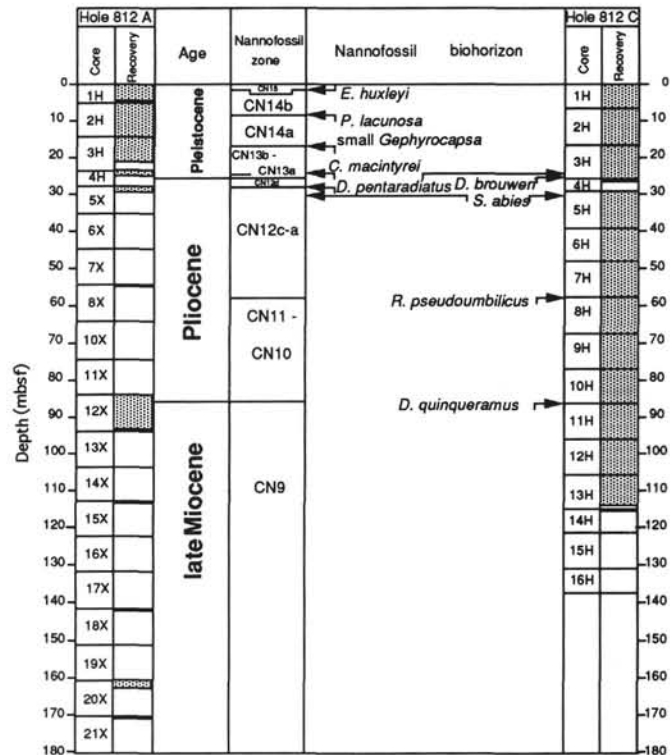


Figure 4. Summary of nannofossil biostratigraphy for Site 812.

macintyreii at 34.07 mbsf (813A-4H-7, 37 cm), followed by the highest occurrence of *Discoaster brouweri* at 40.56 mbsf (813A-5H-4, 36 cm). This last species marks the Pliocene/Pleistocene boundary.

Upper Pliocene biohorizons are also well developed. The highest occurrences of *Discoaster pentaradiatus*, *Discoaster surculus*, and *Discoaster tamalis* are at 53.06 mbsf (813A-6H-6, 36 cm), 54.5 mbsf (813A-6H-7, 36 cm), and 58.06 mbsf (813A-7H-4, 36 cm), respectively. The midpoint of the Pliocene is marked by the highest occurrence of *Reticulofenestra pseudumbilicus* at 81.56 mbsf (813A-9H-6, 36 cm), whereas the highest occurrence of *Sphenolithus abies* is just a short distance above at 80.06 mbsf (813A-9H-5, 36 cm). Although nannofossils remain abundant below this level, preservation deteriorates severely, and it is difficult to identify key markers, except for the highest occurrence of *Discoaster quinqueramus* at 100.56 mbsf (813A-11H-6, 36 cm). The assemblage associated with *Discoaster quinqueramus* also contains forms very similar to the Pliocene *Discoaster asymmetricus*, which, however, may be found also associated with the much older *Discoaster hamatus* and *Discoaster neohamatus*. In any case, it is likely that a hiatus is present in the section at this level. Below the highest occurrence of *Discoaster quinqueramus*, the nannofossil assemblage, although abundant, consists mainly of generalized and poorly preserved reticulofenestrads and of heavily calcified, stemless sphenoliths and is not age-diagnostic.

Site 814

Site 814 lies near and slightly to the east of Site 813. Its sediments are carbonate, much of which is coarse and displaced downslope as gravity-flow deposits. Calcareous nannofossils may be abundant (to 80%) near the top of the section, but decrease sharply to 10% or less at about 100 mbsf and to less than 1% below about 100 mbsf. Between 0 and 100 mbsf, nannofossils may be extremely rare locally in coarse debris flows. Owing to the prevalence of displaced sediments, the biostratigraphy of this site has been revised significantly as a result of examination of additional samples. In spite of the large amount of

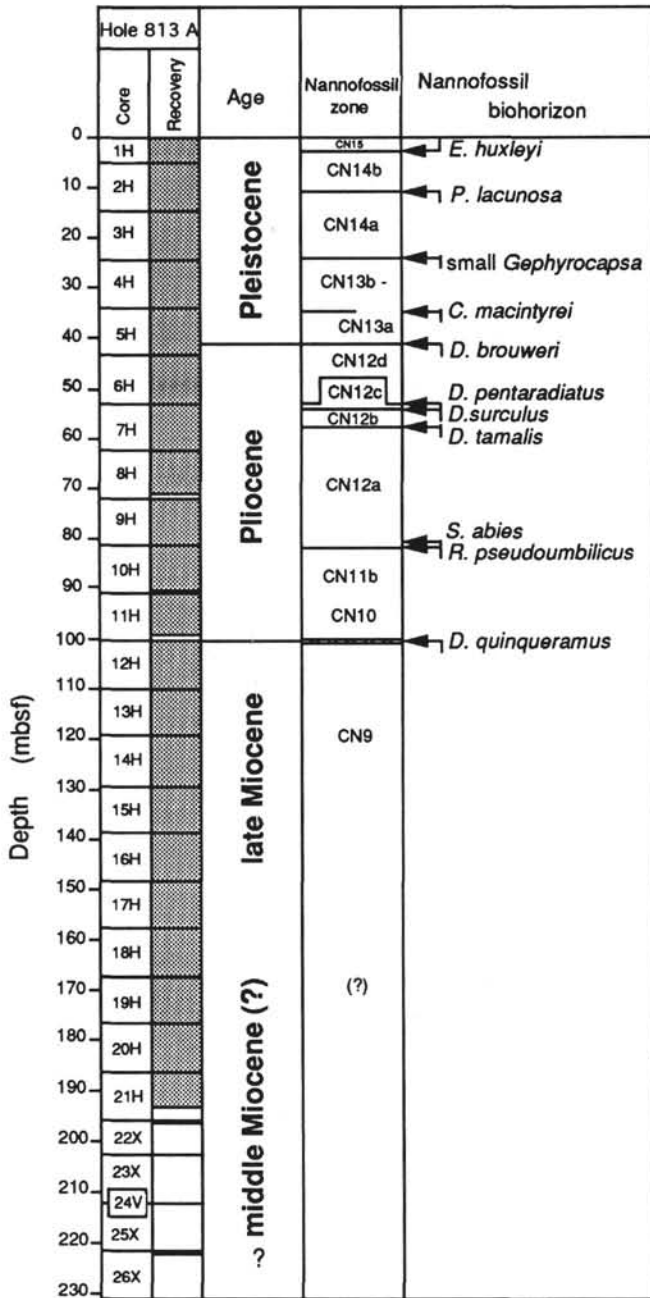


Figure 5. Summary of nannofossil biostratigraphy for Site 813.

redeposition, it is possible to establish a reasonably good biostratigraphy for the Pleistocene and the late Pliocene interval (i.e., to approximately 55 mbsf) (Fig. 6).

The youngest datum is the lowest occurrence of *Emiliania huxleyi* at 3.37 mbsf (814A-1H-2, 37 cm), which is followed by the highest occurrence of *Pseudoemiliania lacunosa* at 10.76 mbsf (814A-2H-3, 36 cm), then by the top of the mid-Pleistocene interval of small *Gephyrocapsa* dominance at 21.76 mbsf (814A-3H-4, 36 cm). The lower Pleistocene highest occurrence of *Calcidiscus macintyreii* is at 29.76 mbsf (814A-4H-3, 36 cm), and the highest occurrence of *Discoaster brouweri* (i.e., the Pliocene/Pleistocene boundary) is at 34.26 mbsf (814A-4H-6, 36 cm).

Three late Pliocene biohorizons also are well developed. The highest occurrence of *Discoaster pentaradiatus* is at 42.26 mbsf (814A-5H-5, 36 cm), that of *Discoaster surculus* at 45.26 mbsf (814A-

5H-7, 36 cm), and of *Discoaster tamalis* at 53.26 mbsf (814A-6H-6, 36 cm). Poor core recovery from about 58 to 67 mbsf renders this interval undecipherable. The highest occurrence of *Sphenolithus abies* is at 67.17 mbsf (814A-9H-1, 67 cm), although the near-contemporary highest occurrence of *Reticulofenestra pseudoumbilicus* cannot be identified in that same core. Nannofossils continue to be abundant in Cores 10H through 12H (10%–15%), but the assemblage is untypical and nearly devoid of discoasters. Rare, symmetrical, five-rayed discoasters (probably *Discoaster quinqueramus*) occur from 76.0 mbsf (814A-10H-1, 37 cm) downward, and that level is taken as the Miocene/Pliocene boundary. Probably, a hiatus exists within Core 9H.

Two additional markers were recorded from this site; however, both are problematic in that they are exceedingly rare and their preservation is only marginally adequate for identification. *Calcidiscus premacintyreii* occurs at 104.5 mbsf (814A-12H-CC), which suggests a middle Miocene age (>11.7 Ma) (Gartner, 1992); however, a five-rayed symmetrical discoaster was recorded from 110.85 mbsf (814A-13H-5, 36 cm), which indicates a younger age (<10.0 Ma) for this level. Clearly, the quality of the nannofossils is insufficient for determining reliable ages over this interval. The second biohorizon is the highest occurrence of *Sphenolithus heteromorphus* at 114.0 mbsf (814A-13H-CC) in a meager nannofossil assemblage. This species is found sporadically to 235 mbsf, but all of the specimens encountered are excessively overgrown and, at best, only suggest a middle Miocene age.

Site 815

Site 815 is located on the south flank of Townsville Trough, just beyond the northern edge of Marion Plateau in a thick pile of late Neogene-age hemipelagic to pelagic sediments (Fig. 1). Much of this pile of pelagic mud—some 400 m in all—is of mid-Pliocene age (nannofossil Subzone CN12a and Zone CN11) and has been interpreted as a contourite deposited by bottom currents adjacent to the steep scarp of Marion Plateau (Fig. 2). Post-cruise study of the nannofossils from this site has led to a significant revision of the shipboard biostratigraphy, particularly with respect to the age of the interval from 40 to 160 mbsf. The biostratigraphy for Site 815 is summarized in Figure 7; a checklist for the site is given in Table 1.

The following important biohorizons were recognized for dating purposes at this site. The youngest biohorizon is the lowest occurrence of *Emiliania huxleyi* at 0.35 mbsf (815A-1H-1, 35 cm), indicating a very low latest Pleistocene and Holocene sedimentation rate. The highest occurrence of *Pseudoemiliania lacunosa* is next at 4.85 mbsf (815A-1H-4, 35 cm), followed by the top of the interval of dominance of small *Gephyrocapsa* at 14.65 mbsf (815A-2H-5, 35 cm), which here as elsewhere is marked by a radical reduction to near zero in the abundance of all *Gephyrocapsa* larger than ~3 μm. At this site the base of this interval also can be identified and occurs at 16.12 mbsf (815A-2H-7, 32 cm). The lower Pleistocene biohorizons include the highest occurrence of *Helicosphaera sellii* at 19.65 mbsf (815A-3H-3, 35 cm) and the highest occurrence of *Calcidiscus macintyreii* at 21.15 mbsf (815A-3H-4, 35 cm). The Pliocene/Pleistocene boundary (as indicated by the highest occurrence of *Discoaster brouweri*) is at 25.65 mbsf (815A-3H-7, 35 cm), and below this were recognized three upper Pliocene discoaster biohorizons: the highest occurrence of *Discoaster pentaradiatus* at 32.15 mbsf (815A-4H-5, 35 cm); the highest occurrence of *Discoaster surculus* at 37.15 mbsf (815A-5H-2, 35 cm); and the highest occurrence of *Discoaster tamalis* at 43.15 mbsf (815A-5H-6, 35 cm).

Below this, sedimentation rate increases nearly twenty-fold, (from about 7 m/m.y. to about 130 m/m.y.), and the next lower biohorizon, the highest occurrence of *Sphenolithus abies*, is encountered at 117.66 mbsf (815A-13H-6, 36 cm). The highest occurrence of *Reticulofenestra pseudoumbilicus* is at 158.9 mbsf (815A-18X-1, 21 cm), which marks approximately the mid-point of the Pliocene. These last two biohorizons are here interpreted differently than was done in the *Initial Reports* volume (Davies, McKenzie, Palmer-Julson, et al., 1991),

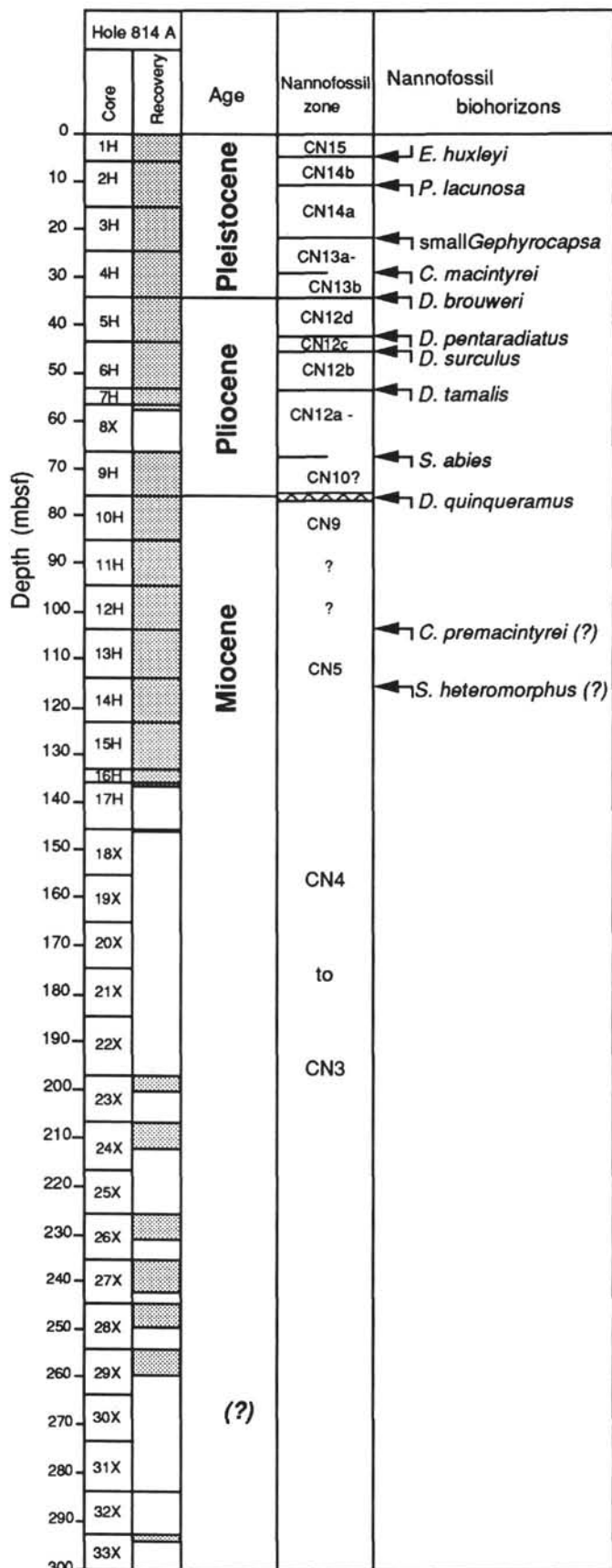


Figure 6. Summary of nannofossil biostratigraphy for Site 814.

because both may appear sparsely and scattered in samples above the levels identified here. Such occurrences, however, almost certainly represent redeposition. Comparable high sedimentation rates also prevailed during the latter part of the early Pliocene, as the next biohorizon, the highest occurrence of *Amaurolithus tricorniculatus*, is at 309.60 mbsf (815A-34X-CC), which is also close to the lowest occurrence of *Pseudoemiliana lacunosa* at 309.26 mbsf (815A-34X-7, 36 cm).

From this level downward, sediments again accumulated at a reduced rate—about 38 m/m.y.—to the Miocene/Pliocene boundary. The next two lower biohorizons are not cited generally; these are the highest occurrence of *Ceratolithus armatus* at 327.10 mbsf (815A-36X-6, 30 cm) and the lowest occurrence of *Amaurolithus tricorniculatus* at 330.86 mbsf (815A-37X-2, 36 cm). Both seem to be useful markers for the early Pliocene, but both will require further documentation in additional sections. The lowest occurrence of *Ceratolithus rugosus* is at 339.07 mbsf (815A-38X-1, 37 cm), and lowest occurrences of birefringent ceratoliths (*Ceratolithus acutus* or *Ceratolithus armatus*) are at 350.25 mbsf (815A-39X-2, 35 cm).

The Miocene/Pliocene boundary is placed at the highest occurrence of *Discoaster quinqueramus* at 353.25 mbsf (815A-39X-4, 35 cm), and the closely related *Discoaster berggrenii* has its highest occurrence at 377.79 mbsf (815A-42X-1, 39 cm). The highest and lowest occurrences of *Amaurolithus amplificus* are also within this core at 379.27 mbsf (815A-42X-2, 37 cm) and 386.77 mbsf (815A-42X-7, 37 cm), respectively. Nannofossils continue in abundance through Core 45X, and the nonbirefringent ceratoliths *Amaurolithus primus* and *Amaurolithus delicatus* are present to the bottom of this core at 415.70 mbsf (815A-45X-CC). Below this point, nannofossils become exceedingly rare; symmetrical discoasters bearing five rays continue to the bottom of Core 47X at 434.90 mbsf (815A-47X-CC), indicating a late Miocene to possibly latest middle Miocene (maximum) age for this level.

Site 816

Site 816 is located slightly south of Site 815 on Marion Plateau, where a relatively thin pelagic section covers the shallow-water carbonate core of the plateau. The pelagic to hemipelagic section extends to approximately 90 mbsf (through Core 10H), and calcareous nannofossils are a significant constituent of the sediment over this interval. Most of this 90 m of hemipelagic sediment is of mid-Pliocene age, and the latest Pliocene and Pleistocene records are relatively attenuated, though apparently complete, within the upper 15 m of the section. Below approximately 90 mbsf, the limestones are barren of calcareous nannofossils. A biostratigraphic summary for Site 816 is given in Figure 8.

The youngest recognizable biohorizon is the lowest occurrence of *Emiliana huxleyi* at 0.37 mbsf (816A-1H-1, 37 cm), followed in the very next lower sample by the highest occurrence of *Pseudoemiliana lacunosa* at 1.87 mbsf (816A-1H-2, 37 cm). The top of the interval of small *Gephyrocapsa* dominance can be recognized at 4.87 mbsf (816A-1H-4, 37 cm), although the base of that interval as well as the highest occurrence of *Helicosphaera sellii* could not be identified. The next lower biohorizon is the highest occurrence of *Calcidiscus macintyreii* at 10.37 mbsf (816A-2H-3, 37 cm), and the Pliocene/Pleistocene boundary was placed at 13.37 mbsf (816A-2H-5, 37 cm), at the highest occurrence of *Discoaster brouweri*. The three uppermost Pliocene discoaster biohorizons follow in a short interval of sediments. The highest occurrence of *Discoaster pentaradiatus* is seen at 15.37 mbsf (816A-3H-1, 37 cm); the highest occurrence of *Discoaster surculus* is at 18.37 mbsf (816A-3H-3, 37 cm); and the highest occurrence of *Discoaster tamalis* is at 19.87 mbsf (816A-3H-4, 37 cm).

Below this point, the sedimentation rate increases markedly (from about 7 m/m.y. to about 67 m/m.y.), and the next biohorizon, the highest occurrence of *Sphenolithus abies*, is at 43.5 mbsf (816A-5H-CC), followed substantially farther down by the only slightly older *Reticulofenestra pseudumbilicus* at 76.86 mbsf (816A-9H-4, 36 cm). This

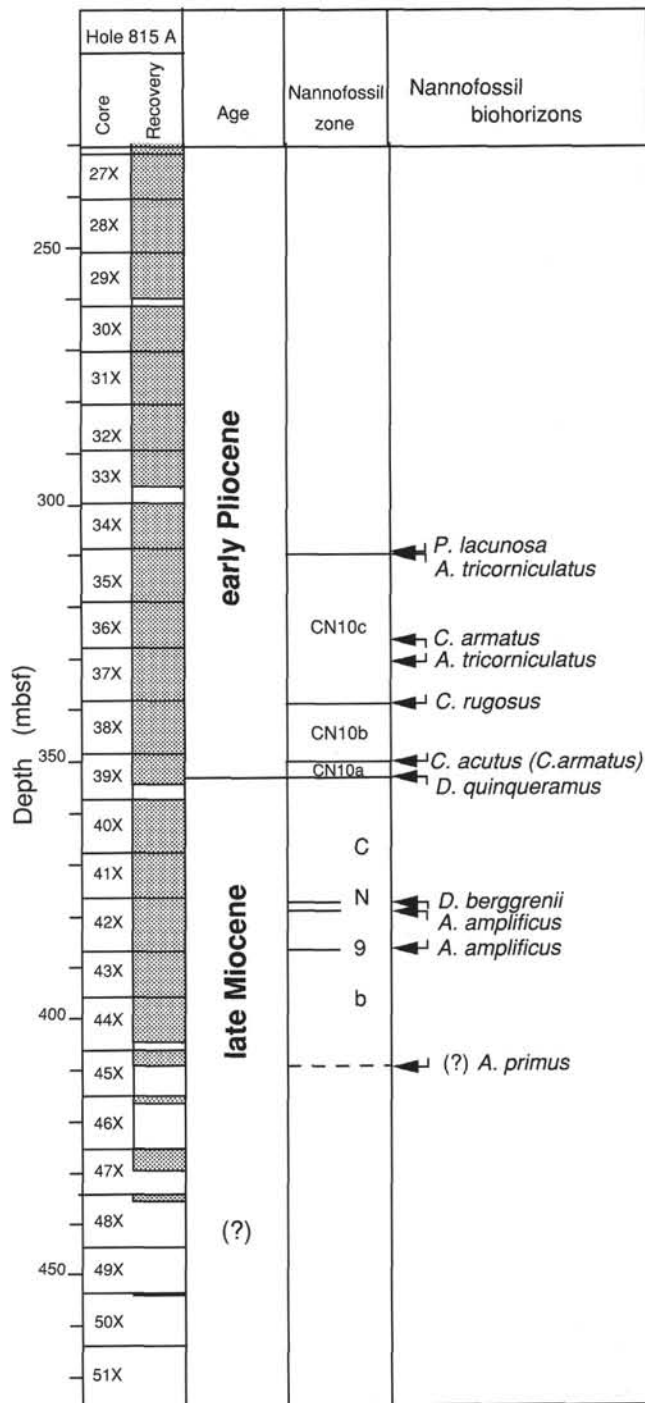
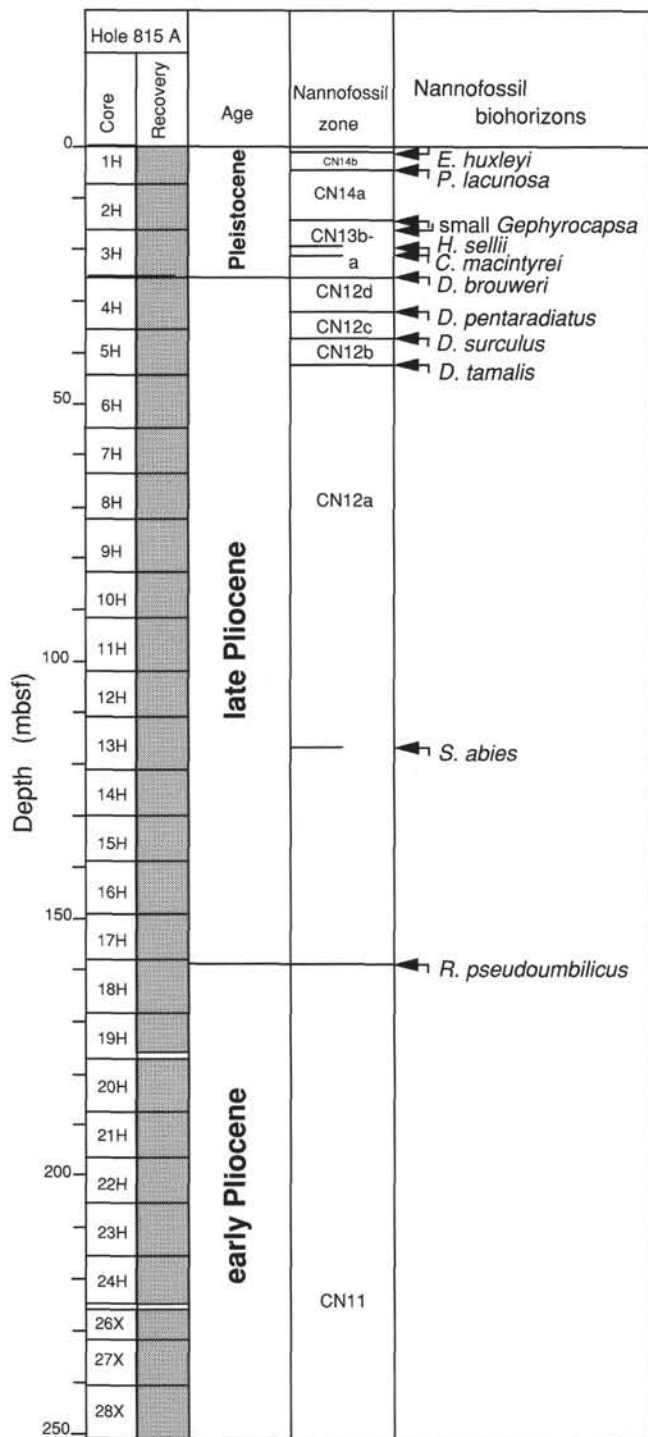


Figure 7. Summary of nannofossil biostratigraphy for Site 815.

datum marks the midpoint of the Pliocene and is the oldest biohorizon recognized at this site. Presumably, the transition from a shallow-water carbonate environment to a pelagic-hemipelagic setting above occurred just before the extinction of *Reticulofenestra pseudumbilicus*, whose age has been determined as 3.51 Ma (see Fig. 3).

Site 817

Site 817 was drilled below the northern flank of Townsville Trough and just below the southern edge of Queensland Plateau. The

sediment is mostly carbonate, chiefly periplatform ooze, but with an abundant pelagic component. Calcareous nannofossils are generally abundant and may constitute from a few percent to more than 50% (estimated) of the bulk of the sediment. Abundance and diversity of nannofossils decrease dramatically at about 200 mbsf, and consequently, the biostratigraphy of the section below that level is less certain than that above it. The Pleistocene and late Pliocene-age intervals contain large amounts of sediment derived from the nearby carbonate platforms and thus are relatively more expanded than the early Pliocene- and late Miocene-age intervals. The biostratigraphy

Table 1. Calcareous nannofossils from Hole 815A.

	Abundance	Preservation	<i>Amaurolithus primus</i>	<i>Amaurolithus tricorniculatus</i>	<i>Calcidiscus leptoporus</i>	<i>Calcidiscus macintyreii</i>	<i>Calcidiscus tropicus</i>	<i>Ceratolithus cristatus</i>	<i>Ceratolithus rugosus</i>	<i>Coccolithus pelagicus</i>	<i>Crenolithus</i> sp.	<i>Cyclolithella</i> cf. <i>C. annulla</i>	<i>Discoaster asymmetricus</i>	<i>Discoaster berggrenii</i>	<i>Discoaster brouweri</i>	<i>Discoaster pentaradiatus</i>	<i>Discoaster quinqueramus</i>	<i>Discoaster surculus</i>	<i>Discoaster tamalis</i>	<i>Discoaster variabilis</i>	<i>Discolithina japonica</i>	<i>Discolithina/Pontosphaera</i> sp.	<i>Discosphaera tubifer</i>	<i>Emiliana huxleyi</i>	<i>Florisphaera</i> sp.
1-1, 35	A	M			C																		C	W	A
1-2, 35	W	P			F																				
1-3, 35	W	P			V																			V	C
1-4, 35	A	P			R																			V	V
1-5, 35	C	P			R																				
2-1, 35	A	P			R																			V	
2-2, 35	A	P			R																			F	
2-3, 35	W	M			F																		R	V	
2-4, 35	W	P			F																		V		
2-5, 35	A	P			R																		V		
2-6, 32	W	P			R																			V	
2-7, 32	W	P			F																		V		
3-1, 35	W	G			F																		V	V	R
3-2, 35	W	G			F																V		V	V	R
3-3, 35	A	M			F																		V		R
3-4, 35	A	M			F	F																	R	F	
3-5, 35	A	M			R	R																		F	R
3-6, 35	A	M				R																			R
3-7, 35	A	P			F					R					V										F
4-1, 15	A	P			V					V															F
4-2, 35	C	P			F	V				A					V								V		F
4-3, 35	C	P			F	R				R	A	V			F								V	V	
4-4, 35	C	P			V	R				R	A				F								R		
4-5, 35	A	P			F	F				R	A	R			F	V							F		
4-6, 35	A	P			R	V					A				R	R							R	V	
5-1, 35	W	M			R					R	F	F			F	R							R	V	
5-2, 35	A	P			R	R				V		F			R	C		R					R		
5-3, 35	A	M			F	C				V	C	R			C	C		V				V	R	V	
5-4, 35	W	M			F	R				V	V	F			F	R							V	V	
5-5, 35	W	M			F	F				V		R			F	F							R		
5-6, 35	W	G			C	C				V	V				F	F		V					R	R	F
5-7, 35	W	G				F				R	F	F	V		F	F		F				V	F	V	V
6-1, 35	W	G			C	V						R	R		F	C		R				V	R		
6-2, 35	W	G			R	F				V		F	R		F	C		V		V	V	V	R	V	
6-3, 35	A	M			F	V				R					F	F		R			V	R	F		
6-4, 35	W	M			F	R				F		F			F	F		R				R	V	V	F
6-5, 35	W	M			F	R				V	R		F		F	C		R				R	V	F	
6-6, 35	W	M			F	F				V	F		F		F	F		R				R			
6-7, 35	W	P			F							F	V		R	R							R		
7-1, 35	W	P			F	V				R		C			R	R		V					R		
7-2, 35	W	P			F	V						F	V			F		V					R		
7-3, 35	A	P			R	R				V		F	V			V		V							
7-4, 35	W	P			F					R		R	V		V	R		V				R			
7-5, 35	A	P			F							R			V			V				V	R		
7-6, 35	W	P			R	R						C			R	R		R					R		
7-7, 35	W	P			R					V		C			R			V				V		R	
8-1, 35	W	P			F	R						C			R			V				V		R	
8-2, 35	A	P			R										V	V		V				R			
8-3, 35	A	P			F	V						F			V	V		V					R		
8-4, 35	A	P			F	F						F			R			R				R		R	
8-5, 35	W	P			F	F						F			R	R		V				V	R		
8-6, 35	W	M			R	F						F			V	R		V					F		
8-7, 20	W	P			F	F						A	C			R		V				V	R		
9-1, 37	A	M			F	R				V		A	F			R		V				V	V	V	
9-2, 37	W	M			F	F						A	F			V		R					V		
9-3, 37	W	M			F	F						C	F	V		R	R		V			V			

Note: Key to symbols: · = Not present; V = Very rare; R = Rare; F = Few; C = Common; A = Abundant; W = Very abundant.

Table 1 (continued).

	<i>Gephyrocapsa caribbeanica</i>	<i>Gephyrocapsa oceanica</i> s.l.	small <i>Gephyrocapsa</i> spp.	<i>Hoyaster perplexus</i>	<i>Helicosphaera carteri</i>	<i>Helicosphaera parallela</i>	<i>Helicosphaera sellii</i>	<i>Oolithotus anillarum</i>	<i>Pseudoemiliania lacunosa</i>	<i>Reticulofenestra minuta</i>	<i>Reticulofenestra minutula</i>	<i>Reticulofenestra pseudoumbilicatus</i>	<i>Reticulofenestra</i> sp.	<i>Rhabdosphaera claviger</i>	<i>Scapholithus fossilis</i>	<i>Scyphosphaera apsteinii</i>	<i>Scyphosphaera procera</i>	<i>Scyphosphaera pulcherrima</i>	<i>Scyphosphaera</i> sp.	<i>Sphenolithus abies</i>	<i>Syracosphaera pulchra</i>	<i>Syracosphaera quadrilaminata</i>	<i>Syracosphaera</i> sp.	<i>Thorosphaera flabellata</i>	<i>Umbellosphaera irregularis</i>	<i>Umbellosphaera tenuis</i>	<i>Umbellosphaera</i> sp.
1-1, 35	F	A	W	.	F	.	.	V	.	.	.	R	V	R	.	.	.	.	.	.	F	.	R	C	V	V	C
1-2, 35	W	.	W	.	V	.	.	.	.	.	.	.	.	F	.	.	.	.	.	.	F	.	R	C	V	V	F
1-3, 35	W	F	F	.	R	.	.	.	R	.	.	.	.	.	.	.	.	.	.	.	R	.	R	V	V	V	F
1-4, 35	W	F	.	.	R	.	.	.	R	F	.	.	.	V	V	.	.	.	.	.	V	.	V	R	V	.	F
1-5, 35	C	R	R	.	.	.	.	.	F	.	.	.	.	.	.	.	.	.	.	.	V	.	.	.	.	.	F
2-1, 35	C	F	R	.	.	.	.	F	.	.	.	.	.	V	.	.	.	.	.	.	R	.	R	.	.	.	F
2-2, 35	C	C	A	.	V	.	.	F	.	.	.	.	.	V	.	.	.	.	.	.	.	.	.	.	.	.	F
2-3, 35	W	R	A	.	F	.	.	C	.	.	.	.	R	.	.	.	.	.	.	.	R	.	.	.	.	.	C
2-4, 35	A	V	C	.	.	.	.	C	.	.	.	.	R	.	.	.	.	.	.	.	F	V	.	V	.	.	C
2-5, 35	.	R	A	.	F	.	.	C	.	.	.	.	.	V	V	.	.	.	.	.	R	.	.	.	.	.	F
2-6, 32	.	.	W	.	.	.	.	A	.	.	.	.	R	V	.	.	.	.	.	.	R	.	.	.	.	.	F
2-7, 32	R	R	W	.	F	.	.	A	.	.	.	.	F	V	.	.	.	.	.	.	F	.	.	.	V	.	C
3-1, 35	A	F	W	.	C	.	V	A	.	.	.	.	F	R	.	.	.	.	.	.	C	V	V	.	.	.	F
3-2, 35	C	F	W	.	V	.	.	C	.	.	.	.	R	R	.	.	.	.	.	.	C	V	.	.	.	.	F
3-3, 35	C	.	A	.	F	V	V	C	.	.	.	.	.	R	R	.	.	.	.	.	F	.	.	.	.	.	F
3-4, 35	.	.	A	.	F	.	.	C	.	.	.	.	R	V	V	.	.	.	.	.	F	.	.	.	.	.	F
3-5, 35	F	.	A	.	F	.	.	C	.	.	.	.	F	R	.	.	.	.	.	.	F	.	.	.	.	.	F
3-6, 35	.	R	A	.	F	.	V	A	.	.	.	.	F	R	.	.	.	.	.	.	F	.	.	.	.	.	F
3-7, 35	.	.	C	V	F	.	V	A	.	.	.	.	F	R	.	.	.	.	.	.	F	.	.	.	.	.	R
4-1, 15	V	V	A	.	F	.	.	C	.	.	.	.	F	.	.	.	.	.	.	.	F	.	.	.	.	.	.
4-2, 35	.	.	.	.	R	V	.	C	.	.	.	.	F	V	.	.	.	.	.	.	F	.	.	.	.	.	.
4-3, 35	.	.	C	.	F	V	.	C	.	.	.	.	R	V	.	.	.	.	.	.	F	.	.	.	.	.	.
4-4, 35	.	.	C	.	F	R	.	C	.	.	.	.	R	F	.	.	.	.	.	V	F	.	.	.	.	.	.
4-5, 35	.	.	.	.	F	R	.	A	.	.	.	.	F	F	.	.	.	.	.	.	F	.	.	.	.	.	.
4-6, 35	.	.	F	.	C	F	.	A	.	.	.	.	F	R	.	.	.	.	.	.	F	.	.	.	.	.	.
5-1, 35	.	.	.	.	C	R	.	A	A	C	.	.	C	F	.	R	.	.	.	.	C	.	.	.	.	.	.
5-2, 35	.	.	.	.	F	R	.	A	F	A	.	.	F	R	.	V	.	V	.	.	C	.	.	.	.	.	.
5-3, 35	.	.	.	.	C	.	V	A	C	A	.	.	F	.	R	V	V	.	.	.	C	.	.	.	.	.	.
5-4, 35	.	.	R	.	C	.	.	A	C	A	.	.	C	R	R	V	V	.	.	.	C	.	.	.	.	.	.
5-5, 35	.	.	R	.	C	.	.	A	A	A	.	.	C	R	R	R	.	.	.	.	C	.	.	.	.	.	.
5-6, 35	.	.	.	.	C	R	V	C	A	A	.	.	C	V	.	.	.	.	.	.	C	.	.	.	.	.	.
5-7, 35	.	.	.	.	F	.	.	C	A	A	.	.	F	V	V	V	V	.	.	.	C	.	.	.	.	.	.
6-1, 35	.	.	.	.	F	.	.	A	A	A	.	.	F	V	V	.	.	.	.	.	C	.	.	.	.	.	.
6-2, 35	.	.	F	.	F	.	.	F	A	A	.	.	F	V	.	.	.	.	.	.	C	.	.	.	.	.	.
6-3, 35	.	.	F	.	F	.	.	F	A	A	.	.	F	V	.	.	V	.	.	.	F	.	.	.	.	.	.
6-4, 35	.	.	C	.	C	.	.	A	A	A	.	.	F	R	.	.	.	.	.	.	F	.	.	.	.	.	.
6-5, 35	.	.	.	.	C	.	V	C	A	A	.	.	R	.	V	V	.	.	.	V	F	.	.	.	.	.	.
6-6, 35	.	.	W	.	C	.	.	A	R	F	.	.	F	V	.	.	.	.	.	.	C	.	.	.	.	.	.
6-7, 35	.	.	W	.	F	.	V	A	F	A	.	.	R	V	.	V	.	.	.	.	C	.	.	.	.	.	.
7-1, 35	.	.	A	.	R	.	.	A	.	A	.	.	R	.	.	.	.	.	.	.	F	.	.	.	.	.	.
7-2, 35	.	.	A	.	F	.	.	A	A	A	.	.	R	R	.	.	V	.	.	.	F	.	.	.	.	.	.
7-3, 35	.	.	A	.	F	.	.	C	C	A	.	.	.	.	.	V	.	.	.	.	R	.	.	.	.	.	.
7-4, 35	.	.	W	.	C	.	V	A	A	A	.	.	R	.	V	.	.	.	.	.	R	.	.	.	.	.	.
7-5, 35	.	.	A	.	C	.	.	A	A	A	.	.	R	.	V	.	.	.	.	.	R	.	.	.	.	.	.
7-6, 35	.	.	A	.	C	.	.	C	A	A	.	.	R	.	.	.	.	.	.	.	F	.	.	.	.	.	.
7-7, 35	.	.	A	.	F	.	.	A	A	A	.	.	R	R	.	.	.	.	.	.	F	.	.	.	.	.	.
8-1, 35	.	.	A	.	R	.	.	A	A	A	.	.	R	V	R	.	.	.	.	.	F	.	.	.	.	.	.
8-2, 35	.	.	A	.	F	.	.	A	A	A	.	.	R	.	.	.	.	.	.	.	F	.	.	.	.	.	.
8-3, 35	.	.	A	.	R	.	.	A	A	A	.	.	F	.	.	.	.	.	.	.	F	.	.	.	.	.	.
8-4, 35	.	.	C	.	R	.	.	C	A	A	.	.	V	.	.	.	V	.	.	.	F	.	.	.	.	.	.
8-5, 35	.	.	A	.	R	.	.	C	.	A	.	.	R	V	.	.	V	.	.	.	F	.	.	.	.	.	.
8-6, 35	.	.	A	.	F	.	.	C	.	W	.	.	F	.	.	.	.	.	.	.	F	.	.	.	.	.	.
8-7, 20	.	.	C	.	F	.	.	F	A	A	.	.	.	V	.	.	V	.	.	.	F	.	.	.	.	.	.
9-1, 37	.	.	.	.	R	.	V	F	A	A	.	.	R	V	.	.	.	.	.	.	F	.	.	.	.	.	.
9-2, 37	.	.	F	.	F	.	.	F	A	A	.	.	R	V	.	.	V	V	.	.	F	.	.	.	.	.	.
9-3, 37	.	.	A	.	F	.	V	F	A	A	.	.	F	V	V	.	.	.	.	.	F	.	.	.	.	.	.

Table 1 (continued).

	Abundance	Preservation	<i>Anatrolithus primus</i>	<i>Anatrolithus tricorniculatus</i>	<i>Calcidiscus leptoporus</i>	<i>Calcidiscus macintyreii</i>	<i>Calcidiscus tropicus</i>	<i>Ceratolithus cristatus</i>	<i>Ceratolithus rugosus</i>	<i>Coccolithus pelagicus</i>	<i>Crenolithus</i> sp.	<i>Cyclolithella</i> cf. <i>C. annalla</i>	<i>Discoaster asymmetricus</i>	<i>Discoaster bergrenii</i>	<i>Discoaster brouweri</i>	<i>Discoaster pentaradiatus</i>	<i>Discoaster quinqueramus</i>	<i>Discoaster surculus</i>	<i>Discoaster tamalis</i>	<i>Discoaster variabilis</i>	<i>Discolithina japonica</i>	<i>Discolithina/Pontosphaera</i> sp.	<i>Discosphaera tubifer</i>	<i>Emiliana huxleyi</i>	<i>Florisphaera</i> sp.
9-4, 37	W	M		F						F	F			R	R		V			V	R	V			
9-5, 37	W	M		C	V				V	C	C			R	R		V			V	R				
9-6, 37	W	M		F	F					A	C			R	R						R				
9-7, 37	A	P		R	R						A	C						V							
10-1, 36	W	M		F	F				V	C	F	V		V					V		V				
10-2, 36	A	P		F	R						F	V		V	R		V								
10-3, 36	A	P		F	R						R	V		V	R		V				V				
10-4, 36	A	P		R	R						R			V							V				
10-5, 36	A	P		R	F						F			V							R				
10-6, 36	A	P		R	F				V		R			V	V							V			
10-7, 36	A	P		R	F						R						V								
11-1, 36	A	P			R																				
11-2, 36	A	P		F	F						R			V	V		V				V				
11-3, 36	A	P		R	F						A	F		V			V				R				
11-4, 36	A	P		R	F						C			R	V					V	F				
11-5, 36	A	P		R	F						C	F					R				R				
11-6, 36	A	P		R	F					A	F	F		V	R						R				
11-7, 36	W	P		F	F						F			V	R						R				
12-1, 36	W	P		F	F						F	V			R				V		R				
12-2, 36	W	P		R	F						F			R	C						R	V			
13-1, 36	A	P		F	F						F														
14-1, 36	A	P		F	V						F			R			R				R				
15-1, 36	A	P		F	R						F										R	V			
16-1, 36	A	P		F	R						F	V									R	V			
17-1, 29	A	P		F	R						V														
18-1, 21	A	P		F	F										V		R				R				
19-1, 36	A	P		V	F						F			F							R				
20-1, 47	A	P		V	V						R			R			V			V	R				
21-1, 36	A	P		F	R						R			R	R		R		V	V	R				
22-1, 36	W	P		R	F			V	C		R				F		V				R				
23-1, 36	W	P		F					F		R				R		V				R				
24-1, 36	A	P		F	R						F			R	R		R				R	V			
24-6, 36	W	P		F	R				F		F			R	F		V				V				
26-1, 36	A	P		F	F			V	F		F			R	F						V				
27-1, 36	A	P		F	F				F		F			F	F		R				R				
28-1, 36	W	P		R	F			V	F		F			R	F		R				V				
29-1, 36	A	P		F				V	F		F	V		V	V		V		V		R				
30-1, 36	A	P		F					C		C			R	R		R								
31-1, 36	W	P		C	C			V	R		C			F	R		R			V	R				
32-1, 36	W	P		F	F				R					F	R		R				F				
33-1, 36	W	P		F	V				R		F			R	F		R				F				
34-1, 36	W	M		F	V				V		F			R	F		R				V				
35-1, 36	W	M		F	V				V		R			R	F						R				
36-1, 35	W	M		V	F	F			R					R	R		V				R				
37-1, 35	W	M		F	R				V		R			R	R		V				R				
38-1, 37	W	G		F	V				F		F			F	F		V		V		F				
39-1, 35	W	G		F	R				F		F			R	V						V			A	
40-1, 37	W	G		F					F		F			F	R	C	R		R					A	
41-1, 36	W	M		F	V									V		C					V			R	
42-1, 39	W	M		F					R		F			R	V	F	F		V		V			F	
43-1, 39	W	P		F					F		R			R	V	F	F								
44-1, 37	A	P		R	V				C		V			F	R	V	V		R		R				
45-1, 36	W	P	V	R		R			F		C			R		F	F				V				
46-1, 36	C	P		R		V			R		R					V									
47-1, 36	C	P		V					F		R					C					V				
48-1, 12	C	P		V							F														

Table 1 (continued).

	<i>Gephyrocapsa caribbeanica</i>	<i>Gephyrocapsa oceanica</i> s.l.	small <i>Gephyrocapsa</i> spp.	<i>Hayaster perplexus</i>	<i>Helicosphaera carteri</i>	<i>Helicosphaera parallela</i>	<i>Helicosphaera sellii</i>	<i>Oolithotus antillarum</i>	<i>Pseudoemiliania lacunosa</i>	<i>Reticulofenestra minuta</i>	<i>Reticulofenestra minutata</i>	<i>Reticulofenestra pseudombilicus</i>	<i>Reticulofenestra</i> sp.	<i>Rhabdosphaera claviger</i>	<i>Scapholithus fossilis</i>	<i>Scyphosphaera apsteinii</i>	<i>Scyphosphaera procera</i>	<i>Scyphosphaera pulcherrima</i>	<i>Scyphosphaera</i> sp.	<i>Sphenolithus abies</i>	<i>Syracosphaera pulchra</i>	<i>Syracosphaera quadrilaminata</i>	<i>Syracosphaera</i> sp.	<i>Thorosphaera flabellata</i>	<i>Umbellosphaera irregularis</i>	<i>Umbellosphaera tenuis</i>	<i>Umbilicosphaera</i> sp.
9-4, 37	+	+	C	+	F	+	R	+	C	A	A	+	+	F	V	+	+	+	+	+	F	+	+	+	+	+	+
9-5, 37	+	+	R	+	F	+	+	+	F	A	A	+	+	+	V	+	V	+	+	+	F	+	+	+	+	+	+
9-6, 37	+	+	R	+	F	+	+	+	F	A	A	+	+	R	R	+	+	+	+	+	F	+	+	+	+	+	+
9-7, 37	+	+	R	+	R	+	+	+	F	A	A	+	+	+	+	+	+	+	+	+	V	+	+	+	+	+	+
10-1, 36	+	+	A	+	R	+	V	+	A	W	W	+	+	V	R	+	+	+	+	+	R	+	+	+	+	+	+
10-2, 36	+	+	C	+	F	+	+	+	F	A	A	+	+	V	+	V	V	+	+	+	R	+	+	+	+	+	+
10-3, 36	+	+	C	+	F	+	V	+	F	A	A	+	+	+	V	+	+	+	+	+	R	+	+	+	+	+	+
10-4, 36	+	+	C	+	C	+	+	+	A	A	A	+	+	+	+	+	+	+	+	+	V	+	+	+	+	+	+
10-5, 36	+	+	+	+	F	+	+	+	C	A	A	+	+	+	V	+	+	+	+	+	V	+	+	+	+	+	V
10-6, 36	+	+	C	V	F	+	+	+	C	A	A	+	+	R	+	+	+	+	+	+	V	+	+	+	+	+	+
10-7, 36	+	+	C	+	F	+	+	+	C	A	A	+	+	+	R	+	+	+	+	+	+	+	+	+	+	+	+
11-1, 36	+	+	C	+	F	+	+	+	C	A	A	+	+	+	V	+	+	+	+	+	R	+	+	+	+	+	+
11-2, 36	+	+	C	+	F	+	+	+	F	C	A	+	+	+	V	+	+	+	+	+	+	+	+	+	+	+	+
11-3, 36	+	+	A	+	F	+	+	+	A	+	A	+	+	V	+	+	+	+	+	+	+	+	+	+	+	+	+
11-4, 36	+	+	+	+	F	+	+	+	F	+	A	+	+	+	V	+	+	+	+	+	+	+	+	+	+	+	+
11-5, 36	+	+	A	+	F	+	+	+	F	A	A	+	+	R	+	+	+	+	+	+	+	+	+	+	+	+	+
11-6, 36	+	+	C	+	F	+	+	+	F	A	A	+	+	R	+	+	+	+	+	+	V	+	+	+	+	+	+
11-7, 36	+	+	W	+	F	+	+	+	C	+	A	+	+	R	V	+	+	+	+	+	R	+	+	+	+	+	+
12-1, 36	+	+	W	+	F	+	+	+	C	+	A	+	+	R	V	+	V	+	+	+	R	+	+	+	+	+	+
12-2, 36	+	+	A	V	F	+	+	+	C	A	A	+	+	V	V	+	+	+	+	+	V	+	+	+	+	+	+
13-1, 36	+	+	C	+	F	+	+	+	C	+	A	+	+	+	+	+	+	+	+	+	R	+	+	+	+	+	+
14-1, 36	+	+	A	+	F	+	V	+	C	+	A	+	+	R	V	+	+	+	+	+	R	+	+	+	+	+	+
15-1, 36	+	+	A	+	F	+	F	V	C	A	A	+	+	+	+	+	+	+	+	+	R	+	+	+	+	+	+
16-1, 36	+	+	W	+	F	+	+	+	A	+	A	+	+	R	V	+	+	+	+	+	R	+	+	+	+	+	+
17-1, 29	+	+	A	+	F	+	+	+	A	A	A	+	+	R	V	+	+	+	+	+	F	+	+	+	+	+	+
18-1, 21	+	+	A	+	C	+	+	+	F	+	A	+	R	V	+	+	+	+	+	+	C	+	+	+	+	+	+
19-1, 36	+	+	W	V	F	+	+	+	F	+	A	+	F	V	+	+	+	+	+	+	C	+	+	+	+	+	+
20-1, 47	+	+	A	+	C	+	+	+	F	+	A	+	F	R	+	+	+	+	+	+	C	+	+	+	+	+	+
21-1, 36	+	+	A	+	F	+	+	+	+	+	A	+	R	+	V	+	+	+	+	+	C	+	+	+	+	+	+
22-1, 36	+	+	W	+	C	+	+	+	F	A	A	F	+	+	V	+	+	+	+	+	A	+	+	+	+	+	+
23-1, 36	+	+	C	+	F	+	+	+	R	A	A	F	+	+	+	+	+	+	+	+	C	+	+	+	+	+	+
24-1, 36	+	+	A	+	F	+	+	+	R	A	A	F	+	R	V	+	+	+	+	+	C	+	+	+	+	+	+
24-6, 36	+	+	A	+	C	+	+	+	F	A	A	F	+	+	+	+	+	+	+	+	C	+	+	+	+	+	+
26-1, 36	+	+	C	+	F	+	+	+	C	A	A	F	+	R	V	+	+	+	+	+	C	+	+	+	+	+	+
27-1, 36	+	+	A	+	C	+	+	+	C	A	A	F	+	+	+	+	+	+	+	+	C	+	+	+	+	+	+
28-1, 36	+	+	C	+	F	+	+	+	C	W	A	F	+	R	+	+	+	+	+	+	C	+	+	+	+	+	+
29-1, 36	+	+	C	+	F	+	+	+	C	A	A	F	+	R	+	+	+	+	+	+	C	+	+	+	+	+	+
30-1, 36	+	+	C	+	F	+	+	+	F	A	A	F	+	R	+	+	+	+	+	+	C	+	+	+	+	+	+
31-1, 36	+	+	C	+	C	+	+	+	C	W	A	F	+	V	+	+	+	+	+	+	C	+	+	+	+	+	+
32-1, 36	+	+	R	+	C	+	+	+	F	W	A	F	+	R	V	+	+	+	+	+	C	+	+	+	+	+	+
33-1, 36	+	+	+	+	C	+	+	+	F	W	C	F	+	R	+	+	+	+	+	+	C	+	+	+	+	+	+
34-1, 36	+	+	+	+	C	+	+	+	F	W	C	C	+	R	+	+	+	+	+	+	C	+	+	+	+	+	+
35-1, 36	+	+	+	+	F	+	+	+	+	W	W	A	+	R	+	+	+	+	+	+	C	+	+	+	+	+	+
36-1, 35	+	+	+	+	C	+	+	+	+	W	+	A	+	R	V	+	+	+	+	+	C	+	+	+	+	+	+
37-1, 35	+	+	+	+	C	+	+	+	+	W	+	A	+	V	V	+	+	+	+	+	A	+	+	+	+	+	+
38-1, 37	+	+	+	+	C	+	R	+	+	W	+	A	+	R	V	+	+	V	+	+	A	+	+	+	+	+	+
39-1, 35	+	+	+	+	F	+	+	+	+	W	+	A	+	R	V	+	+	+	+	+	A	+	+	+	+	+	+
40-1, 37	+	+	+	+	F	+	+	+	+	W	+	A	+	R	V	+	+	+	+	+	A	+	+	+	+	+	+
41-1, 36	+	+	+	+	C	+	+	+	+	W	+	A	C	+	+	+	+	+	+	+	A	+	+	+	+	+	+
42-1, 39	+	+	+	+	F	+	+	+	+	A	A	C	+	V	+	+	+	+	+	+	A	+	+	+	+	+	+
43-1, 39	+	+	+	+	C	+	+	+	+	W	+	C	+	+	V	+	+	+	+	+	A	+	+	+	+	+	+
44-1, 37	+	+	+	+	C	+	+	+	+	A	+	A	+	R	+	+	+	+	+	+	A	+	+	+	+	+	+
45-1, 36	+	+	+	+	C	+	+	+	+	W	+	C	+	R	V	+	+	+	+	+	A	+	+	+	+	+	+
46-1, 36	+	+	V	+	V	+	+	+	+	F	V	+	+	+	+	+	+	+	+	+	C	+	+	+	+	+	+
47-1, 36	+	+	+	+	V	+	+	+	+	F	R	+	+	+	+	+	+	+	+	+	C	+	+	+	+	+	+
48-1, 12	+	+	+	+	+	+	+	+	+	C	R	+	+	+	+	+	+	+	+	+	C	+	+	+	+	+	+

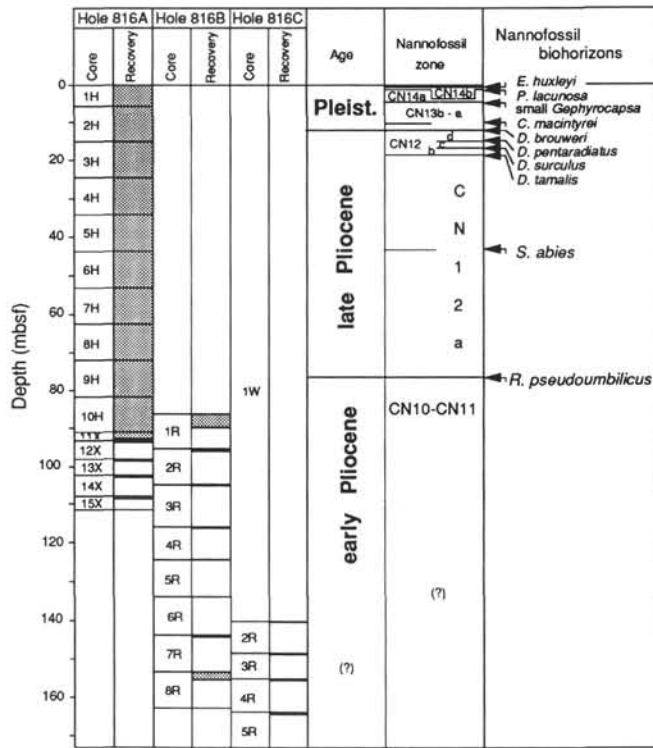


Figure 8. Summary of nannofossil biostratigraphy for Site 816.

of Site 817 has been revised significantly from that given in the Leg 133 *Initial Reports* volume, which is not surprising, given the large amount of redeposition that is associated with the turbidites and slumps encountered in the sediments. The biostratigraphy of the site is summarized in Figure 9, and a complete checklist for the site is given in Table 2 (back pocket).

The youngest biohorizon recognizable is the lower limit of the *Emiliania huxleyi* Acme at 7.58 mbsf (817A-2H-2, 38 cm), which level has an age of only about 0.075 Ma and, thus, indicates a sedimentation rate of close to 100 m/m.y. for the Pleistocene and Holocene interval. The lowest occurrence of *Emiliania huxleyi* is at 25.07 mbsf (817A-4H-1, 37 cm), which datum has an age of 0.275 Ma and indicates that the high sedimentation rate commenced at least that far back. The next lower biohorizon, the highest occurrence of *Pseudoemiliania lacunosa* is only a short distance lower at 28.07 mbsf (817A-4H-3, 37 cm) and, because this datum has an age of 0.465 Ma, the sedimentation rate between this and the next higher biohorizon is much lower—only 10 to 15 m/m.y. Possibly a hiatus is present between the last two biohorizons. The small *Gephyrocapsa* dominance interval extends from 45.56 (817A-6H-2, 36 cm) to 51.46 mbsf (817A-6H-6, 36 cm), and highest occurrence of *Calcidiscus macintyreii* is at 63.06 mbsf (817A-8H-1, 36 cm).

Several biohorizons cluster at 72.56 mbsf (817A-9H-1, 36 cm), including the lowest occurrence of large specimens of *Gephyrocapsa* (= *Gephyrocapsa* spp.), and the highest occurrences of *Discoaster brouweri*, *Discoaster pentaradiatus*, and *Discoaster surculus*. The first and the last biohorizons have ages of 1.59 and 2.43 Ma, respectively, which indicates that there must be a hiatus at this level that spans at least 0.84 m.y. Clearly, turbidity currents removed, as well as deposited, sediments at this location. The highest occurrence of *Discoaster tamalis* is slightly lower at 75.56 mbsf (817A-9H-3, 36 cm).

The highest occurrence of *Sphenolithus abies* is at 155.70 mbsf (817A-17H-5, 150 cm), which is also the highest occurrence of *Reticulofenestra pseudoumbilicus*. Although these two biohorizons are separated by only a short time interval, they do not coincide, and the close correspondence may indicate that a minor hiatus is present at this level.

The next lower biohorizon is the lowest occurrence of *Discoaster tamalis* at 158.06 cm (817A-18H-2, 36 cm), followed shortly by the lowest occurrence of *Pseudoemiliania lacunosa* and the highest occurrence of *Amaurolithus tricorniculatus* at 161.06 mbsf (817A-18H-3, 36 cm). Birefringent ceratoliths (*Ceratolithus armatus* and *Ceratolithus rugosus*) occur downward to 176.70 mbsf (817A-19H-CC), and the consistent occurrence of *Amaurolithus tricorniculatus* downward to this same level suggests that there is probably a hiatus in the lower Pliocene interval. The highest occurrence of *Discoaster quinqueramus* (i.e., the Miocene/Pliocene boundary) is just a short distance below at 180.06 mbsf (817A-20H-3, 37 cm).

Upper Miocene biohorizons include the highest occurrence of *Amaurolithus amplificus* at 186.07 mbsf (817A-20H-7, 37 cm), the highest occurrence of *Discoaster berggrenii* at 189.57 mbsf (817A-21X-3, 37 cm), the lowest occurrence of *Amaurolithus amplificus* at 195.57 mbsf (817A-21H-7, 37 cm), and the lowest occurrence of *Amaurolithus primus* at 200.56 mbsf (817A-22H-4, 36 cm). The lowest occurrence of *Discoaster quinqueramus* is at 205.20 mbsf (817A-22H-CC), which suggests that the section between the last two biohorizons has been shortened by a significant hiatus. The section below the last datum is chalky and yielded a more generalized assemblage that is not suitable for precise zonation of the interval, although four additional biohorizons can be identified.

The highest occurrence of *Coccolithus miopelagicus* is at 227.76 mbsf (817A-25X-3, 36 cm); this is probably the closest datum for marking the middle Miocene to late Miocene transition. The highest occurrence of *Cyclicargolithus floridanus* is at 234.0 mbsf (817A-25X-CC); the highest occurrence of *Calcidiscus premacintyreii* is at 259.66 mbsf (817A-28X-5, 36 cm); and the lowest biohorizon, the highest occurrence of *Discoaster exilis*, is at 272.70 mbsf (817A-29X-CC). The last two biohorizons, and particularly the highest occurrence of *Discoaster exilis*, may not be entirely reliable because they are based on relatively scarce occurrences of the markers in a generally unfavorable lithology.

Site 818

Site 818 also is located on the north side of Townsville Trough, east of Site 817 (see Fig. 1). The biostratigraphic summary for this site is given in Figure 10. Calcareous nannofossils are abundant, except at the very bottom of the cored interval, but preservation is highly variable, from near pristine at the top of the section to excessively calcified and overgrown in sandy and chalky intervals. The succession of biohorizons at this site is similar to the succession at Site 817, especially for the Pleistocene and the latest Pliocene, although the section is more expanded.

The youngest biohorizon recognized is the lowest occurrence of *Emiliania huxleyi* at 8.78 mbsf (818B-2H-1, 38 cm), followed by the highest occurrence of *Pseudoemiliania lacunosa* at 14.7 mbsf (818B-2H-5, 38 cm). The spacing of these two biohorizons suggests a more or less constant sedimentation rate of about 31 m/m.y. for the latest Pleistocene (i.e., the last 0.5 m.y.). The next lower biohorizon is the top of the interval of small *Gephyrocapsa* dominance at 52.76 mbsf (818B-6H-5, 36 cm), which is much lower than would be projected from the previous two biohorizons. Next below can be identified the highest occurrence of *Calcidiscus macintyreii* at 79.76 mbsf (818B-9H-4, 36 cm), followed by the simultaneous highest occurrences of *Discoaster brouweri* and *Discoaster pentaradiatus* at 84.77 mbsf (818B-10H-1, 37 cm). The co-occurrence of these two markers suggests a significant hiatus in the vicinity of the Pliocene/Pleistocene boundary, as was true at Site 817 also. The upper Pliocene section at Site 818 is more expanded and more complete than that at Site 817. The highest occurrence of *Discoaster surculus* is at 105.26 mbsf (818B-12H-1, 36 cm), followed by the highest occurrence of *Discoaster tamalis* at 176.27 mbsf (818B-19H-5, 37 cm), the highest occurrence of *Sphenolithus abies* at 246.26 mbsf (818B-27H-1, 36 cm), and the highest occurrence of *Reticulofenestra pseudoum-*

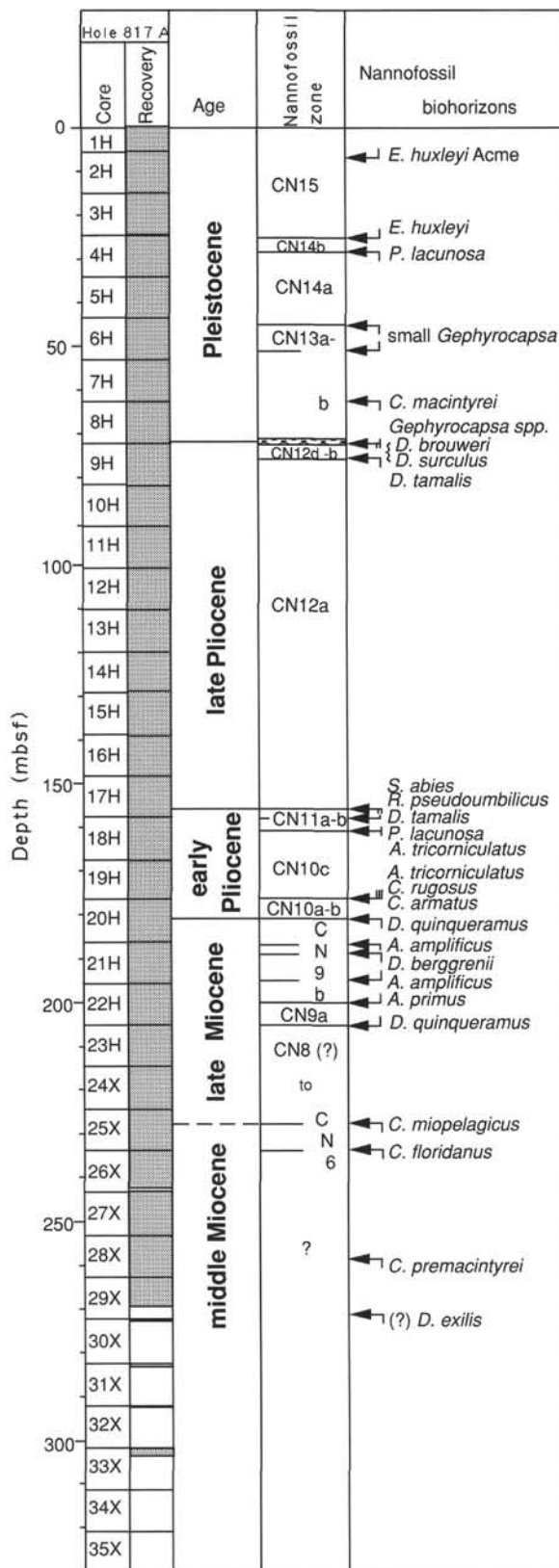


Figure 9. Summary of nannofossil biostratigraphy for Site 817.

bilicus at 258.76 mbsf (818B-28H-3, 36 cm). Thus, the upper Pliocene section is about twice as thick at this site as that at the nearby Site 817.

No further biohorizons were identified at this site and the remaining 40 m of the section (through Core 32H) has been assigned a latest early Pliocene age.

BIOSTRATIGRAPHIC PROBLEMS AND PROSPECTS

The location of Leg 133 drilling—moderate depth tropical oceans, expanded sections of hemipelagic sediments—makes this material a particularly attractive subject for further study. The abundance and diversity of calcareous nannofossils permitted precision in the dating of sediments, limited only by the distance separating adjacent samples and by the time available for processing the large number of samples. Nevertheless, other important constraints exist. As elsewhere, preservation of calcareous nannofossils is best in clay-rich sediments and tends to deteriorate rapidly downcore in sediments in which the pelagic component is diluted mainly by platform-derived, shallow-water carbonates. Where shallow-water carbonate deposition dominated, nannofossil recovery becomes insufficient for dating. The upper Miocene marker *Discoaster quinqueramus* proved useful in marginally preserved assemblages because, even in an overgrown or corroded state, this species can be identified with some confidence. The middle Miocene *Sphenolithus heteromorphus*, *Cyclicargolithus floridanus*, and, surprisingly, *Calcidiscus premacintyreii* were encountered most often in otherwise unpromising shallow-water carbonates.

The lack of a usable magnetic stratigraphy in the Leg 133 sediments is disappointing in that these sediments will not be useful for refining nannofossil biochronology. Combining the biostratigraphy with isotope stratigraphy may ultimately prove more tractable.

Figure 11 (back pocket) is a diagrammatic representation of the sites from the southern transect of Townsville Trough. An age scale is given on the two extremes of the illustration; the seven sites from north and south of Townsville Trough are represented as depth sections. Dashed lines connect the sites and the time scales at the Pliocene/Pleistocene boundary, at the late Pliocene/early Pliocene boundary (= *Reticulofenestra pseudoumbilicus* highest occurrence), and at the Miocene/Pliocene boundary. The dramatic differences in sedimentation rate in the hemipelagic interval at adjacent sites can be seen clearly and traced in this representation.

HIATUSES AND EXPANDED INTERVALS

Table 3 is a listing of the ages and depths of the various biohorizons identified at Sites 812 through 818. Age/depth plots of all of these data are given in a single graph in Figure 12. Combining the several representations of the data, the following generalizations can be offered. At Sites 812, 813, and 814, the three shallow sites on the southern flank of Queensland Plateau, pelagic sedimentation became significant just below the highest occurrence of *Discoaster quinqueramus* (i.e., immediately preceding the end of the Miocene). The precise timing can be constrained to between 5.26 and 5.6 Ma, the highest occurrences, respectively, of *Discoaster quinqueramus* and *Amaurolithus amplificus*. At two of these sites, 813 and 814, the transition is marked by a distinct hiatus. This hiatus encompasses much of the lower Pliocene at Site 814, and all but the uppermost part of the lower Pliocene at Site 813. Conceivably, part of the uppermost Miocene may be included as well. Nondeposition, probably caused by currents impinging on the southern edge of Queensland Plateau, is the preferred interpretation, as no significant lithologic change is associated with this hiatus.

The onset of current activity may be associated with local events or may be connected with the major reorganization of ocean circulation and/or sea-level changes known to have occurred toward the end of the Miocene. As these sites descended progressively below the effective depth of surface currents, pelagic sediments and periplat-

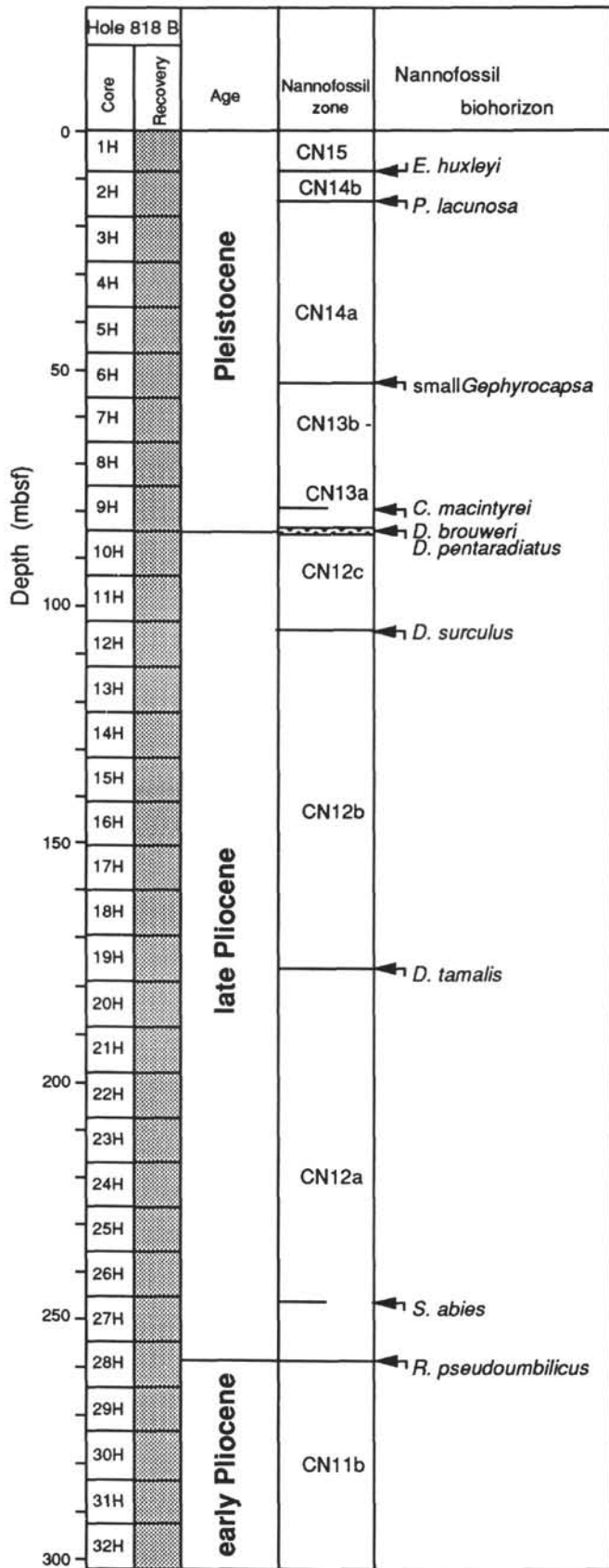


Figure 10. Summary of nannofossil biostratigraphy for Site 818.

form oozes commenced to accumulate, although the timing and rate may have been influenced also by local topography. Site 812 is significantly shallower and behind a positive topographic feature, and this may have kept it from experiencing similar erosion, although biostratigraphic resolution is not good enough to say this with certainty. At all three sites the latest Pliocene through Pleistocene record is without detectable hiatuses, and a stable sedimentary regime, much like today's, seems to have prevailed for about the past 2.5–3.5 m.y.

The sediments at Sites 817 and 818, the two deeper sites on the southern edge of Queensland Plateau, have a more pelagic aspect; consequently, a more detailed biostratigraphy could be extracted. At Site 817 a minor episode of nondeposition or deep current erosion is indicated in the lower Pliocene by the correspondence of three biohorizons, the lowest occurrences of *Amaurolithus tricorniculatus*, *Ceratolithus rugosus*, and *Ceratolithus armatus*, and in the mid-Pliocene by the correspondence of the highest occurrence of *Reticulofenestra pseudoumbilicus* and *Sphenolithus abies*. The lowermost Pliocene was not penetrated at Site 818, and the mid-Pliocene shows no evidence of a hiatus there. Both sites, however, have a significant hiatus straddling the Pliocene/Pleistocene boundary. At both sites the hiatus extends only into the lowermost Pleistocene, but nondeposition is manifested somewhat lower at Site 817 than at Site 818 (2.6 Ma vs. ~2.8 Ma). This may be explained by the fact that at Site 818 late Pliocene-age deposition occurred in a depression, a channel formed during an earlier erosional episode. No further hiatuses are apparent in the Pleistocene.

In contrast to the sites on the north side of Townsville Trough (southern flank of Queensland Plateau), Sites 815 and 816, cored on the south side of the trough (northern flank of Marion Plateau), have no discernable hiatuses within the interval represented by hemipelagic sediments (i.e., the upper Miocene to Holocene for Site 815 and the mid-Pliocene to Holocene for Site 816). At both sites, however, the mid-Pliocene section is greatly expanded relative to older sediments at Site 815, and relative to younger sediments at both sites. When this expanded section is examined on seismic sections (Davies, McKenzie, Palmer-Julson, et al., 1991), it is clear that much of this sediment was redeposited, probably by contour currents. Remarkably, redeposition appears to have involved only contemporaneous sediment, as virtually no redeposited nannofossils are evident within the expanded interval.

The data base (number of sites cored) is almost certainly too small for this complex area, and the site selection no doubt has a built-in bias, so that generalizations about hiatuses and expanded sections on the flanks of Townsville Trough probably are not justified. Clearly, bottom currents have had a significant role in rearranging of hemipelagic sediments in Townsville Trough. Within limited areas, distinct episodes of erosion and of deposition can be recognized. Moreover, currents have been sufficiently intense to prevent deposition of hemipelagic sediments of the entire spectrum of particle sizes, but not strong enough to scour and erode older hemipelagic deposits.

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APPENDIX

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

- Amaurolithus amplificus* (Bukry and Percival, 1971) Gartner and Bukry, 1975
- Amaurolithus bizzarus* (Bukry, 1973) Gartner and Bukry, 1975
- Amaurolithus delicatus* Gartner and Bukry, 1975
- Amaurolithus primus* (Bukry and Percival, 1971) Gartner and Bukry, 1975
- Amaurolithus tricorniculatus* (Gartner, 1967) Gartner and Bukry, 1975
- Braarudosphaera bigelowi* (Gran and Braarud, 1935) Deflandre, 1947
- Calcidiscus leptoporus* (Murray and Blackman, 1898) Loeblich and Tappan, 1978
- Calcidiscus macintyreii* (Bukry and Baramlette, 1969) Loeblich and Tappan, 1978
- Calcidiscus pataecus* (Gartner, 1967)
- Coccolithus pataecus* Gartner, 1967
- Calcidiscus premacintyreii* Theodorides, 1984
- Calcidiscus tropicus* Kamptner, 1955 (see Gartner, 1992)
- Ceratolithus acutus* Gartner and Bukry, 1974
- Ceratolithus cristatus* Kamptner, 1950
- Ceratolithus rugosus* Bukry and Baramlette, 1969
- Ceratolithus telesmus* Norris, 1965
- Coccolithus minimus* Kamptner, 1963
- Coccolithus miopelagicus* Bukry, 1971
- Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930
- Coronocyclus nitescens* (Kamptner, 1963) Bramlette and Wilcoxon, 1967
- Cricosphaera quadrilaminata* Okada and McIntyre, 1977
- Cryptococcolithus takayamae* Gartner, 1992
- Cyclicargolithus floridanus* (Roth and Hay, 1967) Bukry, 1971
- Cyclococcolithus cricotus* Gartner, 1967
- Cyclolithella annula* (Cohen, 1964) Boudreaux and Hay, 1969
- Dictyococcites antarcticus* Haq, 1976
- Dictyococcites productus* (Kamptner, 1963) Backman, 1980
- Discoaster adamanteus* Bramlette and Wilcoxon, 1967
- Discoaster asymmetricus* Gartner, 1969
- Discoaster berggrenii* Bukry, 1971
- Discoaster blackstockae* Bukry, 1973
- Discoaster brouweri* Tan, 1927
- Discoaster challengerii* Bramlette and Riedel, 1954
- Discoaster deflandrei* Bramlette and Riedel, 1954
- Discoaster druggii* Bramlette and Wilcoxon, 1967
- Discoaster exilis* Martini and Bramlette, 1963
- Discoaster formosus* Martini and Worsley, 1971
- Discoaster intercalaris* Bukry, 1971
- Discoaster loeblichii* Bukry, 1971
- Discoaster moorei* Bukry, 1971
- Discoaster neohamatus* Bukry and Bramlette, 1969
- Discoaster neorectus* Bukry, 1971
- Discoaster pansus* (Bukry and Percival, 1971) Bukry, 1973
- Discoaster pentaradiatus* Tan, 1927
- Discoaster quadramus* Bukry, 1973
- Discoaster quinquerramus* Gartner, 1969
- Discoaster surculus* Martini and Bramlette, 1963
- Discoaster tamalis* Kamptner, 1967
- Discoaster triradiatus* Tan, 1927
- Discoaster variabilis* Martini and Bramlette, 1963
- Discolithina discopora* (Schiller, 1925) = *Pontosphaera discopora* Schiller, 1925
- Discolithina indoceanica* (Cepek, 1973) = *Pontosphaera indoceanica* Cepek, 1973
- Discolithina japonica* Takayama, 1967
- Discolithina multipora* Kamptner, 1948
- Discolithina rimosa* Bramlette and Sullivan, 1961
- Discolithina scutellum* (Kamptner, 1952) = *Pontosphaera scutellum* Kamptner, 1952
- Discolithina syracusana* (Lohmann, 1902) = *Pontosphaera syracusana* Lohmann, 1902
- Discosphaera tubifer* (Murray and Blackman, 1898) Ostenfeld, 1900
- Emiliana huxleyi* (Lohman, 1902) Hay and Mohler, 1967
- Florisphaera profunda* Okada and Honjo, 1973
- Gephyrocapsa caribbeanica* Boudreaux and Hay, 1969
- Gephyrocapsa marginellii* Breheret, 1978
- Gephyrocapsa muelleriae* Breheret, 1978
- Gephyrocapsa oceanica* Kamptner, 1943
- Hayaster perplexus* (Bramlette and Ridel, 1953) Bukry, 1973
- Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954
- Helicosphaera euphrates* Haq, 1966
- Helicosphaera hyalina* Gaarder, 1970
- Helicosphaera inversa* Gartner, 1980
- Helicosphaera obliqua* (Bramlette and Wilcoxon, 1967)
- Helicosphaera orientalis* Black, 1971
- Helicosphaera parallela* (Bramlette and Wilcoxon, 1967)
- Helicosphaera sellii* Bukry and Bramlette, 1969
- Helicosphaera wallichi* (Lohmann, 1902) Boudreaux and Hay, 1969
- Holodiscolithus macroporus* (Deflandre, 1954) Roth, 1970
- Oolithotus antillarum* (Cohen, 1964) Reinhardt, 1968
- Oolithotus fragilis* (Lohmann, 1912) Martini and Mueller, 1972
- Pseudoemiliana lacunosa* (Kamptner, 1963) Gartner, 1969
- Reticulofenestra minuta* Roth, 1970
- Reticulofenestra minutula* (Gartner, 1967) Haq and Berggren, 1978
- Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969
- Rhabdosphaera claviger* Murray and Blackman, 1898
- Rhabdosphaera longistylis* Schiller, 1925
- Rhabdosphaera procera* Martini, 1969
- Rhabdosphaera stylifer* Lohmann, 1902
- Scapholithus fossilis* Deflandre, 1954
- Scyphosphaera apsteinii* Lohmann, 1902
- Scyphosphaera pulcherrima* Deflandre, 1942
- Sphenolithus abies* Deflandre, 1954
- Sphenolithus moriformis* (Bronnimann and Stradner, 1960) Bramlette and Wilcoxon, 1967
- Syracosphaera binodata* Kamptner, 1937
- Syracosphaera histrica* Kamptner, 1941
- Syracosphaera lamina* Lecal-Schlauder, 1951
- Syracosphaera nodosa* Kamptner, 1941
- Syracosphaera pulchra* Lohmann, 1902
- Thoracosphaera fossata* Jafar, 1975
- Thoracosphaera hemii* (Lohmann, 1919) Kamptner, 1941
- Thoracosphaera saxea* Stradner, 1961
- Thorosphaera flabellata* Halldal and Markali, 1955
- Triquetrorhabdulus rugosus* Bramlette and Wilcoxon, 1967
- Umbilicosphaera dilatata* Kamptner, 1963
- Umbilicosphaera hulburtiana* Gaarder, 1955
- Umbilicosphaera lexis* (Kamptner, 1963) = *Tiarolithus laxus* Kamptner, 1963
- Umbilicosphaera sibogae* (Weber-van Bosse, 1901) Gaarder, 1970
- Umbellosphaera irregularis* Paasche, 1955
- Umbellosphaera tenuis* (Kamptner, 1937) Paasche, 1955

Table 3. Calcareous nannofossil biohorizons, Sites 812–818.

Biohorizon	Age (Ma)	Hole 812A Depth (mbsf)	Hole 812C Depth (mbsf)	Hole 813A Depth (mbsf)	Hole 814A Depth (mbsf)	Hole 815A Depth (mbsf)	Hole 816A Depth (mbsf)	Hole 817A Depth (mbsf)	Hole 818B Depth (mbsf)
<i>Emiliana huxleyi</i> LO	0.275	2.67		2.63	4.12	1.1	0.37	25.07	9.53
<i>Pseudoemiliana lacunosa</i> HO	0.465	7.52		9.83	10.01	4.1	1.87	28.07	14.03
small <i>Gephyrocapsa</i> Acme top	0.93	17.02		23.82	21.01	13.9	4.87	45.56	53.51
small <i>Gephyrocapsa</i> Acme bottom	1.1					17.4		51.56	
<i>Helicosphaera sellii</i> HO	1.27					18.9			
<i>Calcidiscus macintyreii</i> HO	1.48	23.9	*23.27–24.77	33.32	29.01	20.4	9.62	63.06	80.51
<i>Gephyrocapsa oceanica</i> s.l. LO	1.59							72.56	
<i>Discoaster brouweri</i> HO	1.88		25.9	39.81	33.51	24.9	12.62	72.56	84.58
<i>Discoaster pentaradiatus</i> HO	2.29	*25.96–27.90	*26.85–29.0	52.31	41.51	31.4	15.18	72.56	84.58
<i>Discoaster surculus</i> HO	2.42			53.81	44.51	36.4	17.62	72.56	106.01
<i>Discoaster asymmetricus</i> HO	2.42								
<i>Discoaster tamalis</i> HO	2.6			57.31	52.51	44.72	19.12	75.56	177.02
<i>Discoaster variabilis</i> HO	2.9								
<i>Sphenolithus abies</i> HO	3.45	*29.26–35.40		79.31	66.83	116.91	43.5	155.7	246.08
<i>Reticulofenestra pseudoumbilicus</i> HO	3.51		53.61	80.81		158.9	76.11	155.7	259.51
<i>Pseudoemiliana lacunosa</i> LO	4.21					309.46		161.06	
<i>Amaurolithus tricorniculatus</i> HO	4.24					309.46		161.06	
<i>Ceratolithus armatus</i> HO	4.6					326.35			
<i>Amaurolithus tricorniculatus</i> LO	4.7					331.61		176.7	
<i>Ceratolithus rugosus</i> LO	4.72							176.7	
<i>Ceratolithus armatus</i> LO	5.06					351			
<i>Discoaster quinqueramus</i> HO	5.26		85.61	99.81	76	354		180.07	
<i>Amaurolithus amplifucus</i> HO	5.6					378.54		186.07	
<i>Discoaster berggrenii</i> HO	5.8					377.04		189.57	
<i>Amaurolithus amplifucus</i> LO	5.9					387.3		195.57	
<i>Amaurolithus primus/A. delicatus</i> LO	6.74					409.36		200.56	

* Core loss. LO = lowest occurrence; HO = highest occurrence.

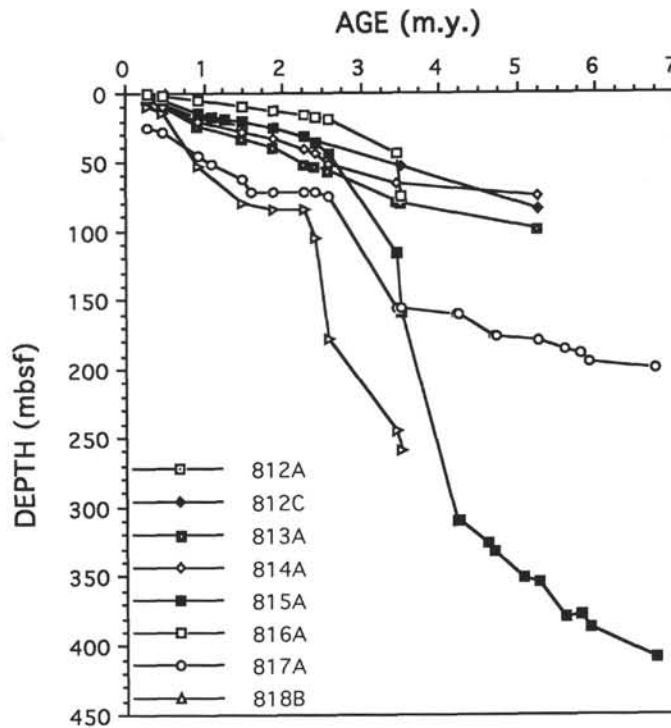


Figure 12. Plots of age vs. depth for all sites from the southern transect of Townsville Trough.