# 5. CENOZOIC CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY FROM THE NORTH-EASTERN ATLANTIC OCEAN-DEEP SEA DRILLING PROJECT LEG 811

Jan Backman, University of Stockholm<sup>2</sup>

## ABSTRACT

Using calcareous nannofossils, a biostratigraphic analysis of sedimentary sequences drilled during Leg 81 reveals continuous upper Neogene deposition at all sites, except at Site 555 where the Pliocene is missing. The series of Pliocene discoaster disappearances are practically synchronous with their low latitude extinctions. An exception is Discoaster surculus which disappears at the initiation of ice-rafted deposition, 0.1 m.y. prior to its extinction age; D. pentaradiatus disappears at the beginning of the second lowest cycle of ice rafting, very close to its extinction age. The onset of ice rafting is an abrupt event, which reflects the initiation of major northern European glaciation at 2.4 m.y. ago.

The lower and middle Miocene sequences are poorly represented, except at Site 555 which shows an expanded and continuous middle Miocene sequence. Site 554 shows the longest Oligocene sequence, but it is condensed (11.5 m) and probably marred by hiatuses. Manganese formation took place during the early Oligocene (Hole 552A) and during the Eocene at Site 554 (overlain by upper Eocene). The upper and middle Eocene intervals are poorly represented; for example, the Chiasmolithus gigas subzone (Subzone CP13b or Zone NP15) is only present in a single 2-cm thick horizon (Hole 552A). Site 552 shows the most complete record of the Eocene Zones NP11 through NP14, whereas Zone NP10 is considerably expanded at Sites 553 and 555. Definite upper Paleocene (Zone NP9) is only recovered at Site 555, where this sequence is interbedded between two basalt piles.

## INTRODUCTION

Eight holes at four sites were drilled at the southwest margin of the Rockall Plateau in the northeast Atlantic Ocean during Leg 81 of the Deep Sea Drilling Project. Site locations are shown in Figure 1. The sediments recovered yielded Pleistocene through upper Paleocene calcareous nannofossils, and their distribution is presented from selected samples in Tables 1-8. Approximately 1200 samples were investigated. The upper Neogene and lower Eocene reflect virtually continuous deposition, whereas only fragments of the intervening intervals are preserved. Therefore the Neogene and Paleogene sequences are presented and discussed separately. The distribution of taxa is presented through qualitatively estimated relative abundances. The Neogene tables show three levels of relative abundance: filled circles represent an abundance in excess of 10% of the total assemblage; open circles represent an abundance between 1 and 10%; crosses represent an abundance less than 1% of the total assemblage.

Smear slides made from the lower Eocene and upper Paleocene shelf sediments contain, as a rule, very low abundances of coccoliths. In many samples considerable difficulties were met in finding enough specimens to estimate relative abundances, and in many other samples this estimate turned out to be completely meaningless. Because consistent estimates of relative abundances could not be successfully achieved, Paleogene abundances are shown either as "rare" (open squares) or "more commonly occurring" (filled squares). Oligocene



Figure 1. Locations of sites drilled during Leg 81 (Sites 552-555), Leg 48 (Sites 403-404), and Leg 12 (Site 117).

and upper-middle Eocene assemblages are incorporated in this system for internal consistency in the tables, although the way of representing abundances in the Neogene samples could have been applied at several sample levels.

## ZONATION

Previous studies of calcareous nannofossil biostratigraphy from the Rockall area include those of Perch-Nielsen (1972) and Müller (1979). These authors, as well as the present one, have predominantly relied on biostratigraphic zonations suggested by Martini (1971), Bukry (1973, 1975), and Okada and Bukry (1980). Their zonal schemes primarily reflect stratigraphic relationships of exits and entries of species in tropical and subtropical areas. As a consequence some stratigraphic in-

<sup>&</sup>lt;sup>1</sup> Roberts, D. G., Schnitker, D., et al., Init. Repts. DSDP, 81: Washington (U.S. Govt. Printing Office). <sup>2</sup> Address: Department of Geology, University of Stockholm, S-106 91 Stockholm, Swe-

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tervals at the Rockall sites, hosting temperate surface waters, are characterized by a reduced biostratigraphic resolution or by an absence of marker fossils. The Paleocene/Eocene boundary and the lowest Eocene, the upper Oligocene, the middle Miocene, and the lower Pliocene represent such intervals.

Fasciculiths in co-occurrence with Discoaster multiradiatus are used to denote Zone NP9 of the upper Paleocene (Lowrie et al., 1982; Shackleton et al., 1984a), and the boundary between Zones NP10 and NP11 is drawn at the entry of Tribrachiatus orthostylus (Lowrie et al., 1982). Triquetrorhabdulus carinatus and Cyclicargolithus abisectus are used to mark the base of Zones NP25 and NP24, respectively (Müller, 1979). The Neogene/Paleogene boundary (Zones NN1/NP25) is placed at the extinction of Dictyococcites bisectus, in accord with Bukry's (1973) suggestion. Distinction is made between Zones NN6 and NN7 based on the extinctions of C. abisectus and C. floridanus (Müller, 1981). Zones NN8 and NN9 are separated on the basis of the extinction of Coccolithus miopelagicus (Bukry, 1973). To date there are no obvious auxiliary markers that can be used for reliable subdivisions of the lower Pliocene in the Rockall area.

# PRESERVATION

All sites were drilled in moderately deep waters. As a rule the Neogene assemblages show varying degrees of overgrowth of secondary calcite. Dissolution has affected the Neogene assemblages at some levels within the Pleistocene and upper Pliocene sequences in conjunction with intense ice-rafted deposition. Samples taken within a few centimeters of the upper and middle Miocene hiatuses commonly show dissolved assemblages. The condensed Paleogene chalk sequences generally show dissolution, together with some diagenetic overgrowth of calcite. For example, whereas the chiasmoliths were dissolved (central area crosses missing), specimens of Isthmolithus recurvus generally appeared as more or less solid bars. The lower Eocene and upper Paleocene assemblages are primarily affected by dissolution, although diagenetic calcite also played a role in destroying primary morphological features.

## SITE SUMMARIES

## Site 552

Two holes (Holes 552 and 552A) were drilled at Site 552 ( $56^{\circ}02.56'N$ ,  $23^{\circ}13.88'W$ , water depth: 2301 m). Hole 552A was hydraulically piston cored, whereas Hole 552 was drilled with the conventional rotary drill equipment. The first three cores of Hole 552 were spot cored at 0, 51, and 108 m respectively, whereafter the hole was continuously cored. Despite being drilled at the same locality, there is a depth discrepancy between the two holes. Correlatable bio- and lithostratigraphic horizons are located deeper in Hole 552A. The difference ranges between approximately 8.4 and 12.4 m. Taking into consideration that the individual drilling pipe length is 9.0 m (9.5 m with the core catcher), it is possible that a single pipe was unac-

counted for during the spot coring of the upper part of Hole 552.

The overlapping sequences of the two holes show practically identical nannofossil assemblages, so the distribution of the Pleistocene through Miocene taxa are shown from Hole 552A (Table 2) because that sequence has a better recovery and shows less drilling disturbance than Hole 552. The Neogene-Paleogene transition is discussed below and presented in Figure 2. Table 1 summarizes the distribution of Eocene taxa from Hole 552.





## The Neogene of Hole 552

Core 1 of Hole 552 shows an upper Pleistocene assemblage, lacking Pseudoemiliania lacunosa but with abundant small (<3  $\mu$ m) placoliths, which are interpreted as Emiliania huxleyi. The boundary between Zones NN15 and NN16 is present between 48 and 100 cm in Section 552-2-1, with common Reticulofenestra pseudoumbilica at the deeper level. Typical Pliocene discoasters occur throughout Core 552-2, including Discoaster brouweri, D. pentaradiatus, and D. surculus; D. asymmetricus is present in Sample 552-2, CC but not in Sample 552-2-1, 100 cm. The reverse relationship is true for P. lacunosa, which is present in Sample 552-2-1, 100 cm but not in the core catcher. Comparison with Hole 552A (see below and Figure 5) suggests that the depth discrepancy between Holes 552 and 552A is above the extinction level of R. pseudoumbilica.

The range of D. quinqueramus defines Zone NN11, and this species was observed in very low numbers in Samples 552-3-1, 11 cm and 552-3, CC. Zone NN11 continues down to Sample 552-7-1, 143 cm. Ceratoliths were observed at one level in this interval, namely in Sample 552-4, CC where Amaurolithus primus and A. tricorniculatus co-occur. Sample 552-7-1, 37 cm contains Pliocene contaminants; both Ceratolithus rugosus and D. tamalis are present, although the assemblage has a predominantly Miocene character. Zone NN9 can seldom be identified with accuracy at high latitudes in the North Atlantic because D. hamatus is exceedingly rare or absent. Consequently the base of Zone NN10 is difficult to identify with precision. However, Bukry's (1973 and subsequent) zonal and subzonal marker species in this part of the stratigraphic column do appear with some regularity in the Rockall area. One of these markers is D. loeblichii, which is present from Sample 552-7-1, 143 cm to Sample 552-7-4, 19 cm. The species indicates the Discoaster neorectus subzone, which compares with the upper part of Zone NN10. Discoaster bellus is present in Sample 552-7,CC, suggesting a Zone NN9-NN10 assignment for this level. The disappearance of Coccolithus miopelagicus is a consistent and comparatively distinct datum event in the Rockall area. According to Bukry (1973) it occurs within Zone NN8. In Hole 552 this event occurs at Sample 552-8-1, 110 cm, where Cyclicargolithus abisectus is also present in low numbers, possibly indicating Zone NN6 (Müller, 1981). Reworking of C. abisectus into the upper part of Core 552-8 cannot be excluded, because it is not accompanied by C. floridanus.

Zone NN5 with its diagnostic species Sphenolithus heteromorphus can be observed from Sample 552-8-3, 20 cm to the Neogene-Paleogene transition at Sample 552-8-4, 45 cm, which is marked by a lithologic change and a hiatus. The occurrence of glauconite in the Miocene part of Core 552-8 may indicate that this interval is condensed, but it has not been possible to determine whether, above Zone NN5, the NN6-NN8 interval is reduced or condensed. The nannofossils in the zeolitic nannofossil chalk underlying the indigenous Miocene sediments in Core 552-8 (Sample 552-8-4, 45-85 cm)

represent a mixture of Miocene, Eocene, and probably Oligocene forms. This stratigraphic transition is described in detail below (see Hole 552A).

## The Paleogene of Hole 552

The Miocene element between 45 and 85 cm in Section 552-8-4 originates from the overlying Zone NN5, whereas the Paleogene element represents a mixture of primarily Eocene forms, which are derived from different stratigraphic levels within the Eocene. The preservation is generally bad in this interval, showing both severe dissolution and secondary overgrowth of calcite.

A major part of the lower Eocene and the lowest part of the middle Eocene is represented between the sediment/basalt contact and the Neogene-Paleogene transition in Hole 552 (Table 1). This part of the sequence is more complete at Site 552 as compared to the corresponding sequences at the adjacent Site 403 of Leg 48 and Sites 553, 554, and 555 of Leg 81, although it is conceivable that the sequence at Site 552 may also be incomplete.

Zone NP14 is represented from Sample 552-8,CC to Sample 552-10,CC (Core 552-11 and its core catcher were empty). Chiasmoliths and the ubiquitous *Coccolithus pelagicus* dominate the assemblages, together with *Reticulofenestra dictyoda* at some levels. *Discoaster sublodoensis* occurs in all samples in this interval. The presence of *Nannotetrina cristata* throughout the interval indicates that only the upper part of Zone NP14 is represented between Samples 552-8,CC and 552-10,CC (see Bramlette and Sullivan, 1961; Romein, 1979). This is supported by the absence of *D. lodoensis* in the uppermost sample (Sample 552-8,CC). It is not clear whether the lower part of Zone NP14 is missing at Site 552 or whether it is represented by the underlying interval of no recovery.

The assemblage in Zone NP13 differs from that in Zone NP14 by showing a comparatively higher abundance and a greater diversity of pontosphaerids. This feature also characterizes Zones NP12 and NP11 (see also Sites 553 and 555). Similar abundance and diversity patterns of the pontosphaerids, particularly as concern Zone NP12, have been documented by Bramlette and Sullivan (1961) from the Lodo Formation in California, by Okada and Thierstein (1979) from Deep Sea Drilling Project (DSDP) Site 386 (western North Atlantic), and by Romein (1979) from the Nahal Advat sequence in Israel.

Only one section in Core 552-13 was filled with sediment, and samples from this section were barren of nannofossils. Samples from Core 552-14 show poorly preserved assemblages, affected both by dissolution and diagenetic overgrowth of calcite. Arguments can be raised for placement of the lower boundary of Zone NP13 at two levels: within Section 552-14-2 or between Sections 552-15-1 and 552-16-1.

The guide species, *Tribrachiatus orthostylus*, is present as a very rare component of the assemblage at Sample 552-14-2, 56-58 cm. This level represents the uppermost occurrence of *T. orthostylus* and thus should be considered as the top of Zone NP12, an assignment not dis-

# Table 1. Distribution of Paleogene calcareous nannofossils at Hole 552.

Epoch	Zone (Okada & Bukry, 1980)	Zone (Martini, 1971)	Sample (552 core-section, cm)	Abundance Preservetion	Braarudosphaera bigelowii B. discula Campylosphaera dela	Chiasmolithus californicus C. consuetus	C. eograndis C. expansus	L. grandis L. solitus Loccolithus crassus	C. cribellum r formosus	<ul> <li>C. pelagicus</li> <li>Cyclicargolithus pseudogammation</li> </ul>	Cyclolithella spp. Discoaster barbadiensis	D. binodosus D. diastypus D. distinctus	D. gemmifer	D. lodoensis D. martinii	D. nonaradiatus D. robustus	D. septemradiatus D. strictus	U. sublodoensis Ellipsolithus macellus Helicosphaera lophota	H. seminulum Imperiaster obscurus Lattacrites minutus	Lainneine minuus Lopadolithus nascens Markalius spp.	Micrantholithus spp. Nannotetrina cristata	Neochiastozygus junctus Neococcolithes dubius N protenus	Pontosphaera duocava P. exilis	P. fimbriata P. panarium P. partinata	P. plana P. pulcheroides	P. pulchra P. rimosa P. veren	Prinsius bisulcus Reticulofenestra dictyoda	R.minuta Rhabdosphaera crebra R.truncata	Sphenolithus anarrhopus S. moriformis S. radians	Towerus magnicrassus T. occultatus	Tribrachiatus orthostylus Zygodiscus plectopons Zygrhablithus bijugatus
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Note: Open squares = rare, filled squares = more commonly occurring.

agreeing with the magnetostratigraphy. Core 552-14 is characterized by normal polarity (Krumsiek, this volume), which probably represents magnetic Anomaly 23. T. orthostylus disappears within Anomaly 23 according to Lowrie et al. (1982), which justifies a top Zone NP12 assignment at Sample 552-14-2, 56-68 cm, but it should be kept in mind that Cores 552-15 and 552-16 have a recovery of 14 and 11% respectively, and do not preserve any known magnetic polarity direction. These cores consequently also may fit the correlation between Anomaly 23 and the T. orthostylus extinction. Unfortunately, the isolated occurrence of T. orthostylus in Section 552-14-2 cannot, at least with any degree of certainty, be disregarded as due to reworking since (1) one may assume that ecological gradients have been strong in the shallow-water environment in which these sediments were deposited, thus providing conditions that could favor sporadic occurrences of many taxa; (2) isolated, apparently indigenous, occurrences of taxa are not uncommon (see, for example, the lowest and next to lowest occurrence of D. lodoensis in Table 1); (3) reworking appears not to be significant in the sequence. The occurrence of T. orthostylus at Section 552-14-2 thus may represent an indigenous presence.

Another line of reasoning suggests that placing the top of Zone NP12 within Section 552-14-2 would be erroneous. The first appearance of R. dictyoda was observed in Sample 552-14-4, 25-26 cm. Based on material from the very adjacent Site 404, which shows a sequence and a nannofossil assemblage highly comparable to that of Hole 552, Müller (1979) observed that R. dictvoda (referred to as R. umbilica) has its first appearance close to the base, but within, Zone NP13. Her result is in perfect agreement with that of Romein (1979). Placing the Zone NP12/Zone NP13 boundary within Section 552-14-2 thus implies that R. dictyoda appears within Zone NP12, which is inconsistent relative to Müller's and Romein's results. The uppermost continuous presence of T. orthostylus is in Section 552-16-1, which could justify a placement of the Zone NP12/Zone NP13 boundary between Sections 552-15-1 and 552-16-1 and which would cause a consistent first appearance of R. dictyoda close to the base of Zone NP13. The two possible positions of the Zone NP12/Zone NP13 boundary at Site 552 are indicated in Table 1. Interestingly, the base of Bukry's (1973) Zone CP11 (first appearance of C. crassus) coincides with the base of Martini's Zone NP13 if placed between Sections 552-15-1 and 552-16-1.

Several changes occur in the assemblage between Zone NP13 and Zone NP12. The latter zone shows the following characteristics: a downward increase in braarudosphaerids; a decrease in the diversity of chiasmoliths; *C. eograndis* becoming the most frequently occurring chiasmolith taxon; *C. cribellum* is common at some levels and is one of the dominant taxa in one sample; micrantholiths, fragments mostly, start to occur; sphenoliths begin to occur consistently, including *Sphenolithus anarrhopus* which has its highest occurrence in this zone (at this site); *Zygodiscus plectopons* is restricted to this zone at Site 552; *Zygrhablithus bijugatus* becomes one of the major elements of the assemblages; *Toweius occultatus* disappears at the top part of the zone; *Prinsius bisulcus* decreases significantly in abundance, and last, a few specimens of the distinct species D. robustus were noted for the first time, going downwards, toward the base of Zone NP12.

An unchanged assemblage character of Zone NP12, as compared to that of Zone NP13, is that *D. kuepperi* remains the most abundant discoaster.

Zone NP11 is not used in the sense of Martini's original definition since its base here is defined by the first appearance of Tribrachiatus orthostylus, following the suggestion by Lowrie et al. (1982). T. orthostylus is present in Sample 552-21-3, 39 cm but was not observed, even after long search, in a sample taken 5 cm above the sediment/basalt contact in Sample 552-21-3, 65 cm. The last occurrences of Toweius magnicrassus and Ellipsolithus macellus coincide with the first appearance of Tribrachiatus orthostylus in Sample 552-21-3, 39 cm. The implication of this in relation to the relative age of the sediment/basalt contact is discussed below, where it is concluded that it seems likely that the contact occurs within, but close to the base of, Zone NP11 as defined here, despite the absence of T. orthostylus at the 60-cm level in Section 552-21-3. However, two possible interpretations are indicated in Table 1.

## The Neogene of Hole 552A

The greater part of the sequence from Hole 552A is unique in that it preserves the most complete and least disturbed upper Neogene sedimentary record ever retrieved from a high-latitude North Atlantic DSDP site. This sequence consequently provides the best material premises from that region for studies of late Neogene paleoceanography and paleoclimatology. Only two cores are severely disturbed (Cores 552A-6 and 552A-13). No hiatuses were discovered above Core 552A-35 (lowest lower Miocene), but the resolution decreases below Core 552A-29 owing to low sedimentation rates. A remarkable character of the sequence is its long record of northern European glacials-interglacials, including the transition from preglacial to glacial conditions. The record of ice-rafted material of the Rockall area represents a direct evidence of past ice ages in northern Europe. Studies of this sequence therefore will improve our understanding of how, more or less, indirect indications of paleoclimatic and paleoceanographic changes-like stable isotopes, faunal and floral paleobiogeographic patterns, and sedimentary processes such as winnowing, erosion, and dissolution-are related to the glacial-interglacial climatic system in northern Europe. This is particularly true for the Pliocene part of the Hole 552A sequence since there exists a controversy, or confusion, about the timing of the initial phase of the glacial evolution in the northern hemisphere. Moreover, at present there is little consensus about which paleoceanographic changes represent responses to the northern hemisphere glacial-interglacial system and which changes represent responses to other phenomena; the time interval between 2.5 and 3.2 m.y. ago is of particular interest in this respect (see, for example, Berggren, 1972; Poore and Berggren, 1974; 1975; Shackleton and Kennett, 1975a; Shackleton and Opdyke, 1977; Ledbetter et al., 1978; Backman, 1979; Keigwin and Thunell, 1979; Shor and Poore, 1979; Hodell et al., 1983). This chapter is focused on the biostratigraphy of Leg 81, and the Hole 552A sequence thus is discussed primarily from a biostratigraphic and chronologic point of view.

The samples from Hole 552A shown in Table 2 represent only a fraction of the number of samples investigated from that sequence. However, those shown illustrate time-related changes in the assemblages. It appears immediately from Table 2 that the qualitatively estimated abundances in each sample are characterized by a few dominant taxa, which are accompanied by a number of rare taxa (<1%). Individual discoaster species consistently occupy less than 1% of the total assemblage, but on the generic level discoasters may reach 1– 2% of the assemblage in the occasional sample.

The oxygen isotope stratigraphy of Hole 552A (Shackleton and Hall, this volume) presents a very refined chronostratigraphy for the Pleistocene sequence. Two reliable nannofossil events in the Pleistocene can be determined using light-microscope techniques: the last occurrences of *Pseudoemiliania lacunosa* and *Calcidiscus macintyrei*. Both events have been quantified using the methodology of Backman and Shackleton (1983).

The extinction of *P. lacunosa* is shown in Figure 3, together with the calcium carbonate percentages. It is evident that the abundance pattern of *P. lacunosa* varies independently of the calcium carbonate record. The extinction at Sample 552A-2-3, 60 cm occurs in the middle



Figure 3. Abundance of *P. lacunosa* at the time of extinction. Note that there is no correlation between calcium carbonate percentage (Zimmerman, this volume) and *P. lacunosa's* abundance. Oxygen isotope stages are from Shackleton and Hall (this volume).

part of oxygen isotope Stage 12, which is in excellent agreement with the results of Thierstein et al. (1977). It is notable, however, that although these authors documented a relative abundance of approximately 0.5% of P. lacunosa in K708-7 immediately prior to its extinction, the figure is much lower in the Hole 552A sequence. Hole 552A is only about two degrees latitude north of K708-7. Percentages of P. lacunosa have not been determined from Hole 552A, but it can be estimated that 10 specimens of P. lacunosa in Figure 3 grossly represent a few per thousand of the total assemblage: the content of 20 view fields was counted in each sample and approximately 200 nannofossil specimens were present in each view field. Thus, for reasons unknown, P. lacunosa is considerably less abundant at Hole 552A than at K708-7 near its extinction level.

The last occurrence of *Helicosphaera sellii* is in Sample 552A-5,CC. Backman and Shackleton (1983) demonstrated that this species has a diachronous disappearance with latitude. Its last occurrence is not examined in detail in Hole 552A, but nevertheless, it is later in Hole 552A than in the equatorial Pacific. There appears to be a difference of several hundred thousand years between the Pacific date (1.37 m.y. ago in V28-239) and the one from Hole 552A (0.93-1.17 m.y. ago; Samples 552A-4,CC to 552A-5,CC).

The last occurrence of *C. macintyrei* is shown in Figure 4, where the calcium carbonate record is also presented. The species disappears within an interval characterized by high calcium carbonate values, that is, within an interglacial. This suggests that the disappearance of *C. macintyrei* in Section 552A-7-1 is the true extinction. The rise in abundance at the bottom of Section 552A-7-1 coincides with an increased percentage of calcium carbonate. From the bottom of Section 552A-7-2



Figure 4. Abundance of *C. macintyrei* at the time of extinction. See text for discussion of co-variation between calcium carbonate percentage (Zimmerman, this volume) and abundance of *C. macintyrei*.

upwards, the abundance of C. macintyrei and the calcium carbonate values decrease significantly although the high carbonate percentage persists up to one sample interval (10 cm) above the high abundance interval of C. macintyrei. The lag may be due either to a sample position bias or to an ecologically governed behavior of C. macintyrei at the transition from interglacial to glacial (cooling of surface waters precedes the short glacial starting at Sample 552A-7-2, 120 cm?). The high calcium carbonate values between approximately 60 and 80/ 90 cm in Section 552A-7-2 are not accompanied by an increase in abundance of C. macintyrei. However, the 60-, 70-, and 80-cm levels in Section 552A-7-2 are characterized by a virtually monospecific assemblage of C. pelagicus. This very characteristic monospecific composition was also observed at the outskirts of other glacial intervals. The phenomenon has not been systematically investigated.

Little attention has been paid to the series of first appearances of gephyrocapsids (*Gephyrocapsa aperta, G. caribbeanica*, and *G. oceanica*) during late Pliocene and early Pleistocene times. Samtleben (1980) demonstrated convincingly that a thorough morphometrical investigation of gephyrocapsids from many oceanic regions is needed before the group can provide any reliable biostratigraphic information.

The series of disappearances of Pliocene discoasters, a warm(er)-water-preferring group, has been investigated in detail, partly because it is not fully understood whether these disappearances reflect migratory events or genuine extinctions in the high-latitude North Atlantic. The following taxa are involved: *Discoaster brouweri*, and its triradiate variety, *D. pentaradiatus*, *D. surculus*, *D. asymmetricus*, *D. tamalis*, and *D. variabilis*.

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The relative abundances of these discoasters are very low in the investigated interval (from the lower half of Core 552A-7 through Core 552A-10). Two reasons argue against reworking as being the mechanism that explains the presence of discoasters in the late Pliocene interval.

First, discoasters are rare throughout the Neogene which implies that a considerable amount of pre-late Pliocene sediment has to be reworked into the late Pliocene interval in order to get reworked discoasters. Only negligible amounts of pre-late Pliocene contaminants are present in the late Pliocene interval; for example Reticulofenestra pseudoumbilica, which has a late early Pliocene extinction datum and is very abundant through much of the Neogene, is very rare in the late Pliocene (Fig. 5). On this basis, little reworking of pre-late Pliocene material into the late Pliocene is considered to have occurred. Second, Backman and Shackleton (1983) documented a rise in abundance of the triradiate variety of D. brouweri relative to D. brouweri; a peak abundance lasting approximately 0.1-0.15 m.y. before their simultaneous extinction. This increase was found to occur consistently whenever the appropriate stratigraphic interval was investigated in detail. Moreover, the triradiate variety was observed to be rare during the entire part of its range that precedes the last period of peak abundance, despite very high abundances of discoasters. Therefore, the peak abundances of the triradiate variety relative to D. brouweri are considered to be indigenous, because reworking cannot produce peak abundances of this form relative to D. brouweri (Backman and Shackleton, 1983). This characteristic increase of the triradiate variety also exists in the Hole 552A sequence.

It is estimated that, in the late Pliocene interval of Hole 552A, a discoaster/coccolith ratio of 1/10,000 or



Figure 5. Abundance of *R. pseudoumbilica* in Cores 552A-11 through 552A-14. Three samples analyzed from Core 552A-13 revealed an abundance not exceeding that of Cores 552A-11 and 552A-12. The distinct decrease in abundance at the very top of Core 552A-14 is considered to represent the extinction of *R. pseudoumbilica*. Notice low level of reworking in Cores 552A-11 and 552A-12.

1/20,000 is the rule rather than the exception. Because of their very low abundance, discoasters are of course easily overlooked or neglected as being reworked, although they are not, according to the above observations.

Samples were investigated every 10 cm, with the following results: *D. brouweri* disappears at Sample 552A-8-1, 40 cm and the triradiate variety 10 cm higher up. The peak abundance of the triradiate variety begins in the middle part or lower half of Core 552A-8. The last occurrence of *D. pentaradiatus* is at Sample 552A-9-3, 20 cm. At Sample 552A-9-4, 10 cm *D. surculus* disappears; *D. asymmetricus* disappears at Sample 552A-9,CC (1 cm), and *D. tamalis* disappears at Sample 552A-10-1, 20 cm. The highest occurrence of *D. variabilis* is probably situated in the lower part of Core 552A-10, but sporadic occurrences make this difficult to ascertain.

The disappearance of R. pseudoumbilica is the lowermost event that has been quantified in the Hole 552A sequence (Fig. 5). The profound decrease in abundance at the top of Core 552A-14 is interpreted as the extinction level of R. pseudoumbilica. Core 552A-13 is severely disturbed and the sediment is homogenized; a sample from a particular level may represent any level within Core 552A-13. Three samples analyzed from Core 552A-13 did not show an abundance of R. pseudoumbilica exceeding that in Core 552A-12.

Pliocene paleomagnetic reversals of Hole 552A (Shackleton et al., 1984b) and the nannofossil extinction events from C. macintyrei to R. pseudoumbilica are plotted versus time in Figure 6. The age assignments of the extinctions are derived from low and middle lati-

tudes of the Pacific Ocean (Backman and Shackleton, 1983). The disappearance of D. brouweri in Hole 552A correlates well with its extinction date from low latitudes; the same is true for C. macintyrei. Both D. pentaradiatus and D. surculus have disappearance levels in Hole 552A coinciding with transitions from oozes to ice-rafted marls; D. surculus at the beginning of the lowest cycle of ice-rafted debris, and D. pentaradiatus at the beginning of the second cycle. It appears from Figure 6 that the disappearance of D. surculus in Hole 552A clearly occurs close to 0.1 m.y. before its Pacific extinction age. Depending on how the sedimentation rate curve is drawn in Figure 6, D. pentaradiatus either disappears 0.05 m.y. prior to its Pacific date or coincides, approximately, with that date. Backman and Shackleton (1983) did not provide any extinction age for D. asymmetricus, but they suggested that this datum event occurs between the top of Gauss and the base of Olduvai. In Hole 552A, D. asymmetricus disappears between 43.8 and 44.5 m, which is well within the upper Gauss. D. tamalis appears to have a slightly younger disappearance age in Hole 552A than in the low-latitude Pacific. However, the last relatively substantial abundance of D. tamalis is 0.7 m further down in Core 552A-10, and one cannot exclude the possibility that a few stray specimens were reworked up to the last occurrence level shown in Figure 6. If this is the case no difference would exist between the Hole 552A and the Pacific ages. D. variabilis has an indistinct disappearance in the lower part of Core 552A-10.

Surprisingly, one may conclude that the series of late Pliocene discoaster disappearances at this high-latitude locality agrees well with their low- and midlatitude ex-



Figure 6. Sedimentation rate plot of the early Pleistocene and late Pliocene of Hole 552A. The timescale of Ness et al. (1980) is used. The magnetostratigraphy of Hole 552A is from Shackleton et al. (1984b). The plot indicates a significant change in sedimentation rate at 3.25 m.y. ago, where the rate decreases by a factor of approximately 3.5 going upwards. See text for further discussion of the data shown.

tinction ages, although it is far more tedious to determine the extinctions at high latitudes due to low relative abundances.

The last occurrence of nonbirefringent ceratoliths, which defines the top of Zone NN14, cannot be determined accurately at high latitudes because of their discontinuous, extremely rare occurrences. The same problem hampers determination of the top of Zone NN12 (first appearance of C. rugosus). The top of Zone NN13 (first appearance of D. asymmetricus) cannot be determined accurately at any latitude (Backman and Shackleton, 1983). The rare findings of these taxa in Hole 552A are shown in Table 2. The first continuous presence of D. asymmetricus begins at Sample 552A-14-2, 20 cm (note proximity to R. pseudoumbilica extinction), where also the lowest occurrence of D. tamalis was observed. The latter species begins to occur continuously from Sample 552A-14-1, 50 cm, thus shortly overlapping the extinction level of R. pseudoumbilica. This pattern is consistent with that documented from low latitudes (Backman and Shackleton, 1983).

Specimens of C. rugosus were observed at the bottom of Section 552A-19-2, and Ceratolithus acutus is present in Sample 552A-22, CC. Zone NN11 ranges from Core 552A-27 to Core 552A-33. It has not been possible to subdivide this zone in Hole 552A since nonbirefringent ceratoliths were not recorded, in contrast to observations in Hole 552. The lowermost presence of D. quinqueramus is in Sample 552A-33-3, 100 cm, and D. loeblichii and D. neohamatus are present in Sample 552A-33,CC, suggesting that the latter level belongs to Zone NN10. The high abundance of large Dictyococcites perplexus is conspicuous in the Zone NN9-Zone NN10 interval. Previously this species has been reported from high latitudes in the southern hemisphere (Burns, 1975; Haq, 1976-who referred to the species as D. antarcticus) and from the Rockall area (Site 116; Backman, 1980).

Müller (1981) suggested that C. abisectus and C. floridanus disappear within Zone NN6. The absence of these taxa in Sample 552A-35, CC and the presence of C. miopelagicus (see Bukry, 1973) indicate that this level can be referred to Zones NN7 or NN8.

At high latitudes the calcareous nannofossil biostratigraphic resolution is low from the middle Miocene through the lower Pliocene, due to the scarcity of marker fossils. In order to increase the resolution, it appears that one has to make the laborious detour via counts of relative abundances and determination of acme horizons, as outlined by Haq and Lohmann (1976). This requires distinct changes in dominance of assemblage elements over time and well-dated sequences. The most promising assemblage elements in this respect are considered to be *C. pelagicus, D. productus* (Pliocene), *D. perplexus* (Miocene), and the reticulofenestrids.

## The Paleogene of Hole 552A

The Paleogene of Hole 552A is represented from Sample 552A-36-3, 140 cm down to Sample 552A-38,CC (172.9-183.5 m). The Neogene is separated from the Paleogene by a hiatus encompassing the lower Miocene and uppermost Oligocene. Sediment of Oligocene age characterizes lower Core 552A-36 and upper Core 552A-37. Most of Section 552A-37-1 is severely disturbed, partly due to intense burrowing; consequently it is difficult to assign this interval to specific biostratigraphic zones based on primary markers. However, the interval from Section 552A-37-2 to Sample 552A-38,CC contains sediments that belong to Zone NP14 of the middle Eocene. Reworking is common particularly in Section 552A-37-1, in which the stratigraphic order is illogical at some levels, with a sample providing a certain biostratigraphic zonal assignment having a stratigraphically higher position than a sample giving a younger zonal assignment. Thus, detailed stratigraphic analysis is not meaningful in Section 552A-37-1. The stratigraphy of the short Paleogene sequence in Hole 552A is based on 35 samples, but the samples discussed below are those which can be arranged in a logical stratigraphic order (see Fig. 2, where the correlation to Hole 552 is shown).

Sample 552A-36-3, 141 cm and several others down to Sample 552A-36,CC (15 cm) show a virtually uniform composition, in which Cyclicargolithus floridanus, Coccolithus pelagicus, Chiasmolithus altus, Dictyococcites bisectus, D. hesslandii, Reticulofenestra daviesi, and Zygrhablithus bijugatus are dominating elements. Sphenolithus distentus occurs occasionally and in very low numbers. Moreover, Triquetrorhabdulus carinatus is absent and Cyclicargolithus abisectus is common in this sequence except in the lowest sample, in which it is rare. A Zone NP24 assignment therefore appears reasonable for the lowermost part of Core 552A-36 (see Poore et al., 1982; Müller, 1979).

Sample 552A-37-1, 15 cm is taken immediately above a big manganese nodule. Although this level lacks Isthmolithus recurvus, it is otherwise similar in composition to the 55- and 70-cm levels in Section 552A-37-1. Among the most abundant taxa are Chiasmolithus altus, Coccolithus pelagicus, Cyclicargolithus floridanus, D. bisectus, D. hesslandii, Ericsonia fenestrata, R. dictvoda, R. hillae, R. umbilica, and Z. bijugatus. Other taxa occur sporadically (Chiasmolithus oamaruensis, Coccolithus eopelagicus, D. deflandrei, E. subdisticha, Helicosphaera bramlettei, and S. moriformis). One specimen of C. formosus (extinction defines Zone NP21/Zone NP22 boundary) was observed in both the 15- and 70cm levels, but not at the 55-cm level, in Sample 552A-37-1. This exceedingly rare presence is likely to represent reworking and is therefore neglected. The late Eocene discoasters were not observed.

Bukry (1975) demonstrated that *I. recurvus* shows a preference for mid to high latitudes, suggesting that its presence in Samples 552A-37-1, 55 cm and 552A-37-1, 70 cm is indigenous. There exists some uncertainty as to the upper stratigraphic range of *I. recurvus*, but studies from high latitudes in the North Atlantic region (Martini, 1971; Perch-Nielsen, 1972; Müller, 1979) indicate that *I. recurvus* disappears within Zone NP22. Taking this into account, it appears reasonable to suggest that (1) Sample 552A-37-1, 15 cm belongs to the upper part of Zone NP22 (*R. umbilica* is present, *I. recurvus* is absent), (2) the 55- and 70-cm levels in Section 552A-37-1

Table 2. Distribution of Neogene calcareous nannofossils at Hole 552A.

Note: filled circles = abundance > 10% of total assemblage, open circles = abundance 1-10% of total assemblage, crosses = abundance < 1% of total assemblage.

represent the lower part of this zone (I. recurvus is present), and (3) the manganese formation took place during the lower part of Zone NP22. A second possibility is provided by the information presented by Poore et al. (1982). Their data-derived from 26°S-suggest that I. recurvus disappears within the upper part of Zone NP21, at the top of magnetic Anomaly 13. This would place the Sample 552A-37-1, 15 cm in Zone NP22 and the samples at the 55- and 70-cm levels in Zone NP21. However, the first possibility, based on data derived from 45-55°N, which is supported by data from Site 554 (see below), indicates that the observation of Poore et al. (1982) is not valid for the high-latitude North Atlantic region. Nevertheless, it follows that Zone NP23, which represents a substantial part of the Oligocene, is missing between Samples 552A-36,CC (15 cm) and 552A-37-1, 15 cm. It is also noteworthy that the manganese nodule was formed at a time characterized by one of the most pronounced reorganizations of deep waters that has occurred in the Cenozoic world ocean (see, for example, Shackleton and Kennett, 1975b).

A downhole change in lithology occurs at approximately Sample 552A-37-1, 75 cm, from foraminifernannofossil chalk to zeolitic mudstone. Two samples from the zeolitic mudstone, Samples 552A-37-1, 86 cm and 552A-37-1, 117 cm, are barren of nannofossils, but a 2-cm-thin band of the foraminifer-nannofossil chalk, Sample 552A-37-1, 137-138 cm, contains nannofossils clearly indicating Zone NP15 of Martini (1971) or subzone CB 13b (C. gigas subzone) of Okada and Bukry (1980). This thin band is the only sediment recovered during Leg 81 that represents the middle Eocene Zone NP15. Typical forms include: Chiasmolithus expansus, C. gigas, Chiasmolithus grandis, C. solitus, Coccolithus pelagicus, C. formosus, D. barbadiensis, Markalius spp., Nannotetrina fulgens, R. dictyoda, R. reticulata, and Rhabdosphaera tenuis.

Zones NP16 through NP19 and NP20, or CP13c through CP15, are missing (through a hiatus) in Hole 552A.

The nannofossils in the sediments from Samples 552A-37-2, 20 cm to 552A-38, CC indicate Zone NP14. Consequently the lowest part of Zone NP15 (CP13a) is also missing in this sequence. Probably only the upper part of Zone NP14 (CP12b, *Rhabdosphaera inflata* subzone of Okada and Bukry, 1980) is represented, since *R. inflata* and *N. cristata* occur sporadically in the sequence, the latter including Sample 552A-38, CC. The assemblage within the Zone NP14 interval of Hole 552A is very similar to the one that is presented in Table 1 from Hole 552.

# Site 553

Three holes were drilled at Site 553 ( $56^{\circ}05.32'$ N; 23°20.61'W; water depth: 2329 m): Hole 553 consists of a single core cut at the mudline; 59 cores were taken at Hole 553A, the upper 37 of which are sedimentary and the remainder of which are basaltic; the four cores of Hole 553B were hydraulically piston cored using the 9-meter core barrel, which unfortunately caused severe disturbance.

# The Neogene of Holes 553, 553A, and 553B

The Neogene cores of Site 553 have two characteristics making them less attractive for study. First, the cores are severely disturbed by drilling processes, including those cored using the hydraulic piston core (HPC) at Hole 553B. Second, a major part of the Neogene sequence was spot cored. The Miocene/Oligocene boundary is determined at 231.5 m, but continuous coring started at a depth of 179.5 m (Core 553A-4). Hole 553B was continuously cored to the terminal depth of 28.5 m, and Cores 553A-1 to 553A-3 begin at depths of 65.5, 103.5, and 151.0 m respectively. The only hiatus detected is in the lower Miocene, where Zones NN2-NN4 are missing. The nannofossil distribution down to Zone NN5 is summarized in Table 3.

Samples 553-1,CC, 553B-1,CC, and 553B-2,CC are referred to the upper Pleistocene (Zones NN20-NN21) owing to the absence of Pseudoemiliania lacunosa. The remaining part of Hole 553B belongs to Zone NN19. Cores 553A-1 and 553A-2 contain an upper Pliocene assemblage, Core 553A-3 a lower Pliocene assemblage, and Cores 553A-4 and 553A-5 are referred to the upper Miocene. Coccolithus miopelagicus has its highest occurrence in Sample 553A-6, CC and co-occurs with C. abisectus in Samples 553A-7,CC and 553A-8-1, 75 cm. In the absence of Sphenolithus heteromorphus, the latter two levels are referred to Zone NN6 (see Bukry, 1973; Müller, 1981). Zone NN5 ranges from Sample 553A-8-2, 75 cm to Sample 553A-8-3, 125 cm. The biostratigraphy of the lowest Miocene (Zone NN1) and the Paleogene is shown in Table 4.

# The Neogene-Paleogene Transition in Hole 553A

Sample 553A-8,CC is the highest sample showing abundant Cyclicargolithus abisectus. Bukry (1973) used this characteristic to subdivide the lowest Miocene. However, C. abisectus shows low frequencies in several samples below its highest peak occurrence, and thus the somewhat vague expression of the C. abisectus acme at Hole 553A must be considered with caution; the possibility is nevertheless indicated in Table 4. The Zone NP25/Zone NN1 (Oligocene/Miocene) boundary is placed at the extinction level of Dictyococcites bisectus. This species decreases in abundance by about 90% from Sample 553A-9-4, 10 cm to Sample 553A-9-4, 5 cm, but continues above as a rare component throughout Core 553A-9. This is compatible with the core's low abundance of some obviously reworked Eocene taxa. Undoubtedly, the extinction of D. bisectus is the most distinct datum event, in terms of abundance prior to extinction, that can be used for consistent recognition of the Oligocene/Miocene boundary in the Rockall area. The rare and sporadic occurrences of Helicosphaera recta (extinction defines top Zone NP25 according to Martini, 1971) within the lowest Miocene may or may not be indigenous. In the light of the reworking observed, the few specimens recorded, and the distinctly expressed D. bisectus' extinction, it is reasonable to neglect these H. recta specimens from a biostratigraphic point of view.

									-																								
Epoch	Zone (Okada & Bukry, 1980)	Zone (Martini, 1971)	Sample (553, 553A, 553B) (core-section, cm)	Abundance	Preservation	Calcidiscus leptoporus	C. macintyrei Coccolithus miopelaaicus	C. pelagicus C. radiatus	Coronocyclus nitescens	Lyciicargoiirnus abisecrus C. floridanus	Uictyococcites hesslandii D. perplexus	D. productus	Discoaster bellus	u. vivuweri D. challengeri	D. deflandrei	D. exilis	U. infercalaris D. neohamatus	D. pentaradiatus	D. surculus	U. variabilis Fmiliania, huvlevi	Geminilithella rotula	Gephyrocapsa spp. Helicosphaera carteri	H. granulata H. intermedia	H. sellii	Pontosphaera japonica P jonesi	Pseudoemiliania lacunosa Dativilofanastra haaii	R. minuta	R. pseudoumbilica	Rhabdosphaera clavigera	Scyphosphaera spp. Sphenolithus heteromorphus	S. moriformis	s neuuves Syracosphaera spp.	Triquetrorhabdulus rugosus Zygrhablithus bijuga tus
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Table 3. Distribution of Neogene calcareous nannofossils at Holes 553, 553A, and 553B.

Note: Filled circles = abundance < 10% of total assemblage, open circles = abundance 1-10% of total assemblage, crosses = abundance > 1% of total assemblage.

Müller (1979) suggested that the first appearance of *Triquetrorhabdulus carinatus* can be used to approximately determine the base of Zone NP25 in the North Atlantic when lacking *Sphenolithus distentus*. In Hole 553A, however, the first appearance of *T. carinatus* occurs immediately above (5 cm) the extinction level of *D. bisectus*, which is used to mark the top of Zone NP25. Taking into account the restricted knowledge we have about how the above-mentioned markers exactly relate to each other stratigraphically in the Rockall area, it is not impossible that the interval from Sample 553A-9A-4, 10 cm to Sample 553A-9A-6, 25 cm represents Zone NP24. This uncertainty is indicated in Table 4.

# The Paleogene of Hole 553A

A hiatus lasting some 10 to 15 m.y. separates the upper Oligocene nannofossil-foraminifer chalk in Sample 553A-9-4, 25 cm from the underlying middle Eocene biosiliceous foraminifer chalk in Sample 553A-9-4, 35 cm. Chiasmoliths are abundant in the underlying middle Eocene interval, notably Chiasmolithus nitidus and C. solitus. Discoaster bifax was observed at two levels within Core 553A-10, and Reticulofenestra umbilica is present from Sample 553A-9-6, 35 cm to Sample 553A-10-3, 100 cm. This interval consequently is referred to Zone NP16 or the Discoaster bifax subzone (CP14a). Markalius spp. (M. astroporus in this case) occurs throughout the interval. According to Okada and Thierstein (1979), M. astroporus disappears in the lowest part of the Discoaster bifax subzone, possibly suggesting that only the lower part of the subzone is represented in this interval. This idea is supported by the fact that the interval is bracketed by hiatuses.

Zone NP15 is missing at Hole 553A, and the entire interval from Zones NP11-NP14 is represented by less than two cores. Nondeposition and/or erosion have probably influenced the sedimentation process in the Zone NP11-Zone NP14 interval, thus preserving only parts of each zone. Discoaster lodoensis occurs throughout Zone NP14 and Nannotetrina cristata is present at the base of the zone, which may suggest that both the uppermost and the lowest parts of this zone are missing (see Site 552). The pontosphaerids begin to increase in abundance and diversity in Zone NP13, although the acme of these fossils occurs in Zone NP12. Prinsius bisulcus decreases in abundance at the top of Zone NP12, and the last occurrence of Toweius occultatus is at the very top of Zone NP12. The first appearance of R. dictyoda occurs in the uppermost sample belonging to Zone NP12. This could imply that reworking has displaced the last occurrence level of Tribrachiatus orthostylus in the Hole 553A sequence. Okada and Thierstein (1979) noticed that the last occurrence of T. orthostylus and the first appearance of R. dictyoda (referred to as R. samodurovii by these authors) coincide at Site 386. Obviously these two datum events virtually coincide over huge geographic distances (Müller, 1979; Okada and Thierstein, 1979; Romein, 1979; this chapter). Presence of T. orthostylus far above the first appearance level of R. dictyoda thus strongly suggests that the former species is reworked. On the other hand, their simultaneous disappearance and appearance may be regarded as a reliable biostratigraphic indication. Bukry (1973) avoided using the last occurrence of *T. orthostylus* in his zonation since he had observed the species as high as Zone NP15 from the Arroy El Bulito sequence in California. This unusually high stratigraphic position of *T. orthostylus* probably can be disregarded as being due to reworking. Unfortunately, this led Bukry to choose the first appearance of *Coccolithus crassus*, which is difficult to identify accurately and thus consistently (the opposite is true regarding both *T. orthostylus* and *R. dictyoda*), to subdivide the interval between the first appearances of *D. lodoensis* (base Zone NP12) and *D. sublodoensis* (base Zone NP14).

It is on the fringe of an understatement to say that T. contortus and T. nunnii are rare in the Hole 553A (and Hole 555) sequence(s). The upper limit of the former and the lower limit of the latter species define the top and the base of Zone NP10 respectively. The data of Lowrie et al. (1982), Okada and Thierstein (1979), and Romein (1979) indicate that the first appearance of T. orthostylus closely approximates the last occurrence of T. contortus. The base of Zone NP11 is therefore drawn at the first appearance level of T. orthostylus (see Table 4). The short length of Zone NP11 and the many exits and entrances of taxa in the proximity of the base of the zone is conspicuous (Chiasmolithus bidens, D. kuepperi, Ellipsolithus macellus, Imperiaster obscurus, Lanternithus spp., Rhabdosphaera scabrosa, and T. magnicrassus). The base of the glauconitic unit also occurs at this level in Core 553A-12, indicating a transgression over the area (Morton et al., this volume). It seems reasonable to suggest that the base of Zone NP11 at Hole 553A is slightly younger than the chronostratigraphic age of the Zone NP10/Zone NP11 boundary.

Zone NP10 is represented in approximately 25 cores overlying the basalt but roughly 19 of these cores are barren, and the remaining cores are characterized by low diversity and low abundances of nannofossils. Regardless of the poor control of the exact sedimentation rate in this interval, the rate was clearly very high, compatible with the tectonically active situation and the shallow water depositional environment over this part of the sequence. It is noteworthy that fasciculiths are absent in Core 553A-37. This genus has its last occurrence in the upper part of Zone NP9 of the upper Paleocene (Shackleton, in press). The occurrence of Rhomboaster calcitrapa in Sample 553A-37-4, 50 cm may imply that this level belongs to the very top of Zone NP9, very close to the Zone NP9/Zone NP10 boundary (Paleocene/Eocene boundary).

## Site 554

There were two holes drilled at Site 554 ( $56^{\circ}17.41'$ N; 23°31.69'W; water depth: 2576 m). Drilling commenced at Hole 554A at the level where Hole 554 terminated (76 m). The sequence contains calcareous nannofossils down to a depth of 123.5 m (Sample 554A-5,CC). The underlying cores of Hole 554A (Cores 6-14) consist primarily of coarse volcanigenic sediment interbedded with basalt flows. The uppermost 106 m (Pleistocene-middle Miocene) probably reflect an unbroken record. The

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# Table 4. Distribution of Paleogene calcareous nannofossils at Hole 553A.

Eboch		Zone (Dkada Bukry, 1980)	Zone (Martine, 1971)	Sample (553A. care-section cm)	Abundance Preservation	Braarudosphaera spp Campylosphaera dela C. eodela C. badela C. budens	C consuetus C eograndis C eraporsus C grandis	C admartensis C solitus C hiphragmalithus C calathus	C. crubellum C. expedigrcus C. formosus C. fortigrcus	c. suograficmas Corricorgalithus mitescens Cyclicorgalithus abisectus C flandiaus C biseudogamation C bisectus	Discoaster adamanteus D Darbadensis D britas D britas D brindacus	D drastypus D drstmetus D meupperi D ientralaris	D. mediosus D. multiradia tus D. madifer D. madifer D. converba	D. solganesis D. solganesis D. sthretus D. sublodoensis	E marellus Ericsonia fenestrata Helicosphaera dinesenii H eughtoths	H laphofa H ablauc H recta H recta	ruper taker ubstands Lanternthus spp Landol thus mochlophocus L. nascens Markdus spp	Nacadation contraction of the contraction of the contraction of the continents of the continents of the contraction of the cont	Pentosphaera duocava Pentosphaera duocava Pechoata Pectivata	P pulthra P rimosa P versa Prinsvis bisultus Prinsvis inversus	P. arangensis Rehiculofenestra daviesi R. aritoda B. miutae	R reficulata R reficulata Rhabdosphaera trebia R scarrosa	R Teruns R truncata Rhomboaster calcifrapa R cuspis Commanithus amerikans	S moriforms S vadians Takens magnicrassus T occutatus Tribrachiatus confortus	T munnii T orthostylus Triquetrachabdolus carinatus Zygachablichus byugatus
EARLY MIDCENE		116 	NN1	8-3, 135 8-4, 12 8. CC 9-1, 5 9-2, 5 9-3, 5 9-4, 5	M M M M M M M				0 																
LATE	Sourcocene	9 9	25	9 - 4, 10 9 - 4, 125 9 - 6, 20 9 - 6, 25	M M M M M									÷.					E.					0 0 0	
EDCENE	CP	Kał	NP16	9, CC 10-1, 90 10-3, 9 10-3, 70						000000000000000000000000000000000000000			0		u		0 0	0 0 0		0			0	a a a a	
MIDDLE	CF	12 1	~~~ NP 14	10-3, 100 10-3, 130 10-4, 40 10-4, 87 10-6, 59	C C C F F	0			0				00000			0	0 0	a a							
		,	NP 13	11-1, 10 11-1, 53 11-1, 121 11-2, 40 11-2, 80 11-4, 125	F P P P F F P M P	0	0 0 0 0 0 0 0 0			0	0 0					0 0 0 3	0 0 0							a o o	
		10-	NP 12	11-5, 40 11-5, 112 11-5, 149 11-6, 25 11-6, 75	F F F G G G G	0 0	• •	0 0			0 0 0 0 0 0	00000				0							0		
an an	- -	96 M	NP 11	11, CC 12-1, 26 12-1, 44 12-1, 74 12-3,143 12, CC	C C C R R P										o										
FARIY FOCF				13-1, 25 13-2, 90 13, CC 14-1, 51 14-2, 50 14, CC 15-1, 116 15-2, 40 15-3, 90/21, CC	BARREN BARREN BARREN R P R P R M R P R P BARREN D P	0 0 0 0 0 0 0 0 0		0 0 1	00000			0 0	-		0 0 0		0							0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	0 0 0 0
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LATE PALEO-	CENE ?	852 1	NP9?	24-1, 60 24, CC/36, CC 37-1, 50 37-2, 35 37-3, 49 37-4, 13 37-4, 50 37-4, 117 37-5,	R P BARREN R P R P R P R P R P BARREN								0 11						3				c		

Note: Open squares = rare, filled squares = more commonly occurring.

lower half of the Miocene and most of the Eocene are missing. In contrast to all other sites drilled during Leg 81 the Oligocene is well represented at Site 554, albeit condensed into 11.5 m.

# The Neogene of Holes 554 and 554A

The distribution of Neogene nannofossils is shown in Table 5. Most Neogene cores are severely disturbed by drilling processes. Core 554-4 was empty. Assemblages are similar to those observed at Sites 552 and 553: A few taxa occur in great abundances, and these are accompanied by a number of comparatively rare taxa.

In the Pleistocene, gephyrocapsids tend to be the most prominent assemblage elements, although Coccolithus pelagicus and Dictyococcites productus occasionally may be abundant. Diagenetic overgrowth of calcite may blur the morphologic characters used to distinguish between gephyrocapsids and D. productus. Reticulofenestrids, C. pelagicus, and D. productus dominate the Pliocene assemblages. Abundant large D. perplexus characterize the assemblages during earliest late and late middle Miocene times, together with C. pelagicus and reticulofenestrids.

The last occurrence of Pseudoemiliania lacunosa is in Sample 554-2, CC, that of Calcidiscus macintyrei is in Sample 554-3-5, 35 cm, and that of Discoaster brouweri is in Sample 554-3, CC. Zones NN16 and NN17 apparently lie within the empty Core 554-4, because the uppermost part of Core 554-5 belongs to Zone NN15. Cetatolithus acutus is present in Sample 554-6-5, 46 cm and C. rugosus in Sample 554-5, CC suggesting that the Zone NN12/Zone NN13 boundary should be placed between these two levels. Two samples taken at the bottom of Core 554-5 (see Table 5) contain Amaurolithus delicatus, C. rugosus (one sample), and D. asymmetricus. As the lower range of the last taxon is uncertain these two samples are referred to Zones NN13-NN14, even though the first appearance of D. asymmetricus was used by Martini (1971) to define the base of Zone NN14. Zone NN11 is represented from 554-6, CC to 554-1, CC. Samples 554A-2,CC and 554A-3, 90 cm are referred to Zones NN9-NN10 since both Coccolithus miopelagicus and D. quinqueramus are absent. Presence of the former species and the absence of Cyclicargolithus abisectus and C. floridanus suggest an assignment to Zones NN7 and NN8 for Samples 554A-3-3, 145 cm and 554A-4-4, 145 cm.

A 25-cm thick unit of glauconitic nannofossil-foraminifer chalk at the top of Section 554A-4-2 is bounded by hiatuses; the upper one being distinct, encompassing the interval from Zones NN3 or NN4 to NN6, whereas the duration of the lower hiatus is shorter (Zone NN1). Bukry (1973) and Martini (1971) give different ranges for Sphenolithus belemnos and D. druggii. Bukry uses the first appearances of D. druggii and S. belemnos to define the base and top of Subzone CN1c respectively, whereas Martini claims that these two events coincide at the base of Zone NN2. Both these taxa are present at the 10- and 21-cm levels in Section 554A-4-2, together with Helicosphaera aff. H. ampliaperta which has a short range in Zone NN2 (see Müller, 1981). The present material does not allow determination of the exact stratigraphic relationships of the ranges of *D. druggii*, *H.* aff. *ampliaperta*, and *S. belemnos*. Thus it seems fair to suggest a Zone NN2-Zone NN3 (or CN1c-CN2) assignment for this 25-cm-thick interval (Sample 554A-4-2, 0-25 cm). Subzones CN1a-b are missing.

## The Paleogene of Hole 554A

Dictyococcites bisectus and Triquetrorhabdulus carinatus co-occur immediately below the above-discussed 25cm (lower Miocene) interval. The latter taxon is present continuously to Sample 554A-4-2, 145 cm, suggesting a Zone NP25 assignment (Müller, 1979). Since diagnostic sphenoliths are rare at mid and high latitudes Müller also suggested that the first appearance of Cyclicargolithus abisectus could be used to approximately determine the base of Zone NP24, a suggestion supported by the data of Poore et al. (1982). The first appearance of C. abisectus is distinct at Hole 554A, occurring between 80 and 145 cm in Section 554A-4-3. In practically all samples containing C. abisectus and C. floridanus there are specimens intermediate between these two taxa. There is no problem in distinguishing between end members of these morphologically similar taxa. But, since size is the character that provides the most efficient means to separate C. abisectus from C. floridanus, it is recommended to measure the overall size (e.g., placolith diameter) in order to apply consistent species concepts. This work ought to be done on a better sequence than that provided at Site 554.

Reticulofenestra umbilica has its last occurrence between Samples 554A-4, CC (10 cm) and 554A-4-4, 25. Isthmolithus recurvus also disappears at the latter level (the range of *I. recurvus* above the highest occurrence of *C. formosus* is noteworthy). This would imply the presence of a hiatus at the bottom of Core 554A-4, covering the upper part of Zone NP22 and a substantial part of Zone NP23. The zonal assignments of the Oligocene at Hole 554A (Table 6) should be regarded as tentative because of the condensed nature of the sequence and the absence of some of the primary zonal markers.

Discoaster saipanensis and R. reticulata disappear in Sample 554A-5-3, 104 cm. These taxa co-occur with I. recurvus down to the manganese crust in Sample 554A-5-4, 20 cm. The assemblage immediately above the manganese crust can thus be referred to the uppermost Eocene (Zone NP19/20 or CP15b). If the biostratigraphy of Hole 552A is correctly interpreted, this implies that the manganese formation took place earlier at Hole 554A than at Hole 552A.

The sediment below the manganese crust at Hole 554A is intensively burrowed, and upper Eocene assemblage contaminants are mixed into the lower Eocene (Zone NP11). It is estimated that inmixing decreases by approximately 85–90% within 8 cm from beneath the manganese crust, but the upper Eocene contaminants continue to be present in low numbers for roughly 35 cm below the manganese thus indicating the depth penetration of the burrowing organisms.

The interval between 39 and 104 cm in Section 554A-5-4 shows a dull assemblage referable to Zone NP11.

# Table 5. Distribution of Neogene calcareous nannofossils at Holes 554 and 554A.

									-						-																					_					
Epoch	Zone (Okada & Bukry 1980)	Zone (Martini, 1971)	Sample (554, 554A core-section, cm)	Ahundance	Preservation	Amaurolithus delicatus	C. macintyrei	Ceratolitus acutus Erunnsus	Coccolithus miopelagicus	c. pelagicus C. radiatus	Coronocyclus nitescens Cyclicargolithus abisectus	C. floridanus Dictuoraritas baselandii	D. perplexus	D. productus Discoaster asymmetricus	D. brouweri	D. challengeri	D. deflandrei D. deflandrei	D. exilis	D. loeblichii D. loeblichii	D. pentaradiatus D. prepentaradiatus	D. quinqueramus	D. surculus	u variabilis Emiliania huxleyi	Geminilithella rotula Genhuroransa enn	uepingrouppaera aff. ampliaperta	H. carteri H. granulata	H sellii	Pontosphaera japonica P. jonesi	P. multipora	Pseudoemiliania lacunosa Pyrocyclus hermosus	P. inversus	Reindorenesina aanesi R. haqii	R. minuta	K. minurula R. pseudoumbilica	Rhabdosphaera clavigera	Scyphosphaera spp.	Sphenolithus abies S. belemnos	S. moriformis S. neonbies	Syracosphaera spp. Triguetrorhabdulus carinatus	T. milowii	ı. rugosus Zygrhablithus bijugatus
	CN 146-	NN 20-	1, CC	A	G		-			0				0											•	+	-	+ +											+		
LEISTO	CN 13- 14a	NN 19	2, CC 3-4, 50	AA	MG		2			•				•												+ +	0	0 0		0					+						
LATE	CNI124	NINI 10	3-5, 35	A	M		0		-	0		-		•	-		_	+		_	-			-	•	+	0	+	8 	0	-			+	+	+			+	$\rightarrow$	-
PLIOCEN	CN 120	NIN 10	5, 00	A	M					-	_	-			+			+		-	-			-		+	-	+ +		0			-			-			_	-	-
רא א ש	CIVIT	NINIS	5-1, 70	A	INI			3	-		_	-	_	• •	+			+		<b>T</b>	-			-	_	0	-		_	_	· *	-	0	-	+	- T	<b>T</b>	. *		+	
EARI	CN 10c	NN13-14	5-6, 140 5, CC	A	M	+ 0	0 + 0 0	4		•				• +	++	+			+	+		+		+		o +		++				0	+	+ +	. +	++	+	+			
٩.	CN 10a-b	NN 12	6-5, 46	A	М	(	) +	+							+					+		+	+	+		0 +		+				0	•	+ •		+		+			
	CNION		6, CC	A	G		<b>b</b> +			0				•	+	+	2				+	+	+	+		+ +						0		•							
U N	CNAD	NINI 11	7, CC	A	М	+ (	+ (			•			0		+	+					+	1	+	+	_	o +	_					+	+	+ •	£	-	+				÷ .
OC OC	CNOG	1414 11	8, CC	A	G	0	> +			• +			0		+	+			+		+	3	0			+					+	+	+	+ •						1	
Σ	CNAG		1A, CC	A	G		+ +			• +					+	+ +			+ +	+	+	+	0			+			+	+	+		+	0	2			+		1.1	+
	CN 7.9	NIN O 10	2 A, CC	A	М	11 - 5	+ +			•					+	+	2	1 1	+	+		1	+	+		+ +							+					+			+
JULE .	1014 /-0	1414 9-10	3A-3,90	A	G		+ +	-		•			•	1	+	+	1.00		1	_			+	+		+			-		+		0			_		+	-	1	
000	CN 5b-	NN 7-8	3A-3,145	A	M		+	100	+	•			•	0.02	1			+		<u></u> /			+	+		+ +			200	+	+		+	•				+		T	
ENC	Long	h	4A-1, 145	A	М	1 3	+		+	•							+	+					+	+		0 +							+	•	<u>ا</u>			+			
NI- RILY	CN 10-2	NN 2-3	4A-2, 10	A	М					•	+ +	0 0	•				+ -	+							+	+						c					+	+	+	+	+
AME	5	2-3	4 A-2, 21	A	М					•	+ +	0					0 .	-		_			_	_		+ +		_	_	_	+ (	c		-	-		+	+		+	0

Note: Filled circles = abundance > 10% of total assemblage, open circles = abundance 1-10% of total assemblage, crosses = abundance < 1% of total assemblage.

Table 6.	Distribution	of	Paleogene	calcareous	nannofossils	at	Hole :	554A.
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1																																											
Epoch	Zone (Okada & Bukry, 1980)	Zone (Martini, 1971)	Sample (554A core-section cm)	Abundance	Preservation	Chiasmolithus altus	C. eograndis	L. oamaruensis C. solitus	Coccolithus eopelagicus	C. formosus	с. pelagrcus С. subdistichus	Coronocyclus nitescens	Cyclicargolithus abisectus	Dictyococcites bisectus	D. hesslandii	D. barbadiensis	D. binodusus	D. diastypus	D. keupperi	u. mul tiradiatus D. nodifer	D. saipanensis	u. tanı Ellipsolithus macellus	Ericsonia fenestrata	Helicosphaera bramlettei H. comporta	H. euphratis	H. reticulata	isthmolithus recurvus	Markalius spp.	Neococcolithes dubius	Pontosphaera fimbriata	P. rimosa	P. versa	Pyrocyclus hermosus	P. inversus	P. orangensis	Reticulofenestra daviesi R. dictyoda	R. hillae	R. reticulata	R. umbilica	Sphenolithus ciperoenis S. moriformis	Toweius magnicrassus T. occultatus	Tribrachiatus orthostylus Triouetrorhabdulus carinatus	Zygrhablithus bijugatus
L	ų		4-2, 35	A	М					-					0	-	C	1								+							1								1		
μį	CP 191	NP 25	4-2, 80	A	М												E	1																	Ì				1				
A.	š		4-2,145	A_	_P.				4 -	_		_			_!	기_		۱ <u> </u>	.				L	_		1	-	_	-			-				<u> </u>		_					
	CP 190	NP 24	4-3, 80	A_	_M_			14	- 1			-			_	-	_		.		_		0	_	_	4		_	_	_	_	_		_	-	<u> </u>	_	-		_ □		3 <u>-</u>	
1	CP 17-	NP23	4-3,145	A	м	=	1						ା																					101									
	]_10 -		4-4, 25	₽Å-	- M_					- 1	<u> </u>		-	-	_	-	-	-	- +						-	+	-	-	-	-			-		-	-						6 <del>191</del>	-
			5_1 59	A	M	12					5			1.2									12													-							
125	CP17	NP 22	5-1, 50	1	M	-		_			2				-								Ξ.				-						1			_			Ξ.		0		-
AB		141 22	5-2, 50		M								- 9	1													- 2												а.				
μ <u></u>	5		5-3, 48	Â	P		i i						c	, 🖬									1				-																
1 8	CP 16	NP 21	5-3.84	A	M			0								+				_				1	0	+		1	1				+		-								
L	J		5-3,104	A	M	-	1						-						+							+							1										
世代		100.00	5-3, 115	A	Ρ		3						- 1			1000							1																				
A		20	5-3, 135	A	Ρ		j.																																-				
			5-4 20	A	Ρ				-				1		5		0	1						_															н.				1
		1	5-4, 39	BAF	REN		-			1									1									1.00															
>	CP9b	NP11	5-4, 50	R	Ρ	(							[						- 1				1			1							•										- 1
R		1	5-4, 92	R	Ρ														1																								
EA I	I		5-4,104_	R	_P.		<u> </u>	_		_	<u> </u>	_	-	_	-	-	-	-	-  -	-	_			_	-	+"	-		_	-	-		-	-	-		_	-	e :==			<u> </u>	믹
	CP 9a	NP 10	5, CC	R	P																																						

Note: Open squares = rare, filled squares = more commonly occurring.

*Tribrachiatus orthostylus* is not present in the lowest sample containing nannofossils, possibly indicating Zone NP10 at that level. Several samples were investigated in Core 554A-6, but all calcite proved to be diagenetic.

# Site 555

The depositional environment of the sequence at Site 555 (56°33.70'N; 20°46.93'W; water depth: 1659 m) differs from those at the other Leg 81 sites in being considerably shallower. The Pliocene is missing at Site 555. A hiatus separates the lower Miocene from the lower Eocene, and not even fragmentary occurrences of sediment representing the Oligocene or the middle-upper Eocene are preserved. Both these characters make the Site 555 sequence different from those at Sites 552, 553, and 554. Two 19-m intervals, between Cores 555-8 and 555-9, and between Cores 555-10 and 555-11, were not cored. The remaining parts of the sequence were continuously cored. The Neogene is represented to a depth of 281 m (Sample 555-26,CC). The Paleogene, which is represented by the lower Eocene and the upper Paleocene (the only definite Paleocene recovered during Leg 81), is very expanded: It begins at 281 m and continues to 870 m (terminal depth: 964 m). The six lowest sedimentary cores are barren of nannofossils; the sediments are mainly comprised of vitric micaceous sandstone and lapilli tuff. Two intervals do not contain sediment, the first between Cores 555-68 (Sample 555-68-2, 35 cm) and 555-83 (Sample 555-83-3, 30 cm), and the second between Cores 555-95 (95-1, 35 cm) and 555-98 (terminal depth). The former consists of basalt and hyaloclastite, the latter wholly basalt.

# The Neogene of Site 555

Ice-rafted sediment and oozes characterize the Pleistocene to the bottom of Section 555-3-3. The assemblage undergoes a distinct change between Samples 555-3-4, 80 cm and 555-3-5, 80 cm. The former level can be assigned an age of between 1.45 and 1.88 m.y. (bottom Zone NN19) owing to presence of *Calcidiscus macintyrei* and absence of *Discoaster brouweri* (see Backman and Shackleton, 1983). Samples 555-3-5, 80 cm and 555-3,CC are referable to the lower Pliocene. Exactly where in the lower Pliocene is more difficult to say. A tentative assignment to Zone NN12 (CN10a) is suggested, based on presence of *Triquetrorhabdulus rugosus* Sample 555-3,CC. In turn, this implies that Zones NN13 through NN18 are not represented.

The interval between Samples 555-3-5, 80 cm and 555-24-4, 135 cm represents continuous deposition with an average sedimentation rate of approximately 2.5 cm/ 1000 years. It is the most complete middle Miocene sequence recovered during Leg 81. Changes in assemblages through time are compatible with those documented from Sites 552, 553, and 554. Reworking may have affected the nannofossil biostratigraphic resolution around the upper/middle Miocene boundary. Sporadic and rare specimens of *Coccolithus miopelagicus* were noted above Sample 555-15, CC but this species becomes a more regular member of the assemblages below Sample 555-15, CC possibly implying that Zone NN8 begins

between Samples 555-14,CC and 555-15,CC (see Bukry, 1973). The possibility cannot be excluded, however, that *C. miopelagicus* is reworked between Samples 555-18,CC and 555-15,CC, since it is still comparatively rare in that interval. This uncertainty is indicated in Table 7. The Zone NN6/Zone NN7 boundary is placed at the last occurrence level of *Cyclicgargolithus abisectus* (Sample 555-22,CC). Presence of *Sphenolithus heteromorphus* and absence of *Helicosphaera ampliaperta* in two samples in Core 555-24 (Table 7) indicate Zone NN5. Zone NN4 is not represented in this sequence, but Zone NN3 is present between Samples 555-24-5, 100 cm and 555-26,CC, as indicated by the presence of both *H. ampliaperta* and *S. belemnos*.

# The Paleogene of Site 555

The lower Eocene is represented by Zones NP10-NP12 (Table 8). Two long intervals comprising 18 cores altogether are barren of nannofossils (Samples 555 31,CC to 555-41,CC; Section 555-46-1 to Sample 555-55,CC), and the interval between Sample 555-55,CC and the uppermost sediment/basalt contact in Core 555-68 contains impoverished assemblages, characterized by highly sporadic occurrences of nannofossils, which are biostratigraphically undiagnostic with respect to the Zone NP9/Zone NP10 boundary (Paleocene/Eocene boundary). The sediments interbedded between the basalt piles are richer in nannofossils and provide a distinct Zone NP9 signal.

A drilling breccia consisting of a mixture of lower Eocene zeolitic clays and chalks from the overlying lower Miocene is present in the uppermost 15 cm of Core 555-27. A sample was taken at Section 555-27-1, 5 cm from the center of a brownish lump clearly belonging to the Eocene lithology. No Miocene contaminants were observed in this sample, in contrast to other samples taken from the breccia. The sample shows a few lower Eocene taxa, including Discoaster lodoensis and Tribrachiatus orthostylus, and no Reticulofenestra dictyoda. This composition indicates Zone NP12. Toweius occultatus is abundant up to Sample 555-27-2, 132 cm. At Site 552 this species disappears in the middle part of Zone NP12, implying that the Sample 555-27-1, 5 cm probably represents the upper part of Zone NP12. D. lodoensis was not observed below the drilling breccia in Sample 555-27-1, but T. orthostylus continues to Sample 555-31,CC. The latter level hence is used to mark the boundary between Zones NP10 and NP11 (see above). A single observation of Tribrachiatus contortus in Sample 555-33-2, 88 cm supports the tentative assignment of the Zone NP10/Zone NP11 boundary at Sample 555-31,CC. As at Sites 552 and 553, the disappearance level of Ellipsolithus macellus coincides with the first appearance level of T. orthostylus at Site 555.

The barren intervals are separated by four cores (Cores 555-42 to 555-45) containing nannofossils. Presence of *D. diastypus* in two samples in Core 555-45 places this interval within Zone NP10. A species that has previously only been reported from Zone NP9 of the upper Paleocene (Edwards and Perch-Nielsen, 1975), *Hornibrookina australis*, was observed within this Zone

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Epoch	Zone (Okada & Bukry 1980)	Zone (Martini, 1971)	Sample (555 core-section cm)	Abundance	Preservation	Calcidiscus leptoporus	L. macintyrei Coccolithus miopelaaicus	C. pelagicus	Loronocyclus nitescens	Lyclicargolithus abisectus C. floridanus	Dicryococcires nessianari D. perplexus D. productus	Discoaster adamateus	u. veius D. braarudii	D. brouweri D. calcaris	D. challengeri	u. deflandrei D. deflandrei	D. exilis D. intercalaris	D. kugleri D. mooroi	D. pentaradiatus	D. pseudovariabilis D. quinqueramus	D. signus D. surculus	D. variabilis Emilionia huvlavi	Geminilithella jafari	G. rotula Gephyrocapsa spp.	Helicosphaera ampliaperta H. carteri	H. euphratis	H. granulata H. intermedia	H. minuta H. sellii	Pontosphaera attentuatus P. japonica	P. jonesi P. multinora	Pseudoemiliania lacunosa	Pyrocycius nermosus P. inversus	P. orangensis Reticulofenestra daviesi	R. haqii R. minuta	R. minutula	K. pseudoumbilica Scyphosphaera spp.	Sphenolithus belemnos S. heteromorphus	S. moriformis S. neoabies	Syracosphaera spp. Triquetrorhabdulus rugosus
W	CN 14b-	NN 20- 21	1, CC	А	G	0		0			0	6					1.540						?	0	0		_		+	+									0
SCE	l.		2. CC	A	M	0		100							1						1			•	+				+	+	+								+
ISTO	CN 13-	NN 19	3-2, 145	A	G	0	0	•																0	0			•		+	+			?•	- C	+			+
L L L	140		3-3, 80	A	G	0	<u> </u>		2															0						+	0					Ť			
hta	CN 10h	n	3-5 80	~	G	•	+	÷	+	-		1		+	+			-	+		+		-	+	+	-+		0	+	+	•	+		0.0	1	• +	-		-
- Lin	CN 100	NN 12	3. CC	Ä	M		+							+	1		+				+			0	+							+		• 0					+
			4-6, 58	A	G	+	+	0	+					+	+				+	+	+	+	-	+	0			+	-			-		0 .	+	• +	_		
			5, CC	A	M	•	+							+	+	+			+	+	+	0					0				-	+			1 8	• +			
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ш	CN 9	NN 11	7, CC	Α	G	•	+	٠			0			+	+		+			+	+	+		+	+		0	+						0 0		• +			
Z U	1.00	(*****)	8, CC	Α	М	0	0		4		+			+	+		+			+	+	+		0	0		0		10					. +	0	+		0	+
00			9, CC	Α	М	+ -	+	٠			0			+	+		+		+	+		+	+	0	0		0		+					+ 0	0	•		+	+
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## Table 7. Distribution of Neogene calcareous nannofossils at Site 555.

Note: Filled circles = abundance >10% of total assemblage, open circles = abundance 1-10% of total assemblage, crosses = abundance <1% of total assemblage.

# CENOZOIC CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY

# Table 8. Distribution of Paleogene calcareous nannofossils at Site 555.

Epoch	Zone (Okada & Bukry, 1980)	Zone (Martini, 1971)	Sample (555 core-section, cm)	A bundance Preservation	Braarudosphaera spp. Campylosphaera eodela Chiasmolithus bidens	C. californicus C. consuetus	C. eograndis C. grandis	Lhiasmolithus spp (small) Coccolithus cribellum C. formosus	C. pelagicus Discoaster barbadiensis	D. binodosus D. diastypus D. elegans	D. falcatus D. kuepperi	D. lenticularis D. lodoensis	D. mediosus	D. mohleri D. multiradiatus Ellipsolithus distichus	E. macellus Fasciculithus tympaniformis	Fasciculithus spp. Heliolithus riedelii Hornibrookina australis	Imperiaster obscurus Markalius spp.	Micrantholithus spp. Neochiastozygus concinnus	N. Juncrus Neochiastozygus spp Neococcolithes dubius	N. protenus	P ocellata	P. pectinata P. plana	P pulchra	P versa Prinsus bisulcus Rhinhdosnhaern srahrosa	Rhomboaster cuspis Semihololithus kerabyi	S moriformis Towerus eminens	T magnicrassus T occultatus	Tribrachiatus contortus T orthostylus Zygodiscus plectopons	Z sigmoides Zygrhablithus byugatus
	CP 10	NP 12	27-1.5	FM				0			0		1				00	0		1								0	
-	СР9Ь	NP11	27, CC 28-1, 64 30-2, 6 31 -2, 33 <u>31, CC</u>	BARREN FM FP FP FM			• •		•	- 	-				0		0 0 0 0									<u>n</u>			-
ARLY EOCENE			32, CC 33-2, 88 33, CC/41, CC 42, CC 43-2, 102 43 CC	F M R P BARREN R P R P R M		00	0			D				00			0	•					0						D
Ū	CP 9a	NP 10	44-1, 45 44-1, 130 44-2, 56 44-2, 96 44, CC 45-1, 91	R P P F P F P F P F P F P F P F P F P F				۵					0					۵			0	1000			0 0 0 0 0				D
			45-2, 93	RP	00								- 22													0			
?	3	?	4-5, UC 4-6-1, 70/55, CC 56-2, 32 56-5, 95 56, CC 57, CC 58-3, 32 58, CC 59-4, 74 59, CC 60-3, 139 60, CC 61-2, 130 61, CC 62-4, 132 64, CC 66, CC 67-3, 98 68-2, 35/83-3, 30 84, CC	RREN RRP RRP RRP RRP RRP RRP RRP R R R R R				-																		0		P	
LATE PALEOCENE	CP 8	NP 9	85 - 1, 60 86 - 2, 76 86 - 3, 96 87 - 3, 111 88 - 1, 92/88 - 2, 95 88 - 4, 20 88 - 4, 48 88 - 4, 65 88 - 4, 85 88 - 4, 111 88, CC/93, CC	R P R P R P BARREN R P R P R P R P R P BARREN	-													D										i I	

Note: Open squares = rare, filled squares = more commonly occurring.

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NP10 interval. However, the range of H. australis, as shown by Edwards and Perch-Nielsen from Site 277, partly overlaps with that of D. diastypus, and the species disappears shortly before E. macellus; it possibly also overlaps in range with T. orthostylus. The range of H. australis at Site 555 thus cannot be regarded as anomalous.

It is noteworthy that *Rhomboaster cuspis* also is present in Cores 555-42 through 555-45.

There is no evidence available that can be used to refer the interval between Cores 555-56 and 555-68 (below the lower barren interval and above the basalt/hyaloclastite pile) to any biostratigraphic zone. The assemblage in this interval is nevertheless considered to be indigenous because of its distinct character from the underlying nannofossil bearing sediment; see, for example, micrantholiths. Unfortunately, depositional rates do not provide any clues as to the placement of this interval. Perhaps the best biostratigraphic indication available is the absence of fasciculiths, which disappear close to the Zone NP9/Zone NP10 boundary, but within Zone NP9 (Shackleton, in press). However, the adverse depositonal environment of this interval, with a water depth representing a shallow shelf environment (Murray, this volume), suggests that absence of certain taxa may be due to environmental causes rather than reflecting biostratigraphic relationships.

Fasciculiths are "common" from the top of Core 555-85 to Sample 555-88-4, 111 cm. Well-developed specimens of *D. multiradiatus* indicate that this interval may be confidently referred to Zone NP9. One specimen of *D. mohleri* was observed in Sample 555-88-4, 85 cm. The interval also shows a co-occurrence of *Toweius eminens* and *T. occultatus*, together with transitional forms between the two. The former species is not present in any other Leg 81 material.

## CORRELATION OF THE PALEOGENE: SW ROCKALL AREA (LEG 48 AND LEG 81)

One of the principal objectives of Leg 81 was to gather evidence and create a conceptual framework of the rifting history between Greenland and the Rockall Plateau and of the early phases of seafloor spreading between these blocks of continental crust. A first step toward the achievement of these objectives is to establish biostratigraphic correlations between the retrieved sequences. The next step involves the interpretation of these correlations in terms of chronology (see Backman and others, this volume).

It may be pertinent in this context to explain why such correlations are not presented for the Neogene sequences. Hole 552A provides the best material premises for study of late Cenozoic paleoenvironments in the Rockall area. The other Neogene sequences drilled during Leg 48 and Leg 81, many of which are spot cored and severely disturbed during drilling, add less crucial insights about the evolution of Neogene paleoceanography and paleoclimatology. In contrast to this, all Paleogene sequences are of critical importance in order to establish a comprehensive understanding of the Greenland-Rockall syn-rift and post-rift development. Sites 552, 553, and 555 are investigated by a single worker. Consistent taxonomic concepts thus are applied in the study of these sequences. The correlations between these sites therefore are presented alone (Fig. 7). The sites in Figure 7 are not arranged in accord with their locations on a west-east transect (see Figure 1). Instead, the correlations between Sites 553 and 555 are emphasized. Apart from biostratigraphic indications, three magnetic normals (RA, RB, and RC; see Krumsiek, this volume) are shown in Figure 7, together with the base of the glauconitic horizon (Morton et al., this volume). Figure 8 is constructed from Müller's (1979) and the present data. The sites are arranged according to their positions on a west-east transect.

It appears from Figures 7 and 8 that no lines of correlation cross each other, indicating that reworking has not affected the biostratigraphic order. Sites 404 and 552 show a good representation of Zones NP11 through NP13. This biostratigraphic interval is short and marred by hiatuses at Sites 403, 553, 554, and 555.

The base of the glauconitic unit represents a major transgression over the area. The first appearance of *Tribrachiatus orthostylus* and the last occurrence of *Ellipsolithus macellus* occur at or slightly above this level at all sites, indicating that sedimentation commenced virtually synchronously after the transgressive event at all drilled locations.

E. macellus survives T. orthostylus at Site 404. The data of Okada and Theirstein (1979) from Site 386 suggest that E. macellus survives T. orthostylus, but not to what extent, since there is a 10-m unsampled interval in their material between the last occurrence level of E. macellus and the first appearance level of Discoaster lodoensis. Nevertheless, Okada and Thierstein's observations imply that Sites 403, 553, and 555 represent discontinuous records at the exit/entrance level of E. macellus and T. orthostylus. It follows that the first appearance levels of T. orthostylus at Sites 403, 553, and 555 must represent a younger age than the age of its first evolutionary appearance. This conclusion is supported by magnetostratigraphic evidence. At Sites 553 and 555 T. orthostylus has its first appearance within a normal period interpreted as Anomaly 24B (Krumsiek, this volume). Lowrie et al. (1982) suggested that T. orthostylus has its first appearance immediately below Anomaly 24B, thus supporting the idea of a late arrival of T. orthostylus at Sites 553 and 555. At Site 403 the entire interval, less one sample, from Core 403-25 to Core 403-41 is reversed (Hailwood, 1979), thus preventing any bio- and magnetostratigraphic conclusions. Site 404 is the only site where the stratigraphic relationship between E. macellus and T. orthostylus agrees with that derived by Okada and Thierstein from Site 386. Not surprisingly, Site 404 also agrees with Lowrie and other's data. That is, T. orthostylus appears immediately below Anomaly 24B.

Site 552 shows normal polarity at Core 552-21 (sediment/basalt contact). The base of the glauconitic unit is not present at this site. Moreover, the last occurrence level of *Toweius magnicrassus* and the first appearance level of *Tribrachiatus orthostylus* coincide at Site 552,



Figure 7. Stratigraphic correlations between Paleogene sequences of Hole 552, Hole 553A, and Hole 555. The data are discussed in the text. Notice that the Hole 555 sequence is divided into two columns.



Figure 8. Stratigraphic correlations between Paleogene sequences of Hole 554A (Leg 81), Site 403 (Leg 48), Hole 553A (Leg 81), Site 404 (Leg 48), and Hole 552 (Leg 81). See Müller (1979) for Leg 48 data. Two possible levels for the first appearance of *D. lodoensis* at Site 404 are indicated. The data are further discussed in the text.

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but not at Sites 553 and 555 where there is a short overlap in ranges of the two species. Since the disappearance level of *Toweius magnicrassus* obviously occurs above the base of the glauconitic unit (Sites 553 and 555), one cannot expect to find the base of this unit in the 26-cm interval separating the sediment/basalt contact and the disappearance level of *T. magnicrassus* at Site 552. It appears likely that indigenous deposition began at the lowermost level containing *Tribrachiatus orthostylus*, which would explain the absence of this species in a sample 5 cm above the sediment/basalt contact.

Abundant Cyclolithella spp. characterize two samples in Core 552-21. Sample 404-14, CC shows a peak abundance of a species that Müller (1979) referred to as *Ericsonia subpertusa.* It is not unlikely that these peak abundances of E. subpertusa and Cyclolithella spp. may represent a single event, which thus provides a possible correlation. If so, this indicates that the D. lodoensis correlation between Samples 552-18-3 and 404-16-1 is erroneous. Müller observed only a "trace" of D. lodoensis in Sample 404-16-1. The species becomes a regular member of the assemblages in Sample 404-11,CC, and was not recorded between Sample 404-11,CC and Section 404-16-1. The correlation between E. subpertusa (Sample 404-14,CC) and Cyclolithella spp. (Section 552-21-1) appears correct assuming that D. lodoensis has its first appearance in Sample 404-11,CC and that the "trace" of this species at Section 404-16-1 is due to contamination. This alternative has the advantage that the lines of correlation between the very closely located Sites 404 and 552 become approximately parallel, assuming that the two sequences should exhibit similar depositional histories. Sample 404-11,CC shows normal polarity (Hailwood, 1979) and may represent Anomaly 24A, which would agree with the data of Lowrie et al. (1982). Unfortunately, the minimal recovery in the critical intervals at both sites neutralizes any serious attempt to estimate how much of the lower part of Zone NP11 may be missing in the sedimentary record at Site 552. But with reference to the Site 404 sequence, placing D. lodoensis in Sample 404-11, CC and using T. orthostylus (at Site 404) and the E. subpertusa/Cyclolithella spp. correlation, as much as 45% of the lower part of Zone NP11 at Site 552 may be missing.

In conclusion, Site 555 exhibits the most expanded sedimentary Zone NP10 interval of all sites drilled during Leg 48 and Leg 81. Good Zone NP10 intervals also are preserved at Sites 403 and 553. These three sites show short and discontinuous lower Eocene records above Zone NP10. Zones NP11 through NP13 (and Zone NP14 at Site 552) are well represented at Sites 404 and 552, although the recovery is poor at both sites. Site 554 shows a very short lower Eocene sequence.

From a biostratigraphic point of view, the lower extension of Zone NP10 is vaguely determined at Sites 403, 404, 553, and 555. The dinoflagellate stratigraphy is possibly even more ambiguous concerning the placement of the Paleocene/Eocene boundary (see Brown and Downie, this volume). On the other hand, the nannofossil biostratigraphic control in the lower Eocene and upper Paleocene is surprisingly good, considering the paleoecological and depositional environments—the extremely shallow or even brackish waters, the high terrestrial sedimentary input, and the substantial deposition of volcanic ash and lapilli.

Finally, it may be of interest to give some attention to Hole 117A of Leg 12 which was drilled on the eastern flank of the Hatton-Rockall Basin. Laughton, Berggren, et al. (1972) suggest that sediment of late Paleocene age was recovered in that sequence. However, Morton et al. (1983) demonstrate that the lowermost nannofossil-bearing sediment belongs to Zone NP10 of the lower Eocene. The short Hole 117A sequence correlates well with a part of the neighboring Site 555 sequence. Hornibrookina australis and Rhomboaster cuspis have limited and virtually identical ranges in both sequences, where the former reaches slightly higher than R. cuspis. Furthermore, a barren interval begins shortly (2 m) below the mutual first appearance level of H. australis and R. cuspis at Hole 117A, which probably compares with the lower barren interval at Site 555. This barren interval encompasses two cores at Hole 117A. The core below contains basalt. Comparing the two sequences, it is clear that the upper part of Zone NP10 is shorter at Site 117 than at Site 555.

## NOTES ON TAXONOMIC USAGE

The reader who is interested in taxonomic nomenclature used in this chapter is referred to Loeblich and Tappan's "Annotated index and bibliography of the calcareous nannoplankton, I-VII," and to the INA Newsletter, Proceedings of the International Nannoplankton Association, Vol. 1-4 (S.E. van Heck, ed.). Nevertheless, a few points need explanation.

Braarudosphaera spp. incorporates specimens that are too poorly preserved to make determinations at the species level. Such groupings are established for the same reason in the following cases: Cyclolithella spp., Fasciculithus spp., Micrantholithus spp., Neochiastozygus spp., and Syracosphaera spp.

The forms referred to as "Chiasmolithus spp. (small)" at Site 555 have a morphology similar to Chiasmolithus sp. 1 of Okada and Thierstein (1979).

Dictyococcites perplexus was described by Burns (1975), and occurs in great numbers around the middle/ upper Miocene boundary in the Rockall area.

As explained in the text, gephyrocapsid specimens observed need extensive morphometric studies before consistent species concepts can be applied.

Two forms are incorporated in the group Markalius spp.: M. astroporus and M. apertus. Intermediate forms between the two were observed. Typical specimens of M apertus were not observed above Zone NP11 of the lower Eocene. Perch-Nielsen (1979) observed this species in lower Paleocene strata from Denmark, whereas Okada and Thierstein (1979) recorded it from the upper Paleocene (northwestern Atlantic Ocean). The latter authors referred to M. apertus as Markalius sp. 1.

Bramlette and Sullivan's (1961) concept of *Pontos*phaera aff. P. pulchra is applied.

Distinction has not been made between Sphenolithus primus and S. moriformis.

The scyphosphaerids are not separated at the species level because, at present, the group offers little stratigraphic information, and intermediate forms of several species are common.

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