

34. BIOSTRATIGRAPHIC AND PALEOCEANOGRAPHIC INTERPRETATION OF LOWER AND MIDDLE MIOCENE SEDIMENTS, ROCKALL PLATEAU REGION, NORTH ATLANTIC OCEAN¹

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ABSTRACT

This chapter compares the lower and lower middle Miocene lithology and diatom assemblages from Sites 610 and 406 in the Rockall Plateau region of the North Atlantic and discusses the implications for paleoceanographic conditions in that area. Tentative correlations with nannofossil zonations are established and some discrepancies discussed.

Three distinct stratigraphic intervals are recognized: (1) The upper interval, in the lower middle Miocene, typically contains common, moderately to well-preserved diatoms, indicating either silica-enriched surface waters within the Rockall Plateau region or diminished dissolution associated with bottom currents. (2) The middle interval, near the lower/middle Miocene boundary, is characterized by poor diatom preservation. Associated with it is a disconformity at Site 406, perhaps caused by intensified bottom-water circulation. (3) The lowermost lower Miocene interval is characterized by common to abundant fragments of *Ethmodiscus*. In present-day oceans, *Ethmodiscus* oozes are concentrated in regions where surface waters are tropical in character, but also in areas where silica is dissolved and sediment winnowed by bottom-water currents.

INTRODUCTION

In sediments recovered from Hole 610 during Leg 94, diatom preservation is variable in the lower and middle Miocene. A general decline in the quality of the diatom preservation downcore in the lower part of the hole corresponds to a gradual increase in the lithification of the sediment and an abrupt increase in seismic velocity (Site 610 chapter, this volume). Material of an equivalent age from Hole 406 shows a similar deterioration that corresponds to an abrupt sedimentological change from calcareous nannofossil chalk to calcareous diatomite. The sub-bottom depth of the preservational and sedimentological change approximates the depth of Reflector "2" of Montadert et al. (1979).

This chapter compares the lower and lower middle Miocene diatom assemblages from Sites 406 and 610 in the Rockall Plateau region of the North Atlantic Ocean (Fig. 1) and discusses the implications for early and early middle Miocene paleoceanographic conditions in that area. Hole 610, in 2417 m of water, is located on the western side of the Rockall Trough on the crest of Feni Ridge, Hole 406 on the southwest margin of the Rockall Plateau region at a water depth of 2907 m. The similar bathymetry and close proximity of both sites suggest that oceanographic conditions may have been similar. Both holes are situated below a water mass influenced by the intermittent southward flow of the Norwegian Sea Overflow Water. This water mass flows over the Iceland-Faroe-Scotland Ridge, branches, and a portion flows south along the eastern and southern margins of the Rockall Plateau, where it turns north and flows along the east side of the Reykjanes Ridge (Miller and Tucholke, 1983; Miller et al., this volume).

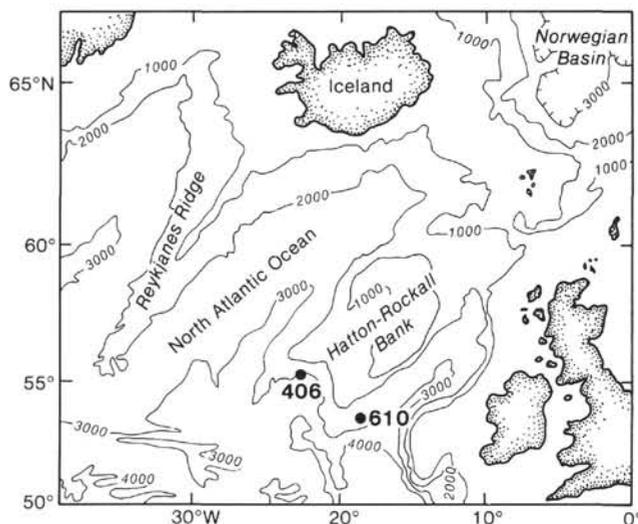


Figure 1. Location of DSDP Sites 406 and 610 in the Rockall Plateau region of the North Atlantic Ocean. Bathymetry in meters.

METHODS

Samples from Sites 406 and 610 were processed and examined using the techniques described by Baldauf (1985; this volume) and abundance and preservation of diatoms in each sample were determined.

The geochronology and chronostratigraphy of Berggren et al. (in press) are used in this study. Calcareous nannofossil and diatom zones are correlated to epoch/stage boundaries following Baldauf et al. (this volume), except for the *Rossiella paleacea* Zone, which is correlated to epoch/stage boundaries following Barron et al. (1985) (Fig. 2).

BIOSTRATIGRAPHY

Hole 610

The lower through middle Miocene diatom biostratigraphy (Baldauf, this volume), calcareous nannofossil stratigraphy (Takayama and Sato, this volume), and planktonic foraminiferal stratigraphy (Jenkins, this volume) of Hole 610 are shown in Figure 3. The interval between

¹ Ruddiman, W. F., Kidd, R. B., Thomas, E., et al., *Init. Repts. DSDP*, 94: Washington (U.S. Govt. Printing Office).

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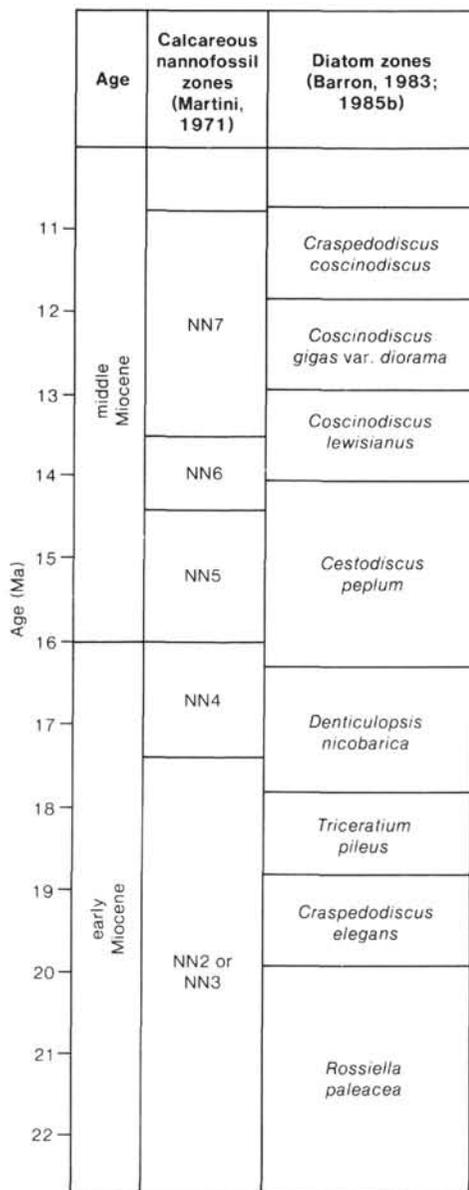


Figure 2. Correlation of the diatom zonation of Barron (1983; 1985b) and the calcareous nannofossil zonation of Martini (1971) with the geochronology of Berggren et al. (in press). The correlation follows that of Baldauf et al. (this volume). The top of calcareous nannofossil Zone NN6 is based on the last appearance of *Cyclicargolithus floridanus* instead of the first appearance of *Discoaster kugleri*.

185.4 and 636.6 m sub-bottom (Cores 610-10 through 610-18) was spot-cored (1 core every 50 m). Samples from Core 610-16 are placed in the *Coscinodiscus lewisianus* diatom Zone of Barron (1983) by the occurrence of *C. lewisianus*. Other diatom species include *Actinocyclus ingens*, *C. gigas* var. *diorama*, *Denticulopsis punctata*, and *D. hustedtii*. For nannofossils, Takayama and Sato (this volume) place Sample 610-16, CC in the middle Miocene *Discoaster exilis* Zone (NN6) based on the continuous occurrence of *Cyclicargolithus floridanus* below Sample 610-15, CC. This suggests that the upper portion of calcareous nannofossil Zone NN6 can be correlated

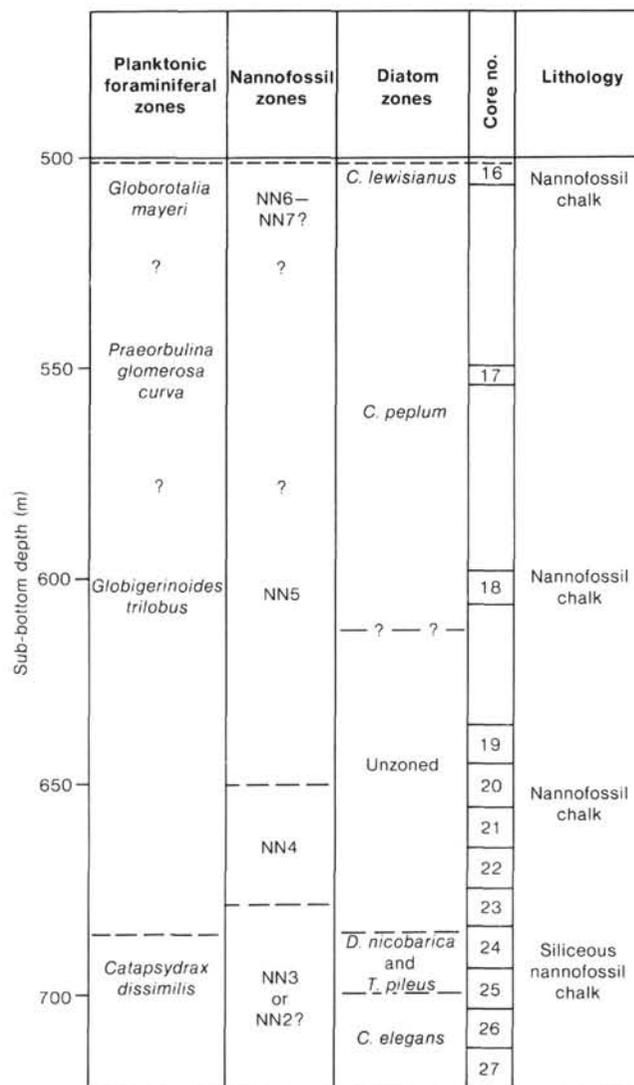


Figure 3. Location of the planktonic foraminiferal zones (Jenkins, this volume), the calcareous nannofossil zones (Takayama and Sato, this volume) and the diatom zones (Baldauf, this volume) in the lower portion of Hole 610 (for lithology see Site 610 site chapter).

to the lower portion of the *Coscinodiscus lewisianus* diatom Zone. However, Takayama and Sato's placement of Sample 610-16, CC in calcareous nannofossil Zone NN6 is based on secondary evidence. The top of NN6 is defined by Martini (1971) as the first stratigraphic occurrence of *Discoaster kugleri*, a datum which, Bukry (1973b) suggests, coincides with the last occurrence of *Cyclicargolithus floridanus*. But Berggren et al. (in press) indicate that in sediments from the central North Atlantic Ocean, the last *C. floridanus* occurs above the first *D. kugleri*. Based on their stratigraphic evidence, Sample 610-16, CC could be placed in calcareous nannofossil Zone NN7, and thus the *Coscinodiscus lewisianus* diatom Zone in the North Atlantic Ocean could just as easily be correlated to NN7 as to NN6. For the equatorial Pacific Ocean, Barron et al. (1985) indicate that the *C. lewisianus* Zone is correlated with calcareous nannofossil Zone NN6. At the present time, it is not possible to de-

termine whether the *C. lewisianus* Zone in the North Atlantic Ocean correlates with nannofossil Zone NN6 or NN7 and in this chapter it is correlated with NN6–NN7.

Samples from Core 610-17 contain a moderately well preserved diatom assemblage that includes specimens of *Actinocyclus ingens*, *Coscinodiscus blysmos*, *C. praenodulifer*, *Cestodiscus peplum*, *Rhizosolenia praebarboi*, and *Ethmodiscus* sp. The presence of *C. peplum* suggests that Core 610-17 belongs in the *C. peplum* Zone of Barron (1983) (Baldauf, this volume). Core 610-18 is also placed in the *C. peplum* Zone by the rare occurrence of *C. peplum*.

Samples 610-17, CC through 610-19, CC are placed by Takayama and Sato (this volume) in calcareous nannofossil Zone NN5 by the occurrence of *Sphenolithus heteromorphus* together with *Coccolithus pelagicus*, *C. miopelagicus*, *Cyclicargolithus floridanus*, and *Reticulofenestra pseudoumbilica*. Samples 610-20, CC and 610-22, CC are tentatively placed in the *Helicosphaera ampliapertura* Zone (NN4) by the occurrence of the nominate species (Takayama and Sato, this volume). The remaining core-catcher samples (Cores 610-23 to -27) are tentatively placed by Takayama and Sato (this volume) in the *Sphenolithus belemnos* Zone (NN3) by the occasional occurrence of *S. belemnos* and the absence of *Triquetrorhabdulus carinatus*.

Jenkins (this volume) places Core 610-16 in the planktonic foraminiferal *Globorotalia mayeri* Zone, Core 610-17 in the *Praeorbulina glomerata curva* Zone, Cores 610-18 through 610-23 in the *Globigerinoides trilobus* Zone and Cores 610-24 through 610-27 in the *Catapsydrax dissimilis* Zone. Clement and Robinson (this volume) tentatively place Core 610-21 in Chron C5C, Cores 610-22 and 610-23 in Chron C5D, Core 610-24 and part of 610-25 in Chron C5E, and the lower part of Core 610-25 (and possibly all cores through to the bottom of the hole) in Chron C6.

Diatoms are rare and generally poorly preserved in samples from Cores 610-19 through 610-21 and are absent in samples from Core 610-22. The diatom zonal assignments of samples from Core 610-24 and the uppermost portion of Core 610-25 are tentative, because these assignments (*Denticulopsis nicobarica* and *Thalassiosira pileus* zones of Barron, 1983) are based on secondary evidence (see Baldauf, this volume, for discussion). Fragments of a species similar to *Ethmodiscus rex* (Wallich) Hendey are abundant in samples from Cores 610-23 and 610-24. The occurrence of *Coscinodiscus rhombicus* in the lower portion of Core 610-25 and in 610-27 suggests that this interval is no younger than the *Craspedodiscus elegans* Zone of Barron (1983).

Thus the *Craspedodiscus elegans* Zone is correlated to calcareous nannofossil Zone NN3, although the nannofossil zonal assignment is tentative. The nannofossil zonal assignment, however, appears to agree with the planktonic foraminiferal zonal assignment (NN3 with the *C. dissimilis* Zone, about N6). Barron et al. (1985) correlate this diatom zone with the upper portion of calcareous nannofossil Zone NN2; they also correlate the *Rossiella paleacea* Zone of Barron (1983) with the middle

and lower portions of NN2 and the upper portion of NN1 and the middle of N5.

Barron et al. (1985) correlate the *C. elegans* Zone with upper paleomagnetic Chron C6 through lower C5E; the *T. pileus* Zone with upper Chron C5E through lower C5D, and the *D. nicobarica* Zone with upper C5D through lower C5C. Paleomagnetic data at Hole 610 are tentatively interpreted as follows (Clement and Robinson, this volume; Baldauf et al., this volume): the *C. elegans* Zone correlates with Chron C6, the *T. pileus* Zone with lower C5E, the *D. nicobarica* Zone with upper C5E. This suggests that the diatom zonal assignments for Cores 610-25 through 610-27 and their correlation with the paleomagnetic stratigraphy may agree with zonal and paleomagnetic correlations completed by Barron et al. (1985) for the equatorial Pacific.

Hole 406

Figure 4 shows the diatom zones and calcareous nannofossil zones as inferred by this author (see below) for Cores 406-21 through 406-29, as well as the calcareous nannofossil results of Müller (1979) and the foraminiferal data from Krashenninikov (1979).

Cores 406-22 and 406-23

Samples from these cores generally contain common, moderately well preserved middle Miocene diatoms, including *Actinocyclus ingens*, *Denticulopsis punctata*, *D. punctata* var. *hustedtii*, *D. hustedtii*, *Craspedodiscus coscinodiscus*, *Thalassionema nitzschioides*, and *Thalassiothrix longissima*. The occurrence of *D. punctata* var. *hustedtii* and the absence of *Coscinodiscus lewisianus* suggest that the cores are younger than the *C. lewisianus* Zone of Barron (1983) and correspond either to the *C. gigas* var. *diorama* or the *Craspedodiscus coscinodiscus* zones of Barron (1983).

Diatom stratigraphy favors the former placement. Several forms of *Cestodiscus* sp. occur in Cores 406-22 and 406-23, suggesting that they belong in the lower *Coscinodiscus gigas* var. *diorama* Zone, assuming that the last *Cestodiscus* in the Atlantic is equivalent to its stratigraphic placement in the equatorial Pacific. This zonal assignment is also suggested by the absence of *Hemidiscus cuneiformis*, which first occurs in the younger *Craspedodiscus coscinodiscus* Zone. It is unlikely that *H. cuneiformis* is ecologically excluded from this sample interval at Site 406: Baldauf (1985) reports a first occurrence in Hole 555 (Rockall Plateau) similar to its first occurrence in the equatorial Pacific Ocean.

Silicoflagellate biostratigraphy supports this zonal placement by diatoms; the occurrence of the silicoflagellate *Distephanus stauracanthus* allows Sample 406-23-1, 110–112 cm to be placed in the *D. stauracanthus* Subzone of the *Corbisema triacantha* Zone of Martini (1971). Bukry (1981) correlates this subzone with calcareous nannofossil Subzone CN5a (*Coccolithus miopelagicus* Subzone). The CN5a Subzone, in turn, is correlated with nannofossil Zone NN6 of Martini (1971) (Berggren et al., in press; Bukry, 1978; and Barron et al., 1985). Barron et al. (1985) relate Zone NN6 to the upper *Coscono-*

	Foraminiferal zones (Krasheninnikov, 1979)	Nannofossil zones (Müller, 1979)	Inferred nannofossil zones	Diatom zones	Core no.	Lithology
Sub-bottom depth (m)	N8	NN5	NN7— NN6	<i>Coscinodiscus gigas</i> var. <i>diorama</i>	21	Nannofossil chalk
					22	Siliceous nannofossil chalk
					23	
	P3—N ₁ ¹	NN4?	NN4?	Unzoned	24	Calcareous diatomite
		—				
		NN1	Unzoned		25	
		—				
		—				
		NP25	NN2—3		<i>C. elegans/ Rossiella paleacea</i>	
—						
—	—	—	27			
—	—	—	28			
—	—	—	29			

Figure 4. Location of the diatom zones and calcareous nannofossil zones as identified in this chapter in the lower and lower middle Miocene intervals of Hole 406, with the calcareous nannofossil zones of Müller (1979). For lithology see Site 406 chapter, fig. 8, table 4 (Montadert et al., 1979).

discus lewisianus and the *C. gigas* var. *diorama* zones of Barron (1985a). Thus diatom and silicoflagellate biostratigraphies indicate that Cores 406-22 and 406-23 are no older than NN6.

Another assignment, however, was made by Müller (1979), who places Samples 406-20-1, 94–95 cm through 406-23, CC in the *Sphenolithus heteromorphus* (NN5) calcareous nannofossil Zone on the basis of rare to common *S. heteromorphus* and *Discoaster exilis*, extremely rare *Coccolithus macintyreii*, and occasional specimens of *S. abies*.

These occurrences suggest NN5, in agreement with the zonal assignment on the basis of planktonic foraminifers (Krasheninnikov, 1979), which assigns Samples 406-20-3, 84–87 cm through 406-24-1, 133–137 cm to the uppermost portion of the *Praeorbulina glomerosa* Zone (N8); N8 has been correlated with upper NN4–lower NN5 and the *C. peplum* Zone by Barron et al. (1985) for the equatorial Pacific. Therefore the zonation by calcareous plankton is in conflict with the zonation by siliceous plankton.

These age differences for Cores 406-22 and -23 (NN5 by calcareous nannofossils and planktonic foraminifers, and no older than NN6 by diatoms and silicoflagellates) are not at present resolved. Possibly the calcareous nannofossils are reworked, but possibly *Sphenolithus heteromorphus* has a longer stratigraphic range at Site 406 than elsewhere. Müller (1979) indicates that few to abundant nannofossils occur in samples from Cores 406-20 through 406-23 and that nannofossil preservation is generally poor; specimens are broken and slightly etched. Occasional samples contain a moderately well preserved nannofossil assemblage, and reworked specimens occur in Samples 406-21-1, 29–31 cm and 406-23-1, 104–105 cm (Müller, 1979). Within Cores 406-22 and 406-23, occasional reworked diatom specimens are observed. For ex-

ample, in Sample 406-23-3, 110–112 cm, there are a few well-preserved specimens of *Thalassiosira fraga*, which according to Barron (1983) last occurs in the early Miocene *Denticulopsis nicobarica* Zone. Reworking of the foraminiferal assemblage as described by Krasheninnikov (1979), however, appears to be unlikely; he describes the presence of the species in the evolutionary lineage from *Globigerinoides bisphaerica* to *Praeorbulina* in the expected sequence.

Another possibility is that the age-constraining diatom *Denticulopsis punctata* var. *hustedtii* occurs earlier at Site 406 than elsewhere. At Site 555, also in the Rockall Plateau region, Baldauf (1985) observed this diatom in samples equivalent to the upper portion of the *Coscinodiscus lewisianus*, the *C. gigas* var. *diorama*, and the *Craspedodiscus coscinodiscus* zones of Barron (1983) (see Baldauf, 1985, and this volume for zonal comparison). Unfortunately, the first occurrence of *D. punctata* var. *hustedtii* cannot be exactly determined: samples from Core 555-22 contain poorly preserved diatoms and samples from below Core 555-22 are barren of diatoms. But even if *D. punctata* var. *hustedtii* occurred earlier at Site 406, this would not explain the occurrence of *D. hustedtii* and *Distephanus stauracanthus* and the absence of *Coscinodiscus lewisianus* and *Cestodiscus peplum*.

Cores 406-24 through 406-27

Samples from Cores 406-24 through 406-27 contain abundant fragments of *Ethmodiscus*. Although other species are occasionally observed, stratigraphic markers are generally rare. Sample 406-24-2, 98–100 cm contains poorly preserved and rare diatom fragments; no zonal assignment is possible.

Müller (1979; personal communication, 1985) places Sections 406-24-1 and 406-24-2 in calcareous nannofossil Zone NN4. Sample 406-24, CC and samples from

Cores 406-25 through 406-27 are assigned to the lower Miocene *Triquetrorhabdulus carinatus* Zone (NN1). Cores below 406-24-1, 133–137 cm and above 406-29-3, 98–102 cm cannot be zoned by planktonic foraminifers (Kraheninnikov, 1979) because faunas are poor and not age-diagnostic (undifferentiated uppermost Oligocene–low-ermost Miocene).

Assuming that the diatom and silicoflagellate stratigraphy is correct for Cores 406-22 and 406-23 and that Core 406-24 approximates calcareous nannofossil Zone NN4, then a hiatus must exist between Cores 406-23 (NN6–NN7) and 406-24 (NN4) or in the upper part of Core 406-24. Just below Section 406-24-1 there is a sharp lithological change from nannofossil chalk/siliceous nannofossil/chalk above Section 406-24-1 to a calcareous diatomite, dominated by *Ethmodiscus* fragments, lower in the section.

Cores 406-25 through 406-27 are placed by Müller (1979) in calcareous nannofossil Zone NN1. One specimen of *Coscinodiscus praenodulifer* was observed in Sample 406-25-2, 100–102 cm. Barron (1983) indicates that in the equatorial Pacific Ocean *C. praenodulifer* ranges from the *Rossiella paleacea* Zone to the *Denticulopsis nicobarica* Zone (early Miocene, NN1–NN4 equivalent). Probably this single specimen is reworked, so any zonal placement would be extremely tentative. Also present in Sample 406-25-1, 100–102 cm are the diatom species *Synedra jouseana*, *Macrora stella*, and *Hemiaulus polycystinorum*, and the silicoflagellates *Mesocena apiculata* and *M. apiculata* var. *curvata*.

Cores 406-28 and 406-29

Raphidodiscus marylandicus and *Thalassiosira spumellaroides* occur in Samples 406-28-1, 100–102 cm and 406-29-1, 49–51 cm. Sample 406-29-1, 49–51 cm also contains *Coscinodiscus rhombicus*, *Cestodiscus pulchellus*, s. ampl., and *Coscinodiscus praenodulifer*. Based on these species, Cores 28 and 29 are equivalent to the *Craspedodiscus elegans* or the *Rossiella paleacea* Zones of Barron (1983). The occurrence of *Raphidodiscus marylandicus* suggests that these samples are no older than the lower portion of the *Rossiella paleacea* Zone of Barron (1983). *Raphidodiscus marylandicus* has been observed in lower and middle Miocene sediments of the Norwegian-Greenland Sea region (Schrader and Fenner, 1976). At Site 610, it occurs only in Sample 610-25-3, 38–40 cm, which Baldauf (this volume) placed in the early Miocene *Craspedodiscus elegans* Zone. The presence of *T. spumellaroides* and *Coscinodiscus praenodulifer* supports a zonal placement for Sample 406-29-1, 110–112 cm no older than the *Rossiella paleacea* Zone. The upper zonal constraint is based on the rare occurrence of *C. rhombicus* in Sample 406-29-1, 49–51 cm. This suggests that Core 406-28 and 406-29 are early Miocene in age.

Bukry (1985) places Cores 406-25 through 406-30 in the lower Miocene and Cores 406-31 through 406-33 in the upper Oligocene *Distephanus speculum haliomma* silicoflagellate Subzone, but he also records an acme of *Rocella gelida* in Sample 406-33-1, 90–91 cm. In the South Atlantic Ocean a peak abundance of *R. gelida*

occurs directly below the Oligocene/Miocene boundary (Gombos and Ciesielski, 1983; Gombos, 1983). In the equatorial Pacific Ocean, *R. gelida* last occurs at the top of the *R. gelida* Zone (Barron, 1985b), which corresponds to the base of the *Rossiella paleacea* diatom Zone and is early Miocene in age. If the stratigraphic range of *Rocella gelida* is isochronous in the North Atlantic, then the Oligocene/Miocene boundary should occur just above Sample 406-33-1, 90–91 cm.

The nannofossil biostratigraphy of Müller (1979) for Cores 406-27 through 406-29 conflicts with the diatom and silicoflagellate biostratigraphy. Müller (1979) places the Oligocene/Miocene boundary between Cores 406-27 and 406-28, based on the extinction of *Helicosphaera recta*, and places Samples 406-28-1, 34–35 cm through 406-32-2, 15–17 cm in the late Oligocene *Sphenolithus ciproensis* Zone. As noted, the diatom and silicoflagellate stratigraphies suggest an early Miocene age for Cores 406-28 and 406-29.

Sedimentary Character and Diatom Preservation

The lower and middle Miocene of Hole 610 consist of pale green, laminated, nannofossil chalk (Site 610 chapter; Dolan, this volume; Hill, this volume). The green laminae contain lenses of chalk that have much higher proportions of quartz and smectite clay than the surrounding chalk. On smear slides, the pale green laminae show a high concentration of biogenic silica (primarily sponge spicules) and are associated with Zoophycos burrows. Pressure-solution features are observed in Cores 610-16 and Cores 610-24 through 610-27, and tectonic features such as inclined bedding occur in Core 610-17 and Cores 610-19 through 610-27 (Hill, this volume). The bedding usually has a dip of 10–20°, but in Core 610-24 dips as great as 40° occur and there are also cross-cutting microfaults with slickensides.

The lower and middle Miocene at Site 406 consists of a pale green gray diatom chalk (lower Miocene) that changes abruptly to a nannofossil ooze and chalk (middle Miocene) with a clay fraction dominated by smectite. Shipboard smear slide analyses indicate that diatoms compose up to 60% of the lower Miocene sediment, sponge spicules and radiolarians combined make up 5%, and calcareous nannofossils and foraminifers up to 40%.

The quality of the diatom preservation is poor to good in the lower Miocene in Holes 406 and 610 (*Craspedodiscus elegans* Zone through the lower portion of the *Denticulopsis nicobarica* Zone; Fig. 5). Within this interval, rare to abundant fragments of *Ethmodiscus* are observed. At Site 406 fragments of *Ethmodiscus* are common in samples tentatively placed in the *Rossiella paleacea* Zone and abundant in samples equivalent to the *Triceratium pileus* and *D. nicobarica* zones. Few to abundant fragments of *Ethmodiscus* occur in a few samples equivalent to the *T. pileus* Zone at Site 610 (see below for discussion of *Ethmodiscus* oozes).

Diatom preservation deteriorates in the sedimentary interval at Site 610 representing the latest early Miocene *D. nicobarica* Zone and calcareous nannofossil Zone NN4 (upper portion of Cores 610-24 through 610-22). Diatoms and silicoflagellates are rare or absent within

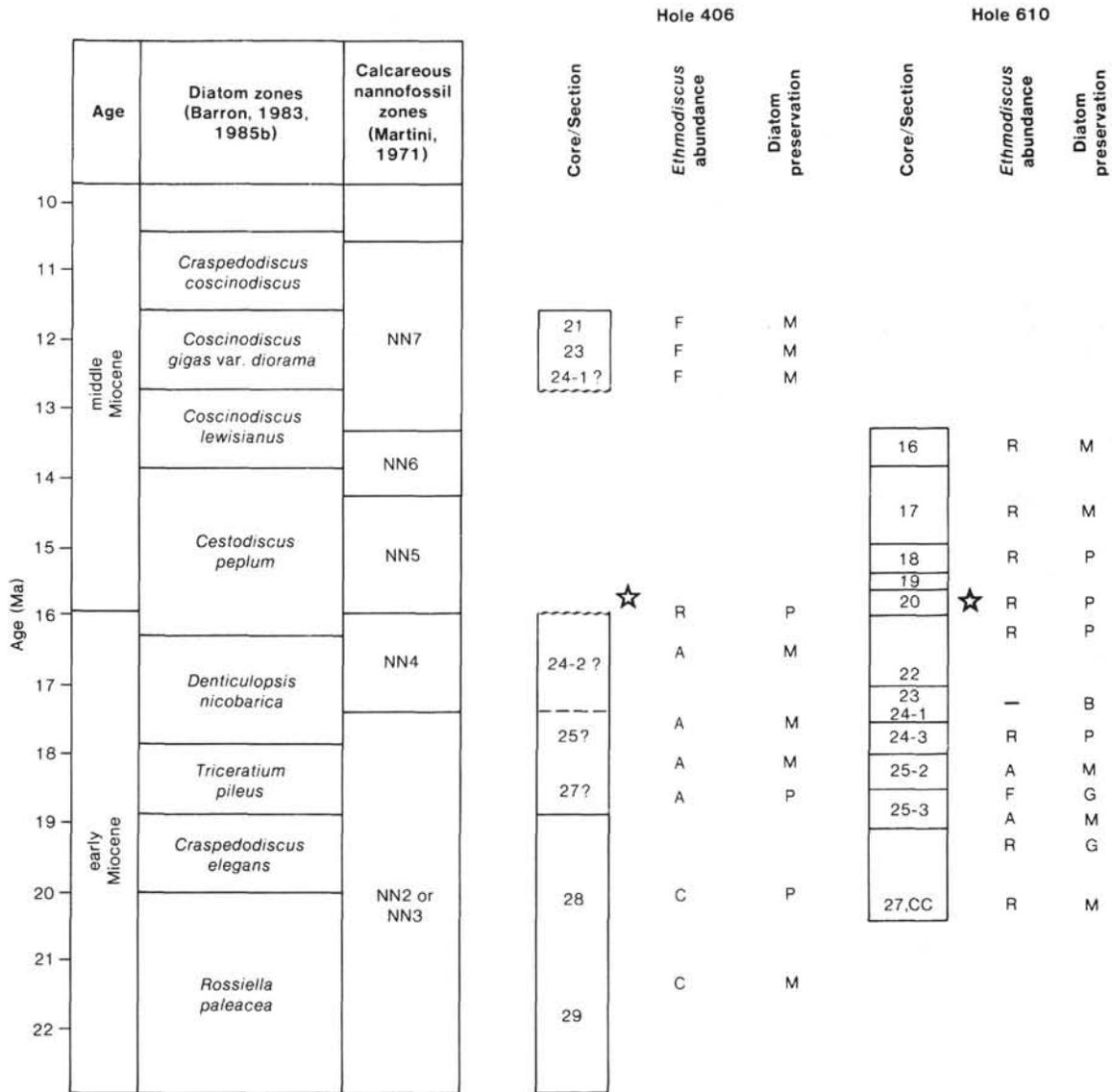


Figure 5. Correlation of the abundance of *Ethmodiscus* fragments, diatom preservation, the “R2” seismic reflector, and the cores in Holes 406 and 610 with the absolute time scale and the diatom zonation of Barron (1983, 1985b) and the nannofossil zonation (Martini, 1971). Biostratigraphic data are after Baldauf (this volume) and Takayama and Sato (this volume) for Hole 610, and as discussed in this chapter for Hole 406. A = abundant, C = common, F = few, R = rare, B = barren. For preservation, P = poor, M = moderate, G = good. The gaps between Cores 610-16 and -19 represent washed intervals. The gap between Cores 406-23 and 406-24 represents a hiatus (as discussed in this chapter). The stars indicate the position of the “R2” reflector.

this interval and fragments of sponge spicules and radiolarians compose most of the biogenic silica. Occasional samples contain large concentrations of sponge spicule fragments (particularly Samples 610-19,CC through 610-21,CC). Diatoms and silicoflagellates become rare at approximately the early middle Miocene boundary (lower *Cestodiscus peplum* Zone). The abrupt decrease in the quality of diatom preservation at Site 610 is not observed at Site 406, but diatoms and silicoflagellates become rare close to the interval where a hiatus is probably present, at approximately the lower/middle Miocene boundary.

Diatom preservation at Site 610 is moderate in the middle Miocene (uppermost *C. peplum* and lower *Coscinodiscus lewisianus* zones) in so far as it is possible to

say in this spot-cored interval. The equivalent interval is missing because of a hiatus at Site 406. Directly above the hiatus (*C. gigas* var. *diorama* Zone) diatoms are moderately well preserved.

Seismic survey profiles from the Rockall Plateau region show a prominent acoustic reflector at 0.75 s sub-bottom (two-way traveltime), which would correspond to the depth interval of Core 610-19. At Site 610, an increase in seismic velocity occurs over the stratigraphic interval from Cores 610-16 through 610-22 (0.62–0.81 s) (Masson and Kidd, this volume), probably resulting from the integration of a relatively sudden increase in seismic velocities over the interval representing 625–675 m sub-bottom (lower *Cestodiscus peplum* through lower *D. nicobarica* zones). The interval of increased seismic ve-

locity coincides with the interval of poor diatom preservation and approximates the early/middle Miocene boundary. A pronounced decrease in the drilling rate for Cores 610-19 through 610-23 also occurs at approximately that boundary; it is the result of increased lithification of the sediment (see Operations section, Site 610 chapter).

At Site 406, the hiatus between Cores 406-24 and 406-23 (Zone NN5), approximates the depth at which Montadert et al. (1979) record an increase in the seismic velocity (0.60 s two-way traveltime) identifying it as Reflector "2," corresponding to the "R2" seismic reflector of Miller and Tucholke (1983). Miller and Tucholke (1983) note that high-latitude North Atlantic DSDP sites, except for Sites 116 and 406, contain a hiatus at approximately the lower/middle Miocene boundary, but this study has shown that such a hiatus may exist at Site 406.

The numerous hiatuses occurring during the early/middle Miocene period have led some authors to postulate increased current activity (Shor and Poore, 1979; Keller and Barron, 1983; Miller et al., this volume). The hiatus at Site 406 corresponds in part to the "NH2" hiatus (approximately 16.0–15.0 Ma), which Keller and Barron (1983) observed throughout the low-latitude Atlantic and Pacific oceans and the Caribbean.

Occurrence of *Ethmodiscus*

Ethmodiscus represents a minor portion of the modern plankton assemblage (Belyayeva, 1968), and yet *Ethmodiscus* oozes are found in upper Miocene, Pliocene, and Pleistocene sediments from various regions of the world's oceans (Mikkelsen, 1977). *Ethmodiscus* was observed at Sites 406 and 610 (this study), and Barron (1983, 1985a) indicates that common fragments of *Ethmodiscus* occur in lower Miocene samples from Sites 495 and 575 in the eastern equatorial Pacific Ocean, most abundantly in the *Triceratium pileus* Zone. These common occurrences are, therefore, approximately synchronous with the similar occurrences at Site 610 within the Rockall Plateau region.

Belyayeva (1968), regarding modern plankton, and Gardner and Burckle (1975), regarding Pleistocene sediments, have observed that *E. rex* has a greater concentration within the equatorial region. Maximum concentrations of this species have been recorded between the equator and 6°N in both the Atlantic and Pacific oceans. Belyayeva (1968) also suggests that *E. rex* may favor regions where surface waters have a low phosphate concentration. Although Gardner and Burckle (1975) could not discount current redeposition as the mechanism producing the upper Pleistocene oozes, they favored the mechanism of intensified phytoplankton blooms, possibly somewhat similar to the modern dinoflagellate "red tide" blooms.

Mikkelsen (1977) has determined that *E. rex* is one of the most dissolution-resistant diatoms and has established types of *E. rex* ooze. The first consists of 99% *E. rex* fragments and results from differential dissolution followed by winnowing of the sediment. The second is dominated by *E. rex* fragments and other solution-resistant species, and Mikkelsen suggests that it results directly

from dissolution. At the present time, arguments can be proposed to support the bloom hypothesis of Gardner and Burckle (1975), the dissolution hypothesis of Mikkelsen (1977), or a combination of both.

If intense monospecific blooms are the main mechanism for creating *Ethmodiscus* oozes, and if such a model can be applied to early Miocene paleoceanographic conditions, then the surface waters within the Rockall Plateau region may have been low in phosphate and tropical in character.

Differential dissolution, however, can also be used to explain the abundant fragments of *Ethmodiscus* in the lower Miocene of the Rockall Plateau region. Dissolution of the diatom assemblage could result from intensified circulation of the middle or bottom waters, which are undersaturated with respect to biogenic silica. The occurrence of only fragments and the absence of finely silicified frustules in samples directly above the *Ethmodiscus* interval at Sites 406 and 610 also suggest silica dissolution, which may or may not be combined with winnowing of the sediment. The strongest evidence for intensification of currents is the possible hiatus that occurs at Site 406, stratigraphically above the *Ethmodiscus* interval.

An additional possibility is that the silica dissolution is postdepositional and may be related to the factors responsible for the microfaults and other sedimentological and lithological changes at Site 610 (Dolan, this volume; Hill, this volume). Further sites and samples must be studied before a model can be adopted.

CONCLUSIONS

The microfossil and sedimentological data for the lower and middle Miocene sediment of Holes 406 and 610 suggest that major oceanographic changes occurred in the Rockall Plateau region of the North Atlantic Ocean during this time. The lower Miocene (*Craspedodiscus elegans*, *Triceratium pileus* zones) is characterized by few to abundant fragments of *Ethmodiscus*. The interval approximating the lower/middle Miocene boundary (upper portion of the *Denticulopsis nicobarica* and the lower portion of the *Cestodiscus peplum* zones) is characterized by a decline in the quality of diatom preservation and by the presence of the "R2" reflector.

At Site 610, the upper middle Miocene (upper *C. peplum* and lower *Coscinodiscus lewisianus* zones) is characterized by a moderately well preserved diatom assemblage. Reinterpretation of the Leg 48 biostratigraphic results using diatoms and silicoflagellates suggests that a hiatus representing the lower/middle Miocene boundary occurs at Site 406 (parts of the *C. peplum* and *C. lewisianus* zones). Few, moderately well preserved diatoms occur above this hiatus.

The occurrences of moderately well preserved diatoms in the middle Miocene suggest that conditions favorable to diatom preservation returned to the Rockall Plateau region during that time. Such conditions may have included increased surface water productivity and rapid burial, decreases in intensity of bottom-water circulation, and decreases in postdepositional dissolution.

SUMMARY

Three stratigraphic intervals can be recognized in lower and middle Miocene sediments from diatoms at Sites 406 and 610. The lower Miocene diatom assemblage is characterized by fragments of *Ethmodiscus*. The interval representing the lower/middle Miocene boundary is characterized by poor diatom preservation. The lower middle Miocene interval generally consists of rare, poorly preserved diatoms. The quality of diatom preservation is moderate in the upper middle Miocene. The common to abundant occurrence of *Ethmodiscus* fragments suggests either increased surface-water productivity or increased dissolution, possibly related to intensified mid- or bottom-water currents.

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REFERENCES

- Baldauf, J. G., 1985. Cenozoic diatom biostratigraphy and paleoceanography of the Rockall Plateau Region of the North Atlantic, Deep Sea Drilling Project Leg 81. In Roberts, D. G., Schnitker, D., et al., *Init. Repts. DSDP*, 81: Washington (U.S. Govt. Printing Office), 439-478.
- Barron, J. A., 1983. Latest Oligocene through early middle Miocene diatom biostratigraphy of the eastern tropical Pacific. *Mar. Micropaleontology*, 7:487-515.
- _____, 1985a. Late Eocene to Holocene diatom biostratigraphy of the equatorial Pacific Ocean, DSDP Leg 85. In Mayer, L., Theyer, F., et al., *Init. Repts. DSDP*, 85: Washington (U.S. Govt. Printing Office), 413-456.
- _____, 1985b. Miocene to Holocene planktic diatoms. In Saunders, J. B., Bolli, H. M., and Perch-Nielsen, K. (Eds.), *Biostratigraphy by Marine Plankton*: Cambridge (Cambridge University Press), pp. 763-809.
- Barron, J. A., Keller, G., and Dunn, D. A., 1985. A multiple microfossil biochronology for the Miocene. In Kennett, J. P. (Ed.), *The Miocene Ocean: Paleoceanography and Biogeography*. Geol. Soc. Am. Mem., 163:21-36.
- Belyayeva, T. V., 1968. Distribution and numbers of diatoms *Ethmodiscus* Castr. in plankton and in bottom sediments of the Pacific Ocean. *Okeanologiya*, 8:102-109.
- Berggren, W. A., Kent, D. V., and Van Couvering, J. A., in press. Neogene geochronology and chronostratigraphy. In Snelling, N. J. (Ed.), *Geochronology and the Geologic Time-Scale*. Geol. Soc. London Mem.
- Bukry, D., 1973. Phytoplankton stratigraphy, central Pacific Ocean, Deep Sea Drilling Project Leg 17. In Winterer, E. L., Ewing J. I., et al., *Init. Repts. DSDP*, 17: Washington (U.S. Govt. Printing Office), 871-881.
- _____, 1978. Cenozoic coccolith and silicoflagellate stratigraphy offshore Northwest Africa, Deep Sea Drilling Project, Leg 41. In Lancelot, Y., Seibold, E., et al., *Init. Repts. DSDP*, 41: Washington (U.S. Govt. Printing Office), 689-708.
- _____, 1981. Synthesis of silicoflagellate stratigraphy for Maestrichtian to Quaternary marine sediments. In Warme, J. E., Douglas, R. G., and Winterer, E. L. (Eds.), *The Deep Sea Drilling Project: A Decade of Progress*. Soc. Econ. Mineral. Paleontol., Spec. Publ., 32:433-444.
- _____, 1985. Cenozoic silicoflagellates from Rockall Plateau, Deep Sea Drilling Project Leg 81. In Roberts, D. G., Schnitker, D., et al., *Init. Repts. DSDP*, 81: Washington (U.S. Govt. Printing Office), 547-564.
- Gardner, J. V., and Burckle, L. H., 1975. Upper Pleistocene *Ethmodiscus rex* oozes from the eastern equatorial Atlantic. *Micropaleontology*, 21(2):236-242.
- Gombos, A. M., Jr., 1983. Survey of diatoms in the upper Oligocene and lower Miocene in Holes 515B and 516F. In Barker, P. F., Carlson, R. L., Johnson, D. A., et al., *Init. Repts. DSDP*, 72: Washington (U.S. Govt. Printing Office), 793-804.
- Gombos, A. M., Jr., and Ciesielski, P. F., 1983. Late Eocene to early Miocene diatoms from the southwest Atlantic. In Ludwig, W. J., Krashennikov, V. A., et al., *Init. Repts. DSDP*, 71: Washington (U.S. Govt. Printing Office), 583-634.
- Keller, G., and Barron, J. A., 1983. Paleocyanographic implications of Miocene deep-sea hiatuses. *Geol. Soc. Am. Bull.*, 94:590-613.
- Krashennikov, V. A., 1979. Stratigraphy and planktonic foraminifers of Cenozoic deposits of the Bay of Biscay and Rockall Plateau, DSDP Leg 48. In Montadert, L., Roberts, D. G., et al., *Init. Repts. DSDP*, 48: Washington (U.S. Govt. Printing Office), 431-450.
- Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In Farinacci, A. (Ed.), *Proc. II Conf. Planktonic Microfossils, Roma* (Vol. 2): Rome (Edizioni Tecnoscienza), 739-786.
- Mikkelsen, N., 1977. On the origin of *Ethmodiscus* ooze. *Mar. Micropaleontology*, 2:35-46.
- Miller, K. G., and Tucholke, B. E., 1983. Development of Cenozoic abyssal circulation south of the Greenland-Scotland Ridge. In Bott, M. H. P., Saxov, S., Talwani, M., and Thiede, J. (Eds.), *Structure and Development of the Greenland-Scotland Ridge*: New York (Plenum), pp. 549-589.
- Montadert, L., Roberts, D. G., et al., 1979. *Init. Repts. DSDP*, 48: Washington (U.S. Govt. Printing Office).
- Müller, C., 1979. Calcareous nannofossils from the North Atlantic (Leg 48). In Montadert, L., Roberts, D. G., et al., *Init. Repts. DSDP*, 48: Washington (U.S. Govt. Printing Office), 589-639.
- Schrader, H. J., and Fenner, 1976. Norwegian Sea Cenozoic diatom biostratigraphy and taxonomy. In Talwani, M., Udintsev, G., et al., *Init. Repts. DSDP*, 38: Washington (U.S. Govt. Printing Office), 921-1099.
- Shor, A. N., and Poore, R. Z., 1979. Bottom currents and ice rafting in the North Atlantic: interpretations of Neogene depositional environments of Leg 49 cores. In Luyendyk, B. P., and Cann, J. R., et al., *Init. Repts. DSDP*, 49: Washington (U.S. Govt. Printing Office), 859-872.

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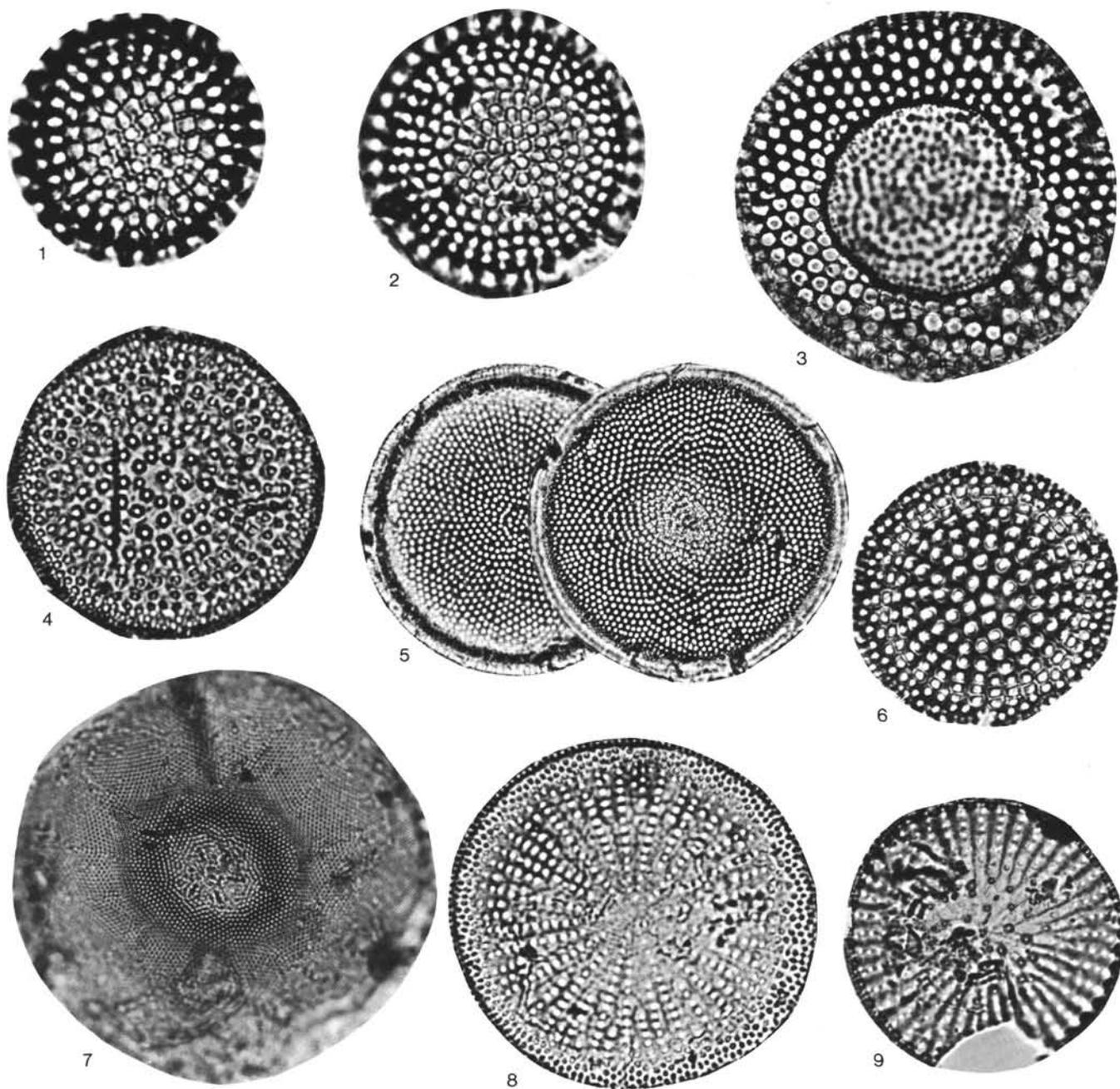


Plate 1. Miocene diatoms. (Sample 610-27-2, 48-50 cm, unless otherwise indicated.) 1, 2. *Thalassiosira fraga* Schrader, (1) diameter 21 μ m, (2) diameter 25 μ m. 3. *Craspedodiscus coscinodiscus* Ehrenberg, Sample 610-16-4, 48-50 cm, diameter 62 μ m. 4. *Cestodiscus pulchellus* Greville, diameter 45 μ m. 5. *Actinocyclus* sp., diameter 56 μ m. 6. *Actinocyclus ingens* Rattray, Sample 406-23-2, 106-108 cm, diameter 35 μ m. 7. *Coscinodiscus symbolophorus* Grunow, diameter 112 μ m. 8. *Cestodiscus* sp., diameter 48 μ m. 9. *Stictodiscus californicus* Greville, Sample 610-27-6, 48-50 cm, diameter 70 μ m.

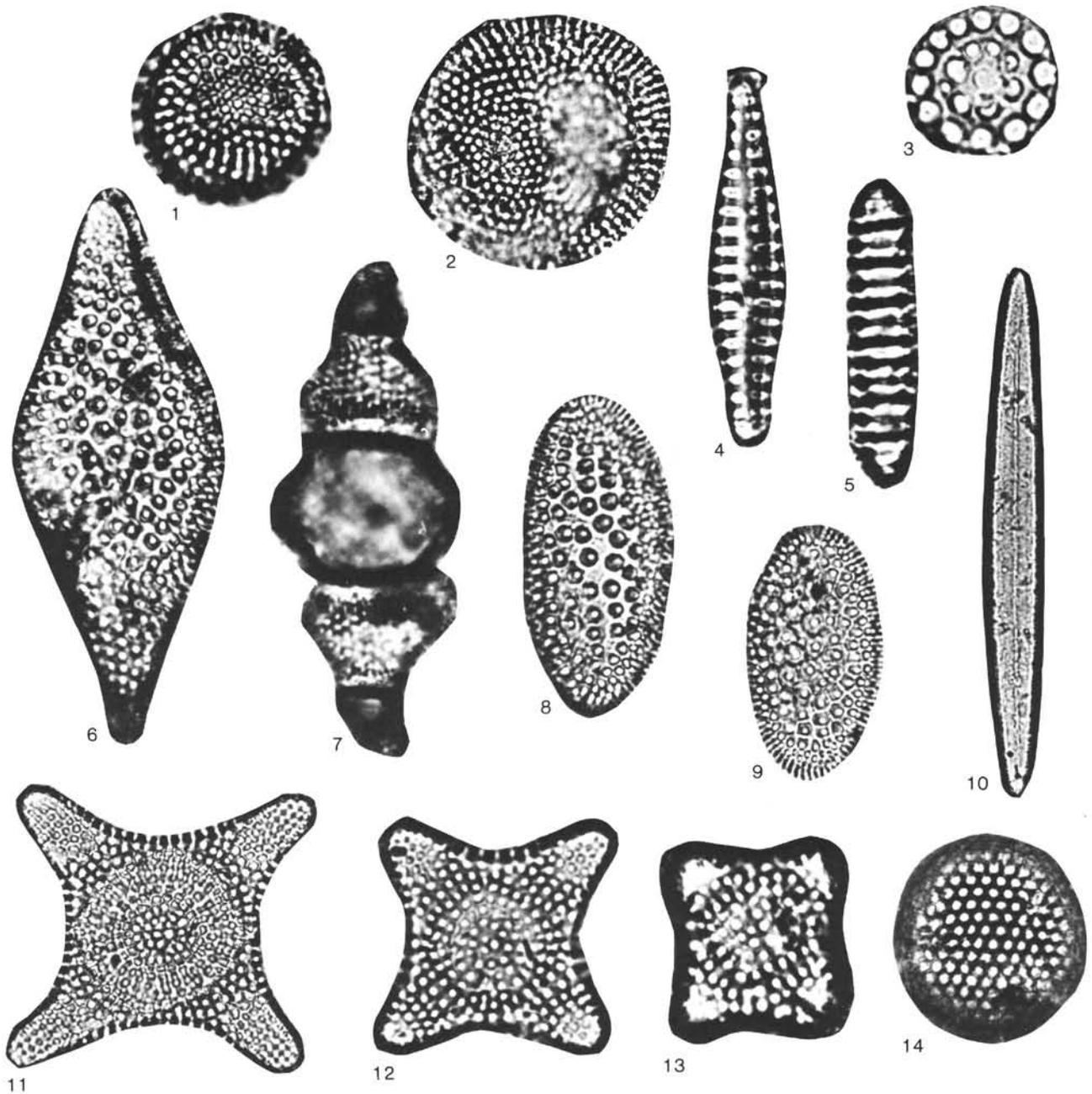
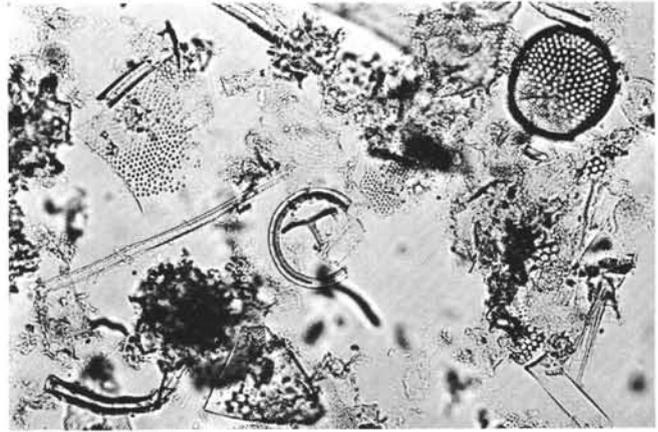


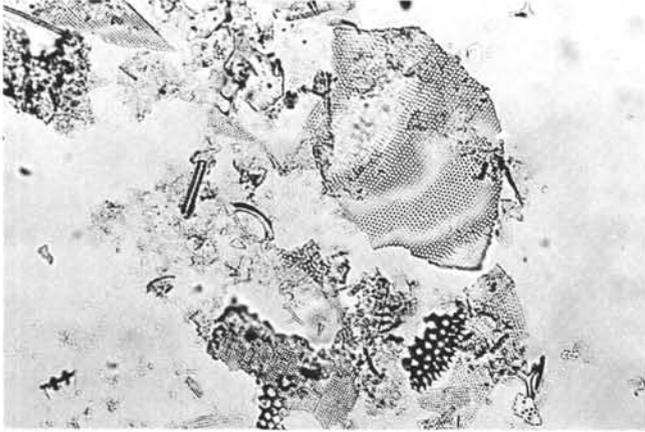
Plate 2. Miocene diatoms. (Sample 610-27-2, 48-50 cm unless otherwise indicated.) 1. *Thalassiosira fraga* Schrader, Sample 610-27-6, 48-50 cm, diameter 17 μm . 2. *Coscinodiscus plicatus* Grunow, Sample 610-16-4, 48-50 cm, diameter 36 μm . 3. *Macrora stella* Hanna, diameter 10 μm . 4. *Sceptroneis* sp., length 43 μm . 5. *Denticulopsis hustedtii* (Simonsen and Kanaya) Simonsen, Sample 610-16-4, 48-50 cm, length 25 μm . 6. *Coscinodiscus rhombicus* Castracane, Sample 610-25-3, 48-50 cm, length 56 μm . 7. *Biddulphia tuomeyi* Roper, Sample 610-27-6, 48-50 cm, length 53 μm . 8. *Coscinodiscus lewisianus* Greville, Sample 610-27-6, 48-50 cm, length 28 μm . 9. *Coscinodiscus* sp., Sample 610-25-3, 48-50 cm, length 27 μm . 10. *Synedra jouseana* Sheshukova-Poretzkaya, length 77 μm . 11. *Trinacria* sp. cf. *T. excavata* var. *tetragona* Rabinovich, length 43 μm . 12, 13. *Trinacria excavata* var. *tetragona* Rabinovich, (12) length 24 μm , (13) length 14 μm . 14. *Stephanopyxis* sp., Sample 406-29-1, 49-51 cm, diameter 23 μm .



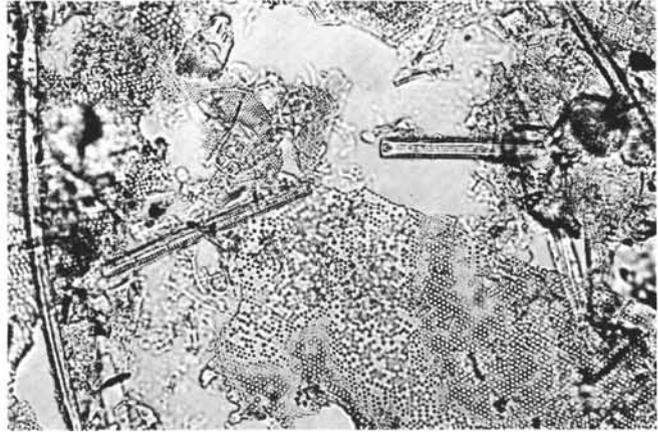
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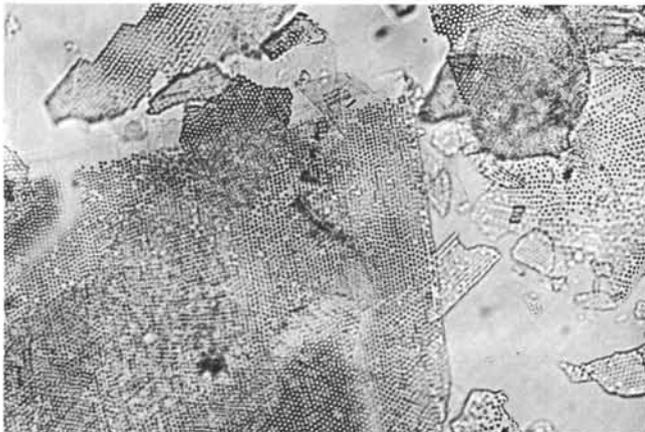
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Plate 3. 1-5. *Ethmodiscus* fragments; width of picture represents one field of view (240 μ m), and preservation of samples is moderate, (1, 5) Sample 406-26-1, 13-15 cm, (2, 3) Sample 406-25-1, 100-102 cm; (4) Sample 610-24-3, 44-46 cm. 6. Fragments of sponge spicules, Sample 610-19, CC; width of picture represents one field of view (240 μ m), and preservation of sample is poor.