29. RECENT TO MIDDLE MIOCENE DIATOM PRODUCTIVITY AT SITE 907, ICELAND PLATEAU[1]

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ABSTRACT

Surface water productivity at Ocean Drilling Program Site 907 has been assessed from total diatom abundance and *Chaetoceros* resting spore frequency. The sediments are divided into four intervals based on relative diatom abundance. Intervals 1 and 4 are mainly barren of diatoms. Interval 2 shows a highly fluctuating abundance pattern, whereas Interval 3 is a biosilica-rich middle to late Miocene (13.7–10.1 Ma) sediment containing abundant diatoms dominated by *Chaetoceros* resting spores. Resting spores of *Chaetoceros* are classified according to their forms. The round to elongate spores with smooth surfaces or spines/ridges dominate the assemblage throughout the biosilica-rich interval. The transition from the diatom barren interval to the biosilica-rich interval at about 13.7 Ma is characterized by extremely high (100%–85%) *Chaetoceros* spore content. The late Miocene to late Pliocene (10.1–3.0 Ma) interval with highly variable diatom content is characterized with lower *Chaetoceros* percentages than in the biosilica-rich interval. We infer that the period between 13.7 and 10.1 Ma reflects high surface water productivity at Site 907. The high percentage of *Chaetoceros* resting spores at this interval suggests upwelling of nutrient-rich subsurface waters during this period.

INTRODUCTION

The Norwegian-Greenland Sea is considered to have two distinct Tertiary biosilica-enriched intervals that occurred during the Eocene and the Miocene. Sediments characterized as biosiliceous rich/diatom ooze have been reported earlier from the Miocene sections of Deep Sea Drilling Project (DSDP) Sites 338, 341, 342, and 348, and from Ocean Drilling Program (ODP) Sites 642 and 643. Preservation of these biosiliceous sediments is interpreted to indicate the presence of highly productive surface waters during these times. Surface water productivity, by controlling the supply rate of siliceous valves to the seafloor and the silica saturation level of the pore waters, exerts a primary control on the abundance of siliceous microfossils in the sediments (Schink et al., 1974; Broecker and Peng, 1982; Pokras and Molfino, 1986). Seawater is typically undersaturated with respect to silica (Lisitzin, 1972; Heath, 1974). Therefore, most of the siliceous skeletons produced in the photic zone dissolve before entering the sedimentary record (Berger, 1976). The impact of this dissolution on the geological record is a function of relative rather than absolute loss of siliceous valves (Pokras, 1986). The rates of biogenic silica accumulation through time are, therefore, a general indication of surface water productivity changes. The recovery of a Holocene to middle Miocene near-continuous sediment sequence with a pristine paleomagnetic record at ODP Site 907 on the Iceland Plateau gave us a unique opportunity to study the evolution of Neogene surface water productivity as assessed from total diatom abundance and *Chaetoceros* resting spore fluctuations.

ODP Leg 151 is the third DSDP/ODP leg in the Norwegian-Greenland Sea. DSDP Leg 38 cored 17 sites. However, due to spot- and rotary-coring techniques employed at these sites, the material recovered was discontinuous and lacked paleomagnetic stratigraphy. ODP Leg 104 (Eldholm, Thiede, Taylor, et al., 1987) concentrated on three holes on the Vøring Plateau. These sites were drilled with the advanced hydraulic piston corer (APC) with high recovery and good sample quality. However, these sequences include a number of Neogene hiatuses, and the interpretation of the paleomagnetic record is problematic. ODP Leg 151 employed APC/XCB (extended core barrel) coring techniques and retrieved 100% recoveries with very good sample quality. Biosiliceous-rich sediments were retrieved from Sites 907, 908, and 913.

Samples from the diatom-rich Oligocene/Eocene interval at ODP Site 913 were processed in an attempt to assess the surface water productivity during these times and to compare it with the diatom assemblage at Site 907. The diatoms at Site 913 were, however, so fragmented that they were not suitable for any quantitative study. It has been difficult to compare the results from Site 907 with available information from DSDP Leg 38, as the diatom investigation from that leg was a pioneering study on Norwegian Sea diatom biostratigraphy and, therefore, only minimally dealt with abundances and *Chaetoceros* spores.

Site 907 is located on the Iceland Plateau in the southwestern part of the Norwegian-Greenland Sea, between the Kolbeinsey Ridge and the Jan Mayen Ridge (Fig. 1). The site represents part of the western extension of a paleoenvironmental transect from the Norwegian (ODP Leg 104) to the Greenland continental margin. The diatom abundance pattern at ODP Site 907 was studied to understand the temporal and spatial distribution of Neogene biosiliceous production in the Norwegian-Greenland Sea.

MATERIALS AND METHODS

For relative diatom abundances at least one sample was examined from each core section (1.5 m). All samples were treated with 37% HCl and 30% hydrogen peroxide and washed with distilled water until a pH of 7 was achieved. Strewn slides of acid-cleaned material were examined at 400×. Species were recorded as abundant (A) if six or more specimens were present in one field of view at 400×; common (C) if one to five specimens occurred in one field of view; few (F) if one to four specimens occurred in five fields of view; or rare (R) if one to 10 specimens occurred per horizontal traverse.
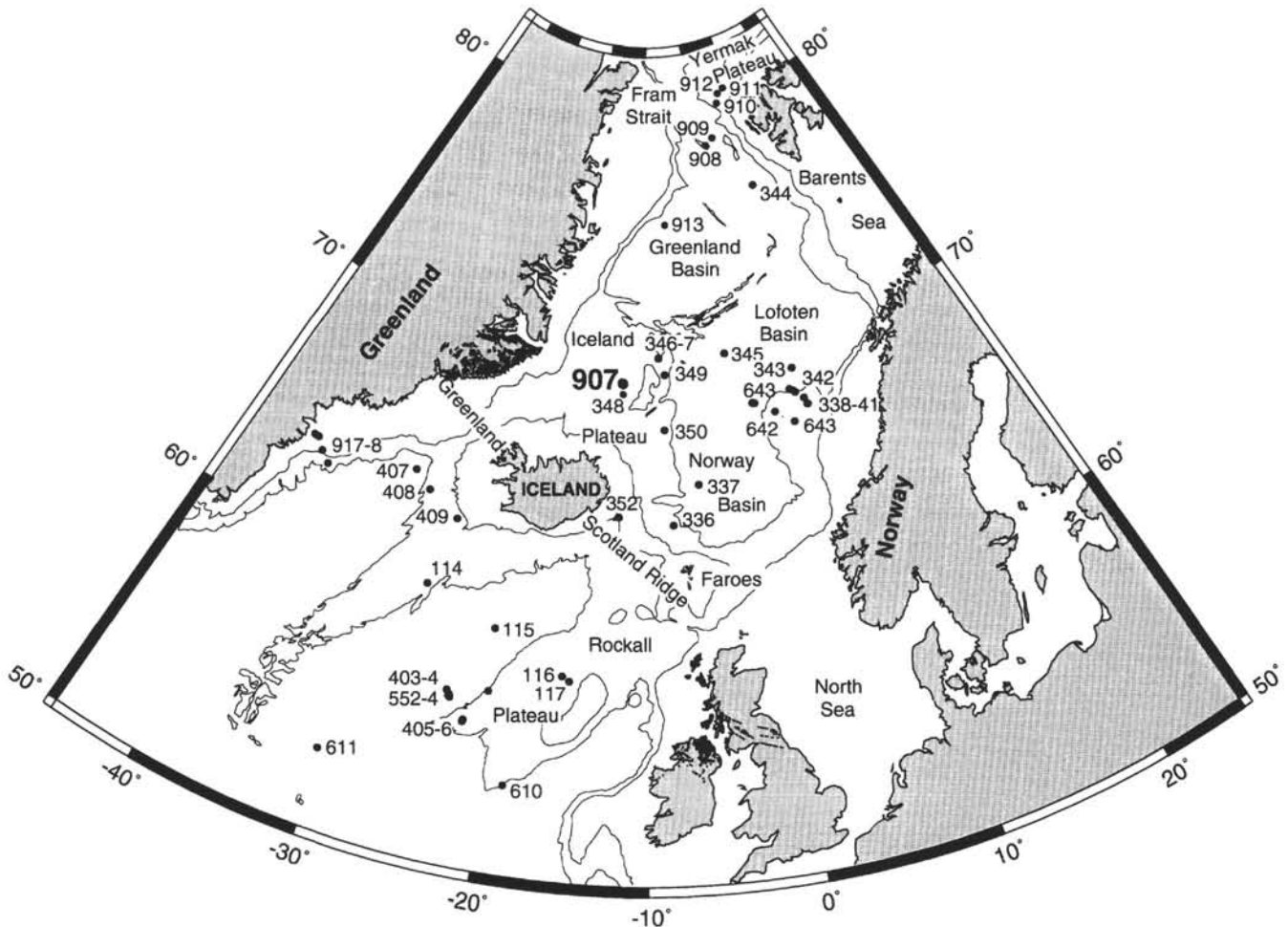
Figure 1. Location map of Site 907 with DSDP/ODP sites marked.

For the biosilica-rich interval, the diatom samples were prepared based on the procedure described in Kaland and Stabell (1981), adding *Lycopodium* spores as a marker for absolute control in quantitative estimates. About 0.02 g dry sediment was oxidized in H_2O_2 and repeatedly washed. Calcareous matter was removed with HCl. For 0.02 g dry sediment about 2.5×10^5 *Lycopodium* spores were added. With this method, only the weight of the sediment sample and the number of Lycopodium spores added need to be known, and the number of diatom valves per gram dry sediment can then be calculated. Diatoms on the quantitative slides from Interval 3 were identified and counted. The percent distribution of resting spores of *Chaetoceros* (see Figs. 4, 5) are based on these counts.

The sediment in this core is, however, characterized by numerous volcanic ash layers. Therefore, absolute abundances in this environment more likely reflect fluctuations in ash content rather than diatom productivity. Mass accumulation rates were, therefore, not calculated. Ages for Site 907 are mainly based on magnetostratigraphy (Koç and Scherer, this volume).

RESULTS

The relative total diatom abundance pattern of Site 907 can be divided into four major intervals (Fig. 2). Interval 1, between 0 and 55 meters below seafloor (mbsf) (Pleistocene to upper upper Pliocene), is mainly barren except for the top of the core (0.04 and 0.13 mbsf).

Interval 2, between 55 and 120 mbsf (upper upper Pliocene to lower upper Miocene), exhibits a fluctuating diatom abundance pattern (from barren to abundant). Interval 3, between 120 and 198 mbsf, consists of continuously abundant diatoms. Interval 4, the lowermost part of the hole between 198 and 220 mbsf, is barren of diatoms. This division also corresponds well with the lithologic units. The sediments recovered at Site 907 were divided into five lithologic units based primarily on the varying amounts of biogenic and siliciclastic material and volcanic glass (Myhre, Thiede, Firth, et al., 1995). The pattern of diatom deposition observed from Site 907 shows an evolution from middle Miocene to Holocene, with high biosilica deposition through the middle-early late Miocene, fluctuating biosilica deposition through the middle late Miocene–middle late Pliocene and very sporadic biosilica deposition through the middle late Pliocene–Holocene.

IRD Record and Diatom Abundance

Changes in diatom abundance patterns correlate well with increase of ice-rafted detritus (IRD) in the area (Fig. 3). The interval containing diatoms have a generally lower gamma-ray attenuation porosity evaluator (GRAPE) density than the intervals where there are no or very sporadic occurrences of diatoms. No IRD is recorded in the diatom-rich interval occurring between 120 and 198 mbsf, indicating warm surface waters during this period of high surface water productivity in the area during the middle and early late Miocene.
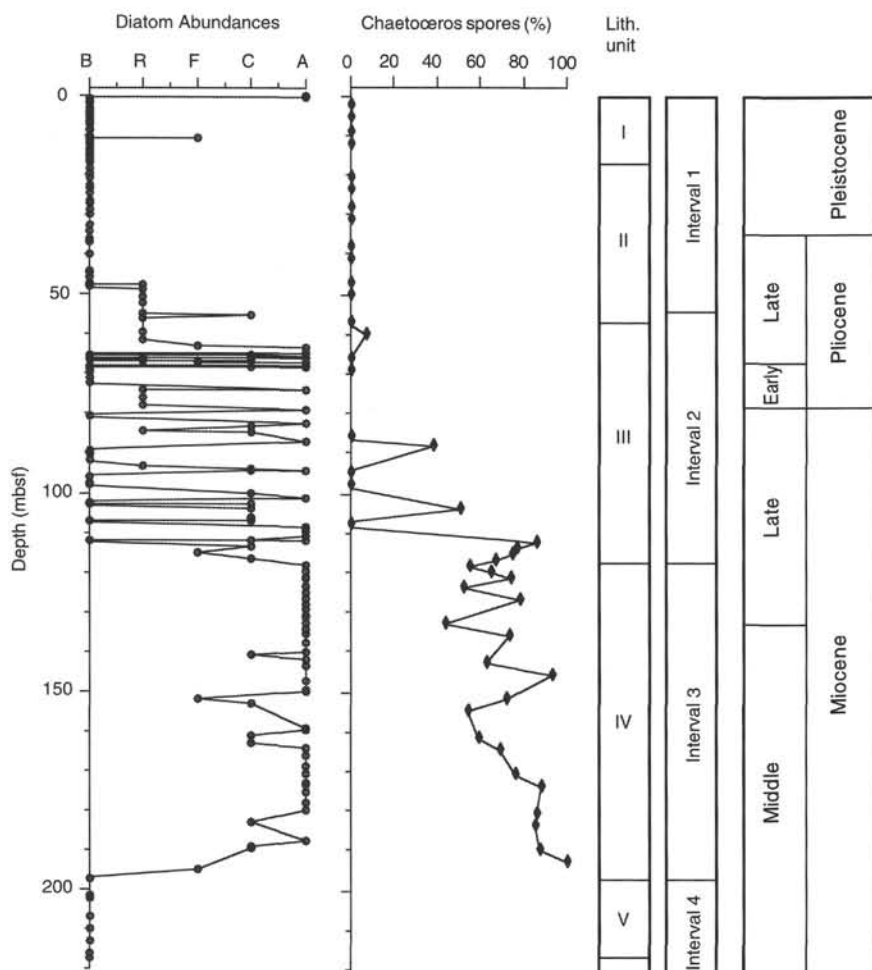
Figure 2. Relative diatom abundances (see text for abbreviations) and percentage distribution of *Chaetoceros* resting spores at Site 907. No resting spores indicates samples also barren in diatoms.

Fluctuating diatom abundances are recorded between 10 and 2.9 Ma. The first IRD at Site 907 is recorded at 118 mbsf (at about 10 Ma; Koç and Scherer, this volume) corresponding to the start of fluctuating diatom abundances indicating variable surface water conditions in response to waxing and waning ice sheets in the surrounding land masses. Low concentrations of IRD persist until 2.9 Ma. Fronval and Jansen (this volume) argue that the period between 6 and 2.9 Ma represents the onset of middle-sized glaciations in the Northern Hemisphere. Diatoms disappear nearly entirely from the sedimentary record of Site 907 as the IRD input to the area intensified around 2.9 Ma, indicating the presence of large-scale glaciations around the Nordic Seas (Fronval and Jansen, this volume).

Chaetoceros **Resting Spores at Site 907**

Interval 4 has little or no biogenic components (Myhre, Thiede, Firth et al., 1995) and is directly overlain by a biosiliceous-rich unit (Unit 3 = Interval 3; Fig. 2). Interval 3 was studied in most detail as this interval showed a continuous high diatom abundance. Diatom resting spores constitute a high percentage of the diatom assemblage in this high-abundance interval. The results of the absolute abundance calculations are shown in Fig. 4A. Total abundances fluctuate from less than 10 to nearly 200 million diatoms per gram dry sediment. These fluctuations are believed to reflect fluctuations in ash content rather than diatom productivity. The biosilica-rich Interval 3 was investigated semi-quantitatively to quantify fluctuations in upwelling by studying variations in the percentage of *Chaetoceros* rest-

ing spores at this interval (Fig. 4B). All but one sample at Interval 3 have more than 50% resting spores. The percent distribution of resting spores shows a gradual decrease from the bottom of this interval (at 193 mbsf) with 100% resting spores to the middle (at 155 mbsf) with about 50% resting spores. Above 155 mbsf, resting spore percentages generally fluctuate between 50% and 80%.

In an attempt to distinguish at least the major spore types, the resting spores were grouped after morphological characteristics (Pl. 1). Group A is round to elongate. A1 has a fairly smooth surface (Pl. 2), resembling *C. lauderi* of Hargraves (1979). A2 has a surface with spines/ridges (Pl. 3), resembling *Xanthiopyxis* of Hargraves (1986). Group B is of the more traditional *Chaetoceros* type with setae (Pl. 4). Group C is the *Chaetoceros/Pterotheca* types, Group D is *Chaetoceros cinctus* types, Group E is a type with a rough surface, and Group F is other (spores not given any other category).

Groups A1 and A2 are the dominant groups throughout the studied interval (Fig. 5). A1 constitutes between 40% and 95% of the total resting spores, while A2 makes up from less than one to 34% of the total. Together they comprise between 61% and 95% of the total resting spore assemblage. Group B has its highest percentages (15%–20%) in the upper and lower part of the investigated section, whereas Group C has high percentages (as much as 25%) between 130 and 160 mbsf. Group D is recorded in three samples with around 5% contribution, while Group E has only been recognized in one sample (126.5 mbsf) where it comprised 13% of the resting spore assemblage. Resting spores not assigned to a specific group vary between 0% and 17%.
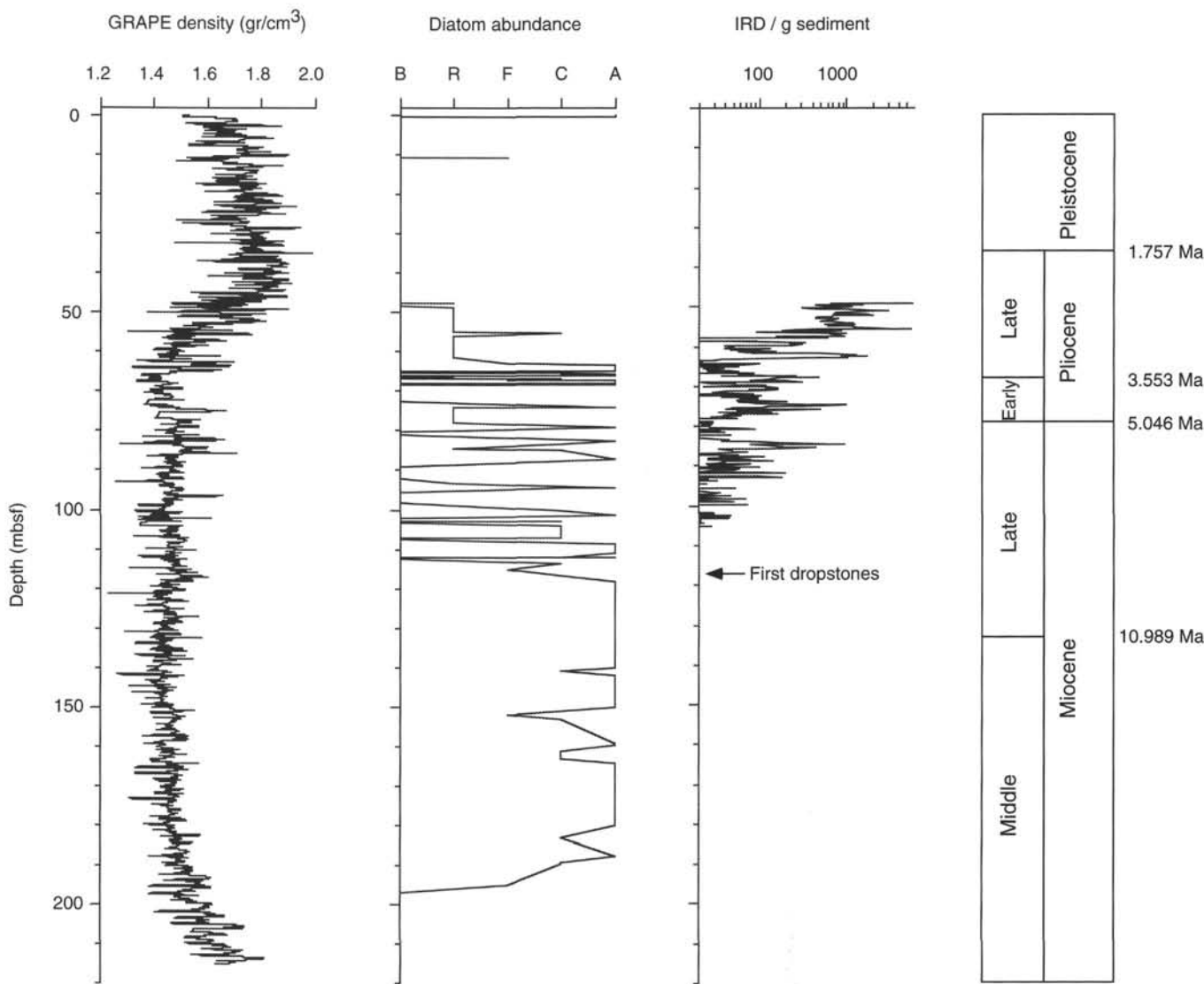
Figure 3. GRAPE data, diatom abundances, and ice-rafted detritus (IRD) content at Site 907.

DISCUSSION

Chaetoceros Resting Spores and Upwelling

Spores of the genus *Chaetoceros* are usually taken as a measure of diatom productivity (Sancetta, 1982; Abrantes, 1988). These spores are believed to characterize the late stage production in coastal upwelling areas, but it is also possible that in an offshore setting they indicate some degree of erosion and lateral advection from shelf sediments (Sancetta et al., 1992). Akiba (1986) discusses the possibility that mass occurrences of *Chaetoceros* resting spores might indicate a shallowing basin environment. Within the water column, diatom resting spores are most often abundant in coastal phytoplankton communities (Hargraves, 1979). *Chaetoceros* species have been considered as being associated with the last stage of species succession, dominating the assemblage in upwelling regions when nutrients are nearly exhausted in the euphotic zone (Margalef, 1978). These spore assemblages can generally account for a major fraction of the opaline sediment component in coastal upwelling regions. Stockwell and Hargraves (1986) state that even though *Chaetoceros* resting spores can be an important component of marine sediments as well as a spe-

cies-specific and useful taxonomic tool, within the thanatocoenoses, the group has generally been lumped taxonomically into the broad category "*Chaetoceros* spores" by most authors. Whether a fossil specimen is a spore or vegetative cell has been subject of some controversy for many years (Hargraves, 1986). Earlier investigations on resting spores dealt traditionally with their biostratigraphy (Schrader and Fenner, 1976). Taxonomic references with good photographs are given, but there is little information on the distribution and abundances of the resting spores except as *Chaetoceros* spores. "Resting spores" in this study refer to diatom resting spores that differ markedly from vegetative cells. However, we concentrate the study especially on those usually characterized as belonging to the genus *Chaetoceros*.

Although the cores have not been sampled in detail, it is interesting to note (Figs. 2, 3) the transition from no diatoms at 199 mbsf via a low-abundance sample with only resting spores at 193 m to a moderate-abundance sample with about 15% diatoms and about 85% resting spores at 190 mbsf. This transition can best be explained by a dominance of *Chaetoceros* spp. and related species being the first diatoms to appear from the time biosilica is preserved in the sediments Only the resting spores from these presumable easily dissolved veg-
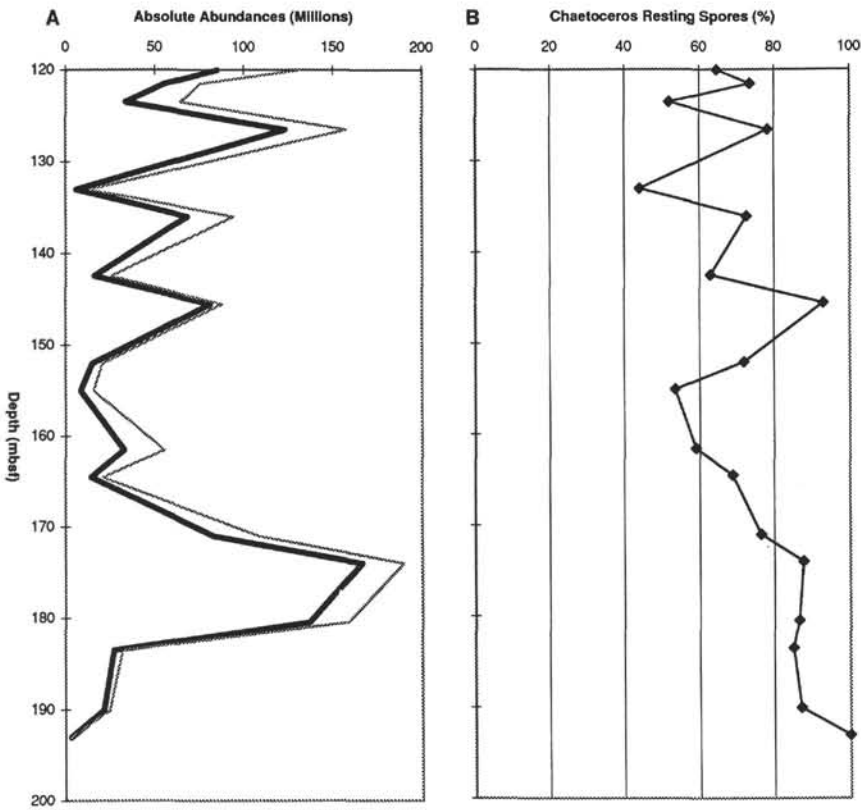
Figure 4. Diatoms in biosiliceous Interval 3. **A.** Absolute abundances. Heavy line denotes *Chaetoceros* resting spores. **B.** Percentages of *Chaetoceros* resting spores.
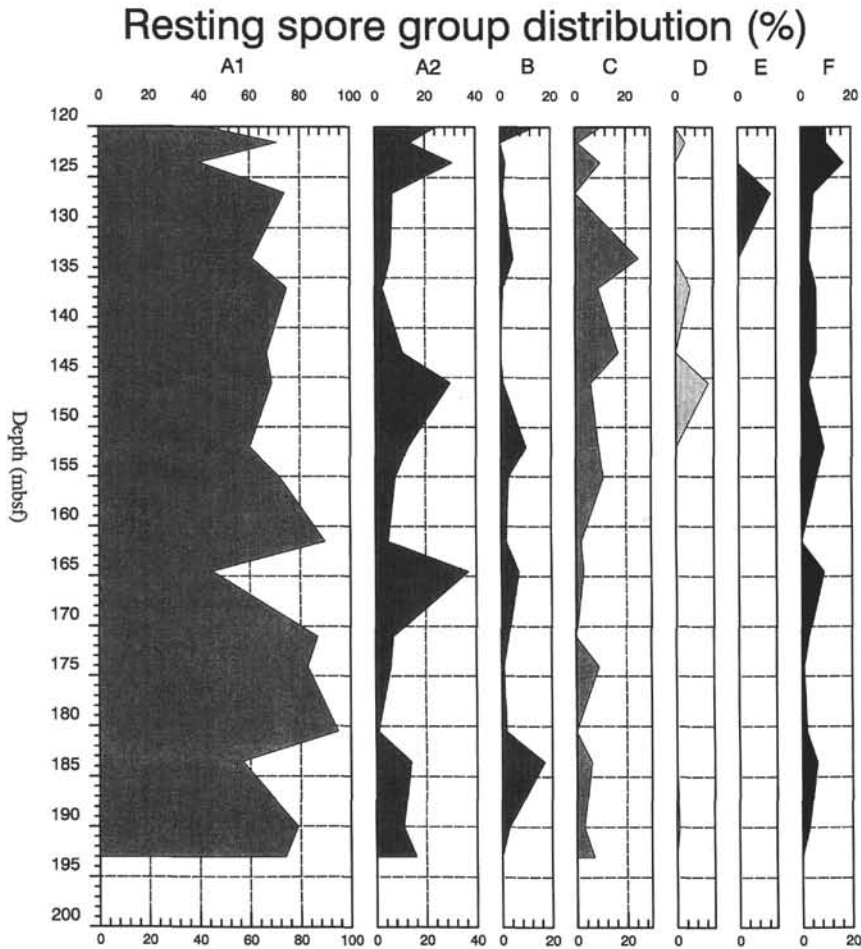
Resting spore group distribution (%)

Figure 5. Percentages of different groups of *Chaetoceros* resting spores through the biosilica-rich interval.

etative cells are preserved in the sediment record. After this initial diatom flora is established, other diatom taxa start occurring, but *Chaetoceros*-type diatoms remain the dominant component. The percentage distribution of resting spores declines as the other diatom taxa are established (155 to 198 mbsf). During the remainder of Interval 3, resting spores fluctuate between about 50% and 80%. During Interval 2 (Fig. 2), the percentage of resting spores decreases sharply to only about 7% at 60 mbsf.

CONCLUSION

The onset of siliceous biogenic deposition at ODP Site 907 is dated to middle middle Miocene (13.7 Ma; Koç and Scherer, this volume). Baldauf (1986) suggests a major change in oceanic circulation just prior to this time, based on a decrease in the quality of diatom preservation and the occurrence of numerous hiatuses at about the early/middle Miocene boundary in the North Atlantic. In the middle- and high-latitude North Atlantic (Baldauf, 1986) and in the Norwegian Sea (ODP Site 907), middle Miocene sediments are enriched with biosilica. However, during the early late Miocene and earliest Pliocene interval the North Atlantic is generally devoid of diatoms. A variable biosilica production continued in the Norwegian Sea (ODP Site 907) throughout this period. Since about 4 Ma, sediments of the middle North Atlantic have been enriched with diatoms. This interval corresponds to very sporadic occurrence of diatoms in the Norwegian Sea (ODP Site 907).

Surface water productivity of the Norwegian-Greenland Seas changed stepwise as the surrounding land masses became glaciated. The change from diatom-rich sediment to a sediment with variable diatom content corresponds to the first IRD record at Site 907 at about 10 Ma. This suggests that the paleoceanographic conditions in the Norwegian-Greenland Seas changed and affected surface water productivity as ice sheets started growing in the surrounding land masses. From 2.9 Ma onward there is an increase in IRD content, suggesting increased glaciations. This interval consists of very sporadic occurrences of diatoms or is mainly barren, indicating rather severe conditions for diatom productivity. It is envisaged that the Iceland Plateau was mostly sea-ice covered during the last 2.9 Ma.

A gradual increase in diatom abundance during an interval of less than 10 m, (comparable to approximately 0.5 m.y.; Koç and Scherer, this volume) from sediments barren of diatoms to diatom-rich sediments are recorded. During this initial phase, *Chaetoceros* spores totally dominate the assemblage. Thereafter, *Chaetoceros* spores make up at least more than 40% of the assemblage, indicating highly productive surface waters. The diatom and *Chaetoceros* spore abundance decrease much more gradually at the end of the diatom-rich sequence, through Interval 2, compared to the initial phase. However, after pulses of diatom-rich sediment with gradually lower *Chaetoceros* spore contents, diatoms disappear from the sediments at Site 907.

Because of the uncertainties in the classification of diatom resting spores (and especially the problems of relating fossil diatom genera to resting spores; Hargraves, 1986) and the fact that resting spores are quite often lumped together under categories such as *Chaetoceros* resting spores, it is difficult to draw ecological interpretations based on the fluctuations of these diatom groups. Future studies will, hopefully, increase information on the ecology of the individual groups.

ACKNOWLEDGMENTS

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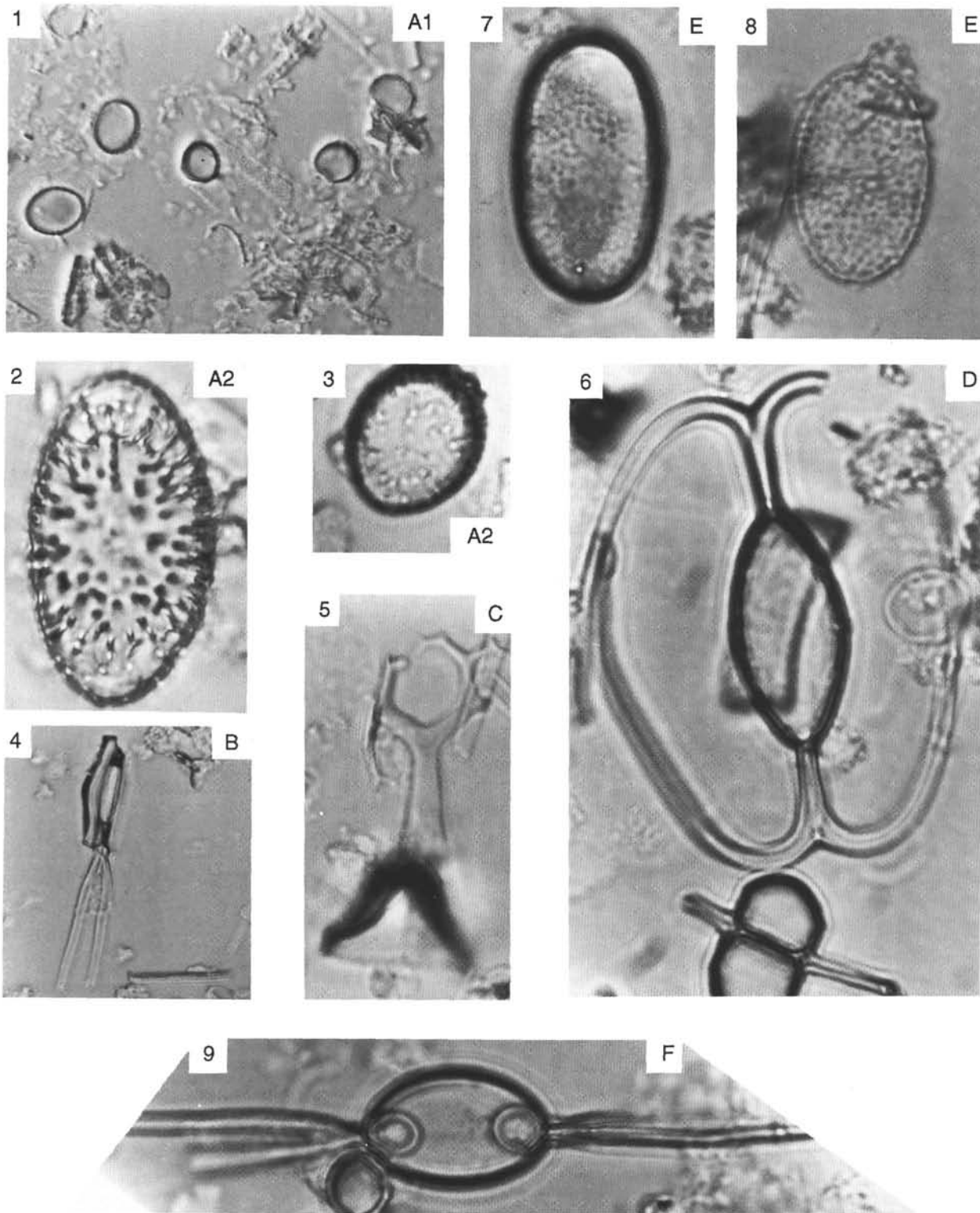
Plate 1. Resting spores representing Groups A through F from Hole 907A. All figures 2500×, except Figure 1 is 1500× and Figure 4 is 1000×. **1.** Group A1; smooth surface, Sample 151-907A-19H-4, 75–76 cm. **2** and **3.** Group A2; surface with spines/ridges. (2) from Sample 151-907A-15H-4, 74–75 cm; (3) from Sample 151-907A-16H-4, 74–75 cm. **4.** Group B; with setae, Sample 151-907A-20H-4, 74–75 cm. **5.** Group C; *Chaetoceros/Pterotheca*-type, Sample 151-907A-15H-2, 74–75 cm. **6.** Group D; *C. cinctus* type, Sample 151-907A-16H-4, 74–75 cm. **7** and **8.** Group E; rough surface, Sample 151-907A-14H-4, 73–74 cm. **9.** Group F; other, Sample 151-907A-16H-4, 74–75 cm.
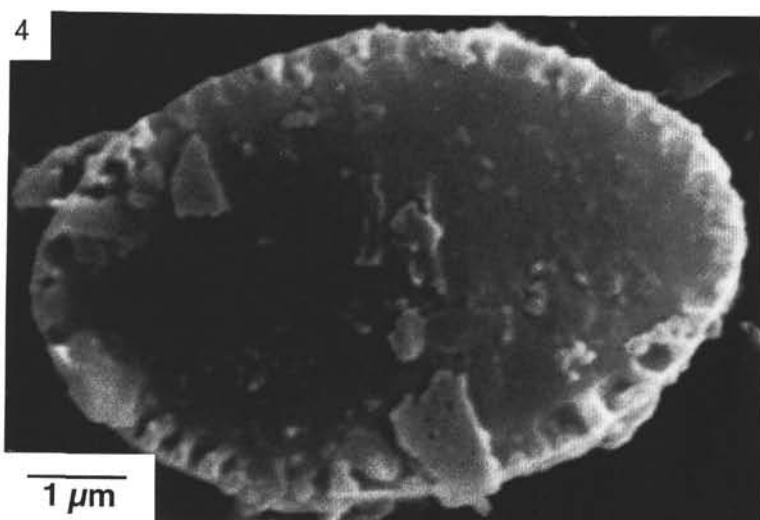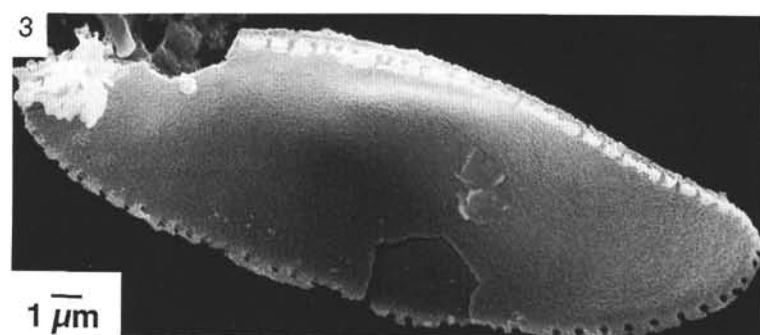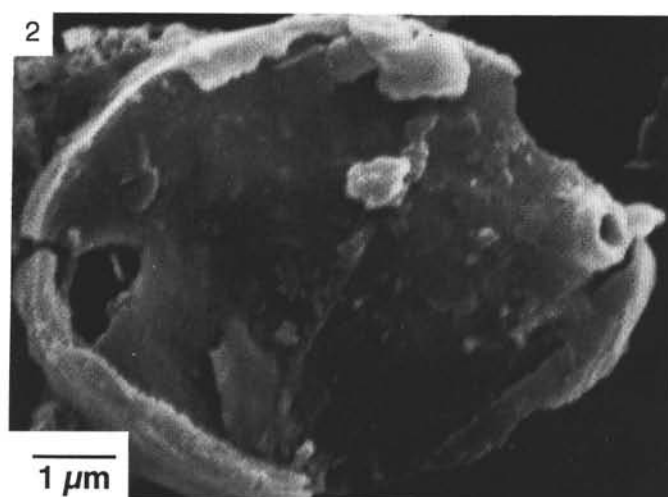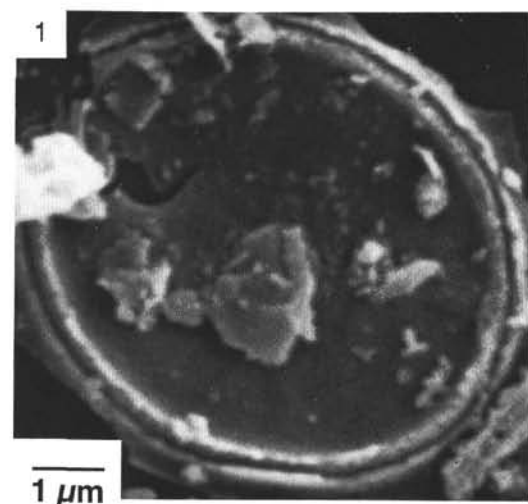
Plate 2. SEM photographs of *Chaetoceros* resting spores of Group A1 from Sample 151-907A-19H-4, 75–76 cm. **1.** Smooth surface, no granules at the margin. **2.** Smooth surface, no granules at margin. Note thickened protrusion at right hand side of spore (labiate-like process?). **3.** Elongate resting spore with smooth surface and broad "teeth" at margin. **4.** Round to elongate spore with smooth surface and "teeth"/granules at margin. **5.** Smooth surface and granules at margin.
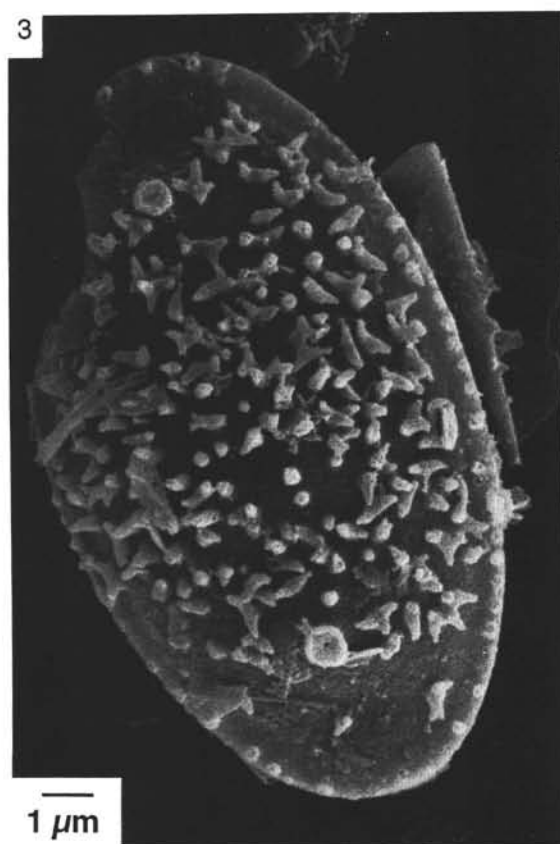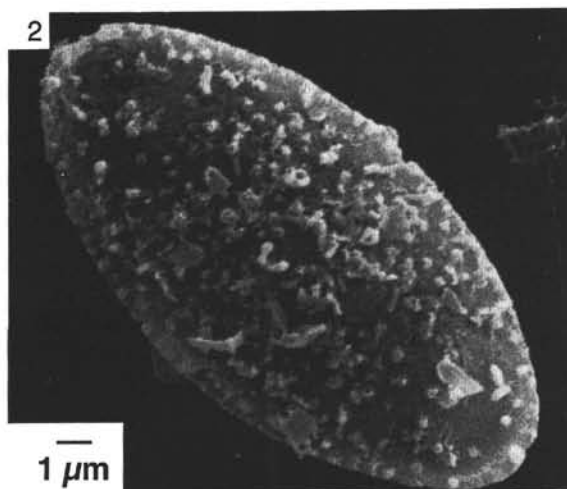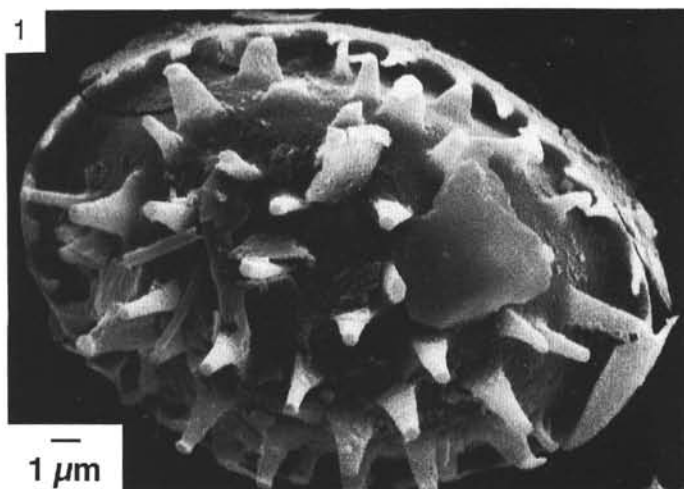
Plate 3. SEM photographs of *Chaetoceros* resting spores of Group A2 (and possibly Groups E and F) from Sample 151-907A-19H-4, 75–76 cm. **1.** Group A2, with spines. **2.** Group A2 or E; rough surface with granules at margin. **3.** Group A2 or E; rough surface with granules at margin. Note circular pores near both ends. **4.** Group F or E; rough? surface, but finer than in (2) and (3), with no granules at margin.
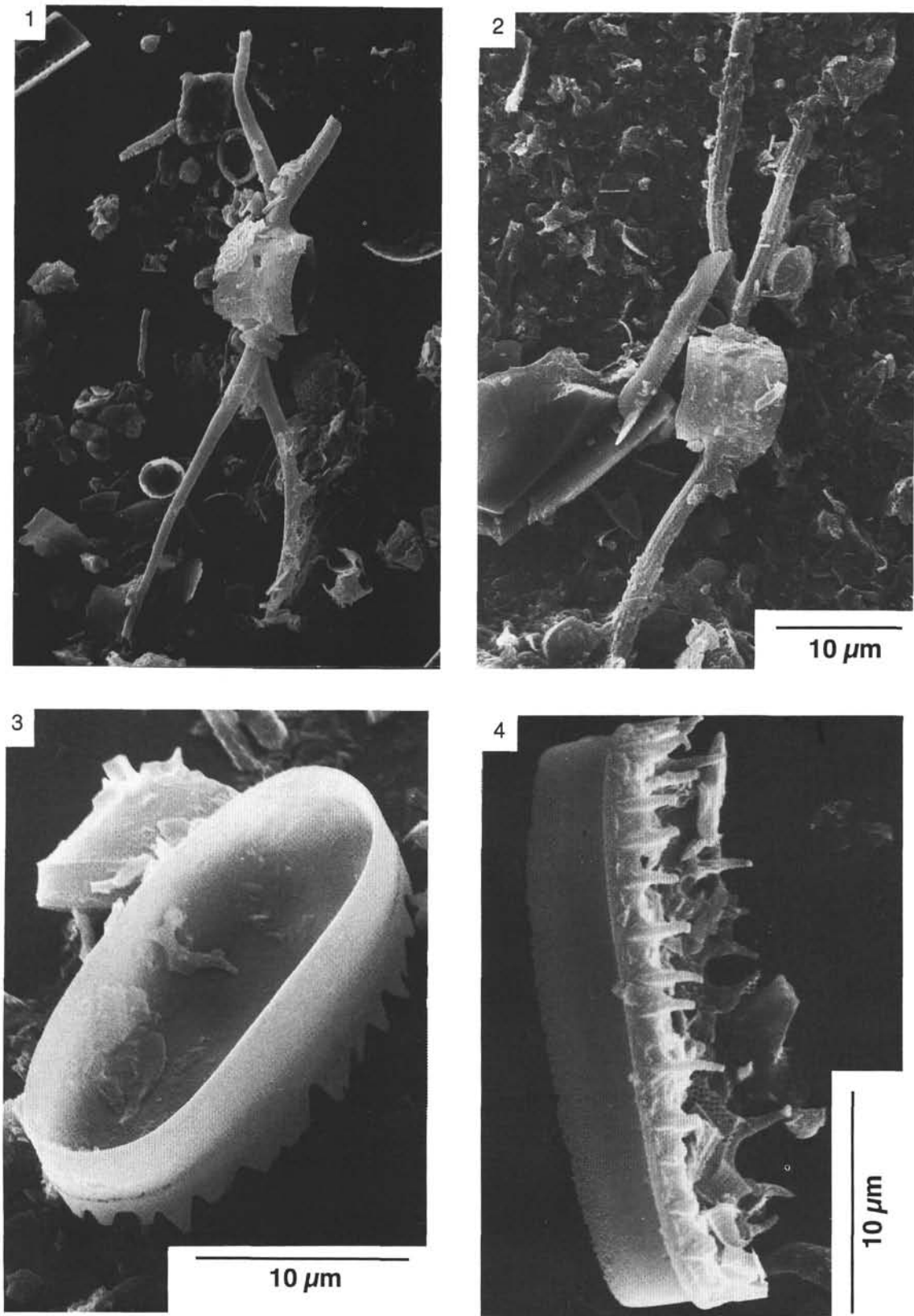
Plate 4. SEM photographs of *Chaetoceros* resting spores of Group B and F from Sample 151-907A-19H-4, 75–76 cm. **1** and **2.** Group B; with setae. **3.** Group F; with broad, pointed spines in a continuous band at margin. **4.** Group F; with single row of spines along the margin.