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4. HIGH-RESOLUTION PLEISTOCENE DIATOM BIOSTRATIGRAPHY OF SITE 983 AND CORRELATIONS WITH ISOTOPE STRATIGRAPHY¹

Nalân Koç,^{2,3} David A. Hodell,⁴ Helga Kleiven,² and Laurent Labeyrie⁵

ABSTRACT

High accumulation rates and the presence of well-preserved, abundant diatoms in Site 983 sediments from the Gardar Drift gave us the opportunity to refine the Pleistocene diatom biostratigraphic resolution of the high-latitude North Atlantic. Eight Pleistocene diatom datum events are identified and, for the first time, tied directly to the oxygen isotope record and paleomagnetic stratigraphy of Site 983. These datum events are (1) the last occurrence (LO) of *Proboscia curvirostris* at 0.3 Ma, (2) the LO of *Thalassiosira jouseae* at 0.3 Ma, (3) the LO of *Nitzschia reinholdii* at 0.6 Ma, (4) the LO of *Nitzschia fossilis* at 0.68 Ma, (5) the LO of *Nitzschia seminae* at 0.84 Ma, (6) the first occurrence (FO) of *N. seminae* at 1.25 Ma, (7) the FO of *Proboscia curvirostris* at 1.53 Ma, and (8) the FO of *Pseudoeunotia doliolus* at 1.89 Ma. Most of these datums are found to be synchronous between the middle and high latitudes of the North Atlantic and the North Pacific. On the basis of these datums, four high-latitude North Atlantic diatom zones are proposed for the Pleistocene. The record of diatom abundance and preservation at Site 983 gives evidence for the influence of fluctuating Pleistocene climatic conditions on diatom productivity in the high-latitude North Atlantic.

INTRODUCTION

The Cenozoic diatom biostratigraphy of the North Atlantic Ocean up to 60°N was established on the basis of material from Deep Sea Drilling Program (DSDP) Legs 81 and 94 (Baldauf, 1984, 1986, 1987). Diatoms were generally present at DSDP sites located in middle latitudes (35°N–50°N) of the North Atlantic during the Pleistocene. However, at higher latitudes (DSDP Sites 552–555 and 610), Pleistocene sediments were generally devoid of diatoms (Fig. 1) (Baldauf, 1984, 1986, 1987). Baldauf (1984) showed that in Hole 552A, at least during the late Quaternary, changes in the abundance of diatoms corresponded to fluctuations of the oxygen isotope curve, indicating a climatic control on the abundance of diatoms. Partly because of the effect of late Quaternary climatic fluctuations on diatom abundances and partly because of sampling resolutions, a Pleistocene diatom zonation for the high-latitude North Atlantic could not be obtained.

Sediments recovered during Ocean Drilling Program (ODP) Legs 151 and 152 to the high-latitude North Atlantic have provided us with more information on the temporal and spatial distribution of diatom-rich sediments (Koç and Scherer, 1996; Koç and Flower, 1998; Scherer and Koç, 1996; Stabell and Koç, 1996). High-resolution diatom biostratigraphy and abundance investigations of Site 919 confirmed the influence of Pleistocene glacial–interglacial climatic fluctuations on the diatom abundance of high-latitude North Atlantic sediments for the last 1 Ma (Koç and Flower, 1998). Furthermore, three diatom datum events (last occurrences [LO] of *Thalassiosira nidulus*, *Proboscia curvirostris*, and *Neodenticula seminae*) were identified and, for the first time, tied directly to the oxygen isotope record of Site 919, making it possible to suggest a more detailed Pleistocene diatom zonation for the high-latitude North Atlantic.

During Leg 162, in combination with Leg 151, broad north-south and east-west transects were drilled to monitor spatial paleoclimatic variability (Jansen, Raymo, Blum, et al., 1996). To study the evolution of millennial-scale climate variability in the North Atlantic, several high-accumulation-rate sites were drilled on sediment drifts. Site 983 (60°24.20'N, 23°38.437'W) is located on the Gardar Drift at a water depth of ~1985 m on the eastern flank of the Reykjanes Ridge (Fig. 1). Recovery of sediment from the holes exceeds 100%. Both calcium carbonate and siliceous microfossils are well preserved throughout the recovered sequence. There is no sedimentological evidence for erosion or winnowing (Jansen, Raymo, Blum, et al., 1996). Because of the presence of well-preserved diatoms and high sedimentation rates at this site, Site 983 was chosen for detailed study to refine the middle- and high-latitude North Atlantic Pleistocene diatom biostratigraphy.

METHODS

One sample from each core section (1.5 m) of Hole 983A was analyzed for its diatom content. Approximately 1–2 g of dry sample was placed in a 250-mL beaker and 10 drops of 37% HCl acid were added. After waiting for at least 15 min for the reaction to stop, 10 drops of 30% hydrogen peroxide were added. The sample was gently heated until the liquid became light yellow. The acidity of the sample was diluted by centrifuging it with distilled water until a pH of 7 was achieved. Slides of acid-cleaned material were examined at 400× to determine relative diatom abundance. Assessment of total diatom abundance was qualitative. Diatoms 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, and rare (R) if one to 10 specimens occurred per horizontal traverse.

Qualitative abundance estimates of individual taxa are based on the number of specimens observed per field of view at 400×. Species were recorded as abundant (A) if two or more specimens were present in one field of view, common (C) if one to five specimens were observed per five fields of view, few (F) if two to 10 specimens were observed per horizontal traverse, rare (R) if one specimen was observed per horizontal traverse, and trace (T) if only fragments of the specimen were observed.

¹Raymo, M.E., Jansen, E., Blum, P., and Herbert, T.D. (Eds.), 1999. *Proc. ODP, Sci. Results*, 162: College Station, TX (Ocean Drilling Program).

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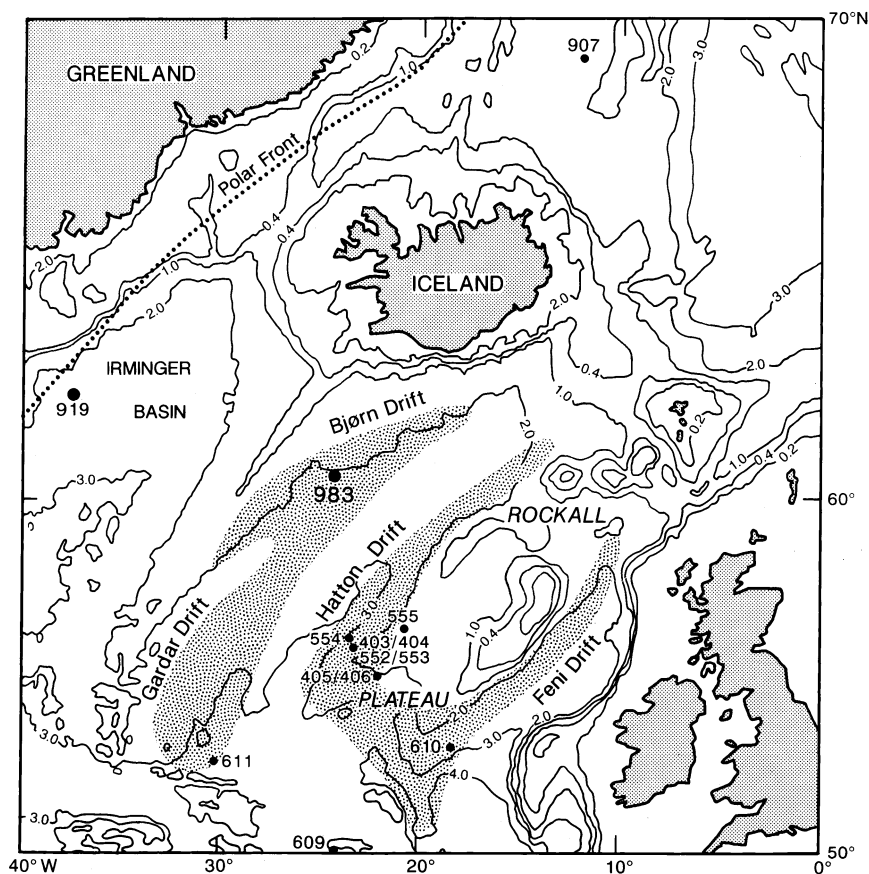


Figure 1. Location of Site 983 plotted with previous DSDP and ODP sites in the area. Areas of sediment drift accumulation are shown by dotted pattern. Position of the Polar Front is indicated by the dotted line.

Diatom preservation was recorded as good (G) when both finely silicified and heavily robust forms were present and no significant alteration of the frustules other than minor fragmentation was observed, moderate (M) when the assemblage showed moderate breakage and slight dissolution, and poor (P) when finely silicified forms were rare or absent and the assemblage was dominated by robust forms and fragments.

PLEISTOCENE DIATOM BIOSTRATIGRAPHY

At present, the area of Site 983 is influenced by subarctic water masses created by the confluence of the polar waters of the ice-laden East Greenland Current with the Atlantic waters of the Irminger Current. The Pleistocene diatom species observed in sediment recovered from Site 983 consist primarily of modern arctic and subarctic species (Koç Karpuz and Schrader, 1990; N. Koç, unpubl. data). These include *Actinocyclus curvatus*, *Thalassiosira gravida* spore and vegetative cells, *Rhizosolenia hebetata*, *Thalassiothrix longissima*, and the warm-water species *Thalassiosira oestrupii* (Table 1).

Diatoms are generally abundant to common and good to moderately preserved in Site 983 sediments (Table 1). Eight biostratigraphic events are observed at Site 983: the last occurrence (LO) and the first occurrence (FO) of *Proboscia curvirostris*, the LO of *Thalassiosira jouseae*, the LO of *Nitzschia reinholdii*, the LO of *Nitzschia fossilis*, the LO and FO of *Neodenticula seminae*, and the FO of *Pseudoeunotia doliolus* (Fig. 2). The LO of *P. curvirostris* and *T. jouseae* occurs in Sample 162-983A-4H-3, 49–50 cm (29.89 meters below seafloor [mbsf]). The FO of *P. curvirostris* is observed in Sample 162-983A-20H-5, 49–50 cm (184.89 mbsf). The LO of *N. reinholdii* is observed in Sample 162-983A-7H-7, 49–50 cm (64.39 mbsf). The LO of *N. fossilis* is noted in Sample 162-983A-8H-7, 49–50 cm

(73.89 mbsf). The LO of *N. seminae* is seen in Sample 162-983A-10H-5, 49–50 cm (89.89 mbsf). The FO of *N. seminae* is observed in Sample 162-983A-16H-1, 49–50 cm (140.89 mbsf). The FO of *P. doliolus* occurs in Sample 162-983A-26H-CC, 0–3 cm (244.99 mbsf) as reported in Jansen, Raymo, Blum, et al. (1996). The depth ranges of these events are presented in Table 2.

Diatom Datum Levels

Age assignments for the biostratigraphic events were achieved by correlation with the magnetostratigraphy (Jansen, Raymo, Blum, et al., 1996) and with the oxygen isotope record of Site 983 (D. Hodell, unpubl. data; H. Kleiven, unpubl. data). Datum levels from youngest to oldest are as follows:

1. The LO of *T. jouseae* and the LO of *P. curvirostris* co-occur at the end of Marine Isotope Stage (MIS) 9 (Fig. 3). Interpolation of age using the stage boundaries gives an age between 0.295 and 0.305 Ma for these events (Table 2). At ODP Site 919, both of these events were recorded within MIS 9 with the LO of *T. jouseae* (referred to as *T. nidulus* in Koç and Flower, 1998) dated to 0.309 Ma and the LO of *P. curvirostris* to an age of 0.335 Ma. In the southern Labrador Sea, at Hole 646A, the LO of *P. curvirostris* was recorded in Sample 105-646A-3H-1, 128–130 cm (Monjanel and Baldauf, 1989). Correlation of this sample with the oxygen isotope record of Site 646 (Aksu et al., 1989) places the event within MIS 8, giving a slightly younger age than at Sites 919 and 983.

Both of these events are also recorded from the North Pacific. The LO of *T. jouseae* is dated between 0.280 and 0.390 Ma in the Northwest Pacific, showing a possible diachrony from high to low latitudes (Koizumi and Tanimura, 1985). The North Atlantic ages for the LO of *T. jouseae* from Sites 646, 919, and 983 fall closer to the younger

Table 1 (continued).

Zone	Core, section, interval (cm)	Preservation	Abundance																			
			<i>Actinocyclus curvatulus</i>	<i>Actinocyclus oculatus</i>	<i>Bacteriatrum hyalinum</i>	<i>Bacterosira fragilis</i>	<i>Chaetoceros</i> spores	<i>Coccinodiscus asteromphalus</i>	<i>Coccinodiscus marginatus</i>	<i>Azpetta nodulifer</i>	<i>Coccinodiscus radiatus</i>	<i>Hemidiscus cuneiformis</i>										
<i>Nitzschia reinholdii</i>	24H-2, 49-50	P	C	R	R	C	F			R												
	24H-3, 49-50	P	C	C		C	F															
	24H-4, 49-50	B																				
	24H-5, 49-50	M	A	C		R	A	F			R	R										
	24H-6, 49-50	M	C	C	F		C	R														
	25H-1, 49-50	B																				
	25H-2, 49-50	P	R				R															
	25H-3, 49-50	P	C	C			C	C														
	25H-4, 49-50	P	C	C			C	C				R	R									
	25H-5, 49-50	P	C	C			C	C														
	25H-6, 49-50	P	R	R			R	R														
	26H-1, 49-50	P	C	C			C	C														
	26H-2, 49-50	M	C	C			R	C	F													
	26H-3, 49-50	P	C	C			C	C	F													
	26H-4, 49-50	P	C	C			C	C	F													
26H-5, 49-50	M	A	C			R	A	F														
26H-6, 49-50	M	A	C			R	C	F														
	27H-1, 49-50	M	A	C		R	C	R	F													
	27H-2, 49-50	M	A	C		C	C	R	R													
	27H-3, 49-50	P	C	C			C	R	F													
	27H-4, 49-50	P	R				C	R	F													
	27H-5, 49-50	P	C	C			C	C	F													
	27H-6, 49-50	P	C	C			C	C	F													
	27H-7, 49-50	M	A	C			R	A	F													

Notes: B = barren, T = trace, R = rare, F = few, C = common, A = abundant. Preservation is either poor (P), moderate (M), or good (G). See Appendix for species list.

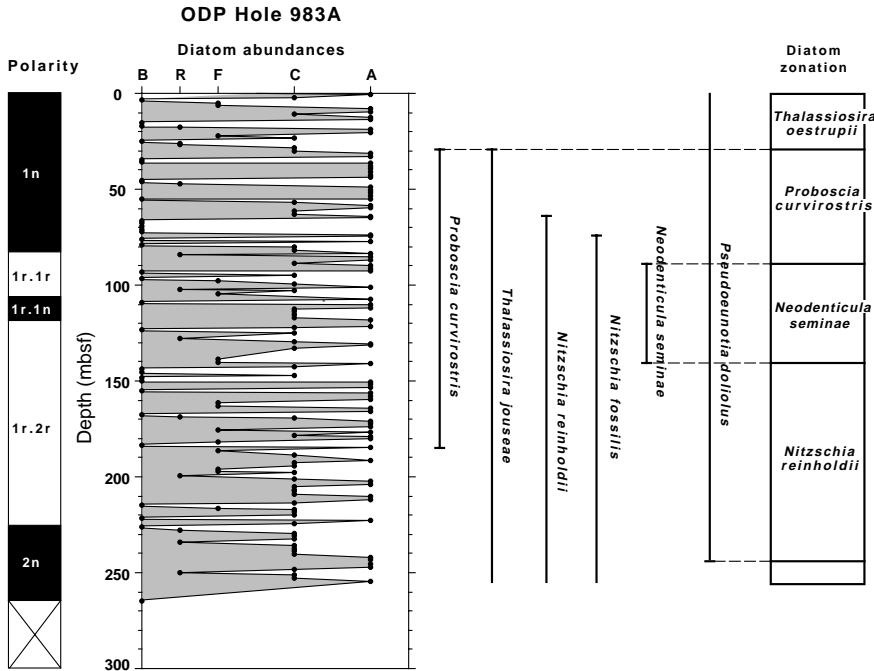


Figure 2. Hole 983A relative diatom abundances (B = barren, R = rare, F = few, C = common, A = abundant) plotted with the paleomagnetic stratigraphy vs. depth. Also shown are diatom biostratigraphic events and their ranges used to propose the high-latitude North Atlantic diatom zonation.

datum from the middle- and high-latitude North Pacific. Thus, it is possible to conclude that this event is synchronous between the middle and high latitudes of both oceans.

The LO of *P. curvirostris* is dated at 0.300–0.350 Ma in the middle- and high-latitude North Pacific (Koizumi and Tanimura, 1985; Koizumi, 1986). The overlap in age observed between the North At-

lantic and the North Pacific suggests synchronicity between these two oceans for this event. *P. curvirostris* is also recorded from Sites 552, 606, 607, 609, and 611 in the North Atlantic (Baldauf, 1984, 1987). It is also recorded from the Nordic Seas Sites 907 (Koç and Scherer, 1996) and 986 (Jansen, Raymo, Blum, et al., 1996), which implies a distribution for *P. curvirostris* that stretches from 40°N to 80°N in the

North Atlantic. It also has a middle- to high-latitude distribution in the North Pacific, which makes it a valuable datum for correlation between the high-latitude North Atlantic and the North Pacific Oceans.

2. The LO of *N. reinholdii* is recorded within MIS 15 with an estimated age of 0.590–0.601 Ma (Table 2; Fig. 3). Baldauf (1987) tentatively estimated the age of this event at 0.44 Ma on the basis of DSDP Sites 607 and 609, which had the most refined sample constraints. We correlated the depth interval (Sample 94-609-4-1, 43–45 cm, 26.64 mbsf) of this event with the oxygen isotope curve of Hole 609 (L. Labeurie, unpubl. data) and found that it plots within MIS 13 (0.46–0.50 Ma) (Fig. 4). We have also correlated the depth interval of this event at Site 607 from Baldauf (1987) with the oxygen isotope record of Site 607 (Ruddiman et al., 1987) and found that it also plots within MIS 13. This suggests that the LO of *N. reinholdii* is diachronous between the middle and high latitudes of the North Atlantic. Furthermore, this species is totally absent from Site 919 sediments

Table 2. Specific diatom events and estimated ages from Hole 983A.

Diatom event	Core, section, interval (cm)	Depth (mbsf)	Depth (mcd)	Estimated age (Ma)
LO <i>Proboscia curvirostris</i>	162-983A-4H-2, 49-50	28.39	32.35	0.295
	4H-3, 49-50	29.89	33.85	0.305
LO <i>Thalassiosira jouseae</i>	4H-2, 49-50	28.39	32.35	0.295
	4H-3, 49-50	29.89	33.85	0.305
LO <i>Nitzschia reinholdii</i>	7H-6, 49-50	62.89	70.19	0.590
	7H-7, 49-50	64.39	71.69	0.601
LO <i>Nitzschia fossilis</i>	8H-6, 49-50	72.39	80.26	0.675
	8H-7, 49-50	73.89	81.76	0.687
LO <i>Neodenticula seminae</i>	10H-4, 49-50	88.39	97.73	0.836
	10H-5, 49-50	89.89	99.23	0.849
FO <i>Neodenticula seminae</i>	16H-1, 49-50	140.89	154.79	1.250
	16H-2, 49-50	142.39	156.29	1.260
FO <i>Proboscia curvirostris</i>	20H-5, 49-50	184.89	202.32	1.521
	20H-6, 49-50	186.39	203.82	1.530
FO <i>Pseudoenotia doliolus</i>	26H-CC, 0-3	244.99	269.03	1.891
	27H-1, 49-50	245.39	270.08	1.893

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

(Koç and Flower, 1998). Koizumi and Tanimura (1985) found that the LO of *N. reinholdii* is almost synchronous at 0.47–0.52 Ma in middle and high latitudes of the North Pacific. This datum correlates well with the Hole 609 datum indicating the synchronicity of this event between the middle latitudes of both oceans.

3. The LO of *N. fossilis* occurs at the end of MIS 17 and has an estimated age of 0.675–0.687 Ma (Fig. 3). Baldauf (1987) estimated an age of 0.58–0.60 Ma for this event in the middle-latitude North Atlantic, indicating that this event is also diachronous between the middle and high latitudes of the North Atlantic. Koizumi and Tanimura (1985) found this event to be synchronous at 0.55 Ma in middle and high latitudes of the North Pacific, which suggests a near synchronicity between the middle and high latitudes of the North Pacific and the middle latitudes of the North Atlantic for the LO of *N. fossilis*.

4. The LO of *N. seminae* occurs within MIS 21 and has an estimated age of 0.836–0.849 Ma (Fig. 3). At Site 919, this event occurs within MIS 22 (Koç and Flower, 1998). However, because there is a barren interval above this event encompassing MIS 21, the age is interpolated to be between 0.817 and 0.895 Ma.

N. seminae belongs to the modern assemblage of the middle- and high-latitude North Pacific (Barron, 1981; Sancetta and Silvestri, 1986). However, it became extinct in the North Atlantic during the late Quaternary (Baldauf, 1986). Baldauf (1986) found the LO of *N. seminae* to be diachronous between Site 607 (~0.8 Ma) and Sites 609 and 611 (~0.7 Ma). We correlated the depth interval of this event at Site 607 from Baldauf (1987) with the oxygen isotope record of Site 607 (Ruddiman et al., 1987) and found that it plots within MIS 21. On Figure 4, we plotted the depth range of this event together with the oxygen isotope record of Site 609 and compared it with the record of Site 983. The event plots within MIS 21 in both sites, indicating a synchronicity between the middle and high latitudes of the North Atlantic.

Montane and Baldauf (1989) recorded the LO of *N. seminae* at Site 646 from the southern Labrador Sea in Sample 105-646A-7H-5, 120–122 cm. We correlated this sample with the oxygen isotope record of Hole 646A (Aksu et al., 1989). It plots near the midpoint of MIS 21, thereby correlating well with other North Atlantic datums for this event. We conclude that the LO of *N. seminae*, which occurs

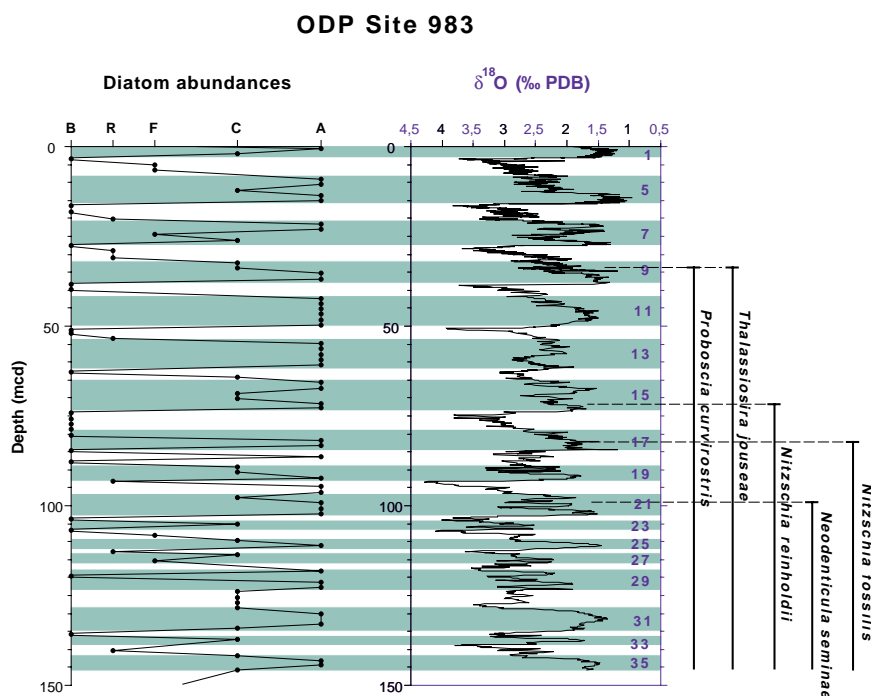


Figure 3. Site 983 relative diatom abundances (B = barren, R = rare, F = few, C = common, A = abundant) plotted with the planktonic $\delta^{18}\text{O}$ record vs. composite depth. Interglacial stages are shaded and numbered. Diatom biostratigraphic events and their ranges are indicated and correlated with the $\delta^{18}\text{O}$ record.

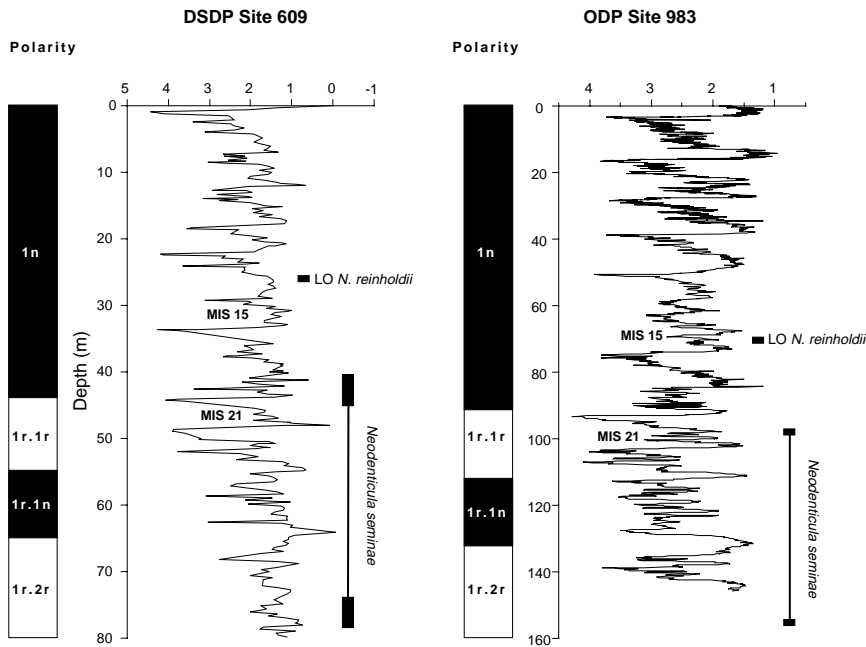


Figure 4. Planktonic $\delta^{18}\text{O}$ records of Site 609 (L. Labeyrie, unpubl. data) and Site 983 (D. Hodell and H. Kleiven, unpubl. data) shown with their respective paleomagnetic stratigraphies. To compare the timing of events between the middle- and high-latitude North Atlantic, we plotted the last occurrence (LO) of *Nitzschia reinholdii*, and the last and first occurrences of *Neodenticula seminae* at both sites. MIS = marine isotope stage.

within MIS 21, is synchronous within the middle and high latitudes of the North Atlantic.

5. The FO of *N. seminae* occurs between 154.79 and 156.29 meters composite depth, which falls toward the end of MIS 37 (M. Raymo, pers. comm., 1998) and has an estimated age of 1.250–1.260 Ma. Baldauf (1987) recorded the FO of *N. seminae* one-fifth of the way between the base of the Jaramillo Subchron and the top of the Gauss paleomagnetic Chron in Holes 607, 609, and 611 and concluded that it is isochronous throughout Leg 94 material. We plotted the depth interval of the FO of *N. seminae* on Site 609 isotope curve and found that it occurs within the interval of MISs 37–35 (Fig. 4). We conclude that the FO of *N. seminae* is also synchronous between the middle and high latitudes of the North Atlantic. The North Pacific datum for this event is uncertain because of previous taxonomic ambiguities between *N. seminae*, *N. koizumii*, and *N. sp. A* (Akiba and Yanagisawa, 1986).

6. The FO of *P. curvirostris* has an estimated age of 1.521–1.530 Ma at Site 983. In the North Pacific, this event seems to be diachronous, migrating from the subarctic North Pacific where it occurred midway between the Olduvai and Jaramillo events. This gave an estimated age of 1.4 Ma to transitional waters at 1.1 Ma and to the subtropics at 0.95 Ma (Koizumi, 1986). A similar diachroneity seems probable also for the North Atlantic based on results from Sites 609 and 611 (Baldauf, 1987).

7. The FO of *P. doliolus* occurs within the Olduvai event and has an estimated age of 1.891–1.893 Ma. Baldauf (1987) assigned an age of 1.84 Ma to this event in the North Atlantic. In the North Pacific, Koizumi and Tanimura (1985) assigned a first-order category to the FO of *P. doliolus* with an approximate age of 1.9 Ma in middle latitudes. These results point to a synchronous first occurrence for *P. doliolus* in the middle and high latitudes of both the North Atlantic and the North Pacific Oceans.

Zonation

The diatom zones for the North Atlantic are defined by warm-temperate species (Baldauf, 1984, 1987). However, because of the latitudinal dependence of diatom distribution after the Miocene, it is necessary to make up at least two kinds of zonal schemes: one for low latitudes and another for high latitudes (Burckle and Opdyke, 1977).

Schrader and Fenner (1976) and Dzinoridze et al. (1978) proposed two different Neogene diatom biostratigraphies for the Nordic Seas on the basis of Leg 38 material. Recently, Koç and Scherer (1996) proposed a new Neogene diatom zonation for the area on the basis of Site 907 material. In all cases, however, the Pleistocene zonation did not have much resolution because of the absence of diatoms in the investigated sediments. Site 919, drilled during Leg 152, provided us with a high-accumulation-rate upper Pleistocene section with abundant diatoms, which enabled us for the first time both to record arctic-subarctic diatom events and to tie them directly to the oxygen isotope record (Koç and Flower, 1998). On the basis of these results, a late Pleistocene zonation for the high-latitude North Atlantic was proposed (Koç and Flower, 1998).

A Pleistocene diatom zonation scheme is proposed for the high-latitude North Atlantic (Figs. 2, 5). Zonal boundaries are judged to be first order because the datum levels that define them are tied either directly to oxygen isotope stages or to the paleomagnetic reversal record. Furthermore, these datums are synchronous between the middle and high latitudes of the North Atlantic and the North Pacific, making correlations between the two oceans possible.

Thalassiosira oestrupii Zone

Authors: Koç and Scherer (1996).

Definition: The interval from the LO of *Proboscia curvirostris* to the present.

Remarks: *Proboscia curvirostris* is a highly silicified species with wide geographic distribution. The LO of *P. curvirostris* is synchronous between the middle and high latitudes of both the North Atlantic and the North Pacific Oceans, making it a very valuable datum. The LO of *T. jousea* occurs at the same time as the LO of *P. curvirostris*, but because of its sparse occurrence in sediments, it can only be used as a secondary datum.

Correlation: This zone correlates with the *Neodenticula seminae* (NPD12) Zone (Donahue, 1970) of the North Pacific, which also uses the LO of *P. curvirostris* to define its base (Fig. 5).

Age: Quaternary, 0.3–0 Ma.

Proboscia curvirostris Zone

Author: Koç (Koç and Flower, 1998).

Definition: The top of the zone is defined by the LO of *P. curvirostris* and the base by the LO of *Neodenticula seminae*.

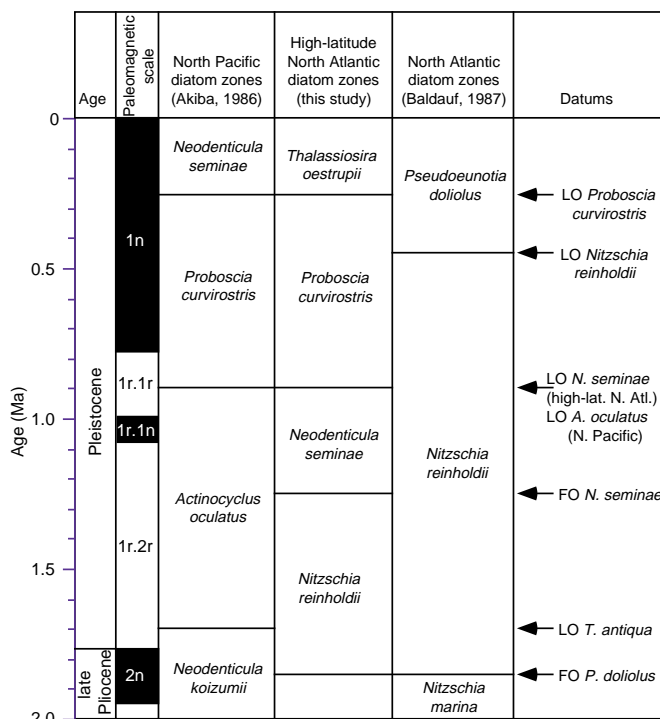


Figure 5. Correlation of various Pleistocene diatom zones and the first-order datums. LO = last occurrence.

Remarks: The base of this zone is modified from its original description by Koç and Scherer (1996) as the interval from the LO of *Thalassiothrix micocenica* to the LO of *P. curvirostris*, which included an extended, mostly barren section at its original site of description (Site 907).

The LO of *N. reinholdii* and *N. fossilis* falls within this zone (Fig. 2). Baldauf (1987) used the LO of *N. reinholdii* datum to separate his *P. doliolus* Zone from the *N. reinholdii* Zone. These species (especially *N. reinholdii*) have sparse and sporadic occurrences in Site 983 sediments and are absent from Site 919 sediments. Therefore, they cannot be used to define zones in the high-latitude North Atlantic.

Correlation: This zone correlates with the *Rhizosolenia curvirostris* (synonym for *Proboscia curvirostris*) Zone of the North Pacific (Donahue, 1970) (Fig. 5).

Age: Quaternary, 0.836–0.849 to 0.3 Ma.

Neodenticula seminae Zone

Author: Koç (this study).

Definition: The top of the zone is defined by the LO of *N. seminae* and the base by the FO of *N. seminae*.

Remarks: This zone is modified from Koç and Flower (1998) where the base of the zone was not reached at Site 919. The FO and LO of *N. seminae* are synchronous within the middle and high latitudes of the North Atlantic.

The LO of *Actinocyclus oculatus* is also recorded at the same level as the LO of *N. seminae* in Site 983 sediments, but because of its sporadic occurrence it is not used to define a zone (Table 1). The LO of *A. oculatus* seems to be synchronous in the North Pacific and at Site 983.

Correlation: This zone correlates with the top part of the *Actinocyclus oculatus* Zone of the North Pacific diatom zones (Koizumi, 1973).

Age: Quaternary, 1.25–1.26 to 0.84–0.85 Ma.

Nitzschia reinholdii Zone

Author: Koç (this study).

Definition: The top of the zone is defined by the FO of *N. seminae* and the base by the FO of *P. doliolus*.

Remarks: This zone is modified from its definition by Baldauf (1987).

The LO of *T. antiqua* is recorded within the bottom half of the zone (Sample 162-983A-22H-7, 49–50 cm, 206.89 mbsf) with an estimated age of 1.65

Ma. This event defines the base of the North Pacific *A. oculatus* Zone and is given an age of 1.7 Ma (Donahue, 1970).

Correlation: This zone correlates with the bottom part of the North Atlantic *N. reinholdii* Zone of Baldauf (1987).

Age: early Pleistocene to latest Pliocene, 1.89 to 1.25–1.26 Ma.

DIATOM ABUNDANCES: PALEOCEANOGRAPHIC IMPLICATIONS

Site 983 lies just south of Iceland at 60°N (Fig. 1). Diatom abundance and preservation at this site fluctuate in response to changing oceanographic conditions affecting diatom productivity. Correlating diatom abundance variations with the oxygen isotope record of Site 983 reveals a great similarity between the two records (Fig. 3). In general, interglacials are related to high diatom productivity (common to abundant diatoms), whereas glacial stages are often barren of diatoms. However, diatom production was significant during glacial Stages 18, 20, and 30.

During the late Quaternary glacial periods, oceanic polar fronts and sea ice migrated equatorward, with some of the most dramatic changes occurring in the North Atlantic (McIntyre, et al., 1976; CLIMAP Project Members, 1981). Reduced surface-water productivity during glacials indicates that these were the intervals during which the Polar Front migrated southeastward, thereby covering Site 983 with sea ice. Considering the proximity of the sea-ice margin to the area at present, it is very probable that these diatom-barren glacial intervals reflect periods when the site was under heavy sea-ice cover.

Presence of significant diatom production during glacial stages 18, 20, and 30 indicates open-marine conditions over Site 983 during these times. High diatom production during glacial stages 18 and 20 is also recorded from Site 919, which suggests that the North Atlantic was free of sea ice during these glacial periods (Koç and Flower, 1998). These glacial stages are within the first 100-k.y. cycles after the Mid-Pleistocene Transition. As indicated by the benthic oxygen isotope records, they were not as severe as the late Quaternary glacials (Mix et al., 1995).

Neodenticula seminae is part of the modern diatom assemblage of the middle- and high-latitude North Pacific (Barron, 1981; Sancetta, 1982). Our results indicate that this species is limited to the interval 0.84–1.26 Ma in the North Atlantic. Baldauf (1986) had interpreted the occurrence of *N. seminae* in the North Atlantic as the presence of cool, low-saline, surface waters in the central North Atlantic during the early Quaternary. The interval of *N. seminae* in the North Atlantic straddles the transition from the dominance of 41-k.y. cycles in the climate records to the dominance of 100-k.y. cycles. It is, therefore, possible to interpret the first occurrence of *N. seminae* in the North Atlantic as a sign for cooling, which started at 1.26 Ma, leading to the establishment of the 100-k.y. cycles with severe glacial periods. The presence of *N. seminae* in the North Atlantic is, therefore, attributable to the unique conditions related to the Mid-Pleistocene Transition.

CONCLUSIONS

Diatom investigations of Site 983 refined and increased the Pleistocene diatom biostratigraphic resolution of the high-latitude North Atlantic. Eight Pleistocene diatom datum events are identified and tied directly to the oxygen isotope record and paleomagnetic stratigraphy of Site 983. These datum events are (1) the LO of *P. curvirostris* at 0.3 Ma, (2) the LO of *T. jouseae* at 0.3 Ma, (3) the LO of *N. reinholdii* at 0.6 Ma, (4) the LO of *N. fossilis* at 0.68 Ma, (5) the LO of *N. seminae* at 0.84 Ma, (6) the FO of *N. seminae* at 1.25 Ma, (7) the FO of *P. curvirostris* at 1.53 Ma, and (8) the FO of *P. doliolus* at 1.89 Ma. On the basis of these datums, four high-latitude North Atlantic diatom zones are proposed for the Pleistocene.

The record of diatom abundance and preservation at Site 983 gives evidence for the influence of fluctuating Pleistocene climatic conditions on diatom productivity in the high-latitude North Atlantic.

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- Bacterosira fragilis* Gran, 1900, p. 114; Jousé, 1962, fig. 2, no. 15; Sancetta, 1982, p. 227, pl. 2, figs. 1–4.
- Coscinodiscus asteromphalus* Ehrenberg, 1844, in Hustedt, 1930, pp. 452–454, fig. 250.
- Coscinodiscus marginatus* Ehrenberg, 1841, p. 142; Hustedt, 1930, p. 416, fig. 223.
- Coscinodiscus radiatus* Ehrenberg, 1839, p. 148, pl. 3, figs. 1a–c; Hustedt, 1930, p. 420, fig. 255.
- Hemidiscus cuneiformis* Wallich, 1860, p. 42, pl. 2, figs. 3, 4; Baldauf, 1984, p. 466, pl. 1, figs. 6, 7.
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- Nitzschia bicapitata* Cleve: Hustedt, 1958, p. 169, figs. 176–190; Hasle, 1960, p. 21, pl. 6, figs. 53–57.
- Nitzschia fossilis* (Frenguelli) Kanaya: Baldauf, 1984, p. 469, pl. 4, figs. 8, 10, 11, 14, 15; Akiba, 1986, p. 473, pl. 22, figs. 6–8.
- Nitzschia marina* Grunow; Baldauf, 1984, p. 470, pl. 5, figs. 1, 2.
- Nitzschia punduriformis* Gregory, 1857, p. 529, fig. 57; Fenner, 1979, p. 525, pl. 32, figs. 27–29; Baldauf, 1984, pl. 5, fig. 8.
- Nitzschia reinholdii* Kanaya; Baldauf, 1984, p. 469, pl. 4, figs. 5–7; Akiba, 1986, p. 473, pl. 22, figs. 4–5.
- Proboscia alata* Sundström, 1986, pp. 99–102, pl. 36, figs. 258–266. **Synonym:** *Rhizosolenia alata* Brightwell, 1858, p. 95, pl. 5, figs. 8, 8a.
- Proboscia curvirostris* Jordan and Priddle, 1991, p. 57. **Synonym:** *Rhizosolenia curvirostris* Jousé, 1959, p. 48, pl. 2, fig. 17; Akiba and Yanagisawa, 1986, p. 497, pl. 42, figs. 1, 2; pl. 45, figs. 1–6.
- Pseudoeunotia doliolus* (Wallich) Grunow, in Van Heurck, 1881, pl. 35, fig. 22; Baldauf, 1984, pl. 5, figs. 5–7.
- Rhizosolenia bergonii* Peragallo: Hustedt, 1930, p. 575, fig. 327; Koizumi and Tanimura, 1985, p. 300, pl. 6, fig. 14.
- Rhizosolenia hebetata* forma *hebetata* Sundström, 1986, pp. 47, 48, pl. 4, figs. 18a, b; pl. 17, figs. 112, 113.
- Rhizosolenia hebetata* forma *semispina* (Hensen) Gran, 1904, p. 524, pl. 17; Sundström, 1986, pp. 48–52, pl. 4, figs. 19, 20; pl. 17, figs. 117, 118.
- Rhizosolenia setigera* Brightwell: Hustedt, 1930, p. 588, fig. 336.
- Rhizosolenia styliformis* Brightwell, 1858, p. 95, pl. 5, figs. 5a, b, d; Baldauf, 1987, pl. 6, fig. 7.
- Roperia tessellata* (Roper) Grunow: Hustedt, 1930, p. 524, fig. 297.
- Stephanopyxis turris* (Greville and Arnott) Ralfs in Pritchard, 1861, p. 826, pl. 5, fig. 74; Schrader and Fenner, 1976, pl. 30, figs. 1–10, 14; pl. 37, figs. 17–19.
- Thalassionema nitzschioides* (Grunow) Van Heurck, 1896, p. 319, fig. 75; Schrader and Fenner, 1976, pl. 5, fig. 8.
- Thalassiosira antiqua* (Grunow) Cleve Euler: Akiba, 1986, p. 463, pl. 12, figs. 1, 3–4.
- Thalassiosira eccentrica* (Ehrenberg) Cleve: Fryxell and Hasle, 1972, p. 297, pl. 1–4, figs. 1a–18.
- Thalassiosira gravida* Cleve, 1896, p. 12, pl. 2, figs. 14–16; Hustedt, 1928, p. 325, fig. 161; Schrader and Fenner, 1976, pl. 16, figs. 5, 6; pl. 17, fig. 2.
- Thalassiosira jouseae* Akiba, 1986, p. 457, pl. 6, figs. 8–10.
- Thalassiosira lineata* Jousé: Hasle and Fryxell, 1977, p. 22, figs. 15–25.
- Thalassiosira nidulus* (Tempère and Brun) Jousé, 1961, p. 63; Akiba, 1986, p. 457, pl. 6, figs. 4–7.
- Thalassiosira nordenskiöldii* Cleve, 1873, p. 7, pl. 1, fig. 11; Hustedt, 1928, p. 321, fig. 157; Sancetta, 1982, p. 242, pl. 5, figs. 8–9.
- Thalassiosira oestrupii* (Ostenfeld) Proshkina-Lavrenko, 1949; Hasle, 1960, p. 8, pl. 1, figs. 5–7; Akiba, 1986, pl. 14, figs. 1–6.
- Thalassiosira trifulta* Fryxell, in Fryxell and Hasle, 1979, p. 16, pls. 1–5, figs. 1–24; Sancetta, 1982, p. 244, pl. 5, figs. 10–12.
- Thalassiothrix longissima* Cleve and Grunow, 1880: Hustedt, 1932, p. 247, fig. 726; Hasle and Semina, 1987, figs. 1–25.

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APPENDIX

List of Flora

- Actinocyclus curvatulus* Janisch, 1878, in Schmidt et al. (1874–1959), pl. 57, fig. 31; Hustedt, 1958, pp. 129–130, pl. 8, fig. 81.
- Actinocyclus oculatus* Jousé, 1968, p. 18, pl. 2, figs. 6, 7; Koizumi, 1973, p. 831, pl. 2, figs. 8, 9.
- Azpeitia nodulifer* (Schmidt), G. Fryxell, P.A. Sims, and T.P. Watkins, 1986, p. 19.

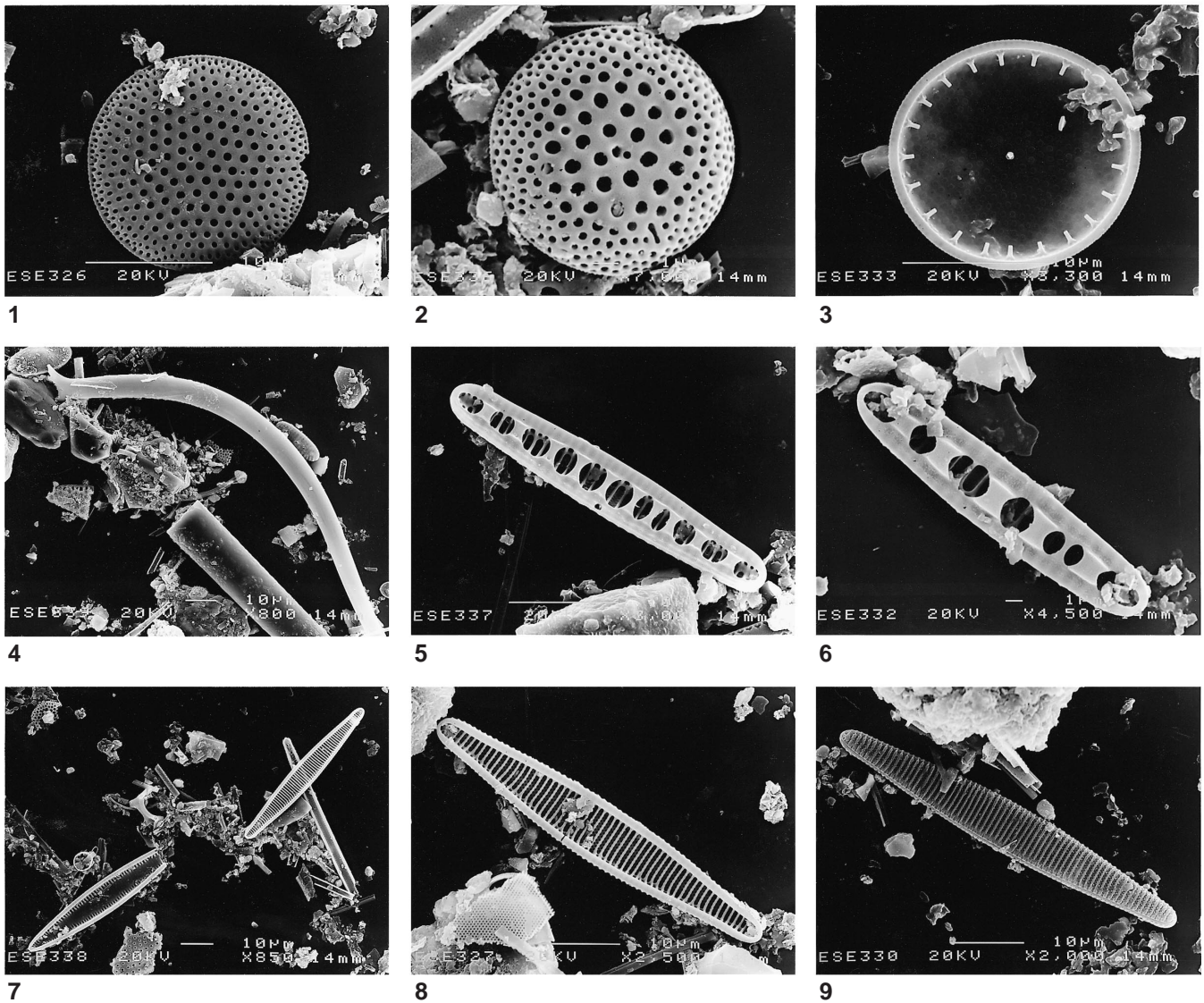


Plate 1. Scale bar = 10 μ m unless otherwise indicated. All are scanning electron microscope (SEM) pictures from Sample 162-983A-13H-7, 49–50 cm. **1, 2.** *Thalassiosira ostrupii* (Ostenfeld) Proshkina-Lavrenko, external views of valve face with a central process and a labiate process halfway between the center and the margin. **3.** *Thalassiosira ostrupii* (Ostenfeld) Proshkina-Lavrenko, internal view of valve face with a row of marginal spines, with a central process and a labiate process halfway between the center and the margin. **4.** *Proboscia curvirostris* Jordan and Priddle. **5.** *Neodenticula seminae* (Simonsen and Kanaya) Akiba and Yanagisawa, internal view of valve face. **6.** *Neodenticula seminae* (Simonsen and Kanaya) Akiba and Yanagisawa, internal view of valve face. Scale bar = 1 μ m. **7.** *Nitzschia reinholdii* Kanaya and Koizumi, at lower left, and *Nitzschia fossilis* (Frenguelli) Kanaya, at top right. **8.** *Nitzschia fossilis* (Frenguelli) Kanaya, internal view. **9.** *Nitzschia fossilis* (Frenguelli) Kanaya, external view.

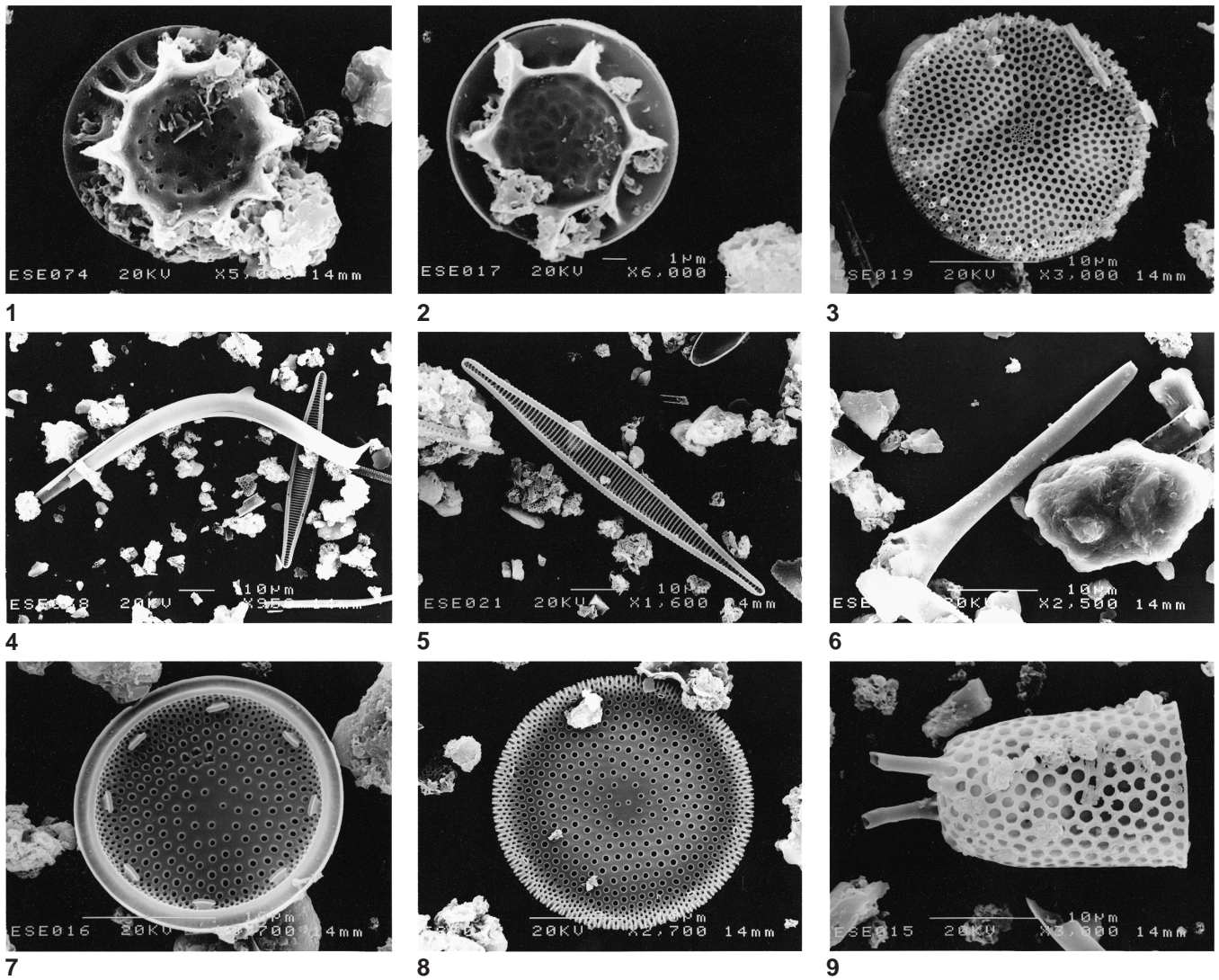


Plate 2. Scale bar = 10 μm unless otherwise indicated. All are SEM pictures. 1, 2. *Thalassiosira jouseae* (Akiba), Sample 162-983A-27H-7, 49–50 cm. 3. *Thalassiosira gravida* (Cleve), vegetative cell, Sample 162-983A-9H-3, 49–50 cm. 4. *Proboscia curvirostris* (Jordan and Priddle) and *Nitzschia fossilis* (Frenguelli) Kanaya, Sample 162-983A-9H-3, 49–50 cm. 5. *Nitzschia fossilis* (Frenguelli) Kanaya, Sample 162-983A-9H-3, 49–50 cm. 6. *Proboscia alata* (Sundström), Sample 162-983A-9H-3, 49–50 cm. 7. *Actinocyclus oculatus* (Jousé), internal view, Sample 162-983A-27H-7, 49–50 cm. 8. *Actinocyclus oculatus* (Jousé), external view, Sample 162-983A-27H-7, 49–50 cm. 9. *Stephanopyxis turris* (Greville and Arnott), Sample 162-983A-27H-7, 49–50 cm.