Arctic Ocean evidence for late Quaternary initiation of northern Eurasian ice sheets

Robert F. Spielhagen GEOMAR Research Center for Marine Geosciences, 24148 Kiel, Germany
Georges Bonani Institute for Particle Physics, ETH Hönggerberg, 8093 Zürich, Switzerland
Anton Eisenhauer Geochemical Institute, Göttingen University, 37077 Göttingen, Germany
Martin Frank Heidelberg Academy of Sciences, 69120 Heidelberg, Germany
Thomas Frederichs Department of Geosciences, University of Bremen, 28334 Bremen, Germany
Heidemarie Kassens GEOMAR Research Center for Marine Geosciences, 24148 Kiel, Germany
Peter W. Kubik Paul Scherrer Institute c/o Institute for Particle Physics, ETH Hönggerberg, 8093 Zürich, Switzerland
Augusto Mangini Heidelberg Academy of Sciences, 69120 Heidelberg, Germany
Niels Nørgaard-Pedersen GEOMAR Research Center for Marine Geosciences, 24148 Kiel, Germany
Norbert R. Nowaczyk GeoForschungsZentrum Potsdam, 14473 Potsdam, Germany
Stefan Schäper Heidelberg Academy of Sciences, 69120 Heidelberg, Germany
Ruediger Stein Alfred-Wegener Institute for Polar and Marine Research, 27586 Bremerhaven, Germany
Jörn Thiede, Ralf Tiedemann GEOMAR Research Center for Marine Geosciences, 24148 Kiel, Germany
Monika Wahsner Alfred-Wegener Institute for Polar and Marine Research, 27586 Bremerhaven, Germany

ABSTRACT

A high-resolution multiparameter stratigraphy allows the identification of late Quaternary glacial and interglacial cycles in a central Arctic Ocean sediment core. Distinct sandy layers in the upper part of the otherwise fine-grained sediment core from the Lomonosov Ridge (lat 87.5°N) correlate to four major glacials since ca. 0.7 Ma. The composition of these ice-rafted terrigenous sediments points to a glaciated northern Siberia as the main source. In contrast, lithic carbonates derived from North America are also present in older sediments and indicate a northern North American glaciation since at least 2.8 Ma. We conclude that large-scale northern Siberian glaciation began much later than other Northern Hemisphere ice sheets.

INTRODUCTION

The global importance of environmental changes in the Arctic region—such as the establishment and decay of ice sheets, outflow of associated meltwater discharge, and changes in extent and composition of the ice cover—is now widely recognized by researchers in the oceanographic and (paleo)climatic field. Previous paleoenvironmental studies in the central Arctic Ocean, based mainly on magnetostratigraphy (e.g., Clark et al., 1980; Herman and Hopkins, 1980), revealed extremely low (1–5 mm/k.y.) average sedimentation rates in the Pliocene-Pleistocene. This fact, and the sparse discontinuous occurrence of microfossils have so far prevented the determination of a high-resolution stratigraphic framework for the central Arctic Ocean sedimentary sequence of the past 5 m.y. Glacial-interglacial cycles could be resolved only in marginal areas (Poore et al., 1993; Eisenhauer et al., 1994).

In this study, we present a multidisciplinary approach for an improved stratigraphy to detect glacial-interglacial changes in sediment core PS2185 from the Lomonosov Ridge (central Arctic Ocean, Fig. 1). Independent paleoenvironmental indicators allow us to reconstruct changes in the composition of the Arctic ice cover, and lithic, ice-rafted sediment components give evidence for the history of circum-Arctic continental ice sheets.

SAMPLING AND METHODS

During expedition ARCTIC'91, box core PS2185-3 (corer size 50 × 50 × 50 cm) and gravity core PS2185-6 (corer size 1150 × 30 × 30 cm) were obtained from the crest of the Lomonosov Ridge (1052 m water depth, lat 87°32.0′N, long 144°22.9′E, and lat 87°32.2′N, long 144°55.6′E, respectively). Using grain-size data for both cores, the total sedimentary record of the two cores comprises 768 cm. Analysis of X-ray photographs gave no evidence for hiatuses in the sedimentary record. Sampling for ^{10}Be and paleomagnetic measurements and for sedimentological studies was carried out in ≤5 cm intervals. Measurements of ^{10}Be concentrations were conducted at the accelerator mass spectrometer (AMS) facility, Eidgenössische Technische Hochschule Zürich, using standard procedures and the internal standard S555. Planktic foraminifer abundances were determined from a representative split (~500 grains) of the 125–500 µm fraction. The composition of the terrigenous >500 µm fraction was determined accordingly. Grain-size determination and X-ray diffractometry for clay-mineral analysis conformed to Stein et al. (1994). The detailed paleomagnetic data set was given in Frederichs (1995).

STRATIGRAPHIC STUDIES

The large-scale chronology of cores PS2185-3 and PS2185-6 is based on magnetostratigraphy. The Brunhes magnetic chronozone spans the upper 342 cm (Fig. 2), whereas the lower boundaries of the Matuyama and Gauss chronozones were found at 450 and 631 cm, respectively. Identification of magnetic events within the chronozones (Cande and Kent, 1995) provides an age of ca. 5.1 Ma for the core base.

The ^{10}Be record of cores PS2185-3 and PS2185-6 exhibits a strong variability, which can be correlated to climate cycles: in sub-Arctic and Arctic Ocean cores, ^{10}Be concentrations in glacial upper Quaternary sediments are low (Eisenhauer et al., 1994). Intercalated interglacial sediments have high concentrations because the flux of the cosmogenically produced ^{10}Be (half-life period: 1.5 m.y.) from the uppermost water column to the sediment is enhanced by sedimentation of clay minerals and bioproduction (cf. Sharma et al., 1987; Kusakabe et al., 1987), two processes that are intensified during interglacials in the Arctic Ocean (Eisenhauer et al., 1994; Gard, 1993). Thus, we interpret peak ^{10}Be concentrations in cores PS2185-3 and PS2185-6 between 0 and 350 cm to mark interglacial oxygen isotope stages 1, 3–5, 7, 9, 11, 13, 15, 17, and 19 (Fig. 2). The small ^{10}Be peak at 70 cm may belong either to stage 5 (5e?) or 6, but strong carbonate dissolution aggra-

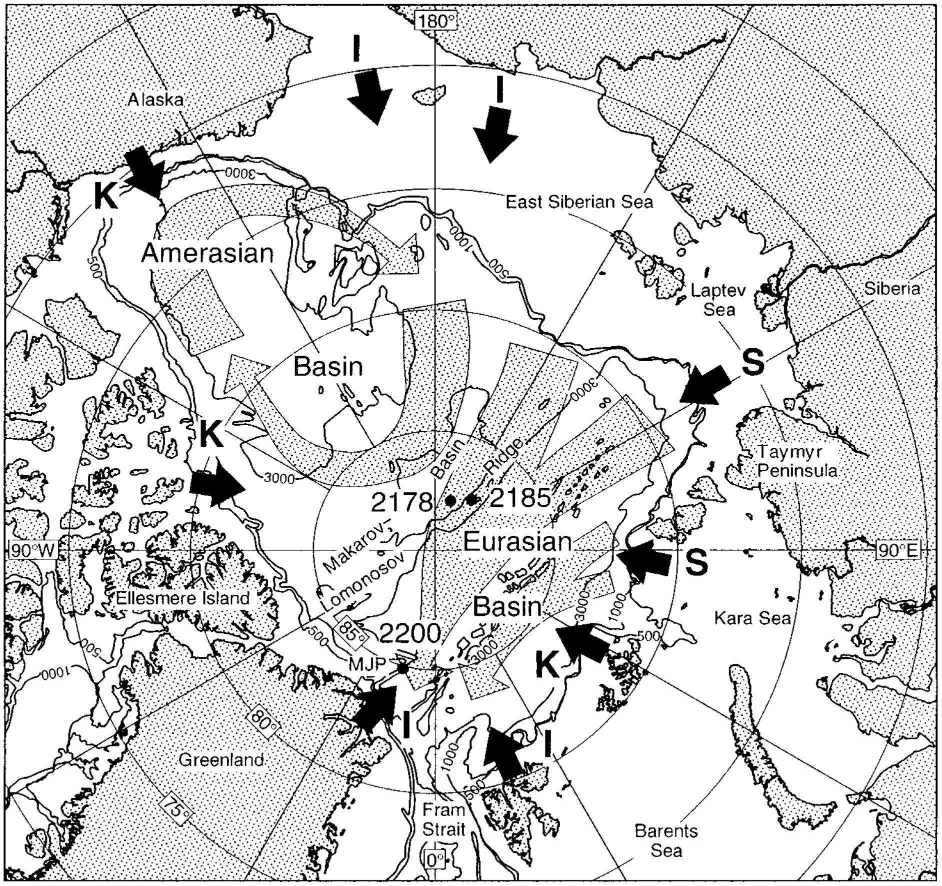

Figure 1. Bathymetry of Arctic Ocean (in meters below sea level) and core sites discussed in this study. MJP is Morris Jesup Plateau. Dotted arrows mark modern ice drift pattern: Beaufort gyre in Amerasian basin and transpolar drift in Eurasian basin of Arctic Ocean. Black arrows mark potential output of different clay minerals from specific circum-Arctic source areas: I = illite, K = kaolinite, S = smectite.

vates correlation to other cores analyzed by Gard (1993). However, this uncertainty does not affect the stratigraphic model for sediments older than stage 6. Nearby core PS2178-5 (830 cm recovery) from the deep Makarov basin (lat 88°1.5′N, long 159°42.2′E, 4008 m water depth) shows a similar pattern of ^{10}Be concentrations and grain-size variations in higher resolution (Schäper, 1994), suggesting that the stratigraphic record of cores PS 2185-3 and 2185-6 is complete. Low ^{10}Be concentrations in glacial sediments from stages 6, 10, 12, and 16 may result from dilution by coarse terrigenous particles, but the persistence of the ^{10}Be variations in the sediments with no significant grain-size variations (below 320 cm) strongly suggests that the ^{10}Be deposition pattern reflects climate variability since 2.9 Ma.

Further data support our stratigraphic model for the Brunhes chronozone having an average sedimentation rate of ~0.5 cm/k.y. AMS ^{14}C dating of the uppermost 30 cm (Table 1) gave infinite ages (≥38 ka) below 20 cm. High planktic foraminifer abundances in ^{10}Be-rich layers around 55, 180, 210, and 240 cm (Fig. 2) indicate enhanced bioproduction during oxygen isotope stages 5, 11, 13, and 15, respectively. On the basis of nannoplankton studies, Henrich and Baumann (1994) identified these stages as the only "very warm" interglacials in the Norwegian Sea during the past 600 k.y. The sparsity of planktic foraminifers in sediments older than 0.7 Ma is well known (Clark et al., 1980; Herman and Hopkins, 1980).

SEDIMENT COMPOSITION, PROVENANCE, AND TRANSPORT

Below 320 cm in cores PS2185-3 and PS2185-6, the sand content is low (5–10 wt%, >63 µm) and exhibits no significant variability. Above, we find four distinct sandy layers (>25%, >63 µm), which are almost barren of planktic foraminifers. A similar grain-size pattern was found previously in other cores from the area (Morris et al., 1985). According to our stratigraphy, the sandy layers were deposited during glacial stages 16, 12, 10, 6, and possibly 5 and/or 4. Whereas fine-grained Arctic sediments are supposed to have been transported mainly by sea ice, sandy layers on topographic highs are indicative of a large number of icebergs in the central Arctic Ocean (Clark and Hanson, 1983). The provenance of these icebergs can be determined from the clay-mineral composition in the sandy layers. Here, smectite concentrations reach 20%–35%, which is two to three times higher than in the fine-grained layers (Fig. 2). The potential main sources for smectite in central Arctic Ocean sediments are the shelves of the Kara and western Laptev seas, where surface sediments reach peak concentrations of 45% (Stein et al., 1994). In other areas, smectite concentrations in surface sediments are significantly lower (as reviewed by Nürnberg et al., 1994). Because of the lowered sea level, a transport of smectite through the Bering Strait (Naidu and Mowatt, 1983) seems unlikely during glacials. Coarse ice-rafted debris (>500 µm) in the sandy layers in cores PS2185-3 and PS2185-6 consists mainly of quartz and feldspar grains and traces of clastic sedimentary and polycrystalline rock fragments. Possible source rocks are present on the Taymyr Peninsula, but are also widespread in other circum-Arctic areas.

Another well-known lithologic tracer in Arctic Ocean sediments is detrital carbonate grains (mainly dolomite). Such ice-rafted debris is abundant in cores from the Amerasian basin and was almost exclusively derived from variable glaciations in northern Canada, that were present both during glacials and interglacials (Bischof et al., 1996). Detrital carbonates in the coarse ice-rafted debris in cores PS2185-3 and PS2185-6 are very rare or absent in the distinct sandy layers, but amount to 30%–60% of the coarse ice-rafted debris in all fine-grained sections above 490 cm. Thus, carbonate-bearing sediments represent all interglacial and some glacial stages (2, 8, 14) since 0.7 Ma, as well as most of the interval 2.8 to 0.7 Ma.

DISCUSSION AND CONCLUSIONS

The variability of the composition of terrigenous sediment components in cores PS2185-3 and PS2185-6 suggests changing sources. Icebergs calving from glaciers and ice sheets are the most likely transport agents for the coarse ice-rafted debris. Variable continental glaciations and ice drift patterns should account for the changes in dominant ice-rafted debris lithologies. However, icebergs are capable of transporting all grain sizes, including fines (Clark and Hanson, 1983). We assume that in times of enhanced iceberg rafting, both the fine- and coarse-grained terrigenous components in a sediment sample stem from roughly the same region. Therefore, we conclude that most of the coarser-grained ice-rafted debris in the smectite-rich sandy layers from glacial stages 16, 12, 10, and 6 was also derived from northern Siberia. Extensive continental glaciations in this area may have originated on the mountainous Taymyr Peninsula and extended onto the wide shelves as marine ice sheets. Such ice sheets are extremely sensitive to sea-level variations (Jones and Keigwin, 1988), and most of the iceberg and ice-rafted debris output from northern Siberia to the Arctic Ocean may have occurred during deglaciations.

Evidence for northern North American glaciations comes from the detrital carbonates in the coarse ice-rafted debris. Their deposition at site PS2185 was variable, but almost continuous between 2.8 and 0.7 Ma. Since 0.7 Ma, carbonate detritus alternated with smectite-rich, carbonate-

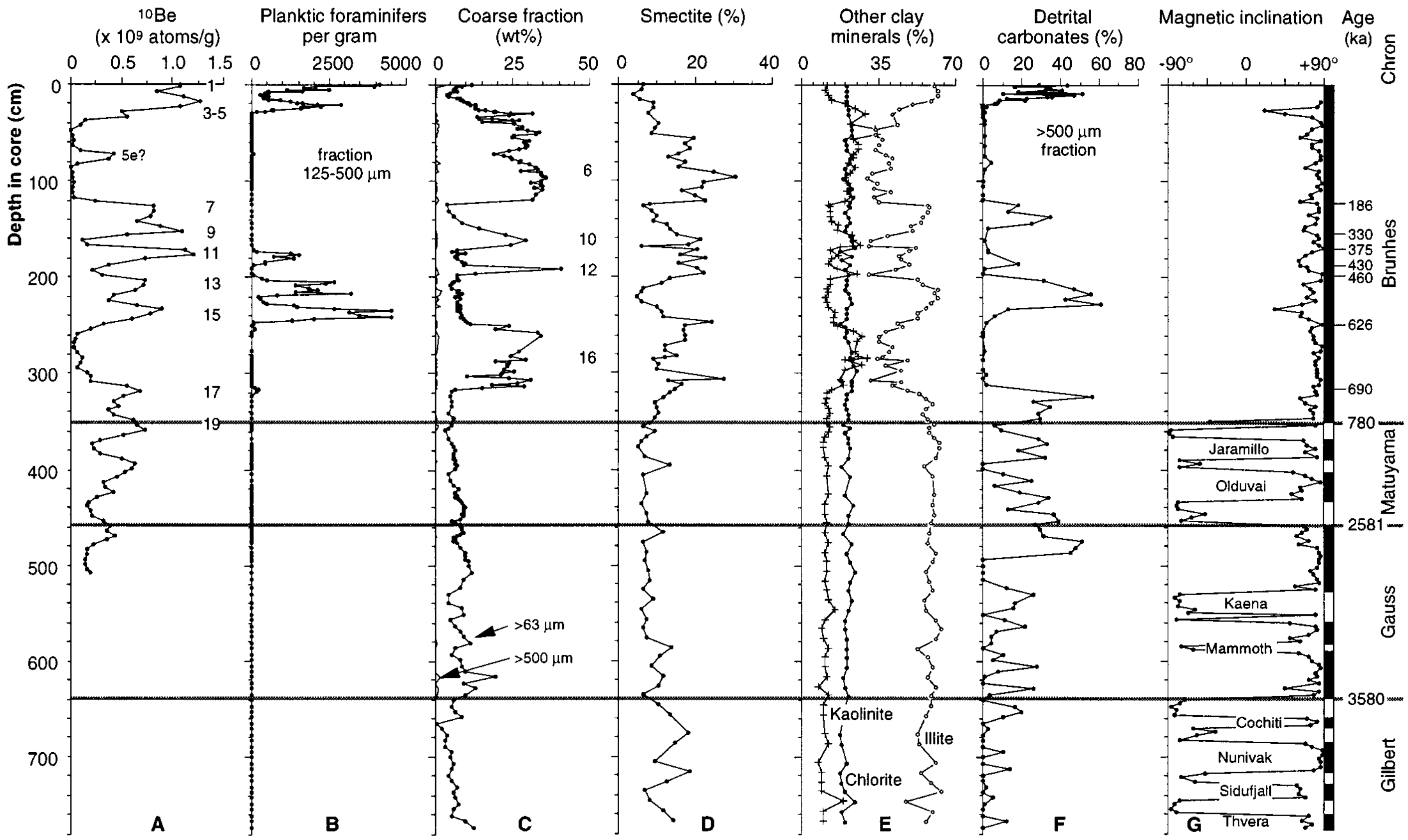

Figure 2. Results of analyses of cores PS2185-3 and PS2185-6. A: ^{10}Be concentrations. B: Planktic foraminifer abundances. C: Grain sizes. D and E: Clay mineral composition. F: Abundance of detrital carbonate particles in >500 µm fraction. G: Magnetic inclination. Numbers in A and C indicate proposed climatic (oxygen isotope) stages. Chronology within Brunhes chron was obtained by correlation of ^{10}Be isotope record to orbitally tuned oxygen isotope record of Ocean Drilling Program hole 659 (Tiedemann et al., 1994).

poor sediments, indicating two main Arctic iceberg sources, of which one was active only sporadically. Glaciers on northern Ellesmere Island, where carbonate rocks crop out, are today the main source of central Arctic Ocean icebergs (Clark and Hanson, 1983). The exact source locality of the abundant carbonates in surficial sediments of core PS2185-3 is not known. However, they clearly document the significance of a minor glaciation in northern North America for the ice-rafted debris deposition in the central Arctic Ocean in the Holocene. Such a minor glaciation and a lack of major iceberg-producing glaciers in other circum-Arctic areas can explain the occurrence of detrital carbonates in older interglacial layers.

During glacials, ice sheets and the iceberg production in northern North America were probably much greater. The lack of carbonates in the smectite-rich sediments from glacial stages 6, 10, 12, and 16, however, suggests that icebergs from North America did not reach site PS2185 during these intervals. We propose that an unusually massive output of icebergs from northern Siberia then covered this area and forced icebergs from North America to remain in the Amerasian basin. The high sedimentation rates (up to 1.7 cm/k.y.) on the Lomonosov Ridge in those glacial stages (especially 6 and 16) demonstrate that sediment transport and deposition of coarse ice-rafted debris from northern Siberia must have been much higher than from other sources or at other times in the Pliocene-Pleistocene.

TABLE 1. ^{14}C DATES OF CORE PS2185-3

Depth interval (cm)	Sample no.	Age (yr B.P.)	± 1 s.d. (yr B.P.)
0-1	ETH9868	3 080	60
9-10	ETH10575	10 710	85
14-15	ETH9872	19 970	290
16-17	ETH9873	30 780	530
20-21	ETH9874	>38 000	N.A.*
28-29	ETH9875	>38 000	N.A.*

Note: Dates were obtained on ca. 1500 specimens of *Neogloboquadrina pachyderma* (sin.) per sample at the PSI/ETH accelerator mass spectrometer facility in Zürich and are corrected for δ^{13}C.
*Not applicable.

Iceberg-producing glaciers may have existed prior to 0.7 Ma in northern Siberia, and it may be argued that, owing to a weaker transpolar drift and/or a wider Beaufort gyre (Fig. 1), the icebergs did not reach site PS2185 before this time. However, records of ^{10}Be, grain size, clay-mineral distribution, and magnetic parameters since 5 Ma from site (gravity core) PS2200 on the Morris Jesup Rise, near the exit of the ice drift from the Arctic Ocean (lat 85°19.4′N, long 14°0.0′W, 1073 m water depth, 770 cm recovery), show a covariant pattern very similar to that in cores PS2185-3 and PS2185-6 (Molnar, 1995; Vogt, 1997). Thus, it is unlikely that lithologic changes in the cores after ca. 0.7 Ma were caused only by a regional shift of the ice-drift pattern. Instead, these changes must have resulted from a much higher variability of the composition of the Arctic ice cover (i.e., the iceberg/sea ice ratio), reflecting highly variable glaciations on surrounding continents.

On the basis of studies of cores from the Amerasian basin, Clark and Hanson (1983) concluded that sea ice has been the major agent for sediment transport at least since 5 Ma. According to our data, ca. 0.7 Ma, depositional environments on the Lomonosov Ridge changed drastically from strongly sea-ice–dominated to mixed iceberg and sea-ice transport of terrigenous sediments during four major glacial intervals. The first strong influx of ice-rafted debris from northern Siberia ca. 0.7 Ma documents an important late Quaternary intensification of continental glaciation in this area. Initial buildup of ice sheets may have started somewhat earlier, but their imprint on sedimentation patterns in the Arctic Ocean was probably limited, possibly because they did not reach the paleocoastline. In contrast, the depositional history of ice-rafted debris rich in detrital carbonates documents a long series of northern North American glaciations since ca. 2.8 Ma. These glaciations were probably strongest during glacial time, but a minor glaciation in this area (similar to today) provided small amounts of this ice-rafted debris to the Arctic Ocean even during interglacials. Occurrences at 580 and 630 cm in cores PS2185-3 and PS2185-6 may reflect even earlier glaciations at 3.2 and 3.5 Ma, respectively.

The late Pliocene onset of almost continuous glaciations in northern North America is roughly contemporaneous with ice rafting in the North Atlantic, Norwegian Sea, Baffin Bay, and North Pacific (Shackleton et al., 1984; Jansen and Sjøholm, 1991; Srivastava et al., 1987; Rea et al., 1993), indicating major ice sheets on adjacent continents after ca. 2.6 Ma. In contrast, a large northern Siberian ice sheet formed much later (ca. 0.7 Ma). Its first large extension to the shelf break, during oxygen isotope stage 16, correlates well with age estimates for the first major marine-based Barents Sea glaciation (Laberg and Vorren, 1996).

The causes for the late Quaternary ice-sheet development in northern Eurasia were probably manifold. In most long deep-sea benthic $\delta^{18}O$ records, stage 16 was identified as the first long Quaternary glacial episode, with a global ice volume unequaled before in the Quaternary (e.g., Shackleton et al., 1990; Tiedemann et al., 1994). It marks the last phase of the mid-Quaternary climatic transition, when glaciation cycles shifted from 41 k.y. in the Matuyama to 100 k.y. cycles thereafter (Ruddiman et al., 1986). Such longer glaciation cycles would allow a longer time for the buildup of (larger) ice sheets. A contemporaneous significant cooling, both in the Arctic and in northern Eurasia (Ruddiman and Kutzbach, 1989), and an intensified northwestward atmospheric circulation in the North Atlantic area, strengthening the North Atlantic Current (Jansen et al., 1990), must have enhanced supply, transport, and precipitation of moisture and strongly favored the formation of large northern Eurasian ice sheets. The first ones probably did not reach the shore, but eventually the stage 16 ice sheet was large enough to leave definite traces of ice-rafted debris in Arctic sediments.

ACKNOWLEDGMENTS

Funded by the German Ministry for Research and Technology, partly through the "Paläoklimaprojekt." We thank the captain, crew, and chief scientist of RV *Polarstern* and the Alfred-Wegener Institut für Polar- und Meeresforschung for their support during cruise ARCTIC'91, S.-O. Bude, J. Paulsen, and S. Steinke for technical assistance, M. Molnar, C. Vogt, and R. Walther for discussions and unpublished data, and W. Ruddiman and one anonymous reader for helpful reviews.

REFERENCES CITED

Bischof, J., Clark, D. L., and Vincent, J.-S., 1996, Origin of ice-rafted debris: Pleistocene paleoceanography in the western Arctic Ocean: Paleoceanography, v. 11, p. 743–756.

Cande, S. C., and Kent, D. V., 1995, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 100, p. 6093–6095.

Clark, D. L., and Hanson, A., 1983, Central Arctic Ocean sediment texture: A key to ice transport mechanism, *in* Molnia, B. F., ed., Glacial-marine sedimentation: New York, Plenum Press, p. 301–330.

Clark, D. L., Whitman, R. R., Morgan, K. A., and Mackey, S. D., 1980, Stratigraphy and glacial-marine sediments of the Amerasian Basin, central Arctic Ocean: Geological Society of America Special Paper 181, 57 p.

Eisenhauer, A., Spielhagen, R. F., Frank, M., Hentzschel, G., Mangini, A., Kubik, P. W., Dittrich-Hannen, B., and Billen, T., 1994, ^{10}Be records of sediment cores from high northern latitudes—Implications for environmental and climatic changes: Earth and Planetary Science Letters, v. 124, p. 171–184.

Frederichs, T., 1995, Regional and temporal variations of rock magnetic parameters in Arctic marine sediments: Berichte zur Polarforschung, v. 164, 212 p.

Gard, G., 1993, Late Quaternary coccoliths at the North Pole: Evidence of ice-free conditions and rapid sedimentation in the central Arctic Ocean: Geology, v. 21, p. 227–230.

Henrich, R., and Baumann, K.-H., 1994, Evolution of the Norwegian current and the Scandinavian ice sheet during the past 2.6 m.y.: Evidence from ODP Leg 104 biogenic carbonate and terrigenous records: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 108, p. 75–94.

Herman, Y., and Hopkins, D. M., 1980, Arctic oceanic climate in late Cenozoic time: Science, v. 209, p. 557–569.

Jansen, E., and Sjøholm, J., 1991, Reconstruction of glaciation over the past 6 Myr from ice-borne deposits in the Norwegian Sea: Nature, v. 349, p. 600–603.

Jansen, E., Sjøholm, J., Bleil, U., and Erichsen, J. A., 1990, Neogene and Pleistocene glaciations in the Northern Hemisphere and late Miocene–Pliocene global ice volume fluctuations: Evidence from the Norwegian Sea, *in* Bleil, U., and Thiede, J., eds., Geological history of the polar oceans: Arctic versus Antarctic: Dordrecht, Kluwer, p. 677–705.

Jones, G. A., and Keigwin, L. D., 1988, Evidence from Fram Strait (78°N) for early deglaciation: Nature, v. 336, p. 56–59.

Kusakabe, M., Ku, T. L., Southon, J. R., Vogel, J. S., Nelson, D. E., Measures, C. I., and Nozaki, Y., 1987, Distribution of ^{10}Be and ^{9}Be in the Pacific Ocean: Earth and Planetary Science Letters, v. 82, p. 231–240.

Laberg, J. S., and Vorren, T. O., 1996, The middle and late Pleistocene evolution of the Bear Island Trough Mouth Fan: Global and Planetary Change, v. 12, p. 309–330.

Molnar, M., 1995, Die Datierung von Sedimentkernen aus dem Arktischen Ozean [Master's thesis]: Heidelberg, Germany, Heidelberg University, 118 p.

Morris, T. H., Clark, D. L., and Blasco, S. M., 1985, Sediments of the Lomonosov Ridge and Makarov Basin: A Pleistocene stratigraphy for the North Pole: Geological Society of America Bulletin, v. 96, p. 901–910.

Naidu, A. S., and Mowatt, T. C., 1983, Sources and dispersal patterns of clay minerals in surface sediments from the continental-shelf areas off Alaska: Geological Society of America Bulletin, v. 94, p. 841–854.

Nürnberg, D., Wollenburg, I., Dethleff, D., Eicken, H., Kassens, H., Letzig, T., Reimnitz, E., and Thiede, J., 1994, Sediments in Arctic sea ice: Implications for entrainment, transport and release: Marine Geology, v. 104, p. 185–214.

Poore, R. Z., Phillips, R. L., and Rieck, H. J., 1993, Paleoclimate record for Northwind Ridge, Western Arctic Ocean: Paleoceanography, v. 8, p. 149–159.

Rea, D. K., Basov, I. A., Janecek, T. R., Palmer-Julson, A., et al., 1993, Proceedings of the Ocean Drilling Project, Initial reports: College Station, Texas, Ocean Drilling Program, v. 145, 1040 p.

Ruddiman, W. F., and Kutzbach, J. E., 1989, Forcing of late Cenozoic Northern Hemisphere climate by plateau uplift in southern Asia and the American West: Journal of Geophysical Research, v. 94, p. 18409–18427.

Ruddiman, W. F., Raymo, M. E., and McIntyre, A., 1986, Matuyama 41,000-year cycles: North Atlantic Ocean and Northern Hemisphere ice sheets: Earth and Planetary Science Letters, v. 80, p. 117–129.

Schäper, S., 1994, Quartäre Sedimentation im polnahen Arktischen Ozean [diploma thesis]: Heidelberg, Germany, Heidelberg University, 113 p.

Shackleton, N. J., and 16 others, 1984, Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region: Nature, v. 307, p. 620–623.

Shackleton, N. J., Berger, A., and Peltier, W. R., 1990, An alternative astronomical calibration of the lower Pleistocene timescale based on ODP site 677: Royal Society of Edinburgh Transactions, Earth Sciences, v. 81, p. 251–261.

Sharma, P., Mahannah, R., Moore, W. S., Ku, T. L., and Southon, J. R., 1987, Transport of ^{10}Be and ^{9}Be in the ocean: Earth and Planetary Science Letters, v. 86, p. 69–76.

Srivastava, S. P., Arthur, M., et al., 1987, Proceedings of the Ocean Drilling Project, Initial reports: College Station, Texas, Ocean Drilling Program, v. 105, 917 p.

Stein, R., Grobe, H., and Wahsner, M., 1994, Organic carbon, carbonate, and clay mineral distributions in eastern central Arctic Ocean surface sediments: Marine Geology, v. 104, p. 269–285.

Tiedemann, R., Sarnthein, M., and Shackleton, N. J., 1994, Astronomic timescale for the Pliocene Atlantic $\delta^{18}O$ and dust flux records of Ocean Drilling Program site 659: Paleoceanography, v. 9, p. 619–638.

Vogt, C., 1997, Zeitliche und räumliche Verteilung von Mineralvergesellschaftungen in spätquartären Sedimenten des Arktischen Ozeans und ihre Nützlichkeit als Klimaindikatoren während der Glazial/Interglazial-Wechsel [Ph.D. thesis]: Bremen, Germany, Bremen University, 335 p.

Manuscript received January 21, 1997
Revised manuscript received May 12, 1997
Manuscript accepted June 12, 1997