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

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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 glacial periods 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 in the composition of the Arctic ice cover, and. The composition of the terrigenous >500 µm fraction was determined accordingly. Grain-size determination and X-ray diffraction 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 chronzone 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 10Be 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, 10Be 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 10Be (half-life period: 1.5 m.y.) from the uppermost water column to the sediment is enhanced by sedimentation of clay minerals and bioproduct (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 10Be 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 10Be peak at 70 cm may belong either to stage 5 (5e?) or 6, but strong carbonate dissolution aggra-
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-
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 iceberg-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 glacial periods, 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.

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 paleo-coastline. 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 Sjøholt, 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 δ¹⁸O 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 glacial cycles shifted from 41 k.y. in the Matuyama to 100 k.y. cycles thereafter (Ruddiman et al., 1986). Such longer glacial 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.

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