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Mineralogical Evidence of Middle Miocene Glacial Ice in the Central Arctic Ocean Sediments

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Abstract

Early glaciations in the surrounding continents of the polar Arctic Ocean have been revealed through the occurrence of ice rafted detritus (IRD) in the marine sediments. The glacigenic origin of the deposited sediment is generally recognised either by the grain size, but also by distinctive grain morphology, grain surface textural features and clay mineral compositions. In this study the mineralogy of the submarine Lomonosov Ridge sediments are analysed using X-ray diffraction (XRD) and scanning electron microscope (SEM) methods. The study combines both the quartz sand grain surface microtextural and clay mineralogical data from drill cores obtained during the IODP Arctic Coring Expedition (ACEX) 302. The studied interval (141–197 m below sea floor) of the coring Site M0002 represents a time slice of 6 million years critical for the onset of glaciation, between ca. 12–18 Ma at the Middle Miocene. The sediments consist mainly of homogenous siliciclastic detritus characterised by low organic carbon concentrations. The specific glacial crushing and transport features – high angularity, conchoidal fractures, steps and subparallel linear fractures – were observed from quartz sand grain surfaces, coinciding with significant drops in the smectite contents. The reduced smectite and corresponding increase in the chlorite and illite contents refer to cooler climate conditions, continental ice generation and increased physical erosion on land.

Key words: Arctic Ocean, clay minerals, glaciations, IRD, Middle Miocene, quartz grain microtextures

1. Introduction

Continental erosion produces detritus which is partly transported by fluvial, glacial or aeolian processes, and finally deposited in the ocean floors. The relative clay mineral composition of detrital sediments, as well as the abundance, fraction-size and morphology/surface texture of the sediment grains, reflects the environmental conditions in the source areas and the intensity of continental weathering and sediment transportation. Thus, the glacial influence in the deposited sediments can be observed reliably through clay mineralogical and quartz grain microtextural studies (e.g. *Mahaney*, 1995a; *Ehrmann*, 1991; *Winkler et al.*, 2002; *Vogt et al.*, 2001; *Krylov et al.*, 2008 and *Strand et al.*, 2008).

In the clay mineralogical part of this study, the four principal clay minerals – smectite, illite, kaolinite and chlorite – were quantified and their relative proportions analysed with XRD. The use of clay minerals as provenance and climatic indicators is well founded as the deposited clay mineral types depend on the type of the source bedrock and the prevailing climatic conditions in the source area (*Velde*, 1992). In this study the clay mineral data was then combined with the quartz grain surface microtextural SEM analysis data. In grain surface microtextural studies quartz is a commonly used mineral due to its high preservation in deposited sediments (e.g. *Krinsley and Doornkamp*, 1973; *Mahaney*, 1995a; *Mahaney*, 2002). The high frequency of glacigenic microtextures in the grain surfaces can be seen as an indication of glacial ice in the sediment source area (*Mahaney*, 1995b) and used to document the advent of early continental glaciation. The relative frequency of the four most characteristic glacigenic features and textures are discussed in this study in relation to the clay mineral proportions.

The Earth's climate cooled dramatically after an extended period of relative warmth in the Mid-Miocene Climatic Optimum from 15 to ~17 Ma. The cooling trend can be seen as the sudden and permanent increase in global deep-sea oxygen isotope records after 15 Ma (*Zachos et al.*, 2001). It is generally assumed that this cooling led to the large-scale increase in polar glaciations (e.g. *Knies and Gaina*, 2008; *Mahaney et al.*, 2009). However, further evidence is needed to clarify the distribution and intensification of these early glaciations. The occurrence of glacial indicators as evidenced by quartz grain microtextures and clay mineral distributions is here used to verify the occurrence and growth of glacial ice in the Arctic region already during the Middle Miocene.

2. Regional setting

The ACEX 302 drilling location in the Lomonosov Ridge is situated 250 kilometres northeast from the North Pole (latitude 87.93°, longitude 139.5°) (Fig. 1). It reaches a present water depth of 1288 m and is surrounded by abyssal plains. Drilling penetrated into the sediment from present to late Cretaceous age at 428 mbsf. The recovered sediment data from sites M0002, M0003, and M0004, all situated within 16 km of each other were combined as one section, all verified by the seismic data. Total sediment recovery was 68.4% (*Backman et al.*, 2006).

The age model of ACEX 302 sediments is based on a ^{10}Be dating for the youngest sediments from present sea floor to 151 metres composite depth (*Frank et al.*, 2008) and on a biochronological interpretation based on dinocysts and silicoflagellates for the sediments beneath (*Backman et al.*, 2008). The beryllium isotope dates by Frank et al. (2008) provide an average sedimentation rate of 14.5± 1 m/Ma for the uppermost 151 m. The time estimations are also based on the palaeomagnetic reversal stratigraphy in the interval from 0 to about 200 mbsf (*O'Regan et al.,* 2008). This study comprises the sediment section from ~141 to ~197 mbsf revealing the time period of about 6 million years in the Middle Miocene. The sediments from ~197 mbsf represent an age of about 18 Ma.

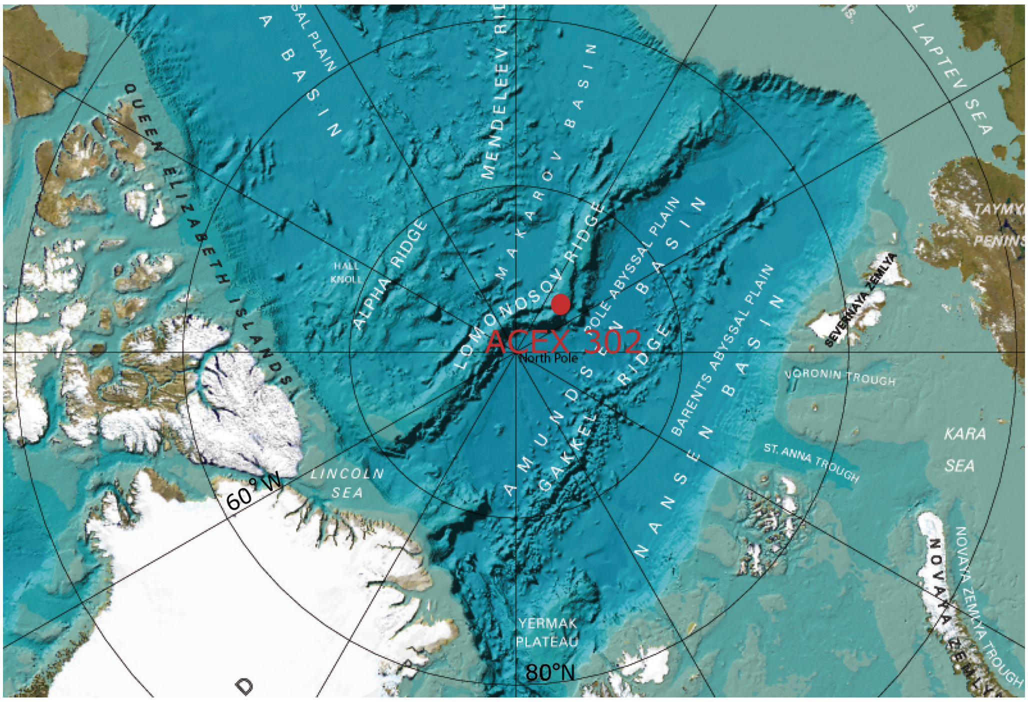

Fig. 1. ACEX 302 drilling site in Lomonosov Ridge, Arctic Ocean (image reproduced from the GEBCO world map, http://www.gebco.net).

3. *Methods*

The clay mineral analysis by x-ray diffraction (XRD) was carried out at the Institute for Electron Microscopy, University of Oulu according to *Hardy and Tucker* (1988). The analysed clays of <2 µm grain-size fraction were separated from the sample sediment by centrifuge, according to Stoke's law. Glycollate treatment (2 hours at 60°C) and heating treatment (2 hours at 550°C) were completed with the sample slides in order to expand the basal spacing of smectite from 12–15Å up to 17Å and, on the other hand, to destroy kaolinite and (certain chlorites) from the kaolinite-chlorite joint peak. Diffractograms were recorded with a Siemens D 5000 device with fixed divergence slit and copper radiation (40 kV, 40 mA) at angles ranging from 2° to 32° 2θ. The four principal clay mineral groups were recognized by their basal spacing at 7Å (kaolinite, chlorite), 10Å (illite), 15–17Å (smectite) and 14Å (chlorite). Chlorite (004) was then identified at 3.54Å and kaolinite (002) at 3.58Å. The peak-area method was used to calculate quantities of kaolinite and chlorite from the joint peak at 7Å. The relative percentages of smectite, illite, kaolinite and chlorite were quantified with the MacDiff graphic evaluation program by *Petschick* (2001).

Quartz grain separation was carried out according to *McManus* (1988) by sieving the 600–250 µm grain-size fraction from the sample sediments. Sample preparation for scanning electron microscopy (SEM) analysis was done according to *Trewin* (1988) and processing was completed with scanning electron microscope Jeol JSM-6400 at the

Institute for Electron Microscopy, University of Oulu. At least 30 grains were selected non-equidistantly from each sample. Photomicrographs were captured digitally with Digital Image Recording System SemAfore 3.0 Pro (JEOL) software. The used magnification varied around x100 – x300. Inca energy dispersive spectrometre with INCA Energy software 4.06 was calibrated to cobalt and used for elemental analysis to ascertain the element consistency of the grains. Quartz grain surface microtexture classification model is based on studies from e.g. *Mahaney* (1995b), *Helland and Holmes* (1997) and *Strand et al.* (2003).

4. Results

The characteristic quartz grain morphologies of the studied sediments show clear heterogenity in the beginning of the Middle Miocene from 197 to 168 mbsf. The frequency of angular to very angular outline (Fig. 2a) fluctuates between 3–43%, however, mechanical texture amounts stay relatively low. Conchoidal fractures (Fig. 2b) fluctuate between 7–20%, steps (Fig. 2c) between 10–47% and subparallel linear fractures (Fig. 2d) between 23–37%. The Middle Miocene interval from 197 to 141 mbsf is also characterized by a significant fluctuation in all clay minerals. Smectite concentration settles in relatively high values from 40 to 20% in the beginning of the Middle Miocene (Fig. 3). Subsequently, the values fluctuate around the level of 12% and after sudden drops to 1% at 159 mbsf and 2% at 151 mbsf, they finally settle down to around 6%. Illite concentration increases from the levels around 30% to 45% after 188 mbsf and finally reaches the values around 50% after 159 mbsf. The quartz grain data from 159 to 151 mbsf is characterized by the dominance of angular to very angular outline with 50–60% of grains. Mechanical textures increase in this phase; conchoidal fractures peak up to 17%, steps up to 67% and subparallel linear fractures up to 37%. Kaolinite concentration stays between 13 and 20% through the studied sediment section. Chlorite concentrations settles around 15% at 197 mbsf but soon afterwards fluctuate around the level of 26%. The most recent part of the studied Miocene sediment section shows a decreasing trend in the frequency of mechanical textures, while the value for conchoidal fractures is 7%, the value for steps 37% and the value for subparallel linear fractures 20%. The frequency of angular to very angular outline decreases to 30% (Fig. 3).

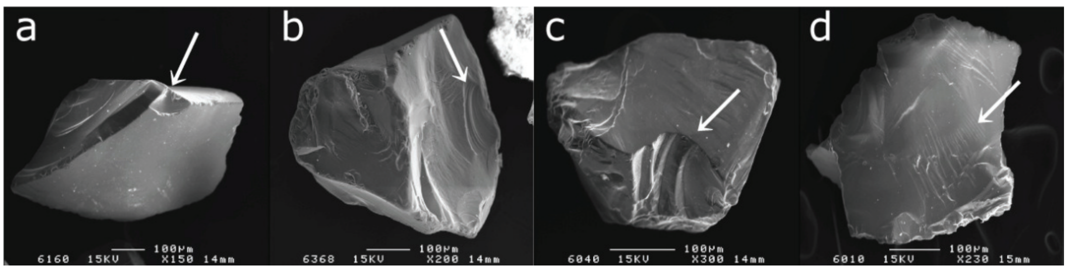

Fig. 2. Middle Miocene glacigenic quartz sand grains from Lomonosov Ridge sediments. Figures 2a and 2b: Angular outline with conchoidal fracture (arrow). Figure 2c: Steps (arrow). Figure 2d: Subparallel linear fractures (arrow).

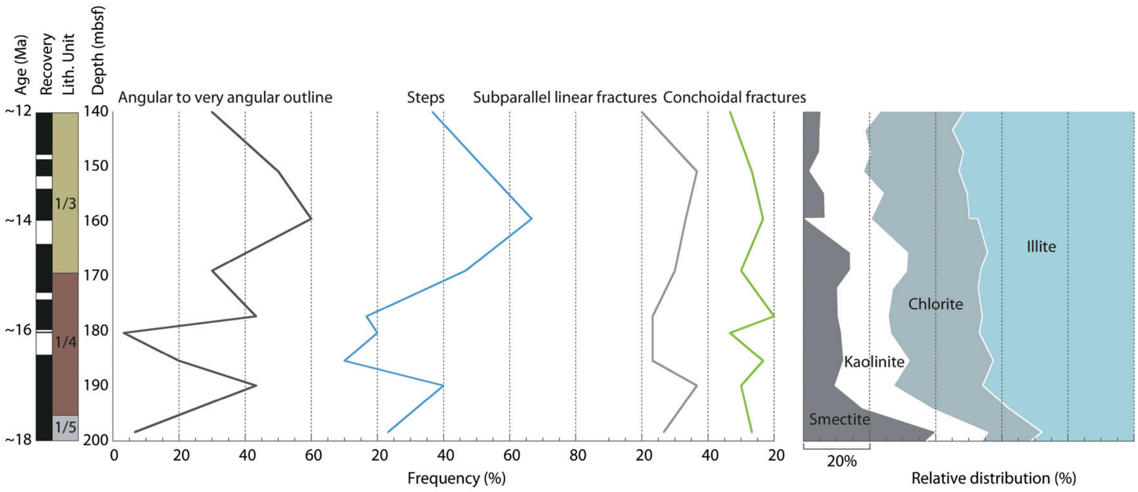

Fig. 3. Combined Middle Miocene data of the frequencies of typical glacigenic microtextures and relative distributions of studied clay minerals. Core recovery is marked as black and non-recovery as white. Lithological units and age data from *Backman et al.* (2006; 2008).

5. *Discussion*

The earliest Middle Miocene quartz grains are suggested to have a distinct fluvial origin because of the high distribution of >250 µm grain-size fraction, the dominance of subrounded to rounded grain morphology and the near total absence of glacially influenced mechanical textures. This interpretation is also supported by the relatively high smectite concentrations. Most of the smectite in the Arctic Ocean sediments is assumed to have continental origin (*Winkler et al.*, 2002) and fluvial supply by the major river systems to the Kara and Laptev Seas (*Wahsner et al.,* 1999). Finally, the continental smectite is transported from the shelf areas of the Arctic Ocean to the Lomonosov Rigde by the sea ice and/or ocean currents.

Illite is a typical clay mineral in cold regions and is derived from all the shelf areas surrounding the Arctic Basin (*Wahsner et al.,* 1999) thus having minor use in provenance studies in the Arctic region. Because kaolinite is a very resistant mineral, in the polar regions it may derive from the reworking of older, kaolinite-bearing sediments (*Chamley,* 1989). The subsequent decrease in the relative smectite concentrations and increase in the chlorite and illite concentrations, as well as the varying appearance of glacigenic microtextures in quartz sand grains, probably result from cooling and the formation and fluctuation of the large-scale glaciers in the continental setting. However, it also has to be noticed that even in low temperatures the increased precipitation at the source areas may lead to a reduction in relative smectite contents of the deposited sediments.

As the Middle Miocene Climate Optimum (~15–17 Ma) was followed by the late Miocene cooling trend (*Zachos et al.*, 2001), the clear glacial influence is evident in the quartz grain microtextural data at the sediment section from 159 to 151 mbsf. The section has a strong dominance of angular to very angular grains, and a near total lack of rounded to well rounded grains. The lack of rounded grains may result from the environmental situation in which the river discharge in the source area is moderately blocked or ceased, possibly due to the glaciers transitioning from sub-temperate to polar. The notion of continental ice sheet formation is also supported by the clay mineralogical data showing relatively low smectite levels coexistent with the abundance of illite resulting from glacial erosion. This seems to coincide also with the relic kaolinite occurrence in the central Arctic Ocean sediments probably due to the physical erosion of older soils on the source continent. Our results show the significance of the reworked kaolinite and illite existence with the increased IRD in order to recognize glacial influence on the deposited sediments. In the youngest Middle Miocene sediment section the glacigenic microtextures, as well as the chlorite and illite concentrations decrease. This may indicate a shift towards warmer climate conditions and non-glacial environments.

6. Conclusions

The fluctuating abundance of the glacigenic microtextures – high angularity, conchoidal fractures, steps and subparallel linear fractures – in ice rafted quartz grains soon after the Mid-Miocene Climate Optimum suggests continental glacial crushing and abrasion. This coincides with a significant drop in smectite content with the increasing reworked kaolinite occurrence and higher chlorite and illite contents referring to increased physical erosion on source continents. Both the quartz sand grain surface microtextural study, and the clay mineralogical study of the Lomonosov Ridge sediments provide clear evidence of Middle Miocene glacial/climatic oscillations in the surrounding continents of the Arctic Ocean.

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