Climatic transitions in the Arctic as revealed by mineralogical evidence from the Upper Cenozoic sediments in the central Arctic Ocean and the Yermak Plateau

Kari Strand, Juho Junttila, Taija Lahtinen & Saija Turunen

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Mineralogical characteristics of the sediments can be used to evaluate critical climate transitions in the Arctic Ocean based on a close relationship between ice-sheet initiation, ice rafting and sea-ice cover changes. Such transitions are found in the Middle Miocene (~ 13.9 Myr ago), when the Earth's climate cooled dramatically after an extended period of relative warmth, and in the Middle Pliocene (at ~3 Myr), when average global temperatures were significantly warmer than they are at present.

This study covers the Middle Miocene to Recent succession at the IODP Expedition 302 Site M0002 (Lomonosov Ridge) and provides a revision of the Middle Pliocene core data from the ODP Site 911 (Yermak Plateau). Both these sites consist of siliciclastic sediments characterised by low organic carbon concentrations. The first key transition coincides with increased, but fluctuating kaolinite occurrence in the central Arctic Ocean, probably due to continental ice generation and increased glacial erosion on land. Periodically, high smectite contents indicate changes to interglacials and more open marine conditions. At the same time, the increased smectite content, pyroxenes and amphiboles of the Middle Pliocene warmth sediments on the Yermak Plateau, indicate that during interglacials transport mechanisms were a combination of both sea-ice and oceanic currents reflecting also significant fresh-water input from the great Siberian rivers.

Kari Strand, Thule Institute, University of Oulu, P.O. Box 7300, FIN-90014, Finland (e-mail: kari.strand@oulu.fi); Juho Junttila,Department of Geology, University of Tromsø, Dramsveien 201, NO-9037, Tromsø, Norway (e-mail: juho.junttila@uit.no); Taija Lahtinen, Department of Geosciences & Thule Institute, University of Oulu, P.O. Box 7300, FIN-90014, Finland (e-mail: taija.lahtinen@oulu.fi). Present address: Talvivaara Mining Company Plc., 88120 Tuhkakylä, Finland (e-mail: taija.lahtinen@talvivaara.com); Turunen, Saija, Department of Geosciences & Thule Institute, University of Oulu, P.O. Box 7300, FIN-90014, Finland. Present address: Department of Geology, University of Turku, Finland (e-mail: saija.turunen@utu.fi)

Introduction

Recently, the first deep sediment cores from the Arctic Ocean basins were recovered enabling the Earth's critical climate transitions and sediment distributions in the Arctic Ocean to be evaluated. The Middle Miocene and Middle Pliocene can be seen as such critical periods, and are further discussed in order to characterise the manner of intensification of the Cenozoic glaciations in the northern hemisphere (cf. Zachos et al. 2001) and periods of paleoclimatic warmth, which were warmer than at present (e.g., Dowsett et al. 1996; Haywood & Valdes 2004). The IODP (Integrated Ocean Drilling Program) Arctic Coring Expedition 302 (ACEX) was carried out in the late summer of 2004 on the Lomonosov Ridge, Central Arctic Ocean and drilled for the first time sediments from such critical periods (Moran et al. 2006). This study sampled the IODP Exp 302 Site M0002 for the first 200 meters below sea floor (m b.s.f.), which extends from the Middle Miocene through to the present. In addition, we revised the Pliocene sediment core data from the ODP Site 911 on the Yermak Plateau, near the gateway between the Atlantic and the Arctic Ocean to get a more complete picture.

In this study clay mineralogy was used to evaluate critical climate transitions in the Arctic close to the Mid-Miocene Climate Optimum and Mid-Pliocene Global Warmth (cf. Zachos et al. 2001). Clay sedimentation has a close relationship between ice-sheet initiation and sea-ice cover changes. Clay minerals can be transported by sea-ice, icebergs, glaciofluvially or by ocean-currents, heavy minerals favour iceberg and sea-ice transportation. The mineralogy of the central Arctic Ocean sediments reflects the source mineralogies of the surrounding landmasses and shelf areas (e.g., Vogt et al. 2001; Krylov et al. 2008) and this can be related to the intensification of glaciations and changes in ice-rafting and sea-ice behavior and oceanic currents (cf. Berner & Wefer 1994; Vogt et al. 2001; Knies et al. 2002; Winkler et al. 2002; Dardy 2008; Knies & Gaina 2008).

Regional setting

The Yermak Plateau and the Fram Strait regions are important water exchange areas between the Arctic Ocean and the Nordic Seas (Myhre et al. 1995). The

Lomonosov Ridge, however, is a sub-marine high that is thought to be a sliver of Eurasian continental crust that broke off due to tectonic movements about 56 Ma ago (Moore et al. 2006). It is situated in the central Arctic Ocean between the Amerasian and Eurasian basins, rising about 3 km above the surrounding abyssal plane. The top of the Ridge is lying in water depths of about 1000 metres. The Lomonosov Ridge is less than 150 km wide and more than 1500 km long extending from Greenland to Siberia (Backman et al. 2008). The drill site on the Lomonosov Ridge is only 250 km away from the North Pole, between 87°N and 88°N, and at depths from 1100 to 1300 meters (Fig. 1). The Yermak Plateau, however, is a topographic marginal high, shallower than 2000 m, northwest of Svalbard (Jokat et al. 2008). Most of the Yermak Plateau is under waters permanently covered with ice; however, in some years the ice retreats to north of 81°N due to the advances of the West Spitsbergen Current. Because of the specific morphologic and tectonic setting, the Lomonosov Ridge and the Yermak Plateau are particularly well suited to study the response of sea ice cover changes, the onset of ice sheets and their fluctuations.

Materials and methods

The sediment cores recovered from Site 911 contained Pliocene and Pleistocene strata. Hole 911A was cored to 505.8 m b.s.f., the water depth being about 901.6 m. The core recovery was 91.8% (Myhre et al. 1995). This study revised the intervals 384.19–440.5 m b.s.f. of Site 911A within the lithological subunit 1B, which is composed of lithologies of very dark grey, dark grey and very dark olive grey silty clay and clayey silt with few dropstones (Fig. 3). The age chronology has been established

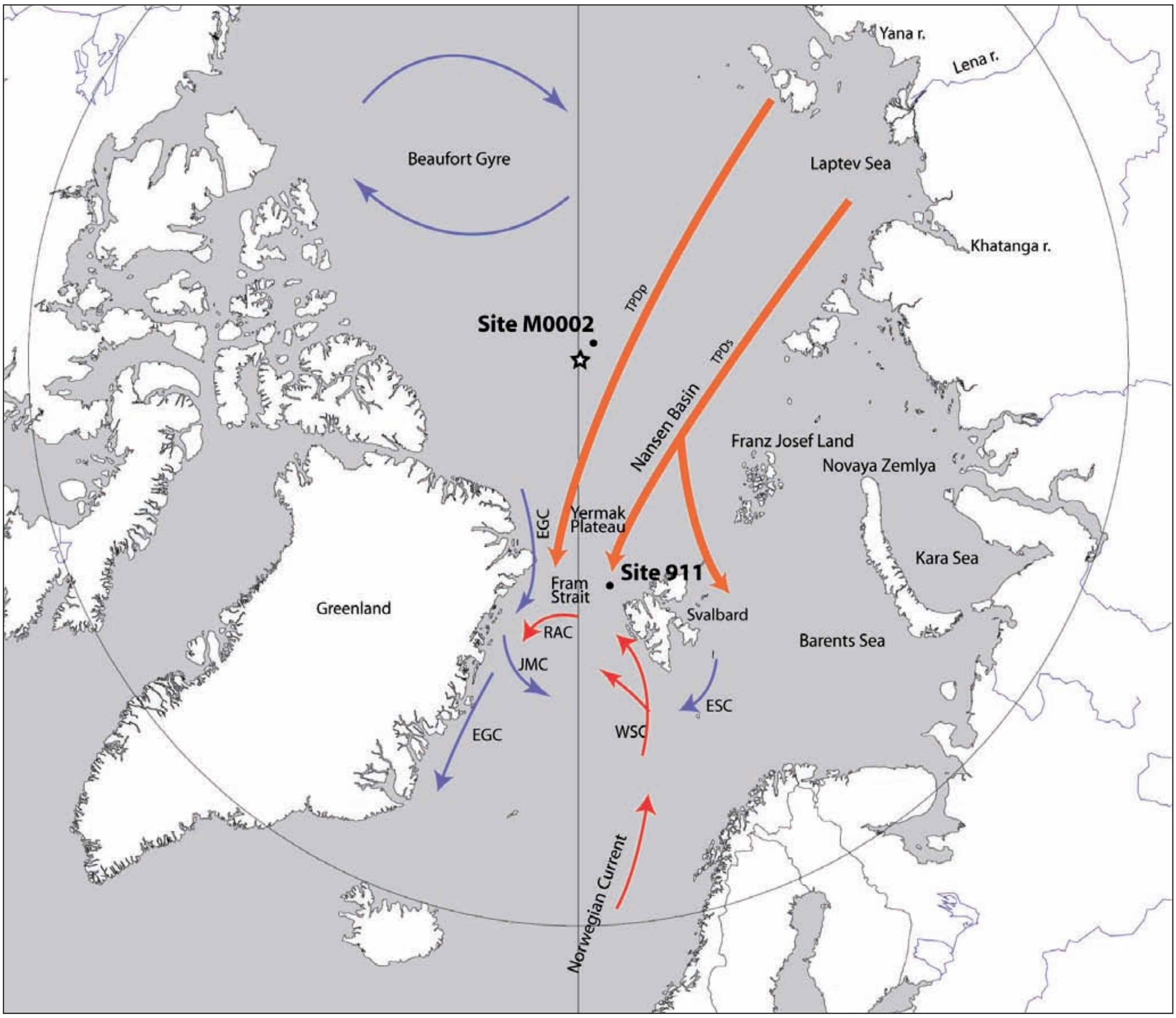


Fig 1. Map of the area discussed in this paper, with present day major circulation patterns, location of ODP Site 911, and IODP Expedition Site M0002. The Transpolar Drift is divided into the Siberian Branch (TPDs) and the Polar Branch (TPDp), Return Atlantic Current (RAC), East-Greenland Current (EGC), East-Spitsbergen Current (ESC), West-Spitsbergen Current (WSC), Jan Mayen Current (JMC) and Norwegian Current.

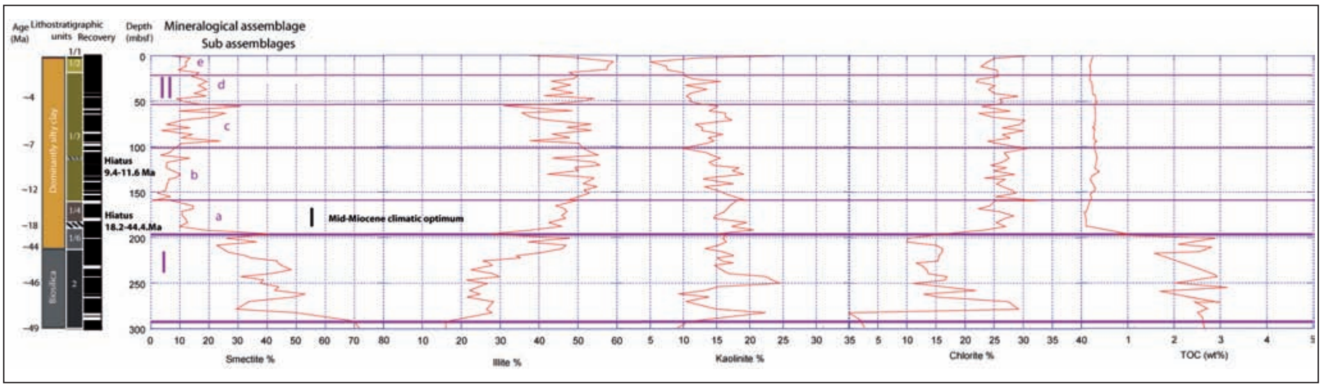
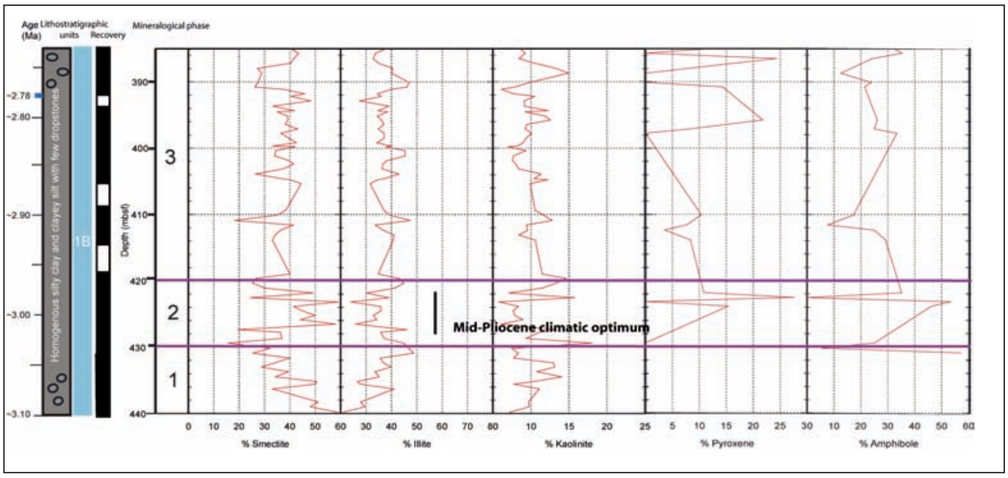


Fig. 2. Age, lithostratigraphic units, core recovery, column plots of clay mineral distribution (mineralogical assemblages are marked as I and II with sub-assemblages a-e), and total organic carbon (TOC) in Site M0002 sediments. Lithological and age data and TOC values from Backman et al. (2006; 2008).

Fig 3. Age, lithology, core recovery and column plot of mineralogical data (three distinct phases marked as numbers 1-3) in Site 911.Lithological data from Myhre et al. (1995). The calcareous nannofossil Datum A event (2.78 Myr) occurs at 391.9 mbsf (Sato & Kameo 1996). The ages are calculated from the estimated sedimentation rates of 150 m/Myr for the Pliocene (Knies et al. 2002). Mineralogical data modified after Junttila et al. (2008).



by means of palaeomagnetic (Myhre et al. 1995) and biostratigraphic data where the calcareous nannofossil Datum A event (2.78 Myr) provides the oldest fix point at 391.9 m b.s.f. (Sato & Kameo 1996). In this study, the Pliocene samples from the Yermak Plateau analysed previously by Junttila et al. (2008) have been reprocessed for comparisons with the Lomonosov Ridge samples.

Three sites (M0002, M0003, and M0004) were drilled in the crest of the Lomonosov Ridge, all situated within 15.7 km of each other (Backman et al. 2006; 2008). A total of 427.6 metres of sediments were recovered, the upper half from Hole M0002A and the rest from the Hole M0004A. The average core recovery in all holes was 68.4%. The recovered sediment section represents Cenozoic biogenic, eolian or ice-rafted sediments. This study concentrates on the first 220.24 m b.s.f. of Site M0002 within the lithostratigraphic Unit 1 dominated by siliciclastic sediments covering the time span between the Holocene and the Middle Eocene. The sediment colour varies from brown to olive, grey, very dark grey and black becoming darker further down the core. There is also a decrease of in the number of sandy lenses downwards as well as the color changes from brown to grey and black and increase in yellow pyrite microconcretions and total organic carbon (TOC) content. The time estimations are mainly based on paleomagnetic reversal stratigraphy in the interval from 0 to about 200 m b.s.f. O'Regan et al. (2008a). They illustrate the chronology for the last 200 ka adopting an age of 55 ka for the components at 1.82 m b.s.f. and 66 ka for the component at 2.08 m b.s.f. 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 when establishing chronostratigraphy for the past 12.3 Ma. The rest of the core is dated using dinocysts and silicoflagellates. There is a 26 million year hiatus around the depth of 200 m b.s.f. showing that sediments are missing from the time interval between about 44 Ma and 18 Ma BP. The hiatus separates freshwater-influenced biosilica-rich deposits of the Middle Eocene from fossil-poor, glaciomarine silty clays of the Early Miocene (O'Regan et al. 2008b).

Mineralogical analysis

X-ray diffraction (XRD) was performed on oriented clay samples as described by Hardy & Tucker (1988). Details of the sample preparations were as follows: the 3 g sediment samples were first decomposed and then centrifuged for 1 min (1000 rounds/minute according to Stoke's law) to all particle sizes larger than clay size particles (< 2 µm) at the bottom of a centrifuge tube and leave clay particles in suspension. The suspension was then removed from the centrifuge tube and then concentrated by centrifugation for 15 min (1000 rounds/minute) to settle the clay to the bottom of another tube, after which the water was decanted. Oriented clay samples were then made. One sample slide was air dried at 60°C for 2 h and analysed. The second slide sample was solvated with ethylene glycol in an underpressured desiccator for at least 2 h at 60°C, under which conditions smectite expands to a basal spacing of about 17Å. The third slide sample was analysed after heating to 550°C for 2 h, at which temperature kaolinite and certain chlorites are destroyed. The diffractograms were recorded at the Institute of Electron Optics at the University of Oulu with a Siemens D 5000 device with fixed divergence slit (FDS), copper radiation (40 kV, 40 mA) at angles ranging from 2° to 32° 2θ (0.02° 2θ per second) immediately after the sample preparations. The four principal clay mineral groups were recognized by their basal spacings 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 (Biscaye 1964). The peak-area method was used to calculate the quantities of kaolinite and chlorite from the joint peak at 7Å. MacDiff software version 4.2.5 by Petschinck (2001) was used for analysis and display of X-ray powder diffractogrammes for quantifing the clay minerals for percentages. The analysed clays were evaluated by peak fitting, which is based on Pseudo Voigt functions in the MacDiff software. Peak fitting makes evaluation of the smectite peak (15–17Å) possible without any disturbance by the chlorite peak (14Å). Since no internal standards were used, the precise accuracy of this procedure is not known, but the quantitative analyses support interpretations of fluctuations around 2%.

For selected heavy mineral separation the samples was cleansed of adhering clays and aggregates, and flocculated particles were dispersed by stirring the sample in distilled water using a glass rod. A dispersant solution, sodium metaphosphate, was added to promote efficient cleaning. The fine fraction was wet-sieved into fractions of 0.25, 0.125 and 0.063 mm, which were poured onto an aluminium holder, dried and weighed. After weighing, the fractions were combined (Carver 1971).The heavy-mineral analysis was applied to the 0.063mm and 0.25mm subfractions. The centrifuge separation of the heavy minerals was done in accordance with the procedure of Mange & Maurer (1992) and Carver (1971). This procedure included the following five steps: (1) Dried and weighed samples were poured into centrifuge tubes with sodium metatungstate [$Na_6(H_2W_{12}O_{40})*H_2O$], (density of 2.90 g/cm^3) and the mixture shaken thoroughly; (2) The sample was centrifuged for 3 min at 2000 rpm to separate the fine-grained sediments; (3) The light fraction was removed with a Pasteur pipette; (4) The heavy fraction was poured into a funnel with a filter paper insert and washed in distilled water; (5) The heavy fraction was dried with the filter paper at 70°C for a few minutes. The exact geochemical composition of up to 40 heavy mineral grains per sample was analysed at the Institute of Electron Optics at the University of Oulu with a Electron Probe Microanalyzer JEOL JXA-8200.

Results

Clay mineral distribution in the Central Arctic Ocean since the Middle Miocene

In this study two distinct clay mineralogical assemblages could be identified at Site M0002 (Fig. 2). Assemblage I shows a general decrease of smectite content and increase in the sand fraction between 197 and 282 m b.s.f. Assemblage II between 0 – 197 m b.s.f. represents clay minerals recorded from the Middle Miocene to the present. It is characterised by a significant fluctuation in all clay minerals. Although the amount of smectite is relatively low, it fluctuates strongly between 2–37%. Kaolinite shows an assemblage-long decreasing trend from the level of 18% to 11%. This assemblage is characterised by the presence of ice rafted debris (IRD) and is divided into five sub-assemblages (a–e) due to variations in the smectite amount.

Sub-assemblage IIa extends from 197 m b.s.f. to 164 m.b.s.f. Smectite fluctuates around the level of 12% staying between 10% and 15%. Illite increases from 38% to 47% while kaolinite remains between 14% and 20%. Chlorite fluctuates around the level of 26%, staying between 22 and 28% except one drop below 22% at the depth of 168 m b.s.f. In sub-assemblage IIb (159–101 m b.s.f.) the smectite decreases to the level of 6% fluctuating mostly between 3% and 10% with a drop to 1% at the depth of 159 m b.s.f. and one rise up to 13% at the depth of 113 m b.s.f. Illite increases until the depth of about 140 m b.s.f. showing the highest values around 55% and then changing to a somewhat decreasing trend. However, a larger scale of fluctuation occurs in the upper part of sub-assemblage b between 42% and 55%. The amount of kaolinite continues a decreasing trend although it fluctuates mainly between 12% and 18% with one drop to 10% at the depth of 102 m b.s.f. Chlorite continues to fluctuate between 22 and 28%. In sub-assemblage IIc (97–53 m b.s.f.) the amount of smectite increases from 8% to 31% with large scale fluctuation between 2% to 31%. Illite and kaolinite both decrease. However, illite fluctuates strongly between 30% and 55%, kaolinite between 10% and 18%. The chlorite level slightly increases, from 26% to 28% at the boundary of the sub assemblage b and c showing larger fluctuation from 22% to 30%. In sub-assemblage IId (51–18 m b.s.f.) the smectite fluctuates slightly around 18% while illite fluctuates around 46%, staying between 41% and 50%. Kaolinite fluctuates between 10% and 15%, and chlorite fluctuates around 24%. The amount of smectite decreases at the boundary of sub-assemblages IId and e (16 m b.s.f. to 0 m b.s.f.) from about 18% to 12%. The amount of illite increases from 46% to its maximum value of 59%, after which it drops suddenly to 37% at the top of assemblage II. Kaolinite decreases to 5% and then shows a sudden increase up to 25% at the end of the assemblage. Chlorite remains around 24%.

Yermak Plateau mineralogical record in the Middle Pliocene

The clay fraction of the Pliocene interval (380.4–440.5 m b.s.f.) at Site 911 is clearly dominated by smectite and illite, which together account for 60–84% (mean 74.89%) of the clay mineral composition (Fig. 3). Smectite fluctuates between 20% and 40%, illite between 20% and 40% and kaolinite between 0 and 20%. The Pliocene clay mineral distribution can be divided into three distinct phases (1-3) with associated heavy minerals (Fig. 3). The heavy mineral fraction of the 380.4–440.5 m b.s.f. sediment sequence is dominated by amphiboles and pyroxenes. According to Junttila et al. (2008) the pyroxene group is comprised predominantly of augite, aegirine-augite and hedenbergite. Augite is the most common of the pyroxenes found here. The content of the pyroxene group minerals in the entire studied sequence fluctuates between 0 and 27%, the mean being 8%. The amphibole group consists mainly of tremolites and tremolite-actinolites. The mean value for the amphibole content is 27%. The group of stable minerals includes epidote, zircon, sphene, rutile, tourmaline and garnet according to Junttila et al. (2008). The mean value for the stable minerals in the entire sequence is 28%. The majority of the opaque minerals are Fe-Ti (ilmenites) and FeO. Some Cr-oxides and Fe-sulphides are also found. The mean for the opaque minerals is 37%.

Between 430 and 440 m b.s.f. the smectite content has a clear decreasing trend towards 430 m b.s.f. Here the smectite content decreases from 59% to 15% (Fig. 3). Both the highest and lowest values of smectite (59% and 15%) occur in this interval. The mean value for smectite is 38%. Illite has an increasing trend towards 430 m b.s.f. The mean value for illite is 37%. The lowest illite concentration, 21%, occurs at 439.79 m b.s.f. and the highest, 49%, at 430.90 m b.s.f. The mean for kaolinite is 10%, which is significantly lower than the smectite and illite concentrations. The kaolinite content has an increasing trend towards 430 m.b.s.f. The highest content of kaolinite (18%) occurs at 429.40 m b.s.f. This interval includes the highest (18%) and the lowest (6%) contents of kaolinite. Within 420–430 m b.s.f., the smectite content rises over 50% (Fig. 3), fluctuates around 50% and then decreases again to around 30%. The amount of illite fluctuates between 25% and 48% and is correlated negatively with smectite. The kaolinite content drops to its lowest level (6%) at 423.17 m b.s.f., and the amount of pyroxene group minerals increases (Fig. 3). The amphibole content also increases in the interval 420–430 mb.s.f. from less than 10% up to 50%, after which the content decreases again. Between 380–420 m b.s.f. the smectite content fluctuates between 25% and 45%. The illite concentration ranges mainly between 27% and 47%. At around 390 m b.s.f., illite and kaolinite have distinctly high values. The fluctuation of kaolinite ranges from 6% to 15% and 5 distinct cyclescan be seen in which the amount of kaolinite exceeds 10%. In this phase, the amount of pyroxene group minerals drops to under 5% between 414 and 410 m b.s.f. (Fig. 3). Between 400 and 380 m b.s.f. the amount of pyroxene group minerals fluctuates greatly, but is generally over 10%. The amphibole content drops to under 10% between 414 and 410 m b.s.f., and between 400 and 380 m b.s.f. it fluctuates between c. 15% and 35%.

Discussion

In the Middle Miocene ~ 13.9 Myr ago, the Earth's climate cooled dramatically after an extended period of relative warmth (Zachos et al. 2001). This key transition in the Earth's climatic evolution marked the start of

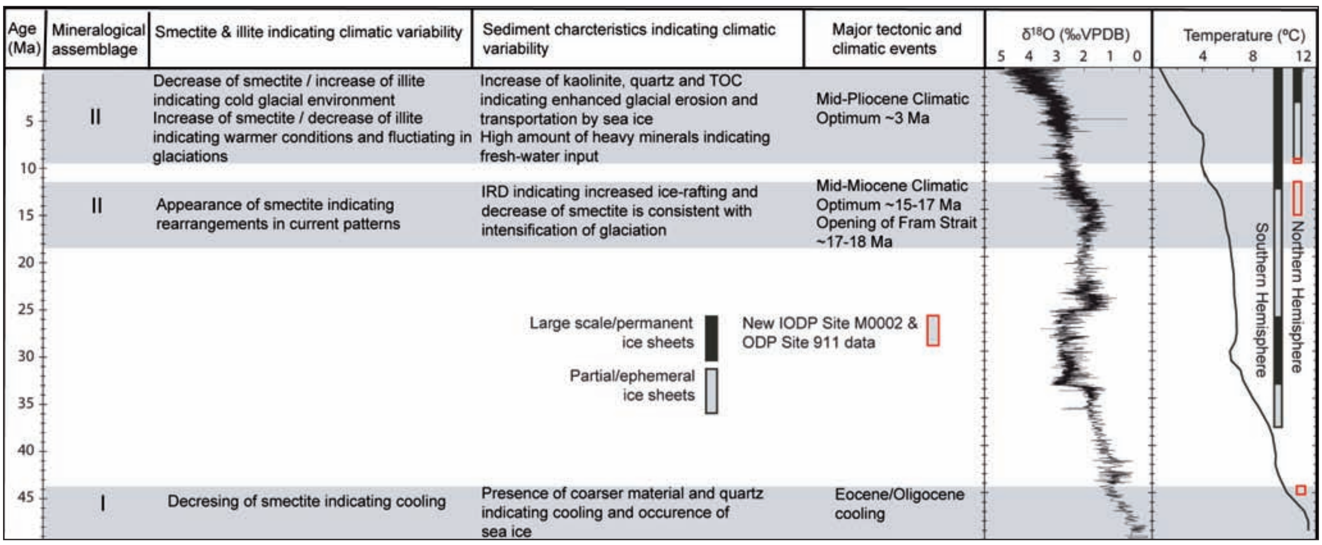


Fig 4. A synthesis of clay minerals and sediment characteristics studied in relation to climatic indicators, modified from Zachos et al. (2001). The age model is according to Backman et al. (2008) consistent with the ACEX related results by Moran et al. (2006), Dardy (2008), Krylov et al. (2008) and St.Johns (2008).

further cooling during the Late Cenozoic. The opening of oceanic gateways and topographic relief changes in the northwestern Barents Sea, may have facilitated a possible growth of continental glacier ice (Knies & Gaina 2008). Global ice volume remained, however, low and bottom water temperatures remained slightly higher until the Middle Miocene, about 15 Ma ago, excluding several brief glaciations during that period (Zachos et al. 2001; Knies & Gaina 2008). At 14 Ma ago, a large accumulation of ice has been recorded (Lear et al. 2000). The Fram Strait started to open down to great depths by 13.7 Ma ago (Jakobsson et al. 2007) and it has been estimated that during the Miocene, sea level varied between 15 and 30 metres. After further deepening, sea level fluctuations were no longer able to cause a return to lake conditions. The final transition occurred after sufficient widening of the Fram Strait when a compensating inflow of saline North Atlantic water initiated and bi-directional two-layer flow, similar to the present system. It seems that opening of the Fram Strait possibly started in the Early Oligocene, but the initiation of the deep water connection to the Greenland Sea and the North Atlantic Ocean through the Fram Strait took place during the Early Miocene.

In this study clay mineralogy was used to evaluate critical climate transitions in the Arctic close to the Mid-Miocene Climate Optimum and in the Mid-Pliocene Global Warmth (cf. Zachos et al. 2001). This is based on the fact that clay sedimentation is closely related to continental ice-sheet initiation and the occurrence of sea-ice cover (Wahsner et al. 1999; Ruikka & Strand 2002; Knies et al. 2002; Junttila et al. 2008). In this study comparison was also made with the Pliocene sediment core data from ODP Site 911 (Yermak Plateau) with samples from IODP Expedition 302 Site M0002 (Lomonosov Ridge) for the first 200 m b.s f., which extends from the Miocene to the present (Fig. 4).

The Middle Miocene transition in the Earth's climatic evolution marked the start of further cooling during late Cenozoic (Fig. 4). Knies & Gaina (2008) hypothesised that the opening of the Atlantic-Arctic gateway at the Middle Miocene transition (~15-14Ma) and intensification of water mass exchange between the Arctic and the North Atlantic, together with an elevated paleo-relief of the NW Barents Sea area, produced meridional heat and vapor transport that initiated large-scale ice growth on the emerged northern Barents Sea area. This seems to coincide with fluctuating (14-20 %), but still relatively high kaolinite occurrence in the central Arctic Ocean, probably due to continental ice generation and existence of physical erosion on land (Fig 4). This is consistent with higher chlorite and illite contents. Periodically, a high smectite content may indicate more open water conditions and interglacials when smectite content fluctuates between 2-37%. Our results present the value of reworked kaolinite and illite in the increased ice rafted debris for recognizing initiation of glaciations and the most probable sources for sediment material.

During the warm Middle Pliocene, the fluctuating heavy mineral content seem to reflect changes in the fresh-water input from the great Siberian rivers which led to changes in the supply of terrigenous material delivered to the shallow Arctic shelves by the rivers. Based on the occurrence of pyroxenes and amphiboles, the source areas of the Yermak Plateau sediments are most likely the Laptev and Kara Seas, with some additional sediment influx from the Barents Sea. In general, the heavy mineral fluctuation could well reflect changes in the amount of sea ice formation which correlates with climatic variations and the general fresh-water input from the continent. Clay minerals were transported by sea-ice, icebergs or by ocean-currents, but, heavy minerals favored iceberg and sea-ice transportation. Combination of data from these two mineral categories might well reflect changes in general freshwater input from the rivers, which ultimately led to changes in the supply of terrigenous material delivered to the shelves. The clay fraction input in the Yermak Plateau sediments during the Middle Pliocene warmth (~ 3.00 Myr) can be mostly related to the transport mechanisms by sea-ice and by oceanic currents. The smectite content shows an abrupt increase. This change can, however, be seen as a drop in the amount of kaolinite and organic carbon concentration. This Late Pliocene cooling led to extensive glaciations in both hemispheres.

Conclusions

The Arctic Ocean is important for understanding climatic changes because it influences global climate through the formation of permanent and seasonal sea-ice cover, transfer of heat to the atmosphere and the renewal and ventilation of deep water. The mineralogical components in sediments can well reflect changes in the amount of sea ice formation which correlates with climate variations and the general fresh-water input from the continent. Clay mineral analysis is a good proxy when determining the onset of glaciations as well as long term cooling, ice-rafting and also land-sea linkages.

In this study, clay sedimentation and the mineralogical characteristics of sediments were used to evaluate some critical climatic transitions in the Arctic Ocean including the Mid-Miocene Climate Optimum and the Mid-Pliocene Global Warmth. Smectite has been transported mainly from the Kara Sea and the Laptev Sea during periods of more open water. It has accumulated on the Lomonosov Ridge and the Yermak Plateau from sea ice because of the warming effect by the West Spitsbergen Current. The Middle Miocene transition marks the start of further cooling during the Late Cenozoic. It seems to coincide with decreasing smectite and significantly the fluctuating kaolinite occurrence in the central Arctic Ocean. This is probably due to continental ice generation and increased erosion on land. Based on the occurrence of pyroxenes and amphiboles, the source area of the Middle Pliocene Yermak Plateau sediments is most likely the Laptev and Kara Seas, with some additional sediment influx from the Barents Sea. In general, the heavy mineral fluctuation can well reflects changes in the amount of sea-ice formation, which correlates with climate variations and the general fresh-water input from the continents. The clay fraction input in the Yermak Plateau sediments during the Middle Pliocene warmth ~ 3.00 Myr can be mostly related to the transport mechanisms by sea-ice and by oceanic currents. The smectite content which indicates open marine conditions shows an abrupt increase, whilst pyroxenes and hornblendes from the Kara and Laptev Seas shows that sea-ice transportation occurred simultaneously.

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