

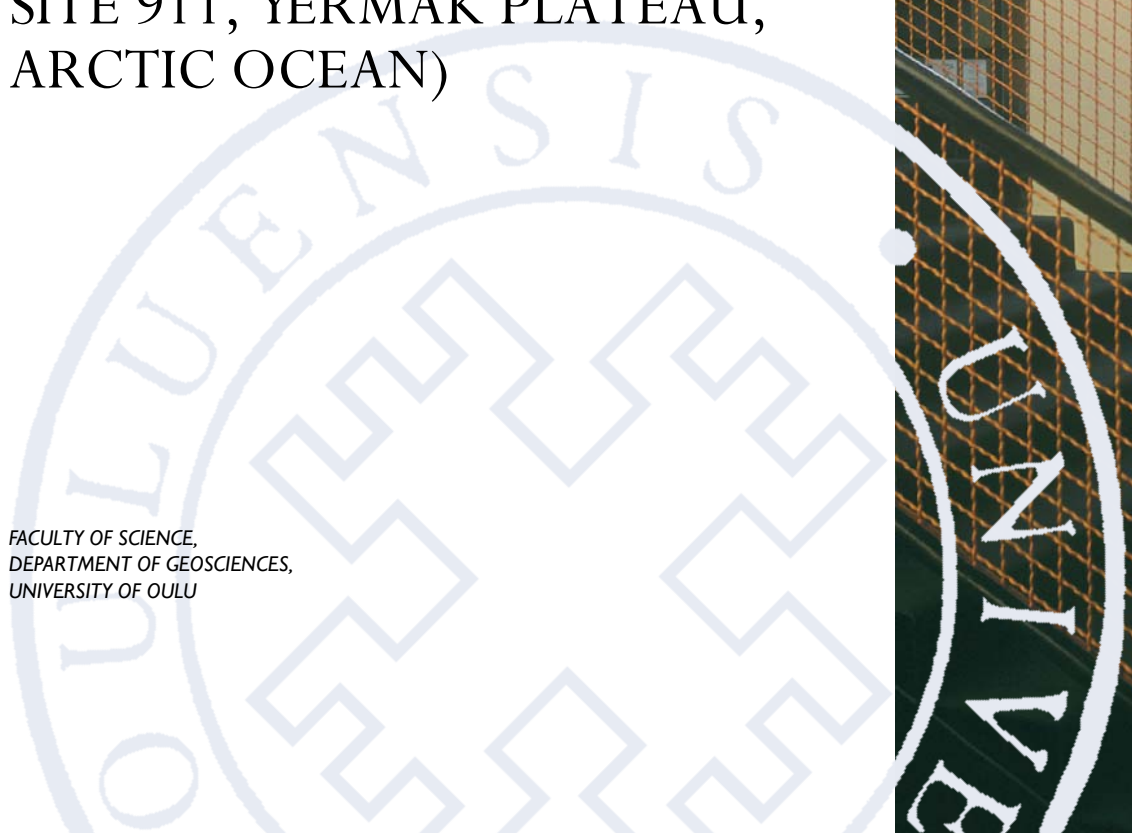
Juho Junttila

CLAY MINERALS IN RESPONSE
TO MID-PLIOCENE GLACIAL
HISTORY AND CLIMATE IN THE
POLAR REGIONS (ODP, SITE 1165,
PRYDZ BAY, ANTARCTICA AND
SITE 911, YERMAK PLATEAU,
ARCTIC OCEAN)

FACULTY OF SCIENCE,
DEPARTMENT OF GEOSCIENCES,
UNIVERSITY OF OULU

A

SCIENTIAE RERUM
NATURALIUM



JUHO JUNTILA

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OCEAN)**

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Abstract

This thesis examines the Mid-Pliocene climatic extreme ca. three million years ago (Ma) which was the latest longtime warm period. It is an important topic because the climate back then was warmer compared with the present. The bipolar regions are studied because they represent the largest areas that control the global climate. This study is based on clay mineral research that may significantly improve our knowledge of the Mid-Pliocene climate when combined with other palaeoenvironmental data. The paleoclimatological objectives of this study were: 1) to investigate how clay minerals reflect the Mid-Pliocene Global Warmth event, 2) to study ice sheet development at high latitudes, especially in East-Antarctica, and the history of ice rafting and sea ice, especially in the Arctic Ocean.

This thesis deals with the clay mineral distribution and compositional analysis of the Pliocene-aged marine sediment sequences provided by the Ocean Drilling Program (ODP). The first studied site, Site 1165, is located at the continental rise of Prydz Bay, East Antarctica, and the second studied site, Site 911, is located at the Yermak Plateau, north of Svalbard, in the Arctic Ocean.

The Pliocene smectite clay minerals at Site 1165 were mainly derived from Antarctic continental sources and transported to the site primarily by bottom currents related to warm events during the last 5 Ma. The evidence obtained in this study shows that the East Antarctic ice sheet may have been a dynamic ice sheet during the past 5 Ma, especially during the Mid-Pliocene. The results from the Mid-Pliocene possibly suggest a general warming trend.

Based on the composition of the heavy minerals and clay minerals, at Site 911, the Pliocene smectite clay minerals were mainly transported within sea ice by the Siberian branch of the Transpolar Drift. The results indicate a warming trend at approximately 3 Ma after which they indicate a shift back to glacial conditions. Based on this study, the Mid-Pliocene Global Warmth can be observed in both the Arctic and Antarctic regions.

Keywords: Arctic Ocean, clay minerals, East Antarctica, marine sediments, Mid-Pliocene Global Warmth, paleoceanography, paleoclimate

Acknowledgements

This work was carried out at the Thule Institute and at the Department of Geosciences, University of Oulu, during 2003–2006. I would like to express my gratitude to my supervisor, Docent Kari Strand for introducing me to marine geology and for his guidance. I would also like to thank my supervisor Professor Juha Pekka Lunkka, for his advice and guidance during this thesis project.

I am grateful to the Ocean Drilling Program (ODP) for providing the samples and data for this study. Cooperation with the following persons is greatly acknowledged: Professor Dethlef A. Warnke concerning ODP Leg 188 studies, Doctor Carl Fredrik Forsberg for his advice in the studies of Legs 188 and 151, Doctor Luigi Marinoni for his advice concerning the methods used in the Leg 188 studies and Doctor Christoph Vogt for his help in the Leg 151 studies. I would also like to thank Doctor Christoph Vogt and Docent Aarno Kotilainen for reviewing this thesis.

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Tornio, December 2006

Juho Junttila

Abbreviations

ACC	Antarctic Circumpolar Current
EAIS	East Antarctic Ice Sheet
EDS	energy dispersive spectrometer
EGC	East Greenland Current
FJL	Franz-Josef Land
FWHM	full width at half maximum
HiRISC	High-Resolution Integrated Stratigraphy Committee
IB	integral breadth or integral width
IRD	ice rafted debris
k.y.	thousand years
Ma	million years ago
MPGW	Mid-Pliocene Global Warmth
m.y.	million years
ODP	Ocean Drilling Program
S	Svalbard
SEM	scanning electron microscope
TOC	total organic carbon
XRD	x-ray diffraction
θ	theta

List of original papers

This thesis is based on the following four papers, referred to as Papers I, II, III, IV:

- I Warnke DA, Richter C, Florindo F, Damuth JE, Balsam WL, Strand K, Ruikka M, Junttila J, Theissen K & Quilty P (2004) Data report: HiRISC (High-Resolution Integrated Stratigraphy Committee) Pliocene–Pleistocene interval, 0–50 mbsf, at ODP Leg 188 Site 1165, Prydz Bay, Antarctica. In: Cooper AK, O'Brien PE & Richter C (Eds) Proceedings of the Ocean Drilling Program, Scientific Results 188: 1–38. Available from: http://www-odp.tamu.edu/publications/188_SR/VOLUME/CHAPTERS/015.PDF
- II Junttila J, Ruikka M & Strand K (2005) Clay Mineral Assemblages in High-Resolution Plio-Pleistocene Interval at ODP Site 188-1165, Prydz Bay, Antarctica. In: Florindo F, Harwood D & Wilson G (Eds) Long-term changes in Southern high latitude ice sheets and climate, the Cenozoic history. *Global and Planetary Change* 45: 51–163.
- III Junttila J & Strand K (2006) Smectite Crystallinity and Composition in Pliocene-Pleistocene Sediments at the Continental Rise (ODP Site 1165), Prydz Bay, Antarctica. *Terra Antarctica* 13(1/2).
- IV Junttila J, Lahtinen T & Strand K (2007) Provenance and Sea Ice Transportation of Mid-Pliocene Sediments, Yermak Plateau, Arctic Ocean (ODP Site 911). Manuscript.

Contributions

The following table indicates the major contributions of the authors of the original articles.

Table 1. Contributions. JJ= Juho Junttila, MR= Mattiina Ruikka, TL= Taija Lahtinen, KS= Kari Strand.

Paper	I	II	III	IV
Planning	JJ, KS	JJ, KS	JJ, KS	JJ, TL, KS
Analysis	JJ, MR	JJ, MR	JJ	JJ, TL
Interpretation of results	JJ, KS	JJ, KS	JJ, KS	JJ, TL
Manuscript preparations	JJ,KS	JJ	JJ	JJ, TL, KS

All the material in this study was provided by the Ocean Drilling Program (ODP). The clay mineral study of Paper I was done by JJ, MR and KS. In addition, the planning and manuscript preparations in Paper I were also done by the HiRISC research group (See Paper I). Paper I was written by JJ and KS. Paper II and III were written by JJ with comments by KS. JJ and TL wrote Paper IV with comments by KS. TL did the heavy mineral study in Paper IV, which is not included in this thesis.

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1 Introduction

In order to understand the changes that may take place in the future, it is important to study the past high latitude geological processes. The Cenozoic Era (65Ma–present) is characterized as a time period when bipolar glaciations took place. However, there are differences in the type and pattern of variability of the glacial ice covers in the Northern and Southern Hemispheres. There is a need to understand how many times short global warmth events are seen in Cenozoic glacial history and the paleoclimate record in the bipolar regions.

One of the warm events within the Cenozoic Era is the Mid-Pliocene Global Warmth period. The Mid-Pliocene Global Warmth period at ~3 Ma is of special interest because conditions during that time were up to 5 °C warmer than they are today (Willard, 1996). Studying the fluctuation of clay minerals is useful in describing the prevailing conditions during extremely warm periods. The Mid-Pliocene climatic extreme is also an important topic to study because of its similarity to the present conditions. Furthermore, the polar regions are studied because they represent the largest areas that control the global climate.

This study is based on bipolar clay mineral research that may significantly improve our knowledge of the Mid-Pliocene climate when integrated with other palaeoenvironmental data. The paleoclimatological objectives of this study were: 1) to study how clay minerals reflect the Mid-Pliocene Global Warmth event, 2) to study ice sheet development in high latitudes, especially in East Antarctica, and the history of ice rafting and sea ice, especially in the Arctic Ocean.

Detrital clay assemblages delivered from ice sheets by icebergs, meltwater, sea ice and ocean currents are major components that produce sediments in the high-latitude ocean basin (Ehrmann, 1991, Ehrmann, 1998, Knies *et al.* 2002, Washner *et al.* 1999). The composition and proportions of individual clay minerals in high-latitude marine sediments depends on climatic conditions on land, the nature of the source rocks, transport agents and the depositional setting. The clay mineralogy of sediments can provide important information about the provenance of the sediments, which helps in reconstructing the sediment transport paths. Sediment transport paths are important when reconstructing the glacial history, paleoclimate and paleoceanography of the polar regions (Ehrmann, 1991, Ehrmann, 1998, Knies *et al.* 2002).

This thesis deals with the clay mineral and compositional analysis of the Plio-Pleistocene marine sediment sequences provided by the Ocean Drilling Program (ODP) at the continental rise off Prydz Bay, Antarctica, (Site 1165) and at the Yermak Plateau in the Arctic Ocean (Site 911). Emphasis is placed on Mid-Pliocene-aged sediments. The continental rise off Prydz Bay, East Antarctica, is situated in a region where the Lambert Glacier- Amery Ice Shelf system, the major glacial drainage system of the East Antarctic ice sheet, discharges ice, icebergs and sediments. On the other hand, the Yermak Plateau, north of Svalbard, is an important water exchange area between the Arctic Ocean and the North Atlantic.

Papers I–III represent the Antarctic contribution to this study. Paper I is a multiproxy study of Plio-Pleistocene-aged sediments at Site 1165 conducted by the High-Resolution Integrated Stratigraphy Committee (HiRISC) research group. The clay mineral study in Paper I was done in order to obtain an overall view of the Plio-Pleistocene time period in Eastern Antarctica. The Mid-Pliocene and Plio-Pleistocene transition intervals were studied in detail in Paper II. Paper III concentrates on the composition and detrital source of smectite clay minerals. The paleoclimatological indications in Papers I–III were partly based on the formation of clay minerals in various climate conditions and partly on the transportation mechanisms of the clay minerals. Paper IV provides the contribution of the Arctic Ocean. The paleoclimatological indication in the Arctic Ocean is based on the sea ice transportation of the clay minerals.

2 The Pliocene climate in the polar regions

The Pliocene period (5.3–1.8 Ma) includes time intervals when the climate was substantially warmer than it is at present and warmer than it was during any of the Pleistocene interglacial periods (Dowsett & Poore, 1990 & 1991). The Pliocene also includes an important transition from a climate regime with high-frequency, low-amplitude oscillations to the typical high-frequency, high-amplitude Pleistocene climate regime. In this transition the temperate Pliocene climate, during which the northern hemisphere lacked substantial ice sheets, changed into the typical Pleistocene climate, characterized by glacial-interglacial cycles that involve the growth and decay of major northern hemisphere ice sheets (Dowsett & Cronin, 1991).

The knowledge of the climate history during the Pliocene is based on a variety of sources. As an example, one source is the oxygen isotope (O^{18}) study by Zachos *et al.* (2001) shown in Fig. 1. The mean annual Sea Surface Temperature (SST) at ODP Site 1165 was approximately 5 °C at 3.7 Ma, representing a 5.5 °C warming relative to the modern mean annual SST (Whitehead & Bohaty, 2003). Oxygen isotope data from molluscs (Krantz, 1990) from Pliocene deposits of the coastal plain of the eastern U.S. show a substantial poleward displacement of faunal provinces and elevated temperatures in shallow marine environments. The measurement of oxygen isotope ratios (O^{18}/O^{16}) at ODP Site 607 in the North Atlantic carried out by Raymo *et al.* (1989) clearly shows climate oscillation from warm to colder climate towards the end of the Pliocene. Palynological records from Pliocene deposits on Meighen Island in the Canadian High Arctic Ocean indicate that trees were growing on the shores of the Arctic Ocean at 80 °N (see Matthews & Ovenden, 1990). Similar palynological evidence from the Eurasian side of the Arctic Ocean has been discovered by Willard (1996).

Paleoenvironmental interpretation of pollen assemblages from Pliocene and Pleistocene sediments from the Yermak Plateau made by Willard (1996) indicate that the Pliocene climate was considerably warmer than it is at present, and that the conditions in the Pleistocene were substantially cooler than those of the Pliocene. Pollen records have indicated temperatures up to 5 °C warmer than today's in areas bordering the North Atlantic Ocean (Willard, 1996). The presence of macrofossils that include boreal forest elements during the Pliocene i.e. in Northern Greenland indicate that the boreal forest zone reached much further north than it does today. Tundra and polar deserts were also

extremely reduced during the Pliocene. Sea surface temperatures in the North Atlantic were up to 6 °C warmer than they are today (Willard, 1996).

The climate during the Mid-Pliocene (ca. 3 Ma) was generally warmer than it is at present. On the global scale, this was particularly the case at middle to high latitudes (Knies *et al.* 2002), but tropical temperatures remained relatively similar to those of today. The Mid-Pliocene Global Warmth (MPGW) was the period lasted ca. 300 kyr during a time when average global temperatures were significantly warmer than they are today. It is known that the MPGW period included higher atmospheric CO₂ levels than at present and significantly stronger ocean thermohaline circulation due to drastic climatic changes in the Southern Ocean (Raymo *et al.* 1996, Knies *et al.* 2002). Seasonally ice-free conditions in the marginal eastern Arctic Ocean during the MPGW period are also assumed to be an important regional moisture source that may have been one trigger for the intensification of Northern Hemisphere glaciation in Svalbard/Barents Sea at ~2.7 Ma (Knies *et al.* 2002). However, the exact factors and mechanisms that caused the MPGW period still remain unclear.

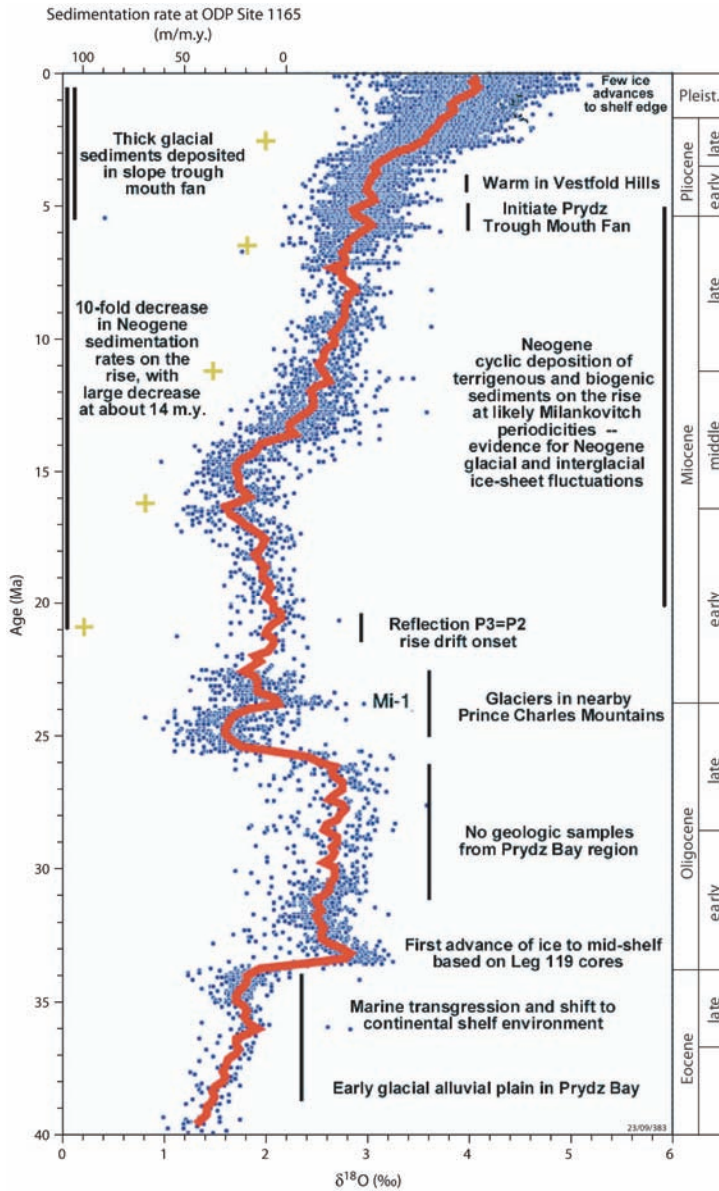


Fig. 1. Summary diagram (Cooper & O'Brien, 2004) showing geologic and glacial events in the Prydz Bay region, compared with the global oxygen isotope curve of Zachos *et al.* (2001). Sedimentation rates are from Shipboard Scientific Party (2001a) and Florindo *et al.* (2003).

3 Regional Setting

3.1 Prydz Bay

Prydz Bay (studied in Papers I, II and III) is an embayment along the East Antarctic margin situated in a major crustal structure, called the Lambert Graben, between 66 °E and 79 °E (Fig. 2a; Fedorov *et al.* 1982, Stagg, 1985, Cooper *et al.* 1991). It is bounded on the southwestern side by the Amery Ice Shelf, in the southeast by the Ingrid Christensen Coast, and in the west by MacRobertson Land, ending at Cape Darnley (Shipboard Scientific Party, 2001b). The steep continental slope in the eastern half of Prydz Bay is cut by submarine canyon tributaries overlain by slump deposits (O'Brien & Leitchenkov, 1997). On the western side of Prydz Bay, contours bulge seaward in the Prydz Channel Fan, which slopes smoothly from the shelf edge to a water depth of ~2700 m (Shipboard Scientific Party, 2001b). The head of Wilkins Canyon (Vanney & Johnson, 1985) is situated just west of the Prydz Channel Fan and north of Fram Bank. Wilkins Canyon runs north from the shelf edge before turning northeast at ~65 °S (Shipboard Scientific Party, 2001b). There is a ridge of drift sediment to the west of Wilkins Canyon separating it from Wild Canyon, which has its head on the continental slope off MacRobertson Land (Kuvaas & Leitchenkov, 1992).

Modern ocean circulation in the Prydz Bay–Cooperation Sea region has many components. Surface circulation in the bay is a cyclonic gyre with cold water inflow from the east and outflow along the west side of Prydz Bay (Fig. 2b) (Smith *et al.* 1984). There is relatively little highly saline deep water due to Prydz Bay's geography and bathymetry (Smith *et al.* 1984). These two factors lead to little downslope bottom water current activity beyond the shelf edge. The deepwater movements on the continental slope and rise (e.g., over Site 1165) are attributed to three large-scale ocean systems: the Polar Current, moving west near the shelf edge; the Antarctic Divergence, producing cyclonic gyres over the slope and inner rise; and the Antarctic Circumpolar Current, moving east over the outer rise and beyond (Cooper & O'Brien, 2004). The interaction of the near-seafloor currents (e.g., downslope density currents and along-slope ocean currents) is believed to control slope and rise sediment deposition in the Prydz Bay region (Kuvaas &

Leitchenkov, 1992), as it does elsewhere, such as in the Antarctic Peninsula region (Rebesco *et al.* 1997).

The broad pattern of ice and sediment movement in the region is controlled by the Lambert Graben. The major glacial drainage system in the region is the Lambert Glacier–Amery Ice Shelf system (Shipboard Scientific Party, 2001). The system drains ~1.09 million km², representing ~20% of the East Antarctic Ice Sheet (Allison, 1979).

3.2 Yermak Plateau

The Yermak Plateau is a marginal topographic high area (shallower than 2000 m) north of Svalbard. It is located at the crossing of the warm West Spitsbergen Current (the remains of the Gulf Stream) and the cold East Greenland Current (the remains of the Transpolar Drift), which is an important water exchange area between the Arctic Ocean and the North Atlantic (see Fig. 3, Myhre *et al.* 1995, Paper IV).

The main components of the surface water current systems of the Norwegian–Greenland Sea include the influx of warm, relatively high-salinity waters via the North Atlantic Drift, which continues its northward flow as the Norwegian Current, and the outflow of cold, low-salinity waters via the East Greenland Current (Fig. 3, Shipboard Scientific Party, 1995). The Norwegian Current is sufficiently cooled to allow deepwater formation within the cyclonic gyre of the Greenland Sea. Another branch of this current continues along the western margin of Svalbard as the West Spitsbergen Current before entering the Arctic Ocean and dipping under the Arctic sea ice cover (Shipboard Scientific Party, 1995). Within the Arctic, this relatively warm water mass mixes with low-salinity surface waters, sinks, and flows counterclockwise as an intermediate water mass before being exported out of the Arctic Ocean via the Fram Strait along the Greenland Margin (Shipboard Scientific Party, 1995).

Most of the marginal Yermak Plateau northwest of the Svalbard archipelago is under waters permanently covered with ice. However, in good ice years the ice retreats to north of 81 °N when the West Spitsbergen Current advances, and in late summer/early autumn, parts of the Yermak Plateau can be accessible (Shipboard Scientific Party, 1995). Because of its specific morphologic and tectonic setting, the Yermak Plateau is particularly well suited for studying the impact of the influx of Atlantic waters, the response of the modern system to glacial/interglacial fluctuations (oceanography, sea ice cover, Barents Sea ice shield), and the paleoceanographic transition of the temperate to the ice-covered Arctic Ocean, which were all part of the scientific objectives of Leg 151 (Shipboard Scientific Party, 1995).

It was recognized very early that the current system in the Fram Strait and its surroundings comprise some of the dynamically most unstable hydrographic elements in the gateways between the Arctic and North Atlantic oceans. Here the West Spitsbergen Current, as a continuation of the Norwegian Current, transports temperate Atlantic Ocean waters through the Fram Strait to the edge of the Arctic sea ice cover (Shipboard Scientific Party, 1995). In the northern Fram Strait these waters are either recirculated into the East Greenland Current or they continue on their path into the Arctic Ocean under the sea ice cover and a relatively thin layer of cold Arctic surface water. The East

Greenland Polar Front (Manley *et al.* 1992), which is marked by a sea surface outcrop of the 0 °C isotherm and which usually coincides with the ice edge, follows the highly turbulent water mass boundary between the Arctic waters of the East Greenland Current and the relatively warm West Spitsbergen Current with a geostrophic velocity of 30–80 cm/s.

Aagaard *et al.* (1985) concluded that nearly 50% of the water volume in the polar and subpolar northern deep seas, including the Amerasian Basin, is potentially in dynamic contact with the world ocean. Hence, these basins may be characterized as belonging to the “lungs” of the present world ocean. The unique topographic constraints provided by a single deep, narrow passageway to the North (Fram Strait) and a major submarine ridge system to the South (Greenland-Scotland Ridge) make the Cenozoic paleoceanography of the world ocean depend on these gateways (Shipboard Scientific Party, 1995).

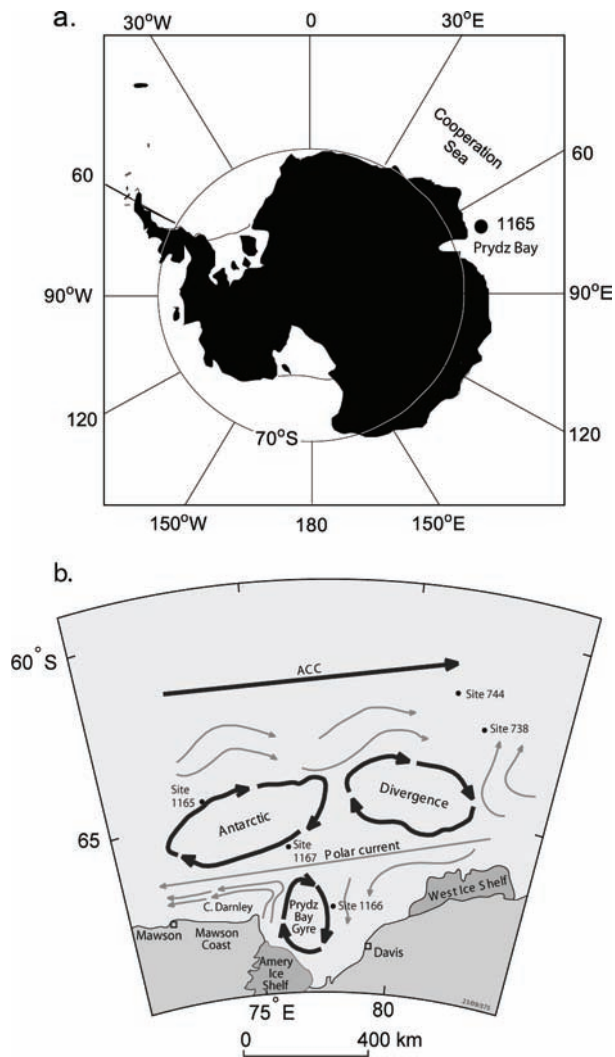


Fig. 2. a) Location of ODP Site 1165 drilled into drift sediments at the continental rise off Prydz Bay, Antarctica (Modified after Grützner *et al.* 2005). b) Generalized map of present-day ocean currents in the Prydz Bay region (modified from Smith *et al.* 1984; Cooper & O'Brien, 2004). ACC = Antarctic Circumpolar Current.

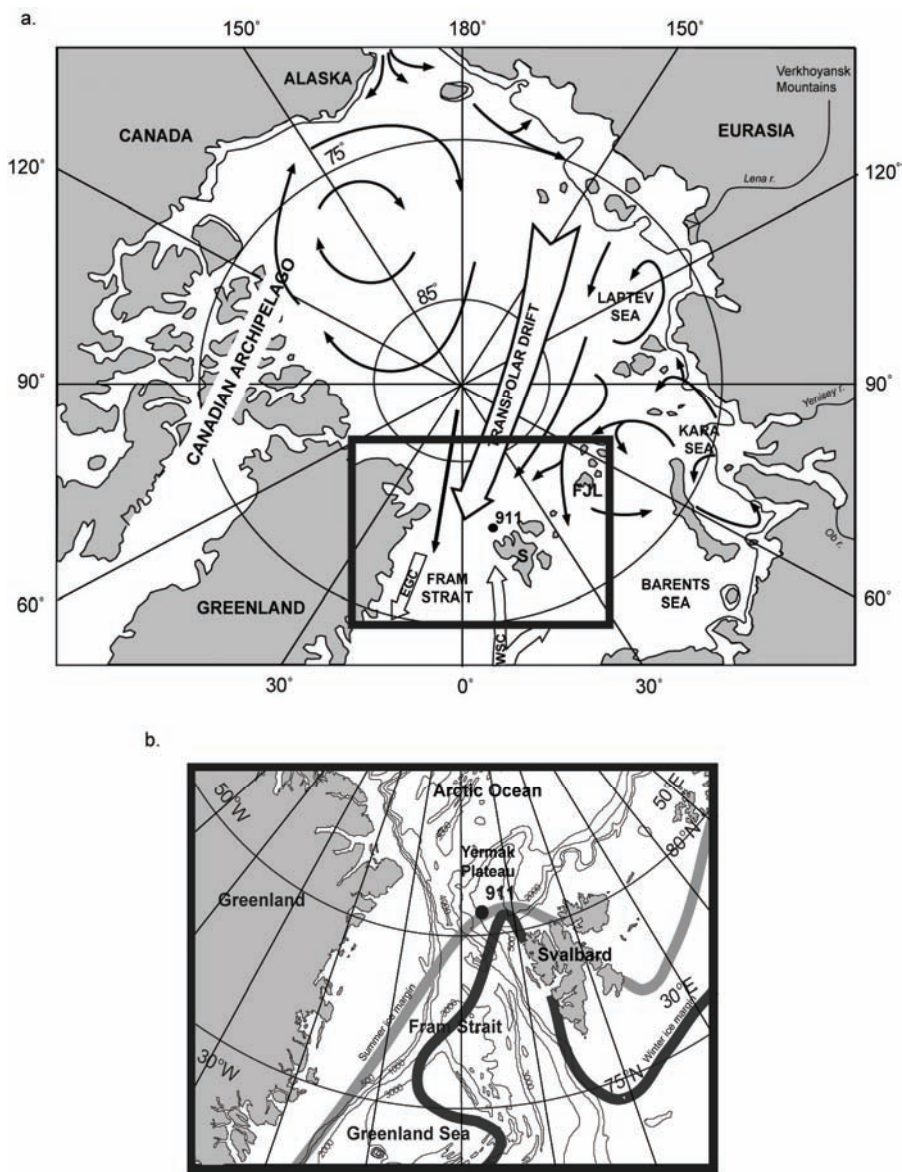


Fig. 3. a) Major circulation patterns of the Arctic Ocean. Shown are the Transpolar Drift, East Greenland Current (EGC), West Spitsbergen Current (WSC), Svalbard (S) and Franz-Josef Land (FJL) in the North Atlantic. The great Siberian rivers are also shown in the figure. (Modified from Willard, 1996). b) A simplified map of the Norwegian-Greenland Sea with the drill site studied. Shown are the summer and winter sea ice margins. (Modified from Thiede *et al.* 1996)

4 Sediment material

4.1 Leg 188, Site 1165

Site 1165 is situated on the continental rise offshore from Prydz Bay (64° 22.77'S, 67° 13.14'E) over mixed pelagic and hemipelagic sediments of the central Wild Drift (Papers I, II and III). This drift is an elongated sediment body formed by the interaction of sediment supplied from the shelf and westward-flowing currents on the continental rise.

The site is at a water depth of 3537 m and it was selected to provide a record of sedimentation that extends back to the onset of contour current-influenced deposition on the rise. Three holes were drilled at the site. Hole 1165A consisted of a mudline core that was dedicated to high-resolution interstitial water sampling. Hole 1165B, studied in this thesis, was cored to 147.9 meters below seafloor (mbsf) with 86.4% recovery and deepened to 682.2 mbsf with 57.3% recovery (Shipboard Scientific Party, 2001b). Hole 1165C was washed down to a depth of 54 mbsf, where a single core was taken at an interval that had been missed in Hole 1165B. Continuous coring began at 673 mbsf and continued to a total depth of 999.1 mbsf, with 80% recovery (Shipboard Scientific Party, 2001b). Drilling at Site 1165 yielded a relatively continuous 999-meter-thick sedimentary sequence of Early Miocene - to Pleistocene-age terrigenous and hemipelagic deposits with only a few minor (<2 m.y.) disconformities (Shipboard Scientific Party, 2001b).

The sedimentary section of Hole 1165B is divided into three lithostratigraphic units: Unit I (0–63.8 mbsf), Unit II (63.8–307.8 mbsf), and Unit III (307.8–999.1 mbsf). These units are characterized by cyclic variations between biogenic-bearing (lighter) and terrigenous-dominated (darker) intervals (Shipboard Scientific Party, 2001b).

Unit I is characterized by structureless brown diatom-bearing silty clay, clay with minor diatom-bearing greenish grey clay containing dispersed grains of sand and lone stones, minor laminated silt, and minor brown foraminifer-bearing clay (Shipboard Scientific Party, 2001b). Unit I consists of Facies I-1 and Facies I-2, which are interpreted as hemipelagic sediments.

Interval 0–50 mbsf from Unit I, Hole 1165B, was selected by the High- Resolution Integrated Stratigraphy Committee (HiRISC) for Plio-Pleistocene study (Paper I). Interval 0–50 mbsf is characterized by structureless brown diatom-bearing silty clay, clay

with minor diatom-bearing greenish grey clay containing dispersed grains of sand and lone stones, minor laminated silt, and minor brown foraminifer-bearing clay, which are interpreted as hemipelagic sediments (Shipboard Scientific Party, 2001b). The minerals of the sediments mostly consist of quartz, calcite, plagioclase, K-feldspar, and a mixture of clay minerals (Shipboard Scientific Party, 2001b).

Dating of the studied interval (0–50 mbsf) is based on siliceous microfossil biostratigraphy studied by Whitehead & Bohaty (2003). The sedimentation rate within 0–50 mbsf was 10m/million years (Cooper & O'Brien, 2004). Papers I–III cover the Plio-Pleistocene-aged sequence between 0–50 mbsf including the more intensively studied intervals of 7.7–16 mbsf (Plio-Pleistocene transition, discussed in Paper II) and 25–34 mbsf (Mid-Pliocene).

4.2 Leg 151, Site 911

ODP Site 911 (studied in Paper IV) is located at the shallow southern part of the Yermak Plateau, on the upper slope towards the Nansen Basin, at 80 °28.466'N, 08 °13.640'E. Based on refraction measurements, the basement is covered with 1,500 to 2,000 m of sediments. This site was selected to provide information on the glacial history of the Arctic Ocean and the influx of Atlantic surface water into the Arctic. The cores recovered from Site 911 (Holes 911A, 911B, 911C) contained Pliocene and Pleistocene strata. Hole 911A was cored to 505.8 mbsf, the water depth being about 901.6 m (Shipboard Scientific Party 1995). The core recovery was 91.8% (Myhre *et al.* 1995).

Site 911 consists of one lithological unit that can be divided into two subunits (1A and 1B). Subunit 1A (Quaternary to Pliocene age) is mainly composed of unlithified, homogeneous, very dark gray silty clay and clayey silt with common occurrences of large dropstones. In general, biogenic particles are rare. Slight to intensive bioturbation is present throughout the entire sequence. The dominant lithologies of the rock fragments are siltstones, fine-grained sandstones, and shales. Fragments of plutonic rocks and limestones are minor (Shipboard Scientific Party 1995).

Lithologic Subunit IB (Pliocene age) is defined by a decrease in dropstones. The sediment texture of Subunit IB indicates high-amplitude fluctuations of the sand-, silt-, and clay-size percentages. The average values for clay (~55%), silt (~39%), and sand (~6%) are nearly similar to those of Subunit IA and within the error range for this type of analysis (Shipboard Scientific Party 1995). The major lithologies of very dark gray, dark gray, and very dark olive gray silty clay and clayey silt seem to be homogeneous. The variation of siliciclastic components reflects high-amplitude fluctuations and shows average values for quartz (18%), feldspar (8%), and mica (trace). Inorganic calcite particles are more commonly present as background (~5%) and in distinct peaks reaching values up to 80% (Shipboard Scientific Party 1995).

Paper IV covers the intervals of 0–75.3 mbsf and 384.19–440.5 mbsf from Site 911A. Interval 0–75.3mbsf represents Pleistocene sediments that accumulated from ca. 0.8 Ma to the present, and interval 384.19–440.5 mbsf represents Pliocene sediments (2.78–3.10Ma). The Pleistocene data analyzed previously by Ruikka & Strand (2002) has been reprocessed for this thesis.

The age chronology was established by means of paleomagnetic (Myhre *et al.* 1995) and biostratigraphic data (Sato & Kameo, 1996). The Brunhes-Matuyama boundary was recorded at 72 mbsf (See Fig. 5) (Myhre *et al.* 1995). The Pliocene-Pleistocene boundary is placed between 217 and 217.5 mbsf and it is based on the occurrence of a calcareous nannofossil Datum 12 event (Sato & Kameo, 1996). A calcareous nannofossil Datum A event (~2.78 Ma) provides the oldest fixed point at 391.9 mbsf (Sato & Kameo, 1996). The ages of the Pleistocene and Pliocene chronologies were calculated from the estimated sedimentation rates of 92 m/Ma for the Pleistocene (Myhre *et al.* 1995) and 150 m/Ma for the Pliocene (Knies *et al.* 2002).

5 Methods

5.1 X-Ray Diffraction

X-ray diffraction (XRD) was performed on oriented clay samples as described by Hardy & Tucker (1988) (see also the glass slide method by Moore & Reynolds, 1997). The 3 g sediment samples were first decomposed (disaggregated by ultrasonic vibration for 30 min in Papers I and II) and then centrifuged for 1 minute (1000 rounds/minute according to Stoke's law) to settle all particle sizes greater than clay-size particles ($<2 \mu\text{m}$) to the bottom of the centrifuge tube and leave clay particles in the suspension. The suspension was removed from the centrifuge tube and placed in another tube. The samples were then concentrated by centrifugation for 15 minutes (1000 rounds/minute) whereupon the clay settled to the bottom of the tube, after which the water was decanted. Oriented and dried clay preparations were made. The first slide was air-dried at 60°C for 2 hr. The second was dissolved with ethylene glycol in the negative pressure desiccator at least 2 hr at 60°C for XRD analysis. Ethylene glycol in the negative pressure desiccator speeds up the expansion process for smectite. The third slide was analyzed after heating to 550°C for 2 hr, at which temperature kaolinite and certain chlorites are destroyed.

The X-ray diffractograms were recorded by a Siemens D 5000 at the Institute of Electron Optics, University of Oulu. Fixed divergence slit (FDS), molybdenum (see paper IV) and copper radiation (40 kV, 40 mA) with Ni filtering were used at angles ranging from 2° to $32^\circ 2\theta$ ($0.02^\circ 2\theta$ per second) immediately after the sample preparations. The four principal clay mineral groups were recognized by their basal spacings at 7\AA (kaolinite, chlorite), 10\AA (illite), $15\text{--}17\text{\AA}$ (smectite), 14\AA (chlorite). Chlorite (004) was identified at 3.54\AA and kaolinite (002) at 3.58\AA (Biscaye, 1964), and the peak-area method was used to calculate the quantities of kaolinite and chlorite from the joint peak at 7\AA .

MacDiff software version 4.2.5 (<http://www.geologie.uni-frankfurt.de/Staff/Homepages/Petschick/RainerE.html>) was used to quantify the clay minerals, which were subsequently used to calculate percentages using weighting factors (Biscaye, 1965). The analyzed 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 ($15\text{--}17\text{\AA}$)

possible without any distractions by the chlorite peak (14Å). Since no internal standards were used, the accuracy of this procedure is not known, but the quantitative analyses justify interpretations of fluctuations around +/- 2%.

The results of the four clay minerals were calculated to 100% which means that a strong increase in one clay mineral depresses all three other clay minerals. This makes the results semiquantitative. The fixed divergence slit used in this study increased the mean values of the smectite content by around 6% (extreme values by 13%), the illite values also increased (mean 3% max 8%), while kaolinite decreased (mean 3%, extremes 5%) and chlorite decreased (mean 6%, max. 8%) compared with the results analyzed with the automatic divergence slit (Rossak *et al.* 1999).

5.2 Smectite crystallinity measurements

Smectite crystallinity was evaluated after the XRD analysis with the MacDiff software according to Petschick *et al.* (1996) (Paper III). The measurements were made by computing the IB (= integral breadth or integral width) of the glycolated 17 Å smectite peak. IB is the width (in $\Delta^{\circ}2\Theta$) of the rectangle that is similar in height and area to the measured peak (cf. Klug & Alexander, 1974, Petschick *et al.* 1996). The smectite peak was 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 distractions by the chlorite peak (14Å) (See Paper III). IB values are more sensitive to peak tail variations than the usually applied FWHM = full width at half maximum (see Krumm & Buggisch, 1991). In the case of step scan measurements, integral breadths can be calculated from the integrated peak area counts multiplied by the step angle size used and divided by the peak intensity (cf. Petschick *et al.*, 1996). The filter cake preparations have less accurate IB values than those observed from oriented, dried preparations, which we preferred for all the crystallinity measurements (cf. Petschick *et al.*, 1996). Crystallinity values can be classified into the following categories: very well crystalline (<1.0), well crystalline (1–1.5), moderately crystalline (1.5–2.0) and poorly crystalline (>2.0) (cf. Diekmann *et al.*, 1996; Ehrmann *et al.*, 2005).

5.3 Scanning Electron Microscope

Scanning Electron Microscope (SEM) analysis presented in Paper III, was done on 13 samples which were chosen to represent the same intervals (Plio-Pleistocene transition and the Mid- Pliocene) that were studied in Paper II. After preparation, the samples were carbon coated and analyzed with JEOL, JSM-6400 SEM with an energy dispersive spectrometer (EDS). After the EDS analysis, a crystal-chemical formula based on the study by López-Galindo *et al.* (1989) was used to attribute the smectite elements to octahedral and tetrahedral sheets (see Paper III, cf. Setti *et al.* 2001). The total amount of 95 individual smectite particles from 13 samples were analyzed and morphologically studied.

6 Results

6.1 Clay minerals at Site 1165

6.1.1 *Clay mineral distribution*

The general clay mineral distribution from 0–50 mbsf (230 samples analyzed in 20 cm intervals) is presented in Papers I and II. Between 0–50 mbsf, smectite can be divided into three assemblages (Paper I). 1) 50–34 mbsf with the smectite content between 20–30%, 2) a transitional interval of 34–22 mbsf with the content between 2–20% and 3) 22–0 mbsf with the content fluctuating between 0–10%. The illite content fluctuates between 50–80%, the kaolinite content mainly between 10–20% and the chlorite content mainly between 0–10%. The illite content fluctuates in parallel with the smectite content and the kaolinite content increases towards the surface. There is also a slight increase in the chlorite content.

The Mid-Pliocene interval, based on the transitional interval (34–22 mbsf) of smectite in Paper I, was studied in detail in Paper II. A total of 78 samples from the Mid-Pliocene interval (34–25 mbsf) were analyzed in 10 cm intervals. During the Mid-Pliocene (Fig. 4), illite dominates the clay mineral composition with a variable content ranging from 40% to 80% (Paper II). The smectite content fluctuates from 5% to 30%. Both the kaolinite and chlorite contents stay around 10%. Kaolinite and chlorite have a minor influence on the overall clay mineral composition. An important general trend seems to occur towards 25 mbsf, where the smectite content increases and the illite content decreases (Fig. 4). The clay mineral ratios were also determined from the clay analysis data in Paper II. The smectite/illite ratio shows a strongly increasing trend towards 25 mbsf. During the Plio-Pleistocene transition (16–7.7 mbsf), smectite fluctuates with a content of <20%. The smectite/illite ratio shows a decreasing trend from 9.6 mbsf towards 7.7 mbsf (Paper II).

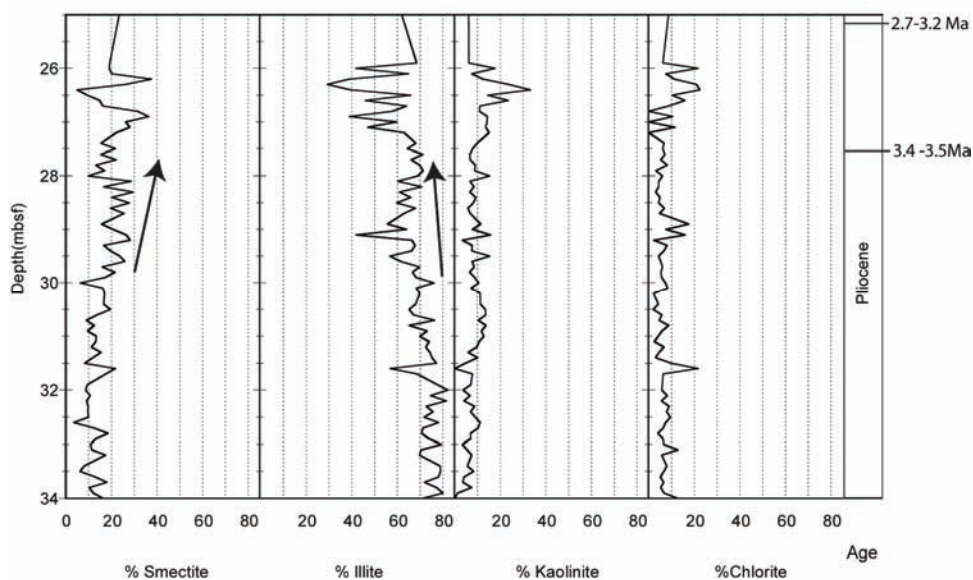


Fig. 4. Mid-Pliocene clay mineral distribution at Site 1165 (Paper II). The arrows show an increasing smectite content and a decreasing illite content towards 3.2 Ma. The ages are from siliceous microfossil biostratigraphy according to Whitehead & Bohaty (2003).

6.1.2 Clay mineral composition

Crystallinity measurements in Paper III show that smectites can be divided into three categories based on the fluctuating levels of their IB (Integral Breath) values. Unit I (50–33 mbsf) represents the Early Pliocene: smectites are moderately to poorly crystallized. Unit II (33–22 mbsf) representing the Middle Pliocene: smectites are well to moderately crystallized. Unit III (22–0 mbsf) represents the Pleistocene: smectites are well to very well crystallized. The morphology of the smectites in the studied sediments is flaky which is typical in detrital smectites (cf. Setti *et al.* 2000, Paper III).

According to SEM analyses, smectites have a constant chemical composition. Smectites are characterized by the presence of Al in tetrahedral and octahedral sheets. The octahedral composition field of smectites, considered on the typical $(Al^{3+} + Fe^{3+})^{VI}$ vs. Mg^{VI} plot of Weaver & Pollard (1975), allows a distinction between dioctahedral (nontronite and beidellite) and trioctahedral smectites (saponite, stevensite, hectorite).

The compositional domains of nontronite and montmorillonite have been reported. It must be underlined, however, that nontronite and beidellite may form a continuous solid solution (Singer *et al.* 1984), and the fields are therefore believed to represent only the end members. Most smectites from the Mid-Pliocene can generally be classified as dioctahedral Al-Fe smectites.

6.2 Clay minerals at Site 911

6.2.1 Clay mineral assemblages

The clay fraction of the Pliocene interval (380.4–440.5 mbsf) discussed in Paper IV is clearly dominated by smectite and illite, which together account for 60–84% (mean 74.89%) of the clay mineral composition (Fig 5b). Smectite fluctuates between 20–40%, illite between 20–40%, and kaolinite and chlorite between 0–20%. The Pliocene clay mineral assemblages can be divided into three distinct units, which are referred to as clay mineral assemblage I (430–440 mbsf), II (420–430 mbsf) and III (380–420 mbsf). Clay mineral assemblage IV (0–74 mbsf) represents the Pleistocene clay mineral distribution for comparative purposes.

6.2.2 Clay mineral assemblage I

Within the interval between 430–440 mbsf, the smectite content has a clearly decreasing trend towards 430 mbsf. The smectite content decreases from 59% to 15% (Fig. 5b). Both the highest and lowest values of smectite (59% and 15%) occur in this interval. The mean percentage value for smectite is 38%. There is also a strong negative correlation between smectite and illite. Illite has an increasing trend towards 430 mbsf. The mean percentage value for illite is 37%. The lowest illite concentration, 21%, occurs at 439.79 mbsf and the highest illite concentration, 49%, is at 430.90 mbsf. The mean percentage for kaolinite is 10%, which is significantly lower than the smectite and illite concentrations. The kaolinite content has an increasing trend towards 430 mbsf. The highest content of kaolinite (18%) occurs at 429.40 mbsf. This interval includes the highest (18%) and the lowest (6%) contents of kaolinite. The chlorite concentration of the studied sequence is also significantly lower than those of smectite and illite. The chlorite concentration fluctuates mainly between 10% and 20%, the mean percentage being 15%. The chlorite content has an increasing trend towards 430 mbsf, increasing from ~11% to > 20%.

6.2.3 Clay mineral assemblage II

Within the interval between 420 – 430 mbsf, the smectite content rises over 50% (Fig. 5b), fluctuates around 50%, and then decreases again to ~30%. The amount of illite fluctuates between 25–48% and is correlated negatively with smectite. The kaolinite content drops to its lowest level (6%) at 423.17 mbsf. The chlorite concentration also drops rapidly from 22% to its lowest value of 9%.

6.2.4 Clay mineral assemblage III

Within 380–420 mbsf, the smectite content fluctuates between 25–45% (Fig. 5b). It also has four low value points within the interval, at ~420 mbsf, ~410 mbsf, ~404 mbsf and ~390 mbsf. The illite concentration ranges mainly between 27% and 47%. At ~390 mbsf illite and kaolinite have distinctly high values. The fluctuation of kaolinite ranges from 6% to 15%, and five distinct cycles can be seen in which the amount of kaolinite exceeds 10%. Chlorite also shows strong variability, although no clear fluctuation pattern exists. It ranges mostly between 12% and 18%, with only a few values over 18%.

6.2.5 Clay mineral assemblage IV

Clay mineral assemblage IV represents Pleistocene sediments (Fig. 5a). The smectite content fluctuates between 1–29%. The mean percentage is 10%. The illite concentration ranges between 24–86%, the mean percentage being 58%. The kaolinite content of the Pleistocene interval varies between 4–31%, the mean percentage being 15%. The chlorite content fluctuates between 6–43%.

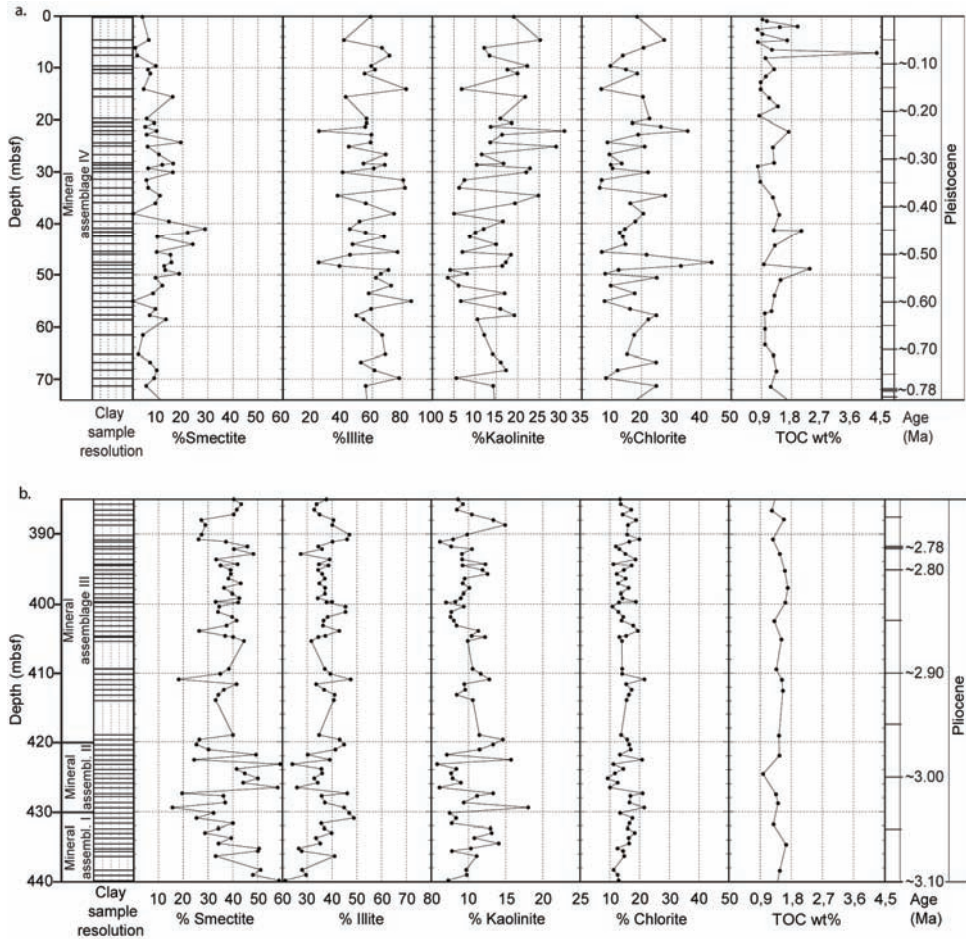


Fig. 5. Amount of individual clay minerals at Site 911 at a depth of 0–74 mbsf (a) and 384.19–440.5 mbsf (b). The Brunhes-Matuyama boundary (0.78 Ma) was recorded at 72 mbsf (Myhre *et al.* 1995) and calcareous nannofossil Datum A event 2.78 Ma at 391.9 mbsf (Sato & Kameo, 1996). TOC is from the study of Myhre *et al.* (1995). Age has been calculated from the estimated sedimentation rates of 92 m/Ma for the Pleistocene (Myhre *et al.* 1995) and 150 m/Ma for the Pliocene (Knies *et al.* 2002).

7 Discussion

7.1 Clay minerals as climatic indicators in the polar regions

Clay minerals in the ocean basins close to continents are mainly derived from land and initially formed as a result of various weathering processes, which are ultimately controlled by the climate. This is also the situation in the Prydz Bay, Antarctica (Papers I, II and III). Clay minerals are especially important climate proxy at high latitudes, where climatic variations and erosional processes are pronounced (cf. Ehrmann, 1991). Investigations of clay mineral assemblages supplement well the paleoclimatic information provided by other proxy data (cf. Chamley, 1989). The other proxies include the following, presented in Paper I: Magnetostratigraphy and magnetic properties, grain-size distributions (granulometry), colorimetry and calcium-carbonate content, characteristics of foraminifera, diatom and radiolarian content, and stable isotopes.

It is generally accepted (cf. Ehrmann, 1998) that illite and chlorite are detrital clay minerals and typical products of physical weathering and glacial erosion. They are therefore the typical clay minerals of high latitudes. In our study area, illite and chlorite are derived from crystalline rocks, which are widespread in East Antarctica and in the Arctic Ocean. Chlorite is a characteristic mineral of low-grade, chlorite-bearing metamorphic and basic source rocks, but it is not resistant to chemical weathering and transportation. Illite is a typical product of acidic rocks and, in contrast to chlorite, relatively resistant (Biscaye, 1965, Griffin *et al.* 1968, Windom, 1976).

Unlike chlorite and illite, kaolinite and smectite are primarily products of chemical weathering. Kaolinite cannot form under polar conditions. Smectite normally forms by hydrolysis under climatic conditions ranging from warm-humid to cold-dry (Chamley, 1989) in environments characterized by very slow movement of water (Ehrmann, 1991). However, there is also an input of smectite from continents into oceans (Ehrmann, 1991). Particularly Cretaceous and older smectites are often thought to have originated from subaerial weathering of basic rocks, such as basalts, under humid to arid climatic regimes (Chamley, 1979, Chamley *et al.* 1984).

7.2 Sources and transportation of clay minerals

The East Antarctic craton provides large quantities of appropriate source rocks, supplying both illites and chlorites, which are glacially transported (Ehrmann, 1991). This area is composed mainly of migmatites and biotite-quartz-feldspar gneiss and smaller areas of charnockite. Kaolinite found in the sediments at Site 1165 is assumed to be recycled. It is most likely derived as a result of the erosion of old kaolinite-bearing sedimentary rocks and/or soils and probably glacially transported to Site 1165 (Papers I–III). The kaolinite source may be the Permian Amery Formation or equivalent rocks that may have occupied the Lambert Graben. However, the extent of the kaolinite source beneath the ice is not exactly known (cf. Ehrmann, 1991, Papers I–III).

Most of the smectite at Site 1165 is derived from the continent. According to Forsberg *et al.* (2001), a large amount of smectite was found at Site 1167 (continental slope of Prydz Bay), which supports the continental source for smectite (Paper II). Knowledge of the prominent smectite sources in the Prydz Bay area is restricted to a few locations studied by Ehrmann *et al.* (2003) (cf. Paper III). The Mid- to Late-Miocene smectites in the Battye Glacier Formation (cf. Ehrmann *et al.* 2003) near the Prydz Bay area may have been formed from volcanic Paleocene olivine–leucite trachybasalts. Ehrmann *et al.* (2003) consider smectite an important and pervasive component of the clay mineral fraction, as it occurs in proportions of 5–26% (mean 15%). The metamorphic basement underlying the Battye Glacier Formation is characterized by upper-amphibolite grade and granulite-grade rocks. They are comprised mainly of orthopyroxene-bearing felsic granulite, garnet–biotite granulite, mafic granulite, felsic gneiss and biotite-, garnet- and pyroxene-bearing gneisses (McKelvey & Stephenson, 1990, Kamenev *et al.* 1993, Mikhailov & Sergeev, 1997, Stephenson & Cook, 1997; Mikhalsky *et al.* 2001). Some small stocks of granites also occur in that same formation (Ravich & Fedorov, 1982, Paper III).

The typical detrital and pedogenic smectites in the Prydz Bay sediments are believed to be more Al-rich than the average of the smectites analyzed (cf. Chamley, 1989, McMurtry *et al.* 1983). However, in a review of published analyses Wilson (1999) highlighted the fact that soil smectites are frequently more Fe-rich than montmorillonite and beidellite *sensu stricto*, and hence they fall into the range of feriferous beidellites. The smectites analyzed from the Mid-Pliocene in Paper III are dioctahedral, but do not give any clear indication of belonging to the beidellite or nontronite series, and hence most of the smectites can generally only be classified as dioctahedral Al-Fe smectites or, at the highest end, feriferous beidellites, as described by Wilson (1999).

The grade of lattice order and the crystallite size of clay minerals, usually referred to as crystallinity, are used to determine the low-temperature metamorphism of shales and slates (Frey, 1987), whereas in young sediments, possible source regions and transport paths can be traced with these characteristics (Petschick *et al.* 1996). Detrital smectites initially formed through chemical weathering processes on the continent are accompanied by other clay phases and generally have low crystallinity (cf. Setti *et al.* 2001). In Paper III, the Pliocene-aged smectites had predominantly moderate or poor crystallinities. They may have been derived from the Battye Glacier Formation (Ehrmann *et al.* 2003) or similar sources and transported to Site 1165 mainly by bottom currents. They may have

been formed by alteration of the chlorite and biotite of metamorphic basement rocks underlying the Battye Glacier Formation in cool temperate conditions (cf. Ross *et al.* 1983, cf. Weaver, 1989). In that case, the formation of smectite would have taken place during warmer periods/interglacials, such as the Mid-Pliocene (cf. Paper II), when East Antarctic conditions may have been closer to cool temperate conditions.

The sources of the clay minerals in the Arctic Ocean are based on their modern day distribution studied by Washner *et al.* (1999) with the hypothesis that the climate conditions during the Mid-Pliocene were similar to present conditions (Paper IV).

Illite is a typical clay mineral in cold regions, and it is derived from all the shelf areas surrounding the Arctic Basin (Wahsner *et al.* 1999). The chlorite distribution of the Arctic Ocean surface sediments is relatively uniform, and none of the shelf areas have particularly high values of chlorite in the Eurasian part of the Arctic (Wahsner *et al.* 1999). However, a slightly higher chlorite component in the Laptev Sea is delivered by the Lena and Yana Rivers (Rossak *et al.* 1999). Cretaceous and older smectites, in particular, are often thought to have originated from subaerial weathering of basic rocks, such as basalts, under humid to arid climatic regimes (Chamley, 1979, Chamley *et al.* 1984). These kinds of basalt are present in the Putorana Plateau, Siberia, which is the main source of the smectites at Site 911 in the Arctic (Paper IV). In the Arctic, the kaolinite is mainly derived from Franz-Josef Land (Washner *et al.* 1999, Paper IV).

Based on the clay mineral study in the Paper IV, the most probable transport path is the Siberian branch of the Transpolar Drift (Fig. 6), and the transportation has taken place under similar conditions recorded by Wahsner *et al.* (1999). Furthermore, it seems evident that the Transpolar Drift followed the same path during the Pliocene as it does at present, as also recorded by Willard (1996). Wahsner *et al.* (1999) suggest that the Kara and Laptev Seas are the potential source areas of the modern siliciclastic material included in the sea ice of the Siberian branch of the Transpolar Drift. The narrow and deeper North American shelves are thought to have been less important for basin-wide sediment transportation by sea ice in the past (cf. Wahsner *et al.* 1999).

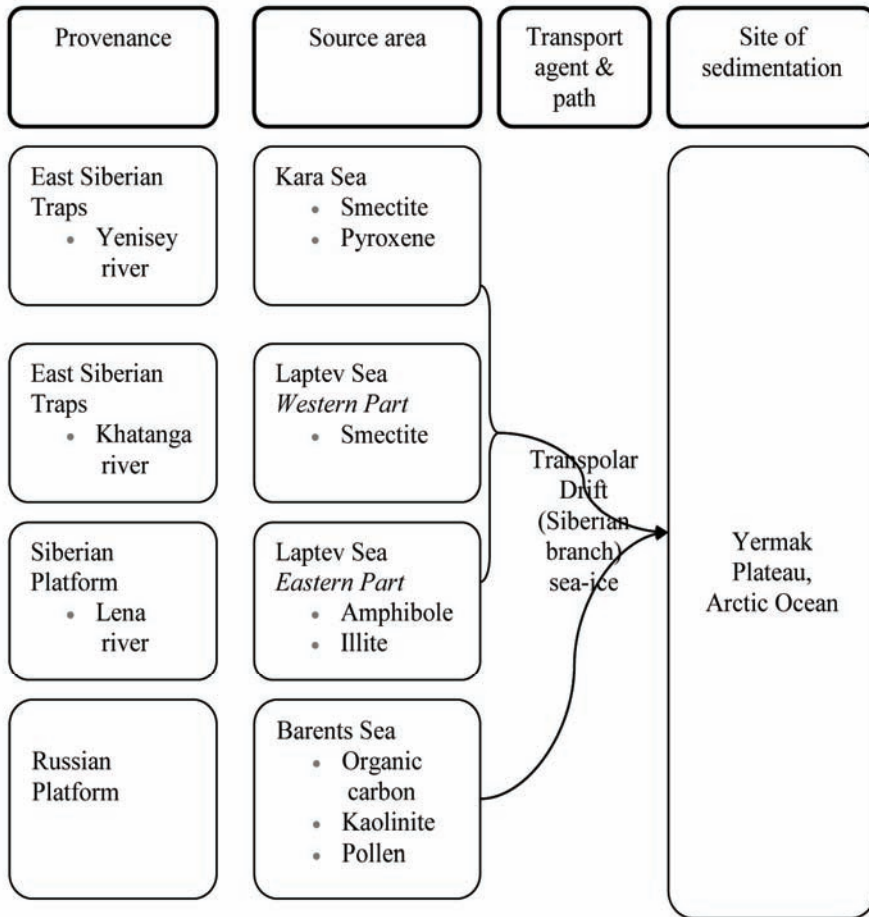


Fig. 6. Synthesis of sediment transportation into Site 911A during the Late Pliocene (Paper IV).

7.3 Mid-Pliocene clay mineral record

7.3.1 Prydz Bay, East Antarctica (Site 1165)

The East Antarctic Ice Sheet (EAIS) is a cold-based continental ice sheet. Generally, most movement (dynamic behavior) occurs at the margins of the EAIS, caused by the increasing amount of water at the bottom of the ice sheet. During warm conditions, the EAIS dynamics at the margins increase, especially at the Lambert Glacier-Amery Ice Shelf system, and the zone of movement shifts more inland. As presented in Paper II, the most noticeable changes in the Prydz Bay during the Mid-Pliocene (25–34 mbsf) were the increasing trend of smectite content and the decreasing illite content towards the 25 mbsf level. The increase in smectite content and the decreasing illite content may indicate possible gradual warming conditions towards the 25 mbsf level. Warm conditions during the Mid-Pliocene, reflected in the smectite and illite ratios, indicate a dynamic ice sheet.

During the Plio-Pleistocene transition (16–7.7 mbsf), the smectite content shows lower values compared with the Mid-Pliocene interval (Paper II). The smectite/illite ratio from the Plio-Pleistocene transition also shows a decreasing trend towards 7.7 mbsf. This could indicate that the climate conditions were much warmer and the ice sheets more dynamic during the Mid-Pliocene than during the Plio-Pleistocene transition.

Ice-rafted debris (IRD, mainly quartz grains), radiolarians, and foraminifera percentages were counted from Site 1165 Plio-Pleistocene sediments by Kupp & Warnke (2006). Below 34 mbsf (early Pliocene), radiolarians tend to dominate the coarse fraction (as much as 74 percent), perhaps also suggesting more open, warmer water than today (cf. Whitehead *et al.* 2005). Their findings suggest that the margins have been dynamic, undergoing significant and repeated advances and retreats of the grounding line, as suggested by Bart (2000). On the other hand, the interior of the East Antarctic Ice Sheet has remained stable throughout the Pliocene-Pleistocene (Marchant & Lewis, 2000). Ice sheets still extended to the ocean during the Pliocene, based on the presence of IRD that show surface features typical of “glacial” quartz grains (see Krinsley & Doornkamp, 1973). Their findings support the dynamic behavior of the ice sheet during the Mid-Pliocene hypothesized in this study, which might have been going on since the Early Pliocene.

Trends in smectite and illite content similar to the Mid-Pliocene situation in this study have also been reported by Ehrmann (1991). Especially the results from Site 744, the Kerguelen Plateau, show an increasing trend in smectite content and a decreasing trend in illite content. However, it should be noted that the study by Ehrmann (1991) concentrated on the sediment sequence spanning from the Eocene to the Quaternary, and the samples were taken at much longer intervals compared with our study in Paper II.

7.3.2 Yermak Plateau, Arctic Ocean (Site 911)

The relationship between smectite and illite in the Arctic Ocean is generally believed to reflect changes in glacial conditions. In Paper IV, smectite dominates in lower mineral assemblage I, decreasing towards mineral assemblage II (Figs. 5b & 7). However, in assemblage I illite starts to increase towards mineral assemblage III, probably indicating increasing glacial weathering, as also noted by Winkler *et al.* (2002). Clay mineral assemblage II is characterized by an increase in the smectite content, which correlates with the Mid-Pliocene Global Warmth (MPGW) period, around 3 Ma (Fig. 7). During the MPGW period, smectite dominates over illite. This may indicate a shift to a more temperate climate, where the chemical weathering of smectite is more abundant. In clay mineral assemblage III smectite decreases and illite starts to dominate. This may indicate a change to glacial conditions similar to the study of Winkler *et al.* (2002). In clay mineral assemblage IV, representing the Pleistocene, smectite shows a generally lower content and illite a higher content compared with Pliocene assemblages I–III. This might reflect the fact that freshwater input was much lower during the Pleistocene compared with the Pliocene. The prevailing glacial conditions during the Pleistocene decreased freshwater input, which diminished sea ice formation and transportation of smectite. For example, Polyak *et al.* (2002) concluded in their study that during the Last Glacial Maximum (LGM), the great Siberian Ob and Yenisey Rivers were blocked by the Barents–Kara ice sheet that occupied the northern part of the Kara Sea.

The amount of kaolinite in the Yermak Plateau sediments is relatively low, between 5% and 15%, and therefore kaolinite is of minor importance in determining the source areas in this study. According to Wahsner *et al.* (1999), the potential source areas for kaolinite are very limited in the Arctic Ocean, as noted earlier (Paper IV).

On the other hand, kaolinite, along with the TOC (total organic carbon) level, is a useful indicator of coastal glacial erosion. Because kaolinite is a very resistant mineral, its occurrence in the polar regions may be derived from the reworking of older, kaolinite-bearing sediments (Darby, 1975, Chamley, 1989, Hambrey *et al.* 1991). The carbon studied at Site 911 is identified by Knies *et al.* (2002) as being of organic/fossil-reworked origin. In the surface sediments north of Svalbard, high contents of mainly terrigenous TOC are associated with relatively high kaolinite contents, undoubtedly pointing to the Barents Sea as the most evident source area (Stein *et al.* 1994, Wahsner *et al.* 1999). A similar correlation between high kaolinite and high TOC values can be seen in the Pliocene sediments. The distribution of total organic carbon and kaolinite seems to decrease during the MPGW period (clay mineral assemblage II), which supports the idea of reduction in glacially induced coastal erosion (Fig. 7). The decrease in kaolinite content during the MPGW period is also noticed in the study of Knies *et al.* (2002). The kaolinite level in the Pleistocene assemblage is a little higher than in the Pliocene assemblages and has an increasing trend towards the surface (cf. Winkler *et al.*, 2002). The TOC values of the Pleistocene assemblage are also a little higher than in the Pliocene, which indicates an increase in glacially induced coastal erosion.

In the studied sediments of the Yermak Plateau, the chlorite content is quite uniform throughout the sequence (between ~10% and 20%), although the chlorite content fluctuates considerably. The chlorite content decreases rapidly and stays at a low level

during the MPGW period mineral assemblage II, probably because of the increasing smectite content. During the Pleistocene mineral assemblage IV, chlorite fluctuates more intensively, but approximately at the same level as during the Pliocene (cf. Winkler *et al.*, 2002). This could be caused by increased glacial/interglacial cycles during the Pleistocene. Wahsner *et al.* (1999) point out that the chlorite distribution of the Arctic Ocean surface sediments is relatively uniform and none of the shelf areas have particularly high values of chlorite in the Eurasian part of the Arctic. However, a slightly higher chlorite component in the Laptev Sea is delivered by the rivers Lena and Yana Rivers (Rossak *et al.* 1999).

The clay and heavy mineral assemblages of Site 911 show fluctuation in the amount of material that was deposited onto the Yermak Plateau during the Pliocene. Smectite occurrence in clay mineral assemblage II supports warm interglacial conditions. The amount of amphiboles, pyroxenes and stable minerals studied in Paper IV is also higher during the MPGW period, which might be caused by two factors. First, the fresh water input from the great rivers of Siberia might have increased due to progressive meltwater production during the interglacial period. This would lead to an increase in the supply of terrigenous material delivered by the rivers. The second factor causing the increase in the amount of heavy minerals in the Yermak Plateau sediments might be that the increased freshwater input led to enhanced sea ice formation, hence increasing sea ice transportation from the shelf areas of the Arctic Ocean. The formation of sea ice continues in the high-latitude areas even when the climate is more temperate; changing salinity conditions in the shelf areas may even increase sea ice formation (See Aagaard & Carmack, 1989 and references therein).

Age (Ma)	Mineral assemblage	Smectite & illite indicating climatic variability	Reworked terrestrial material indicating climatic variability	Heavy minerals indicating variation in fresh-water input
2.78 2.80	III	Decrease of smectite / increase of illite indicating colder conditions	Increase of kaolinite and TOC indicating enhanced glacial erosion in the adjacent continents	
2.90				
3.00	II	Increase of smectite / decrease of illite indicating warmer conditions	Decrease of kaolinite and TOC indicating reduced glacial erosion	Higher amount of heavy minerals indicating increased fresh-water input
3.10	I	Decrease of smectite / increase of illite indicating colder conditions	Increase of kaolinite and TOC indicating enhanced glacial erosion	

Fig. 7. Synthesis of the Pliocene clay and heavy minerals studied in Paper IV and the related proxy data as climatic indicators at Site 911.

8 Conclusions

Based on this study of clay mineral analysis, the Mid-Pliocene Global Warmth period can be noticed in both the Arctic and Antarctic regions. Ice sheet development during the Mid-Pliocene, especially in East Antarctica, is identified, as is the history of ice rafting and sea ice, especially in the Arctic Ocean. The following paragraphs describe the conclusions drawn from the southern and northern hemispheres, respectively.

Prydz Bay, Antarctica (Site 1165) - The Pliocene detrital smectites are mainly derived from Antarctic continental sources, much similar to Battye Glacier Formation, and transported to the site mainly by bottom currents related to warm events during the last 5 Ma (Paper III). The evidence obtained in this study shows that the East Antarctic ice sheet may have behaved as a dynamic ice sheet during the past 5 Ma, especially during the Mid-Pliocene (Papers I and II). The results from the Mid-Pliocene, which show an increase in smectite content and a decrease in illite content towards the surface, possibly suggest a general warming trend towards 3.2 Ma. The smectite/illite ratio also supports this warming trend and suggests a dynamic ice sheet. (Paper II).

Yermak Plateau, Arctic Ocean (Site 911) - Based on the composition of the heavy and clay mineral groups in Paper IV, the most probable transport path is the Siberian branch of the Transpolar Drift. The sea ice in the Transpolar Drift is an important agent, transporting sediments from the shallow Arctic shelves to the place of sedimentation at the Yermak Plateau. The time period of 3.10–3.02 Ma (clay mineral assemblage I) is characterized by a decreasing smectite and increasing illite content, which is interpreted as reflecting cooling conditions (Paper IV). The kaolinite content, along with the total organic carbon (TOC) level, also shows an increase in the amount of glacially eroded matter. The smectite content shows an abrupt increase at the beginning of the Mid-Pliocene Global Warmth period at ca. 3 Ma (clay mineral assemblage II) (Paper IV). The change can also be seen as a drop in the amount of kaolinite and TOC. After 2.98 Ma (clay mineral assemblage III) the smectite content shows a change back to glacial conditions. At the same time the kaolinite and TOC values start to increase, most probably indicating high rates of reworked glacially eroded matter. During the Pleistocene, from 800ka to the present (clay mineral assemblage IV), smectite shows a lower level and illite shows a higher level compared with the Pliocene (assemblages I–III). This might reflect that freshwater input was much lower during the Pleistocene

compared with the Pliocene. The prevailing glacial conditions during the Pleistocene decreased freshwater input, which diminished the sea ice formation and transportation of smectite (Paper IV).

Further paleoclimatological multiproxy studies of both the southern and northern hemispheres are needed to constrain, characterize and correlate the Antarctic and Arctic marine sediments. Integrated studies may significantly improve our knowledge of past climates in the polar regions and our understanding of the climate's evolution, and even of the future.

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- I Warnke DA, Richter C, Florindo F, Damuth JE, Balsam WL, Strand K, Ruikka M, Junttila J, Theissen K & Quilty P (2004) Data report: HiRISC (High-Resolution Integrated Stratigraphy Committee) Pliocene–Pleistocene interval, 0–50 mbsf, at ODP Leg 188 Site 1165, Prydz Bay, Antarctica. In: Cooper AK, O'Brien PE & Richter C (Eds) Proceedings of the Ocean Drilling Program, Scientific Results 188: 1–38. Available from: http://www-odp.tamu.edu/publications/188_SR/VOLUME/CHAPTERS/015.PDF
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