Quaternary paleoceanography of the Arctic Ocean:
A study of sediment stratigraphy and physical properties

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Abstract

A Quaternary perspective on the paleoceanographic evolution of the central Arctic Ocean has been obtained in this PhD thesis by studying sediment cores from all of the Arctic’s major submarine ridges and plateaus. The included cores were mainly recovered during the Healy-Oden Trans-Arctic expedition in 2005 and the Lomonosov Ridge off Greenland expedition in 2007. One of the main thesis objectives is to establish whether different sediment depositional regimes prevailed in different parts of the central Arctic Ocean during the Quaternary and, if so, establish general sedimentation rates for these regimes. This was approached by dating key cores using the decay of the cosmogenic isotopes 10Be and 14C, and through stratigraphic core-to-core correlation using sediment physical properties. However, the Arctic Ocean sea ice complicated the use of 10Be for dating because a solid sea ice cover prevents the 10Be isotopes from reaching the seafloor, resulting in too old ages. Dating using 14C is also complicated due to uncertain marine reservoir age corrections in the central Arctic Ocean. The core-to-core correlations show five areas with different depositional regimes; the northern Mendeleev Ridge and Alpha Ridge, southern Mendeleev Ridge, Morris Jesup Rise, Lomonosov Ridge and Yermak Plateau, listed in the order of increasing sedimentation rates from ~0.5 cm/ka to ~4.8 cm/ka. A detailed study of the relationship between sediment bulk density and grain sizes suggests a strong link between variations in clay abundance and bulk density. Grain size analysis of a Lomonosov Ridge core show that fine silt and clay dominates the interglacials, possibly due to increased suspension freezing of these size fractions into sea ice and/or nepheloid transport. Sediments younger than the marine isotope stage (MIS) 7 generally contain more coarse silt, attributed to a regime shift during the Quaternary with increased iceberg transport into the central Arctic Ocean from MIS 6 and onwards.
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This thesis consists of a summary chapter and six appended papers.

List of papers:


**Paper III:** Hanslik, D., Jakobsson, M., Backman, J., Björck, S., Sellén, E., O’Regan, M., Fornaciari, E., Skog, G. manuscript. Quaternary Arctic Ocean sea ice variations and deep water isolation times. To be submitted to Quaternary Science Reviews

**Paper IV:** O’Regan, M., Sellén, E., Jakobsson, M. manuscript. Predictive relationships between bulk density and grain size in Quaternary sediments from the Lomonosov Ridge. To be submitted to Sedimentology

**Paper V:** Sellén, E. and O’Regan, M. manuscript. Grain size distributions and ice-rafting in the central Arctic Ocean – a million year perspective. To be submitted to Marine Geology

**Paper VI:** Sellén, E., O’Regan, M., Jakobsson, M. manuscript. Spatial and temporal Arctic Ocean depositional regimes: a key to the evolution of ice and current patterns. To be submitted to Quaternary Science Reviews

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My contribution to the papers: I was lead author of Papers I, II, V and VI, for which I carried out the analyses and most of the writing in collaboration with the co-authors. The beryllium analysis in Paper II was made by M. Frank and P. Kubik. In Paper III, I contributed to the stratigraphic correlation and the grain size analysis. In Paper IV, I contributed with the material for the analysis and part of the writing, the statistical analysis was made in cooperation with M. O’Regan.

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Introduction

During the past decade there has been a great increase in interest and awareness of global climate change. The warming of the Earth’s climate has become a reality observed in air and ocean temperatures with effects such as melting of sea ice and glaciers and consequently a rise of global average sea level (Mueller et al., 2003; Meehl et al., 2005; Comiso et al., 2008). We clearly need to better understand the potential environmental impacts from a changing climate and the climate system’s response to different forcings. In this context, a long-term perspective of the past environmental evolution of the ocean and terrestrial system is required. However, a perspective reaching beyond that provided by instrumental records (Moberg et al., 2005) can only be obtained from studies of Earth’s own archives such as tree rings, ice cores and ocean sediments. Chemical analysis of marine sediments and its biogenic content may be used as a proxy for temperature and productivity and changes in sediment physical properties can be used to infer ocean circulation variations (McCave et al., 1995; Spielhagen et al., 2004). In the Arctic Ocean, the preferred sediment cores for these kinds of studies are retrieved from elevated areas of the seafloor where the material originates from processes affected by climate and oceanography, i.e. ice transported debris and biogenic material produced in the water column (Clark and Hanson, 1983). In comparison, sediments from continental slopes and deep basins are mostly deposited through gravitational transport mechanisms and the oceanographic signals may not be possible to distinguish (Stein and Korolev, 1994). This thesis focuses on spatial and temporal variations in sedimentary processes in the Arctic Ocean and their applications to paleoceanographic studies.

Long sediment cores from the Arctic Ocean are scarce and apart from drilled sites at the Yermak Plateau (Thiede et al., 1996) and the central Lomonosov Ridge (Backman and Moran, 2009), only short piston and gravity cores, mostly less than 10 m long, were available from the central Arctic Ocean before 2005.

In 2005 the Healy-Oden Trans-Arctic Expedition (HOTRAX) was carried out with the aim of recovering long piston cores along a transect stretching from the Northwind Ridge north of Alaska via the North Pole to the Yermak Plateau off Svalbard (Figure 1) (Darby et al., 2006). The main purpose for collecting cores across the entire central Arctic Ocean was to link the sediment stratigraphies of the Amerasian and Eurasian Basins, separated by the Lomonosov Ridge, through core-to-core correlations (Figure 1). This had the potential of providing the first spatial view on the sedimentary environments in the central Arctic Ocean across both its major basins, which is necessary for paleoceanographic studies. HOTRAX was a Swedish-American collaboration expedition making use of the Swedish icebreaker Oden and US Coast Guard Cutter Healy. The two icebreakers accompanied each other from a rendezvous at the Alpha Ridge (Figure 1). The geological sampling program was conducted on the Healy and a total of 21 piston cores, on average 12 m long, were recovered along the HOTRAX transect. Many of these cores were retrieved from the Alpha and Mendeleev ridges where few long sediment cores had been previously recovered.

Even if HOTRAX covered large parts of the central Arctic Ocean, spatially huge areas remain un-sampled. In particular, few cores exist from the area north of Greenland and the Canadian Arctic Archipelago, where the most difficult sea ice conditions in the entire Arctic Ocean prevail.
For this reason, and because the area off northern Greenland may hold critical information regarding the Arctic Ocean glacial history (Jakobsson et al., 2008b), the Lomonosov Ridge off Greenland (LOMROG) expedition constituted one of the main Swedish initiatives during the International Polar Year (IPY) 2007/2008 (Jakobsson et al., 2008c). Furthermore, Denmark became full partners in the LOMROG initiative due to their interest in surveying the areas north of Greenland for the purpose of submitting a claim for extending the definition of their Arctic continental shelf under the United Nations Convention of the Law of the Sea (UNCLOS) Article 76. LOMROG was organized and carried out by the Swedish Polar Research Secretariat in 2007 using the icebreaker *Oden* and the Russian nuclear icebreaker “50 Years of Victory”. The southern parts of the Lomonosov Ridge towards Greenland and the Morris Jesup Rise were cored and surveyed with *Oden’s* new multibeam and chirp sonar profiler (Jakobsson et al., 2008c). Several cores were retrieved from previously completely un-sampled areas. Together, the sediment cores from HOTRAX and LOMROG constitute an exceptional sediment archive with material from all of the major ridges and plateaus in the Arctic Ocean. These cores constitute the main materiel studied in this PhD thesis and the results are presented in five papers. An additional paper is based on cores recovered during expeditions prior to HOTRAX and LOMROG.

Figure 1 Schematic map of the Arctic Ocean and adjoining Greenland and Norwegian Seas showing geographical and bathymetrical features. The bathymetry is from IBCAO (Jakobsson et al., 2008a). The 100 m, 1000 m and 2000 m isobaths are shown. The red line represents the track line for USCGC *Healy* during HOTRAX, the orange line is the *Oden* track line from the LOMROG expedition and the core sites are marked with yellow dots. The red square marks the HOTRAX rendezvous point for *Oden* and *Healy*. Abbreviations used in this figure: YP – Yermak Plateau; MJR – Morris Jesup Rise; CP – Chukchi Plateau; NWR – Northwind Ridge; BS – Bering Strait.
Aim of this study

Critical for all paleoceanographic studies based on sediment cores is to establish robust age models, in order to place measured sediment proxies in a chronological context. The most widely applied and reliable methods to date sediment cores require calcareous biogenic material. In Arctic Ocean piston cores, there are only spotty occurrences of calcareous micro- and nannofossils in the upper few meters of the stratigraphy (Backman et al., 2004; O’Regan et al., 2008a). This has resulted in large chronostratigraphic uncertainties and two age model scenarios that differ significantly. One proposes sedimentation rates of mm/ka-scales in the Amerasian Basin of the Arctic Ocean (Steuerwald et al., 1968; Herman, 1974; Clark et al., 1980) and the other, more recent age model for the Lomonosov Ridge and the Eurasian Basin, suggests cm/ka sedimentation rates for the Plio-Pleistocene (Jakobsson et al., 2000, 2001; Nowaczyk et al., 2001; Backman et al., 2004; Spielhagen et al., 2004; O’Regan et al., 2008a).

The initial main objective for this PhD project was to resolve if the different sedimentation rates reported for the Amerasian and Eurasian Basins are products of dating problems or, in fact, due to completely different sedimentary regimes in the two basins.

The HOTRAX transect was designed with this problem in mind: to investigate if cores from the Arctic Ocean transect can be correlated based on any stratigraphical parameter, such as sedimentological and physical properties. If a correlation can be established across the entire Arctic Ocean, the differences in sedimentation rates are probably due to dating problems. This correlation turned out not to be trivial. Another approach to resolve the Arctic Ocean chronostratigraphic problem is to explore the application of new dating methods on cores from both the Amerasian and Eurasian Basins.

In this thesis both approaches are applied in four of the six included scientific papers. The fourth paper investigates how grain size and bulk density are related and the fifth paper is focused on down core grain size variations in a key core on the Lomonosov Ridge, and the paleoceanographic significance of this variability. The scientific objectives for the included papers follows below while summaries of the results and conclusions are provided after the methods section.

**Paper I**

1. To investigate if the widely used standard lithostratigraphy established by Clark et al. (1980) for the Amerasian Basin can be applied to cores from the Lomonosov Ridge. Two of the studied cores from the Lomonosov Ridge crest have been previously correlated to Eurasian Basin cores and, thus, if the Amerasian Basin lithostratigraphy can be recognized in these, a stratigraphic link between the two main basins of the Arctic Ocean can be established.

**Paper II**

2. To use cosmogenic isotope $^{10}$Be decay for dating two cores from the Alpha and Mendeleev ridges in order to evaluate sedimentation rates in the Amerasian Basin.
3. To determine the spatial variations of $^{10}$Be concentrations and fluxes across the Arctic Ocean.

**Paper III**
Hanslik, D., Jakobsson, M., Backman, J., Björck, S., Sellén, E., O’Regan, M., Fornaciari, E., Skog, G. manuscript. Quaternary Arctic Ocean sea ice variations and deep water isolation times. To be submitted to Quaternary Science Reviews

4. To study foraminifers and calcareous nannofossils in a high resolution record from the Intra Basin on the Lomonosov Ridge.
5. Establish an age model for the core based on radiocarbon dating on planktic and benthic foraminifers.
6. Address the issue of applying suitable marine reservoir ages to calibrate the $^{14}$C ages obtained.

**Paper IV**
O’Regan, M., Sellén, E., Jakobsson, M. manuscript. Predictive relationships between bulk density and grain size in Quaternary sediments from the Lomonosov Ridge. To be submitted to Sedimentology
7. Quantitatively compare the results from high-resolution grain size analyses with non-destructive bulk density measurements so that the primary control on bulk density can be identified.

8. Provide a framework for understanding and interpreting downhole variations in physical properties.

**Paper V**
Sellén, E. and O’Regan, M. manuscript. Grain size distributions and ice-rafting in the central Arctic Ocean – a million year perspective. *To be submitted to Marine Geology*

9. Address changes in the grain size distribution within the silt and clay-sized fraction, acquired through analysis using a Sedigraph.

10. Identify independent grain size components that may explain the variation in the grain size distribution by Principal Component Analysis.

11. To account for different modes of transportation that may explain the grain size spectrum.

**Paper VI**
Sellén, E., O’Regan, M., Jakobsson, M. manuscript. Spatial and temporal Arctic Ocean depositional regimes: a key to the evolution of ice and current patterns. *To be submitted to Quaternary Science Reviews*

12. To use physical properties for correlating sediment cores from all of the major ridges and plateaus in the central Arctic Ocean. The cores included in the study consist of a few previously published key cores in addition to those retrieved during the HOTRAX 2005 and LOMROG 2007 expeditions.

13. To identify whether or not there are specific areas in the central Arctic Ocean showing depositional environments that provide similar, correlatable stratigraphies.

14. To establish key stratigraphic parameters for identified areas with similar sediment depositional environments in the central Arctic Ocean that can aid in the correlation of cores and possibly form a Quaternary stratigraphic framework for paleoclimatic and paleoceanographic studies.

![Figure 2](image_url) Arctic Ocean physiographic provinces defined according to their bottom slope or other criteria (adapted from Jakobsson et al., 2003a). Abbreviations used in this figure: YP – Yermak Plateau; MJR – Morris Jesup Rise; CP – Chukchi Plateau; NWR – Northwind Ridge.
Study area – the Arctic Ocean

Physiography

The physiography of an ocean basin is of importance when analyzing accumulated sediments for the purpose of studying paleoceanography. The sea floor bathymetry largely influences ocean currents that in turn govern the sediment transport and deposition, and processes such as mass wasting. Therefore, an overview of the Arctic Ocean main physiographic features is provided here as well as a brief summary of their geologic origins.

The Arctic Ocean, as defined by the International Hydrographic Organization, is the smallest of the world oceans making up 1.4 % of the world ocean volume and 4.3 % of the area (Jakobsson, 2002). The ocean basin is nearly land-locked with broad continental shelves (Figure 1). The continental shelves of the Barents, Kara, Laptev, East Siberian, Chukchi, Lincoln, White, and Beaufort seas and the continental margins off the Canadian Arctic Archipelago and northern Greenland are the most extensive and widest in all of the world oceans (Figure 2). The majority of these shallow shelves are generally less than 100 m deep; the exceptions are the deeper shelves of the Barents, Kara and Beaufort seas (Figure 1). The shelves make up the main source areas for the sediments brought into the Arctic Ocean primarily carried as ice rafted material and deposited on the ridges, plateaus and abyssal plains. This sediment transport mechanism is further described below.

The arctic abyssal plains are about 4000 m deep and characterized by a smooth and flat seafloor due to thick sediment layers draping the ocean crust (Jackson and Oakey, 1990; Jokat et al., 1995; Jakobsson et al., 2003a, 2008a). Another characteristic feature of the Arctic Ocean is the limited connections to other oceans, namely the Pacific and North Atlantic. Shallow connections exist through the Bering Strait, the Canadian Arctic Archipelago, and across the Barents Sea while the only deep water connection is through the Fram Strait (Figure 1). The sediment on this ridge may have a limited stratigraphic record as the Gakkel Ridge is an active spreading ridge. The spreading rate is about 0.06 to 1.3 cm/yr, which is the slowest of the global mid-ocean ridge system (Coakley and Cochran, 1998). The ridge forms a continuation of the Mid-Atlantic Ridge. The deep connection through the Fram Strait, began to open in the early Oligocene around 33 Ma (Engen et al., 2008). However, the Fram Strait was not wide and deep enough to allow a significant water influx from the North Atlantic to the Arctic Ocean until the early Miocene (Jakobsson et al., 2007).

The Lomonosov Ridge formed when rifting and seafloor spreading began to propagate through the Barents-Kara Sea margin and broke off a 1500 km long continental sliver (Wilson, 1963; Vogt et al., 1979) during late Paleocene times. The oldest sediments recovered from the Lomonosov Ridge during the Integrated Ocean Drilling Program (IODP) Leg 302, the Arctic Coring Expedition (ACEX), have an age of ~56 Ma and are situated atop a regional unconformity (Figure 3a) (Backman and Moran, 2009). Seafloor spreading moved the ridge to its current position (Vogt et al., 1979; Brozena et al., 2003), where it forms a bathymetric barrier dividing the Arctic Ocean into the Amerasian and Eurasian Basins (Figure 1). The Lomonosov Ridge crest has its shallowest part located off the northern Canada and Greenland margin where the water depth is less than 1000 m over a relatively large and flat area. There are also areas of the ridge shallower than 1000 m closer to the North Pole. The central part of the Lomonosov Ridge is characterized by a 2700 m deep depression forming an Intra Basin (Figure 3b). This Intra Basin has a sill depth of 1870 m towards the Makarov Basin while the deepest threshold is 2400 m on the Amundsen Basin side (Jokat et al., 1992; Björk et al., 2007; Jakobsson et al., 2008a).

The largest ridge complex in the Arctic Ocean is the Alpha and Mendeleev ridges that divide the

North American ice sheets respectively (Dyke et al., 2002; Svendsen et al., 2004).

The Arctic Ocean ridges and plateaus have different tectonic origins and were formed at different times. The geologic histories of these ridges and plateaus may largely impact their suitability as coring sites when the purpose is to retrieve undisturbed sediment records for paleoceanographic studies. The relatively deep Gakkel Ridge, with ridge flanks at about 3200 m depth, separates the Nansen and Amundsen Basin (Figure 1). The sediment on this ridge may have a limited stratigraphic record as the Gakkel Ridge is an active spreading ridge. The spreading rate is about 0.06 to 1.3 cm/yr, which is the slowest of the global mid-ocean ridge system (Coakley and Cochran, 1998). The ridge forms a continuation of the Mid-Atlantic Ridge. The deep connection through the Fram Strait, began to open in the early Oligocene around 33 Ma (Engen et al., 2008). However, the Fram Strait was not wide and deep enough to allow a significant water influx from the North Atlantic to the Arctic Ocean until the early Miocene (Jakobsson et al., 2007).
Amerasian Basin into the Makarov and Canada Basins (Figure 1). The ridge system stretches more than 1800 km from the East Siberian shelf to the Canadian margin off Ellesmere Island. In contrast to the Lomonosov Ridge, this ridge complex is composed of numerous sea mounts and valleys ranging from 740 m to 2000 m below sea level (Jakobsson et al., 2003b). While the formation of the Alpha and Mendeleev ridges is still debated, the retrieval of ~82 Ma basaltic rocks from the Alpha Ridge indicates an oceanic origin (Jokat, 2003).

There are three smaller ridge systems protruding from the continental shelves into the Arctic Ocean: 1) the Chukchi Borderland, including the Northwind Ridge and the Chukchi Plateau, that extends about 600 km from the Chukchi continental shelf into the Canada Basin, 2) the northward trending Morris Jesup Rise extends from the continental shelf off northern Greenland 200 km into the Amundsen Basin, and 3) the Yermak Plateau is situated at the Svalbard margin extending 400 km into the Nansen Basin (Figure 1). The Chukchi borderland is underlain by sedimentary rocks and has a relatively flat ridge crest of generally less than 1000 m and steep slopes, all indicating that this is a fragment of continental crust (Grantz et al., 1998; Jakobsson et al., 2003b). Magnetic, gravity and seismic observations of the Yermak Plateau and the Morris Jesup Rise indicate a continental origin as well, probably related to the Cretaceous Arctic Large Igneous Province (Engen et al., 2008). However, a partly oceanic origin of both the Yermak Plateau and the Morris Jesup has also been suggested (Feden et al., 1979; Jackson et al., 1984; Jokat et al., 2008). The depths of the fairly smooth and flat crested Morris Jesup Rise range from about 500 m to 2500 m and the Yermak Plateau is between approximately 500 m to 1000 m (Jakobsson et al., 2008a). The Yermak Plateau is characterized by a smooth surface in the southwestern and northern parts, whereas the eastern side is more rough and irregular.

The thickness of the sediment that drapes the Arctic Ocean ridges and plateaus can be up to 1500 m thick, as for example on the Alpha Ridge (Jokat, 2003; Lebedeva-Ivanova et al., 2006). Average sedimentation rates for the Alpha Ridge and Lomonosov Ridge, calculated from the complete sediment thickness and the age of the formation of the ridges, indicate similar sedimentation rates of about 1-2 cm/ka (Jokat, 2003). During ACEX, 428 m of the Lomonosov Ridge sedimentary stratigraphy was drilled through (Figure 3a). The ACEX record shows that central Arctic Ocean sedimentation has been relatively uniform down to almost 200 m, consisting of similar units of fine-grained silts and clays with numerous sand lenses and some pebbles. Below 200 m, the sediment is composed of dark gray siliceous ooze, reflecting a much different and less ventilated depositional environment, when the Fram Strait was closed (Moran et al., 2006; Backman et al., 2008; Engen et al., 2008). The upper stratigraphy of short cores from different parts of the Arctic Ocean is consistently characterized by silty or sandy clay of alternating dark and light brown colors (Clark et al., 1980; Mudie and Blasco, 1985; Jakobsson et al., 2001; Backman et al., 2006).

Recent seafloor mapping in the Arctic Ocean shows that some ridge crests have been affected by
ice erosion above approximately 1000 m present water depth (Vogt et al., 1994; Jakobsson, 1999; Polyak et al., 2001, 2007; Jakobsson et al., 2008b, 2008c). The timing of the most extensive and deep-drafting ice grounding in the central Arctic Ocean has been determined to MIS 6 (Jakobsson et al., 2001, 2008b). The submarine ice erosion has been caused by drifting icebergs and of floating ice shelves, equivalent to what can be observed for the Antarctic Ice Sheet (Polyak et al., 2001; Jakobsson et al., 2008b). The stratigraphy in these ice eroded areas may be disturbed or include hiatuses.

The sediment cores used here have been retrieved from all major ridges and plateaus in the Arctic Ocean (Figure 1). Most coring locations were situated on elevated areas where material is mainly brought by environmentally dependent processes such as ice rafting and biological productivity. The cores are fairly evenly distributed across the Arctic Ocean in order to account for geographical variations in sedimentation regimes. Two of the included cores from the Morris Jesup Rise were recovered within a single ice scour in order to gain information about the timing of the erosion (Jakobsson et al., 2008c).

Oceanography

The Arctic Ocean has an upper, relatively fresh water layer with temperatures near freezing, commonly referred to as the Polar Surface Water. This approximately 50 m thick layer is primarily composed of river runoff, low salinity Pacific water and sea ice melt water (Aagaard et al., 1985; Rudels et al., 1996). Some of the World’s largest rivers discharge into the Arctic Ocean and drain large parts of northern Russia, Siberia, the Canadian Arctic and Alaska (Aagaard et al., 1985; Rudels, 1986; Peterson et al., 2002). The Eurasian Basin surface water flows mainly within the Transpolar Drift from the Siberian shelves towards the Fram Strait, where it exits into the Greenland Sea (Figure 4a). The surface circulation in the Amerasian Basin is dominated by the anti-cyclonic Beaufort Gyre. Most of the Amerasian surface water is transported across the Lomonosov Ridge to the Fram Strait although some of these waters exit through narrow channels in the Canadian Arctic Archipelago (<230 m) to Baffin (Rudels et al., in press).

A halocline exists between about 50 and 250 m, below the mixed layer within the Polar Surface Water. This layer acts as a barrier between the cold and fresh upper mixed layer of the Polar Surface Water and the warmer and more saline water below, that originates from the North Atlantic Ocean (Rudels et al., in press). Underneath the Arctic Ocean halocline a more saline and warm layer is encountered having temperatures >0°C, which is commonly referred to as the Atlantic layer or the Arctic Atlantic Water (Figure 4b). The Atlantic layer between approximately 250 and 600 m water depth originates from North Atlantic Water entering the Arctic Ocean through the Fram Strait and across the Barents Sea (Anderson et al., 1994; Rudels et al., 2000, in press). The Barents Sea branch of Atlantic waters cools and sinks to intermediate depths via the St. Anna Trough into the Nansen Basin where it meets the Fram Strait branch (Rudels et al., in press). Most of the re-circulating Atlantic water in the Eurasian Basin originates from the Fram Strait branch (Anderson et al., 1994), whereas a large part of the Barents Sea branch flows along the Siberian margin into the Makarov Basin and Canada Basin (Rudels et al., 2000).

The intermediate water in the Arctic Ocean consists of the Upper Polar Deep Water, generally between 600 and 1700 m water depth (Rudels et al., in press). This layer is made up of cold shelf water plumes that mixes with the warm Atlantic water forming a dense, saline water, which has decreasing temperatures with depth (Rudels, 1986; Rudels et al., 1994). In paper VI, we point out that most of the cores analyzed in this study from the LOMROG and HOTRAX expeditions, as well as the cores included from previous studies, are located within the Atlantic layer or the Upper Polar Deep Water. This implies that some of the paleoceanographic interpretations based on sediment proxies from these cores will provide information biased towards changes within these water masses. However, this concerns sediment proxies influenced by bottom processes such as currents interacting with the seafloor or changes in bottom ventilation, and not sediment compositional changes due to for example variations in ice rafting.

The deep waters in the Arctic Ocean (Figure 4c) are in exchange with the North Atlantic through the 2550 m deep Fram Strait, with the inflow located close to Svalbard (Jones et al., 1991; Anderson et al., 1994; Rudels et al., 1994, in press). Arctic Ocean deep water flows along the Siberian continental shelf and continues counter-clockwise as a boundary current along
the flanks of the Lomonosov Ridge (Aagaard et al., 1985; Rudels et al., in press). Some of the deep water spills over into Makarov Basin between the Lomonosov Ridge and the Siberian margin and continues along the continental slope to the Alpha-Mendeleev ridges where some of the water crosses over into the Canada Basin (Anderson et al., 1994; Jones et al., 1995; Rudels et al., in press). The Amerasian Basin deep water, commonly named the Canadian Basin Deep Water, has an anti-cyclonic circulation (Anderson et al., 1994) and flows across the Lomonosov Ridge at two places, close to Greenland where the sill depth is approximately 1200 m according to the International Bathymetric Chart of the Arctic Ocean (IBCAO, Jakobsson et al., 2008a) and through the Intra Basin, which has a sill depth of 1870 m (Björk et al., 2007). The Eurasian Basin Deep Water and the Canadian Basin Deep Water join close to the Morris Jesup Rise and exits the Arctic Ocean near Greenland where they mix with Greenland Sea Deep Water and contribute to the Norwegian Sea Deep Water, which spills over into the North Atlantic basin where the North Atlantic Deep Water is formed (Rudels, 1986; Aagaard, 1989). The modern residence times for the Eurasian Deep and Bottom Waters and the Canadian Basin Deep and Bottom Waters are between 100-350 years and 300-360 years respectively (Rudels et al., in press).

Sea ice and sediment transport

The majority of the sediment accumulated on ridges and plateaus in the Arctic Ocean has been entrained in sea ice that forms over the shallow continental shelves and its drift enables the
sediment to spread long distances and over large areas (Bischof, 2000). The Laptev Sea is the largest source for sea ice rafted sediments, although sea ice formation and sediment entrainment take place all along the Arctic Ocean continental shelves (Bischof, 2000). This implies that the sediment composition in the different parts of the Arctic Ocean will depend on the dominating source area of sea ice formation and the type of sediment entrainment for the different areas. The formation of sea ice is facilitated by the large quantities of fresh water discharged into the Arctic Ocean by the Siberian Rivers (Bischof, 2000; Peterson et al., 2002), creating a low-salinity surface water (Aagaard and Carmack, 1989).

There are primarily three different mechanisms entraining sediment into sea ice and this is of great importance for which grain size fractions are subsequently brought through sea ice rafting to different regions of the Arctic Ocean. The most common type of sediment incorporation is (1) suspension freezing, which mainly incorporates the finer end of the grain size spectrum (fine sand, silt and clay) and usually takes place in water depths of less than 30 m (Reimnitz et al., 1993; Dethleff, 2005). Coarser particles, >250 μm, pebbles and macrofauna have usually been entrained as a result of the formation of (2) anchor ice which is a process where ice freezes to the seafloor (Reimnitz et al., 1987). A sediment entrainment process considered to be of minor importance is (3) windblown particles and overwash of flooding rivers onto the pack ice, however, the true significance of this is still unknown (Reimnitz et al., 1993; Nürnberg et al., 1994).

In the modern interglacial Arctic Ocean the iceberg transport of sediment grains is inferior to sea ice transport, although the former is suggested to play a major role during glacials (Bischof, 2000). Today icebergs are produced by the glaciers on Svalbard, Franz Josef Land, Severnaya Zemlya, Ellesmere Island, and Greenland and these icebergs generally transport coarser material than the contemporary sea ice (Reimnitz et al., 1993; Nürnberg et al., 1994; Eicken et al., 2005). However, sea ice can occasionally contain pebbles and cobbles (Reimnitz et al., 1987; Reimnitz et al., 1993; Nürnberg et al., 1994; Darby, 2003). Despite this, intervals in the sediment cores that are dominated by coarse grains have mainly been interpreted as signs of a glacial environment (Bischof, 2000).

Sediment from one ice floe does not always represent one source area. Dirty sea ice samples recovered from the central Arctic Ocean contained sediment from multiple sources, which is the result of a mixture of different generations of sea ice (Darby, 2008). The sediments eroded from the Kara Sea, the Laptev Sea and the Barents Sea region are mainly transported by the Transpolar Drift and deposited as the ice melts across the Lomonosov Ridge and the Eurasian Basin (Spielhagen et al., 2004). In sediment cores from the Amerasian Basin the main source is the Canadian Arctic Archipelago and the Banks Island shelf (Darby, 1989; 2003). The drift paths of the ice today, more or less follows the wind driven circulation via the Beaufort Gyre and the Transpolar Drift patterns, with older multi-year ice more commonly present in the Beaufort Gyre (Figure 5) (Colon and Thorndyke, 1984; Rigor and Wallace, 2004). Sea ice from the Siberian shelves is transported via the North Pole to the Fram Strait over a course of 3-4 years. However, sea ice formed near the Canadian Islands (Ellef Ringnes Island) drift within the Beaufort Gyre up to about 180° longitude where it either remains in the Beaufort Gyre or is caught by the Transpolar Drift which transports the sea

Figure 5 Isochrone map showing the number of years required for an ice floe to exit from the Arctic Ocean through the Fram Strait during a negative Arctic Ocean Oscillation (adapted from Rigor et al., 2002). The transparent areas represent different source areas and approximate distribution of ice rafted debris in the Arctic Ocean based on Figure 6.8a by Bischof (2000). The green area represents the Canadian Arctic Archipelago and Alaska, red indicates a Siberian or Svalbard source, and the Greenland source is marked in blue.
ice towards the Fram Strait, which overall may last 5-6 years (Rigor and Wallace, 2004).

**Paleoceanographic and paleoclimatic variability**

The Arctic Ocean sediment archives contain information on the region’s paleoceanographic evolution including changes in ocean circulation and sea water properties, sea ice and iceberg presence and their drift patterns. On a million year time scale, recovered material reflects a highly variable paleoceanography in the Arctic Ocean. For example, three short cores retrieved from the Alpha Ridge contained Cretaceous sediments. The organic-rich sediments from one of these cores suggest sea surface temperatures of ~15°C at about 70 Ma (Jenkyns et al., 2004). Studies based on the ACEX cores from the Lomonosov Ridge show that the present Arctic Ocean circulation regime was initiated about 17.5 Ma after a period of dramatic oceanographic changes related to the Fram Strait opening (Jakobsson et al., 2007).

Results from the ACEX drilling suggest that a perennial sea ice cover has been present in the central Arctic Ocean for at least 13-14 Ma (Darby, 2008; Krylov et al., 2008) and has probably been an important factor in sediment transport since then. Before perennial sea ice was established, seasonal ice most likely played an important role for transporting sediments to the central basin (St. John, 2008). Sea ice dependent fossil diatoms have been observed in the ACEX stratigraphy, which suggest that seasonal sea ice formation occurred over the marginal shelf areas already in the middle Eocene ~47.5 Ma (Stickley et al., 2009).

A more recent shift affecting the sedimentation environment occurred at the MIS 6/7 boundary when more coarse grained sediments were deposited on the central Lomonosov Ridge (Jakobsson et al., 2000, 2001). This change in grain size was noticed also by Spielhagen et al. (1997), although they assigned a much older age (690 ka). Spielhagen et al. attributed this grain size change to the growth of the marine based Barents-Kara ice sheet. This suggestion was later supported by studies of the ACEX cores (O’Regan et al., 2008a). Provenance studies of ice-rafted Fe oxid mineral grains from the Lomonosov Ridge indicate another change in source material at 50 ka, when the material shifted from being dominated by an Ellesmere Island source to an increased input from near Ellef Ringnes Island, one of the Queen Elizabeth Islands further west (Darby, 2008).

Most Arctic Ocean sediment cores contain interlaminated medium brown and brown layers (Ericson et al., 1964; Jakobsson et al., 2000; Darby et al., 2006). These layers have been attributed to the interglacial and glacial variability, where the darker brown layers correspond to oxygenated interglacial sediments with higher manganese content. The manganese may have been derived from an increasing contribution from northern Siberia or from higher bottom water oxygen concentrations generating, more precipitation of manganese (Jakobsson et al., 2000; Löwemark et al., 2008).

The dramatic drop in sea level during glacial periods exposed the vast continental shelves, as well as closed off the Bering Strait (Jakobsson, 2002). This will have restricted the current circulation to the central Arctic Ocean and the incorporation of sediment in sea ice. Investigations of sediment source areas based on four cores from the Alpha Ridge have resulted in a reconstruction of surface water circulations back to the first inclination change (Bischof and Darby, 1997), now dated to MIS 7 (Jakobsson et al., 2000). During glacial periods, the icebergs from North American sources, transported by the surface currents, did not drift within the anti-cyclonic path of the modern Beaufort Gyre. Instead, they drifted slightly northwards from North America and the Canadian Arctic Archipelago, before turning east towards the Fram Strait and exiting the Arctic Ocean. The pack ice from Russian sources that drifted into the Amerasian Basin also flowed more or less directly across the Lomonosov Ridge, before entering the Greenland Sea via the Fram Strait. This implies that the Beaufort Gyre may not have existed during glacial periods, allowing sea ice and icebergs from the North American Laurentide and Inuitian ice sheets to leave the Arctic Ocean rapidly. However, the modern pattern of the Transpolar Drift seems to have been more or less stable transporting pack ice from the Siberian shelves to the Fram Strait (Bischof and Darby, 1997). Several studies have shown that the inflow of Atlantic warm water was diminished or completely closed off during past glacial periods (Cronin et al., 1995; Hebbeln and Wefer, 1997; Matthiessen et al., 2001; Nørgaard-Pedersen et al., 2003). Ostracode assemblage studies suggest ~1°C colder and lower salinity surface waters during glacial than today (Cronin, 1995). Dense deep and intermediate water were
mainly formed by brine rejection during sea ice formation, mainly in the Kara Sea (Haley et al., 2008).

A shorter-term climatic variability, on the century scale, is the Arctic Ocean Oscillation that affects sea level pressure and sea ice drift (Thompson and Wallace, 1998; Rigor et al., 2002; Darby and Bischof, 2004) and thus the source of sediment. When there is a positive Arctic Ocean Oscillation (Figure 6a), the Transpolar Drift becomes more vigorous and shifts further towards the Amerasian Basin (Rigor et al., 2002; Darby and Bischof, 2004). The intensification of the Transpolar Drift together with the addition of thicker sea ice from the Amerasian Basin, results in more sea ice transported to the Fram Strait. Consequently, the salinity of the Greenland Sea surface water is lowered, which reduces the formation of North Atlantic Deep Water (Aagaard and Carmack, 1989; Raymo et al., 1990; Delworth and Dixon, 2000). A negative Arctic Ocean Oscillation (Figure 6b) is associated with a diminished Transpolar Drift and a surface circulation dominated by the Beaufort Gyre in the Amerasian Basin (Rigor et al., 2002; Darby and Bischof, 2004). Darby and Bischof (2004) showed that these oscillation patterns have been active since at least the last deglaciation (9-11 ka).

**Figure 6** The mean sea ice motion (red vectors) and pressure contours (mb, black) in two time periods. Blue lines are Lagrangian tracer pathways forced continuously by these mean vector fields. The zero vorticity contour (magenta) indicates the main axis of the Transpolar Drift Stream. a) Shows a weak Beaufort Gyre when the Arctic Ocean experienced a strongly positive Arctic Ocean Oscillation index and, b) shows a more vigorous Beaufort Gyre during a negative index (adapted from Steele et al., 2004).

**Litho- and chronostratigraphy**

Sedimentological research in the Arctic Ocean only goes back to the early 20th century when Russian scientists recovered sediment surface samples along the Siberian coastline. In the late 1930’s, the Russians started to use ice floes as platforms for drifting research stations and longer sediment cores could be retrieved. The most famous drifting research station was the ice island T-3 (or Fletcher’s Ice Island), which was established by the U.S. Air Force in 1952. This huge iceberg drifted along the path of the Beaufort Gyre in the central Amerasian Basin and hundreds of sediment piston cores, mostly less than 4-meter long, were collected between 1963 and 1973 (Hunkins and Tiemann, 1977). The ice island T-3 was finally abandoned in 1974 near Ellesmere Island where it was caught in the Transpolar Drift and eventually carried to the Greenland Sea where it melted (Clark, 1969; Weber and Roots, 1990).

These new sediment cores from the central Arctic Ocean lead to a vast improvement in the understanding of sedimentary processes in this area. Based on 67 of these T-3 cores, mainly from the Alpha Ridge, a general lithostratigraphy was established with 13 units (A to M) by Clark et al. (1980) (Figure 7 and 8). The classifications emphasized grain size variations between coarse sandy layers and finer silty mud layers, as well as
characteristic pink and whitish layers that were commonly found in most of the central Arctic cores. This standard lithostratigraphy was then applied to cores retrieved during following expeditions such as the Lomonosov Ridge Expedition (LOREX) in 1979, which drifted across the central Lomonosov Ridge (Weber, 1989) and the Canadian Expedition to Study the Alpha Ridge (CESAR) in 1983. Although the units A to M have been correlated over vast distances in the Amerasian Basin and have been recognized in two cores from the flank of the Lomonosov Ridge toward the Makarov Basin and on what we now know to be a flank of the Intra Basin (Morris et al., 1985), Clark’s standard lithostratigraphy could not be applied to cores from the Eurasian Basin. When longer cores from the Lomonosov Ridge were retrieved from icebreaker expeditions in 1991 and 1996, the lithostratigraphy could not be applied. Mainly there were no pink or whitish layers identified that were important for the classification of the standard lithostratigraphy (this is further discussed in Paper I).

Traditionally, the T-3 cores were dated by identifying the first paleomagnetic full reversal, the Brunhes/Matuyama boundary (781 ka, Lourens et al., 2004), since biogenic material is only sparsely available. This was consistently found around one meter depth in all cores and always within unit K, which implied very low sedimentation rates on the order of mm/ka. In effect, recognition of unit K was more or less all that was needed to date these sediment cores and this scenario was widely accepted for the entire central Arctic Ocean (e.g. Steuerwald et al., 1968; Clark, 1969, 1970, 1971, 1996; Hunkins et al., 1971; Herman, 1974; Clark et al., 1980; Minicucci and Clark, 1983; Witte and Kent, 1988; Spielhagen et al., 1997). However, ages for sediment cores in the Eurasian Basin started to become available based on oxygen isotopes (Markussen et al., 1985), coccolith abundance (Baumann, 1990; Gard, 1993), \(^{10}\)Be isotopes (Aldahan et al., 2000), dinoflagellate cyst stratigraphy and \(^{14}\)C dating (Matthiessen et al., 2001), paleointensity correlations (Nowaczyk et al., 2001), and optically stimulated luminescence (Jakobsson et al., 2003b) that indicated higher sedimentation rates on the order of cm/ka. Also, a study using amino acid epimerisation on a T-3 core from the Mendeleev Ridge suggested an average sedimentation rate of 0.86 cm/ka (Sejrup et al., 1984). Furthermore, the previously firm identification of the Brunhes/Matuyama boundary was questioned as more knowledge about short term paleomagnetic excursions was gained (Bleil and Gard, 1989; Jakobsson et al., 2001; Nowaczyk et al., 2001; Spielhagen et al., 2004). In core 96/12-1pc from the central Lomonosov Ridge the first paleomagnetic polarity change coincided with an interval interpreted as the MIS 7 based on biostratigraphy (Jakobsson et al., 2001), which suggested that this corresponded to the Biwa II excursion (220 ka, Lund et al., 2006). However, the number of excursions recorded in the Arctic Ocean sediments are too many compared to the global record and they last too long. Recent results from a study on a HOTRAX core from the Mendeleev Ridge indicate that the authigenic carrier of natural remanent magnetization, titanomaghemite, causes partial self-reversals, not linked to the actual variability of the Earth’s magnetic field (Channell and Xuan, 2009).

This difference in interpretation of the paleomagnetic record may account for the observed differences in sedimentation rates between the
Amerasian and Eurasian Basin (Figure 8). A thorough evaluation of the different sedimentation rate scenarios was presented by Backman et al. (2004). They concluded that there was no reason for two completely different sedimentation environments and that “the central Arctic Ocean has not been, on average, a sediment starved basin during either Plio–Pleistocene or pre-Pliocene times, and cm/ka-scale sedimentation rates are the rule rather than the exception”. This was the research setting before results from ACEX were presented and before the more recent expeditions recovering long piston cores.

Methods

Piston and gravity coring

The sediment coring during the HOTRAX expedition in 2005 with USCGC Healy was conducted using a Jumbo Piston Corer (JPC) with a core head weight adjustable between 1590 and 2730 kg. During the LOMROG expedition a piston/gravity corer (PC/GC) was used, which also has a core head weight that is possible to modify, 1360 kg was commonly used for PC and 1088 kg for GC. The JPC and PC/GC systems both have 3-meter barrel sections with couplings connecting the individual section to each other. The maximum rigged core length during HOTRAX was 18 m and 12 m during LOMROG. Both corers use a short gravity corer to trigger the release arm (trigger weight core – TC) which resulted in an additional sample from each coring site. A polyvinyl chloride liner is used for the JPC with a diameter of 11.4 cm, while the PC uses an 8.8 cm poly carbonate liner. These liners were cut into 150 cm long sections that subsequently were split and stored as one archive and one working half. Sub-bottom chirp sonar data were acquired to determine the rigged core length based on interpretation of the sediment characteristics and to identify the best suitable coring location. The sediment cores were always taken on bathymetric highs in order to

Figure 8 All cores included in this thesis are shown. Yellow circles marks cores retrieved during the HOTRAX and LOMROG expeditions where no age model has been established. The cores with sedimentation rates on the mm/ka, mainly T3 cores (blue triangles), and cores with cm/ka sedimentation rates (green stars) are marked. The few cores from the HOTRAX and LOMROG expeditions with age models are marked with a dark green square for high sedimentation rates and a blue square for low sedimentation rates.
avoid turbidite sequences. No loss or significant extension of the sediment stratigraphy could be identified in any cores, except for a few piston cores that miss the uppermost cm of stratigraphy. The core lengths during the HOTRAX expedition were longer than most previous coring expeditions in the central Arctic Ocean, with an average length of almost 11.5 m. A total of 21 JPC cores were obtained across the entire Arctic Basin along the HOTRAX transect (Darby et al., 2006) (Figure 1). The LOMROG expedition had a smaller coring program focused to some areas of the southern Lomonosov Ridge and Morris Jesup Rise (Figure 1) and recovered 10 PC/GC cores.

Physical properties – Multi-Sensor Core Logger

The Stockholm University Multi-Sensor Core Logger (MSCL) was used to measure bulk density, magnetic susceptibility and p-wave velocity on whole cores. The cores were logged in their plastic liners, in room temperature, according to the method described in the GEOTEK MSCL manual (Geotek, 2004). The principles of logging cores with a MSCL is described by Weber et al. (1997) and by Best and Gunn (1999). Only a brief summary of the logged parameters and MSCL settings applied during the HOTRAX and LOMROG expeditions is provided here. The bulk density is estimated from attenuation of a gamma-ray beam transmitted from a 137Cs gamma source with a 5 mm collimator and a count time of 15 seconds. To calibrate the system, the attenuation of gamma rays through aluminum and water of known density is measured.

No index samples were acquired during the expeditions to determine accurate bulk densities and the bulk density data provided by the MSCL should therefore only be taken as a relative measure of sediment density. The magnetic susceptibility measurements were made with a Bartington loop sensor with a diameter of 12.5 cm for the HOTRAX cores and 10 cm for the LOMROG cores. The p-wave velocity data have not been included in this study. The HOTRAX P-wave measurements suffered from poor data quality due to problems with the sensor.

Core descriptions and photos

After the physical property measurements all HOTRAX and LOMROG cores were split into half-cores. They were then visually described onboard with respect to sedimentology, color (using the Munsell soil color chart), ice rafted debris (IRD) and visual macrofossils. The cores were also photographed with a Nikon D2X digital camera. The LOMROG cores were, in addition, RGB scanned using a Geoscan III 2048 color line scan camera with a Nikon AF Nikkon 50 mm 1:1.8 D objective and Geotek Imaging 2.4 software. The camera scanner acquires a RGB image set to a vertical and horizontal resolution of 100 ppcm. The system was calibrated according to the manual before the logging of each core.

Grain size

The HOTRAX cores HLY0503-18JPC and HLY0503-18TC have been analyzed for grain size variations. The grain size data is used in Papers III, IV and V. Samples for grain size analysis from HLY0503-18TC and JPC were taken continuously from a u-channel in 2 cm thick slices. All samples were freeze dried and about 3 g of sediment was re-suspended overnight on a shaker-table at a speed of 180 r/min. In order to minimize the carbonate dissolution, de-ionized water saturated with pure calcium carbonate (Pro Analysi) was used as the suspension liquid. The samples were put in an ultra-sonic bath for 4 seconds before sieving at 63 µm. The coarse fraction was rinsed in de-ionized water and oven-dried on the sieves at approximately 60°C and subsequently cooled to room temperature in a desiccator before weighing. The remaining fine fraction (<63 µm) was allowed to settle in the beaker for three days, after which the water was removed.

The fine-fraction was re-suspended with calgon (NaPO3) using an ultra sonic bath and a tube vortex as well as agitated with an ultra sonic probe before being further analyzed for the fine fraction size distribution with a Sedigraph 5100. This method is based on the settling velocity principle and measures the concentration of the suspension by the attenuation of an X-ray beam (Bianchi et al., 1999). The Sedigraph recorded the 1-63 µm-fraction, expressed as cumulative mass percent of equivalent spherical diameter. The percentages obtained from the Sedigraph were corrected for the removal of coarse-fractions.
through sieving. After this correction was applied, the mean sortable silt (10-63 µm as defined by McCave et al., 1995), weight % sortable silt and weight % clay (<2 µm) were calculated.

Beryllium isotope analysis

Cores HLY0503-09JPC (Mendeleev Ridge) and HLY0503-14JPC (Alpha Ridge) were sampled for beryllium isotope analyses aiming to obtain age models and sedimentation rates for the cores (Paper II). One-cm thick samples (approximately 5 cc) were taken, in total 11 samples from core HLY0503-09JPC and 20 samples from HLY0503-14JPC. The samples were dried, homogenized, and subjected to an established weak leaching procedure involving hydroxylamine hydrochloride, which was developed to extract seawater-derived trace metal isotope compositions (Bayon et al., 2002; Gutjahr et al., 2007). The method of Gutjahr et al. (2007), as described by Knudsen et al. (2008), was successfully used to extract seawater-derived \(^{10}\text{Be}/^{9}\text{Be}\).

A known amount of a \(^{9}\text{Be}\) carrier (about 1 mg \(^{9}\text{Be}\)) was added to a weighed aliquot of the leached sediment solution to measure the \(^{10}\text{Be}\) concentration by isotope dilution. Further purifications and preparations of the sample leaches were made before the accelerator mass spectrometry (AMS) analyses following a previously established method (Henken-Mellies et al., 1990; Frank et al., 1994). The AMS facility of the Paul Scherrer Institute and the ETH Zürich, Switzerland, carried out the \(^{10}\text{Be}\) analyses. The ICPMS-Laboratory of the Institute of Geosciences, University of Kiel, Germany, measured the natural authigenic \(^{9}\text{Be}\) data using an AGILENT 7500cs ICP-MS instrument following established standard procedures (Garbe-Schönberg, 1993).

**Figure 9** Correlation of magnetic susceptibility data between PC-08 and PS2200 from the Morris Jesup Rise in Correlator v.1.65. The blue line is the unchanged PC-08 data; the purple line to the left and the green line are the adjusted PC-08 curve. The right purple line is the unchanged data of core PS2200 (the log core). The evaluation graph to the right indicates how well the lines correlate at a specific tie point.
Correlation of sediment cores

The sediment cores were correlated using prominent features in the physical property records. Some well correlated cores within a deposition area were combined to create composite records of bulk density and magnetic susceptibility using the software Correlator ver. 1.65 and Sagan. In Correlator and Sagan the physical property records were aligned and projected to a common depth scale (Figure 9). The depths of the tie points used in the correlations are listed in Table 2, Paper VI. The measurements for all successfully correlated cores within an area were averaged to construct the composite bulk density and magnetic susceptibility record. The depth scale for the composite was then adjusted to represent the average depth of all the included cores. These composite physical property records together with a general lithostratigraphy forms a composite stratigraphy for each depositional area.

Principal component analysis

A varimax rotated principal component analysis (PCA) was performed to study the grain size distribution within 1-63 µm from core HLY0503-18 (Paper V). This statistical method identifies independent grain size components that explain the variation in the dataset (Davis, 2002) and was used to compare the grain size spectra between interglacial/interstadial times with glacial/stadial records.

Results – summary of papers

Paper I: Sedimentary regimes in Arctic’s Amerasian and Eurasian Basins: Clues to differences in sedimentation rates

Clark et al. (1980) introduced a lithostratigraphic classification based on sediment cores from primarily the Alpha and Mendeleev ridges. This lithostratigraphy was synthesized from 67 sediment cores retrieved from the ice island T-3 during the years 1963-1973 (Clark et al., 1980). They defined 13 lithostratigraphic units named A to M, which have been used in attempts to correlate sediment cores over large distances in the Amerasian part of the Arctic Ocean (e.g. Minicucci and Clark, 1983; Morris et al., 1985; Scott et al., 1989; Phillips and Grantz, 2001). Strongly linked to this lithologic classification was an age model based on identification of the first down-core paleomagnetic polarity change. This change was assumed by Clark et al. (1980) to represent the Brunhes/Matuyama reversal, presently assigned an age of 781 ka (Lourens et al., 2004). More recent chronostratigraphic studies of cores from the Lomonosov Ridge in the central Arctic Ocean by Jakobsson et al. (2003b) combined Optically Stimulated Luminescence (OSL) dating with biostratigraphy. The results suggest that the previously interpreted Brunhes/Matuyama reversal in central Arctic Ocean cores seems to coincide in time with the Biwa II excursion (220 ka, Lund et al., 2006).

The purpose of the study presented in Paper I was to evaluate if Clark’s lithostratigraphy could be applied to some of the most well studied cores from the Lomonosov Ridge. If such lithostratigraphic correlation can be established between the Alpha and Mendeleev ridges in the Amerasian Basin and the Lomonosov Ridge, it should become clear if there are indeed two different sedimentary regimes in the Arctic Ocean. Furthermore, this would resolve whether or not the first observed down-core magnetic inclination change has been assigned the wrong age in either the recent studies of Lomonosov Ridge cores or in the older studies of Amerasian Basin cores. A solution of this matter would be the first step towards a more robust chronostratigraphic framework for the Arctic Ocean. In the correlation exercise presented in Paper I, the synthesized lithostratigraphy, paleomagnetic inclination, averaged values for coarse fraction and foraminiferal abundances from a selected set of T-3 cores (Clark et al., 1980) and the same proxies for B-8, B-24 (Morris et al., 1985), PS2185-6 (Spielhagen et al., 2004) and 96/12-1pc (Jakobsson et al., 2001) were used.

The synthesized lithostratigraphy by Clark et al. (1980) was, however, not possible to apply in either core 96/12-1pc or PS2185-6. Despite that Clark’s lithostratigraphic units A to M had been applied on core B-8 (Morris et al., 1985), we were not able to establish clear correlation between this core and the T3 records, using the proxies mentioned above. We note that cores B-8 and B-24 are situated near and within the Intra Basin on the Lomonosov Ridge (Björk et al., 2007), where deposition may in places be affected by dynamic current activities and possibly turbidite deposits. The Intra Basin is further discussed in Paper III, IV, and V.

Assuming that the first prominent down-
core paleomagnetic inclination change is a synchronous event in the Arctic Ocean, the average sedimentation rate is 3 to 4 times lower in the Amerasian Basin than on the Lomonosov Ridge. However, if we correlate the clearly distinguished switch from finer to coarser grain size fractions in the Lomonosov Ridge cores, which has been suggested to correspond to the MIS 6/7 boundary (Jakobsson et al., 2001), to a similar, albeit less prominent, change in the average coarse fractions for the Amerasian Basin cores, a two times lower sedimentation rate can be calculated for the Amerasian Basin. A third possible correlation can be made between the base of the lowermost peak of the abundance of foraminiferal tests. This yields sedimentation rates that are approximately 1.3 times lower for the averaged Alpha Ridge cores compared to cores from the Lomonosov Ridge crest. In summary, the results from Paper I primarily show that the standard lithostratigraphy by Clark et al. (1980) could not be applied to any of the Lomonosov Ridge cores, which indicates that there may be significant differences in sediment regimes between the central Amerasian Basin and the Lomonosov Ridge. Our results suggest higher sedimentation rates on the Lomonosov Ridge. None of the three correlation alternatives applied in this paper suggest a difference on the order of a magnitude as previously hypothesized based on the assumed identification of the Brunhes/Matuyama boundary.

Paper II: Pleistocene variations of beryllium isotopes in central Arctic Ocean sediment cores

This paper addresses the problems of dating Arctic Ocean sediment cores and sedimentation rates raised in Paper I. The problem is approached by applying beryllium-10 isotope (\(^{10}\)Be) dating for the first time on cores from the Alpha-Mendeleev ridges. The results required us to also look at how \(^{10}\)Be concentrations and fluxes vary spatially over the Arctic Ocean. \(^{10}\)Be is formed by spallation in the upper atmosphere and has a half-life of 1.51 ± 0.06 Ma (Hofmann et al., 1987). The global average atmospheric production rate of \(^{10}\)Be has been estimated to 1.21 ± 0.26E+6 atoms/cm\(^2\) yr from precipitation collections (Monaghan et al., 1985/86). Precipitation then transports the \(^{10}\)Be to the Earth’s surface. By measuring the concentration of \(^{10}\)Be in accumulated marine sediments, sedimentation rates can be calculated within the Neogene (Amin et al., 1975; Bourlès et al., 1989; Aldahan and Possnert, 2000; Frank et al., 2008). The dilution effect of higher sedimentation rates can be eliminated by normalizing the \(^{10}\)Be with sea-water derived stable isotope \(^{9}\)Be, which is supplied from the continents.

Cores HLY0503-09JPC (09JPC) from the Mendeleev Ridge and HLY0503-14JPC (14JPC) from the Alpha Ridge were sampled for beryllium isotope analysis. To evaluate if there is a spatial variability of \(^{10}\)Be flux in the Arctic Ocean, which will have implications for sedimentation rate calculations, previously published results on \(^{10}\)Be measurements in cores from the Lomonosov Ridge and the Eurasian Basin were included and compared.

An initial average sedimentation rate was calculated by applying an exponential regression through all measured values, which resulted in 2.7 mm/ka for 09JPC and 2.3 mm/ka for 14JPC. The authigenic \(^{9}\)Be from the same leached aliquot was subsequently used to normalize the \(^{10}\)Be to reduce scatter and short-term dilution caused by varying sedimentation rates. After the normalization, a linear regression through all \(^{10}\)Be/\(^{9}\)Be samples yields average sedimentation rates of 1.9 mm/ka and 1.6 mm/ka for 09JP and 14JPC, respectively. To further improve the regression fit to the data, the cores were divided into sections of more similar sedimentation rates. This exercise resulted in that the average sedimentation rates vary between 1.9 mm/ka and 6.9 mm/ka for 09JPC, and between 0.2 mm/ka and 6.8 mm/ka for 14JPC. However, the comparison of concentrations of \(^{10}\)Be in surface sediments suggests consistently lower concentrations in the Amerasian Basin than in the Eurasian Basin.

To further analyze this observation, \(^{10}\)Be fluxes were calculated for the different intervals in the cores. In general, higher fluxes are observed as we move from the Alpha Ridge towards the Lomonosov Ridge and further to the south, with highest average fluxes on the Yermak Plateau in core PS1533. This highlights the fact that the derived ages for cores 09JPC and 14JPC might be affected from the spatial difference in \(^{10}\)Be fluxes over the Arctic Ocean. Furthermore, there is a large discrepancy between the \(^{10}\)Be dates on 09JPC and other dates obtained from amino acid racemization (Polyak et al., 2009) and calcareous nanofossil biostratigraphy (Backman et al., 2009) on nearby correlated core HLY0503-08JPC. We suggest that the spatial variations in \(^{10}\)Be concentrations and flux values are most likely associated with
diminished inflow of Atlantic waters, which contains relatively high \(^{10}\text{Be}\) and \(^{10}\text{Be}/^{9}\text{Be}\), into the deep Arctic Ocean and a reduced input of \(^{10}\text{Be}\) from the shelves during glacial periods. This may have affected the deep Amerasian Basin to a larger extent than the Eurasian. Similarly, \(^{1}\text{Be}\) would even further reduce \(^{10}\text{Be}/^{9}\text{Be}\) ratios. In addition, the perennial sea ice cover may have restricted the amount of \(^{10}\text{Be}\) that can be entrained into the deep Arctic Ocean (Eisenhauer et al., 1994). The longest modern sea ice residence time ( \(\sim 6\) years) occurs within the Beaufort Gyre and this may account for the low concentrations and fluxes in the Amerasian Basin. Consequently the \(^{10}\text{Be}\) decay in sediment stratigraphy cannot be used directly to calculate sedimentation rates in the most severely sea ice covered areas of the Arctic Ocean. If the higher sedimentation rates suggested for 09JPC and 14JPC by other dating methods than \(^{10}\text{Be}\) are confirmed, the Be isotope results presented here provide strong evidence for fundamentally different past environment conditions such as stronger shielding by sea ice and reduced inflow of Atlantic waters.

Paper III: Quaternary Arctic Ocean sea ice variations and deep water isolation times

In this paper, the 185 cm long trigger weight core HLY0503-18TC and the 12.5 m long piston core HLY0503-18JPC (hereafter referred to as 18TC and 18JPC) from the same site in the previously described Intra Basin on the central Lomonosov Ridge is studied with respect to planktic and benthic foraminiferal abundance, carbon and oxygen isotopes, nannofossils, sediment physical properties and grain size. A total of 16 planktic and 6 benthic foraminifer samples were radiocarbon dated at Lund University Radiocarbon Dating Laboratory using a single stage accelerator mass spectrometer and subsequently calibrated using OxCal 4.0 with the Marine04 dataset (Hughen et al., 2004). The calibration curve established by Fairbanks et al. (2005) was used for two samples that yielded ages beyond the capacity of OxCal. Radiocarbon marine reservoir ages for central Arctic Ocean are unknown. Therefore, in the radiocarbon age calibration process, we elaborate with applying different radiocarbon reservoir corrections ranging from 300 to 1400 years. The variations through time of the proxies, e.g. foraminiferal abundance and grain size, are analyzed for these different reservoir age corrections.

The planktic foraminiferal record of core 18TC is exclusively composed of Neogloboquadrina pachyderma, of which 95 % are left coiled. There are five peaks in abundance identified in both planktic and benthic foraminifers, where the largest peak occurs between about 52 and 62 cm. These abundance peaks are interpreted to represent time periods with less sea ice cover. At 45 cm, the highest abundances of calcareous nannofossils in a central Arctic Ocean sediment core are observed. Below this peak the nannofossil assemblage is dominated by Gephyrocapsa muellerae, indicating that this interval is younger than MIS 7. Between 35 and 40 cm, Emiliania huxleyi takes over in dominance, which suggests an age of late MIS 3 (Backman et al., 2009). The Holocene interval begins at about 30 cm and is recognized by an increase of Coccolithus pelagicus and a continuous dominance of E. huxleyi in combination with decreasing amounts of G. muellerae (Gard and Backman, 1990; Gard, 1993). No clear down-core trend could be observed for the stable oxygen isotope record, nor did low foraminiferal abundances correspond to heavier isotope values. However, the high values in the carbon isotope record correspond to higher foraminiferal and nannofossil abundances, implying higher productivity when the open water is present during the summer months. The radiocarbon method produced finite ages down to 32 cm. A comparison between uncalibrated planktic and benthic ages indicates large differences in age between the bottom waters and surface waters. At 28 cm the difference is 1200 years, which then decreases to 250 years in the surface sample.

The application of four different marine reservoir ages to calibrate the \(^{14}\text{C}\) ages resulted in four vertical positions for the Younger Dryas cold event (ca. 11.7-12.8 ka cal BP, Muscheler et al., 2008; Walker et al., 2009). The proposed Younger Dryas intervals were compared to the biostratigraphy to determine the most appropriate marine reservoir age. Using the oldest reservoir age of 1400 years provided the best fit of the Younger Dryas to an interval of low foraminiferal abundance. A correlation of bulk density, magnetic susceptibility and coarse fraction ( \(>63\) \(\mu\)m) between cores 18TC and 18JPC and other cores from the Lomonosov Ridge crest, supports the interpretation that the lowermost foraminiferal peak corresponds to MIS 3, and places MIS 5
between 230 and 280 cm in 18JPC. This result is of importance for the regional stratigraphic work in Paper V and VI. Higher values of mean size of sortable silt (10-63 µm as defined by McCave et al., 1995) correlate to some extent with the foraminiferal peaks. This may represent an environment with more open waters over this part of the Lomonosov Ridge and stronger currents moving through the Intra Basin. The established age model yields sedimentation rates of 1.3 to 3.3 cm/ka for the Holocene and increasing rates for the deglaciation with up to 9.4 cm/ka, which likely reflect a high sediment influx from collapsing ice sheets.

Core 18TC has given us new insights on late glacial and Holocene central Arctic Ocean marine radiocarbon reservoir ages, which are necessary for converting 14C ages to calendar years. The recommendation based on this study is to use a reservoir age of 700 years for the Holocene and 1400 years for the late glacial, although there are likely to be variations within these intervals as well. The decreasing differences in 14C ages between benthic and planktic foraminifers observed may be attributed to changes in the North Atlantic inflow and variations in deep water formation. The foraminiferal abundance records suggest a more favorable environment for primary production during MIS 3 than for the Holocene, possibly due to a reduced sea ice cover. The foraminiferal record also implies that sediments from the Last Glacial Maximum are missing in 18TC, which is consistent with other sediment records from the central Arctic Ocean (Darby, 1997; Nørgaard-Pedersen, 1998; Poore et al., 1999; Polyak et al., 2004).

Paper IV: Predictive relationships between bulk density and grain size in Quaternary sediments from the Lomonosov Ridge

The ability to stratigraphically correlate cores distributed over relatively large distances can help constrain and refine age models for Arctic Ocean cores (O’Regan et al., 2008a; O’Regan et al., 2008b, Paper VI). These correlations are made using lithology driven changes in the physical properties of sediments. Theoretically, the sediment bulk density is a product of the grain density, fluid density and fractional porosity. Grain size variations influence the bulk density through modifications to the porosity. This manuscript quantitatively compares the results from high-resolution grain size analyses with non-destructive bulk density measurements from core HLY0503-18JPC and its associated trigger weight core (TC), and addresses the question of how much of the bulk density is actually dependent of variations in grain size and whether these override the influence of mineralogical changes affecting the grain density.

The cores HLY0503-18JPC/TC were recovered from the Intra Basin on the Lomonosov Ridge at a water depth of 2598 m. An initial assessment of the relationship between bulk density and grain size was made using cross-plots between a set of grain size parameters. The correlation coefficients based on the best fit curves for each of the regressions indicated that 1) there was no correlation between bulk density and the mean sortable silt (10-63 µm), 2) a good power function correlation to weight % sortable silt ($R^2=0.41$), 3) a fairly good logarithmic correlation to the coarse fraction where $R^2=0.35$, and 4) an inverse linear relationship between bulk density and the weight % clay (<2 µm) with the highest $R^2$ value of 0.50. The generally low correlation coefficients produced by the cross plots and the general patterns were significantly improved by removing the downhole effects of compaction on the porosity of the sediments. Once the compaction effects were removed, bulk density and clay content continued to show a strong linear dependence, while coarse fraction content and bulk density exhibited a logarithmic relationship.

To incorporate both the effects of downhole compaction and grain size induced variations in porosity, a multiple regression analysis was run where bulk density was first compared with the clay fraction and depth and then coarse fraction and depth. We forced the equation for the relationship between clay, depth and bulk density to take the form:

$$\rho_b = C_1 + C_2 \times [\text{clay}] + C_3 \log[\text{depth}],$$

and the equation for coarse fraction content, depth and bulk density to be:

$$\rho_b = C_1 + C_2 \log[\text{coarse fraction}] + C_3 \log[\text{depth}].$$

The results show that once porosity reduction, arising from compaction, is adequately accounted for, the observed variations in bulk density primarily reflect changes in weight % clay, with an $R^2$ value of 0.8. The coarse fraction and depth
had an $R^2$ value of 0.71. This provides insights into the nature of downhole variations in bulk density.

**Paper V: Grain size distributions and ice-rafting in the central Arctic Ocean – a million year perspective**

Fluctuations in transport and provenance of ice-rafted debris on geologic timescales, in the Arctic Ocean are traditionally studied by measuring the relative abundance of sand sized material (63-2000 µm), which is largely assumed to be sea ice and iceberg transported (Bischof, 2000). Increasingly, clay and silt sized fractions are being used to identify the provenance of sea ice. The inference that clay and silt is transported to the central Arctic via sea ice is supported by studies of grain size distributions in sea ice. These studies reveal that terrigenous material within sea ice is dominated by clay and silt (<63 µm) (Clark and Hanson, 1983; Nürnberg et al., 1994; Reimnitz et al., 1998; Hebbeln, 2000; Darby et al., 2009). This observation is attributed to the entrainment of fine fraction material during either suspension freezing or anchor ice formation (Reimnitz et al., 1987; Nürnberg et al., 1994). However, the assumption that all clay and silt sized material is carried into the Arctic Ocean via sea ice is largely untested, and there is still a possibility that a significant portion of the fine fraction material may be delivered by intermediate currents and may have a source independent of the surface ice-floes.

To better understand variations in sea ice and ocean circulation during both glacial and interglacial times, we need more detailed investigations into the processes behind sedimentation in the central Arctic Ocean. In this paper, a detailed grain size analysis has been carried out on the HLY0503-18JPC and HLY0503-18TC, recovered from the Intra Basin on the Lomonosov Ridge. Through a close correlation of bulk density records with the nearby ACEX sediments, an age model stretching back to about 1 million years was established that provides a temporal framework for looking at changing sediment dynamics.

A comparison of all the grain size records, the coarse fraction (>63 µm), the sortable silt (10-63 µm), and the clay fraction (<2 µm) reveals a shift in the sedimentary dynamics around the MIS 6/7 boundary. The last two glacial cycles include several intervals with very coarse sediment while earlier glacial periods before MIS 6 are defined by more subtle shifts towards coarser and more abundant silt sized fractions. The coarse grained intervals of the last two glacial stages are similar to grain size spectra assumed to be related to iceberg transport, while the grain size spectra of earlier glacial and interglacial deposits are both consistent with modern and Holocene studies on sea ice deposited sediments (Clark and Hanson, 1983).

A Principal Component Analysis (PCA) was carried out for the 1-63 µm grain size range. The PCA generated three main Factors that explain 73 percent of the variance in the grain size records and that are important for the variance of the grain size distribution. The first Factor has high positive loadings for fine silt and clay, a peak at mid-sized silt dominates the second Factor and the third Factor has positive loadings for the coarse silt fraction. The warm stages are closely linked to positive scores for the first Factor, indicating a larger proportion of fine silt and clay. Factors 2 and 3 both increase during colder periods indicating an enrichment of both medium and coarse grained silt respectively.

We suggest two processes that may explain the shift towards higher coarse and medium grained silt in glacial sediments that pre-date MIS 6: 1) enhanced entrainment of coarse grained material during suspension freezing, or more prolific anchor ice formation, during relative low sea levels during glacial periods and/or 2), a decrease in the amount of fine fraction material associated with current transport occurring during glacial periods, and thus a less diluted sea ice signal being preserved during these times.

**Paper VI: Spatial and temporal Arctic Ocean depositional regimes: a key to the evolution of ice drift and current patterns**

Although the Arctic Ocean is the smallest of all the world oceans the sedimentation environment is highly dynamic both spatially and temporally. Therefore, as described in Paper I, it has not been possible to correlate the Quaternary sediment stratigraphies between the two main basins, the Amerasian and Eurasian basins. However, in some limited areas, sediment cores have been stratigraphically aligned down to sub-decimeter scale changes (e.g. Clark et al., 1980; Backman et al., 2004; Spielhagen et al., 2004; O’Regan et al., 2008a; Adler et al., 2009). Here in Paper VI, we have compared the physical property
records and lithostratigraphies of all piston and gravity cores retrieved during the HOTRAX 2005 and LOMROG 2007 expeditions. Previously collected key cores, from which results have been widely published, were also included in the correlation exercise. A set of physiographic regions are outlined that are characterized by specific sedimentary environments and, thus, correlatable sediment physical properties. These regions are the southern Mendeleev Ridge, the northern Mendeleev Ridge and Alpha Ridge, the Lomonosov Ridge, the Morris Jesup Rise and the Yermak Plateau. The HOTRAX coring sites on the Chukchi Borderland are from areas subjected to glacial ice grounding erosion or sediment reworking, which prevented the establishment of a regional stratigraphy representing this area.

The similarities within each area suggest small variations in sediment transport to the individual coring sites during late Quaternary times. However, since the five composite stratigraphies could not clearly be correlated to each other, the depositional regime in each area must differ in terms of the amount and composition of material received. The characteristics of these different depositional regimes are directly linked to past ice drift and ocean circulation patterns and can contribute to further our understanding of these processes. One of the main aims of Paper VI is to begin develop stratigraphic frameworks for different Arctic Ocean regions in order to facilitate further paleoceanographic studies based on sediment cores. The available age models for Arctic Ocean sediment are frequently revised as a consequence of existing difficulties of dating Arctic Ocean sediment (Backman et al., 2004; Paper II), therefore, identifying stratigraphic units of the same age is especially important for the Arctic Ocean. This Paper VI comprises a synthesis of the Arctic Ocean sediment stratigraphy based on many of the cores studied in the papers included in this thesis, as well as some additional cores and makes use of the results and conclusions presented in Papers I-V.

Discussion

The available age models for the Arctic Ocean vary in quality and, as they are the foundation for any paleoceanographic study, it is important to improve the quality of these models. Cores containing calcareous microfossils have the best age models. Sediment cores closer to the continental shelves generally contain more complete biostratigraphic records than those from the central Arctic Ocean. The relatively low sedimentation rate prevailing in large parts of the Arctic Ocean is another reason why establishing reliable chronostratigraphies have been difficult. The first age models based on paleomagnetic stratigraphies in the Amerasian Basin indicated sedimentation rates as low as mm/ka (Steuerwald et al., 1968; Clark, 1970). This could not be corroborated in the comparison of previously published sediment records from the Alpha-Mendeleev ridges and the Lomonosov Ridge (Paper I). However, the attempts to compare existing age models by correlating Lomonosov Ridge cores to Amerasian Basin cores indicate that these two regions represent two different deposition systems, requiring two separate age models. The three tentative correlations presented in Paper I based on paleomagnetic stratigraphy, coarse fraction and planktic foraminifers, all imply that the sedimentation rates are lower for the Alpha-Mendeleev Ridge than for the Lomonosov Ridge. The difference is probably less than one order of magnitude (mm/ka versus cm/ka), which was originally suggested by Clark et al. (1980) as well as several other authors (e.g. Aksu, 1985; Morris et al., 1985; Spielhagen et al., 1997; Phillips and Grantz, 2001). In summary, the studies included in this thesis do not support that the sedimentation rates in the Amerasian Basin or on the Lomonosov Ridge are as low as initially suggested after the first studies of cores retrieved from drifting ice islands. The results rather support the conclusion by Backman et al. (2004) that the Plio-Pleistocene Arctic Ocean never was a “sediment starved basin” where mm/ka sedimentation rates prevailed.

Even if the sedimentation rates are not on the order of mm/ka year, substantially lower sedimentation seems to have prevailed on the northern Mendeleev Ridge and Alpha Ridge than on the Lomonosov Ridge and the Eurasian Basin. Why? The contribution of sediment laden sea ice to these areas are considered to be somewhat similar (Eicken et al., 2000; Jakobsson, 2002), although the ice drifts in Amerasian and Eurasian Arctic Ocean are dominated by different surface current systems and the included sediments originate from different sources. A compact lid of sea ice over the pre-Holocene Amerasian Basin may have closed off this part of the Arctic Ocean causing the circulation to become stagnant leading to reduced input of sediment from sea ice and rivers. In Paper II, the results suggest generally lower fluxes of


$^{10}$Be over time in the Alpha Ridge region and one explanation for this could be a denser and more shielding sea ice cover in the Beaufort Gyre than in the Transpolar Drift. To establish a correlation between the Amerasian and Eurasian Basin, cores located much closer together than the HOTRAX cores are required. There is a possibility that retrieving sediment cores from the southern Alpha Ridge and the southern Lomonosov Ridge north of Greenland, moving progressively closer to the central parts, may bridge the correlation gap between the Alpha Ridge and the Lomonosov Ridge.

The attempt to directly resolve the problem of dating Arctic sediment by using the decay of the cosmogenic isotope $^{10}$Be did not provide an easy solution (Paper II). Rather, the results point to a difference between the Amerasian Basin, where the method does not seem to work, and the Lomonosov Ridge, where $^{10}$Be decay dating has been successfully applied to the ACEX record (Frank et al., 2008). One explanation for the low amount of $^{10}$Be in Amerasian Basin sediments, in addition to the above mentioned sea ice cover, can be reduced inflow of $^{10}$Be rich Atlantic water to this interior part, which is further away from the Fram Strait. The lower $^{10}$Be flux in the Amerasian Basin may also have been caused by a more solid and extensive sea ice cover, preventing the beryllium isotopes from reaching the seafloor and transporting the isotopes out of the basin. The $^{10}$Be result from the Lomonosov Ridge, dating sediment back to 12.3 Ma (Frank et al., 2008), suggests that the method may be applicable on longer time scales than those recovered from the Alpha and Mendeleev ridges. Age models for Amerasian Basin cores derived by other methods ($^{14}$C ages from planktic foraminifers, amino acid racemization and natural remanent magnetization) suggest relatively high sedimentation rates of a few cm/ka for the southern Mendeleev Ridge (Kaufman et al., 2008; Adler et al., 2009; Polyak et al., 2009). Correlating this record with HOTRAX cores (10JPC, 11JPC and 14JPC) moving north to the Alpha Ridge indicates a decrease in sedimentation rate to 0.3 cm/ka. Although these sedimentation rates suggested for the Alpha Ridge are comparable with the outcome of the $^{10}$Be study, there is a large discrepancy between the Mendeleev Ridge results. As there is no reason to believe that the Alpha Ridge sediment could have received more $^{10}$Be than the Mendeleev Ridge, none of the $^{10}$Be derived age models from this part of the Arctic Ocean can be considered reliable.

However, measurements of natural radionuclides ($^{210}$Pb, $^{226}$Ra, $^{230}$Th) in several of the HOTRAX multi-cores support the very low sedimentation rates (Not et al., 2008). Although, several studies indicate lower sedimentation rates for the Alpha Ridge consistent with the scenario presented by Clark et al. (1980). There is still a pressing need to establish more reliable age models, in particular for the central Amerasian Basin, as the published dating results are not conclusive. For example the variation of the reservoir effect of $^{14}$C through time is not fully understood and the amino acid racemization technique is partially dependent on calibration with some known ages, for example derived from $^{14}$C dating.

The unusually high resolution record of core 18TC from the Intra Basin on the Lomonosov Ridge is ideal for detailed biostratigraphy and $^{14}$C dating (Paper III). This study revealed much older reservoir ages (up to 1400 years) for the central Arctic Ocean when calibrating the $^{14}$C results than those generally applied. This will especially influence chronostratigraphic interpretations of Holocene sediment. The older water masses during glacials may indicate a more stagnant circulation system with a reduced inflow of Atlantic Water, as suggested by the results of the $^{10}$Be study. In addition, a varying amount of formation of deep water by brine rejection could influence the reservoir age. As in paper II, this highlights the necessity of accounting for the sea ice effect as well as environmental differences between the interglacial and glacial modes. The established age model for 18TC revealed a hiatus around the timing of the Last Glacial Maximum (more or less corresponding to MIS 2), which seems to be a fairly wide-spread phenomenon as this has been observed in sediment cores from both sides of the Lomonosov Ridge (Darby, 1997; Nørgaard-Pedersen, 1998; Poore et al., 1999; Polyak et al., 2004). Assuming that this has not been caused by erosion, there must have been a reduction of sediment input during this glacial, at least in the central Arctic Ocean. The $^{14}$C dates together with correlations to nearby cores from the Lomonosov Ridge crest, suggest a MIS 3 age for the oldest foraminiferal and calcareous nannofossils and thus, only MIS 1 and MIS 3 have been preserved in the biostratigraphic record. In contrast, relatively large calcareous planktic foraminiferal abundances in MIS 5.5 and some occurrences in MIS 7 are observed in sediment cores from the approximately 1000 m deep crest of the central part of the Lomonosov Ridge (Jakobsson et al., 2001;
In the ACEX record the oldest planktic foraminiferal peak was attributed to MIS 9 (Cronin et al., 2008). The explanation for this may be that the water masses in the more than 2500 m deep Intra Basin of the Lomonosov Ridge, where 18TC was retrieved, were more acidic than the intermediate water masses at the ridge crest, prior to MIS 3. Unusually high abundances of foraminifers and calcareous nanofossils occur in MIS 3 and can be seen as evidence for more open waters, with higher productivity than the Holocene (MIS 1). Surprisingly, this is not confirmed by results from the nearby Lomonosov Ridge cores and may possibly be the result of a scavenging effect restricted to the Intra Basin. The definition of the MIS1 to 3 in 18TC is important for the studies of this core in Paper IV and V.

Two important aspects to consider from Paper III is that even when we recover a high resolution record, the limited preservation of calcareous biogenic material greatly hampers our ability to establish a robust age model. In order to make use of the all available chronostratigraphic information from an area, correlating physical properties between cores is a commonly used strategy. On the central Lomonosov Ridge, bulk density was used for correlating sediment cores (Paper IV, O’Regan et al., 2008a). The non-linear multiple regression analyses performed on cores 18JPC and 18TC from the Lomonosov Ridge indicate a closer link between bulk density and clay, as opposed to the coarse fraction, once compaction of the sediment was accounted for. The clay content variability in these sediment cores may depend on a combination of the supply of IRD and ocean circulation changes. The uncompacted bulk density record will reflect this variability. The unambiguous correlations based on bulk density among four cores from the Lomonosov Ridge indicate that the sediment source and transportation processes controlling the lithological properties, vary uniformly across glacial and interglacial for at least the later part of the Quaternary and over a distance of at least 150 km.

The origin of the fine fraction material is of interest, as indicated in Paper IV, because differences in provenance of the fine fraction affect the sediment characteristics. The establishment of an age model for core 18 based on results from Paper III and O’Regan et al. (2008a) was necessary for studying the glacial-interglacial variability and evaluating the sedimentation transport to the Intra Basin (Paper V). The observed shift at the MIS 6/7 boundary towards coarser grained material in the cold stages is most likely due to the growth of the Barents-Kara ice sheet (Jakobsson et al., 2001; O’Regan et al., 2008a). Below this boundary iceberg rafted material may not have been a dominating sediment source during glacials. Instead, the grain size record reflects the sea ice variability. The change in the glacial sedimentation regime possibly affected the Eurasian Basin to a larger extent due to its proximity and may not be recorded in Amerasian Basin sediments. The characteristic grain size distribution patterns in the size frequency plots for the warm stages indicate that the interglacial environment has been similar throughout this record, possibly dating back to about 1 Ma. The same can be said for the glacial stages below the MIS 6/7 boundary. The patterns were corroborated in the PCA with warm intervals closely related to the Factor linked to fine silt and clay and the cold intervals were closely connected to the Factor indicating more coarse silt. In comparison to the PCA interpretations by Darby et al. (2009), the fine fraction dominating the warm stages has been transported to the central Lomonosov Ridge by sea ice through suspension freezing. However, a nepheloid transportation of the fine silts and clays cannot be excluded. The increasing fine material input possibly can be a result of the deeper water covering the shelves and/or more vigorous circulation keeping this material in suspension. In contrast, the medium to coarse silt dominating the sediments in the cold intervals may be a result of coarser material being incorporated into the sea ice as an effect of the lower sea level. Another possibility is that less fine grained material can be carried by nepheloid transport if the currents are weakened during glacials, resulting in an apparent increase of the coarse silt content. The main conclusion here is that the dramatic changes in climate between glacial and interglacials lead to similarly major shifts in depositional regimes. This can be observed in both the coarse fraction and fine fraction.

The areas of depositional regimes in Paper VI have been identified based on the sediment lithostratigraphy and physical properties for at least the later part of the Quaternary. However, in some cases one or a few parameters may correlate across the identified regions. For example, the same glacial/interglacial grain size characteristics are observed in core 18JPC/TC from the Lomonosov Ridge (Paper V) as in Amerasian Basin cores (Clark and Hanson, 1983). This indicates that changes in depositional process controlling
Figure 10 a) A summary of the oceanographical, biological and climatological environment in the Arctic Ocean during interglacial or interstadial regimes (Bischof, 2000; Jakobsson et al., 2000, 2008a; Rudels et al., in press).
A summary of the oceanographical, biological and climatological environment in the Arctic Ocean during glacial or stadial regimes (Bischof and Darby, 1997; Bischof, 2000; Jakobsson et al., 2000, 2008a; Adler et al., 2009; Rudels et al., in press). Note that the sea level is below the present day sea level (here presented at 100 m below the present sea level). The main part of the ice rafting is likely to take place during the deglaciation.
grain size are the same on the Lomonosov Ridge and in the Amerasian Basin during interglacials and glacialts, and may only be true for sediment accumulated away from the continental shelves. Furthermore, the surface circulation boundary between the Beaufort Gyre and the Transpolar Drift that goes along and across the Lomonosov Ridge may partly explain why the sediment records cannot be correlated on either side of this boundary. The change in sediment characteristics above and below the MIS 6/7 boundary seen in the bulk density and grain size records (Paper IV and V) is also recognized in Paper VI as the physical properties within the southern Mendeleev Ridge and Lomonosov Ridge are more difficult to align above this boundary and more uniform below. This is an abnormal state as most of the remaining parts of the records correlate well within the deposition regimes. A highly variable sedimentation setting due to the impact of the marine based glaciers on the Barents-Kara shelves may account for this. The sediment properties in each of these unique areas are key to determine temporal and spatial variations in ice transport and ocean circulation patterns.

The ultimate goal for the composite stratigraphies is to form a stratigraphic framework that may help to establish a robust age model for Arctic Ocean sediment. The inferred age models from cores within each depositional regime suggest 1) that the lowest average sedimentation rates of the Arctic Ocean are observed on the northern Mendeleev Ridge and Alpha Ridge, 2) the Morris Jesup Rise and the southern Mendeleev Ridge have intermediate sedimentation rates, 3) the second highest average rate is observed on the Lomonosov Ridge, and 4) the highest rates are observed on the Yermak Plateau (Figure 10 a and b). The lowest sedimentation rates may be explained by a thick and stable sea-ice cap covering these areas, preventing significant sea ice melt and consequently a release of sedimentary material. Furthermore, recent results suggest that the Amerasian Basin hosted large ice shelves during MIS 6 and smaller less extensive ice shelves may have existed also during the later glacial periods (Jakobsson et al., submitted). This may also have a large influence on the sedimentation in the Arctic Ocean.

Conclusions

The initial motivation for this thesis project was to investigate whether reported differences in sedimentation rates for the Amerasian Basin and the Eurasian Basin are real. The results in this thesis support the suggestion that the central part of the Amerasian Basin has generally lower sedimentation rates than the Eurasian Basin. However, the previously reported differences on the order of one magnitude are not supported by the conclusions in this thesis. The results rather point to sedimentation rates of 1-2 cm/ka for the southern Mendeleev Ridge, the Lomonosov Ridge, and the Morris Jesup Rise, and even higher on the Yermak Plateau, whereas on the Alpha Ridge, in the central Amerasian Basin, sedimentation rates may be around 0.5 cm/ka. The main conclusions of the six included papers are:

Paper I

1. The standard lithostratigraphy by Clark et al. (1980) could not be applied to Lomonosov Ridge cores. The initial conclusion from Paper I was that no reliable correlations could be made using the existing data, based on paleomagnetic inclination variability, grain size or foraminifera abundances. Therefore, no definite answer to whether the reported sedimentation rate differences between the Amerasian and Eurasian Basins were real could be made. However, all suggested correlations point to generally lower sedimentation rates in the Amerasian Basin compared to the Eurasian Basin. The outstanding question is perhaps not if, but how much lower. This was further addressed in Papers II and VI.

Paper II

2. Dating sediment cores on the Alpha and Mendeleev ridges using \(^{10}\text{Be}\) decay was not straightforward. This dating method resulted in apparently too old ages for at least the Mendeleev Ridge core and probably also for the Alpha Ridge core. Depending on how the data are divided for statistical regression analysis, sedimentation rates vary from 0.2 to 6.9 mm/ka. The effects of a stable sea ice cover need to be accounted for as this may block the influx of radiogenic \(^{10}\text{Be}\) and was suggested to cause too low \(^{10}\text{Be}\) concentrations in this part of the Arctic Ocean.
3. There is a spatial variability in both the surface concentrations and fluxes of $^{10}\text{Be}$ in the Arctic Ocean. The trends show consistently lower concentrations and fluxes in the Amerasian Basin, with increasing values moving towards the Fram Strait. These variations may be a result of the generally thicker and more stable sea ice cover over the Amerasian Basin.

**Paper III**

4. Unusually high abundance of calcareous nannofossils in MIS 3 of core 18TC from the Lomonosov Ridge Intra Basin indicate comparable ice cover for this stage to the Holocene suggesting substantial inflow of Atlantic Water during these periods. MIS 3 has not previously been observed this prominently in Arctic Ocean cores before and is enriched in calcareous microfossils in the upper 0.65 m.

5. A detailed age for the Holocene and MIS 3 was established based on $^{14}\text{C}$ dating. In comparison with other central Arctic Ocean sediment cores, this Holocene to late glacial record can be considered as a high resolution record. Also, the chronostratigraphic study revealed a hiatus spanning MIS 2 and that the sediments are barren of calcareous biogenic material below MIS 3.

6. The most reliable marine reservoir ages determined in the study of core 18TC were 700 years for the Holocene and 1400 years for the late glacial. These reservoir ages were chosen based on the position of the Younger Dryas cold event in relation to the foraminiferal record. This result is corroborated by the benthic-planktic $^{14}\text{C}$ pairs indicating a decreased difference between the age of the deep water and the surface water of almost 1000 years from the late glacial to the late Holocene.

**Paper IV**

7. Non-linear multiple regression analyses showed that once down-core sediment compaction is accounted for, the primary control on bulk density is the clay fraction content. The total variance of uncompacted bulk density could be explained up to 80 % using the clay fractions, whereas the coarse fraction only explains 71 % of the variability. It is important to note that in both instances the depth is transformed onto a logarithmic scale to account for mechanical compaction processes, while clay content remained linear but coarse fraction also required logarithmic transformation. A more complete analysis of the lithologic changes reflected in the uncompacted bulk density measurements would be achieved by accounting for the varying compression indices of different clay minerals.

8. On the Lomonosov Ridge, where sediments are composed primarily of fine grained terrigenous materials, the clay content can be estimated by non-destructive, uncompacted bulk density measurements. The abundance and composition of clay in the sediment core depends on both the IRD input and the changes in the ocean circulation. The bulk density record will therefore reflect this.

**Paper V**

9. Three grain size distribution patterns characterize sediments on the Lomonosov Ridge. These distributions are linked to deposition during interglacials/interstadials, glacials/stadials post-MIS 6, and glacial/stadials pre-MIS 6. The warm intervals in core 18 were recognized by a peak in the fine silt to clay fraction. The cold stages above the MIS 6/7 boundary, are associated with more coarse sand input than the older glacials. The grain size distribution in these intervals was less sorted with more mid- to coarse sized silt grains. The older glacials/stadials seemed to be an intermediate version of the more extreme patterns observed during the last two glacials and the interglacial cycles, with only slightly coarser grains than the interglacials/interstadials.

10. The PCA identified three main Factors important for explaining the 1-63 µm grain size variances in core 18. The first Factor explains most of the fine silt and clay fraction variability, which was closely related to the interglacial/interstadials intervals. The second Factor is related to the mid-sized silt fraction, which is linked to the cold intervals and inversely connected to the warm stages. Factor 3 is important for explaining the coarse silt fraction and is mostly associated with the colder intervals.

11. The variation in sediment grain sizes between warm and cold stages throughout the core reflects changes in sediment transport processes. In a warm Arctic Ocean climate, fine grained material is generally transported to the central ocean basin, either through suspension freezing
or increased nepheloid transport. The glacials/stadials are characterized by more coarse grained sediment and may be a result of transportation processes such as anchor ice and/or intermittent suspension. Another possibility is that the fine fraction has been removed by current reworking or more likely reduced as an effect of weaker boundary currents and thus, apparently elevating the coarse silt abundance.

**Paper VI**

12. Correlation of sediment cores based on bulk density and magnetic susceptibility is possible across large distances (>500 km) in the Arctic Ocean.

Stratigraphic alignment could be achieved between almost all of HOTRAX cores and the four LOMROG cores. Correlations were also possible to achieve between these and cores retrieved during earlier expeditions. For some cores, physical property features were possible to correlate down to decimeter scales.

13. Six distinct regions of similar late Quaternary sedimentation patterns could be identified in the Arctic Ocean.

These six regions are the Chukchi Borderland, the southern Mendeleev Ridge, the northern Mendeleev Ridge and the Alpha Ridge, the Lomonosov Ridge, the Morris Jesup Rise and the Yermak Plateau. Within each area, except for the ice-eroded Chukchi Borderland, very detailed correlations could be made, however, between the areas no robust correlation using sediment physical properties was possible.

14. Composite stratigraphies based on bulk density, magnetic susceptibility, and lithology could be established for five areas of characteristic sedimentary regimes.

The compilation of all available results for each of these areas will eventually result in better constrained paleoceanographic and paleoclimatic interpretations for the Arctic Ocean.

**Future research**

The Arctic Ocean is still one of the most unexplored oceans, despite the many longer piston and gravity cores retrieved recently. More areas need to be sampled and further stratigraphic analyses are required to better our understanding of the depositional patterns in the Arctic Ocean. Some of the results in this thesis contribute towards solving the problem of dating Arctic Ocean sediment cores. However, no unambiguous solution to the problem has been put forth yet. Cores from the LOMROG 2007 expedition remain to be analyzed in detail and may provide more clues to past depositional variations. In addition, new sediment cores from the central Lomonosov Ridge were recovered this year during the LOMROG II expedition. An especially interesting target area is the southern part of the Lomonosov Ridge off Greenland, which may receives a mixture of material typical for both the Amerasian and Eurasian Basin. Perhaps this area holds the key for correlating across basins. Studying the LOMROG core PC-04 located here would be the first approach. Although, more and longer cores from this region would be useful, preferably along a transect going from the southern Alpha Ridge across to the Amundsen Basin flank of the Lomonosov Ridge.

Detailed grain size studies on more cores from other areas are also of interest. Further investigations of the already analyzed core 14JPC are possible within the near future. Further investigations of the grain size record presented in Paper V may include an attempt to discriminate between ice rafted fine grained material and current sorted material. A detailed grain size analysis for each of the defined depositional regimes may characterize these further. Setting up a new analysis, I would want to include a larger part of the clay spectra to better account for variations in this fraction. For example Darby et al. (2009) analyzed grains down to 0.3 µm).

Although dating of sediment from the Arctic Ocean has proven difficult due to the unique environmental factors, more attempts and a development of existing methods are essential.

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