Quaternary Sedimentation in the Arctic Ocean

RECENT ADVANCES AND FURTHER CHALLENGES

BY LEONID POLYAK AND MARTIN JAKOBSSON

The photo shows a working moment during the 2007 LOMROG (Lomonosov Ridge off Greenland) expedition, where the scientific part was performed from the Swedish icebreaker *Oden* (at the photo's bottom), and breaking heavily ridged ice was aided by the Russian nuclear-powered icebreaker *50 Years of Victory* (on the left). More specifically, this moment was an attempt to salvage the seismic hydrophone streamer jammed in ice.

ABSTRACT. This paper reviews current knowledge of sedimentation patterns in the Arctic Ocean during the pronounced climatic cycles of the last several hundred thousand years, an especially relevant time period that provides long-term context for present climate change. The review is largely based on data collected during recent research icebreaker cruises to the Arctic Ocean, with a focus on the 2005 *Healy-Oden* TransArctic Expedition (HOTRAX) and 2007 Lomonosov Ridge Off Greenland (LOMROG) expedition. The sediment cores and geophysical seafloor mapping data collected enable reconstruction of past oceanic environments. Evaluation of these data suggests that the two major Arctic Ocean circulation systems, the Trans-Polar Drift and the Beaufort Gyre, persisted throughout most of the Late to Middle Quaternary, approximately the last 0.5 to 0.7 million years. Extreme conditions, nonanalogous to modern environments, also occurred in the past, especially during Pleistocene glacial intervals. Some of these intervals likely featured much thickened and/or concentrated sea ice and incursions of ice shelves and armadas of megasized icebergs from the margins to the center of the Arctic Ocean. In contrast, much warmer conditions with reduced sea ice extent existed during interglacial periods. Characterization of ice conditions during these intervals is critical for evaluating the present and projected future reduction of Arctic sea ice.

INTRODUCTION

Seafloor sedimentary records can provide a wealth of information on oceanic environments through different geological times with different climatic conditions. Paleoceanographic studies shed light on past fundamental processes such as ocean circulation, water exchange between ocean basins, biological production, and the marine cryosphere (primarily sea ice). The Arctic Ocean sedimentary archive holds the long-time perspective on sea ice evolution, a component required to understand dramatic Arctic sea ice retreat over the last decades (Figure 1) and projection of its future change (see Polyak et al., 2010, and Jakobsson et al., 2010a, for reviews). However, the history of sedimentation in the Arctic Ocean and even its modern sedimentary processes and patterns are only fragmentarily understood. This limited knowledge is due to a combination of difficulties that include collecting sediment cores and mapping the seafloor in a still perennially ice-bound ocean, and complications with interpreting Arctic sedimentary records, which seem to be intrinsically related to the presence of sea ice cover.

Stratigraphic and sedimentological investigation of Arctic Ocean seafloor sediments began more than 50 years ago when multiple, small-diameter and fairly short sediment cores started to be collected throughout the basin in the 1950s to 1970s—initially from Soviet drifting ice camps and then from their US and Canadian counterparts (see Weber and Roots, 1990, and Stein, 2008, for overviews). However, the mostly small volume and large spacing of sediment-core samples in these early works, combined with laboratory methods cruder than today's, resulted in often confusing results and a lack of stratigraphic coherency.

The new phase of Arctic Ocean research began in the 1980s with the regular use of icebreakers capable of collecting larger-diameter and longer (up to 10–15 m) sediment cores from locations selected based on geophysical mapping (see Stein, 2008, for an overview). The accumulation of this higher-quality core material, together with advances in chronostratigraphic and proxy-based methods, eventually led to the development of a new stratigraphy based on the apparent cyclicity of paleoclimate-related proxies and refinement of paleomagnetic data (Jakobsson et al., 2000). The new approach, largely constraining the last ca. 250,000 years (Marine Isotope Stages [MIS] 1–7), became widely accepted with some variations by all research groups working with Arctic Ocean sediments (e.g., Backman et al., 2004; Spielhagen et al., 2004; Polyak et al., 2004). These developments clearly demonstrated strong variability in Arctic sedimentary environments related to paleoceanographic and climatic fluctuations. At the same time, the new results highlighted the shortcomings of existing sediment-core collections, notably relatively short core length and limited geographic coverage, and the need to further develop stratigraphic correlation, dating tools, and proxy-based paleoclimatic reconstructions. Furthermore, advanced geophysical seafloor surveys, including swath imaging, began to provide evidence for large-scale past events that disrupted normal marine sedimentation, especially impacts related to Arctic Ocean glaciations (Vogt et al., 1994; Jakobsson, 1999; Polyak et al., 2001). These data highlighted the importance of combining more thorough Arctic seafloor mapping with sediment coring in key locations.

This paper presents the major results

of the most recent collection of sediment cores and seafloor mapping data from the Arctic Ocean that have not been covered by earlier review papers. The focus of this review is on sediment-core and geomorphic data that help comprehend Quaternary sedimentary environments pertinent to understanding the trajectory and consequences of the present Arctic change.

RECENT ACHIEVEMENTS

During the last few years, concerns about the abruptness of climate change in the Arctic stimulated advances in the collection of Arctic Ocean sediments (Figure 1). The first development was the ability to conduct scientific drilling in the central Arctic with sea ice present. The Integrated Ocean Drilling Program's Arctic Coring Expedition (ACEX; Backman et al., 2006) recovered the first long Cenozoic sedimentary sequence from the central Arctic Ocean. The recovered core greatly expanded our understanding of Earth's long-term climate evolution and also the Arctic's tectonic, paleogeographic, and climatic settings going back an estimated 56 million years (Moran et al., 2006; Backman and Moran, 2009). The second development was expansion of the geographic coverage of coring programs carried out from research vessels. These programs resulted from coordinated efforts of several research groups that organized expeditions with two icebreakers supporting one another, which offers multiple advantages in severe ice conditions. The two-ship expeditions that constitute the focus of this paper are the 2005 *Healy-Oden* TransArctic Expedition (HOTRAX) and the 2007 Lomonosov Ridge Off Greenland (LOMROG) cruise that collected a plethora of quality cores as well as geophysical seafloor mapping data from vast expanses of the Arctic Ocean, including difficult-to-access, heavily ice-bound waters (Darby et al., 2005; Jakobsson et al., 2008b; Figure 1). Other new high-quality data important for deciphering Quaternary sedimentary environments of the central Arctic Ocean were collected during the 2008 *Polarstern* ARK-XXIII/3 expedition to the Mendeleev Ridge (Stein et al., 2010a,b) and a series of seafloor mapping cruises to the Chukchi Borderland (Mayer, 2003, 2004; Mayer and Armstrong, 2007, 2008).

HOTRAX 2005 was the first completed trans-Arctic crossing conducted for scientific purposes from the Pacific toward the Atlantic, facilitated by coordinated voyages of the US Coast Guard cutter *Healy* and the Swedish icebreaker *Oden* (Figure 2). Twenty-one large-diameter cores up to 15 m in length and accompanying multicore sediment samples and geophysical records were collected from a number of morphological structures across the Arctic Ocean (Figure 1). The focus was to collect data on submarine ridges and plateaus, where sediments are only minimally subjected to redeposition by downslope processes. In addition, eight long cores were raised from a higher-sedimentation continental shelf and slope setting at the Chukchi Alaskan margin. It is important that HOTRAX cores were collected across a wide range of modern sea ice conditions, from nearly open water to heavily ice-covered areas with climatological ice concentrations of almost 90% (Figure 2). This geographic coverage makes the collection especially valuable for reconstructing past ice conditions.

LOMROG 2007 was the first scientific icebreaker expedition to reach the virtually unexplored part of the Arctic Ocean north of Greenland (Figure 1). This area is characterized by the most severe sea ice conditions in the entire Arctic and is projected to be the last to become seasonally ice free in a continued global warming scenario (Wang and Overland, 2009). Except for LOMROG, marine geological, geophysical, and oceanographic research north of Greenland has only been carried out from ice camps established on drifting sea ice, with limited capabilities for collection of sediment cores and geophysical seafloor data (e.g., Nørgaard-Pedersen et al., 2007). LOMROG was a two-ship operation, with the Russian nuclear icebreaker *Fifty Years of Victory* assisting *Oden* in taking sediment cores and mapping the seafloor with its hull-mounted multibeam echosounder and CHIRP sonar subbottom profiler along the expedition route (Figure 2). Ten cores were raised from the southern Lomonosov Ridge and Morris Jessup Rise at sites selected following interpretation of newly acquired geophysical mapping data (Figure 1). The sediment cores retrieved during LOMROG complement and significantly expand the HOTRAX collection. Most important are coring locations with the potential to reveal Arctic Ocean sea ice dynamics. If studies of the LOMROG cores indicate past periods of seasonally ice-free waters north of Greenland, this will indicate the possibility of mostly open-water conditions for the entire Arctic Ocean.

Leonid Polyak *(polyak.1@osu.edu) is Senior Research Scientist, Byrd Polar Research Center, Ohio State University, Columbus, OH, USA.* **Martin Jakobsson** *is Professor, Department of Geological Sciences, Stockholm University, Stockholm, Sweden.*

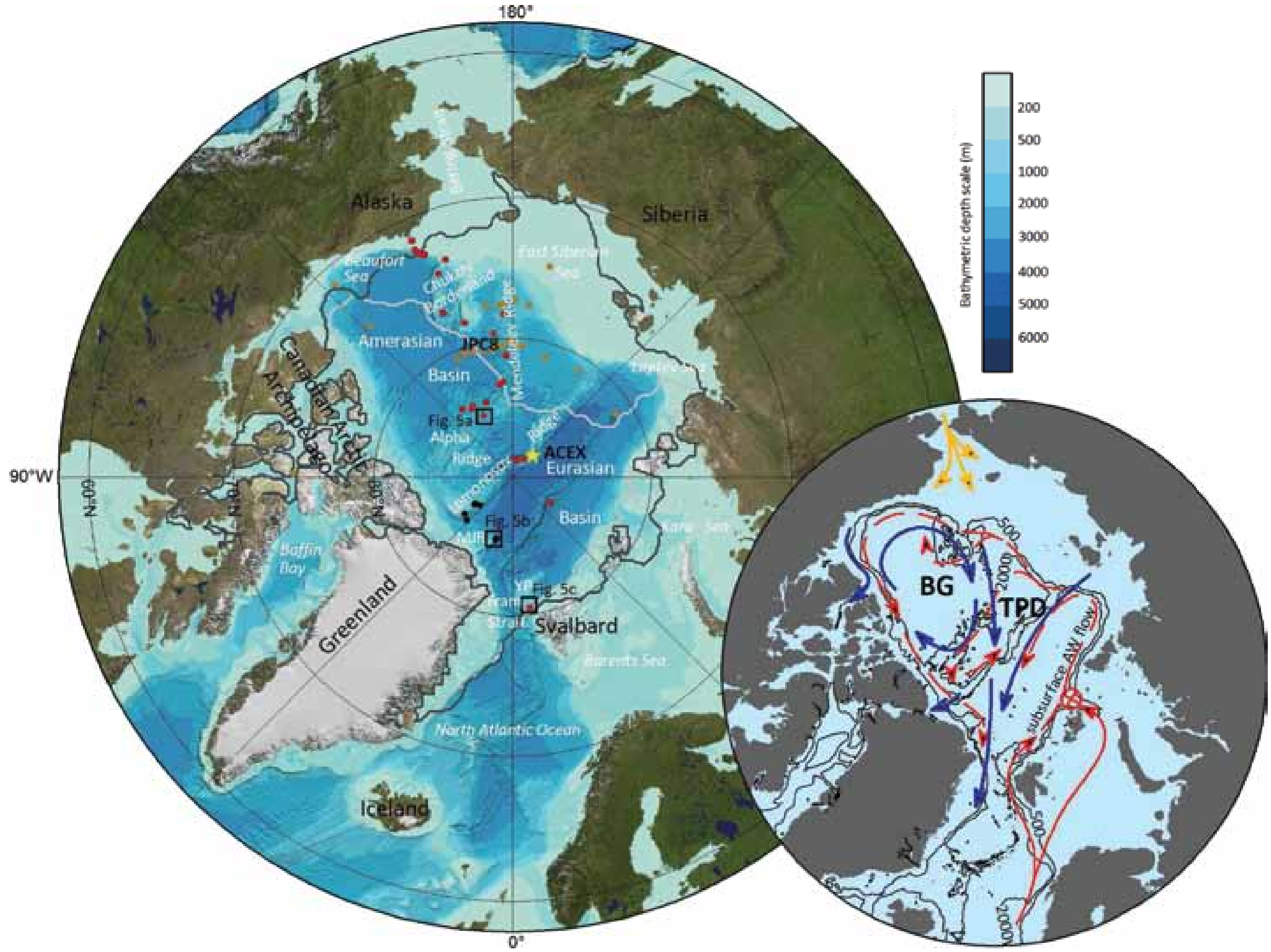


Figure 1. Bathymetric map of the Arctic Ocean (IBCAO-2; Jakobsson et al., 2008a) with key core locations marked (red, black, and orange circles for HOTRAX'05, LOMROG'07, and *Polarstern*'08 cores, respectively) and summer sea ice margins outlined, demonstrating the ongoing ice retreat (dark and light-colored lines for 1987 and 2007, respectively; data courtesy NSIDC). Arrows on the inset show major circulation features: Dark blue = Beaufort Gyre and Trans-Polar Drift circulation systems. Yellow = Pacific water inflow. Solid red = Atlantic water inflow. Dashed red = submerged Atlantic-derived water. (HOTRAX indicates the 2005 *Healy-Oden* TransArctic Expedition, LOMROG the 2007 Lomonosov Ridge Off Greenland expedition, and *Polarstern*'08 the 2008 *Polarstern* ARK-XXIII/3 expedition to the Mendeleev Ridge).

SEDIMENT CORE STRATIGRAPHY AND SEDIMENTARY ENVIRONMENTS

Although age constraints for Arctic Ocean sediments are still tentative, especially for older strata, the general impression is that the age of sediment cores collected during HOTRAX, LOMROG, and comparable cruises generally does not extend to the base of the Quaternary (e.g., Polyak et al., 2009; Sellén et al., 2010; Stein et al., 2010a,b). This result suggests that the cores represent the overall frigid, but vigorously fluctuating climate of the last couple of million years, with large ice sheets growing and waning at the Arctic periphery on multimillennial (Milankovitch) time scales (see Fitzpatrick et al., 2010, and companion papers for an overview). Sea level falls accompanying glaciations repeatedly turned the Arctic Ocean into a much smaller basin, with broad and shallow continental margins exposed or covered by ice sheets, riverine fluxes diminished, and connections to other oceans limited to Fram Strait alone (Figure 1). In fact, the wide and relatively shallow Arctic shelves occupy more than half of the Arctic Ocean area, implying that it was more than 50% smaller during peak glacial times (Jakobsson, 2002).

In addition, during some Quaternary glaciations, the Arctic Ocean probably hosted extensive ice shelves (e.g., Polyak et al., 2001; Jakobsson et al., 2008c, 2010b; Dowdeswell et al., 2010) similar to the present Antarctic ice shelves. Such contrasting environments inevitably affected hydrographic, biotic, and sedimentary conditions in the ocean. Accordingly, sediment records from the

Arctic Ocean are principally composed of cyclically alternating layers with distinct lithological, chemical, and paleobiological characteristics. In a generalized picture, three major sediment types are distinguished, corresponding to interglacial/interstadial, deglacial (iceberg dominated), and full-glacial environments (Jakobsson et al., 2000; Polyak et al., 2004; O'Regan et al., 2008; Adler et al., 2009; Sellén et al., 2010; Stein et al., 2010a,b; Yurco et al., 2010). Alternation of these lithologies and, thus, glacial-interglacial contrast is especially explicit in the western Arctic Ocean (Amerasia Basin), which is more isolated hydrographically due to predominance of the Beaufort Gyre circulation and remoteness from Atlantic influence (Figure 1).

Interglacial (and major interstadial) sediments, including the uppermost Holocene unit, are characterized by a number of proxies such as brownish color due to high manganese content, low L* and high a* color spectral indices (lightness and redness, respectively), low to moderate sand content and bulk density, abundant microfossils (unless dissolved), and generally enriched $\delta^{18}O$ and $\delta^{13}C$ compositions in foraminiferal calcite. Higher biological production inferred from these proxies is consistent with more open ice conditions and/or higher fluxes of biogenic material from continental shelves during warmer periods. The occurrence of

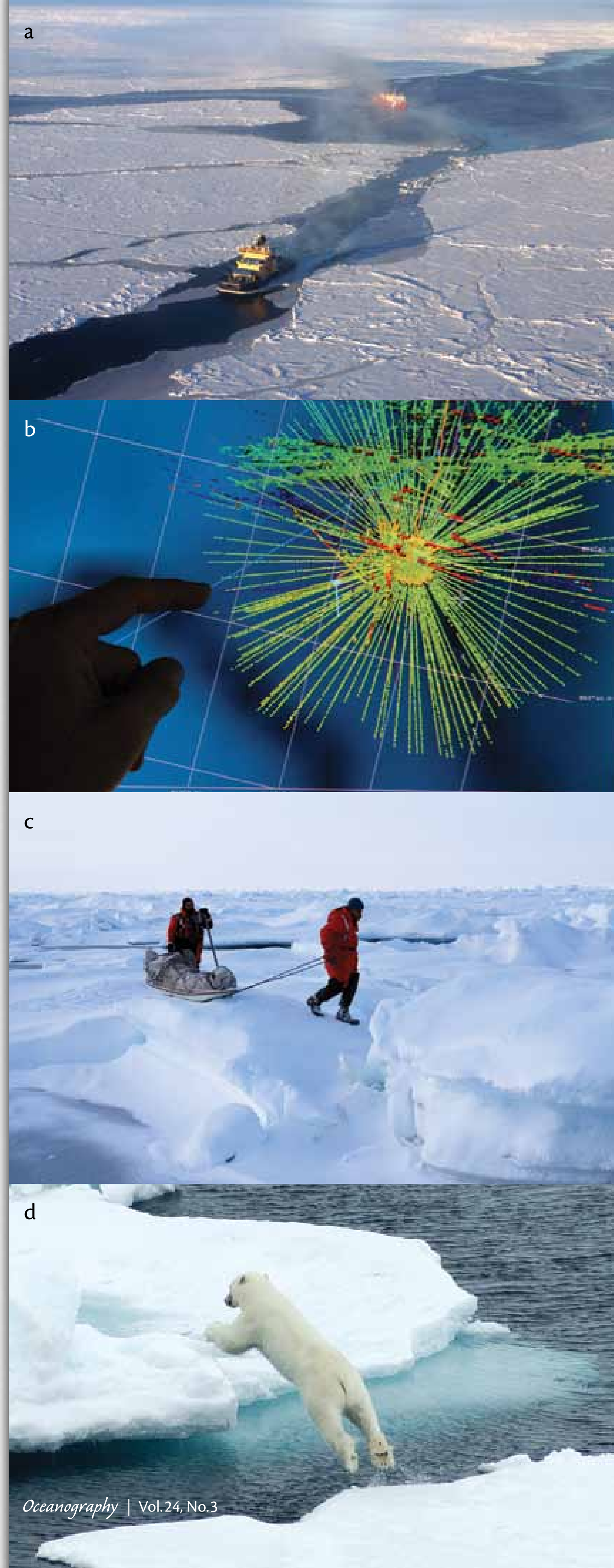


Figure 2. Photographs from the HOTRAX'05 and LOMROG'07 expeditions. (a) Icebreakers *Oden* and *Healy* making their way through ice. (b) "Pirouette technique" of collecting multibeam sonar data in heavy ice conditions in the LOMROG area. (c) Ice sampling party in heavily ridged sea ice near the North Pole. (d) Polar bear jumping across a lead north of Svalbard. *Photographs by M. Jakobsson*

subpolar species in some of these intervals such as the last interglacial (MIS 5e, ca. 130,000 years ago) likely indicates lowest sea ice conditions, especially relevant as paleoclimatic analogs for understanding the current sea ice retreat (Nørgaard-Pedersen et al., 2007; Adler et al., 2009). This proxy, however, needs more investigation for nonanalog conditions such as abundance of subpolar planktonic foraminifers in interstadial MIS 5a (ca. 80,000 years ago), but not in the early Holocene, which is regarded as one of the closest paleoanalogs for modern warming. The use of biogenic proxies is further complicated by common dissolution of fossils with shells of calcium carbonate in sediments older than estimated MIS 7 (ca. 250,000 years ago) or even at younger levels, especially in the eastern Arctic. Nevertheless, identification of warm/low-ice intervals is aided by associated lithological and geochemical proxies such as Mn content and related color indices, ^{10}Be concentrations, and some paleomagnetic parameters (such as kARM/k—magnetic susceptibility proxy for magnetic grain size) (Jakobsson et al., 2000; Spielhagen et al., 2004; Lőwemark et al., 2008; O'Regan et al., 2008; Polyak et al., 2009; Stein et al., 2010a,b; Yurco et al., 2010).

Sediment size and mineralogical composition suggest that interglacial sediments are primarily deposited by melt out from sea ice and may be partially redistributed by near-bottom currents (e.g., Darby et al., 2009; Polyak et al., 2009). Based on the upper portions of cores investigated with reasonably developed stratigraphy to estimated MIS 7, these sediments were deposited at low to moderate sedimentation rates, from several millimeters to 1–2 cm kyr^{-1} (Backman et al., 2004; Polyak et al., 2009; Stein et al., 2010b). The lowest sedimentation rates predictably characterize the central part of the western Arctic Ocean, which is dominated by the Beaufort Gyre circulation system with especially stable, thick sea ice cover. It is important, however, to distinguish between paleoceanographic changes caused by variations in sea ice vs. ice sheets at the Arctic perimeter, which may have similar impacts on sedimentary proxies; for example, higher sea ice conditions and higher glacial inputs both suppress Arctic Ocean biota.

Glacial sediments typically have olive gray to yellowish color with high L* and low a* values, very low numbers of biological and related proxies, and depleted calcite δ^{18}O and δ^{13}C compositions (e.g., Jakobsson et al., 2000; Spielhagen et al., 2004; O'Regan et al., 2008; Adler et al., 2009; Polyak et al., 2009; Stein et al., 2010a,b). Sediments identified as full glacial have fine-grained composition and appear to have especially low depositional rates to a complete hiatus, as constrained by ^{14}C dating for the Last Glacial Maximum (Nørgaard-Pedersen et al., 2003; Polyak et al., 2009; Hanslik et al., 2010). Because of very low sediment deposition, this stratigraphic interval can be elusive and is found mostly in the western Arctic, where it is suggested to originate from glacial flour delivered by meltwater from ice sheet margins, including possible outbursts of subglacial lakes (Adler et al., 2009; Polyak et al., 2009; Yamamoto and Polyak, 2009).

Deglacial intervals stand out by high content of sand and coarser sediment indicative of deposition from icebergs, with elevated sedimentation rates of several centimeters per thousand years. Some of these intervals in the western Arctic, labeled PW (pink-white) layers in the earlier literature (e.g., Clark et al., 1980), have a characteristically high detrital carbonate content, mostly dolomites that can be traced to Canadian Shield rocks (Bischof et al., 1996; Phillips and Grantz, 2001; Polyak et al., 2009; Stein et al., 2010a,b; Yurco et al., 2010). These layers likely indicate catastrophic discharges of icebergs from the Laurentide Ice Sheet, similar to Heinrich events in the North Atlantic, and make useful stratigraphic markers for core correlation across the western Arctic. In the area north of Greenland, some of these layers have a peculiar high-magnesium calcite composition, probably reflecting contributions from proximal sources on Ellesmere Island and Greenland (Nørgaard-Pedersen et al., 2007). A much bigger difference is displayed by iceberg events in the eastern Arctic Ocean (Eurasia Basin including the Eurasian and central segments of the Lomonosov Ridge), which primarily carry material from the Barents-Kara Ice Sheet (e.g., Spielhagen et al., 2004; O'Regan et al., 2008).

Differences in sedimentation patterns between the eastern and western Arctic Ocean are not only reflected in sediment provenance and sedimentation rates but also result in different stratigraphies related to the histories of Eurasian and North American ice sheets. Notably, massive fluxes of sediment from Eurasian icebergs initiated at MIS 6, from ca. 130,000 to 190,000 years ago (Jakobsson et al., 2001; Spielhagen et al., 2004; O'Regan et al., 2008, 2010), when the united Barents-Kara Ice Sheet expanded to the shelf break and began to shed large volumes of icebergs directly into the Arctic Ocean basin (Svendsen et al., 2004). Although the age control for older sediments is still provisional, it is clear that in the western Arctic Ocean, a comparable influx of coarse sediment, originating in this case from North American ice sheets, started several hundred thousand years earlier than MIS 6, possibly at or soon after MIS 16 (Figure 3; Polyak et al., 2009; Stein et al., 2010a,b). This difference indicates that the high sea ice concentration inferred from the low content of coarse ice-rafted debris in the Middle Pleistocene (pre-MIS6) section of ACEX (O'Regan et al., 2010) may be characteristic of the eastern, but not the western, Arctic Ocean. It is notable that the sharp rise in sediment content of Laurentide provenance at or near the onset of the Middle Pleistocene is consistent with the broadly accepted view that the Mid-Pleistocene Transition in Earth's response to orbital variability (Milankovitch cycles) was related to the growth in the volume of the Laurentide Ice Sheet (Clark et al., 2006, and references therein).

The existence of major sedimentological events in Arctic Ocean history, combined with long-range transport by sea ice and icebergs, allows for a correlation of sediment cores across large areas of the seafloor using easy-to-measure proxies such as bulk density and magnetic susceptibility logs (e.g., Sellén et al., 2010). This approach facilitates extensive spatial reconstruction of paleoceanographic and related paleoclimatic conditions using a limited number of reference cores with well-developed age control. However, caution must be taken as different regions of the Arctic Ocean may vary considerably in sedimentary environments, notably, provenance, background sedimentation rates, and local sediment redistribution. Such heterogeneities may mislead correlations and require several lines of evidence from independent proxies. More robust correlations are enabled by the combined use of textural, geochemical, paleobiological, and paleomagnetic data, including unique events such as pronounced swings in paleomagnetic inclination, specific foraminiferal assemblages, and a distinct increase in detrital carbonates with increasing Laurentide fluxes (Spielhagen et al., 2004; Polyak et al., 2009; Stein et al., 2010b). Figure 4 illustrates the distribution of detrital carbonates and estimated average Middle-Late Quaternary sedimentation rates based on these correlations, with new data added from the LOMROG area (Hanslik, 2011). We note that although age estimates are mostly tentative, especially for the older parts of the stratigraphy, they do not affect the relative spatial difference in sedimentation rates. The apparent relationship in geographic patterns of detrital carbonates and long-term sedimentation rates suggests that the Beaufort Gyre circulation and the North American ice sheet impact were predominant factors in the western Arctic Ocean paleoenvironments during most of the Middle-Late Quaternary (last ca. 0.5–0.7 million years).

It must be noted that correlation is especially difficult to achieve between

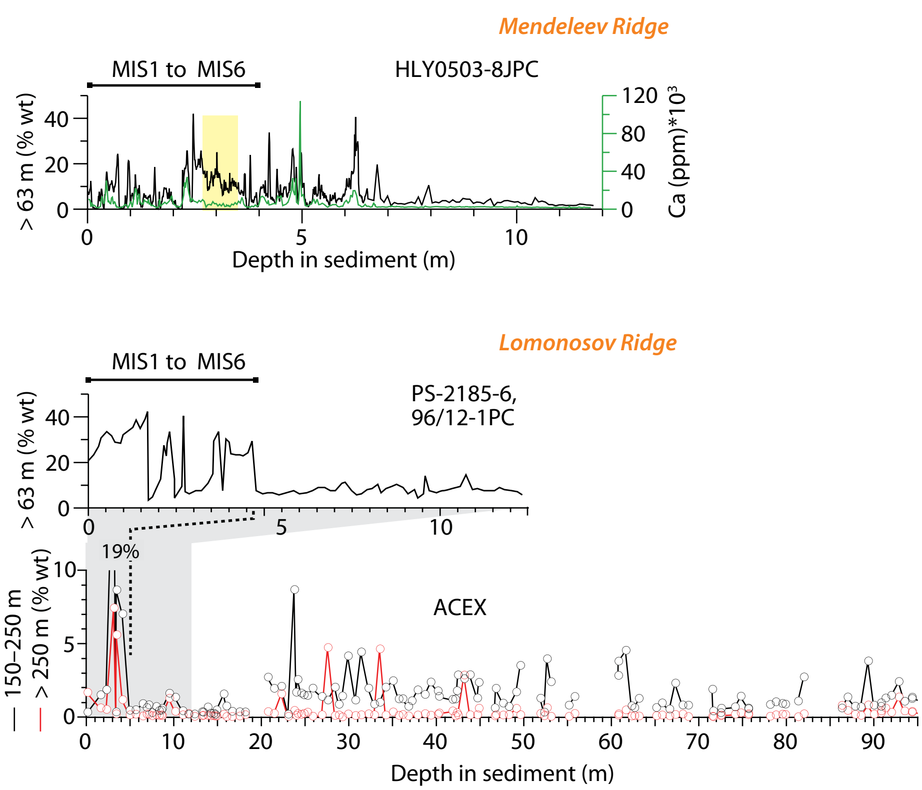


Figure 3. Comparison of sample sediment records from the central Lomonosov Ridge (LR; from O'Regan et al., 2010) and Mendeleev Ridge (MR; Adler et al., 2009; Polyak et al., 2009) exemplifying the Trans-Polar Drift and Beaufort Gyre circulation systems, respectively (Figure 1). LR cores show an abrupt increase of coarse sediment from the Barents-Kara Ice Sheet at Marine Isotope Stage (MIS) 6 (~ 130,000–190,000 years ago), whereas MR and other western Arctic Ocean cores show a much earlier increase in coarse sediment from the North American ice sheets (tentatively bracketed between MIS 12 and 16, ~ 0.5–0.7 million years ago). The latter increase is marked notably by high concentrations of calcium primarily from detrital carbonates, mostly dolomites of Canadian Shield provenance (see also Stein et al., 2010a,b; Yurco et al., 2010). Yellow fill on the MR graph shows slump within MIS 6.

the eastern and western parts of the Arctic Ocean due to principal differences in ocean circulation and sediment provenance, further complicated by severe fossil dissolution in Eurasia Basin sediments. This difference necessitates the development of robust independent age controls for reference records from both basins, a challenging task due to various chronostratigraphic complications in Arctic environments (e.g., Polyak et al., 2009, for an overview) and a virtual lack of long stratigraphic records other than ACEX.

LARGE-SCALE SEDIMENTARY PATTERNS DERIVED FROM SEAFLOOR MAPPING

While sediment cores are undoubtedly critical for proxy-based paleoceanographic studies, the usefulness of a core is limited without knowledge of seafloor processes influencing its sedimentary environments on both local and regional scales. Geophysical mapping, including multibeam swath bathymetry and high-resolution subbottom profiling, will, under most circumstances, provide the much needed spatial context for a sediment core record. For example, geophysical mapping may reveal patterns of sediment erosion and redeposition by currents, glacial processes, or mass wasting—features that are often difficult to identify in a sediment core. Major research icebreakers that currently operate in the Arctic Ocean, such as *Polarstern*, *Healy*, and *Oden*, are each equipped with a modern multibeam echosounder and a subbottom profiler capable of mapping the seafloor morphology and uppermost ~ 30–100 m of sediment stratigraphy in considerable detail (e.g., Mayer and Armstrong, 2007, 2008; Dowdeswell et al., 2010; Jakobsson et al., 2010b; Stein et al., 2010b). The continuing growth of these data combined with earlier, mostly opportunity-based mapping efforts (e.g., Edwards and Coakley, 2003) provides an invaluable asset for comprehending the history of the Arctic Ocean and related climatic changes.

The major types of geomorphic forms on the ocean floor (bedforms) are usually related to erosional and depositional activities of downslope mass-wasting processes and bottom currents (e.g., Figure 5a). In addition, polar areas both in the Arctic and around the Antarctic feature numerous bedforms generated by deep-draft ice. These features include iceberg scours (plowmarks) and glacial sole markings, primarily flutes or megascale lineations, but sometimes also other glacigenic forms such as drumlins and morainic

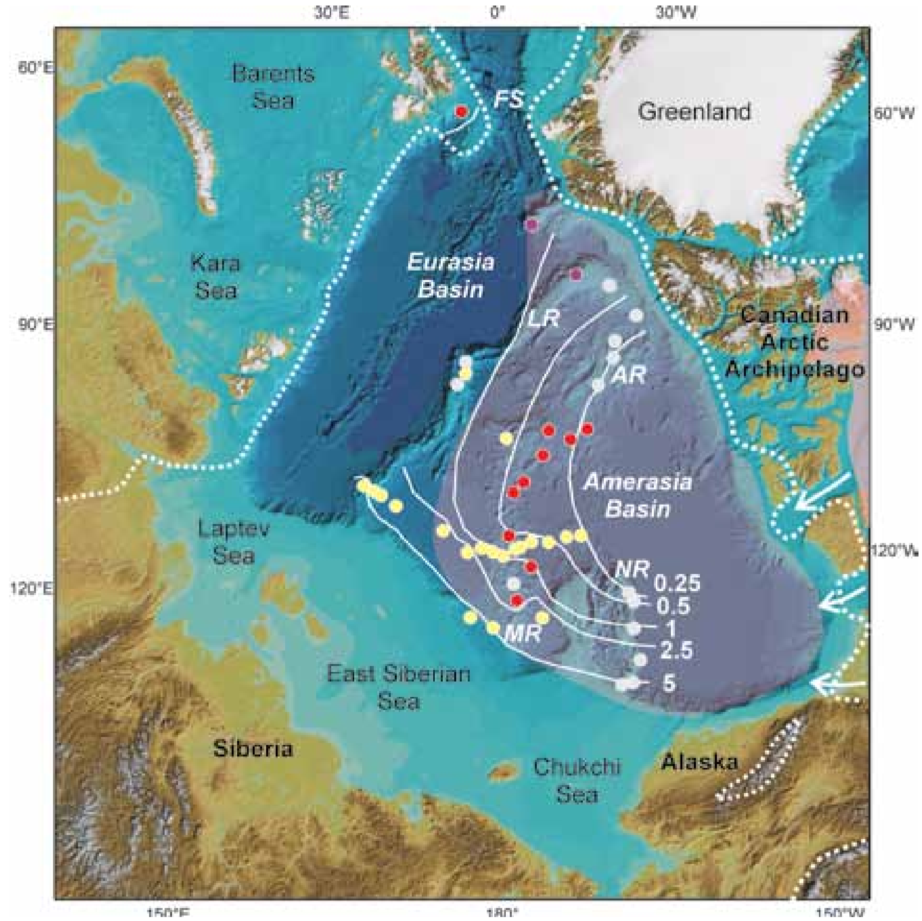
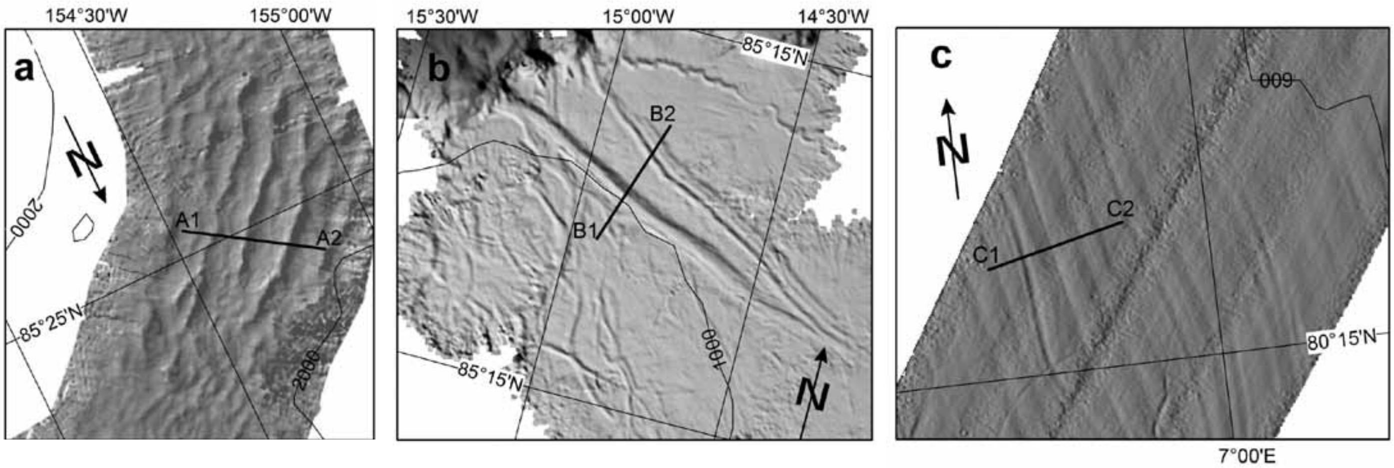


Figure 4. Geographic distribution of detrital carbonates in sediment cores (violet semitransparent fill) and estimated average long-term (Middle-Late Quaternary) sedimentation rates in the western Arctic Ocean (cm kyr^{-1}, white lines). Carbonates in the Amerasia Basin sediments are mostly composed of dolomite (pink semitransparent fill for major provenance), although north of Greenland they also have a significant high-magnesium calcite component. Sedimentation rates are based on age estimates at least to the bottom of MIS 7 (ca. 250,000 years ago) and, where recovered, to the initial peak of high Laurentide sediment inputs (Figure 3). Core sites are shown in red (HOTRAX), violet (LOMROG), yellow (*Polarstern*: Stein et al., 2010b), and grey (other collections). Dotted white lines show reconstructed maximal extent of Pleistocene ice sheets (Dyke et al., 2002; Svendsen et al., 2004); white arrows indicate major ice streams at the northern Laurentide margin. MR, NR, AR, and LR are for Mendeleev, Northwind, Alpha, and Lomonosov Ridges, respectively.



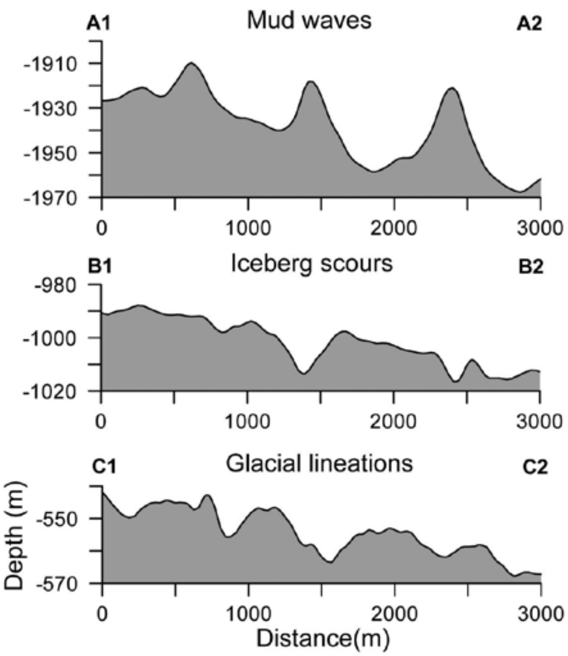


Figure 5. Multibeam sonar images and bathymetric cross sections of megascale seafloor geomorphic features: (a) mud waves in the Alpha Ridge area, (b) iceberg scours on Lomonosov Ridge off Greenland, and (c) glacial lineations on Yermak Plateau (see Figure 1 for locations). Note differences between the three bedform types in both areal and bathymetric cross-section patterns.

ridges (Figure 5b,c; see Jakobsson et al., 2008c). Mapping of these bedforms with multibeam bathymetry or side-scan sonar, combined with stratigraphic studies from subbottom profiler records and sediment cores, allows comprehensive reconstruction of the history of ocean-ice sheet interactions (e.g., Anderson et al., 2002; Ottesen et al., 2005). In the Arctic Ocean, this task is limited by the relatively small number of seafloor areas such as submarine ridges and plateaus with water depths shallow enough to be within the reach of deep-draft ice, that is, not exceeding present depths of ~ 1,000 m (Figure 1). Nevertheless, mapping efforts and related research over the last decade provide a spectacular data set that enables a new level of understanding of the glacial history of the Arctic Ocean and its perimeter.

The most important discovery resulting from Arctic Ocean floor mapping is the consistent evidence of ice grounding on most bathymetric highs shallower than ~ 1,000 m water depth. These features indicate that expansive ice shelves and/or ice rises capped a large part or the entirety of the basin during some of the Pleistocene glaciations (Vogt et al., 1994; Jakobsson, 1999; Polyak et al., 2001, 2007; Jakobsson et al., 2005, 2008c, 2010b; Mayer and Armstrong, 2007, 2008; Engels et al., 2008; Dowdeswell et al., 2010). This extensive ice cover was first suggested for the central Arctic Ocean, when *Oden* mapped a portion of the Lomonosov Ridge with a towed CHIRP subbottom profiler in 1996 (Jakobsson, 1999). Although difficult ice conditions only allowed towing the fragile CHIRP over short stretches, the acquired subbottom profiles revealed a pronounced erosional surface on the ridge crest close to the North Pole. More comprehensive evidence of this erosion was provided in 1999 when the US nuclear submarine USS *Hawkbill* systematically mapped this section of the Lomonosov Ridge using both a CHIRP and a side-scan sonar for detailed imaging of the seafloor surface (SCICEX program; Edwards and Coakley, 2003). Erosion was found to be widespread; eroded sediment had been displaced onto the Amerasian flank of the ridge, and iceberg plowmarks and glacigenic lineations were associated with the eroded surface. Similar data were also collected on this cruise from the Chukchi Borderland

(Chukchi Plateau and Rise and the Northwind Ridge) north of the Alaskan margin. These results demonstrated for the first time the vastness of past glacial invasions into the Arctic Ocean in the form of ice shelves and ice rises, accompanied by armadas of megabergs (Polyak et al., 2001).

During the HOTRAX´05 cruise, *Healy* collected multibeam imagery that confirmed and detailed earlier findings of glacigenic bedforms on the Chukchi Borderland (Jakobsson et al., 2008c). Similarly, during LOMROG, *Oden's* multibeam mapped glacigenic landforms on the Yermak Plateau, Morris Jessup Rise, and Lomonosov Ridge off Greenland (Dowdeswell et al., 2010; Jakobsson et al., 2010b; Figure 5b,c). Glacial landforms on Yermak Plateau as well as ice scours on Morris Jessup Rise were observed previously (Vogt et al., 1994; Kristoffersen et al., 2004; Spielhagen et al., 2004), but the new multibeam bathymetry provided a more comprehensive picture and, in combination with retrieved sediment cores, enabled stratigraphic evaluation of the timing of the glacial impact. Geophysical data combined with stratigraphically constrained cores from HOTRAX, LOMROG, and other expeditions (Vogt et al., 1994; Polyak et al., 2001, 2007; Jakobsson et al. 2001, 2005, 2008c; Engels et al., 2008; Stein et al., 2010b) suggest the possibility of multiple deep-draft erosional events during several glacial intervals. An extensive marine ice sheet complex, probably including ice shelves and ice rises, existed in the Arctic Ocean during MIS 6 at least in the Amerasia Basin (Jakobsson et al., 2010b). This conclusion is consistent with reconstruction of a supersized Barents-Kara Ice Sheet that likely extended all the way to the shelf edge along the entire Barents-Kara and part of the Laptev Sea margin during MIS 6 (Svendsen et al., 2004). The Arctic margin of North American ice sheets predating the Last Glacial Maximum cannot be well constrained from terrestrial studies; more research is needed on the glacial history of the Chukchi Borderland and adjacent North American margin, where sediment stratigraphy indicates at least three episodes of glacial erosion (Polyak et al., 2007; Engels et al., 2008; Jakobsson et al., 2010b).

In contrast to glacigenic markings, which are limited to bathymetric highs, bedforms related to current activities occur over a much broader and deeper depth range. Remarkable mud waves were discovered on Alpha Ridge at four distinctly separate areas along a stretch of 180 km of the HOTRAX track in water depths from 1,900 to 2,300 m (Figures 1, 5). In one area, the mud waves show a pattern of two generations interfering at an oblique angle. Wave heights are between 10 and 50 m, and wave lengths (crest to crest) are between 300 and 1000 m. Buried sediment waves with similar dimensions are known from seismic reflection studies in this area (Hall, 1970), but HOTRAX multibeam data demonstrated for the first time that these features occur on the seafloor surface. Due to the limited data set, notably a lack of high-resolution seismostratigraphy, the origin and age of these mud waves is difficult to constrain, which has given ground to speculative interpretations such as a relationship to a shock wave from an asteroid impact (Kristoffersen et al., 2008). Sediment cores collected in the mud wave area do not show evident signs of erosional events, indicating that they either predated the sediments recovered or were relatively slow and had only a minimal impact on depositional processes. Contour or turbidity currents, the most common agents of deep-sea sediment wave formation (Wynn and Stow, 2002), are not likely for the middle of the Amerasia Basin. The intersecting pattern of wave generations suggests that they may be related to basin-scale tidal processes. Deepwater currents induced from internal tides and internal waves are known to be capable of forming large, kilometer-scale mudwaves on the seafloor (He et al., 2008). Recent observations indicate the likelihood of vertical motions with amplitudes of 10–20 m in the deep Amerasia Basin (Timmermans et al., 2007), and even larger-scale, mega-tidal pumping has been modeled for the Arctic Ocean during glacial periods (Griffiths and Peltier, 2008, 2009).

SUMMARY

This review of recent icebreaker-based, complex, geological/geophysical expeditions to the Arctic Ocean, with a focus on HOTRAX'05 and LOMROG'07, shows that the data collected significantly expand our understanding of sedimentary and related paleoceanographic/paleoclimatic processes during the Quaternary (estimated age limit for sediment cores retrieved). This time interval is especially important for evaluating natural climatic variability, sensitivity, and feedbacks—critical knowledge for understanding present climate change and projecting its future course. Two principal types of data collected are sediment cores and geophysical mapping of the seafloor, including multibeam bathymetry and subbottom profiling. Sediment core records are critical for reconstructing paleoenvironments at a specific location and constraining their ages. Geophysical mapping provides spatial context and can be especially helpful where sedimentation is strongly variable and includes erosional or nondepositional events. Such settings are common in polar areas due to the effects of the marine cryosphere (sea ice, icebergs, and marine portions of ice sheets), including potential blockage of sediment delivery by an ice canopy and direct impact of deep-draft ice on the seafloor.

One principal conclusion from available sediment core data is that the Trans-Polar Drift and the Beaufort Gyre were likely the robust major features of Arctic Ocean circulation throughout the time period covered, estimated to extend to at least the beginning of the Middle Quaternary (ca. 650,000 years ago), possibly excepting glacial maxima. This circulation system resulted in considerably different sedimentary patterns in the eastern and western parts of the Arctic Ocean (roughly corresponding to the Eurasia and Amerasia Basins, respectively). A practical implication of this conclusion is that comprehensive stratigraphies and paleoceanographic histories need to be developed for both basins as no single site can represent the entire Arctic Ocean. Meanwhile, to date, only one long paleoceanographic record (ca. 56 million years, with discontinuities) has been recovered from the central Arctic Ocean.

Despite the inferred general long-term stability of Arctic Ocean circulation, large deviations from historically observed conditions occurred repeatedly during Quaternary climatic fluctuations, driven by Earth's orbital cyclicity. Arctic environments were especially extreme during the major ice ages that were likely characterized not only by much thicker and more solid sea ice cover but also by invasions of vast Pleistocene ice sheets from the margins into the central part of the Arctic Ocean. Although the exact patterns and timing of these ice sheet expansions into the oceanic realm have yet to be investigated, available data reveal erosion and sculpting of submarine ridges and plateaus by ice throughout the ocean at modern water depths reaching ~ 1,000 m. These events were succeeded by episodes of ice sheet disintegration, likely sometimes abrupt, when armadas of icebergs with drafts reaching several hundred meters were ubiquitous in the Arctic Ocean. Icebergs were exceptionally potent agents of sediment delivery to remote corners of the ocean from the areas eroded by ice sheets. This process is exemplified by the dispersal of detrital carbonates from the hinterland of the Canadian Shield into and throughout the western Arctic Ocean. During some interglacial periods, climatic conditions were warmer than at present. These intervals are not yet sufficiently investigated, but some data, such as the abundance of paleobiota, especially the presence of subarctic species, indicate the possibility of considerably reduced sea ice cover. Both cold and warm time extreme events encompassed nonanalog conditions, which must be considered in paleoclimatic modeling. Another aspect of Arctic paleoceanography that requires in-depth investigation is distinguishing impacts of sea ice from those of ice sheets in sedimentary records.

Arctic paleoceanography problems reviewed here help define the priorities and strategies of future data collection and research. One obvious, although very challenging, goal is to drill more long boreholes to characterize the long-time history of the Arctic Ocean. Another objective is to increase the coverage of multibeam seafloor mapping, especially in key areas, such as the sites of ice-shelf grounding, in order to better understand the ocean's geological and paleoclimatic history. Development and refinement of paleoenvironmental proxies is also critical for characterizing past conditions, especially those that can be applied to evaluation of modern climate change. For example, the growing field of biomarker research shows potential for evaluating paleochanges in sea ice (e.g., Belt et al., 2007; Műller et al., 2009) and adjacent terrestrial environments (Cooke et al., 2009). There is also much need for advancement of chronostratigraphic tools for placing Arctic sedimentary records in the global paleoclimatic context.

ACKNOWLEDGMENTS

LP's work on this paper was supported by the US National Science Foundation awards ARC-0806999 and ARC-1003777. MJ's support was received from the Swedish Research Council (VR), the Knut and Alice Wallenberg Foundation, and the Bert Bolin Centre for Climate Research at Stockholm University through a Formas grant. We thank R. Spielhagen and an anonymous reviewer for constructive comments.

REFERENCES

Adler, R.E., L. Polyak, J.D. Ortiz, D.S. Kaufman, J.E.T. Channell, C. Xuan, A.G. Grottoli, E. Sellen, and K.A. Crawford. 2009. Sediment record from the western Arctic Ocean with an improved Late Quaternary age resolution: HOTRAX core HLY0503-8JPC, Mendeleev Ridge. *Global and Planetary Change* 68:18–29, http://dx.doi.org/10.1016/j.gloplacha.2009.03.026.

Anderson, J.B., S.S. Shipp, A.L. Lowe, J.S. Wellner, and A.B. Mosola. 2002. The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: A review. *Quaternary Science Reviews* 21:49–70, http://dx.doi.org/10.1016/S0277-3791(01)00083-X.

Backman, J., M. Jakobsson, R. Løvlie, L. Polyak, and L.A. Febo. 2004. Is the central Arctic Ocean a sediment starved basin? *Quaternary Science Reviews* 23:1,435–1,454, http://dx.doi.org/10.1016/j.quascirev.2003.12.005.

Backman, J., and K. Moran. 2009. Expanding the Cenozoic paleoceanographic record in the Central Arctic Ocean: IODP Expedition 302 Synthesis. *Central European Journal of Geosciences* 1:157–175, http://dx.doi.org/10.2478/v10085-009-0015-6.

Backman, J., K. Moran, D.B. McInroy, L.A. Mayer, and Expedition 302 Scientists. 2006. *Expedition 302 of the Mission-Specific Drilling Platform from and to Tromsø, Norway, Sites M0001–M0004, 7 August 2004–13 September 2004*. Integrated Ocean Drilling Program, Management International Inc., http://dx.doi.org/10.2204/iodp.proc.302.2006.

Belt, S.T., G. Masse, S.J. Rowland, M. Poulin, C. Michel, and B. LeBlanc. 2007. A novel chemical fossil of palaeo sea ice: IP25. *Organic Geochemistry* 38:16–27, http://dx.doi.org/10.1016/j.orggeochem.2006.09.013.

Bischof, J., D.L. Clark, and J. Vincent. 1996. Origin of ice-rafted debris: Pleistocene paleoceanography in the western Arctic Ocean. *Paleoceanography* 11:743–756, http://dx.doi.org/10.1029/96PA02557.

Clark, D.L., R.R. Whitman, K.A. Morgan, and S.D. Mackey. 1980. Stratigraphy and glacial marine sediments of the Amerasian Basin, Central Arctic Ocean. *Geological Society of America Special Paper 181*, 57 pp.

Clark, P.U., D. Archer, D. Pollard, J.D. Blum, J.A. Rial, V. Brovkin, A.C. Mix, N.G. Pisias, and M. Roy. 2006. The middle Pleistocene transition: Characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2. *Quaternary Science Reviews* 25:3,150–3,184, http://dx.doi.org/10.1016/j.quascirev.2006.07.008.

Cooke, M.P., B.E. van Dongen, H.M. Talbot, I. Semiletov, N. Shakhova, L. Guo, and Ö. Gustafsson. 2009. Bacteriohopanepolyol biomarker composition of organic matter exported to the Arctic Ocean by seven of the major Arctic rivers. *Organic Geochemistry* 40:1,151–1,159, http://dx.doi.org/10.1016/j.orggeochem.2009.07.014.

Darby, D., M. Jakobsson, and L. Polyak. 2005. Icebreaker expedition collects key Arctic seafloor and ice data. *Eos, Transactions, American Geophysical Union* 86:549–556, http://dx.doi.org/10.1029/2005EO520001.

Darby, D.A., J.D. Ortiz, L. Polyak, S. Lund, M. Jakobsson, and R.A. Woodgate. 2009. The role of currents and sea ice in both slowly deposited central Arctic and rapidly deposited Chukchi-Alaskan margin sediments. *Global and Planetary Change* 68:58–72, http://dx.doi.org/10.1016/j.gloplacha.2009.02.007.

Dowdeswell, J.A., M. Jakobsson, K.A. Hogan, M. O'Regan, D. Antony, J. Backman, D. Darby, B. Eriksson, D.J.A. Evans, B. Hell, and others. 2010. High-resolution geophysical observations from the Yermak Plateau and northern Svalbard margin: Implications for ice-sheet grounding and deep-keeled icebergs. *Quaternary Science Reviews* 29:3,518–3,531, http://dx.doi.org/10.1016/j.quascirev.2010.06.002.

Dyke, A.S., J.T. Andrews, P.U. Clark, J.H. England, G.H. Miller, J. Shaw, and J.J. Veillette. 2002. The Laurentide and Innuitian Ice Sheets during the Last Glacial Maximum. *Quaternary Science Reviews* 21:9–31, http://dx.doi.org/10.1016/S0277-3791(01)00095-6.

Edwards, M.H., and B.J. Coakley. 2003. SCICEX Investigations of the Arctic Ocean System. *Chemie der Erde* 63:281–328, http://dx.doi.org/10.1078/0009-2819-00039.

Engels, J.L., M.H. Edwards, L. Polyak, and P.D. Johnson. 2008. Seafloor evidence for ice shelf flow across the Alaska/Beaufort margin of the Arctic Ocean. *Earth Surface Processes and Landforms* 33:1,047–1,063, http://dx.doi.org/10.1002/esp.1601.

Fitzpatrick, J.J., R.B. Alley, J. Brigham-Grette, G.H. Miller, L. Polyak, and J.W.C. White. 2010. Arctic paleoclimate synthesis thematic papers: Introduction. *Quaternary Science Reviews* 29:1,674–1,678, http://dx.doi.org/10.1016/j.quascirev.2009.09.016.

Griffiths, S.D., and W.R. Peltier. 2008. Megatides in the Arctic Ocean under glacial conditions. *Geophysical Research Letters* 35, L08605, http://dx.doi.org/10.1029/2008GL033263.

Griffiths, S.D., and W.R. Peltier. 2009. Modeling of polar ocean tides at the Last Glacial Maximum: Amplification, sensitivity, and climatological implications. *Journal of Climate* 22:2,905–2,924, http://dx.doi.org/10.1175/2008JCLI2540.1.

Hall, J.K. 1970. *Arctic Ocean Geophysical Studies: The Alpha Cordillera and Mendeleev Ridge*. Office of Naval Research, Technical Report No. CU-2-70, Washington, DC, 105 pp.

Hanslik, D. 2011. Late Quaternary biostratigraphy and paleoceanography of the central Arctic Ocean. PhD Thesis, Stockholm University.

Hanslik, D., M. Jakobsson, J. Backman, S. Björck, E. Sellén, M. O'Regan, E. Fornaciari, and G. Skog. 2010. Quaternary Arctic Ocean sea ice variations and radiocarbon reservoir age corrections. *Quaternary Science Reviews* 29:3,430–3,441, http://dx.doi.org/10.1016/j.quascirev.2010.06.011.

He, Y., Z. Gao, J. Luo, S. Luo, and X. Liu. 2008. Characteristics of internal-wave and internal-tide deposits and their hydrocarbon potential. *Petroleum Science* 5:37–44, http://dx.doi.org/10.1007/s12182-008-0006-4.

Jakobsson, M. 1999. First high-resolution chirp sonar profiles from the central Arctic Ocean reveal erosion of Lomonosov Ridge sediments. *Marine Geology* 158:111–123, http://dx.doi.org/10.1016/S0025-3227(98)00186-8.

Jakobsson, M., J.V. Gardner, P.R. Vogt, L.A. Mayer, A. Armstrong, J. Backman, R. Brennan, B. Calder, J.K. Hall, and B. Kraft. 2005. Multibeam bathymetric and sediment profiler evidence for ice grounding on the Chukchi Borderland, Arctic Ocean. *Quaternary Research* 63:150–160, http://dx.doi.org/10.1016/j.yqres.2004.12.004.

Jakobsson, M., R. Løvlie, H. Al-Hanbali, E. Arnold, J. Backman, and M. Mörth. 2000. Manganese color cycles in Arctic Ocean sediments constrain Pleistocene chronology. *Geology* 28:23–26, http://dx.doi.org/10.1130/0091-7613(2000)28<23:MACCIA>2.0.CO;2.

Jakobsson, M., R. Løvlie, E.M. Arnold, J. Backman, L. Polyak, J.-O. Knutsen, and E. Musatov. 2001. Pleistocene stratigraphy and paleoenvironmental variation from Lomonosov Ridge sediments, Central Arctic Ocean. *Global and Planetary Change* 31:1–22, http://dx.doi.org/10.1016/S0921-8181(01)00110-2.

Jakobsson, M. 2002. Hypsometry and volume of the Arctic Ocean and its constituent seas. *Geochemistry, Geophysics, Geosystems* 3:1–18, http://dx.doi.org/10.1029/2001GC000302.

Jakobsson, M., R. Macnab, L. Mayer, R. Anderson, M. Edwards, J. Hatzky, H.W. Schenke, and P. Johnson. 2008a. An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses. *Geophysical Research Letters* 35, L07602, http://dx.doi.org/10.1029/2008GL033520.

Jakobsson, M., C. Marcussen, and LOMROG Scientific Party. 2008b. *Lomonosov Ridge off Greenland 2007 (LOMROG): Cruise Report*. Special Publication, Geological Survey of Denmark and Greenland, Copenhagen, Denmark, 122 pp.

Jakobsson, M., L. Polyak, M. Edwards, J. Kleman, and B. Coakley. 2008c. Glacial geomorphology of the Central Arctic Ocean: The Chukchi Borderland and the Lomonosov Ridge. *Earth Surface Processes and Landforms* 33:526–545, http://dx.doi.org/10.1002/esp.1667.

Jakobsson, M., A. Long, Ó. Ingólfsson, K.H. Kjær, and R.F. Spielhagen. 2010a. New insights on Arctic Quaternary climate variability from palaeo-records and numerical modelling. *Quaternary Science Reviews* 29:3,349–3,358, http://dx.doi.org/10.1016/j.quascirev.2010.08.016.

Jakobsson, M., J. Nilsson, M. O'Regan, J. Backman, L. Löwemark, J.A. Dowdeswell, L. Mayer, L. Polyak, F. Colleoni, L. Anderson, and others. 2010b. An Arctic Ocean ice shelf during MIS 6 constrained by new geophysical and geological data. *Quaternary Science Reviews* 29:3,505–3,517, http://dx.doi.org/10.1016/j.quascirev.2010.03.015.

Kristoffersen, Y., B. Coakley, W. Jokat, M. Edwards, H. Brekke, and J. Gjengedal. 2004. Seabed erosion on the Lomonosov Ridge, central Arctic Ocean: A tale of deep draft icebergs in the Eurasia Basin and the influence of Atlantic water inflow on iceberg motion? *Paleoceanography* 19, PA3006, http://dx.doi.org/10.1029/2003PA000985.

Kristoffersen, Y., J.K. Hall, K. Hunkins, J. Ardai, B.J. Coakley, J.R. Hopper, and *Healy* 2005 Seismic Team. 2008. Extensive local seabed disturbance, erosion and mass wasting on Alpha Ridge, Central Arctic Ocean: Possible evidence for an extra-terrestrial impact? *Norwegian Journal of Geology* 88:313–320.

Löwemark, L., M. Jakobsson, M. Mörth, and J. Backman. 2008. Arctic Ocean manganese contents and sediment colour cycles. *Polar Research* 27:105–113.

Mayer, L.A. 2003. *USCGC Icebreaker* Healy *(WAGB-20) US Law of the Sea Cruise to Map the Foot of the Slope and 2500-m Isobath of the US Arctic Ocean Margin. Cruises HE-0302*. Cruise Report, University of New Hampshire, 19 pp.

Mayer, L.A. 2004. *USCGC Icebreaker* Healy *(WAGB-20) US Law of the Sea Cruise to Map the Foot of the Slope and 2500-m Isobath of the US Arctic Ocean Margin. Cruises HE-0405*. Cruise Report, University of New Hampshire, 47 pp.

Mayer, L.A., and A. Armstrong. 2007. *USCGC Icebreaker* Healy *(WAGB-20) US Law of the Sea Cruise to Map the Foot of the Slope and 2500-m Isobath of the US Arctic Ocean Margin. Cruises HE-0703*. Cruise Report, University of New Hampshire, 182 pp.

Mayer, L.A., and A. Armstrong. 2008. *USCGC Icebreaker* Healy *(WAGB-20) U.S. Law of the Sea Cruise to Map the Foot of the Slope and 2500-m Isobath of the US Arctic Ocean Margin. Cruises HE-0805*. Cruise Report, University of New Hampshire, 179 pp.

Moran, K., J. Backman, H. Brinkhuis, S.C. Clemens, T. Cronin, G.R. Dickens, F. Eynaud, J. Gattacceca, M. Jakobsson, R.W. Jordan, and others. 2006. The Cenozoic palaeoenvironment of the Arctic Ocean. *Nature* 441:601–605, http://dx.doi.org/10.1038/nature04800.

Műller, J., G. Masse, R. Stein, and S.T. Belt. 2009. Variability of sea-ice conditions in the Fram Strait over the past 30,000 years. *Nature Geoscience* 2:772–776, http://dx.doi.org/10.1038/ngeo665.

Nørgaard-Pedersen, N., R.F. Spielhagen, H. Erlenkeuser, P.M. Grootes, J. Heinemeier, and J. Knies. 2003. Arctic Ocean during the Last Glacial Maximum: Atlantic and polar domains of surface water mass distribution and ice cover. *Paleoceanography* 18, 1063, http://dx.doi.org/10.1029/2002PA000781.

Nørgaard-Pedersen, N., N. Mikkelsen, and Y. Kristoffersen. 2007. Arctic Ocean record of last two glacial-interglacial cycles off North Greenland/Ellesmere Island: Implications for glacial history. *Marine Geology* 244:93–108.

O'Regan, M., J. King, J. Backman, M. Jakobsson, H. Pälike, K. Moran, C. Heil, T. Sakamoto, T.M. Cronin, and R. Jordan. 2008. Constraints on the Pleistocene chronology of sediments from the Lomonosov Ridge. *Paleoceanography* 23, PA1S19, http://dx.doi.org/10.1029/2007PA001551.

O'Regan, M., K. St. John, K. Moran, J. Backman, J. King, B.A. Haley, M. Jakobsson, M. Frank, and U. Röhl. 2010. Plio-Pleistocene trends in ice rafted debris on the Lomonosov Ridge. *Quaternary International* 219:168–176.

Ottesen, D., J.A. Dowdeswell, and L. Rise. 2005. Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2500-km-long Norwegian-Svalbard margin (57°–80°N). *Geological Society of America Bulletin* 117:1,033–1,050, http://dx.doi.org/10.1130/B25577.1.

Phillips, R.L., and A. Grantz. 2001. Regional variations in provenance and abundance of ice rafted clasts in Arctic Ocean sediments: Implications for the configuration of late Quaternary oceanic and atmospheric circulation in the Arctic. *Marine Geology* 172:91–115, http://dx.doi.org/10.1016/S0025-3227(00)00101-8.

Polyak, L., R.B. Alley, J.T. Andrews, J. Brigham-Grette, T.M. Cronin, D.A. Darby, A.S. Dyke, J.J. Fitzpatrick, S. Funder, M. Holland, and others. 2010. History of sea ice in the Arctic. *Quaternary Science Reviews* 29:1,757–1,778, http://dx.doi.org/10.1016/j.quascirev.2010.02.010.

Polyak, L., J. Bischof, J.D. Ortiz, D.A. Darby, J.E.T. Channell, C. Xuan, D.S. Kaufman, R. Løvlie, D.A. Schneider, D.D. Eberl, and others. 2009. Late Quaternary stratigraphy and sedimentation patterns in the western Arctic Ocean. *Global and Planetary Change* 68:5–17, http://dx.doi.org/10.1016/j.gloplacha.2009.03.014.

Polyak, L., W.B. Curry, D.A. Darby, J. Bischof, and T.M. Cronin. 2004. Contrasting glacial/interglacial regimes in the western Arctic Ocean as exemplified by a sedimentary record from the Mendeleev Ridge. *Palaeogeography, Palaeoclimatology, Palaeoecology* 203:73–93, http://dx.doi.org/10.1016/S0031-0182(03)00661-8.

Polyak, L., D.A. Darby, J. Bischof, and M. Jakobsson. 2007. Stratigraphic constraints on late Pleistocene glacial erosion and deglaciation of the Chukchi margin, Arctic Ocean. *Quaternary Research* 67:234–245, http://dx.doi.org/10.1016/j.yqres.2006.08.001.

Polyak, L., M.H. Edwards, B.J. Coakley, and M. Jakobsson. 2001. Ice shelves in the Pleistocene Arctic Ocean inferred from glaciogenic deep-sea bedforms. *Nature* 410:453–459, http://dx.doi.org/10.1038/35068536.

Sellén, E., M. Jakobsson, and M. O'Regan. 2010. Spatial and temporal Arctic Ocean depositional regimes: A key to the evolution of ice drift and current patterns. *Quaternary Science Reviews* 29:3,644–3,664, http://dx.doi.org/10.1016/j.quascirev.2010.06.005.

Spielhagen, R., K. Baumann, H. Erlenkeuser, N. Nowaczyk, N. Nørgaard-Pedersen, C. Vogt, and D. Weiel. 2004. Arctic Ocean deep-sea record of northern Eurasian ice sheet history. *Quaternary Science Reviews* 23:1,455–1,483, http://dx.doi.org/10.1016/j.quascirev.2003.12.015.

Stein, R. 2008. *Arctic Ocean Sediments: Processes, Proxies, and Paleoenvironment*. Elsevier, Amsterdam, 592 pp.

Stein, R., J. Matthiessen, and F. Niessen. 2010a. Re-coring at Ice Island T3 site of key core FL-224 (Nautilus Basin, Amerasian Arctic): Sediment characteristics and stratigraphic framework. *Polarforschung* 79:81–96.

Stein, R., J. Matthiessen, F. Niessen, A. Krylov, S. Nam, E. Bazhenova, and Shipboard Geology Group. 2010b. Towards a better (litho-) stratigraphy and reconstruction of Quaternary paleoenvironment in the Amerasian Basin (Arctic Ocean). *Polarforschung* 79:97–121.

Svendsen, J.I., H. Alexanderson, V.I. Astakhov, I. Demidov, J.A. Dowdeswell, S. Funder, V. Gataullin, M. Henriksen, C. Hjort, M. Houmark-Nielsen, and others. 2004. Late Quaternary ice sheet history of northern Eurasia. *Quaternary Science Reviews* 23:1,229–1,271, http://dx.doi.org/10.1016/j.quascirev.2003.12.008.

Timmermans, M.-L., H. Melling, and L. Rainville. 2007. Dynamics in the deep Canada Basin, Arctic Ocean, inferred by thermistor chain time series. *Journal of Physical Oceanography* 37:1,066–1,076, http://dx.doi.org/10.1175/JPO3032.1.

Vogt, P.R., K. Crane, and E. Sundvor. 1994. Deep Pleistocene iceberg plowmarks on the Yermak Plateau: Sidescan and 3.5 kHz evidence for thick calving ice fronts and a possible marine ice sheet in the Arctic Ocean. *Geology* 22:403–406, http://dx.doi.org/10.1130/0091-7613(1994)022<0403:DPIPOT>2.3.CO;2.

Wang, M., and J.E. Overland. 2009. A sea ice free summer Arctic within 30 years? *Geophysical Research Letters* 36, L07502, http://dx.doi.org/10.1029/2009GL037820.

Weber, J.R., and E.F. Roots. 1990. Historical background: Exploration, concepts, and observations. Pp. 5–36 in *The Arctic Ocean Region*. A. Grantz, G.L. Johnson, and J.F. Sweeney, eds, The Geology of North America, vol. L, Geological Society of America, Boulder.

Wynn, R.B., and D.A.V. Stow. 2002. Classification and characterisation of deep-water sediment waves. *Marine Geology* 192:7–22, http://dx.doi.org/10.1016/S0025-3227(02)00547-9.

Yamamoto, M., and L. Polyak. 2009. Changes in terrestrial organic matter input to the Mendeleev Ridge, western Arctic Ocean, during the Late Quaternary. *Global and Planetary Change* 68:30–37, http://dx.doi.org/10.1016/j.gloplacha.2009.03.012.

Yurco, L.N., J.D. Ortiz, L. Polyak, D.A. Darby, and K.A. Crawford. 2010. Clay mineral cycles identified by diffuse spectral reflectance in Quaternary sediments from the Northwind Ridge: Implications for glacial-interglacial sedimentation patterns in the Arctic Ocean. *Polar Research* 29:176–197, http://dx.doi.org/10.1111/j.1751-8369.2010.00160.x.