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Quaternary history of sea ice in the western Arctic Ocean based on foraminifera

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ABSTRACT

Sediment cores from the Northwind Ridge, western Arctic Ocean, including uniquely preserved calcareous microfossils, provide the first continuous proxy record of sea ice in the Arctic Ocean encompassing more than half of the Quaternary. The cores were investigated for foraminiferal assemblages along with coarse grain size and bulk chemical composition. By combination of glacial cycles and unique events reflected in the stratigraphy, the age of the foraminiferal record was estimated as ca 1.5 Ma. Foraminiferal abundances, diversity, and composition of benthic assemblages, especially phytodetritus and polar species, were used as proxies for sea-ice conditions. Foraminiferal Assemblage Zone 2 in the Lower Pleistocene indicates diminished, mostly seasonal sea ice, probably facilitated by enhanced inflow of Pacific waters. A gradual decrease in ice-free season with episodes of abrupt ice expansion is interpreted for the Mid-Pleistocene Transition, consistent with climatic cooling and ice-sheet growth in the Northern Hemisphere. A principal faunal and sedimentary turnover occurred near the Early–Middle Pleistocene boundary ca 0.75 Ma, with mostly perennial sea ice indicated by the overlying Assemblage Zone 1. Two steps of further increase in sea-ice coverage are inferred from foraminiferal assemblage changes in the "Glacial" Pleistocene by ca 0.4 and 0.24 Ma, possibly related to hemispheric (Mid-Brunhes Event) and Laurentide ice sheet growth, respectively. These results suggest that year-round ice in the western Arctic was a norm for the last several 100 ka, in contrast to rapidly disappearing summer ice today.

1. Introduction

As global climate conditions continue to shift toward a warmer planet, the Arctic Ocean is becoming increasingly vulnerable to warming and its associated effects, due to a set of positive feedbacks regarded as Arctic Amplification (Serreze and Barry, 2011). Sea ice is an integral factor that determines the magnitude of these feedbacks including the albedo in summer and insulation in winter. Knowledge of paleo-ice conditions is essential for understanding the trajectory of rapid retreat of sea ice in the Arctic (e.g., Stroeve et al., 2011) and related climatic and hydrographic changes affecting the global thermohaline circulation (Rashid et al., 2011).

Reconstruction of sea-ice extent in the Arctic is complicated by the lack of any one unequivocal proxy, and is further complicated by very low sedimentation rates and biogenic content in the areas of high sea-ice coverage (e.g., Polyak et al., 2010). Not surprisingly, reconstructions of paleo sea ice are being developed for marginal-ice areas such as the Fram Strait (Müller et al., 2009, 2012; Bonnet et al., 2010; Spielhagen et al., 2011), but not for the central parts of the Arctic Ocean.

This paper aims to reconstruct Quaternary sea-ice conditions in the western Arctic based on a foraminiferal record from the Northwind Ridge, western Arctic Ocean (Fig. 1), where modern sea-ice retreat is especially pronounced (Stroeve et al., 2011). Unlike most sediment cores from the Arctic Ocean, where calcareous material is preserved only in the Late and, partially, Middle Pleistocene (e.g., Jakobsson et al., 2001; Spielhagen et al., 2004; Polyak et al., 2009; Stein et al., 2010), the record under study has abundant calcareous microfossils going back into the Early Pleistocene, estimated ca 1.5 Ma. Pronounced changes in benthic foraminiferal assemblages, along with lithostratigraphic proxies, allow for the first-time characterization of the Quaternary history of sea ice in the western Arctic Ocean, the most ice-covered oceanic region of the world.

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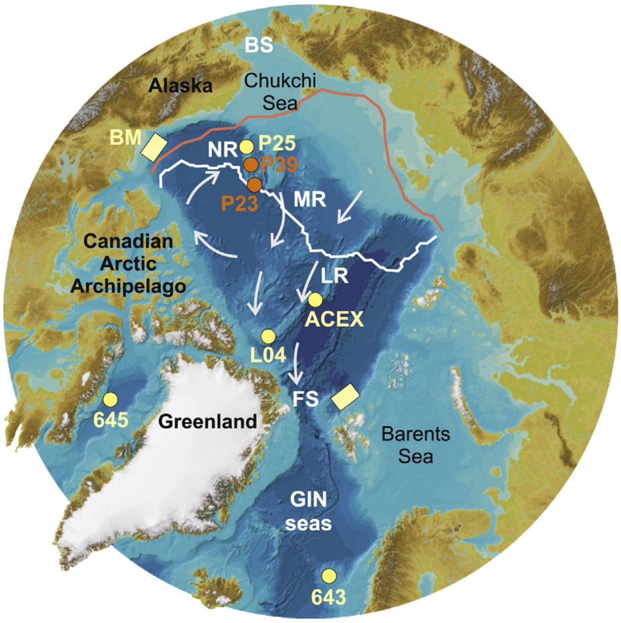

Fig. 1. Index map with location of cores P23 and P39 (red circles) and other sites discussed in the paper (yellow circles). Arrows show Transpolar Drift and Beaufort Gyre circulation. Pink line – climatological late-20th century summer ice extent (15% concentration), white line – 2007 summer ice extent (historical minimum). Yellow boxes – sites of earlier paleo-sea-ice studies based on benthic foraminifers. NR, MR, and LR – Northwind, Mendeleev, and Lomonosov ridges, respectively. FS and BS – Fram and Bering straits. BM – Beaufort–Mackenzie area. GIN seas – Greenland–Iceland–Norwegian seas.

2. Paleoceanographic context

A cyclic character of lithological, geochemical, and paleobiological proxy changes has been identified from recent detailed studies of sediment cores from various parts of the Arctic Ocean (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., 2010). Although not all proxies are completely deciphered, the general interpretation recognizes that these changes have been caused by alternation of full-glacial, deglacial (iceberg dominated), and interglacial/major interstadial environments of the Late to Middle Quaternary. Glacial–interglacial contrasts are most pronounced in the hydrographically more isolated western Arctic Ocean due to its remoteness from the deep-water connection with the Atlantic and the gyre-type surface circulation (Beaufort Gyre) (Polyak and Jakobsson, 2011). Early Pleistocene to pre-Quaternary history of the Arctic Ocean has been partially investigated only in the ACEX deep borehole (Fig. 1) representing the Transpolar Drift-dominated environments and suffering from poor preservation of paleontological remains (Backman et al., 2006; O'Regan et al., 2008).

Despite a generally robust identification of glacial–interglacial cyclicity, changes in associated sea-ice conditions in the Arctic Ocean remain mostly unassessed. A notable exception is an elevated occurrence of subpolar planktonic foraminifers at some stratigraphic intervals including the estimated Last Interglacial (Nørgaard-Pedersen et al., 2007; Adler et al., 2009). Although more understanding is needed for the distribution of these foraminifers (local blooms vs. long-distance transport by currents, selective preservation, etc) and for the accurate age of these events, they clearly show the potential of paleobiological proxies for representing sea-ice conditions. In this study we capitalize on the stratigraphically longest calcareous foraminiferal record recovered thus far from the Arctic Ocean to gain insights into sea-ice history in the western Arctic. We especially focus on benthic foraminifers that have been thus far underutilized as paleo-sea ice proxies due to preservation and counting size issues (e.g., Cronin et al., 2008; Scott et al., 2008) and perennial sea ice predominance in recent Arctic history, which complicates identification of proxies related to lower ice extent.

3. Materials and methods

Piston cores 92AR-P39 and 93AR-P23 (hereafter referred to as P39 and P23) were collected on the 1992 and 1993 U.S. Geological Survey P1 cruises from the Northwind Ridge extending from the Chukchi Sea margin to the interior of the western Arctic Ocean (Fig. 1; Table 1). Both core sites are bathed by the Upper Polar Deep Water, with shallower P23 site being close to the lower boundary of the Arctic Atlantic Water (Rudels, 2009). The summer sea-ice margin was located south of the ridge in climatological data, but shifted to its northern edge in recent years (e.g., Stroeve et al., 2011), which makes the Northwind Ridge an area of choice for studying the history of sea ice in the western Arctic.

Two samples from core P23 investigated by Mullen and McNeil (1995) contained calcareous benthic foraminifers that had similarity to pre-Quaternary (Pliocene to Late Miocene) fauna from the Beaufort–Mackenzie Basin of Arctic Canada. However, stratigraphic and paleoceanographic context for this core remained uninvestigated. To test the earlier assessment of foraminiferal assemblages and utilize them for evaluating paleo-environments, we have performed a detailed study of core P23 along with P39 collected farther south on the Northwind Ridge (Fig. 1). Due to its more southern location, P39 represents overall lower long-term ice cover resulting in higher sedimentation rates and, thus, a higher-resolution record (Polyak et al., 2009; Crawford, 2010). Difference in water depths may also contribute to varying sedimentation rates as P23 site at the ridge top is more likely affected by currents.

Upon collection, cores have been stored in a refrigerated facility (USGS Menlo Park) and, other than partially drying out, remained in a very good condition. Due to a negligible amount of labile organic matter and strong oxic conditions on the central Arctic Ocean floor (e.g., Stein and Macdonald, 2004), carbonaceous material in these sediments is minimally affected by diagenetic dissolution caused by post-collection oxidation (unlike sediments from the continental margins). Cores have been sampled on several occasions for various analyses including discrete and u-channel samples. Earlier litho- and magnetostratigraphic results on a series of cores from the western Arctic Ocean including P23 and P39 have been described in Polyak et al. (2009). To detail earlier bulk chemical composition XRF measurements spaced at 2–6 cm, u-channels from core P23 were analyzed with the 0.5 cm resolution on the Itrax XRF scanner at the INRS-ETE (Quebec City). Foraminiferal counts along with coarse (>63 μm) grain content measurements were done at the Byrd Polar Research Center, with samples mostly taken at 2-cm intervals from subsections cut along the core length. Total planktonic and calcareous benthic foraminifers >150 μm were counted in almost all samples collected (Fig. 2; Suppl. 1), with sparser intervals in the unfossiliferous lower part of P39. Detailed counts of benthic foraminifers in 63–125 and >125 μm size fractions were primarily

Table 1
Sediment core information.

Core ##	Latitude N	Longitude W	Water depth (m)	Core length (cm)	Core diameter (cm)
P1-92AR-P39	75° 50.7′	156° 01.9′	1470	687	8
P1-93AR-P23	76° 57.3′	155° 03.9′	951	572	8

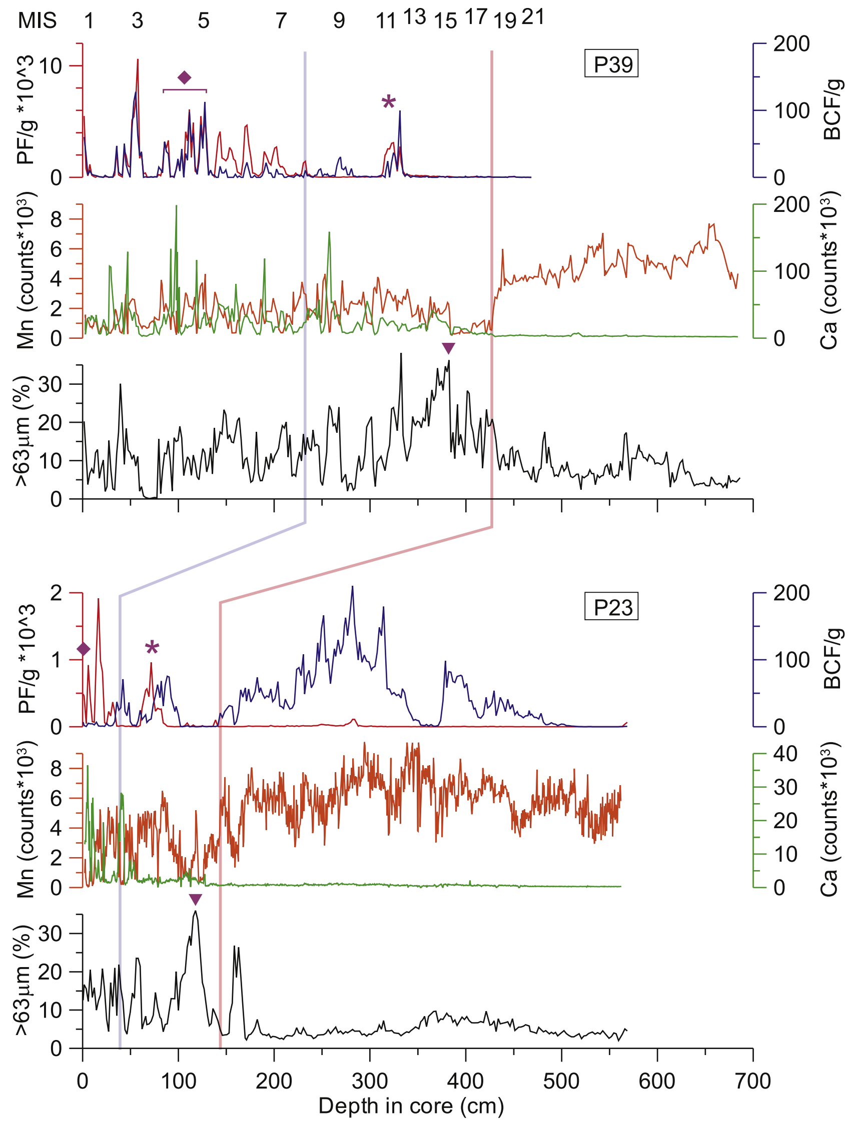

Fig. 2. Correlation of P23 and P39: content of sand and coarser grains (>63 μm), XRF Mn and Ca (bulk sediment; Itrax data for P23, hand-held scanner data for P39), abundances of planktonic (PF) and calcareous benthic (BCF) foraminifers per gram. Blue and pink correlation lines – major inclination drop and the top of predominantly brown sediment, respectively; diamond – *B. aculeata* peak; asterisk – warm-water planktonic peak; triangle – prominent IRD peak. Interglacial Marine Isotope Stages to MIS21 (most apparent) are shown to the right.

done in core P23, with P39 added for an enhanced characterization of the uppermost stratigraphy that is strongly compressed and partially missing in P23 (Suppl. 2–3). Detailed counts in P23 were performed at mostly 2-cm intervals in the upper 35 cm, at 4 cm between 35 and 90 cm, at 8 cm between 90 and 180 cm, and at ∼15 cm in the rest of the core; in P39 similar counts were done in the uppermost 200 cm at every 4 cm. This sampling strategy was aimed at characterizing the Early to Middle Pleistocene transition and the “Glacial” Pleistocene above in most detail, as discussed below (Fig. 3).

Foraminiferal abundances were calculated per gram of dry sediment excluding large pebbles. Using sample volumes instead of weights would have introduced more bias as sediment has partially dried out during storage. All samples had a similar volume of ∼6–7 cm^3. Identification of benthic foraminifers in small size fractions (at least >63 μm) is essential for a comprehensive characterization of the assemblages, especially in polar areas (e.g., Lagoe, 1977; Scott and Vilks, 1991), while >125 μm counts are helpful for a comparison with many other studies. Taxonomic identifications were compared to multiple sources with a focus on Arctic studies (Green, 1960; Lagoe, 1977; Scott and Vilks, 1991; Wollenburg, 1992; Ishman and Foley, 1996; McNeil, 1997; Scott et al., 2008) (Suppl. 4). Fisher α and Shannon–Wiener *H(S)* diversity indices (Figs. 3 and 4) were calculated using the PAST (PAleontology STatistics) program (Hammer et al., 2001). A preliminary study of ostracodes has also been performed by T. Cronin in pilot samples from P23.

4. Foraminiferal proxy approach

Benthic foraminifers were divided into three proxy groups based on their ecological preferences. One comprises taxa that are commonly considered to be Arctic or bipolar endemics (e.g., Green, 1960; Herman, 1973; Lagoe, 1977) predominated in our material by *Stetsonia horvathi* and *Bolivina arctica*, and also including *Valvulineria arctica*, *Epistominella arctica*, *Buliminella elegantissima hensoni*, *Eponides tumidulus horvathi*, and a few accessorial species. Some of these taxa were also reported from Subantarctic (Cornelius and Gooday, 2004) and Quaternary deposits in the North Atlantic

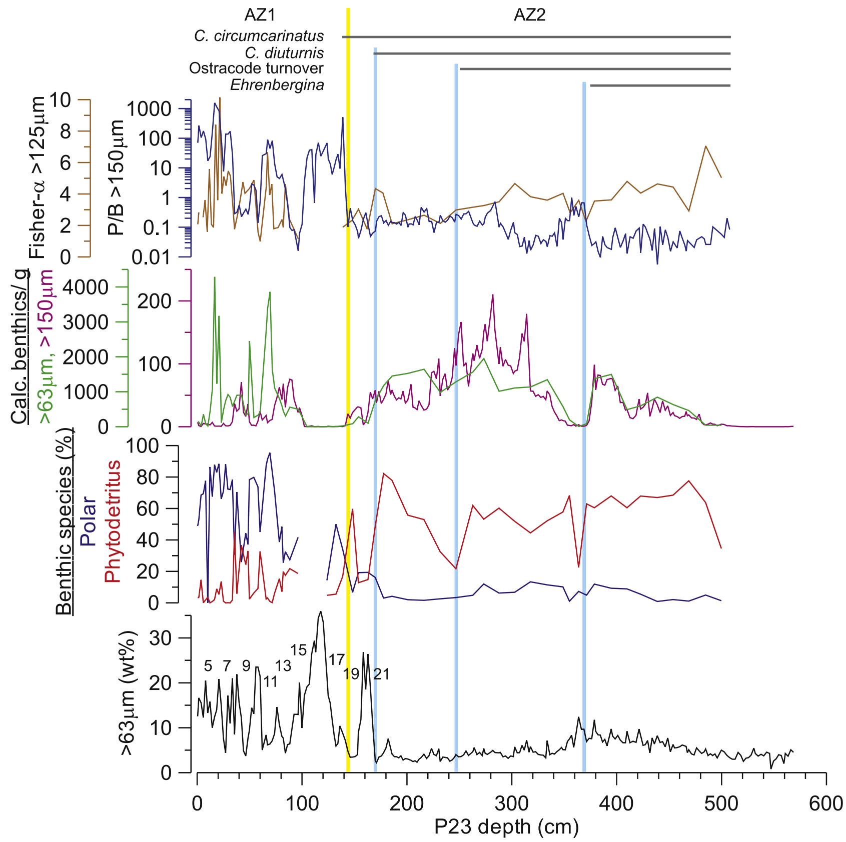

Fig. 3. Major characteristics of foraminiferal distribution in P23 (polar and phytodetritus species content, total abundances in >63 and >150 mm size fractions, Fisher α diversity index, planktonic/benthic ratio) along with sand (>63 μm) content. Ranges of extinct species are shown on top. Vertical lines show inferred events of sea-ice expansion; yellow line marks the turnover between foraminiferal Assemblage Zones 2 and 1. Interglacial Marine Isotope Stages to MIS21 are shown above the sand curve.

(Pawlowski, 1991; Collins et al., 1996) co-occurring with either modern presence of sea ice or its extension to lower latitudes during glacial periods. One notable exception is the occurrence of *Stetsonia arctica* (*S. horvathi* of most authors) in the deposits of the Bengal Fan (Scott and Leger, 1990), which indicates that the ultimate control on this species is probably not sea ice, but low content of fresh food in organic matter inputs to sea floor. Nevertheless, sea ice is one of the major factors in modulating this type of benthic environment (e.g., Stein and Macdonald, 2004), and the consistency in co-occurrence of sea-ice dominated settings with this and related species suggests their strong relation to ice-covered waters.

The other foraminiferal group that is a key for reconstructing ice conditions comprises the so-called phytodetritus species, notably *Epistominella exigua* and *Eponides weddellensis*. Distribution of these species peaks in the frontal oceanic zones, where conditions are suitable for pulsed, seasonal production and export of fresh organic matter (phytodetritus) utilized by fast-response benthic meiofauna (e.g., Gooday, 1988, 1993; Smart et al., 1994; Thomas et al., 1995). The Marginal Ice Zone (MIZ) in the Arctic is one example of such a frontal zone, as demonstrated by direct observations including long-term deep-sea stations (e.g., Falk-Petersen et al., 2000; Hoste et al., 2007). Foraminiferal composition from

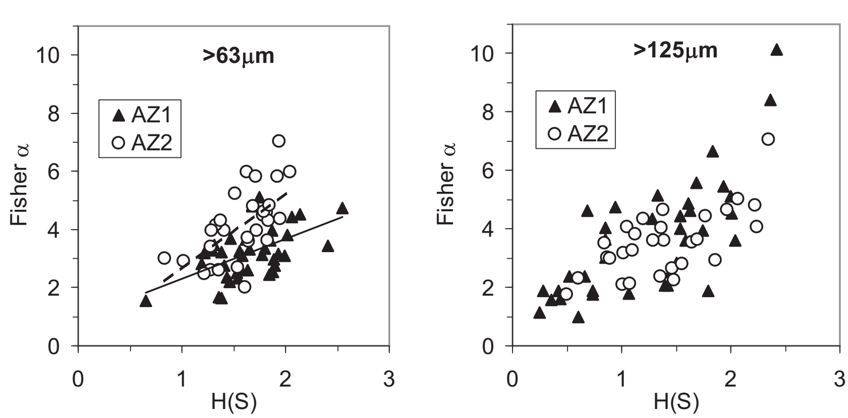

Fig. 4. Plots of faunal diversity indices (Fisher α vs. *H(S)*) in >63 μm and >125 μm size fractions in P23. Data points from Assemblage Zones 1 and 2 (Fig. 3) are shown by triangles and circles, respectively. Diversity patterns differ between the assemblage zones, especially in the >63 μm size fraction, as emphasized by regression lines (solid for AZ1 and punctured for AZ2).

the Arctic MIZ has not been investigated in detail due to its strong localization and widespread dissolution of carbonaceous remains in bottom waters under seasonal ice cover (Steinsund and Hald, 1994; Husum and Hald, 2012). Nevertheless, phytodetritus species in modern/surficial Arctic sediments has been reported only from areas adjacent to the MIZ (Polyak, 1990; Hald and Steinsund, 1992; Wollenburg and Mackensen, 1998). A more complete picture is likely more complex as some of the polar species may be capable of feeding on phytodetritus (Cornelius and Gooday, 2004) and may occupy transitional habitats between ice-covered and MIZ environments, e.g., *Epistominella arctica* (Pawlowski, 1991; Wollenburg and Mackensen, 1998; Cornelius and Gooday, 2004).

Some cosmopolitan species that are common in the Arctic Ocean (e.g., *Cibicidoides wuellerstorfi, Oridorsalis tener, Cassidulina teretis* (*neoteretis*)) may also have specific adaptations to habitats under the ice cover, but a wide distribution of these species complicates their use for reconstructing ice conditions. In particular, *C. teretis* is common throughout the Arctic Ocean with an apparent affinity to Atlantic-derived waters at depths of ∼200–900 m (Lagoe, 1979; Polyak, 1990; Ishman and Foley, 1996), and is therefore commonly used as an indicator of this water mass in paleo records (e.g., Jennings and Weiner, 1996; Lubinski et al., 2001). However, the actual controls on the Arctic habitats of this species may be related to food supply and need more in-depth investigation (Wollenburg and Mackensen, 1998).

5. Results

5.1. Lithology and general stratigraphy

Both cores consist of interlaminating grayish and brown bands with layers of coarse (sand or coarser) detritus (to ∼145 cm in P23 and 422 cm in P39) and predominantly brown, bioturbated, overall finer-grained sediment below (especially consistent from 170 cm in P23) (Fig. 2; Crawford, 2010). The brown coloration in Arctic Ocean sediments is largely controlled by the content of manganese oxyhydroxides (Jakobsson et al., 2000; Polyak et al., 2004; März et al., 2011), and is accordingly well approximated by the distribution of Mn (Fig. 2). Multiple studies suggest that high-Mn sedimentary units represent interglacial or major interstadial intervals, probably in relation to higher inputs from the margins due to higher sea level and lower sea-ice extent (e.g., Jakobsson et al., 2000; O'Regan et al., 2008; Adler et al., 2009; Löwemark et al., 2012). Co-occurrence with bioturbation further confirms more productive conditions, which require less extensive ice cover (Löwemark et al., 2012). In contrast, grayish units, commonly with high content of coarse grains (Ice Rafted Debris, IRD) are indicative of glacial/deglacial environments. Some IRD peaks have characteristically high composition of detrital carbonates approximated by Ca content (Fig. 2; Clark et al., 1980; Polyak et al., 2009; Stein et al., 2010). These carbonates, mostly composed of dolomites, are associated with the Canadian Arctic provenance and thus indicate pulses of iceberg discharge from the Laurentide ice sheet. In cores with elevated sedimentation rates, IRD layers are distinguished from fine-grained, gray sediments representing maximal glaciations (e.g., Adler et al., 2009; Polyak et al., 2009), but in a compressed record such as core P23 these lithologies merge together as generalized IRD-rich glacial intervals.

Downcore distribution of Mn, Ca, and coarse grain peaks, almost entirely composed of IRD in the upper unit, provides a robust lithostratigraphic correlation of cores P23 and P39, further reinforced by the position of unique litho-, bio-, and magnetostratigraphic events (Fig. 2). Consistent with higher sedimentation rates at a more southern site, core P39 has a more expanded but, accordingly, shorter stratigraphy. A combination of the two cores allows for an identification of more details in the upper part of the record as well as an evaluation of the longer stratigraphy. Even more detail for the uppermost stratigraphy can be obtained through correlation with the Northwind Ridge cores such as 92AR-P25 (P25 in Fig. 1) (Crawford, 2010; Yurco et al., 2010) and closely located 88AR-P3 and P5 (Poore et al., 1994), collected yet farther south.

Calcareous foraminiferal abundance patterns correlate well between the Northwind Ridge cores, exemplified by P23 and P39, in the upper part of the record (above pink correlation line in Fig. 2). However, further down-core P39 is practically barren of any calcareous skeletal remains, similar to almost all known Arctic Ocean cores (e.g., Cronin et al., 2008); whereas, core P23 contains well preserved benthic and planktonic foraminifers and ostracodes in the lower part of the record. Regardless of the causes for this preservation, it provides a rare opportunity to gain insights into the earlier Quaternary Arctic oceanic environments. Similar microfaunal distribution has been found in HOTRAX'05 core HLY0503-03JPC (Darby et al., 2009) raised close to P23 from 590-m water depth. This core has not yet been investigated in detail, but a preliminary evaluation indicates the consistency of P23 biostratigraphy for the top of the Northwind Ridge.

5.2. Age model

Constraining the age of Arctic Ocean sediments has been, and continues to be difficult. Various chronostratigraphic methods that work well in other oceans encounter problems in the Arctic because of very low sedimentation rates, low biological production, and strong oxygenation of bottom sediments that causes diagenetic alteration of biogenic material and even magnetic carriers (Channell and Xuan, 2009; Xuan and Channell, 2010; Xuan et al., 2012). However, the explicitly cyclic nature of Quaternary Arctic Ocean sediments allows for a comparison with the global glacial–interglacial cyclicity, which produced meaningful results on several cores with relatively high resolution (Jakobsson et al., 2000; Adler et al., 2009; Stein et al., 2010) and has been verified against a longer-term stratigraphy in the ACEX record (O'Regan et al., 2008). We have applied this approach to the Northwind Ridge cores by counting IRD-rich grayish layers and Mn-rich brown layers as glacial and interglacial intervals, respectively. Resultant stratigraphy is verified by several unique events (Fig. 2):

(1) Peak occurrence of benthic foraminifer *Bulimina aculeata* (Ishman et al., 1996) at the level estimated as MIS5a in the revised stratigraphy (Jakobsson et al., 2001; Nørgaard-Pedersen et al., 2007; Adler et al., 2009);
(2) Prominent drop in paleomagnetic inclination that consistently occurs in Arctic Ocean cores at the level estimated as MIS7 (Jakobsson et al., 2000; Spielhagen et al., 2004; O'Regan et al., 2008; Polyak et al., 2009);
(3) Peak of planktonic foraminifers almost entirely composed of a temperate-water species *Turborotalita egelida* (possibly a subspecies of *T. quinqueloba*) at a stratigraphic level estimated as MIS11, which makes perfect sense for such an anomalously warm-water fauna (more discussion in Cronin et al., 2013);
(4) Prominent IRD peak with the first noticeable increase in detrital carbonates signifying the onset of massive iceberg discharges from the Laurentide ice sheet (Polyak et al., 2009; Stein et al., 2010; Polyak and Jakobsson, 2011). The likely timing of this event is MIS16, which was a pivotal point in the development of 100-ka cyclicity (e.g., Clark et al., 2006) and the beginning of Laurentide iceberg pulses (Heinrich events) in the North Atlantic (Hodell et al., 2008).

In the absence of event tie-points below MIS16 we have tentatively counted apparent lithostratigraphic cycles, to estimated MIS21, to cover the major turnover in foraminiferal fauna as described below (Fig. 3). The close proximity of this turnover with the estimated position of the Early/Middle Pleistocene boundary (MIS 19; Brunhes–Matuyama paleomagnetic boundary) is consistent with coeval major paleoclimatic shift (e.g., Lisiecki and Raymo, 2005; Clark et al., 2006) and, thus, corroborates the validity of the suggested age model. The continued count of smaller amplitude, yet identifiable IRD peaks combined with Mn and, where possible, foraminiferal abundance variability indicates approximately 40 more cycles presumably related to fluctuations in sea ice and/or glacial fluxes. Assuming the overarching prevalence of the obliquity signal in the "pre-100-ka world" (Raymo and Nisancioglu, 2003), this approach provides a tentative estimate of the core-bottom age of ca 1.8 Ma.

Based on this age assessment, sedimentation rates in core P23 constitute ~0.2 cm/ka in the "Glacial" (Middle to Late) Pleistocene and ~0.4 cm/ka in the Early Pleistocene. Higher sedimentation rates prior to the development of major glaciations in the Northern Hemisphere are consistent with oceanic environments less prone to an extensive ice cover (e.g., Hodell et al., 2008; Expedition 323 Scientists, 2009). As expected, sedimentation rates in core P39 are in average three times higher than in P23 in the "Glacial" Pleistocene (not estimated for the nonfossiliferous lower stratigraphy), and an order of magnitude higher in core P25 farther south (MIS 1–7 stratigraphic range; Yurco et al., 2010).

5.3. Foraminiferal stratigraphy

Calcareous benthic foraminifers are abundant to ~3.2-m depth in P39 (estimated MIS 1–11, ca 0.42 Ma) and throughout most of core P23 length to 5-m depth (estimated ca 1.5 Ma), except for a few short intervals, notably at 100–130 and 350–370 cm (Figs. 2 and 3). Below 500 cm in P23 sediment is almost barren except for a few centimeters at the core bottom, which were discarded to avoid possible coring contamination. Abundance of >150 μm specimens shows several broad maxima with superimposed cyclic fluctuations, where peaks usually occur in high-Mn intervals. Although smaller size fractions have been counted more sparsely, >63 μm abundances are clearly consistent with those of >150 μm in the Early Pleistocene, but have a very different pattern in the "Glacial" Pleistocene with a different faunal composition (Fig. 3). Planktonic foraminifers, as counted in >150 μm size fraction, are considerably less abundant than benthic in the Early Pleistocene, but predominate in most of the younger stratigraphy, with a sharp increase at the Early/Middle Pleistocene boundary.

Two major foraminiferal assemblage zones (AZ) can be identified in core P23 based on the distribution of the ecological/stratigraphic groups defined above and foraminiferal abundances (Fig. 3). AZ2 (140–500 cm) is dominated by phytodetritus species (especially consistent below 170 cm), features several extinction events, and has very low planktonic to benthic (P/B) ratio of <1. The most abundant species is mostly *E. exigua*, but *E. weddellensis* dominates in the central part of AZ2 between two extinction levels at 250 and 370 cm. AZ1 (0–140 cm in P23) is largely composed of polar species, with *S. horvathi* and *B. arctica* interchanging as the most abundant species and has mostly high P/B ratio. The content of polar species markedly increases at 75–80 cm (estimated MIS 12/11, ca 0.4–0.45 Ma). Elevated percentages of phytodetritus species, mostly *E. exigua*, recur in interglacial intervals above this level, with largest peaks occurring up to 35 cm (estimated bottom of MIS7, ca 0.24 Ma). In the uppermost part of AZ1, within estimated MIS5 (studied primarily in core P39; Fig. 5) benthic assemblages undergo another change expressed notably in the rise of *O. tener* and miliolids as well as a decrease in the content of *S. horvathi* and especially *B. arctica* among polar species. A similar change has been reported from other records throughout the western Arctic Ocean adjusted to the up-to-date age model (Scott et al., 1989; Ishman et al., 1996; Polyak et al., 2004). The resultant assemblage is similar to those described from surficial (Holocene) Arctic Ocean sediments from comparable water depths (e.g., Lagoe, 1979; Ishman and Foley, 1996; Polyak et al., 2004). *C. teretis* is common throughout the entire P23/P39 record.

Distribution of diversity indices, Fisher α and Shannon–Wiener *H(S)*, was compared by assemblage zones (Fig. 4). In the size fraction >63 μm diversity indices behave differently in AZ 1 and 2, and the overall pattern of both indices is relatively featureless. In a more restricted >125 μm data, distribution of diversity is more consistent across the AZ's and between the Fisher α and *H(S)* indices. This difference may reflect more biases associated with smaller foraminifers due to stronger abundance changes, potentially higher susceptibility to dissolution, and taxonomic uncertainties. Overall, >125 μm diversity indices show a gradual decrease throughout AZ2 and strong fluctuations in AZ1, with maxima in interglacial intervals (Fig. 3).

A unique feature of the foraminiferal record in AZ2 is the presence of extinct species with last occurrences at different stratigraphic levels in the Early Pleistocene : *Cibicidoides* spp. (mostly *C. diuturnis*/*tumulus* and *C. circumcarinatus*[1]), *Ehrenbergina* sp., and several accessorial species such as uniserial foraminifers *Stilostomella*/*Nodosaria* spp. that require more detailed taxonomic study. This fauna has been described from the Beaufort–Mackenzie Basin (Fig. 1) (McNeil, 1989, 1990, 1997), where its last occurrence corresponds to the Late Miocene (Akpak Sequence) overlain by a prominent uncomformity (McNeil et al., 2001). However, a simple translation of these ages to the central Arctic Ocean stratigraphy may be misleading because benthic species can persist in the deep ocean longer than on the margins, which are subjected to strong effects of sea-level changes, as exemplified by the distribution of *Cibicides grossus* in the North Sea basin and Norwegian–Greenland sea (King, 1989; Anthonissen, 2008). Furthermore, the age control for the Plio-Pleistocene deposits in the Beaufort–Mackenzie Basin is not definitive; for example, strontium-isotope values in foraminiferal tests indicate ages possibly as young as ca 1 Ma in the Iperk Sequence regarded as Upper Pliocene (McNeil et al., 2001). In a broader context, the estimated age range of extinctions in core P23 corresponds to the time of the last global deep-ocean foraminiferal turnover that culminated during the Mid-Pleistocene Transition (MPT), between ca 1.2 and 0.7 Ma (Hayward, 2002; Hayward et al., 2007, 2010; O'Neill et al., 2007). This correspondence indicates that paleoceanographic changes in the western Arctic Ocean were likely linked to the global climatic transformation during the MPT associated with a shift from the obliquity to 100-ka-cycle world (e.g., Lisiecki and Raymo, 2005; Clark et al., 2006).

6. Discussion

6.1. Foraminifers as paleo-sea-ice proxies

Several papers dealt with the interpretation of sea-ice conditions in the Arctic based on benthic foraminifers via paleoproductivity estimates (Wollenburg and Kuhnt, 2000; Wollenburg et al., 2001, 2004, 2007) or empirical observations of

[1] A few specimens of these species have been also found in estimated MIS5c in P39; more studies are needed to verify the *in situ* status of these specimens and to detail the stratigraphic range of the species involved.

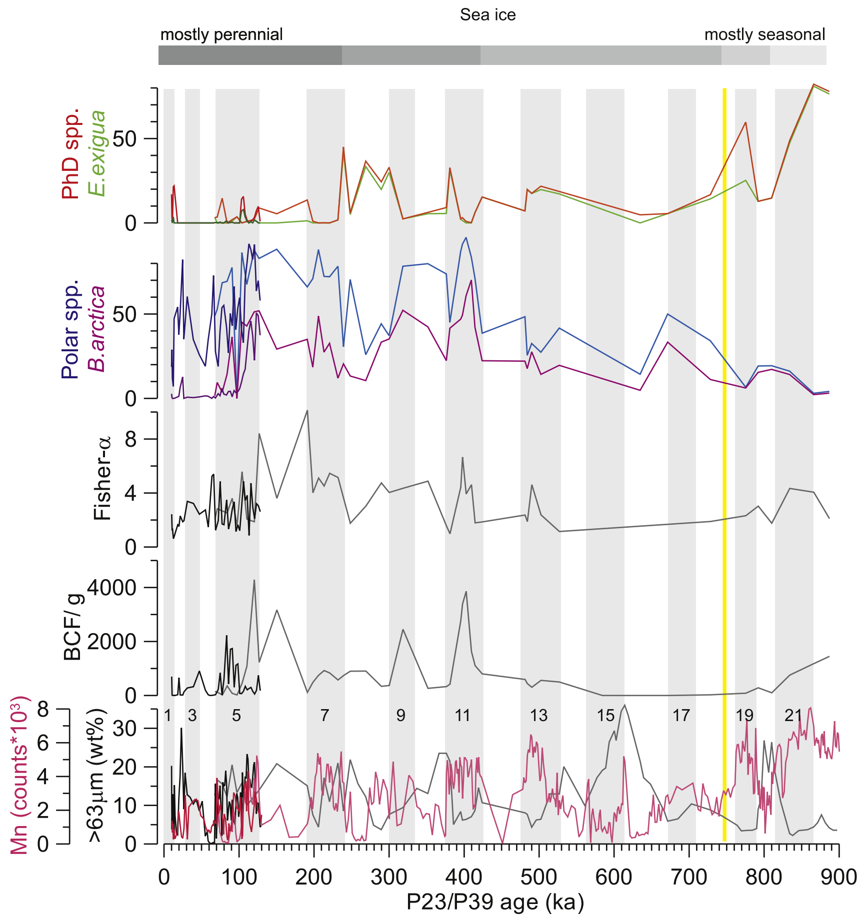

Fig. 5. Characteristics of foraminiferal assemblages in the composite P23/P39 record vs. estimated age for the last ca 0.9 Ma. Tentative age model is based on tuning the Mn content variations to global Marine Isotope Stages (MIS onset ages after Lisiecki and Raymo, 2005) (Suppl. 5). Interglacial stages are highlighted and numbered. Yellow line shows boundary between Assemblage Zones 2 and 1. Foraminiferal numbers and composition are given for >63 µm fraction; Fisher α diversity index for >125 µm assemblages. Interpreted changes in sea-ice conditions are shown above.

foraminiferal assemblages from ice-affected areas (Schell et al., 2008; Scott et al., 2008). These studies discuss Late Pleistocene to Holocene sea-ice histories for the Barents Sea margin and the Mackenzie area, respectively (Fig. 1, yellow boxes), with complications resulting from other factors such as glaciations, circulation changes, and taphonomic processes. These results have only limited applicability to our data that represent a much longer stratigraphy from central part of the western Arctic Ocean. For a more effective use of our foraminiferal data for paleo-ice assessment, we are employing sea-ice related ecological groups as defined above. The two major groups, polar and phytodetritus species combined comprise on average ~70% of the total assemblage in core P23 samples (Fig. 3), thus demonstrating a very good relevance of this approach.

Foraminiferal abundance, when unbiased by dissolution or sediment dilution, also reveals paleoproductivity and, thus, sea-ice conditions (Wollenburg and Kuhnt, 2000). Dissolution does not appear to be a big issue in the P23 record except for may be the core bottom. Sediment dilution is likely in the glacial discharge peaks in the Middle/Upper Pleistocene, with an especially pronounced peak at estimated MIS16 corresponding to a prolonged depression in foraminiferal numbers (Figs. 3 and 5). In contrast, in the intermittent intervals of the “Glacial” Pleistocene foraminiferal abundances may be over-elevated due to very low sedimentation rates. As a result, we regard total abundances as especially useful for sea-ice evaluation in the Early Pleistocene between ~150 and 500 cm core depth.

Diversity of benthic assemblages in the Arctic has also been found to be related to organic carbon fluxes, but its relationship to sea ice is less straightforward (Wollenburg and Kuhnt, 2000; Wollenburg et al., 2007). As our data fall into two distinct assemblage zones reflecting two ecological and sea-ice regimes, we believe that biodiversity as sea-ice proxy should be considered separately for these zones. This approach is supported by different behaviors of Fisher α and *H(S)* indices between the assemblage zones, especially in the >63 µm size fraction (Fig. 4).

The pattern of planktonic/benthic (P/B) ratio in core P23, with a notable sharp increase at the transition from Early to Middle Pleistocene (Fig. 3), may also be related to changes in sea ice. It has been suggested that high P/B ratios may be indicative of a decrease in organic productivity provided selective dissolution is not an issue (Berger and Diester-Haass, 1988; van der Zwaan et al., 1990). However, in the Arctic this relationship may have an additional implication as planktonic foraminifers in the “Glacial” Pleistocene are predominantly *Neogloboquadrina pachyderma* (sinistral), a species uniquely adapted to life under the ice cover (e.g., Volkmann, 2000). Exceptions are elevated numbers of subpolar planktonic foraminifers at some interglacials (Nørgaard-Pedersen et al., 2007; Adler et al., 2009), with an especially prominent peak of *T. egelida* in MIS11 (Fig. 2; Cronin et al., 2013). During glacial intervals, however, planktonic abundances suffer pronounced decreases combined with minima in benthic diversity (Figs. 2 and 3), which may be related to low nutrient availability and impacts of glacial meltwater and high turbidity.

6.2. Foraminiferal sea-ice record in P23/P39

High content of phytodetritus species combined with overall high foraminiferal abundances and low P/B ratio in Assemblage Zone 2 (Fig. 3) strongly indicates seasonal ice conditions, possibly with a frequent proximity of MIZ similar to Fram Strait today (NSIDC, Boulder, USA). Cyclic fluctuations of foraminiferal abundances may reflect variability in sea-ice conditions on glacial–interglacial (low–high sea level) scale; more detailed investigation of AZ2 is needed to test this assumption. The presence of extinct species further supports the more open-water interpretation of AZ2 based on their occurrence in the Arctic since Oligocene (McNeil, 1997) and the non-polar distribution of related species such as *Cibicidoides* spp. (except for *C. wuellerstorfi*) and *Ehrenbergina* spp. Last occurrences of these species in core P23 correspond to pronounced drops in total abundances and in the content of phytodetritus species (Fig. 3); a similar change at 240–250 cm has no evident foraminiferal extinction but a turnover of the ostracode fauna (Cronin, pers. com, 2011). This pattern suggests that extinctions were related to events of sea-ice expansion caused by stepwise cooling and/or glacial meltwater inputs, probably on the background of a gradual shortening of ice-free season as reflected in the decreasing faunal diversity. Foraminiferal abundance, however, shows maximal numbers in the central part of AZ2 rather than a gradual decrease (Fig. 3). We suggest that this maximum, corresponding to the dominance of *E. weddellensis* in the assemblage, may be related to the most frequent occurrence of MIZ at the core site, with a more northern average position before and more southern after this time interval. The last sea-ice spreading event at ~145 cm signifies a final establishment of mostly perennial ice at the Early/Middle Pleistocene boundary as reflected in a principal faunal turnover to the polar-species dominated AZ1 and a complete disappearance of extinct species (Fig. 3).

Foraminiferal changes within AZ1 appear to reflect progressively increasing ice coverage (Fig. 5). The transitional assemblage ending at ~75–80 cm (estimated ca 0.4–0.45 Ma) has low foraminiferal abundances, probably associated with strong glacial sedimentary inputs in MIS16 to 14, and is dominated by *C. teretis* along with moderate contents of both polar and phytodetritus species. Above this interval polar fauna consistently predominates, while elevated percentages of phytodetritus species, mostly *E. exigua*, in interglacial intervals up to estimated ca 0.24 Ma indicate recurring conditions with low sea-ice extent in MIS 13, 11 (upper part), and 9. The uppermost stratigraphy (MIS 7 and younger) is interpreted to represent most severe sea-ice cover, with some ice retreat during interglacials marked by a moderate increase in phytodetritus species content. Overall, we conclude that mostly perennial sea-ice conditions persisted in the western Arctic Ocean throughout most of the Middle to Late Pleistocene.

Changes in benthic assemblages in the uppermost stratigraphy (starting within estimated MIS 5; Fig. 5) do not affect phytodetritus or combined polar species contents, and may be related to environmental factors other than sea ice, such as intensification of intermediate water circulation. The latter possibility is consistent with the increasing gradient in sedimentation rates on the ridge tops vs. slopes (erosion vs. deposition) as evident on both the Northwind Ridge (this study) and Mendeleev Ridge (Cronin et al., 2013).

Diversity indices in AZ1 reach high values in the interglacials, comparable to those in the lower part of AZ2 (Figs. 3 and 5). However, a direct comparison of diversities between the AZ's may be misleading because of their principally different ecologies, so that high values in AZ1 probably indicate only relative amelioration of ice conditions or adaptation of the polar fauna to thrive in low-productive environments. Pronounced drops in diversity indices in glacial intervals co-occur with sharp decreases in planktonic abundances and may be related to especially thick/solid ice cover, low nutrient supply from the margins, or an additional stress from glacial meltwater and turbidity.

6.3. Broader implications

As core P23 offers a uniquely preserved Early Pleistocene Arctic foraminiferal record, a question arises, whether it represents a significant part of the Arctic Ocean or relatively local conditions. Considering the location of this site in the interior of the western Arctic and the similarity of its litho- and magnetostratigraphy with other records from the Beaufort Gyre circulation system (e.g., Fig. 2; Polyak et al., 2009), we infer that P23 is representative of the sedimentation history in the western Arctic Ocean. On the other hand, prevailing carbonate dissolution in the Lower Pleistocene stratigraphy of most other cores indicates unusual paleoceanographic feature(s) at the Northwind Ridge. One possibility is that the lysocline at that time was shallower than today, and only ridge tops were unaffected by dissolution. However, correlative sediments from similar water depths on the Mendeleev Ridge lack carbonates (Cronin et al., 2013), indicating hydrographic variance between these locations as opposed to a more uniform, Atlantic-derived intermediate water in modern conditions. We infer that this difference was related to the influence of Pacific waters, which were likely saltier and warmer than later in the Pleistocene due to lower glacial inputs (Expedition 323 Scientists, 2009). These waters could have had a warming effect on the western Arctic and contribute to the counterclockwise intermediate-depth circulation affecting the Northwind Ridge.

This inference is corroborated by foraminiferal data from core LOMROG P04 from the Lomonosov Ridge north of Greenland (L04 in Fig. 1; 811 mwd), an exit area for both the Beaufort Gyre and intermediate-depth waters (Hanslik, 2011). Although foraminifers were counted only in >125 μm fraction that does not characterize the entire assemblage, they do show a Late/Middle Pleistocene stratigraphic succession similar to that in core P23, with a presence of extinct *C. circumcarinatus* near the core bottom. Thus, this stratigraphy captures the AZ2-AZ1 crossover as in P23, indicating a change from principally seasonal to perennial sea-ice environments, and confirms that the Northwind Ridge and the LOMROG area were bathed by the same intermediate water.

The mostly seasonal-ice conditions in the western Arctic Ocean in the Early Pleistocene as characterized by AZ2 differ from the interpretation of the coeval interval in the ACEX borehole inferring mostly perennial ice cover (O'Regan et al., 2009). This apparent discrepancy may be not that surprising as ACEX represents a circulation regime controlled by the Transpolar Drift as opposed to the Beaufort Gyre in the western Arctic (Fig. 1). This oceanographic setting can explain the differences in climatic and sedimentation histories inferred from the ACEX and the western Arctic paleo records (Polyak and Jakobsson, 2011, and references therein).

Terrestrial data indicate a considerably warm Pliocene climate in the western Arctic, with annual temperatures almost 20 °C warmer than at present, not compatible with perennial sea ice in the adjacent ocean (e.g., Elias and Matthews, 2002; Ballantyne et al., 2010). Warm interglacial conditions inferred from relatively warm-water coastal-marine fauna and expansions of woodlands in Northern Alaska and Greenland continued in the Early Quaternary to at least estimated 2 Ma (Carter et al., 1986; Brigham-Grette and Carter, 1992; Kaufman and Brigham-Grette, 1993; Funder et al., 2001). Our data provide the first insight into oceanic Early Pleistocene conditions in the western Arctic covering the time interval of the MPT, the major climatic transition to full-scale Quaternary ice ages.

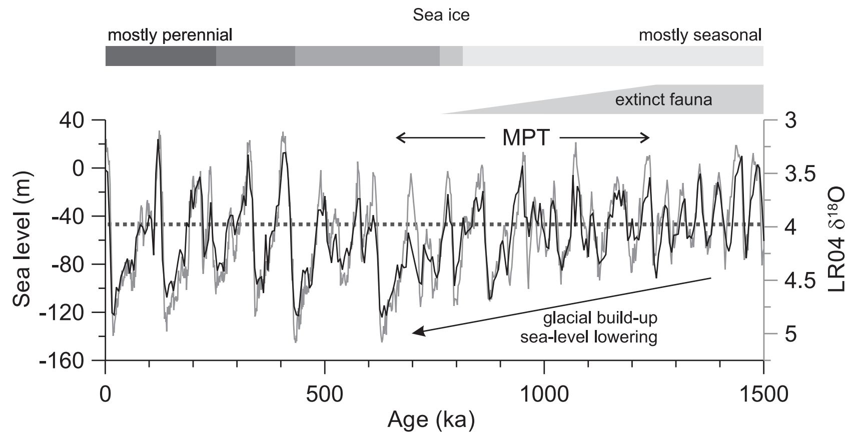

Fig. 6. Interpreted western Arctic sea-ice changes in the context of global sea-level and glaciation history. Black curve – sea level (Miller et al., 2005), gray curve – LR04 benthic $\delta^{18}O$ (Lisiecki and Raymo, 2005). Dotted line – Bering Strait depth.

Prolonged warm pre-MPT intervals were likely fostered by relatively high atmospheric CO_2 concentrations during glacial periods (Hönisch et al., 2009) and the strong Arctic Amplification (Miller et al., 2010); however, these factors do not explain the inferred asymmetry between the western and the eastern Arctic. A plausible control for such an asymmetry would be an increased Pacific input. Higher glacial sea levels in the Early Pleistocene, progressively lowering between ca 1.5 and 0.9 Ma (Miller et al., 2005), allowed overall more time for the open Bering Strait and, thus, more warmth delivered to the western Arctic Ocean (Fig. 6). This circulation was accompanied by warmer and more productive waters in the North Pacific until the onset of strong glacial influence at MIS 22 (ca 0.9 Ma) (Expedition 323 Scientists, 2009; Kender et al., 2011). This development is consistent with our interpretation of AZ2 implying predominantly seasonal sea ice with gradually rising extent, punctuated by episodes of cooling and ice expansion. The principal change to mostly perennial ice according to our age model occurred between MIS21 and 18 (Fig. 5), shortly after the major hydrographic shift in the North Pacific. A more rigorous age control is needed to verify this timing, which may be important for understanding the linkages involved. The broad climatic significance of the AZ2/1 transition is corroborated by the basin-wide correlation of the corresponding litho- and magnetostratigraphic boundary (Fig. 2; Polyak et al., 2009) and the indication of a similar foraminiferal history in a core north of Greenland (Hanslik, 2011). Furthermore, a comparable foraminiferal stratigraphy is evident in ODP Hole 645 from the Baffin Bay (Fig. 1), where the content of polar species rises sharply at ~150 m core depth, near the estimated Brunhes/Matuyama boundary (Kaminski et al., 1989). Expansions of sea ice and associated foraminiferal fauna into the North Atlantic during glacial periods likely initiated at the same stratigraphic level as indicated by ODP Hole 643 from the Norwegian Sea (Fig. 1) (Osterman and Qvale, 1989; Osterman, 1992).

Based on a strong rise in polar species content toward estimated MIS11 (Figs. 3 and 5), ice conditions became yet more severe, probably with the predominance of perennial ice. This step event does not seem to be accompanied by changes in lithological proxies and cannot be easily connected with changes in regional climatic/oceanographic conditions. Its timing, however, co-occurs with the marked amplitude shift in the global benthic $\delta^{18}O$ curve (e.g., Fig. 6) and the inferred intensification of glaciations in the Northern Hemisphere at ca 0.4 Ma known as the Mid-Brunhes Event (Jansen et al., 1986; Wang et al., 2004), which suggests a potential climatic linkage.

We note that a somewhat later onset of perennial sea ice during MIS 10/9 is inferred from the appearance of the ostracode *Acetabulostoma arcticum* on the Mendeleev Ridge (Cronin et al., 2013). This offset may reflect a geographic difference or, alternatively, a variety of faunal responses to various degrees of sea-ice coverage. While *A. arcticum* habitat depends directly on perennial ice, benthic assemblages reflect surface-to-bottom ecosystem links. A comparison of ostracode and foraminiferal faunas in the same cores is therefore important for understanding the linkages between sea ice and biota in the Arctic Ocean.

A continuing resurgence of phytodetritus species indicates recurring conditions with low sea-ice extent during interglaciations, especially until MIS7 (Fig. 5), which presumably marks another step in the consolidation of perennial ice regime. This change co-occurs with an amplitude increase in Ca peaks indicating higher IRD inputs from the Canadian provenance and, thus, growth of the Laurentide ice sheet, which may have facilitated sea-ice spread through regional cooling and meltwater discharge.

7. Summary

The distinct record of preserved calcareous foraminifera in core P23 from the northern Northwind Ridge provides a unique insight into the history of oceanographic and climatic environments in the Arctic Ocean during a large part of the Quaternary, estimated ca 1.5 Ma. Foraminiferal abundances, diversity, and composition of benthic assemblages, especially phytodetritus and polar species, were investigated along with lithological proxies to reconstruct changes in sea ice in the context of climatic perturbations during the Mid-Pleistocene Transition and ensuing full-scale glacial cycles.

Foraminiferal Assemblage Zone 2 in the Lower Pleistocene is predominated by phytodetritus species with a contribution of extinct species showing several last occurrence levels. This AZ is interpreted to reflect mostly seasonal sea ice with a frequent proximity to the Marginal Ice Zone. We infer that this environmental state was facilitated by inflow of Pacific waters due to relatively elevated sea levels during incompletely developed Early Pleistocene glaciations (Miller et al., 2005). Gradually decreasing faunal diversity suggests an overall shortening of the ice-free season, consistent with progressively larger glaciations and related decrease in atmospheric pCO_2 (Lisiecki and Raymo, 2005; Hönisch et al., 2009). This gradual transition was punctuated by episodes of sea-ice expansion as indicated by drops in foraminiferal abundances, phytodetritus species content, and last occurrence levels. The latest of these events signified a complete turnover of foraminiferal fauna as well as lithological proxies at the Early–Middle Pleistocene boundary, ca 0.8 Ma, indicating the establishment of mostly perennial sea ice. This change happened at the background

of a major climatic shift involving the growth of Northern Hemisphere ice sheets paced at 100-ka cycles and associated hydrographic changes affecting notably circulation in the North Pacific (Expedition 323 Scientists, 2009). The wide-scale nature of the turnover in core P23 is confirmed by a basin-wide lithostratigraphic correlation (Polyak et al., 2009) and several examples of similar changes in foraminiferal stratigraphy extending into the North Atlantic (Kaminski et al., 1989; Osterman and Qvale, 1989; Hanslik, 2011).

The subsequent evolution of foraminiferal assemblages (AZ1) indicates further increase in sea-ice coverage. The first step of this increase is reflected in a pronounced rise in the content of polar species co-occurring with the intensification of Northern hemisphere glaciations (Mid-Bruhnes Event) around ca 0.4 Ma (Jansen et al., 1986; Wang et al., 2004), although the connection involved is yet to be investigated. Intervals with elevated content of phytodetritus species corresponding to more seasonal sea-ice environments repeatedly occurred during interglaciations, especially pronounced until estimated MIS7, ca 0.24 ka. This stratigraphic level co-occurs with a rise in sedimentary inputs of the Laurentide provenance, expressed notably in high-amplitude peaks of Ca content. The growth of the Laurentide ice sheet is a likely cause of sea-ice expansion. Another step in the increase in perennial ice is inferred from an ostracode proxy on the Mendeleev Ridge around 0.35 Ma (Cronin et al., 2013), necessitating a comparison of ostracode and foraminiferal faunas in the same cores.

Overall, AZ1 indicates that perennial sea ice was a norm during the "Glacial" Pleistocene with some degree of ice retreat occurring during major interglacial intervals. This paleoclimatic setting highlights the anomalous pattern of the current shrinkage of Arctic sea-ice cover, especially pronounced in the western Arctic (e.g., Stroeve et al., 2011). We note, however, that the "Glacial" Pleistocene has multiple non-analogous conditions because of the overwhelming effect of glaciations on the relatively small and almost landlocked Artic Ocean. The Early Pleistocene environments, such as explored by this study, potentially provide a better paleoclimatic analog for evaluating the modern Arctic change.

This study provides the first account of paleoceanographic environments, including sea ice conditions, in the western Arctic Ocean for the time period extending into the Early Pleistocene. Results obtained thus far are to be verified and detailed by more rigorous age constraints and more comprehensive proxy investigations. For example, stable isotopes in benthic and planktonic foraminifers may provide more insights into productivity patterns along with meltwater fluxes, and radiogenic isotopes can help understand deep-water circulation.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2012.12.018.

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