Late Quaternary spatial and temporal variability in Arctic deep-sea bioturbation and its relation to Mn cycles

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ABSTRACT

Changes in intensity and composition of bioturbation and trace fossils in deep-sea settings are directly related to changes in environmental parameters such as food availability, bottom water oxygenation, or substrate consistency. Because trace fossils

are practically always preserved *in situ*, and are often present in environments where other environmental indicators are scarce or may have been compromised or removed by diagenetic processes, the trace fossils provide an important source of paleoenvironmental information in regions such as the deep Arctic Ocean. Detailed analysis of X-ray radiographs from 12 piston and gravity cores from a transect spanning from the Makarov Basin to the Yermak Plateau via the Lomonosov Ridge, the Morris Jesup Rise, and the Gakkel Ridge reveal both spatial and temporal variations in an ichnofauna consisting of *Chondrites, Nereites, Phycosiphon, Planolites, Scolicia, Trichichnus, Zoophycos*, as well as deformational biogenic structures. The spatial variability in abundance and diversity are in close correspondence to observed patterns in the distribution of modern benthos, suggesting that food availability and food flux to the sea floor are the most important parameters controlling variations in bioturbation in the Arctic Ocean. The most diverse ichnofaunas were observed at sites on the central Lomonosov Ridge that today have partially ice free conditions and relatively high summer productivity. In contrast, the most sparse ichnofauna was observed in the ice-infested region on the Lomonosov Ridge north of Greenland. Since primary productivity, and therefore also the food flux at a certain location, is ultimately controlled by the geographical position in relation to ice margin and the continental shelves, temporal variations in abundance and diversity of trace fossils have the potential to reveal changes in food flux, and consequently sea ice conditions on glacial-interglacial time scales. Down core analysis reveal clearly increased abundance and diversity during interglacial/interstadial intervals that were identified through strongly enhanced Mn levels and the presence of micro- and nannofossils. Warm stages are characterized by larger trace fossils such as *Scolicia, Planolites* or *Nereites*, while cold stages typically display an ichnofauna dominated by

small deep penetrating trace fossils such as *Chondrites* or *Trichichnus*. The presence of biogenic structures in glacial intervals clearly show that the Arctic deep waters must have remained fairly well ventilated also during glacials, thereby lending support to the hypothesis that the conspicuous brown layers rich in Mn which are found ubiquitously over the Arctic basins are related to input from rivers and coastal erosion during sea level high-stands rather than redox processes in the water column and on the sea floor. However, the X-ray radiograph study also revealed the presence of apparently post-sedimentary, diagenetically formed Mn-layers which are not directly related to Mn input from rivers and shelves. These observations thus bolster the hypothesis that the bioturbated, brownish Mn-rich layers can be used for stratigraphic correlation over large distances in the Arcitc Ocean, but only if post sedimentary diagenetic layers can be identified and accounted for in the Mn-cycle stratigraphy.

Keywords: bioturbation, trace fossils, Arctic Ocean, diagenesis, Manganese

1 Introduction

Variations in the type and intensity of bioturbation in Arctic sediments have been studied from sea-floor photographs (e.g., Kitchell, 1979; Kitchell et al., 1978; MacDonald et al., 2010), and down-core variations in trace fossils and lebensspuren have been noted in several previous studies, (e.g., Clark et al., 1980; Phillips and Grantz, 1997; Scott et al., 1989). However, despite the relatively large number of cores now available from the deep Arctic Ocean (Stein, 2008), no systematic studies on Arctic deep-sea ichnology have been published. Here we present the first detailed ichnological studies of spatial and temporal variation in the composition of the Arctic

Ocean ichnofauna, and focus on how observed changes may be related to past changes in circulation and sea-ice coverage.

Because the composition and activities of the benthic fauna is determined by parameters such as food flux or availability, bottom water oxygenation, and substrate consistency, downcore variations in the traces left by the organisms can be used as proxies to reconstruct past variations in environmental conditions (e.g., Savrda, 2007; Wetzel, 1991). Trace fossils have certain advantages over other environmental proxies as they are preserved *in situ* and cannot be redistributed and therefore by necessity reflect the environment at the position where they are found. Furthermore, trace fossils are commonly preserved in settings where other proxies are missing or have been obliterated, in fact, they are quite resistant to diagenetic processes which often act to even enhance their visibility. However, in unlithified, homogeneously coloured sediment, trace fossils can sometimes be hard to make out. Here X-ray radiographs of the sediment offer a powerful tool to reveal both physical and biological structures in the sediment that would otherwise be invisible to the naked eye (cf. Bouma, 1964). These characteristics make trace fossils particularly promising in regions such as the Arctic Ocean where dating and paleoceanographic reconstructions are difficult due to the scarcity of nanno- and microfossils, a complex magnetostratigraphy (Backman et al., 2009; Spielhagen et al., 2004), and problematic absolute dating methods (e.g., 14C and 10Be, Sellén et al., 2009)

In an effort to address the dating problem, it has been argued that the recurrent downhole occurrence of strongly bioturbated, brownish (enriched in Mn) intervals in many central Arctic Ocean sediments provides a possibility for age control, as these cycles could be correlated to the low-latitude stable oxygen isotope curve (Jakobsson et al., 2000). Following IODP Expedition 302 to the Lomonosov Ridge (the Arctic

Coring Expedition – ACEX), downhole variations in Mn content in Quaternary sediments were shown to be strongly correlated to cyclostratigraphic changes in the physical, chemical and magnetic properties of the sediments, and were found to coincide with occurrences of agglutinated benthic forams, supporting the assertion that Mn enrichment occurs during interglacial/interstadial periods throughout the middle and latter part of the Quaternary (O'Regan et al., 2008; O'Regan et al., 2010).

Three main mechanisms have been proposed to explain the observed cyclicity in Mn enrichment: 1) variations in deep-water circulation causing precipitation or dissolution of Mn; 2) variations in the input of Mn to the Arctic Ocean; and 3) diagenetic processes redistributing the Mn within the sediment (e.g., Jakobsson et al., 2000; Löwemark et al., 2008; Macdonald and Gobeil, 2011; März et al., 2011). Here detailed studies of variations in deep sea bioturbation in combination with sediment geochemical analysis may provide information on the relative importance of the different processes, a prerequisite for an improved understanding of the Arctic paleoclimate system.

The aims of this study therefore are to: a) perform the first inventory of deep marine Arctic trace fossils and their spatial and temporal variability, b) study the genetic relationship between bioturbation and the Mn-rich layers, and c) elucidate the environmental implications from the observed patterns in trace fossil distribution.

2 Background

2.1 Arctic hydrography

The Arctic Ocean is a semi-confined ocean with over half its area composed of shallow shelves (Fig. 1) (Jakobsson et al., 2003), and a narrow opening at the Fram Strait which provides the only deep-water connection to the World Ocean. These features make the Arctic Ocean especially sensitive to glaciations and associated sea-

level changes. The Arctic Ocean is separated into the Amerasian Basin and the Eurasian Basin by the Lomonosov Ridge. The Lomonosov Ridge is a sliver of continental crust rifted from the Eurasian continent about 55 Ma (Jokat et al., 1992) and rises steeply from the abyssal plains with depths of 3-5 km up to about 1000 m below the sea surface. It therefore acts like a barrier between the two basins resulting in considerably longer residence times for the deep waters in the Amerasian Basin (Tomczak and Godfrey, 2002). In the central part of the ridge, a bathymetric depression forms an intra-ridge basin, the so-called intrabasin. This intrabasin is connected to the Makarov Basin on the Amerasian side and the Amundsen Basin on the Eurasian side through relatively narrow channels with sill depths of about 1800 m (Björk et al., 2010; Björk et al., 2007). These conduit allows an exchange between the otherwise isolated deep waters of the two basins. The Lomonosov Ridge also forces the intermediate waters of Atlantic origin to form a cyclonic gyre in the Eurasian basin. On its way through the Eurasian basin the Arctic intermediate water is mixed with extremely cold waters that form on the shelves during sea ice formation. This cold and dense water then leaves the Arctic Ocean through the Fram Strait to form an important part of the global thermohaline circulation (Meincke et al., 1997; Tomczak and Godfrey, 2002). Surface and halocline water properties in the Eurasian Basin are mainly controlled by the inflow of Atlantic waters through the Fram Strait and via the Barents Sea, and mixing processes on the shelf areas (Rudels et al., 2004).

The surface circulation of the Arctic Ocean is dominated by the wind driven Beaufort Gyre over the Amerasian Basin and the Transpolar Drift that transports sea ice across the Eurasian Basin from the Siberian shelves to the Fram Strait. Sea ice is the main transporting agent for particles larger than clay and the position of the boundary between the Beaufort Gyre and the Transpolar Drift consequently has an

important role in controlling the composition of sediments deposited in the central Arctic region (e.g. Sellén et al., 2010). Today, primary productivity in the central Arctic Ocean is dominated by phytoplankton and ice-algae (Horner and Schrader, 1982) and almost all primary productivity takes place during the spring/summer season in open leads or under the thinner first year ice (Arrigo et al., 2012; Arrigo et al., 2008).

2.2 Arctic macrobenthos

Although the Arctic basin is considerably understudied in comparison to other oceans, several larger studies were performed in recent years addressing variation and abundance of benthic fauna from the shelves to the deep basins (e.g. Clough et al., 1997; Kröncke, 1994; MacDonald et al., 2010; Vanreusel et al., 2000). The results suggest that the fauna of the deep-sea floor is more diverse than previously believed. Biomass and macrofaunal diversity was found to be comparable to the lower end of the spectrum observed in other oligotrophic regions of the world (Piepenburg, 2005; Vanreusel et al., 2000). Although the organisms vary from site to site, significant regional differences exist (Renaud et al., 2006). Most studies found that the benthic fauna was dominated by polychaetes, crustaceans, echinodermata and bivalves (Bluhm et al., 2005; Deubel, 2000; MacDonald et al., 2010). Polychaetes being the most common in terms of abundance and taxon number (MacDonald et al., 2010). This dominance of polychaetes was especially apparent at deeper stations. Sea-floor photographs along a transect from the Chukchi Borderland to the Amerasian abyssal plain showed lebensspuren such as solitary holes, gastropod and crustacean tracks, as well as different trails at all stations (MacDonald et al., 2010).

The macrofauna in the Arctic Ocean is mostly of Atlantic type, and only a few endemic species are found (Kröncke, 1994). However, true species diversity is still

poorly known due to the sparse sampling density - the first quantitative megafauna studies were published in 2010 (MacDonald et al., 2010). Most of the benthic organisms found were deposit feeders, but increased numbers of suspension feeders were reported from rises such as the flanks of the Lomonosov Ridge (Deubel, 2000; Iken et al., 2005; Kröncke, 1998; Piepenburg, 2005). Food web structure studies based on $\delta^{13}C$ and $\delta^{15}N$ also showed that many benthic organisms were deposit feeders and that they use refractory organic material to a large extent in their metabolism (Iken et al., 2005).

These studies show a general pattern where biomass, abundance and diversity of the benthic fauna is inversely correlated with water depth and latitude, where latitude is a measure of the distance to the shelves and ice-margin (Bluhm et al., 2005; Clough et al., 1997; MacDonald et al., 2010; Piepenburg, 2005; Renaud et al., 2006; Van Averbeke et al., 1997). Similar results have been obtained from studies of benthic foraminifer (Wollenburg and Kuhnt, 2000) and ostracode (Cronin et al., 2010) distributions. Some studies noted an increase in biomass and abundances towards the Lomonosov Ridge (Clough et al., 1997; Kröncke, 1994), possibly related to a lateral input of organic material by ocean circulation along the slope of the ridge.

2.3 Arctic sediments

Arctic Ocean sediments differ from the general oceanic sediments in several ways. The sediments show extreme variations in grain size, varying from hemipelagic muds to coarse-grained ice rafted debris (IRD), with maximum IRD content characteristically occurring in intervals corresponding to late glacial and deglacial intervals (*Phillips and Grantz*, 2001). There are also larger spatial and temporal variations in sedimentation rates than typically found in the open oceans because of variations in the transport paths of sea ice and icebergs. The processes delivering

sediment to the Arctic Ocean are dominated by river discharge, coastal erosion, current transport, turbidites and slumping, while aeolian transport plays only a minor role (*Stein*, 2008). The bulk of the sediment deposited in the central Arctic Ocean is transported by sea ice or icebergs, whose trajectories are governed by the two major circulation patterns, the Beaufort Gyre and the Transpolar Drift. The mineralogical composition of the sediment that enters the Arctic is controlled by the geology of the surrounding land masses, with the Canadian Arctic and Greenland containing abundant carbonate rocks, while widespread basaltic rocks on the Eurasian side results in sediment with abundant heavy minerals (*Stein*, 2008). It has long been recognized that these differences in bedrocks results in clearly distinguishable mineral assemblages (*Lapina*, 1965; *Levitan et al.*, 1999) or chemical composition (*Rachold et al.*, 1999) in the IRD, reflecting the origin of the sediment. These differences also result in characteristic distributions of clay minerals in the Arctic region, providing a powerful tool to tie Arctic sediments to their source regions (Wahsner et al., 1999; Vogt, 1997).

One of the most conspicuous features of late Quaternary Arctic sediments is the cyclical occurrence of brownish, Mn-rich layers observed in sediment cores from all over the deep Arctic Ocean (Clark et al., 1980; Jakobsson et al., 2000; Polyak, 1986; Poore et al., 1993). Biostratigraphic dating and the cooccurrence with enhanced levels of benthic and planktonic foraminifera show that these layers formed during interglacial conditions (Jakobsson et al., 2000; Löwemark et al., 2008; Poore et al., 1993) (O'Regan et al., 2008; O'Regan et al., 2010). However, the mechanism for the formation of these layers remains debated, and several different physical and chemical processes have been invoked (Macdonald and Gobeil, 2011; März et al., 2011). In most modern sediments, Mn-rich layers typically form close to the sediment surface

where Mn mobilized by the degradation of organic matter encounters downwards diffusing oxygen from the bottom waters, thereby marking the position of the redox boundary (e.g., Burdige, 2006; Froehlich et al., 1979). It has therefore been suggested that the Mn observed in Arctic sediments would largely represent diagenetic processes (Li et al., 1969). However, the recurrent down-core and near synchronous occurrence of Mn enrichment, bioturbation, and calcareous micro- and nannofossils strongly suggest that the Mn enrichment formed as a direct response to environmental conditions in the circum Arctic region. Changes in deep water ventilation and the related dissolution or precipitation of Mn, and variations in Mn input from the terrestrial realm are the two main mechanisms that have been discussed (e.g., Jakobsson et al., 2000; Löwemark et al., 2008; Macdonald and Gobeil, 2011; Mashiotta et al., 1999). That the dramatic changes in basin geometry and sea ice cover related to glacial-interglacial climatic swings also greatly affect Arctic deep water circulation is obvious (Haley et al., 2008; Jakobsson et al., 2010; Poirier et al., 2012). However, in order to remove Mn from the sediment the bottom waters must become depleted of oxygen, which would require a steady flux of labile organic matter to the sea floor. As primary productivity reaches absolute minima during glacial periods, a depletion of bottom water oxygen seems unlikely. Further arguments against oxygen depletion of Arctic bottom waters comes from the presence of benthic ostracodes which persist also in glacial intervals, evidencing at least minimal oxygen levels in the deep basins (Poirier et al., 2012). An active removal of Mn from the sediment during glacial intervals was also deemed unlikely when the ratios of Mn to Al were studied. März et al (2011) demonstrated that glacial Mn/Al ratios actually lie close to average shale values, strongly suggesting that no Mn was dissolved from the sediments.

Instead, Maconald and Gobeil (Macdonald and Gobeil, 2011) demonstrated through Mn budget calculations that changes in coastal erosion and riverine input can explain the large variability in Mn observed. During interglacials, the high sea level promoted intense coastal erosion and remobilization of Mn on the shelves at the same time as the Mn-rich circum-Arctic rivers flew unhindered into the Arctic Ocean. In contrast, during glacial periods, the low sea level hindered coastal erosion while the Arctic rivers were blocked by the Eurasian ice sheet, both processes limiting the supply of Mn to the Arctic Ocean. Maconald and Gobeil (Macdonald and Gobeil, 2011) did not include hydrothermal input into their budget calculations as data is still exceedingly scarce, but several lines of evidence speak against a hydrothermal origin of the Mn enriched layers. First, modern Mn concentrations are highest in near surface waters and show a clear correlation with salinity minima (Middag et al., 2011), strongly indicating a riverine or shelf origin rather than a hydrothermal. Second, the Mn plume observed in the water column over the Gakkel Ridge shows a maximum between 2000 and 4000 m, and very low values above 2000 m (Middag et al., 2011). Since Mn enriched layers are ubiquitous in sediments retrieved at water depths even shallower than 1000 m (Jakobsson et al., 2000; Macdonald and Gobeil, 2011), hydrothermal sources are considered unlikely. Third, Mn concentrations in the water column show exponentially decreasing values with distance from the ridge (Middag et al., 2011), making a basin wide influence unlikely although locally the effect of hydrothermal input may be significant. Fourth, there is no reason to assume any significant glacial-interglacial variability in the hydrothermal input of Mn.

3 Material and methods

The core material used in this study was obtained during four expeditions to the Arctic Ocean using the ice breakers Ymer (YMER 80) and Oden (Arctic Ocean

96, LOMROG-07, LOMROG-09) as research platforms. The 12 piston and gravity cores vary in length between 198 and 765 cm (Table 1) and consist primarily of ice rafted debris (IRD) and pelagic muds. The sampled area spans from the Makarov Basin to the Yermak Plateau via the central Lomonosov Ridge, the Lomonosov Ridge off Greenland, the Gakkel Ridge, and the Morris Jesup Rise (Fig. 1).

Physical properties were analyzed onboard using a GEOTEK Multi Sensor Core Logger during LOMROG-07 and LOMROG-09, while AO96-12pc was measured at Stockholm University. Variations in Mn distribution were determined directly on split cores using the Itrax XRF-core scanner (cf. Croudace et al., 2006) at Stockholm University. The resolution used for XRF-scanning ranged from 0.2 to 5 mm. Exposure times were adjusted to the individual cores and typically vary between 5 and 20 seconds. X-ray radiographs were produced by cutting thin slabs of sediment from the cores using plastic boxes approximately 6 mm thick (cf. Löwemark and Werner, 2001; Werner, 1967). The slabs were then analyzed (55kV/3mA, 3 minutes) at the X-ray facility in the Faculty of Geosciences at the University of Bremen.

On a limited number of the sediment slabs used for X-ray radiography from AO96-14GC, detailed studies were performed using microscope and scanning electron microscope. In intervals containing denser, horizontal layers in the radiographs, the corresponding sediment slabs were meticulously subsampled and the sediment studied under microscope to identify the aggregates causing this layering. A number of grains were selected and analyzed with SEM and electron microprobe (Philips Analytical XL-30- *ESEM*-FEG) to study the chemical composition of individual grains.

4 Results

4.1 Trace fossils and spatial differences in their distribution

The trace fossil fauna is generally sparse with only a few ichnospecies or ichnogenera present. In most sediment cores *Planolites*-like structures were observed and many cores contain small, mineralized burrows similar to *Trichichnus*. The trace fossils *Chondrites*, *Phycosiphon*, and *Scolicia* occur sporadically. In two of the cores isolated occurrences of *Zoophycos* were noted. *Nereites*-like traces were abundant in core LOMROG09-PC10, but occurred only sporadically in a few other cores. On several occasions, biodeformational structures (cf. Bromley, 1996) without any identifiable trace fossils were observed. Basic trace fossil morphology and ethology is described in Table 2.

The abundance of trace fossils in the cores shows a clear spatial pattern. The cores from the central Lomonosov Ridge, the Makarov Basin and the Yermak Plateau display stronger bioturbation with more diverse ichnofauna than those from the Lomonosov Ridge off Greenland, Morris Jesup Rise and the Gakkel Ridge (Fig. 2). In cores from the Lomonosov Ridge off Greenland, a few *Planolites*-like traces were found in the top sections and a few mineralized tubes scattered in the lower parts of the cores. A common feature in the cores from the Lomonosov Ridge off Greenland, the Morris Jesup Rise, and the Gakkel Ridge is the high content of IRD seen in the radiographs. The core from the Gakkel Ridge is almost completely devoid of biogenic structures. This core was taken on the flank towards the Amundsen Basin, and the sediment fabric is almost totally dominated by primary sediment structures indicating that it could be a contourite body. With the exception of the Gakkel Ridge, areas with few trace fossils correspond to the regions experiencing the most severe ice-

conditions, today characterized by nearly complete ice-coverage even during summer (Comiso et al., 2008).

4.2 Chronostratigraphy and sedimentation rate variability

To allow comparisons between down-core variations in trace fossil composition and paleoclimatic variations, we relied on published age models and stratigraphic correlations between relatively closely spaced cores. Abundances of calcareous nanno- and microfossils were previously used to locate marine isotope stages (MIS) 5, 3 and 1 on the Lomonosov Ridge (Backman et al., 2009; Spielhagen et al., 2004), Lomonosov Ridge off Greenland (Jakobsson et al., 2010), Morris Jessup Rise (Hanslik et al., in press; Jakobsson et al., 2010) and the Yermak Plateau (Dowdeswell et al, 2010).

Only some of the cores from the central Lomonosov Ridge have tentative age models that extend beyond MIS 6. These are based on the cyclostratigraphic analysis of the ACEX record (O'Regan et al., 2008), and stratigraphic correlations to near-by sediments using bulk density and XRF-derived Mn profiles (Fig.3).

A number of cores collected from the Lomonosov Ridge (LOMROG09-PC08, LOMROG09-PC05, LOMROG09-PC10, AO96-14GC, AO96-16-GC) and Gakkel Ridge (AO96-B13-1PC) either lack the required physical property data for establishing stratigraphic correlations, or display a more complex downhole bulk density profile that precludes straightforward alignment with the ACEX record (Fig. 4). To provide tentative age control, we rely on a distinct dark-grey layer as a common tie point to other cores from the region. It is characterized by a sharp lower boundary, enhanced IRD content, prominent variations in elements such as Fe and Ti, and often bounded by a sharp shift in Mn content. The sharp lower boundary and the distinct sedimentary and geochemical features of this layer suggest synchronous

deposition over much of the Eurasian Basin. On the central Lomonosov Ridge, the grey-layer is found near the base of a coarse grained diamicton deposited around the MIS 3/4 boundary (Spielhagen et al., 2004). In some cores, a second grey layer is found near the base of a second prominent coarse-grained diamicton associated with MIS6 (Fig. 4). Below these grey layers and the associated Mn minima, MIS 5 can usually be identified through the correlation of a triplet of Mn peaks (Fig. 4). We do not attempt to extend the age model further back than MIS 5 in these records.

Sedimentation rates in the studied cores range from 0.2 to 2.1 cm/ky with typical values around 0.5-1 cm/ky (Table 3), which is in agreement with what has been observed in earlier studies (Backman et al., 2004; Sellén et al., 2008; Spielhagen et al., 2004). The cores from the central Lomonosov Ridge have higher average sedimentation rates compared to the cores from the Makarov Basin, Morris Jesup Rise, and the Lomonosov Ridge off Greenland, where sedimentation rates are generally below 1 cm/ky. The Gakkel Ridge is somewhere intermediate with 1 cm/ky, but the age model lacks any firm age control points. The highest sedimentation rates were observed on the Yermak Plateau (2.0cm/ky) and in the top section of LOMROG09-PC08 from the crest of the Lomonosov Ridge (2.1cm/ky).

A seemingly general difference in sedimentation rates was observed between gravity cores and piston cores, the later having higher sedimentation rates. It is uncertain whether this is due to sediment shortening, which is often observed in gravity cores (Emery and Hülsemann, 1964; Löwemark et al., 2006), or if it represents an actual difference in sedimentation rate between the sites. Sedimentation rates in the younger interval, MIS 1 to 7, are considerably higher than in the older intervals, where sedimentation rates are often half or less. Explanations for this observation include a) the expected downhole decrease in sediment porosity due to mechanical

compaction, which is especially pronounced in the upper few meters of sediments, and b) the occurrence of relatively thick sandy intervals previously described as diamictons (Svindland and Vorren, 2002) that occur during late Quaternary glacial/stadial stages (MIS 6, 5b, 5/4 and 3/4) in the central Lomonosov Ridge cores (Spielhagen et al., 2004).

4.3 Temporal variations in trace fossils and bioturbation

4.3.1 Lomonosov Ridge off Greenland, Morris Jesup Rise, and the Yermak Plateau

In the cores from the Lomonosov Ridge off Greenland, the ichnofauna is sparse consisting primarily of *Planolites*-like burrows concentrated to the brown layers in MIS 1 and 5 (Fig. 5). In the lower part, below MIS 5, only occasional, mineralized *Trichichnus* and *Chondrites* were found. Both cores contain large amounts of IRD, and in the lower part conspicuous bands of closely spaced, horizontal, thin layers are visible in the X-ray radiographs. High-resolution XRF-scanner measurements clearly show that these thin and dense layers are enriched in Mn. The core from the Morris Jesup Rise was taken in the centre of an iceberg-scour (Jakobsson et al., 2010) and the sediments below the erosional surface at about 128 cm are likely pre-Quaternary. Some *Planolites*-like traces were observed in MIS 5 while glacial intervals are free of trace fossils. The core contains abundant IRD, although not as much as the cores from the Lomonosov Ridge off Greenland. Just below MIS 1, which consists of homogenous, IRD-rich, non-bioturbated sediment, a number of horizontal, Mn-rich bands similar to the ones observed in the cores on the Lomonosov Ridge off Greenland are seen.

The core from the Yermak Plateau differs markedly from the cores on the Lomonosov Ridge off Greenland and the Morris Jesup Rise (Fig. 5). Sedimentation

rates are almost an order of magnitude higher here and bioturbation is much more intense and diverse with *Planolites*, *Phycosiphon*, and possibly *Trichichnus* in the Holocene part, and biodeformational structures in the last glacial interval. MIS 3 is characterized by enhanced levels of IRD and an ichnofauna dominated by *Planolites* and *Trichichnus*. Interestingly, an interval in MIS 3 characterized by brownish colour and high Mn content is totally barren of trace fossils but contains extreme amounts of IRD.

4.3.2 Central Lomonosov Ridge

The cores from the central Lomonosov Ridge display a more intense bioturbation and diverse ichnofauna consisting of large numbers of *Planolites*-like burrows, occasional *Phycosiphon*, numerous mineralized small tubes belonging to *Chondrites* and *Trichichnus*, abundant *Nereites* in certain intervals, and a few occurrences of *Zoophycos* in the deeper cores. In all cores there is a clear overall correspondence between bioturbation intensity and intervals with brown, mottled sediments rich in Mn (Figs. 6 & 7). There is also a more diverse ichnofauna in the deeper cores from the slope and intrabasin as compared to the cores from the ridge crest (Table 3). The ichnofauna in the cores from deeper sites contain more complex traces such as *Nereites* and *Zoophycos*.

4.3.3 Makarov Basin and the Gakkel Ridge

The two cores from the basins, LOMROG09-GC03 (3814 m water depth) from the Makarov Basin and AO96-B13 (2079 m water depth) from the Gakkel Ridge, display diametrically opposed patterns although both are situated in relatively deep waters away from the Lomonosov Ridge. In the Makarov Basin the ichnofauna is fairly diverse with four different ichnospecies: *Chondrites*, *Nereites*, *Phycosiphon*, and

Planolites. In contrast, on the Gakkel Ridge only uncertain *Planolites*-like traces were observed. In the Makarov Basin the trace fossils display the same pattern as on the ridge crest, closely following variations in Mn (Fig. 7).

4.4 Individual trace fossils and their interpretation

The sparse occurrence of trace fossils and the low diversity make it difficult to determine the ichnofacies of the studied cores. However, the presence of *Zoophycos* and *Nereites* together with the generally deep bathymetric position of the cores suggest either *Zoophycos*- or *Nereites*-ichnofacies (cf. Seilacher, 1964). The low ichnodiversity also makes it irrelevant to use terms such as ichnocoenosis or ichnoassemblages to describe the ichnofabric, which is almost always totally dominated by one or two ichnospecies. The low ichnodiversity also limits the development of tiering of different trace fossils into different vertical zones in the sediment. There is little evidence for any deep-reaching burrows apart from mineralized, thin tubes such as *Trichichnus* and *Chondrites* which are seen to cross-cut the other trace fossils. A thorough look at the individual trace fossil species reveals additional information about the depositional settings and the variations in environmental parameters.

4.4.1 Chondrites

Chondrites occurs sporadically in 9 out of 12 cores and is usually found in or just below sediments with enhanced Mn levels. It often occurs together with *Trichichnus* or *Planolites*. Together with *Trichichnus* it is usually the trace fossil reaching deepest into the sediment, cross-cutting the other traces.

Chondrites are believed to represent a chemosymbiotic behavior where the producing organism utilizes the redox gradient between anoxic pore waters and

oxic/dysoxic bottom waters to cultivate microbes for food or energy (Fu, 1991; McBride and Picard, 1991; Seilacher, 1990). The burrow producers consequently have a high tolerance for low-oxygen pore-water conditions. Massive occurrences of *Chondrites* have been interpreted to be indicative of poorly oxygenated bottom waters creating favourable conditions for an opportunistic colonization of a niche inaccessible to other burrowers (Ekdale, 1985; Ekdale and Mason, 1988). In contrast, where deep reaching *Chondrites* occupy the deepest tiers, it represents a equilibrium behaviour. For example, on the Iceland-Færø ridge, where bottom water conditions on the northern side are sluggish, the ichnofauna is dominated by dense occurrences of *Chondrites*, while the southern slope where bottom water circulation is more vigorous, the ichnofauna is characterized by a diverse set of trace fossils (Fu and Werner, 1994). Similarly, on the Portuguese continental slope massive occurrences of *Chondrites* are found in intervals characterized by sluggish bottom-water currents and the deposition of organic-rich sediments. Conversely, intervals where TOC content and grain size indicated well-oxygenated conditions were characterized by *Chondrites* at deep tiers below the other traces indicating equilibrium positions (Löwemark, 2003).

Accordingly, in the Arctic Ocean, the sparse occurrence of *Chondrites* rather suggest stable conditions with oxygenated bottom waters where *Chondrites* occupies the deepest tier and therefore avoids obliteration by larger burrowers (cf. Savrda and Bottjer, 1986). In most cores they are primarily found in the interglacial sections where they inhabit a deep tier cross-cutting the few other traces present. This suggests an equilibrium behavior where the producers colonize the deeper parts of the sediment whenever the food flux is rich enough.

4.4.2 Nereites

Nereites, or Nereites-like traces, only occur in three cores. In LOMROG09-GC03 from the Makarov Basin, it is found in the interstadial/glacial interval around MIS 3 and during an interglacial interval tentatively associated with MIS 11. In LOMROG09-PC05 from the intrabasin only one uncertain observation at the top of what is believed to be the interglacial MIS 5 was made. In contrast, the third core containing *Nereites*, LOMROG09-PC10 from the slope of the Lomonosov Ridge, shows massive occurrences of *Nereites* in all interglacials before MIS 5, but no *Nereites* in stage 5 or younger sediment. These three cores were taken at water depths exceeding 2 km. *Nereites* is generally cross-cut by other traces suggesting a shallow tier.

The winding horizontal trace fossil *Nereites* is so common in fossil strata from turbiditic settings that Seilacher (1967) named one of his archetypical ichnofacies after it. Later the *Nereites* ichnofacies was expanded to encompass bathyal to abyssal settings with slow stable sedimentation and well oxygenated conditions (Frey and Pemberton, 1984).

In fossil strata, *Nereites* is usually the uppermost tier and is almost exclusively preserved as horizontal, winding traces (Seilacher, 1962). The preservation is often linked to frequent turbidites preventing a subsequent obliteration by later, deeper burrowers. The shallow tier makes observations on *Nereites* in sediment cores rare as top sediments are usually too soupy to allow the preparation of X-ray radiographs, and in the part of the core under the mixed layer, deeper penetrating traces have destroyed *Nereites*. However, in a suite of 19 box cores taken in the South China Sea, detailed studies show that the trace fossil starts almost vertical and penetrates down to just above the redox boundary where it levels out and becomes almost horizontal,

keeping a constant distance of 1-2 cm to the redox boundary (Wetzel, 2002). Wetzel (2002) suggested that the producers fed on bacteria which thrived on organic matter available at the boundary between reducing and oxidizing conditions. In the Arctic Ocean material, *Nereites* only occurs in settings deeper than 2 km and it is only on the Amundsen basin slope of the Lomonosov Ridge (LOMROG09-PC10) that *Nereites* occurs abundantly. This abundant occurrence in presumably interglacial intervals indicates fairly high food fluxes, well-oxygenated bottom waters, and a redox boundary that is situated some 3 to 9 cm into the sediment (cf. Wetzel, 2002). The disappearance of *Nereites* in glacial intervals with low Mn content could suggest either decreased food flux or decreased bottom water oxygenation or a combination of both.

Today the Eurasian flank of the Lomonosov Ridge experiences enhanced food flux because of lateral advection by the Arctic Intermediate Water. Deubel (2000) indeed found lateral sediment transport along the Lomonosov Ridge to be an important mechanism for the distribution of food and consequently for the distribution of benthos. In this context it is therefore interesting to note a distinct change in the ichnofauna from abundant *Nereites* below MIS 5 to no *Nereites* in MIS 5 and above, in core LOMROG09-PC10. This could be indicative of a major reorganization in the Arctic deep-water circulation around the boundary between MIS 6 and 5. The nature of this oceanographic change remains elusive, however.

4.4.3 Phycosiphon

Phycosiphon was only found in one short interval in the core from the Yermak Plateau where it is situated between a *Planolites* dominated interval below, and *Trichichnus* burrows above. *Phycosiphon* is the trace of a deposit feeder and is interpreted to be an indicator for oxic to dysoxic conditions (Ekdale and Mason,

1988). Studies of *Phycosiphon* from the Indian Ocean (Wetzel and Wijayananda, 1990) and the Iceland-Faroe Ridge (Fu and Werner, 1994) both show a shallow tier position and a preference for well oxygenated conditions. The position above an interval with *Planolites*, which require high oxygen levels, but below an interval with *Trichichnus*, which tolerate low oxygen levels, therefore could indicate a trend of decreasing bottom water oxygenation in the upper part of the Holocene section of this core.

4.4.4 Planolites

Planolites, or rather *Planolites*-like traces were observed in all cores. The occurrences of *Planolites* show a close correspondence to brownish layers and increased Mn content.

Planolites is a trace left by a wide range of deposit-feeding organisms that require rather well-oxygenated conditions. As larger organisms require more oxygen for their metabolism than small ones (Savrda and Bottjer, 1989), the size of *Planolites* has been used as an indicator for variations in bottom water oxygen levels (Tyszka, 1994; Wetzel, 1991). Studies of trace fossils from the continental slope off Portugal (Löwemark et al., 2004) and the Iceland-Faroe Ridge (Fu and Werner, 1994) show that in sediments deposited under sluggish, poorly oxygenated bottom waters, only few and small *Planolites* were observed and the ichnofauna was dominated by traces such as *Chondrites*. In contrast, where bottom water ventilation was vigorous the ichnofauna contained numerous, large *Planolites* and other traces such as *Scolicia* that are known to thrive under well-oxygenated conditions.

The strong correspondence between *Planolites* and Mn-enrichment therefore suggest that bottom waters were fairly well oxygenated during the interglacial intervals when Mn was precipitated.

4.4.5 Scolicia

Scolicia-like traces were observed in core LOMROG09-PC08 and AO9616-2GC from the crest of the Lomonosov Ridge, and in LOMROG09-PC10 from the slope of the Lomonosov Ridge. *Scolicia* is a deposit feeding trace produced by irregular sea urchins, and the producers have a profound preference for well-oxygenated, silty sediment (Fu and Werner, 2000). The occurrence together with numerous oxygen demanding traces such as *Planolites* or *Nereites*, in sediment with low IRD-content consequently agrees well with the stratigraphic positions in interstadial MIS 3 when more food, less IRD, and better oxygenated bottom waters would be expected.

4.4.6 Trichichnus

Trichichnus and similar trace fossils with cemented tubes occur in about half of the studied cores, often the burrows are mineralized, presumably by the formation of Rhodochrosite (cf. Eriksson et al., submitted; Taldenkova et al., 2010). In cores with weak bioturbation the *Trichichnus* tubes tend to be concentrated to Mn-rich intervals while in more strongly bioturbated cores with abundant trace fossils the *Trichichnus* tend to occupy the Mn-poor intervals between the interglacial intervals. This pattern is especially apparent in cores LOMROG09-PC08 and LOMROG09-PC10 (Fig. 6). On the Vöring Plateau off Norway, sipunculid worms were shown to produce modern *Trichichnus* (Romero-Wetzel, 1987), and the trace has been interpreted to represent a chemosymbiotic behavior where the organism utilizes the redox gradient much in the same way as the producers of *Chondrites* (McBride and Picard, 1991). The occurrence of *Trichichnus* between strongly bioturbated intervals therefore may be the opportunistic response to a niche that cannot be accessed by other burrowers because of decreased food flux during glacials. The decrease in input

of organic carbon would result in a downwards shift in the redox boundary, forcing the trace makers to construct the long vertical burrows observed in the glacial sediment. Deep below the sediment surface they then utilize microbes to access the refractory carbon available in the sediment.

The fact that the glacial intervals between the *Nereites*-dominated sections are characterized by numerous *Trichichnus* and *Chondrites* burrows, whose producers are believed to utilize the redox gradient between dysoxic pore waters and oxic bottom waters (Blanpied and Bellaiche, 1981; Löwemark, 2003; McBride and Picard, 1991), suggest that Arctic bottom water oxygenation levels remained oxic even during glacial intervals. This interpretation is further supported by the presence of ostracodes in glacial intervals (Poirier et al., 2012), which require oxygenated waters to survive.

4.4.7 Zoophycos

Zoophycos spreiten occur in conjunction with interglacial intervals in the core from the intrabasin, and in the core from the slope towards the Amundsen Basin. Both single horizontal spreiten and inclined spreiten diverging from a central axis were observed. However, neither the central shaft nor open marginal tubes were found in the studied material. None of the spreiten show the typical minor lamellae found in many types of *Zoophycos*, but are homogeneous.

Zoophycos is actually a diverse group of complex spreiten structures for which a plethora of ethological explanations has been put forward (cf. Bromley, 1991; Fu and Werner, 1995; Gong et al., 2008; Kotake, 1997; Olivero, 1995). For the *Zoophycos* found in Quaternary deep marine settings, however, it has been shown that the trace likely is a cache where food is squirreled away for use when food becomes less plentiful (Löwemark, 2012; Löwemark and Schäfer, 2003).

Thus, although the presence of *Zoophycos* is sparse, it can be viewed as an adaptation by the benthos to the strong seasonality in food flux (Arrigo et al., 2008) observed in the Arctic Ocean today. It has been postulated that this kind of adaption would be expected in the Arctic Ocean because of the extreme difference in food flux between summer and winter seasons (Van Averbeke et al., 1997). During Arctic summers the primary productivity is extremely high due to the permanent sun-light and high nutrient concentrations. Conversely, during Arctic winters, the complete ice coverage and total darkness results in extremely low food fluxes to the sea floor. The *Zoophycos* producers would collect food during the rich summer months and store it deep in the sediment to be used during the poor winter months (Löwemark, 2012). In contrast, during glacial intervals the ice cover may have neared 100% also during in summers, with primary productivity limited all year round, resulting in unfavourable conditions even for *Zoophycos*.

4.5. Horizontal bands of Mn

In four of the studied cores, distinct thin, horizontal bands were observed in the radiographs, and are expressed as higher Mn values in the XRF-scanner data (Fig. 8). These bands have the appearance of horizontal layers that are lighter, thus more dense, than surrounding sediment, or as layers of frost-like crystals that extend in a dendritic fashion downwards and therefore must have formed *in situ*. This kind of horizontal bands were found in two cores from the Lomonosov Ridge off Greenland, on the Morris Jesup Rise and in one core from the crest of the central Lomonosov Ridge. Only in core LOMROG07-GC10 on Morris Jesup Rise can the layers be dated with any certainty as they occur between MIS 1 and a dark grey layer likely deposited at the MIS 3-4 boundary. In the cores from the Lomonosov Ridge off Greenland they occur in what could be MIS 5 and MIS 7, but here age control is weak. In AO96-

14GC from the central Lomonosov Ridge the horizontal bands are situated between MIS 5 and MIS 7. The bands occur in sediment that does not show any sign of bioturbation and in three of the intervals the sediment does not display the typical brownish colour associated with Mn-rich sediments despite the high Mn content. High-resolution XRF-scanning was performed on a selected number of sediment slabs used for X-ray radiography in core AO96-14GC. Subsamples taken in the interval containing the frost-like crystals show that the grains consist of small blackish aggregates of quartz grains cemented and draped by a Mn-rich matrix (Fig. 9).

5 Discussion

5.1 Spatial variability in bioturbation and trace fossils

The difference in abundance and diversity between the individual regions, with sparse ichnofauna on the Lomonosov Ridge off Greenland and on the Morris Jesup Rise, and relatively abundant and diverse ichnofauna in the central Arctic, is in agreement with the spatial variability of several environmental parameters. For one, the cores from the sites north of Greenland contain considerably more IRD than the sites from the central Arctic. Although sediment composition and substrate consistency exert a major control on animal behavior and burrow construction (Bromley, 1996), studies from the Greenland Sea suggest that grain-size variations and IRD has only minor influence on benthic biomass and diversity (Schnack, 1998). In contrast, a recent review showed that grain size variation, bottom-water oxygenation, food flux and bottom-current intensity are the main factors controlling species abundance and diversity (Levin et al., 2001). These are also the factors identified as the most important ones controlling variations in trace fossils (Wetzel, 1991). In the area north of Greenland food flux is low because of the tough sea-ice

conditions (Comiso and Nishio, 2008) and the sediment has been impacted by drifting icebergs at least during MIS 6 (Jakobsson et al., 2010). In sediments on the West Antarctic Peninsula increased iceberg scouring was shown to strongly increase the mortality of benthic organisms (Barnes and Souster, 2011). It remains unclear, however, if iceberg scouring during glacial periods would have any impact on the interglacial benthic fauna. Nevertheless, a combination of factors unfavourable for benthic organisms coincides and results in a sparse ichnofauna and weak bioturbation in this region. In the central Arctic, summer sea-ice conditions are less severe resulting in stronger food flux, and the sediment contain less IRD, creating more favourable conditions for benthic life.

The most intense bioturbation was found in the core from the Yermak Plateau while the weakest bioturbation was found on the Gakkel Ridge, with the central Lomonosov Ridge taking a middle position. This agrees with observations on the modern distribution of benthos in the Eurasian Basin. The biomass on the Morris Jesup Rise and on Gakkel Ridge showed low values similar to the deep basins while the Lomonosov Ridge and the Yermak Plateau displayed higher biomass (Kröncke, 1994; Kröncke, 1998). It is therefore reasonable to assume that the factors controlling the benthos today should also be reflected in the down-core variations in bioturbation intensity and trace fossil composition.

5.2 Temporal variability in bioturbation and trace fossils

That food is an important factor controlling bioturbation is corroborated by the temporal variability in trace fossil abundance and diversity. The cores from the central Arctic clearly show a strong increase in bioturbation during interglacial intervals when decreased sea-ice and more open-water conditions led to enhanced primary productivity. In the area north of Greenland this connection is not as distinct as there

is only a sparse ichnofauna to begin with, but the few trace fossils that do occur are concentrated to interglacial intervals. The hypothesis that brownish, Mn-rich intervals were deposited under interglacial conditions when biological activity at the sea-floor was stronger therefore seems to be validated. However, while the Mn cycles representing glacial-interglacial changes are ubiquitous in both the Eurasian and Amerasian Basins (Clark, 1970; März et al., 2011; Phillips and Grantz, 1997), the response in bioturbation appears more spatially limited and is likely a consequence of variations in perennial sea-ice cover.

From the observations on trace fossil distribution and Mn cycles in combination with recent work on the Arctic Mn-budget (Macdonald and Gobeil, 2011) and detailed studies on the geochemistry of the Mn-rich layers (März et al., 2011), a conceptual model for the formation of the Mn layers may be drafted.

During interglacial periods (Fig. 10), when ice sheet are restricted to Greenland and high sea levels flood the huge shelf areas, large amounts of Mn enters the Arctic Ocean from riverine input and coastal erosion. This Mn is initially deposited on the shelves where it undergoes a number of redox cycles before it enters the deep ocean where the low organic carbon levels allow preservation and incorporation into the geological archive (Macdonald and Gobeil, 2011). The enhanced primary productivity caused by increased open waters led to an increased food flux, resulting in a more intense bioturbation. As organic particles are known to effectively scavenge Mn from the water column (Johnson et al., 1996; Martin and Knauer, 1980), this process also most likely contributed substantially to the enhanced Mn levels observed in interglacial sediments. The bio-irrigation of the sediment caused by the mixing activities of the benthic organisms control the depth of the redox boundary, and therefore also ensure a close to synchronous position of increased Mn

levels and increased bioturbational structures in the sediment. Post sedimentary Mn diagensis, although locally of large importance, play an insignificant role in the formation of the interglacial Mn maxima

During glacial periods, characterized by the enormous ice sheet and drastically lowered sea level, the input of Mn by rivers and coastal erosion was limited to a minimum (Macdonald and Gobeil, 2011), while the perennial ice pack that covered the remaining Arctic basin prohibited or at least strongly limited primary productivity even during the summer months, and as a consequence the food flux to the sea floor also decreased, resulting in a sparse benthic fauna. A decreased flux of organic particles through the water column would also drastically reduce scavenging of Mn. The remaining benthic organism resorted to the use of refractory carbon deep in the sediment which they accessed with the help of chemosymbiotic strategies involving microbes that took advantage of the redox gradient between pore waters and bottom waters. The resulting sediments are characterized by a sparse ichnofauna dominated by *Chondrites* and *Trichichnus*, Mn levels close to lithogenic background levels and few or no planktic foraminifera.

5.3. The horizontal bands of Mn and diagenetic alteration of Mn-distributio

The comparison of X-ray radiographs, XRF-scanner data of down-core Mn variations, and lithological appearance of the sediment reveal two deviations from the general pattern of strong bioturbation in the Mn-rich sediments, and weak bioturbation in sediments with low Mn content. First, some intervals display vigorous bioturbation although XRF-scan data show minima in Mn, and second, in other intervals strong maxima in Mn occur in sediments completely devoid of trace fossils. The first case is clearly related to an IRD-rich grey layer often found close to the boundary between MIS 3 and 4, but in some instances also near MIS 6. Below these

grey layers, the Mn content drops to levels close to zero, but the sediment still contains numerous trace fossils indicating interglacial/interstadial conditions. For example, in AO96-14GC from the central Lomonosov Ridge the sediment below the layer is vigorously bioturbated by *Planolites*-like structures but the Mn content is close to zero. Just below the boundary between the overlying IRD-rich layer and the bioturbated, fine grained sediment, a sub-vertical trace fossil with the characteristics of an escape trace can be seen (Fig. 11). The sharp boundary marking the shift from fine-grained sediments to IRD-rich sediments and the escape trace suggest that this layer was deposited extremely rapidly. This event-like layer would act as a lid shutting off downwards diffusion of oxygen into the sediment. As pore-water oxygen in the underlying sediment is consumed, pore water would become anoxic and the Mn originally present would dissolve and diffuse and re-precipitate in overlying regions. This is seen as a sharp Mn peaks just above the grey, Mn-poor intervals (Fig. 6). Thus, the Mn originally deposited during interglacial conditions has disappeared, but the trace fossils remain as witnesses. The extremely low levels of Mn underneath the grey layer also is a strong argument against the hypothesis that oxygen depletion of the bottom waters during glacial intervals would be the explanation for the low Mn content in these intervals. The XRF-scanner data clearly show that most glacial intervals still contain Mn, while the interval just below the grey layer is close to zero, evidently because of dissolution of Mn under anoxic conditions.

The formation of the thin, horizontal Mn layers is more enigmatic. The horizontal closely spaced banding and the presence of repeated layers of frost-like crystals clearly show that these layers must have formed by repeated shifts in the position of the redox boundary, and that the redox boundary was situated well below any active bioturbation. However, why the redox boundary fluctuated strongly in

certain intervals is presently unclear. We can only speculate that intermittent inflow of well-oxygenated waters during glacial intervals resulted in the repeated diffusion of oxygen into dysoxic pore waters and controlled the formation of these layers.

6 Conclusions

The detailed observation of variations in type and intensity of bioturbation in combination with high-resolution XRF-scanner data on Mn variations in sediment cores from the Arctic Ocean allow a number of conclusions to be made:

- The Arctic deep-sea ichnofauna is sparse consisting primarily of *Planolites*, *Trichichnus*, and *Chondrites*, locally abundant *Nereites*, and occasional *Phycosiphon*, *Scolicia*, and *Zoophycos*. The trace fossil fauna suggest an *Nereites* or *Zoohycos* ichnofacies.
- The spatial variability in trace fossil abundance and diversity agree with modern patterns in the distribution of benthic organisms, indicating that the trace fossil variability is strongly controlled by food flux, which is controlled by the geographic positions in relation to continental shelf breaks and sea ice margin.
- Trace fossil abundance and diversity show strong glacial-interglacial variability.
- During interglacial periods the increased food flux rather than changes in deep water circulation are responsible for the enhanced abundance and diversity in the ichnofauna.
- In the glacial intervals, the impoverished ichnofauna consisting almost exclusively of *Trichichnus* and *Chondrites* is a response to extremely low food flux causing the burrowing organisms to use microbes to convert refractory carbon in the sediment to a labile food source. The presence of trace fossil in the

glacial intervals also indicate that bottom water remained oxic even during peak glacial.

- There is a close correlation between enhanced Mn content and increased trace fossil size, abundance, and diversity. Exceptions are found in areas with strong currents or extreme ice conditions even during interglacials.
- Detailed comparison of X-ray radiographs and XRF-scanner data show that Mn deposited under interglacial conditions may be dissolved and precipitate on new positions. Where the Mn has been dissolved, trace fossils can still be used to positively identify the original position of the interglacial sediment. Diagenetically precipitated layers of Mn show a distinct banding not present in the interglacially deposited brown, Mn-rich layers. Thus, by using radiographs, dissolved and diagenetically formed layers can be identified and accounted for in stratigraphic correlations, allowing robust correlations over large distances in the Arctic Ocean.

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9 Figure captions

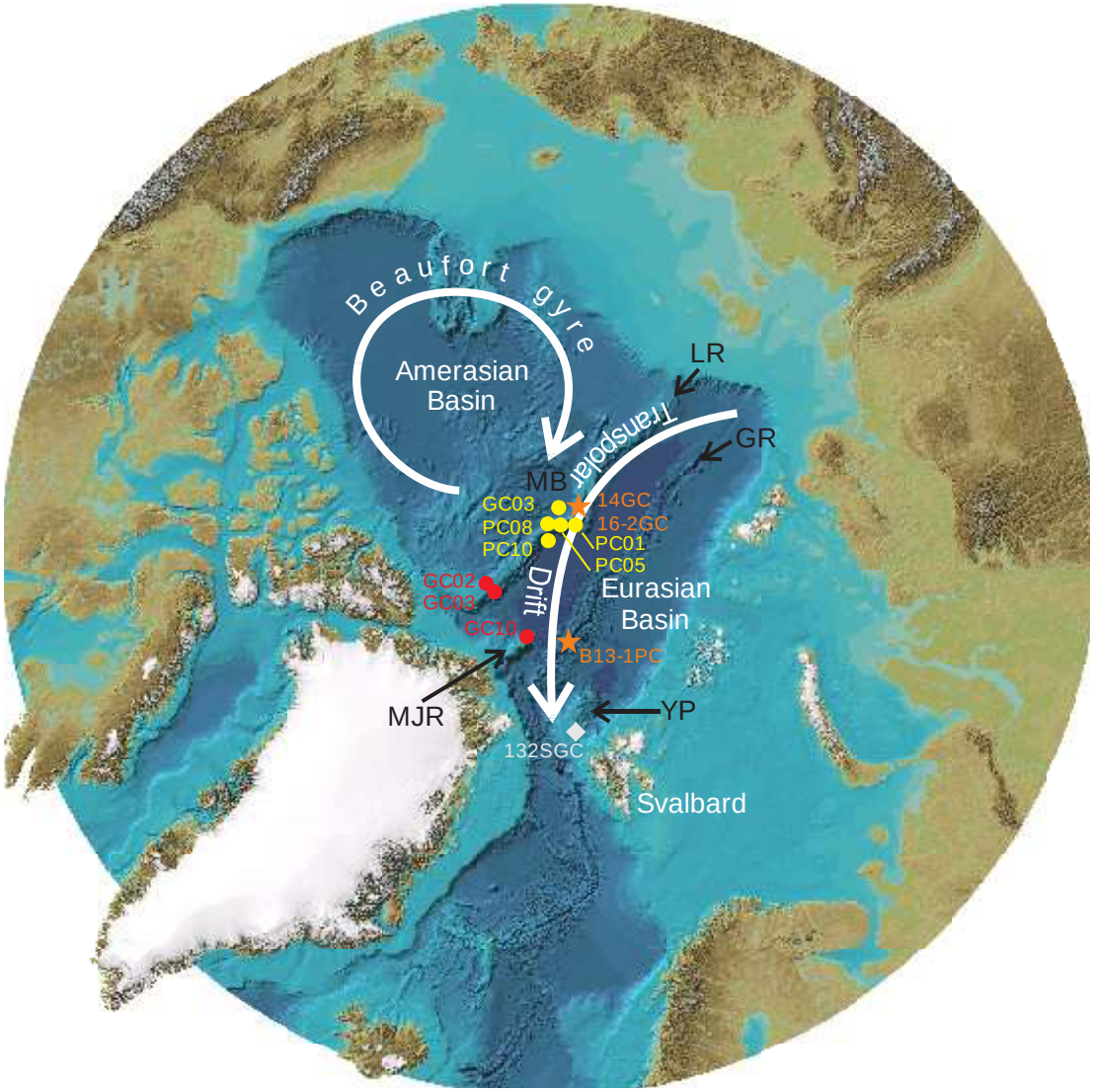

Fig. 1

Bathymetric chart of the Arctic Ocean (Jakobsson et al., 2008) showing the positions of the studied cores and sea-ice circulation. GR=Gakkel Ridge, LR=Lomonosov Ridge, MB=Makarov Basin, MJR=Morris Jesup Rise, YP=Yermak Plateau. Grey diamond=YMER80 core, Orange stars=AO96-cores, Red circles=LOMROG I-cores, Yellow circles=LOMROG II-cores

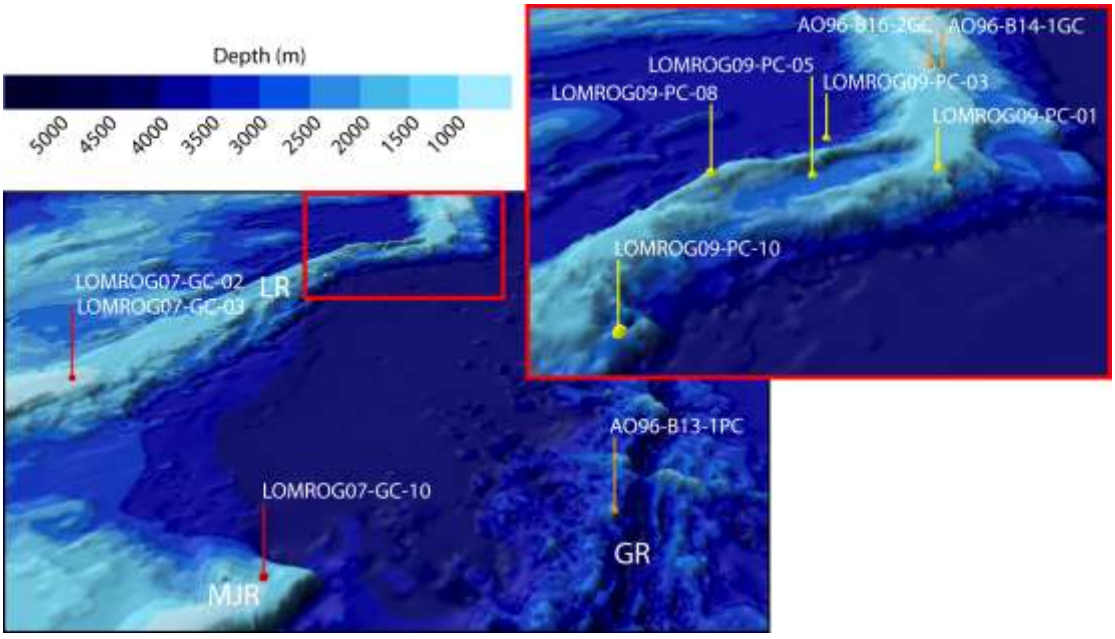

Fig. 2

Digital elevation model showing the position of the cores relative to major topographic features. Cores on the central Lomonosov Ridge show intense bioturbation in interglacial intervals, while the cores on Morris Jesup Rise and the Lomonosov Ridge off Greenland show sparse ichnofauna even during interglacial periods.

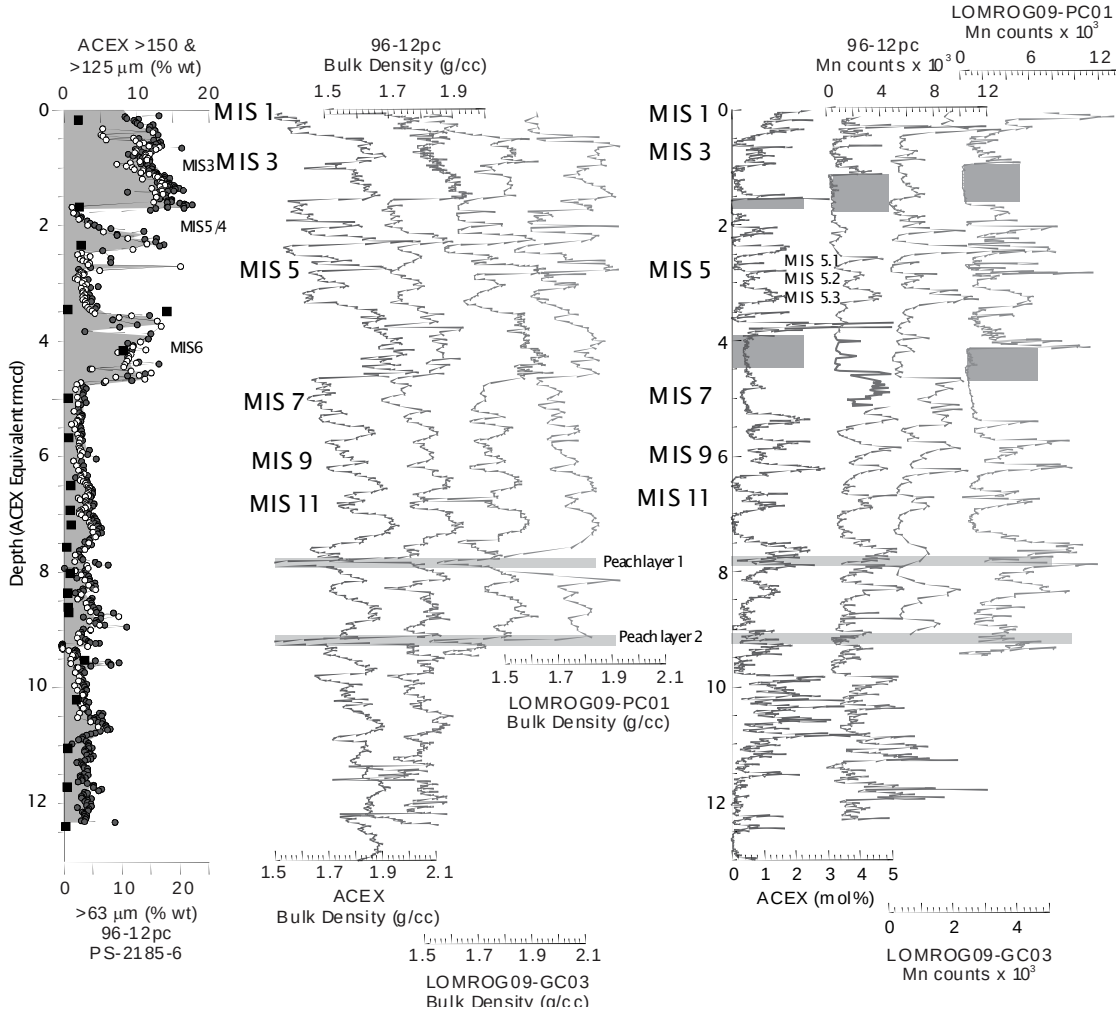

Fig. 3

Correlations between central Lomonosov Ridge cores migrated onto the ACEX depth scale to highlight the fidelity of the correlation using both bulk density and relative Mn abundances. A) Stacked coarse fraction content records from ACEX (>125 um, black squares), AO-96-12pc (>63 um, grey circles) and PS-2185-6 (>63 um, open circles) showing the thick recurrent coarse grained diamictons found during the last 2 glacial cycles B) Correlation of cores based on bulk density records (O'Regan, 2011). Positions of MIS boundaries based on O'Regan et al. (2008), Jakobsson et al. (2000) and Spielhagen et al. (2004). C) Correlation of Mn abundances. Grey boxes indicate thickness and position of characteristic grey layers,

which all show a depletion in Mn and possible redistribution of Mn in sediments overlying the grey layer(s).

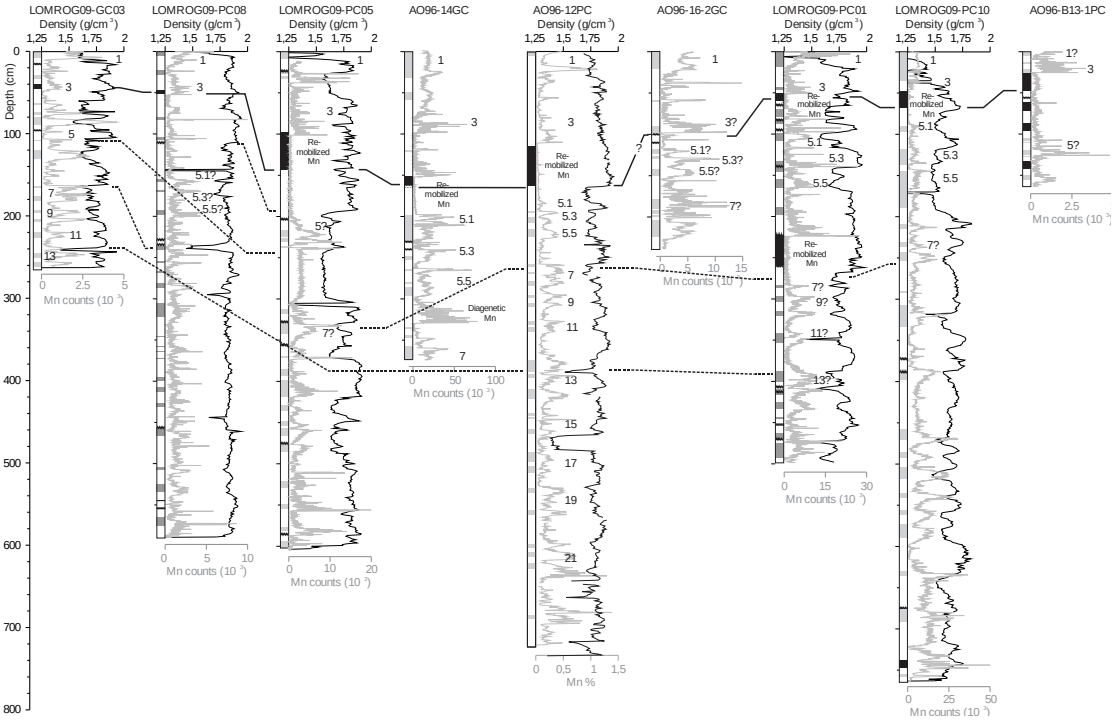

Fig.4

Chronostratigraphic frame work for the studied cores. Correlations are made to core AO96-12pc through lithological marker horizons, variations in Mn content and distinct shifts in bulk density that can be followed over large areas. Correlations between LOMROG09-GC03, and LOMROG09-PC01, AO96-12pc, and other cores from the LR were published by O'Regan (2011). LOMROG09-PC08, and LOMROG09-PC10 display a more complex pattern in downhole physical property changes and prevents a detailed correlation below the grey layer marking the boundary around MIS3/4. AO96-14gc, AO96-16-2gc, and LOMROG09-PC08 are correlated based on characteristic Mn patterns surrounding the MIS 3/4 grey layer.

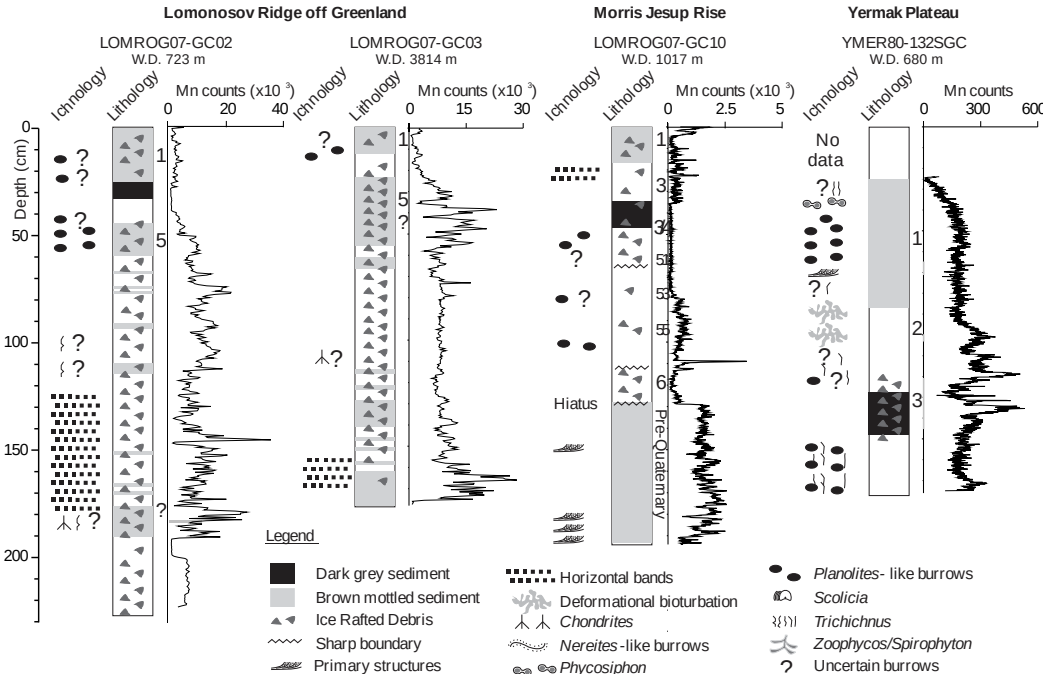

Fig. 5

Variations in trace fossil content, simplified lithology, and Mn variations in the cores from the Lomonosov Ridge off Greenland, the Morris Jesup Rise, and the Yermak Plateau. Numbers between lithology and Mn log indicate marine isotope stages. The cores from the Lomonosov Ridge and Morris Jesup Rise contain diagenetic Mn layers, high levels of IRD, and sparse bioturbation focused to MIS 1 and 5.

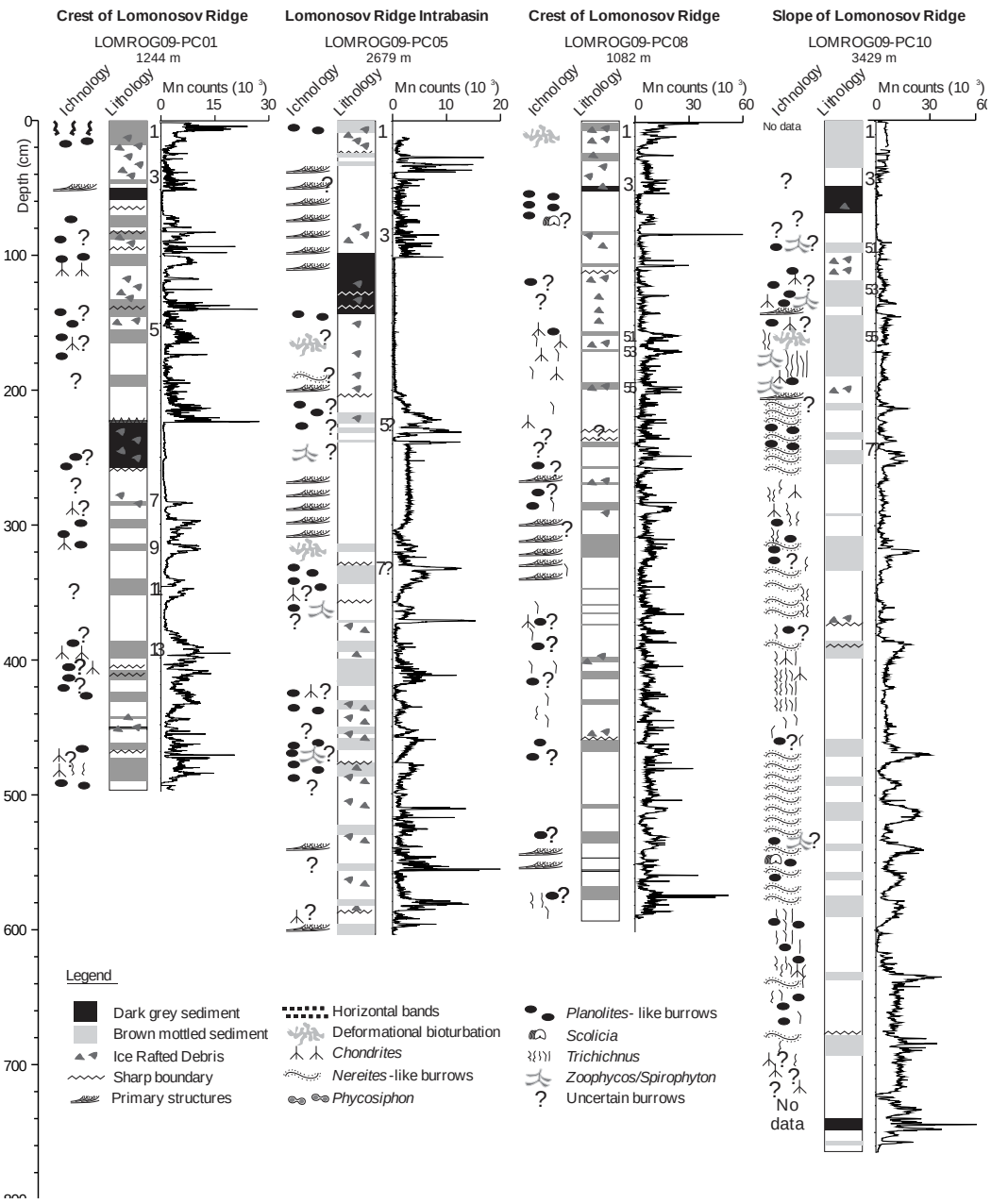

Fig. 6

Variations in trace fossil content, simplified lithology, and Mn variations in the cores from the central Arctic Ocean on the Lomonosov Ridge. Numbers between lithology and Mn log indicate marine isotope stages.

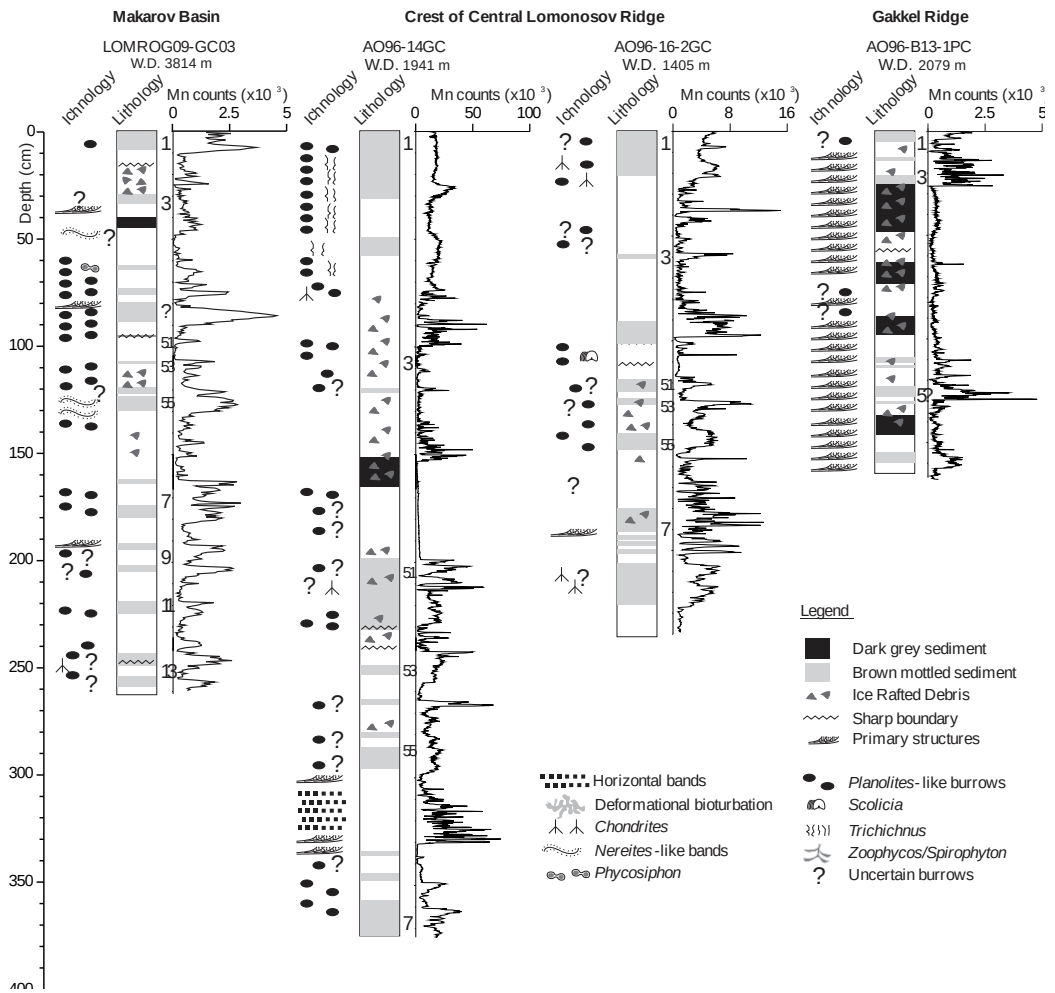

Fig. 7

Variations in trace fossil content, simplified lithology, and Mn variations in the cores from the Makarov Basin, central Lomonosov Ridge, and the Gakkel Ridge. Numbers between lithology and Mn log indicate marine isotope stages.

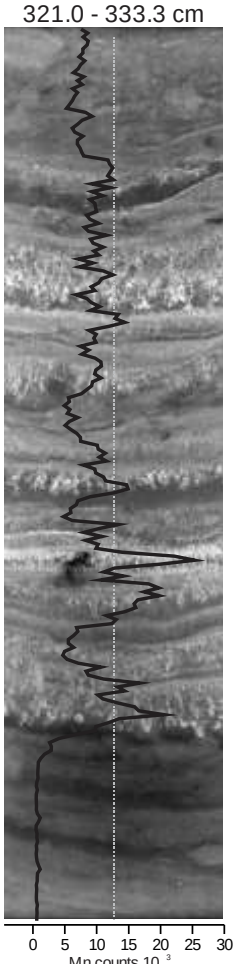

Fig. 8

Layers of denser material appear as lighter as light bands in the X-ray radiographs. XRF-scans demonstrate that these layers contain strongly enhanced levels of Mn.

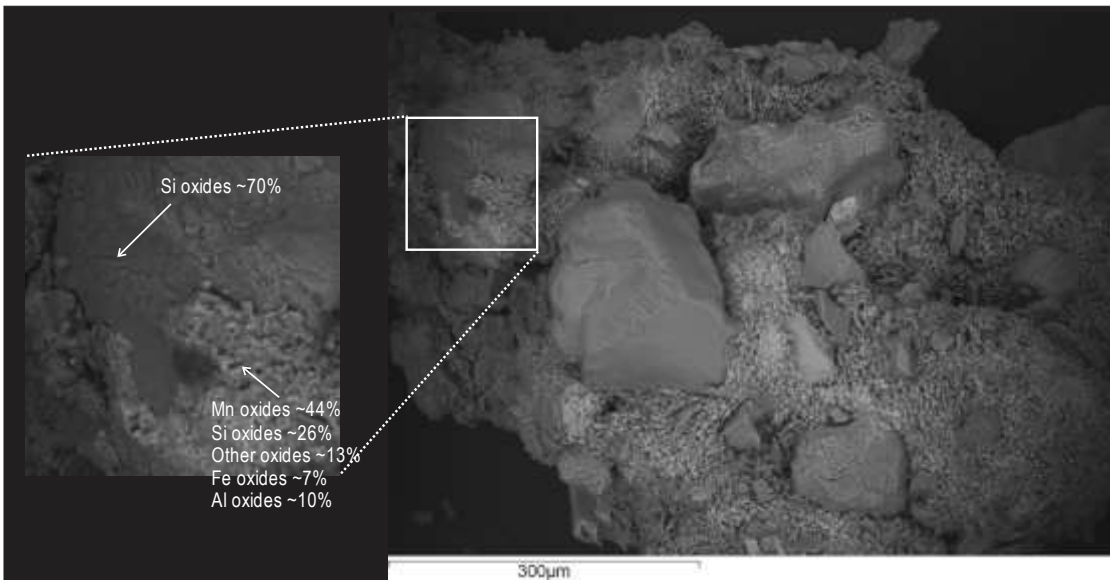

Fig. 9

SEM-analysis of grains taken from the crystal-like layers shows that they are aggregates of Si-grains held together by a matrix of Mn minerals.

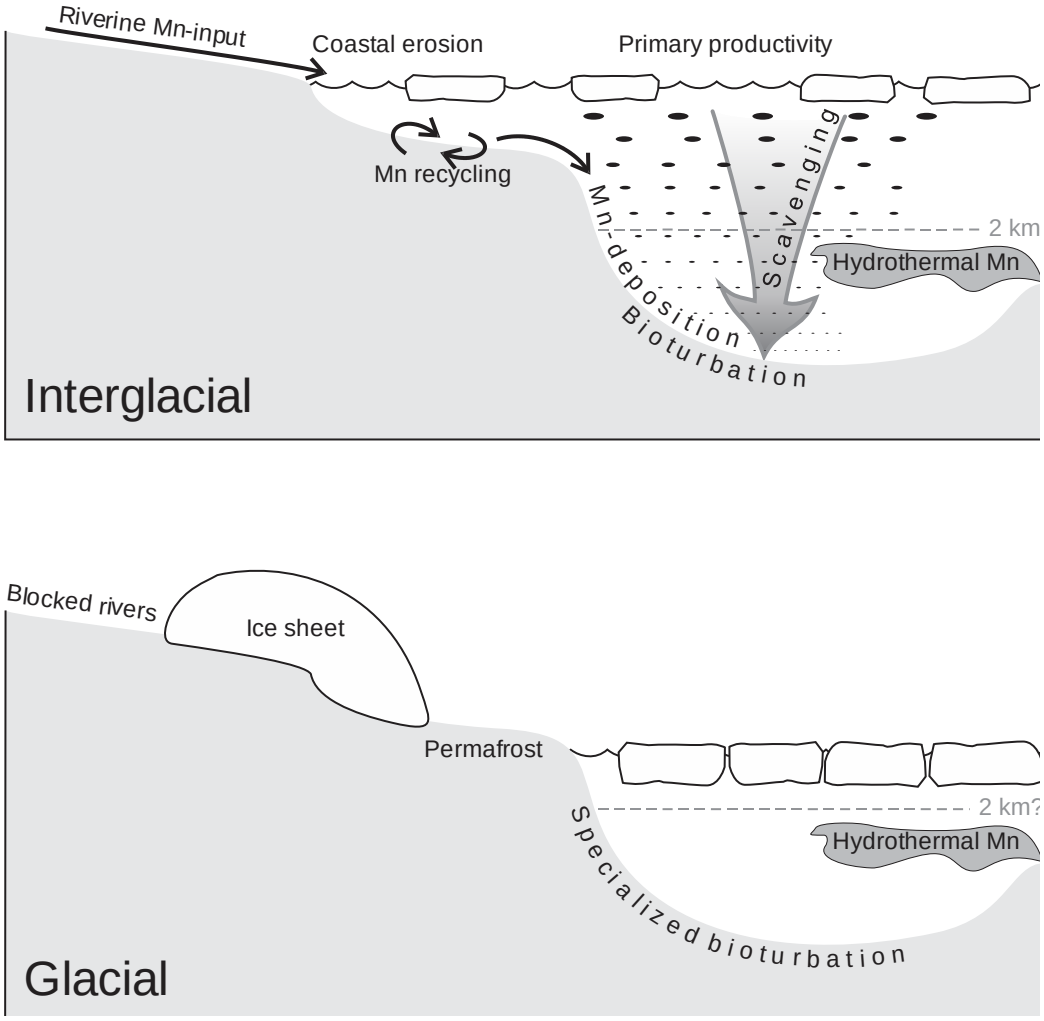

Fig. 10

Conceptual model for the formation of Mn-rich layers during interglacials, and Mn-poor layers during glacial periods. During interglacial conditions, the Mn budget is controlled by the input of Mn from Arctic rivers and coastal erosion on the shelves (Macdonald and Gobeil, 2011). On the shelves, the Mn goes through a number of redox cycles before entering the ocean basin where scavenging by organic particles helps to effectively bring the Mn to the sea floor (Johnson et al., 1996; Martin and Knauer, 1980). The increased primary productivity also supports abundant and diverse benthic activities. Hydrothermal Mn is of local importance, but is today not detected above 2km water depth, lending little support to the idea that the Mn on the upper slopes should be of hydrothermal origin.

During glacial periods, the Arctic rivers are blocked by continental ice sheets, and Mn on the exposed shelves is stored in the permafrost, drastically reducing Mn input. The sever pack ice decreases primary productivity, and thus reduces both scavenging of Mn from the water column and the benthic activity on the sea floor. The trace fossils left in glacial sediments therefore represent specialized behaviours to utilized refractory carbon deep in the substrate. Hydrothermal Mn input likely was of minor influence.

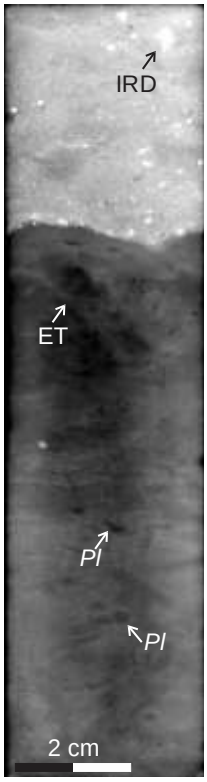

Fig. 11

X-ray radiograph from AO96-14GC (162.3-176cm) showing the base of the grey layer and the underlying intensely bioturbated sediment. A few cm under the sharp boundary an escape trace can be seen. ET = escape trace, *Pl* = *Planolites*, IRD = ice rafted debris