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Central Arctic Ocean paleoceanography from ~50 ka to present, on the basis of ostracode faunal assemblages from SWERUS 2014 expedition

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Abstract

Late Quaternary paleoceanographic changes in the central Arctic Ocean were reconstructed from a multicore and gravity core from the Lomonosov Ridge (Arctic Ocean) collected during the 2014 SWERUS-C3 Expedition. Ostracode assemblages dated by accelerator mass spectrometry (AMS) indicate changing sea-ice conditions and warm Atlantic Water (AW) inflow to the Arctic Ocean from ~50 ka to present. Key taxa used as environmental indicators include *Acetabulastoma arcticum* (perennial sea ice), *Polycope* spp. (productivity and sea ice), *Krithe hunti* (partially sea-ice free conditions, deep water inflow), and *Rabilimis mirabilis* (high nutrient, AW inflow). Results indicate seasonally sea-ice free conditions during Marine Isotope Stage (MIS) 3 (~57-29 ka), rapid deglacial changes in water mass conditions (15-11 ka), seasonally sea-ice free conditions during the early Holocene (~10-7 ka) and perennial sea ice during the late Holocene. Comparisons with faunal records from other cores from the Mendeleev and Lomonosov Ridges suggest generally similar patterns, although sea-ice cover during the last glacial maximum may have been less extensive at the southern Lomonosov Ridge at our core site (~85.15°N, 152°E) than farther north and towards Greenland. The new data also provide evidence for abrupt, large-scale shifts in ostracode species depth and geographical distributions during rapid climatic transitions.

1. Introduction

The observed, rapidly changing environmental conditions in the Arctic Ocean, including diminishing sea-ice extent and thickness (Stroeve et al., 2012, 2014; Laxon et al., 2013), glacial retreat (Zemp et al., 2015) and changes in ocean circulation (Moore et al, 2015), chemistry (Chierici and Fransson 2009; Rabe et al.,

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2011) and ecology (Grebmeier et al., 2006, 2012; Wassmann et al., 2011), are only possible to fully assess with a longer time perspective at hand. Such environmental perspective reaching further back in time is best acquired through paleoceanographic studies of sediment cores from the Arctic Ocean. This study examines temporal changes in ostracode indicator species of biological productivity and sea-ice extent during the last ~50 ka, including Marine Isotope Stages (MIS) 3, the Last Glacial Maximum (LGM), the deglacial interval and the Holocene, at about 85.15°N, 152°E on the Lomonosov Ridge in the central Arctic Ocean. Marine Ostracoda are bivalved Crustacea that inhabit Arctic marine habitats and whose assemblages (Cronin et al., 1994, 1995, 2010; Poirier et al., 2012) and shell chemistry (Cronin et al., 2012) have been used extensively as proxies to reconstruct Arctic paleooceanography.

New ostracode faunal analyses are derived from two sediment cores collected on the Lomonosov Ridge during the 2014 SWERUS-C3 (Swedish – Russian – US Arctic Ocean Investigation of Climate-Cryosphere-Carbon Interactions) Leg 2 expedition, and results are compared to published faunal records from past expeditions to the Lomonosov, Mendeleev and Northwind Ridges (Fig. 1a, Table 1). The new sites are located beneath the Transpolar Drift, a surface circulation pattern that transports sea ice across the central Arctic Ocean from the Siberian and Latpev seas towards the Fram Strait, and hence influences ice export into the Nordic Seas and the North Atlantic.

The central Arctic Ocean has exhibited significant oceanographic changes over orbital timescales as reflected in various lithological, geochemical and micropaleontological proxies (Nørgaard-Pederson et al., 1998; O'Regan et al., 2008; Marzen et al., 2016). In addition to records of orbitally forced climate changes, some Arctic Ocean records contain evidence for suborbital changes, including the prevalence of frequent, rapid geographic range shifts of ecologically sensitive species. For example, prior studies have documented range shifts in Arctic benthic foraminifera during the last deglaciation ~15-10 ka (Taldenkova et al., 2012) and during MIS 3 ~57-29 ka (Polyak et al., 1986; Ishman et al., 1996). In the new records presented here, evidence for similar range shifts in the ostracode species *Rabilimis mirabilis* is described, and we briefly discuss these exceptional, but only partially understood, biological events.

2. Arctic oceanography

The following summary of Arctic water masses and circulation is taken from Aagaard and Carmack (1989), Anderson et al. (1994), Jones (2001), Olsson and Anderson (1997), and Rudels et al. (2012 and 2013). Arctic Ocean water masses include a fresh, cold polar surface layer ([PSW], T= ~0°C to -2°C, S= ~32 to 34), that is found between ~0 to 50 m, and overlays a warmer, denser water mass of North Atlantic origin (the Atlantic water [AW], ~200 to 1000 m, T= >0°C, S= ~34.6 to 34.8). One branch of the AW flows into the Arctic Ocean from the Nordic seas along the eastern Fram Strait off the west coast of Spitsbergen and another branch flows through the Barents Sea. Bathymetry is a dominant factor in creating circulation patterns for AW and all deeper water, and a sharp front over the Lomonosov Ridge near the SWERUS-C3 cores studied here nearly isolates these

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waters in the Eurasian Basin from the Canadian Basin (Fig. 1b). Into the western Arctic Ocean, nutrient-rich, low salinity water enters from the North Pacific/Bering Sea region through the Bering Strait (~53 m). A halocline separates the cold, fresher water beneath the sea-ice cover from the underlying warmer and saltier AW.

An intermediate-depth water mass below the AW in the Eurasian Basin at ~1000-1500 m is called the Arctic Intermediate water ([AIW], T= -0.5 to 0°C, S= ~34.6 to 34.8). Below 2000 m, the deep Arctic basins are filled with Arctic Ocean Deep Water ([AODW], T= -1.0°C to -0.6°C, S= 34.9, Somavilla et al., 2013). Figure 1b shows a cross section of these major water masses in the eastern and central basin of the Arctic Ocean near the study site on the Lomonosov Ridge.

3. Materials and methods

3.1 Core material and sample processing

Cores for this study were obtained during the September 2014 SWERUS-C3 (Leg 2) expedition to the eastern Arctic Ocean aboard Swedish Icebreaker *Oden*. Figure 1 shows the location of multicore SWERUS-L2-32-MC4 (85.14°N, 151.57°E, 837 m) and nearby gravity core SWERUS-L2-32-GC2 (85.15°N, 151.66°E, 828 m) on the Lomonosov Ridge. These cores are hereafter referred to as 32-MC and 32-GC, respectively. Both cores were stored at 4°C and sampled at the Department of Geological Sciences, Stockholm University. Processing of the samples involved washing the sediment with water through a 63-µm mesh sieve. Core 32-MC was processed in Stockholm while 32-GC was processed at the U.S. Geological Survey (USGS) laboratory in Reston, Virginia. Sediment samples (1-cm thick, ~30 g prior to processing) were taken every centimeter in 32-MC along its 32 cm length. Section 1 (117 cm) of 32-GC was sampled every 2-3 cm (2-cm thick, ~45-60 g wet weight).

After processing and oven drying the samples, the residual >125 µm size fraction was sprinkled on a picking tray and ostracodes were removed to a slide. One exception for expediency is that specimens of the genus *Polycope* were counted and not removed from the sediment. A total of ~300 specimens were studied from each sample of 32-MC. More detailed counts of some samples in 32-MC were done periodically, where all specimens were picked and/or counted to ensure that 300 specimens provided a representative assemblage. In 32-GC, all specimens were picked and/or counted in each sample. Ostracodes were present throughout the entire studied intervals of both 32-MC and down to 62 cm in 32-GC. Planktic and benthic foraminifers were also present in abundance but not studied.

3.2 Chronology, reservoir corrections and sedimentation

We obtained nine radiocarbon (^{14}C) ages from core 32-MC using accelerator mass spectrometry (AMS) (Fig. 2, Table 2). Most dates were obtained on mollusks (*Nuculidae* and *Arcidae* spp.), except a few where mollusks and benthic foraminifera were combined. We obtained two ages from 32-GC using a combination of mollusks, foraminifera and ostracode shells. The final age models representing the two cores combined are based on all the calibrated ^{14}C ages listed in Table 2. Calibration into calendar years was done using Oxcal4.2 (Bronk

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Ramsey, 2009) and the Marine13 calibration curve (Reimer et al., 2013). In addition to the global marine correction of 402 years (Stuiver and Reimer 2010), a ΔR value of 300±100 ^{14}C years was used to account for regional reservoir effects (Reimer and Reimer, 2001).

Similar patterns in ostracode assemblages were used to depth align 32-MC and 32-GC and a 3-cm offset was applied to 32-GC. After adding the 3-cm offset to sample depths of 32-GC, we applied the 32-MC core chronology down to 31.5 cm core depth (dated at 39.6 ka). The average sedimentation rate was ~1.5 cm/ka which is typical of central Arctic Ocean ridges (Backman et al., 2004; Polyak et al., 2009).

The lower section of 32-GC, from 31.5 cm to 61 cm, is beyond the limit of radiocarbon dating. However, the litho-stratigraphy of the gravity core can be readily correlated to other records from the central Lomonosov ridge, where multiple dating techniques constrain the approximate positions of MIS 4 and 5 boundaries (Jakobsson et al., 2001; O'Regan, 2011). A correlation between SWERUS-C3 32-GC and AO96/12-1PC was previously presented in Jakobsson et al. (2016). The correlation is supported by the occurrences in 32-GC of the calcareous nanonnofossil *E. huxleyii* (Fig. 2). Based on this longer-term correlation, sediments between 31 and 61 cm are less than 50 ka. This is consistent with previous work on the Lomonosov Ridge, revealing a prominent transition from coarse-grained, microfossil-poor sediments (diamict) into bioturbated, finer-grained microfossiliferous sediments occuring during MIS 3 at approximately 50 ka (Spielhagen et al., 2004; Nørgaard-Pederson et al., 2007).

4. Results

4.1 Ostracode taxonomy and ecology

The SWERUS 32 cores contained a total of 13,767 ostracode specimens in 32-MC and a total of 5,330 specimens in the uppermost 5-62 cm of 32-GC (the top few centimeters below the seafloor were not recovered in the gravity core). The bottom 54 cm of 32-GC (section 1 from 63-117 cm) was barren of calcareous material. Twenty-eight ostracode species were identified in 32-MC and 21 species were identified in 32-GC. Supplementary Tables S1 and S2 provide all species and genus census data for 32-MC and 32-GC, respectively. Data will also be accessible at NOAA's National Centers for Environmental Information (NCEI, https://www.ncdc.noaa.gov/paleo-search/). The primary sources of taxonomy and ecology were papers by Cronin et al. (1994, 1995, 2010), Gemery et al. (2015), Joy and Clark (1977), Stepanova (2006), Stepanova et al. (2003, 2007, 2010), Whatley et al. (1996, 1998), and Yasuhara et al. (2014).

Most ostracodes were identified at the species level except the genera *Cytheropteron* and *Polycope.* Table 3 provides a list of species included in the genus-level groups, which was sufficient to reconstruct paleoenvironmental changes. There are several species of *Cytheropteron* in the deep Arctic Ocean but they are not ideal indicator species given their widespread modern distributions. There are at least 8 species of *Polycope* in the Arctic Ocean, but juvenile molts of *Polycope* species are difficult to distinguish from one another. Most specimens in 32-MC and 32-GC belonged to *P. inornata* Joy & Clark, 1977 and *P. bireticulata*

Joy & Clark, 1977. Nonetheless, most *Polycope* species co-occur with one another, are opportunistic in their ecological strategy, and dominate assemblages associated with high surface productivity and organic matter flux to the bottom (Karanovic and Brandão, 2012, 2016).

The relative frequency (percent abundance) of individual dominant taxa is plotted in Figure 3 and listed in Supplementary Table S3. Abundances were computed by dividing the number of individual species found in each sample by the total number of specimens found. For 32-MC, using the algorithm for a binomial probability distribution provided by Raup (1991), ranges of uncertainty ("error bars") were calculated at the 95% fractile for the relative frequency in each sample to the relative frequency of each species and the total specimen count of each sample at a given core depth (Supplementary Table S4). For this study of the SWERUS-C3 32 cores, our focus was on the following taxa: *Acetabulastoma arcticum, Krithe hunti*, *Polycope* spp., *Cytheropteron* spp., *Pseudocythere caudata,* and *Rabilimis mirabilis.* Table 4 provides an overview of pertinent aspects of these species' ecology that have paleoceanographic application.

4.2 Temporal patterns in ostracode indicator species from SWERUS-C3 32-MC/GC

The faunal patterns in cores from the SWERUS-C3 32-MC/GC sites confirm faunal patterns occurring over much of the central Arctic Ocean during the last 50 ka, including MIS 3-2 (~50 to 15 ka), the last deglacial interval (~15 to 11 ka), and the Holocene (~11 ka to present). We briefly discuss the paleoceanographic significance of each period in the following sections 4.3 - 4.5 based on the comparison cores presented in Figs 4 and 5. Relative frequencies of indicator taxa in cores 32-MC and 32-GC (Fig. 3) show four distinct assemblages, which we refer to as informal faunal zones following prior workers (Cronin et al., 1995; Poirier et al., 2012). These are: (1) *Krithe* zone (primary abundance up to 80% during ~45-42 ka and a secondary abundance of 5-10% during ~42-35 ka); (2) *Polycope* zone (with abundance of 50 to 75% during ~40-12 ka, also containing a double peak in abundance of *P. caudata*); (3) *Cytheropteron-Krithe* zone (12-7 ka); and (4) *Acetabulastoma arcticum* zone (~7 ka-present). Similar patterns are seen in both the multicore and gravity core. In addition, the ostracode data reveal two *Rabilimis mirabilis* "events," or intervals containing high proportions of this shallow water species (dated at ~45-36 ka and 9-8 ka).

Figures 4 and 5 compare the new SWERUS-C3 results from 32-MC with published data from box and multicores from the Lomonosov and Mendeleev Ridges, respectively, covering a range of water depths from 700-1990 m. Most records extend back to at least 45 ka, and the age model for each core site is based on calibrated radiocarbon ages from that site (Cronin et al., 2013, 2010; Poirier et al., 2012).

4.3 MIS 3-2 (~50-15 ka)

A strong peak in the abundance of *Krithe hunti* (Fig. 3) is seen in 32-GC sediments estimated to be ~45-42 ka in age. A similar peak of lower but still significant abundance also occurs in sediments dated between 42 and 35 ka, and this is consistent with other cores on the Mendeleev Ridge and particularly on the

Lomonosov Ridge (Figs 4, 5). Prior studies of Arctic ostracodes have shown that *Krithe* typically signifies cold well-ventilated deep water and perhaps low food supply (Poirier et al., 2012 and references therein). *Krithe* is also a dominant component (>30%) of North Atlantic Deep Water (NADW) in the subpolar North Atlantic Ocean. Its abundance varies during glacial-interglacial cycles, reaching maxima during interglacial and interstadial periods (Alvarez Zarikian et al., 2009). Peaks in the abundance of *Krithe* in the Arctic Ocean probably signify faunal exchange between the North Atlantic Ocean and the Greenland-Norwegian Seas through the Denmark Strait and Iceland Faroes Ridge and the Greenland-Norwegian Seas and the central Arctic through the Fram Strait. In other Arctic Ocean cores, the ostracode genus *Henryhowella* is often associated with *Krithe* sp. in sediments dated between ~50 to 29 ka (MIS 3), and its absence in the 32-MC/GC cores may reflect the relatively shallow depth at the coring site.

A. arcticum is present in low abundance (~5%) in sediment dated at ~42 to 32 ka in 32-MC/GC (Fig. 3), signifying intermittent perennial sea ice. A *Krithe* to *Polycope* shift occurs at ~35-30 ka. This "K-P shift" is a well documented Arctic-wide transition (Cronin et al., 2014) that has paleoceanographic significance as well as biostratigraphic utility. *Polycope* is clearly the dominant genus group from sediment dated ~40-12 ka in 32-MC/GC and all sites on the Lomonosov and Mendeleev Ridges (Figs. 4, 5), signifying high productivity likely due to an intermittent, rapidly oscillating sea-ice edge at the surface. *P. caudata* has varying percentages (3-14%) in sediment dated ~40-12 ka, depending on the site. *Cytheropteron* spp. is present in moderate abundance (20-30%) in sediment dated ~35-15 ka.

4.4 The Last Deglacial Interval (~15 to 11 ka)

The major shift from *Polycope*-dominated to *Cytheropteron*-*Krithe*-dominated assemblages occurs in sediment dated ~15-12 ka in 32-MC/GC and other Lomonosov and Mendeleev Ridge cores. Both *Cytheropteron* and *Krithe* are typical faunas in NADW. Although low sedimentation rates prevent precise dating of this shift, it almost certainly began ~14.5 ka at the Bølling-Allerød warming transition. Because the Bering Strait had not opened yet (Jakobsson et al., 2017), this faunal shift must have been related to one or several of the following changes: (1) atmospheric warming; (2) strong Atlantic Water inflow through the Barents Sea; and (3) strong Atlantic Water inflow through the eastern Fram Strait. *A. arcticum* is absent or rare (<2% of the assemblage) in sediment dated ~15-12 ka, suggesting minimal perennial sea ice cover and probably summer sea-ice free conditions during late deglacial warming.

4.5 The Holocene (~11 to Present)

Krithe and *Cytheropteron* remain abundant in sediment dated ~10-7 ka (early Holocene) across most of the central Arctic Basin, signifying continued influence of water derived from the North Atlantic Ocean (Figs. 4, 5). *A. arcticum* (which represents the *A. arcticum* zone) increases to >6-8% abundance beginning in sediment dated ~7 ka, and increases to >10% abundance in sediment dated ~3 ka. This increase in abundance is correlated with an increase in perennial-sea ice, and is more prominent in Lomonosov Ridge cores than in cores from the Mendeleev Ridge (most likely due to more persistent perennial sea ice cover over the Lomonosov Ridge sites). The inferred middle to late Holocene development of

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perennial sea ice is consistent with interpretations from other sea-ice proxies (Xiao et al., 2015) and with the transition from an early-middle Holocene "thermal maximum" (Kaufman et al., 2004, 2016) to cooler conditions during the last few thousand years.

5. Discussion

5.1 Faunal events in the Arctic Ocean

Major paleoceanographic shifts inferred from ostracode assemblages presented above signify orbital and, at least at low resolution, millennial events during the last 50 ka. In general, the data confirm the sensitivity of Arctic benthic fauna to relatively large climate transitions, such as those seen in benthic foraminifera during the last deglacial and Holocene intervals from the Laptev Sea (Taldenkova et al., 2008, 2013) and the Beaufort Sea and Amundsen Gulf (Scott et al., 2009). These records provide a useful context for understanding orbital-scale Arctic faunal variability during the last 500 ka, as seen in benthic foraminifera and ostracodes (Cronin et al., 2014; Marzen et al., 2016).

These millennial faunal changes seem to be distinct from microfaunal events in which a species is found in certain stratigraphic intervals in sediment cores located far outside that species normal depth and/or geographic range. One example is *Bulimina aculeata* (Polyak et al., 1986, 2004; Ishman et al., 1996), a species that occurs in narrow (few cm thick) stratigraphic intervals such that it serves as a useful biostratigraphic marker in sediment dated ~96-71 ka (MIS 5c-5a; Cronin et al., 2014). As reviewed by (Polyak et al., 2004), *B. aculeata* is almost completely absent from the modern Arctic Ocean, and its widespread occurrence as a double peak in abundance across much of the Arctic Ocean in sediment dated ~96-71 ka (late MIS 5) must signify a unique but still poorly understood oceanographic situation. Polyak et al. (2004) noted a similar stratigraphic situation for *Epistominella exigua* and other benthic foraminiferal species in the western Arctic Ocean. In the eastern Arctic Ocean, Wollenburg et al. (2001) also discusses how peaks in abundance of *Melonis zaandami* represent brief paleoceanographic events. These and other examples where species have pulse-like spikes in abundance and geographically widespread stratigraphic distributions signify brief, large-scale changes in species dominance. The causes of such events suggests a rapid environmental change, such as changing sea ice cover or periods of enhanced surface-ocean productivity with a food supply flux to the ocean bottom.

5.2 *Rabilimis mirabilis*

The distribution of the ostracode *Rabilimis mirabilis* in SWERUS-C3 32-MC/GC and other Arctic cores represents a similar pattern to that seen for *B. aculeata*, *E. exigua*, and *M. zaandami*, when a brief, uncharacteristic yet significant faunal dominance of a taxa is indicative of rapid environmental change. In SWERUS-C3 32-MC/GC, *R. mirabilis* occurs in sediment dated ~45-36 ka (MIS 3) with abundance reaching 60%, and again in sediment dated ~9-8 ka (early Holocene) with abundance reaching 41-55%. These two intervals of high abundance signify an unusual stratigraphic appearance of a shallow-water species in a relatively deep-water (837 m) core site.

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The modern circum-Arctic distribution of *R. mirabilis* is confined to relatively shallow (<200 m) water depths (Fig. 6a, b, and c; Hazel, 1970; Neale and Howe, 1975; Taldenkova et al., 2005; Stepanova, 2006; Gemery et al., 2015). *R. mirabilis* can also tolerate a range of salinities, explaining its presence in regions near river mouths with reduced salinity (Fig. 6a).

Rabilimis mirabilis also occurs in 2014 SWERUS-C3 multicore top samples at deeper than usual depths on the Eastern Siberian Sea slope. Examples of these occurrences are listed in Supplementary Table S5 and include SWERUS-C3 Cores 23-MC4 (4%, 522 m); 18-MC4 (18%, 349 m); 16-MC4 (11%, 1023 m); 15-MC4 (41%, 501 m) and 14-MC4 (70%, 837 m). These locations correspond to the summer sea-ice edge that has receded during recent decades over the Lomonosov Ridge and may be indicative of warming and/or surface-to-bottom nutrient flux.

Data from the current study, from Cronin et al. (2014) and other Arctic core studies reveal new information about the stratigraphic occurrence of *R. mirabilis* (Fig. 7a, 7b, Table 5). In the central Arctic Ocean, *R. mirabilis* occurs on the Lomonosov Ridge (96-12-1PC), the Mendeleev Ridge (P1-94-AR-PC10) and Northwind Ridge (P1-92-AR-PC40) and in longer cores on the Lomonosov and Northwind Ridge (Fig 7b). Age models for these sites suggest a range extension of *R. mirabilis* into deeper water (700 to 1673 m) during interstadial periods (MIS 5c, 5a, 3). *R. mirabilis'* abundance reaches 40-50% of the total assemblage at Lomonosov Ridge site 96-12-1PC at a water depth of 1003 m. Such anomalously high percentages of well-preserved adult and juvenile specimens of *R. mirabilis* indicate that they were not brought to the site through sediment transport from the shelf. Instead, we interpret the *R. mirabilis* events to represent in-situ populations.

Although not all *R. mirabilis* events are synchronous, most occur in sediment dated ~96-71 ka (late MIS 5) and at SWERUS-C3 coring sites of 32-MC and 32-GC in sediment dated 45-36 ka and ~9-8 ka (early Holocene). These *R. mirabilis* events are correlated with interglacial/interstadial periods that experienced summer sea-ice free and/or sea-ice edge environments where there may have been enhanced flux of surface-to-bottom organic matter. We hypothesize that the locations of the *R. mirabilis* events on the southern Lomonosov and Mendeleev Ridges received an influx of nutrient-enriched water through the Bering Strait into the western Arctic Ocean. However, to confirm the paleoceanographic significance of *R. mirabilis* migration events, additional study of cores from Arctic margins is required.

6. Conclusions

SWERUS-C3 Cores 32-MC and 32-GC on the Lomonosov Ridge are characterized by fluctuating dominance of key ostracode taxa that indicate various water mass regimes from ~50 ka to present (MIS 3-1). Key indicator taxa and their associations with specific water masses show the following four major ostracode assemblage changes in Cores 32-MC/GC as characterized by peaks in dominant ostracode taxa: (1) *Krithe* zone (~45-35 ka); (2) *Polycope* zone (~40-12 ka); (3) *Cytheropteron-Krithe* zone (~12-7 ka); and (4) *Acetabulastoma arcticum* zone (~7 ka-present). These benthic faunal events, and unusual events like *Rabilimis* *mirabilis* shelf-to-ridge migration events, indicate abrupt changes in Eurasian Basin environmental conditions related to sea ice extent and the relative strength of Atlantic Water influx to the Arctic Ocean.

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Fig 1. a.) International Bathymetric Chart of the Arctic Ocean showing the location of this study's primary sediment cores on the Lomonosov Ridge (red star: 32-GC2 and 32-MC4), and other core sites discussed in this paper (black circles, white circles). (See Table 1 for supplemental core data.) White circles designate cores that contain *Rabilimis mirabilis* events. Red arrows show generalized circulation patterns of warm Atlantic water in the Arctic Ocean. Transect line through the map from "1" in the Chukchi Sea to "2" in the Barents Sea shows direction of temperature profile in Fig1b.

b.) Cross section of modern Arctic Ocean temperature profile from showing major water masses. PSW: polar surface water, AL: Atlantic layer, AIW: Arctic intermediate Water, AODW: Arctic Ocean Deep water. Ocean Data View Source: Schlitzer, 2012. Ocean Data View: http//odv.awi.de

Fig. 2 Chronology and stratigraphy of SWERUS-32-GC and 32-MC. Bulk density and magnetic susceptibility profiles for 32GC were previously correlated to the well-dated 96-12-1PC core by Jakobsson et al. (2016). Bulk density primarily reflects changes in grain size, with coarser material having a higher density than finer grained material. The overall position of MIS 5 is supported by the occurrence of *E. huxleyi*. The chronology for the upper 30-35 cm is based on radiocarbon dating in both 32-MC and 32-GC. Beyond the range of radiocarbon dating, an extrapolation to the inferred position of MIS 3/4 boundary (57 ka at 105 cm) is applied.

Fig 3. Relative frequencies (percent abundance) of dominant taxa in SWERUS-C3 32-MC and 32-GC. The y-axis shows the modeled, mean age during a 2-sigma range of uncertainty.

Fig 4. Relative frequencies (percent abundance) of dominant taxa in SWERUS 32-MC (dotted line) compared to other Lomonosov Ridge cores 2185, 2179 and AOS94 28 (Poirier et al., 2012).

Fig 5. Relative frequencies (percent abundance) of dominant taxa in SWERUS 32-MC (dotted line) compared to other Mendeleev Ridge cores AOS94 8 (Poirier et al., 2012), AOS94 12, and HLY6.

Fig 6. a.) Occurrence map of *Rabilimis mirabilis* in the Arctic Ocean and surrounding seas based on 1340 modern surface samples in the Arctic Ostracode Database (AOD; Gemery et al., 2015).
b.) Modern depth and c.) latitudinal distribution of *R. mirabilis* based on 1340-modern surface samples in the AOD (Gemery et al., 2015).

Fig 7. a.) Relative frequency (percent abundance) of *R. mirabilis* in SWERUS-32 cores and in central Arctic Ocean cores,160 ka to present. b.) *R. mirabilis* in core LOMROG07-04 from 260 ka to present and in core P1-92-AR-PC30 from 340 ka to present.

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Table 1. Expedition and core site data for cores presented in this study.

Year	Expedition	Core name	Latitude	Longitude	Water depth (m)	Location
2014	SWERUS-L2	SWERUS-L2-32-MC4	85.14	151.59	837	Lomonosov Ridge
2014	SWERUS-L2	SWERUS-L2-32-GC2	85.15	151.66	828	Lomonosov Ridge
2014	SWERUS-L2	SWERUS-L2-24-MC4	78.80	165.38	982	E. Siberian Sea Slope
2014	SWERUS-L2	SWERUS-L2-28-MC1	79.92	154.35	1145	E. Siberian Sea Slope
2014	SWERUS-L2	SWERUS-L2-33-TWC1	84.28	148.65	888	Lomonosov Ridge
2014	SWERUS-L2	SWERUS-L2-34-MC4	84.28	148.71	886	Lomonosov Ridge
1994	AOS SR96-1994	PI-94-AR-BC28	88.87	140.18	1990	Lomonosov Ridge
1991	Arctic 91	PS 2179-3 MC	87.75	138.16	1228	Lomonosov Ridge
1991	Arctic 91	PS 2185-4 MC	87.53	144.48	1051	Lomonosov Ridge
1994	AOS SR96-1994	PI-94-AR-BC8	78.13	176.75	1031	Mendeleev Ridge
1994	AOS SR96-1994	PI-94-AR-BC12A	79.99	174.29	1683	Mendeleev Ridge
2005	HOTRAX	HLY0503-6	78.29	-176.99	800	Mendeleev Ridge
1994	AOS SR96-1994	P1-94-AR-PC10	78.15	-174.63	1673	Mendeleev Ridge
1992	USGS-Polar Star	P1-92-AR P40	76.26	-157.55	700	Northwind Ridge
1992	USGS-Polar Star	P1-92-AR-P30	75.31	-158.05	765	Northwind Ridge
2007	LOMROG 07	LOMROG07-PC-04	86.70	-53.77	811	Lomonosov Ridge
1996	Oden 96	96-12-1PC	87.10	144.77	1003	Lomonosov Ridge

Table 2. Radiocarbon dates for SWERUS 32 cores, uncalibrated ^{14}C age and calibrated ^{14}C chronology.

32-MC/GC chronology					Unmodelled				Modelled	
		2 sigma (2 std dev)				2 sigma (2 std dev)				
Lab number (^{14}C date age, error)	Depth (cm)	from	to	mean	errror	from	to	mean**	error
OS-124799 (3410, 25)	2.5	3168	2698	2912	124	3045	2605	2802	105
OS-124798 (6110, 20)	4.5	6435	5974	6213	116	6317	5902	6140	113
OS-124599 (7920, 35)	5.5	8313	7874	8085	110	8176	7766	7972	101
OS-124598 (8290, 30)	8.5	8715	8207	8465	119	8576	8187	8385	99
OS-124597 (11000, 35)	11.5	12525	11661	12094	222	12191	11353	11831	230

OS-124754 (11200, 40)	14.5	12635	12040	12365	164	12625	12008	12381	165
OS-125185 (18650, 80)	19.5	22116	21357	21729	183	21973	21252	21637	179
OS-125190 (29400, 280)	24.5	33567	31805	32733	462	33298	31585	32423	455
OS-125192 (35400, 560)	31.5	40705	38099	39301	638	40858	38451	39608	608
OS-127484 (40000, 1700)	33*	47589	40881	43837	1646	44472	40403	42428	1002

All ages as calibrated years BP

ΔR = 300 ±100 years (Reimer and Reimer, 2001)
Marine13 calibration curve (Reimer et al., 2013)
*Sample collected from 32-GC, original depth was 36 cm but corrected by 3 cm based on ostracode correlation with 32-MC
**We used the modeled, mean, 2-sigma age to plot species' relative frequencies.

Table 3. List of species included in genus-level groups.

Group name	**Species included in Group:**
Cytheropteron spp.	*Cytheropteron higashikawai* Ishizaki 1981, *Cytheropteron scoresbyi* Whatley and Eynon 1996, *Cytheropteron sedovi* Schneider 1969 and *Cytheropteron parahamatum* Yasuhara, Stepanova, Okahashi, Cronin and Brouwers 2014.
Polycope spp.	*P. inornata* Joy & Clark, 1977 and *P. bireticulata* Joy & Clark, 1977. (For scanning electron microscope images, see Joy & Clark 1977: Plate 3, Fig. 1; Yasuhara et al., 2014: Plate 3, Figs 2-5 and Plate 2, Figs 1-2.) May include: *P. arcys* (Joy & Clark, 1977), *P. punctata* (Sars 1869), *P. bispinosa* Joy & Clark 1977, *P. horrida* Joy & Clark 1977, *P. moenia* Joy & Clark 1977, *P. semipunctata* Joy & Clark 1977, *P. obicularis* Sars 1866. *P. pseudoinornata* Chavtur, 1983 and *P. reticulata* Muller 1894

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Table 4. Summary of indicator species, pertinent aspects of their modern ecology and paleoenvironmental significance.

Species	Modern ecology / paleoenvironmental significance
Acetabulastoma arcticum (Schornikov, 1970).	The stratigraphic distribution of *A. arcticum* is used as an indicator of periods when the Arctic Ocean experienced thicker sea-ice conditions. This pelagic ostracode is a parasite on *Gammarus* amphipods that live under sea ice in modern, perennially sea-ice-covered regions in the Arctic (Schornikov, 1970). Cronin et al. (2010) used *A. arcticum's* presence in 49 late Quaternary Arctic sediment cores as a proxy to reconstruct the Arctic Ocean's sea-ice history during the last ~45 ka.
Krithe spp.	Species of the genus *Krithe* typically occur in low-nutrient habitats spanning across a range of cold, interstadial temperatures but are especially characteristic of AODW (Cronin et al., 1994; 1995; 2014). In SWERUS-32 cores, *K. hunti* was far more prevalent than *K. minima.* From a modern depth-distribution analysis using AOD, *K. hunti* appears in greatest abundance (50-80% of the assemblage) at depths between 2000-4400 m, however, this taxon is also found in significant numbers (20-50%) at depths between 400-2000 m. With a preference for deeper, cold, well-ventilated depths, *Krithe spp*. events are useful in identifying late Quaternary shifts in Arctic Ocean water masses and making biostratigraphic correlations (Cronin et al., 2014).
Polycope spp.	Today, this Atlantic-derived genus is in highest abundance (40-60% of assemblage) in cold intermediate-depth waters between 800-2300 mwd. It characterizes fine-grained, organic rich sediment in well-oxygenated water. In fossil assemblages, *Polycope* is indicative of areas with high productivity that are seasonally ice-free or have variable or thin sea-ice cover (Cronin et al., 1995; Poirier et al., 2012).
Cytheropteron spp.	The two dominant *Cytheropteron* species in 32-MC and 32-GC are *C. sedovi* and *C. scoresbyi,* along with lower but significant numbers of *C. parahamatum* (reaches 24% of assemblage at 10 ka) and *C. higashikawai* (fluctuates in very low numbers between 0-3% at any given time in downcore samples). These particular *Cytheropteron* species are broadly diagnostic of deeper, well-ventilated water masses (AIW and AODW).
Pseudocythere caudata Sars 1866	This species of N. Atlantic origin rarely exceeds >15% in modern Arctic Ocean assemblages. It characterizes lower AW and AI water at depths of 1000-2500 m and usually co-occurs with *Polycope* spp. in fossil assemblages. (Cronin et al., 1994, 1995).

Table 5. Although *R. mirabilis* (Brady, 1868) is known and named from Pleistocene sediments in England and Scotland (Brady et al., 1874), this list cites various workers since that have documented this species in Arctic deposits dating back to the late Pliocene, when summer bottom temperatures were inferred to be up to 4°C warmer than today.

Citation	Location / Formation (Age)
Siddiqui (1988)	Eastern Beaufort Sea's Iperk sequence (Plio-Pleistocene)
Repenning et al. (1987)	Alaska's North Slope Gubik Formation (Pliocene)
Penney (1990)	Central North Sea deposits (early Pleistocene age,1.0-0.73 Ma)
Feyling-Hassen (1990)	East Greenland's Kap København Formation (late Pliocene)
Penney (1993)	East Greenland's Lodin Elv Formation (late Pliocene)

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Figures 1-7

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Fig. 1

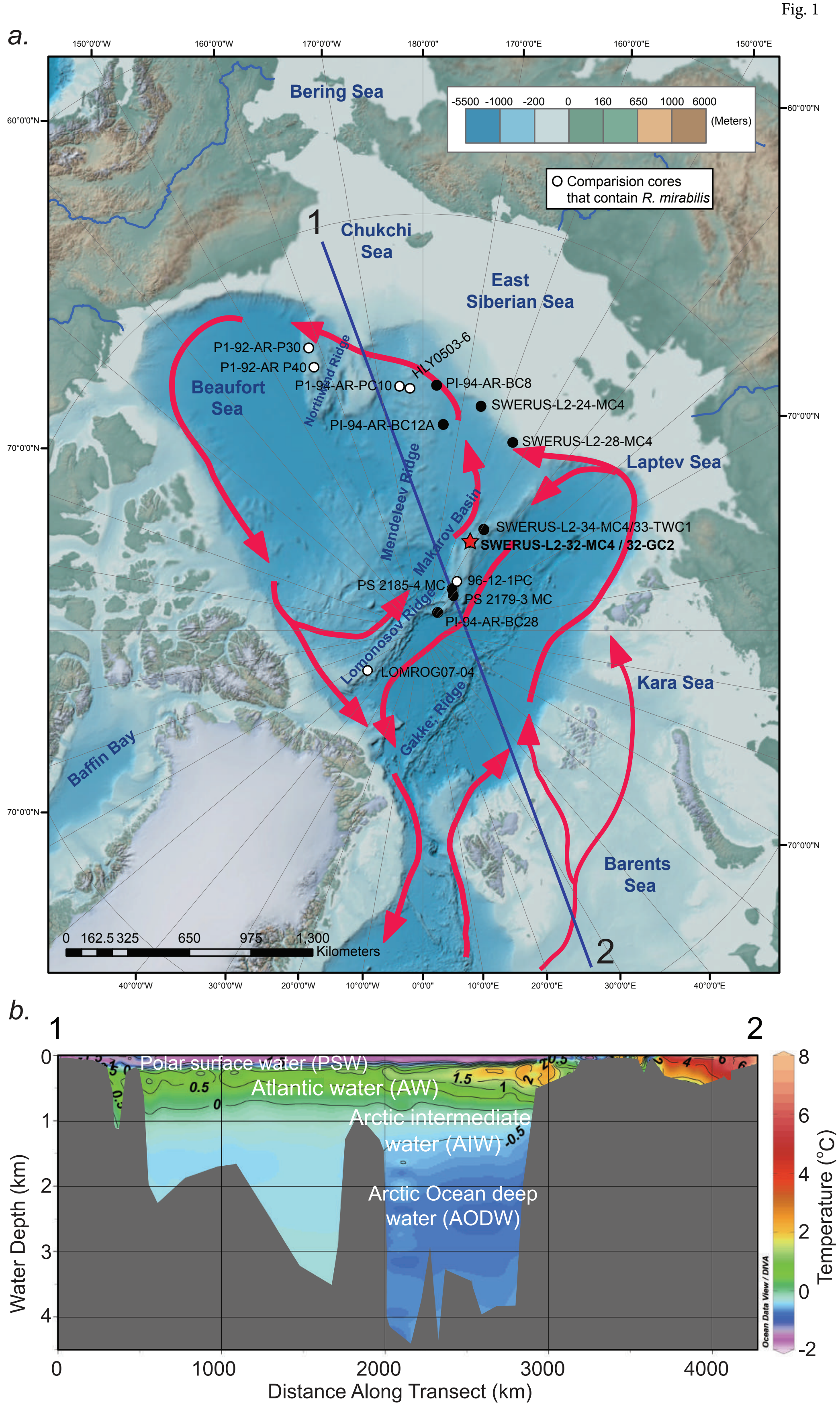

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Fig. 2

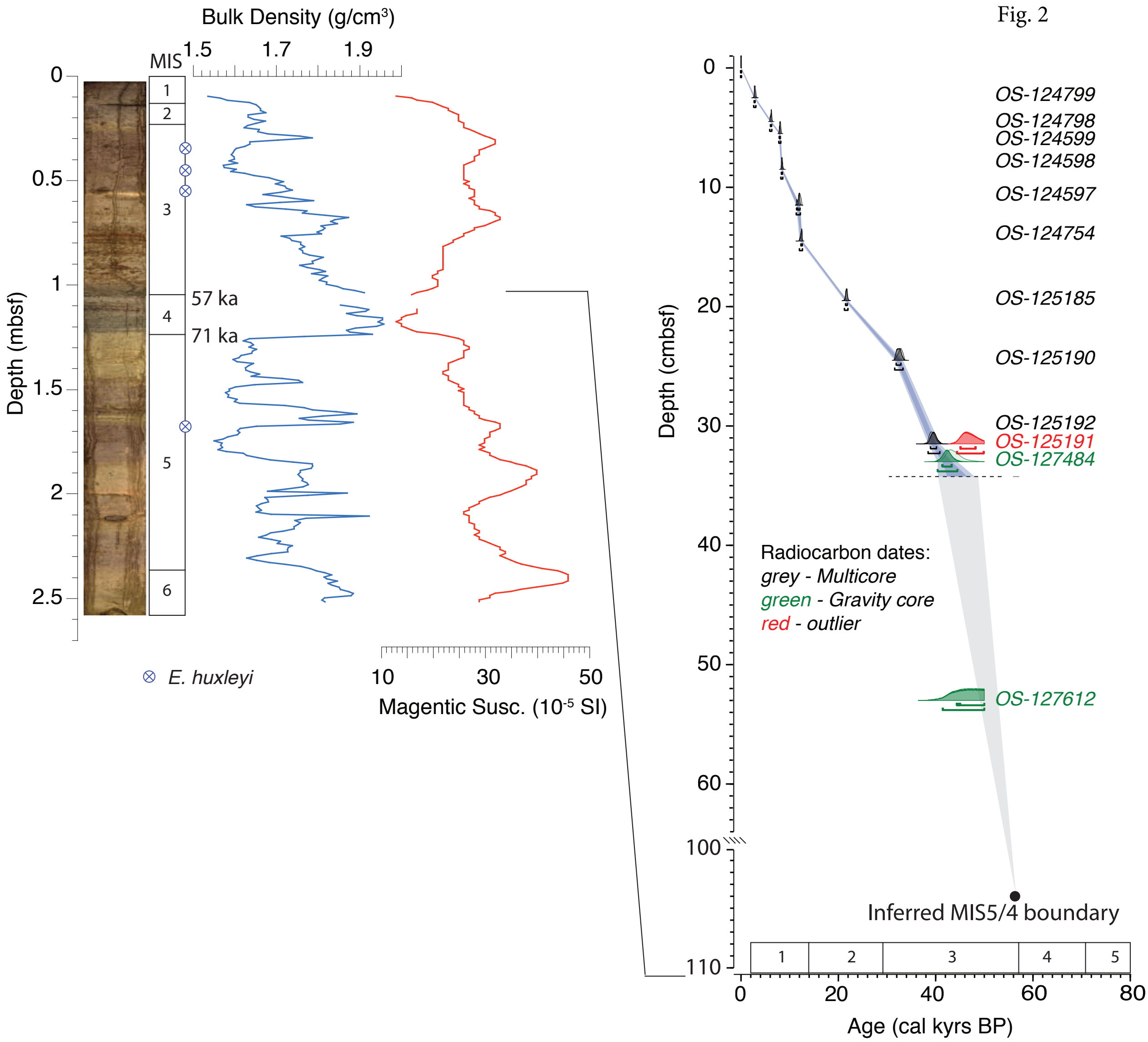

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Fig. 3

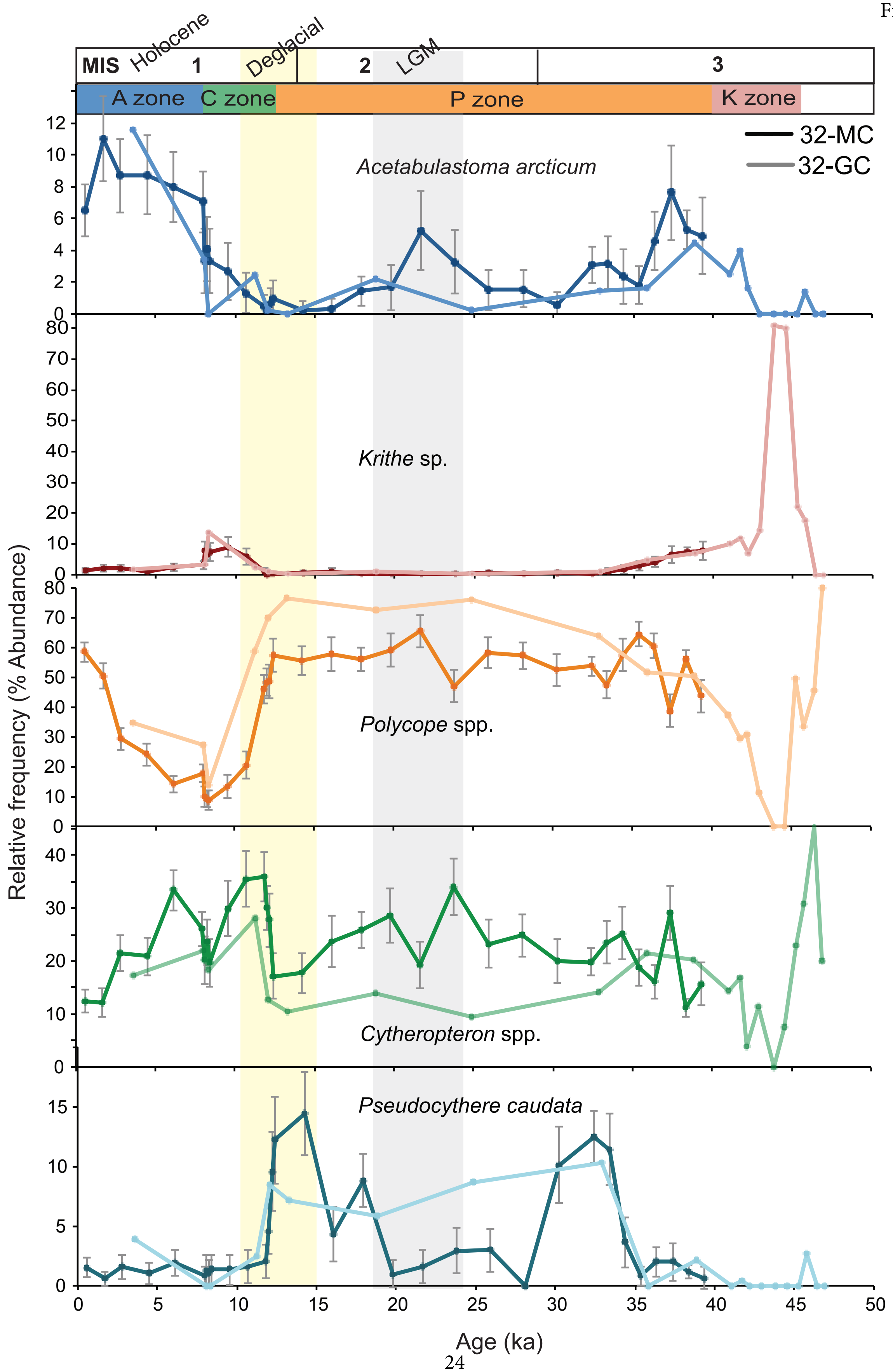

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Fig. 4

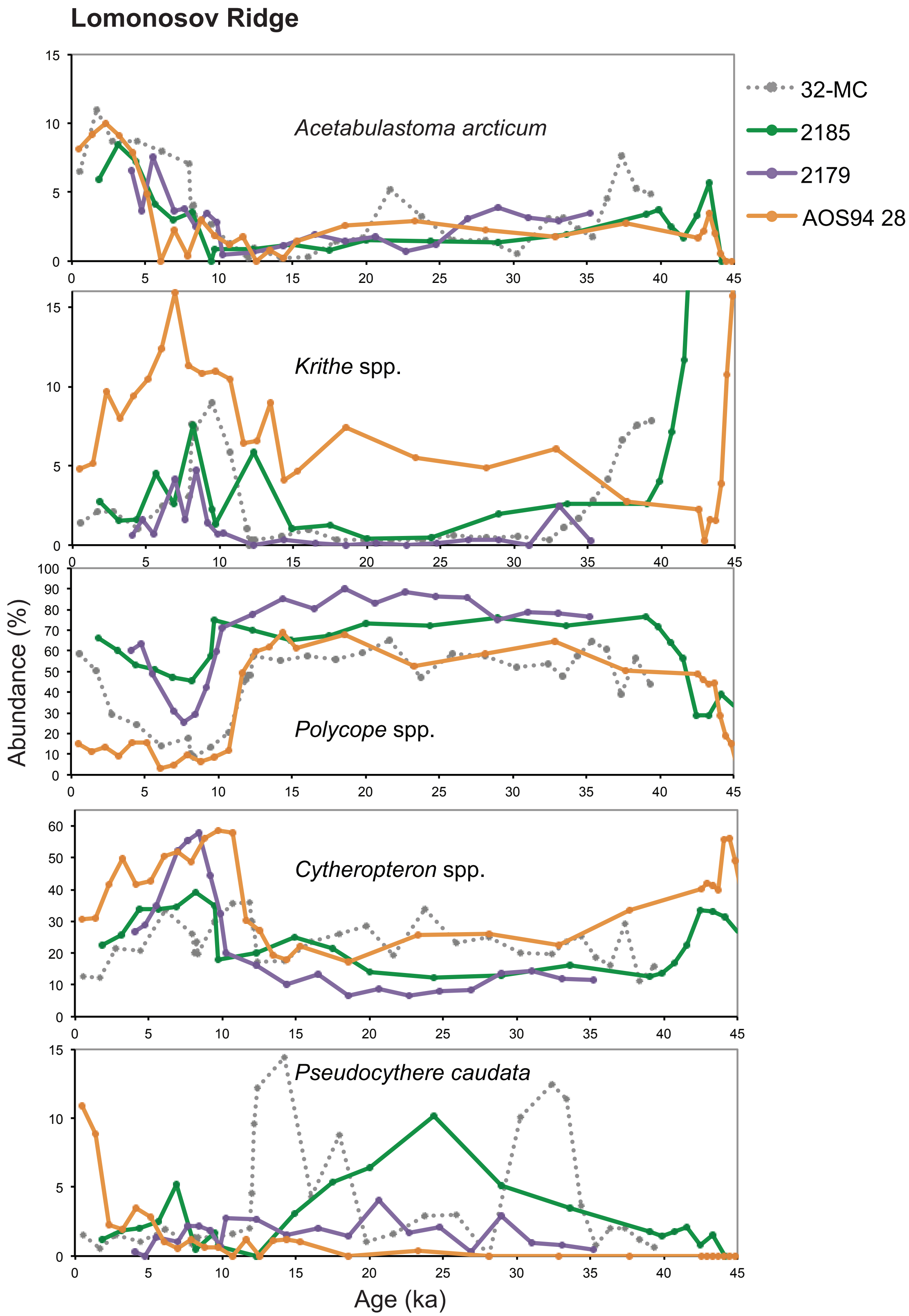

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Fig. 5

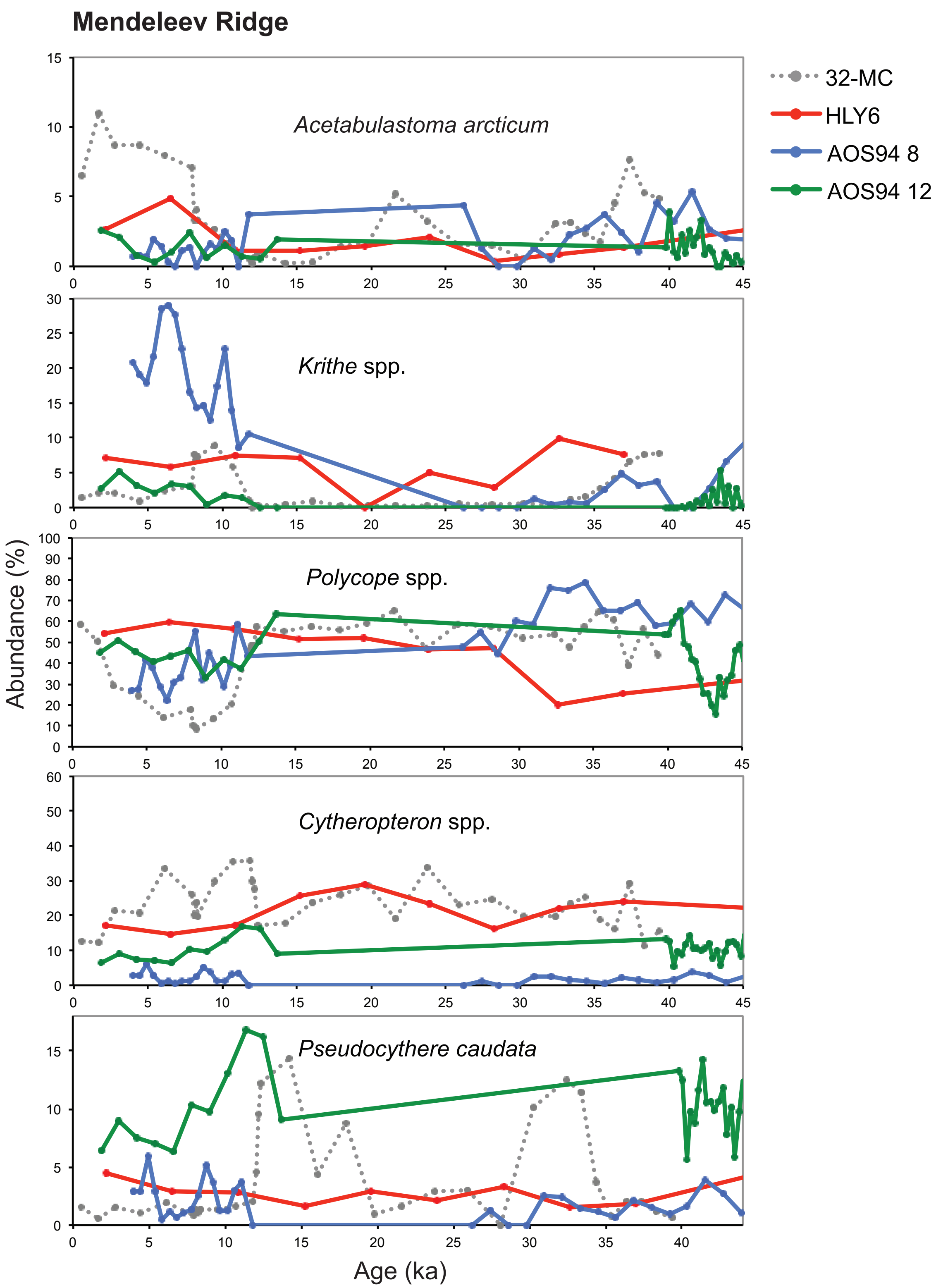

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Fig. 6

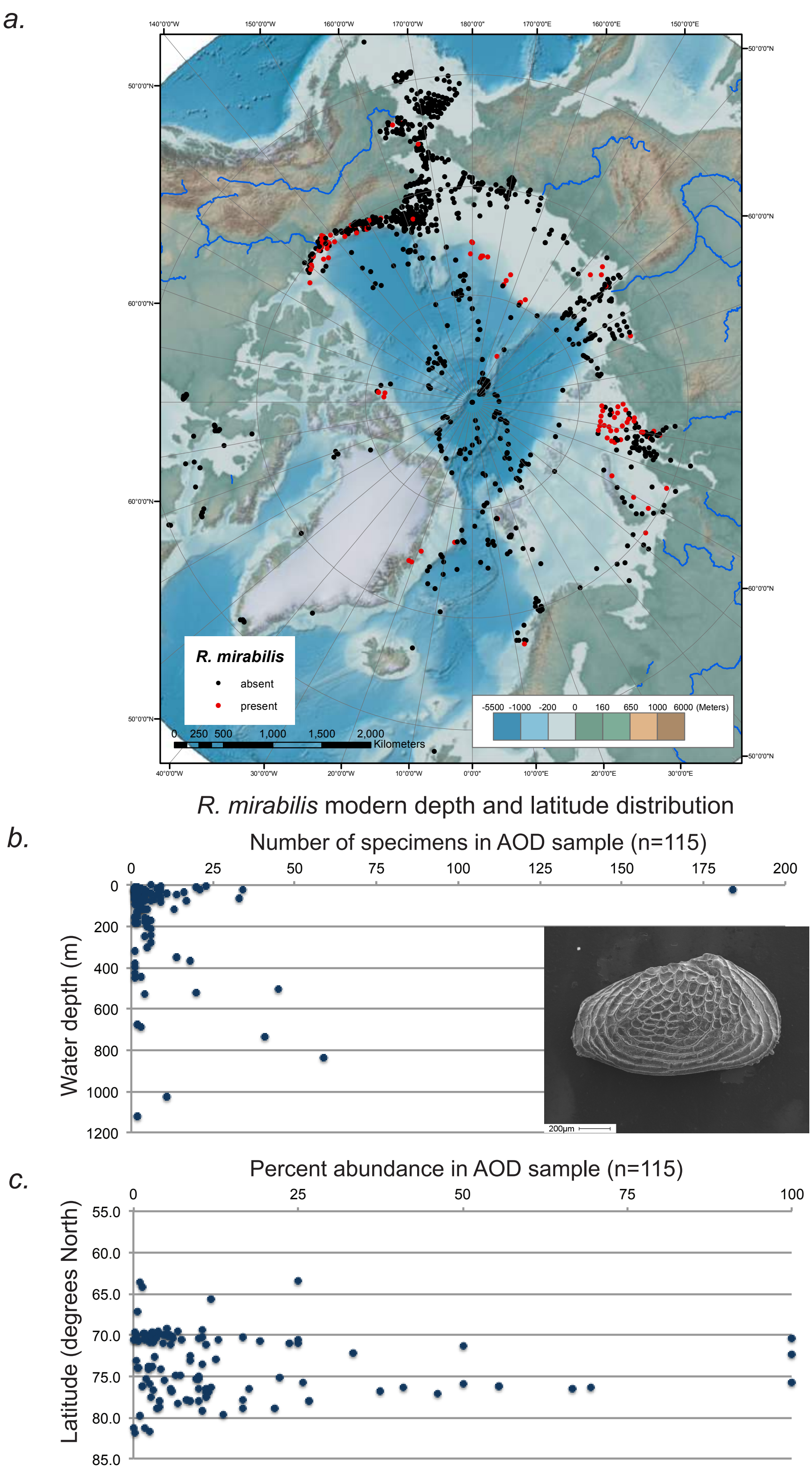

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Fig. 7