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ARCTIC OCEAN BENTHIC FORAMINIFERAL FAUNAL CHANGE ASSOCIATED WITH
THE ONSET OF PERENNIAL SEA ICE IN THE MIDDLE MIOCENE

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ABSTRACT

Understanding how Arctic Ocean deep-water ecology responded to past climatic events is of importance in assessing the region's sensitivity to environmental change. Here we present the first quantitative Miocene-Pliocene benthic foraminiferal records from the central Arctic Ocean, Lomonosov Ridge, IODP Hole M0002A. Despite significant dissolution and the absence of calcareous tests, these data show a significant faunal change occurred at ~14 Ma, characterized by a change from an older relatively diverse assemblage including *Reticulophragmium pusillum*, *Ammolagena clavata*, and *Recurvoides brideauxi*, associated with open-ocean environments and a paleodepth probably >200 m, to a younger assemblage dominated by *Rhabdammina* spp. and the endemic Arctic benthic foraminifera *Alveolophragmium polarensis*. Sedimentologic proxies indicate the onset of perennial sea ice in the central Arctic Ocean likely occurred in conjunction with the faunal change, suggesting that this onset and increased ice rafting had a long-term impact on bottom-water ecology in the central Arctic Ocean. This ecologic change may have been related to changes in the type, quantity, and duration of organic carbon flux, which may also explain the documented increase in total sedimentary organic carbon at the same time, possibly indicative of increased productivity. In the younger section of M0002A, from ~12.6 Ma, abundances are too low for clear paleoecologic interpretations.

INTRODUCTION

The Arctic Ocean supplies perennial sea ice which, in addition to regulating global temperature via the sea-ice albedo feedback, affects the location of North Atlantic Deep Water formation, a major component of Atlantic thermohaline circulation (Aagaard and others, 1985; Ganopolski and others, 1998; Nørgaard-Pedersen and others, 2003). The reduced primary productivity beneath perennial sea ice due to low insolation renders the central Arctic oligotrophic (Kröncke and others, 2000), whereas the seasonally variable sea-ice concentration and extent near the ice margin causes variable and sometimes extremely high primary productivity (Wheeler and others, 1996; Kröncke and others, 2000; Renaud and others, 2007; Arrigo and others, 2012). In the Arctic a close relationship between primary productivity and benthic community structure has been well demonstrated (Grebmeier and Barry, 1991; Piepenburg and others, 1997; Wollenberg and Kuhnt, 2000; Renaud and others, 2007; Cochrane and others, 2009), and benthic foraminiferal communities in the deep Arctic Ocean (Schroder-Adams and McNeil, 1994; Wollenberg and Kuhnt, 2000; Wollenberg and others, 2007; Cronin and others, 2008; Kaminski and others, 2009) thus show differences from Atlantic faunas (e.g., Belanger and Streeter, 1980; Kaminski and others, 2005), as they have adapted to these different conditions. Understanding the history of Arctic Ocean deep-water ecology and its link to surface-water processes in response to past episodes of climate change is thus of importance to understanding impacts of future change.

In 2004 the Arctic Coring Expedition (ACEX; Integrated Ocean Drilling Program, Expedition 302) recovered the first pre-Pleistocene sedimentary records from the central Arctic Ocean. Kaminski and others (2009) reported the taxonomy and geographic distribution of the

Neogene benthic foraminifera from the Lomonosov Ridge (1209-m water depth), and provided the first non-quantitative data on faunal distributions as evidence that deep-water connections with the Atlantic were in place from at least ~17.5 Ma (Kaminski and others, 2009). Here we present the first quantitative records of deep-water foraminiferal faunas from Hole M0002A, Lomonosov Ridge, from ~17.5–1.5 Myr. Sedimentologic and geochemical proxies for the existence of perennial sea ice (Haley and others, 2008; Krylov and others, 2008; St. John, 2008), as well as a more robust age model (Backman and others, 2008), allow us to place faunal changes in context with surface-water changes. In this study we explore the significance of the benthic faunas, and link the largest faunal and implied ecologic change to the inception of perennial sea ice in the central Arctic.

PHYSICAL SETTING

MODERN ARCTIC SEA ICE AND PRODUCTIVITY PATTERNS

The central Arctic Ocean is characterized by low primary productivity due to perennial sea ice (Wheeler and others, 1996; Kröncke and others, 2000), which moves towards the Fram Strait and Greenland Sea via the Transpolar Drift (Fig. 1). Arctic sea-ice thickness, concentration, and extent has changed markedly over the last 40 years, with an average thickness (submarine draft measured from sonar) of 3.64 m in 1980 reducing to 1.89 m by 2008 and both concentration and extent (where ice concentration >15%) falling over this period (Rothrock and others, 2008; Kwok and Rothrock, 2009). Although our knowledge of the distribution of Arctic productivity and sea-ice thickness, concentration, and extent is incomplete, changes in sea-ice

thickness and composition have widely varying impacts on primary productivity. Areas of less concentrated and thinner sea ice allow light to penetrate, and can form habitats for variable and patchy but highly productive ice algal blooms (Renaud and others, 2007). Recent studies have shown that productivity beneath thin Chukchi Sea, first-year ice can be extremely high (≤ 4 times higher than in open waters), due to better optical transmission than snow covered multi-year ice (Arrigo and others, 2012). In July and August 1994, water-column productivity was lowest in the central Arctic Makarov Basin ($32 \pm 13 \text{ mg C m}^{-2} \text{ d}^{-1}$) and Amundsen Basin ($30 \pm 10 \text{ mg C m}^{-2} \text{ d}^{-1}$), where sea-ice coverage ranged from 90–100%, and highest in the Chukchi shelf ($858 \pm 594 \text{ mg C m}^{-2} \text{ d}^{-1}$) and Nansen basin ($263 \pm 238 \text{ mg C m}^{-2} \text{ d}^{-1}$), where sea ice coverage was 50–80% and 80%, respectively (Wheeler and others, 1996). The Arctic marginal seas, also affected by river runoff, exhibit high seasonal productivity and support some of the richest benthic communities in the world (Carmack and Wassmann, 2006; Renaud and others, 2007). Although organic carbon appears to reach great depths from occasional down-canyon transport of sedimentary organic material (Clough and others, 2005), the isolated nature of the Lomonosov Ridge largely precludes this form of sedimentation.

ARCTIC DEEP-WATER ECOLOGY

There is strong evidence for a close relationship between primary productivity and benthic communities (benthic-pelagic coupling) in the Arctic Ocean (Grebmeier and Barry, 1991; Piepenburg and others, 1997; Wollenberg and Kuhnt, 2000; Renaud and others, 2007; Cochrane and others, 2009). Many ecologic parameters affect marine benthic communities, and Levin and others (2001) identified food input, bottom flow, bottom-water oxygen levels,

sediment heterogeneity, and ecologic disturbance as the most important. On the deep (1209 m) Lomonosov Ridge, ecologic disturbance, bottom-water currents, and sediment heterogeneity are at a minimum. Although oxygen levels are known to heavily affect benthic foraminiferal communities, this is only the case below $\sim 1\text{--}2\text{ ml l}^{-1}$ (Jorissen and others, 1995; Levin and others, 2001; Murray, 2001), which is well below the high levels found in the deep Arctic Ocean. As by far the most variable ecologic parameter affecting benthic communities in the deep Arctic Ocean is sea-floor carbon flux, which is directly related to primary productivity and water depth, sea-ice cover has been widely regarded as an important driving force of community structure through control on primary productivity (Lagoe, 1976; Wollenburg and Kuhnt, 2000; Wollenburg and others, 2007).

Extensive studies of living benthic foraminifera from the Arctic Ocean show a clear differentiation between assemblages beneath perennial thick sea ice and those beneath the ice margin (Schröder-Adams and others, 1990; Wollenburg and Kuhnt, 2000), in contrast to those from ice-free zones (Belanger and Streeter, 1980). While intermediate water-depth (600–1500 m) assemblages in the Greenland-Norwegian Sea are dominated by *Melonis barleeaanum* (Williamson), *Pullenia bulloides* (d'Orbigny), *Islandiella norcrossi* (Cushman), and *Cassidulina teretis* Tappan (Belanger and Streeter, 1980), intermediate-water benthic assemblages north of Spitsbergen close to the ice margin zone show wide variability and include the species *Hormosinelloides guttifer* (Brady), *Adercotryma glomerata* (Brady), *Stetsonia arctica* (Green) and *Portatrochammina karica* (Shchedrina) (Wollenburg and Kuhnt, 2000). In contrast the perennially ice-covered central Arctic contains less variable assemblages including *Stetsonia arctica* and *Adercotryma glomerata* (Scott and Vilks, 1991; Wollenburg and Kuhnt, 2000).

MIDDLE MIOCENE ONSET OF PERENNIAL SEA ICE

Evidence for the onset of perennial sea ice in the central Arctic Ocean (as opposed to seasonal sea ice initiation in the Eocene; Stickley and others, 2009) comes from an increase in sedimentary hornblende between ~14.2–12.9 Myr (Krylov and others, 2008; Fig. 2G), which is most likely derived from the East Siberian and Laptev Seas and indicates at least one year of no-summer melting assuming modern sea-ice trajectories and velocities (Krylov and others, 2008). Using the same assumptions it is also apparent, from the presence of sedimentary Fe oxide minerals that could only have been delivered by ice rafting for over one year, that the Arctic experienced perennial sea ice (at least one year of no-summer melting) over at least the last 14 Myr (Darby, 2008), although this record does not extend further back in time. However, it is not clear from these records if perennial sea ice was persistently or episodically present throughout this time period. Further evidence for an increase in sea ice at ~14 Ma comes from elevated ice-rafted debris (St. John, 2008; Fig. 2F), although this may have been delivered either via sea ice or icebergs. In addition, an increase in sedimentary neodymium (ϵ_{Nd}) values through this interval (Fig. 2H) suggests an increase in intermediate-water formation on the Eurasian shelf via brine rejection, associated with shelf-ice build-up presumably from regional cooling (Haley and others, 2008). It is clear from these published records that perennial sea ice has been present in the central Arctic for at least the last ~14 Myr.

METHODS

All samples were collected from Lithologic Subunits 1/3 and 1/4 of ACEX Hole M0002A on the Lomonosov Ridge, and consist of silty clay and silty mud (Backman and others, 2006). Sediment samples of approximately 20-cm² volume were washed through a 63- μ m sieve and oven dried. Foraminifera specimens were placed into faunal slides and all species were identified and counted (Appendix 1). The vast majority were recovered from the >125- μ m fraction, with smaller specimens present as fragments of agglutinated foraminiferal tests. Some other studies have used the >45- μ m fraction (e.g. Scott and others, 2009), and recovered higher numbers of calcareous foraminifera. Taxonomic work on this core was carried out by Kaminski and others (2009). Samples were collected at an average ~1.5-m spacing. The age model used (Backman and others, 2008) indicates a sample resolution on average of ~120 kyr. Correspondence Analysis was carried out on all data using the software of Hammer and others (2005). The foraminiferal specimens were photographed using a Zeiss-940 digital scanning electron microscope at the Department of Earth Sciences, University College London. All core sites discussed in this work are shown in Fig. 1 and Table 1.

RESULTS

Twenty-five species of benthic foraminifera were recovered from Hole M0002A (Fig. 3; Appendix 1), with abundances averaging ~30 specimens/sample prior to ~12.5 Ma, and ~10/sample in the remainder (Fig. 2C). All species were agglutinated which, considering a large proportion of benthic foraminifera from the Arctic Ocean today are calcareous (Wollenburg and

Kuhnt, 2000) and sedimentary biogenic carbonate is absent in this part of the core (Backman and others, 2006), indicates severe dissolution was the primary cause of low abundance and diversity. Many agglutinated foraminifera use organic cement and sand grains for their test-wall construction and can therefore be more dissolution-resistant in certain circumstances, which may explain their presence in the ACEX cores. Kaminski and others (2009) identified that the highest abundances and diversity of foraminifera between ~195–155 m (Fig. 3) coincided with elevated pore-water biogenic silica (Backman and others 2006), and argued this was due to increased availability of biogenic silica, which replaces organic cement in early diagenesis, allowing better preservation. Thus, the better preservation of agglutinated foraminifera in the interval ~195–155 m (Assemblages 1 and 2) allows a tentative reconstruction of possible ecologic changes for two of the three assemblages defined in Hole M0002A (Fig. 2B).

Assemblage 1, from 192.64–166.69 mbsf (17.5–14.2 Myr), is characterized by relatively high abundance (average 40 specimens/sample, total 837 specimens) and low diversity (average 5 species/sample, total 21 species) agglutinated foraminifera, dominated by *Recurvoides* spp. (Fig. 2D), *R. brideauxi* Schröder-Adams and McNeil and *Reticulophragmium pusillum* (Brady), and also containing *Psammosphaera fusca* Schultze, *Ammolagena clavata* Jones and Parker, *Hyperammia rugosa* Verdenius and van Hinte and *Reticulophragmium projectum* Schröder-Adams and McNeil. This interval broadly encompasses lithologic subunit 1/4, characterized by silty clay with total organic carbon (TOC) ~0.1 wt% (Backman and others, 2006).

Assemblage 2, from 166.73–154.11 mbsf (14.1–12.7 Myr), is characterized by medium abundance (average 22 specimens/sample, total 260 specimens) and low diversity (average 5 species/sample, total 17 species) of agglutinated foraminifera, dominated by *Alveolophragmium polarensis* O'Neill (Fig. 2E, J) and also containing *Cyclammina cancellata* Brady,

Reticulophragmium spp., *Rhabdammina* spp., and *Recurvoides* spp. This interval is at the base of lithologic subunit 1/3, characterized by silty clay and silty mud, with TOC ~0.25 wt% (Backman and others, 2006).

Assemblage 3, from 153.87–17.5 mbsf (12.6–1.5 Myr), contains low abundance (average 6 specimens/sample, total 494 specimens) and very low diversity (average 1 species/sample, total 13 species) agglutinated foraminifera, characterized by *Rhabdammina* spp., *A. polarensis*, and *P. fusca*. This interval sits within lithologic subunit 1/3, characterized by silty clay and silty mud, with TOC ~0.25 wt% (Backman and others, 2006).

Correspondence Analysis utilizing all data (Fig. 4) reveals Assemblage 1 (A1) and A2 are distinct from each other in their species composition, indicating that, despite significant post-mortem dissolution, a shift in benthic ecology likely occurred at ~14 Ma (Hammer and Harper, 2006). Assemblage A3 is more closely allied to A2 and is best defined as simply a reduction in abundance likely from poorer preservation possibly due to reduced pore water silica availability (Kaminski et al 2009). All species present are indicative of fully marine deep-water (bathyal) environments (Kaminski and Gradstein, 2005).

DISCUSSION

FAUNAL CHANGES

Assemblage 1 (A1) contains the highest abundances of agglutinated foraminifera in the studied section. *Reticulophragmium pusillum* and *A. clavata* are species found in the deep (bathyal–abyssal) North Atlantic, and their occurrence indicates that the Fram Strait deep

connection to the Atlantic was open by at least ~17.5 Ma (Kaminski and others, 2009). Although this fauna suggests a paleodepth >200 m (Kaminski and others, 2009), precise estimates are difficult to make as agglutinated foraminifera commonly extend to anomalously shallow depths in Arctic seas probably due to reduced productivity (Wollenburg and Kuhnt, 2000). Abundant alveolar-walled deep-sea foraminifera (e.g., *Reticulophragmium*, *Cyclammina*) have commonly been described from environments of high organic carbon flux (e.g., Kender and others, 2008a; 2008b), but there is no evidence that oxygen levels were significantly reduced over the studied interval. *Recurvoides brideauxi* and *R. projectum* were endemic Arctic species described from the Oligocene and Miocene of the Beaufort-Mackenzie Basin (McNeil, 1989), a region that may not have been affected by perennial sea ice at that time. The shift from A1 to A2 (~14 Ma) is characterized by an abrupt change in the agglutinated foraminiferal assemblage to a less abundant but similarly diverse assemblage, dominated by *A. polarensis* and *Rhabdammina*. Although it is possible the species *A. polarensis*, *R. brideauxi*, and *R. projectum* have been synonymized with other taxonomic groups, these species are believed to be endemic to the Arctic as they were not recorded in either Paleogene or Neogene agglutinated foraminiferal assemblages from the Fram Strait (Kaminski and others, 2005), North Sea, and Labrador Sea (Gradstein and Kaminski, 1989; Gradstein and others, 1994), or Bering Sea (Takahashi and others, 2011; Kaminski and others, 2012).

The change from A1 to A2 was unlikely due simply to dissolution, as abundance and preservation does not significantly decline over this transition, and *A. polarensis* has its first persistent occurrence here (Fig. 3). Although the complete absence of calcareous tests (in contrast to the modern Arctic, Wollenburg and Kuhnt, 2000) suggests this is a residual fauna affected by severe dissolution, the significant and persistent faunal change between A1 and A2 is

best explained by a shift in bottom water properties and benthic ecology. Further evidence for a change in benthic ecology is the shift from lithologic subunits 1/4 to 1/3 (Fig. 2A), characterized by a persistent elevation in sedimentary TOC from 0.1 wt% to 0.25 wt% (Backman and others, 2006). The faunal shift from A1 to A2 (~14 Ma) was, therefore, unlikely caused by increased water depth from the gradual subsidence of the Lomonosov Ridge (likely to have been occurring at this time interval, O'Regan and others, 2008), as the faunal boundary is sharp rather than gradual and the increase in TOC runs counter to the relationship of reduced organic carbon flux with greater water depth (Lagoe, 1976; Kröncke and others, 2000).

ALVEOLOPHRAGMIUM POLARENSIS

The most common foraminifera from A2 is *A. polarensis* (Fig. 2E, J), which remains a persistent component of A3. Although not recorded in core top studies of the Arctic Ocean (Belanger and Streeter, 1980; Schröder-Adams and others, 1990; Scott and Vilks, 1991; Wollenburg and Kuhnt, 2000), on the Lomonosov Ridge, *A. polarensis* became much reduced after Marine Isotope Stages 22–24 (~0.9 Ma) in Hole M0004C (Cronin and others, 2008), and disappeared on the Lomonosov Ridge above 2 m in Hole PS 2185-6 (Evans and Kaminski, 1998), which equates to ~0.14 Ma using the ACEX age model (Fig. 5). The species was first described by O'Neill (1981) from several piston cores in the central Arctic (Sites FL224–FL506, Fig. 1). It was not present in the deepest sites (FL224 and FL268, >3000-m depth), but was present in the majority of the others ranging from ~2600 to ~1400-m water depth. As the amount of organic carbon reaching benthic communities decreases with water depth (Lagoe, 1976; Kröncke and others, 2000), this suggests reduced organic carbon supply associated with the

deeper sites was not preferable for this species. In Sites FL283–FL506 (~2600 to ~1400-m water depth), *A. polarensis* does not occur above ~2-m sediment depth (lithologic unit D, O’Neill, 1981). This was originally interpreted as late Pliocene (Clark and others, 1980; O’Neill, 1981; also see Backman and others, 2004). However, since the ACEX Expedition it has become clear that Neogene sedimentation rates in the Arctic were much higher than previously suspected at around 12 m Myr⁻¹ (Backman and others, 2004, 2008), which gives a possible age of ~0.16 Ma. If *A. polarensis* was absent in the deeper sites (FL224 and FL268) due to a reduced carbon flux, it is possible the reduction in *A. polarensis* at ~0.9 Ma on the Lomonosov Ridge was also associated with a reduction in sea-floor carbon flux, which could have been caused by sea-ice thickening or increased concentration during the Mid-Pleistocene Transition (~0.6–1.2 Myr, as also suggested by Cronin and others, 2008). Its possible disappearance at ~0.14 Ma in the central Arctic Ocean (O’Neill, 1981; Evans and Kaminski, 1998) could be due to further ice thickening or increased concentration, reducing organic carbon supply still further. However these interpretations are tentative due to a lack of comprehensive distributional data or biological studies.

Evans and Kaminski (1998) also recorded *A. polarensis* from cores PS2200-5 (Morris Jessup Rise) and PS2212-3 (Yermak Plateau, Fig. 1). At PS2200-5 *A. polarensis* exhibited occasionally high abundances in the older part of the core below 3 m (Fig. 5), with lower abundances in the younger part. In contrast, in PS2212-3 it had highest abundances in the younger part (top ~2 m), including the top-most recent sample. Core PS2212-3 is in closer proximity to the ice margin today (Fig. 1), where productivity is likely to have been higher than at the Morris Jessup Rise, as ice here is thicker and more concentrated (Bourke and Garrett, 1987). Thus, *A. polarensis* may have tolerated an environment with variable and patchy organic

carbon supply beneath perennial sea ice (e.g., Yermak Plateau), but that an organic carbon supply threshold existed below which this species could not thrive (deep central Arctic Ocean, O'Neill, 1981; Recent Lomonosov Ridge, Evans and Kaminski, 1998; Cronin and others, 2008).

ENVIRONMENTAL CHANGES AT 14 MA

In summary, it is not possible from the residual agglutinated fauna recovered in core M0002A to fully characterize the ecologic change associated with the faunal change at ~14 Ma (Figs 2 and 4). However, as the shift from A1–A2 was the most significant long-term change to be recorded in the benthic foraminiferal assemblages from ~17.5–12.5 Myr (Fig. 4) and it is associated with a lithologic change and increase in sedimentary TOC (Fig. 2), it appears that a significant change to bottom-water ecology occurred at this time. As *A. polarensis* appears to have been highly sensitive to changing Arctic habitats (see section above), driven largely by organic carbon supply (Levin and others, 2001; Renaud and others, 2007; Cochrane and others, 2009), and as there is an increase in TOC (Backman and others, 2006), we believe that a shift in the ecology was most likely related to a change in the type, quantity, and/or regularity of organic carbon supply, which would in turn have been driven by surface-water changes. An increase in TOC is difficult to clearly interpret but would be consistent with increased primary productivity, which can be extremely high under thin Arctic sea ice compared to ice-free zones (Arrigo and others, 2012). Other studies also indicate Arctic faunas with an agglutinated foraminiferal component may coincide with higher productivity (Scott and others, 2009). Subsidence of the Lomonosov Ridge is unlikely to have been the primary cause, due to an increase in TOC at ~14 Ma and the rapid nature of the transition. Although it is possible there was a change in the

dominant intermediate water mass, the most likely explanation for changing organic carbon supply is the onset of perennial sea ice (Fig. 2; Krylov and others, 2008; Darby, 2008) that is supported by the co-occurrence of the first persistent *A. polarensis* and abundant IRD (Fig. 2; St. John, 2008), marking the onset of significant sea-surface ice and changing productivity patterns. Sea ice is known to heavily impact productivity and bottom-water ecology, leading to a variable but occasionally large food supply (Renaud and others, 2007; Cochrane and others 2009).

SUMMARY AND CONCLUSIONS

1. We quantitatively document agglutinated foraminifera from IODP Hole M0002A, Lomonosov Ridge, over the interval ~17.5–1.5 Myr. Residual agglutinated assemblages occur in low abundance throughout the section, with two assemblage changes recognized at ~14 Ma and ~12.6 Ma. The first assemblage change is associated with a shift in the dominant fauna, and therefore indicates a benthic ecologic change. The second assemblage change is associated primarily with a reduction in abundance (such that paleoenvironmental interpretations here are not possible), and probably indicates a preservation and possibly sedimentologic geochemical change.
2. The faunal shift at ~14 Ma includes the appearance of persistent *A. polarensis*, a species endemic to the Arctic Ocean (O'Neill, 1981; Evans and Kaminski, 1998; Cronin and others, 2008). Although the ecologic preferences of this species are unknown for lack of comprehensive geographic and biological information, available distributional evidence suggests this species was highly sensitive to changing Arctic habitats below sea ice, which

in the modern deep Arctic Ocean is primarily driven by organic carbon flux (Levin and others, 2001; Renaud and others, 2007; Cochrane and others, 2009).

3. The faunal shift and appearance of abundant *A. polarensis* at ~14 Ma coincide with the onset of sedimentologic proxies for perennial sea-ice cover over the central Arctic Ocean (Krylov and others, 2008; Darby, 2008), a sharp increase in sedimentary IRD (St John, 2008), a lithologic change, and an increase in sedimentary TOC (Backman and others, 2006). Together these changes point to a significant shift in bottom water properties and benthic ecology, most likely caused by sea ice affecting the type, quantity, and/or regularity of organic carbon reaching the sea floor. Our results indicate future reductions in Arctic Ocean perennial sea-ice cover may affect bottom-water ecology.

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Site	Location	Latitude	Longitude	Water depth	Reference
M0002A*	Lomonosov Ridge	87°55.271'N	139°21.901'E	1209 m	This study
M0004C*	Lomonosov Ridge	87°52.065'N	136°11.381'E	1288 m	Cronin and others (2008)
PS2185-6*	Lomonosov Ridge	87°32.2'N	144°55.6'E	1052 m	Evans and Kaminski (1998)
PS2200-5*	Morris Jessup Rise	85°19.4'N	14°00.0'W	1073 m	Evans and Kaminski (1998)
PS2212-3*	Yermak Plateau	82°4.2'N	15°51.2'E	2550 m	Evans and Kaminski (1998)
FL224	Eurasian Basin	80°27.74'N	158°48.51'W	3467 m	O'Neill (1981)
FL268	Eurasian Basin	83°16.32'N	152°58.48'W	3062 m	O'Neill (1981)
FL283*	Alpha Ridge	83°48.06'N	146°12.65'W	2639 m	O'Neill (1981)
FL292*	Alpha Ridge	84°18.28'N	143°41.02'W	2330 m	O'Neill (1981)
FL314*	Alpha Ridge	85°27.00'N	139°23.54'W	1927 m	O'Neill (1981)
FL322*	Alpha Ridge	84°27.00'N	135°18.33'W	2446 m	O'Neill (1981)
FL365*	Alpha Ridge	84°28.48'N	131°22.31'W	2732 m	O'Neill (1981)
FL393*	Alpha Ridge	84°59.61'N	126°12.97'W	1414 m	O'Neill (1981)
FL506*	Alpha Ridge	84°06.62'N	112°43.87'W	1871 m	O'Neill (1981)
909C	Fram Strait	78°35.096'N	3°4.222'E	2518 m	Kaminski and others (2005)

TABLE 1. Location and information of all core sites discussed in this study. Asterisk marks sites where *Alveolophragmium polarensis* has been recorded.

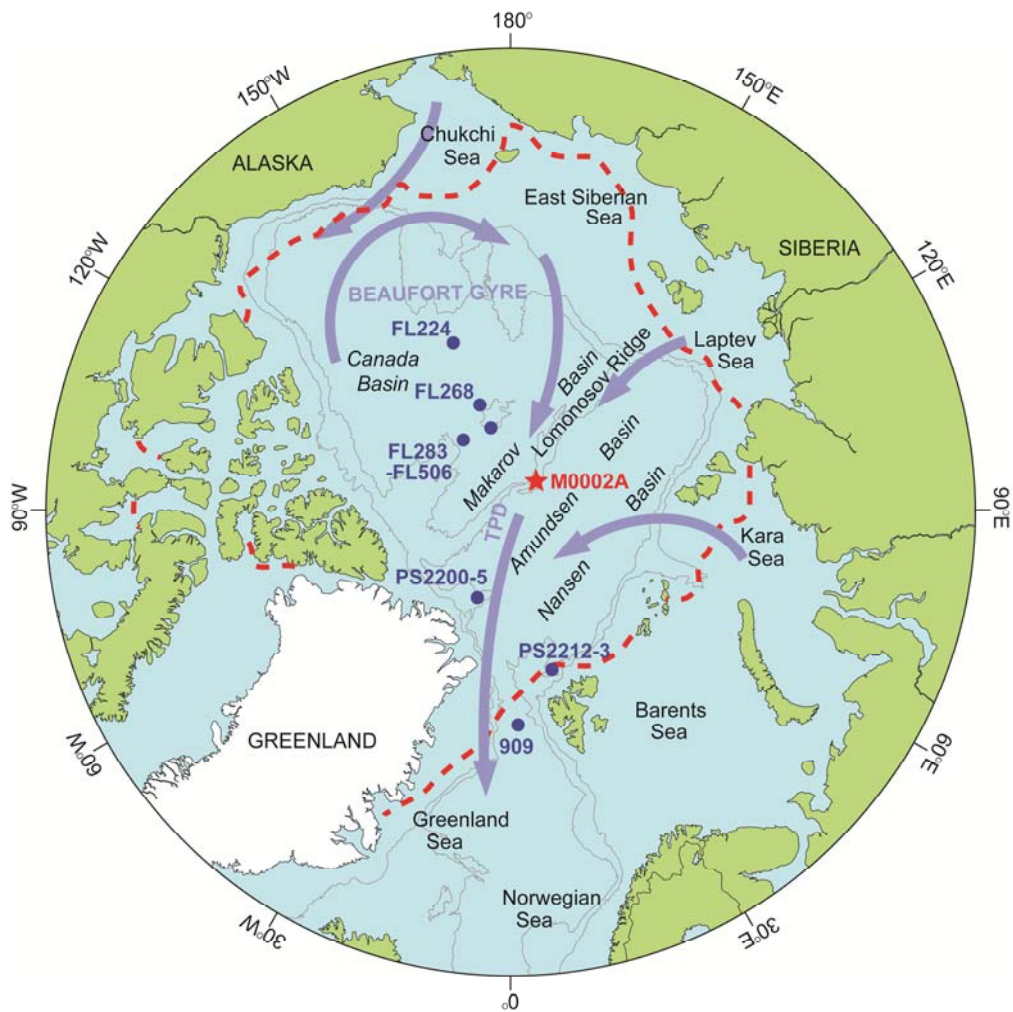


FIGURE 1. Map of the Arctic Ocean, showing the location of IODP Hole M0002A (this study, similar location for M0004C) and various sites discussed in the text. Dashed red line indicates the extent of 30-year average summer sea ice for 1979–2000 (National Snow and Ice Data Center, USA). Arrows indicate cold surface water currents. TPD—Trans-Polar Drift.

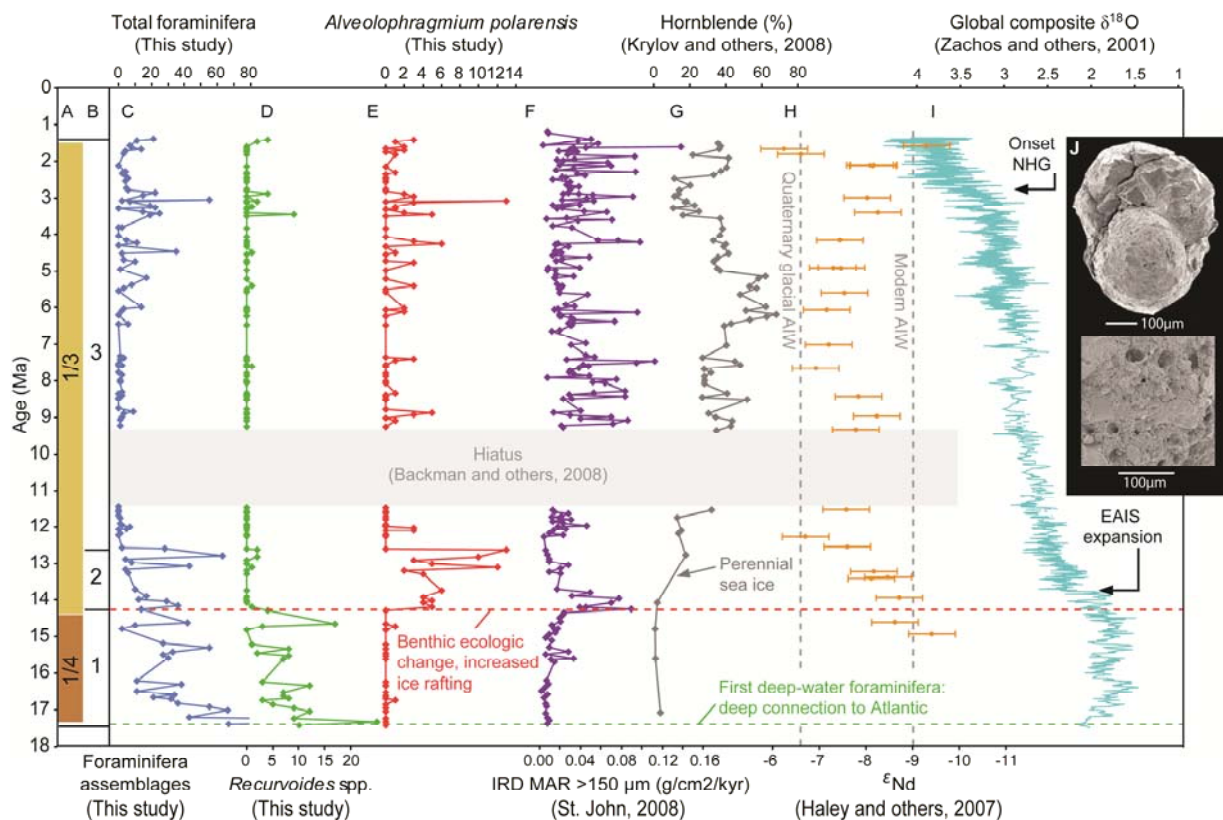
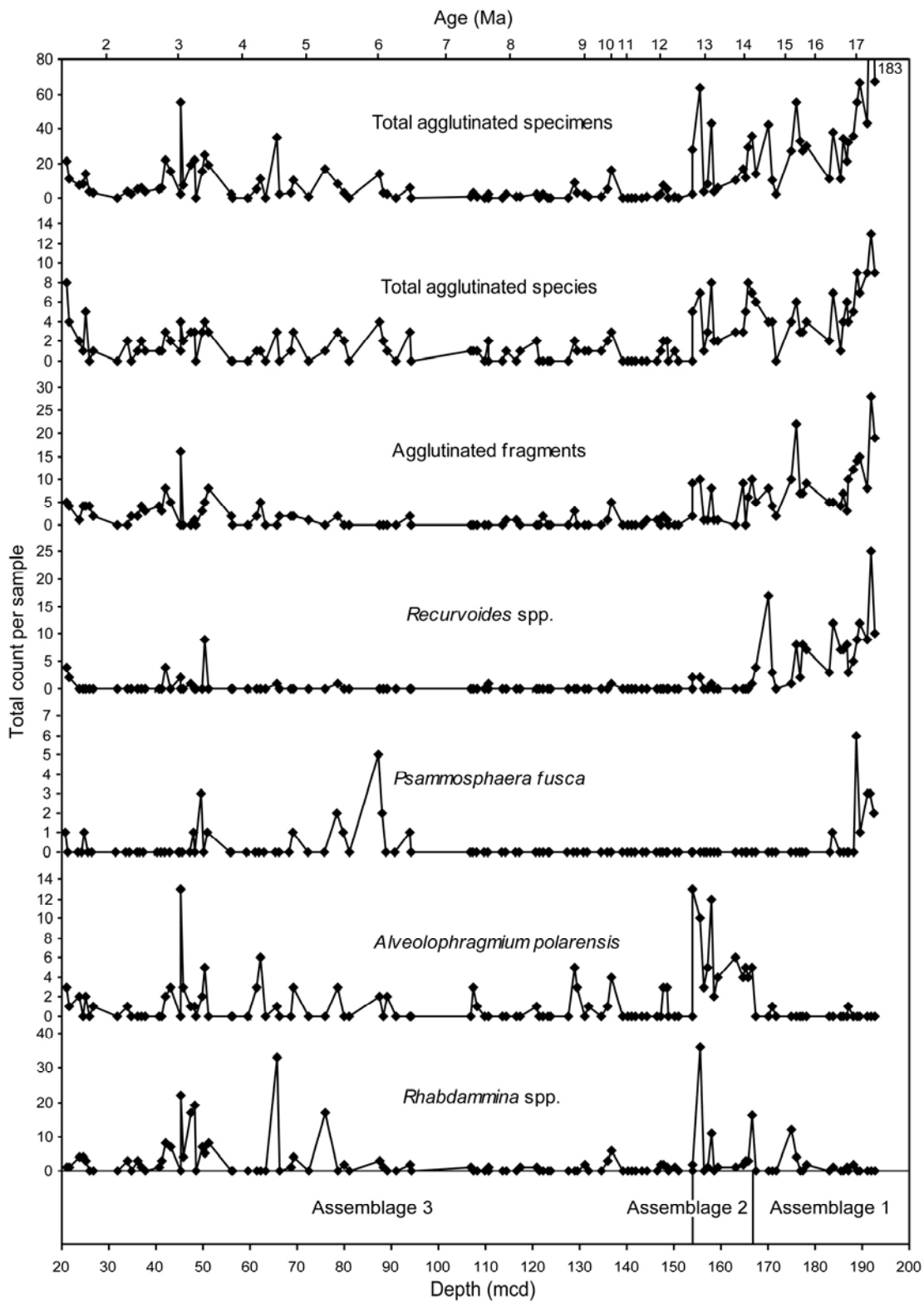


FIGURE 2. Various data from IODP Hole M0002A, plotted against age (Backman and others, 2008). **A** Lithologic units: 1/3, predominantly olive gray silty clay and mud; 1/4, predominantly dark brown silty clay (Backman and others, 2006). **B** Foraminiferal assemblages (this study). **C** Total counts of foraminifera (agglutinated) per sample (this study). **D** Total *Recurvoides* spp., one of the species characterizing Assemblage 1 which shows Atlantic affinities. **E** Total *Alveolophragmium polarensis*, the most important constituent of Assemblages 2 and 3. **F** Ice-Rafted Debris (IRD), indicating the extent of icebergs/sea ice (St. John, 2008). **G** Hornblende as a percentage of total heavy minerals, thought to be derived from East Siberian and Laptev seas and to indicate perennial sea ice (Krylov and others, 2008). **H** Sedimentary ϵ_{Nd} , with modern and Last Glacial Maximum values as gray dashed lines (Haley and others, 2008). **I** Global composite record of benthic foraminiferal $\delta^{18}O$ (‰ Vienna Peedee belemnite, Zachos and others, 2001). **J** Scanning electron microscope images of *Alveolophragmium polarensis*. Upper image apertural view (M0002A, 38X-4, 134–136 cm); lower image of broken specimen with abraded wall, revealing large simple alveoles (M0002A, 38X-1, 18–22 cm).



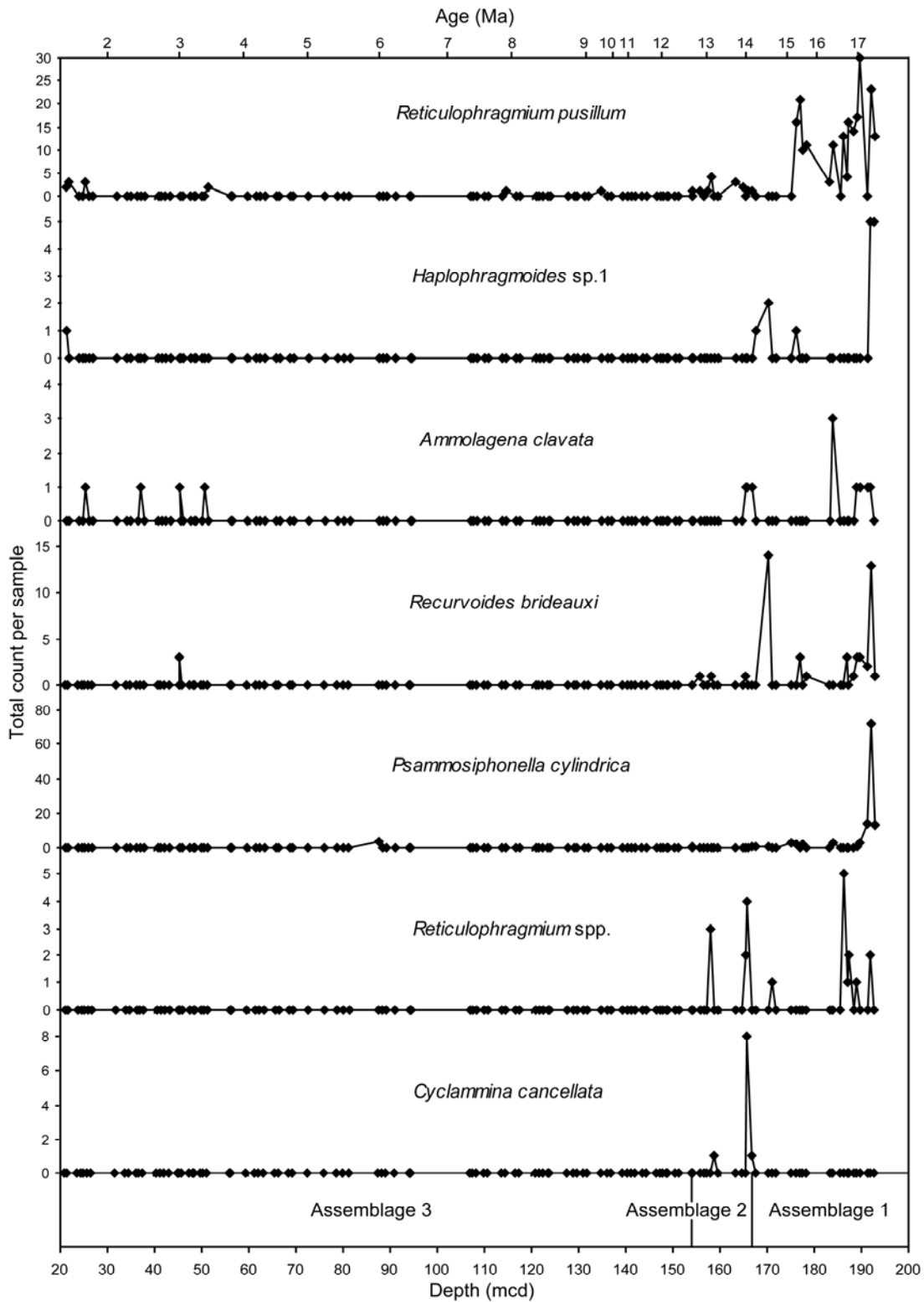


FIGURE 3. Graphs showing the absolute foraminiferal abundance of the most common species encountered in the studied samples, and the designated assemblages.

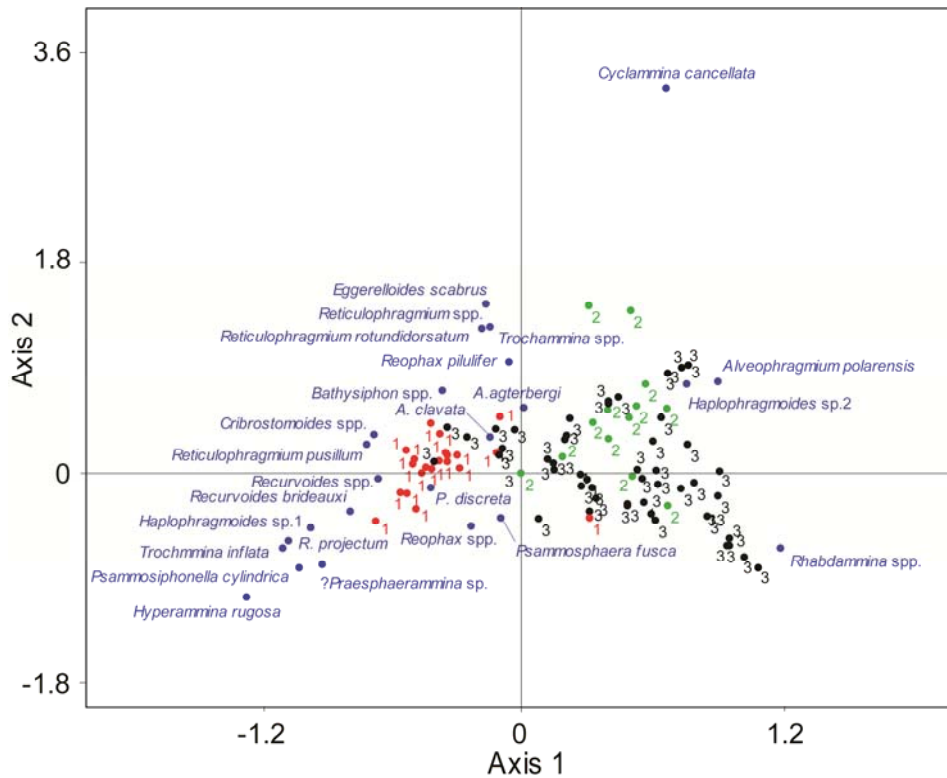


FIGURE 4. Results of Correspondence Analysis on all data from the studied samples, plotted against the two axes of greatest variance. Species scores (blue dots) show clustering around samples (black, green, and red dots) for which they are more abundant. The sample numbers refer to the assemblage for which the samples belong. Assemblage 1 is separate from Assemblage 2, indicating statistical difference between the two assemblages. Assemblage 2 is characterized by *Alveolophragmium polarensis*; Assemblage 1 by *Reticulophragmium pusillum*, *Recurvoides* spp., and *Psammosphaera fusca* among others, and has higher diversity. Assemblage 3 shows affinities to Assemblage 2, and is best defined as a reduction in total abundance compared to Assemblage 2.

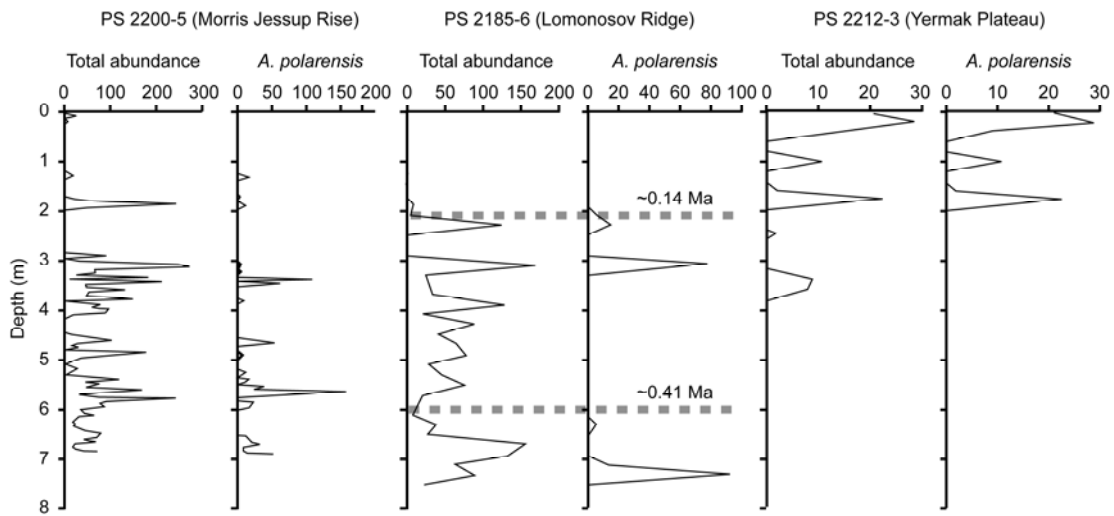


FIGURE 5. Number of foraminiferal specimens/sample and total *A. polarensis*/sample in cores PS2185-6, PS2200-5, and PS2212-3 (Evans and Kaminski, 1998). Age models are not well-constrained. Ages shown are from nearby Hole M0004C on the Lomonosov Ridge (Backman and others, 2008).