Miocene deep-water agglutinated foraminifera from the Lomonosov Ridge and the opening of the Fram Strait

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ABSTRACT: Deep-water agglutinated Foraminifera (DWAF) were recovered from Miocene to Pliocene sediments in 103 samples from IODP Hole M0002A on the Lomonosov Ridge. The First Occurrence of DWAF in Hole M0002A is observed just above the color change corresponding to the boundary between Lithological Subunits 1/4 and 1/5 in Core section –44X-1. The foraminiferal record of Hole M0002A consists entirely of agglutinated benthic species, largely sparse assemblages containing *Cyclammina pusilla* and *Alveolophragmium polarensis*. The faunal succession in Hole M0002A is subdivided into three assemblages based on the stratigraphic ranges of characteristic taxa: (1) a relatively diverse assemblage at the base of Lithological Subunit 1/4 (Cores 44X-1 to –38X), with abundant agglutinated foraminifera including *Reticulophragmium pusillum* and *Ammolagena clavata*, indicating connections with the North Atlantic. This assemblage displays the best preservation, which is here attributed to higher concentrations of dissolved silica in pore waters (2) A less diverse assemblage characterized by *Alveolophragmium polarensis* with *Adercotryma agterbergi*, in the lower part of Lithological Subunit 1/3 (Cores –38X to –35X); (3) a sparse residual assemblage within Lithological Subunit 1/3 with *Rhabdammina* spp., *A. polarensis* and *R. pusillum* indicating poor preservation of organically-cemented DWAF in Cores –34X to –10X.

A comparison of the DWAF assemblages from the Lomonosov Ridge with previously studied Miocene assemblages from ODP Hole 909C in the Fram Strait, Norwegian-Greenland Sea (Kaminski et al. 2005), suggests that the inflow of Atlantic intermediate water into the Arctic Ocean began prior to 17.5 Ma.

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INTRODUCTION

The Arctic Ocean is the last remaining frontier for deep-ocean drilling. The pre-Quaternary record of the Central Arctic Ocean is virtually unknown below the last few glacial/interglacial cycles, as so few piston cores have penetrated into older sediments. The primary goal of the Integrated Ocean Drilling Program Expedition 302, Arctic Coring Expedition (ACEX) (August 7 – September 14, 2004), was to core a complete sedimentary section on the Lomonosov Ridge in the Central Arctic, to study the Arctic's sedimentary, climatic, and biotic history (text-fig. 1). This major aim was successfully achieved – drilling during the ACEX cruise recovered a composite section of Cenozoic sediments overlying Campanian-age sedimentary basement.

The ACEX cruise recovered a 198-m thick section of Neogene sediments in Hole M0002A. Owing to corrosive pore waters the sediments in this hole contain no calcareous microfossils below approximately 21 mcd, but they do contain assemblages of agglutinated foraminifera similar to the Pleistocene assemblages described by Evans & Kaminski (1998) from long piston cores collected nearby. Initial examination of shipboard core-catcher samples revealed that the agglutinated foraminifera constitute the only microfossil group continuously present in this noncalcareous interval of Lithological Unit 1 (Subunits 1/3 and 1/4). A major hiatus occurs at 198.7 mcd, spanning a 26 m.y. interval from the early Miocene to the middle Eocene. The age

model and chronostratigraphy of the recovered cores from Hole M0002A is summarized by Backman et al. (2008).

The overall goal of scientific drilling on the Lomonosov Ridge was to decipher the paleoenvironmental evolution of the Central Arctic Ocean over the Cenozoic. One of the specific initial scientific objectives of the ACEX cruise was to "investigate the development of the Fram Strait and deepwater exchange between the Arctic Ocean and the Norwegian-Greenland Sea" (Expedition 302 Scientists in Backman et al. 2006). The purpose of this study was to obtain new information about the Neogene of Hole M0002A, with an aim to (1) document the agglutinated foraminiferal assemblages recovered from the hole; and (2) interpret the environmental significance of the deep-marine claystone unit of Lithological Subunits 1/3 and 1/4, by comparison with the Miocene record of Hole 909C in the Fram Strait. Pleistocene assemblages from the upper part of the sediment column will be discussed separately by Cronin et al. (2008).

METHODS

Standard sample processing methods were applied to 103 samples collected from Hole M0002A, from Lithological Subunits 1/3 and 1/4. The average sample volume was 20 cc, and two samples were collected from each core section. The volume of core-catcher samples processed during the cruise was variable, but generally averaged 10–20 cc. Samples processed in the shorebased laboratory were first dried overnight at about 40-50ºC and then boiled in water with sodium carbonate (Na_2CO_3) until disaggregated, and washed over a 63μm sieve. The residues were retained and dried at about 40-50ºC. Foraminifera were picked from the entire >63μm residue,

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mounted on cardboard slides, and are currently housed in the micropaleontological collections of University College London. In this report, the abundances per 10-20 cc sample are characterized as follows: B= barren; R= rare (1-5 specimens); F= few (5-10 specimens); and C= common (10-30 specimens). No samples contained species abundances that can be termed "abundant". The foraminiferal specimens were photographed using a Zeiss-940 digital scanning electron microscope at Department of Earth Sciences, University College London.

PREVIOUS STUDIES

While numerous studies have investigated the modern foraminifera of the Central Arctic (see review by Wollenburg 1992), owing to the lack of long sedimentary records only sparse information exists on the pre-Quaternary micropaleontology of the Arctic Ocean. Piston cores collected from the Alpha Ridge only penetrated the top 5 meters of the sediment column (O'Neill 1981), and the site survey cores collected from the Lomonosov Ridge during the Polarstern ARC 91 Cruise only recovered the last few glacial cycles. These cores contain a sparse record of agglutinated foraminifera (O'Neill 1981; Evans et al. 1995; Evans and Kaminski 1998). Until the ACEX cruise the deeper sedimentary record of the Central Arctic remained unknown.

The usefulness of agglutinated foraminifera for stratigraphical correlation in the Boreal Seas has been emphasized in a series of studies since the early 1980s. A zonal scheme based on Cenozoic foraminifera established for the Canadian Arctic Shelf (Beaufort-MacKenzie Basin) was first published by McNeil (1989). This scheme was later refined by Schröder-Adams & McNeil (1994a,b) who documented the Oligocene to Miocene agglutinated foraminifera from nine wells, representing a range of environments from deltaic to deep marine. Stratigraphic range charts of benthic foraminifera in the offshore Beaufort-MacKenzie Basin were published by McNeil (1996). However, no formal benthic foraminiferal zonation has been proposed for the Central Arctic Ocean owing to the lack of recovery. The Miocene foraminiferal stratigraphy of ODP Site 909 in the Fram Strait was first investigated by Osterman & Spiegler (1996). In preparation for the ACEX Cruise, the Miocene of ODP Hole 909C was resampled by the current authors and a revised taxonomic and biostratigraphical scheme has been published (Kaminski et al. 2005).

RESULTS

The examination of samples from Hole M0002A yielded 19 foraminiferal species and generic groupings. The specimens throughout the studied interval are generally uncrushed, but preservation varies from good to poor. Abundance and diversity display maximum values in the basal part of the Lithological Subunit 1/4, while agglutinated are rare and more fragmentary in the upper part of the section. Samples collected from the blue-grey clays of underlying Lithological Subunit 1/5 were barren of foraminifera. The composition of DWAF in our samples displays strong similarities to the assemblages described by Evans and Kaminski (1998) from Central Arctic piston cores and by Kaminski et al. (2005) from the Miocene of ODP Hole 909C. Based on the ranges of distinctive taxa, we suggest a subdivision into three assemblages (from oldest to youngest). The distribution of DWAF in Hole M0002A is given in Table 1.

Assemblage 1 (Cores –44X-1 to –38X)

This assemblage occurs over an interval in Hole M0002A corresponding to Lithological Subunit 1/4, consisting of dark

brown and very dark greyish brown silty clay with organic carbon contents below 0.2%. Pore waters in this interval contain elevated values of dissolved silica, which is apparently derived from the Eocene biosiliceous sediments found deeper in the core (Expedition 302 Scientists 2006). A relatively diverse assemblage of DWAF is found in this interval, especially in Cores –44X-1 and –43X, that includes several species known from older sediments in the Norwegian-Greenland Sea region. These include *Psammosiphonella discreta, P. cylindrica, Hyperammina rugosa, Psammosphaera fusca, Ammolagena clavata, Adercotryma agterbergi, Reticulophragmium pusillum, R. rotundidorsatum,* and *Cyclammina cancellata.* These species are accompanied by Arctic species such as *Reticulophragmium projectum* and *Recurvoides brideauxi*, which were first described from exploration wells in the MacKenzie Delta. The presence of bathyal DWAF such as *Ammolagena, Psammosiphonella, Cyclammina*, and *Reticulophragmium* just above the color change in Core section 44X-1 suggests a paleodepth in excess of 200 m. However, the exact water depth is difficult to interpret precisely because deep-water species typically extend to anomalously shallow water depths in polar seas owing to reduced productivity in permanently ice-covered areas (Wollenburg and Mackensen 1998). The abundance and preservation state of DWAF is best at the bottom of the interval, and gradually deteriorates upcore.

Assemblage 2 (Cores –38X to – 35X)

This assemblage occurs in the lower part of Lithological Subunit 1/3, comprised of banded olive, olive brown, olive grey, dark grey, and light olive brown silty clays and muds. The interval is characterized by lower abundance and diversity of DWAF, with between 3 – 5 species occurring in a given sample. The first consistent occurrence of *Alveolophragmium polarensis* is observed in Sample 38X-1, 18-20cm. This species is accompanied by *Psammosiphonella, R. pusillum, A. clavata, A. agterbergi, Recurvoides,* and rare fragments of *C. cancellata.* Samples from Core –34X were barren of foraminifera.

Assemblage 3: (Cores –33X to – 10X):

DWAF assemblages from the middle part of Lithological Subunit 1/3 are depauperate, with numerous barren samples. The assemblage consists of scattered occurrences of *Psammosiphonella, P. fusca, Recurvoides* spp., *R. pusillum,* and *A. polarensis.* Many of the specimens are fragmentary, and only very loosely cemented. The assemblage is a residual one, with only robust forms still preserved. The abundance of foraminifera increases somewhat at the top of the studied interval, although specimens are still mostly fragmentary. A single occurrence of *Ammolagena clavata* was observed in Sample –10X-1, 64-66cm.

DISCUSSION

Preservation of Foraminifera

The DWAF assemblages recovered in our samples are generally sparse and of low diversity. This is in contrast with the diverse agglutinated faunas known from the modern Arctic Ocean (Wollenberg 1992). In general, only the more robust species with thick agglutinated walls are present in our samples, and even these are poorly cemented. Our Miocene DWAF assemblages from Hole M0002A are less diverse and more poorly preserved than the coeval material from ODP Hole 909C in the Fram Strait.

TEXT-FIGURE 1
Location of studied ODP Sites in the Fram Strait and on the Lomonosov Ridge.

Agglutinated foraminifera cement mineral grains using an organic cement, which is generally replaced by silica after the death of the organism. The intergranular space between the agglutinated grains becomes filled with a form of opaline silica (Hemleben and Kaminski 1990). In some cases, this process apparently takes place quite rapidly – under laboratory conditions silica is known to encrust and replace bacterial cell walls within a matter of days (Westall et al. 1995), and often additional silica is deposited inside the empty foraminiferal test, as seen by the preservation of silicified foraminiferal linings in acid residue samples (Galeotti et al. 2004). With the passage of time, the fossil test of an agglutinated foraminifer becomes increasingly silicified, and essentially becomes a quartz grain.

In Hole M0002A, the most abundant and well-preserved DWAF assemblages are present at the base of the studied interval, just above the lithological subunit boundary in Core –44X. In specimens collected from this level, the grain faces appear to be covered with spheres of opaline silica, and siliceous cement is visible at grain contacts (Plate 6, figs 3-4). Beneath the hiatus at 198.7 mcd, sediments contain increasing amounts of biogenic silica with depth. Shipboard analyses of pore waters reveals that the amount of dissolved silica begins to increase below Core –37X, then increases dramatically below the lithological boundary in Core –44X. The silica profile suggests the release of Si to pore waters between 200 and 300 mcd and precipitation above these depths (Dickens, in Backman et al.

2006). It is possible that the poor preservation of DWAF in middle and upper Miocene sediment above Core —37X is linked to the decreased availability of dissolved silica in pore waters and bottom waters at the time of deposition. Additionally, the sediments above Core 44X are poor in organic matter. In specimens analyzed from Core –11X the intergranular space is open, and no trace of organic cement remains. As the organic matrix binding the agglutinated grains in the test wall eventually degrades, species with more delicate tests are lost, leaving behind a low-diversity residual assemblage of robust species.

Significance of the Hiatus between Lithological Subunits 1/5 and 1/6

A significant hiatus at the top of the (middle) Eocene interval at 198.7 mcd is unusually pronounced and represents about 26 m.y. of extremely low to non-deposition (see "Timescale and sedimentation rates" in the "Sites M0001–M0004" chapter, in Backman et al. 2006). At the time the hiatus was forming the site should have subsided to approx 1000m paleodepth (Moore et al. 2006), a level that today is just below the influence of inflowing Atlantic Intermediate Water. The presence of sand lenses and the character of the bedding just above the Eocene section lead Moore et al., (2006) to suggest the hiatus was associated with relatively strong currents that eroded, reworked, and redeposited sediment.

If the hiatus was caused by strong currents, what was their origin? Climate records from the Late Eocene to the middle Miocene interval indicate this is a time that included several global climatic cooling events (Miller et al. 1987). The first of these events resulted in a global sea-level fall on the order of 50 to 60m from the late Eocene to the Early Oligocene (Miller et al. 2005). Indeed, sedimentary strata of Oligocene age are consistently absent around the entire Arctic margin (Harrison et al. 1999), and lowered sea level is a likely explanation. At the Lomonosov Ridge, it is possible that even in a brackish sea strong seasonal cooling may have caused vertical convection that caused submarine erosion (Moore et al. 2006). However, the hypothesis of quiescent thermal subsidence of the Lomonosov Ridge may not be justified, and in our opinion the origin of the current that eroded sediments on the Lomonosov Ridge likely has a tectonic cause.

An alternative scenario for the hiatus has been proposed that differs markedly from the subsidence history published by Moore et al. (2006). Owing to plate tectonic movements that took place in northern Greenland associated with the Rifting of the Yermak and Morris Jesup Plateaus at ~33 Ma, parts of the Lomonosov Ridge were likely uplifted above sea level and became subaerial for some extended period of time. In West Greenland, a phase of tectonic uplift on the order of 1 km took place between 30 and 36 Ma (Bonow et al. 2006). Offshore wells in the West Greenland basin also show a depositional hiatus between the Eocene and middle Miocene (Nøhr-Hansen 2003). On the Norwegian continental margin, a basal Miocene angular unconformity caused by uplift of the Norwegian margin has been well-documented by the petroleum industry (Stoker et al. 2005). It is likely that the same phase of regional uplift that affected Greenland and offshore Norway was also felt at the Lomonosov Ridge. Evidence for subareal exposure of the Lomosov Ridge includes the discovery of interspersed gypsum crystals (G. Dickens, unpublished) and the presence of oxidized organic matter dominated by terrestrial palynomorphs in Lithological Subunit 1/6 directly beneath the hiatus (Sangiorgi et al., in press). Above the hiatus the sediments of the "zebra-stripe interval" of Lithological Subunit 1/5 contain reworked dinocysts of Cretaceous to Oligocene age, indicating erosion and redeposition of nearby sediments. If this scenerio is correct, the "zebra-stripe interval" then indicates the return to shallow water deposition as the drill site once again subsided below sea level. Accordingly, the claystone sediments of Lithological Subunit 1/4 represent hemipelagic deposition as the site subsided below wave base.

Paleobiogeography of Agglutinated Foraminifera and the Opening of the Fram Strait

Presently, the Fram Strait constitutes the only deep marine passageway for the exchange of deep waters between the Arctic Ocean and the Norwegian-Greenland Sea. The West Spitsbergen Current (WSC) carries warm, salty Atlantic Water northward into the Eurasian Basin (text-fig. 2). The main flow of the West Spitsbergen Current is constrained by topography, flowing along the Barents Sea continental slope. The complicated topography of the Fram Strait causes the West Spitsbergen Current to branch. Only part of the Atlantic Water enters the Arctic Ocean, while the majority mixes and then flows south with the East Greenland current as a return flow (Quadfasel et al. 1987). Estimates of the volume transport of water entering the Arctic vary widely, with a recent estimate of mean northward transport of 6.4 Sv. (Maslakowski et al. 2004). Upon entering the Arctic Ocean the Atlantic water is joined by

an additional Atlantic source that enters via the Barents Sea shelf (Pfirman et al. 1994). This combined flow then circulates around the Eurasian Basin in a counterclockwise gyre, with one branch returning along the Nansen Ridge and another along the Eurasian side of the Lomonosov Ridge. The boundary between the Atlantic water and Arctic Ocean Deep Water is at about 600–800m (Rudels et al. 1994). At present, the Lomonosov Ridge is covered by Arctic Ocean Deep Water.

A long-standing debate has existed in the literature regarding the timing of the opening of the Fram Strait passageway. Faunal evidence suggests that the establishment of a marine connection may have begun as early as the Early Oligocene, based on the appearance of Atlantic species in the Beaufort Sea – MacKenzie Delta biostratigraphic record (Schröder-Adams and McNeil 1994b, Kaminski & Gradstein 2005). In this basin, cosmopolitan species (such as *A. clavata, Reophax pilulifer, R. elongatus, Cyclammina cancellata*, and *Psamminopelta gradsteini*) that are known from the Atlantic-Tethyan region appeared successively during the Oligocene.

The plate tectonic reconstructions are more controversial. The reconstructions published by Lawver et al., (1990) show a middle Miocene age for the separation between Svalbard and Greenland. Lawver et al. were of the opinion that a shallow water connection may have existed during the Middle Miocene, but stated that the corridor of ocean crust in the Fram Strait was not wide enough to allow deep water circulation until the late Miocene (7.5 to 5 Ma). These authors speculated that until then "the Arctic Ocean may have been isolated with respect to deep-water passages". Kristoffersen (1990), on the other hand, preferred an earlier (mid-Oligocene) opening for the Fram Strait, stating that a 2 km deep passage was in place by the middle Miocene. Stoker et al. (2005) attributed the formation of submarine hiatus formation and contourite sediment drift deposition in the Norwegian Sea during the Early Miocene to the opening of the Fram Strait.

Drilling in the Fram Strait during ODP Leg 151 was carried out with the goal of determining the age of the thick sequence of marine sediments preserved there. At Site 909, located near the Fram Strait sill, a thick Miocene sequence was cored that contains diverse DWAF assemblages with Atlantic/Norwegian Sea affinities. The oldest sediments recovered at this site contain cosmopolitan DWAF, and the base of the sediment column was not cored. Although the age of the oldest cored sediment was not well-constrained biostratigraphically, calcareous nannofossil biostratigraphy suggested an "earliest" Miocene age (Shipboard Scientific Party 1995). This occurrence of cosmopolitan DWAF in the oldest recovered sediments suggested to us that the estuarine circulation pattern of the Arctic Ocean had been in place since the Early Miocene (Kaminski et al. 2005), which favors Kristofferson's interpretation of the geophysical data suggesting an early opening of the Fram Strait.

The present-day West Spitsbergen Current only extends to a depth of about 700m (Walczowski et al. 2005). If Kristoffersen's estimate is correct, a proto-WSC could have been well-established by the mid-Miocene and probably somewhat earlier. Because the Lomonosov Ridge was bathymetrically shallower at the time, it is possible that the recirculating Atlantic water mass caused the erosion and reworking within the "zebra stripe interval" at our site.

The new sedimentological and micropaleontological results from the ACEX Cruise mean that timing of the Fram Strait
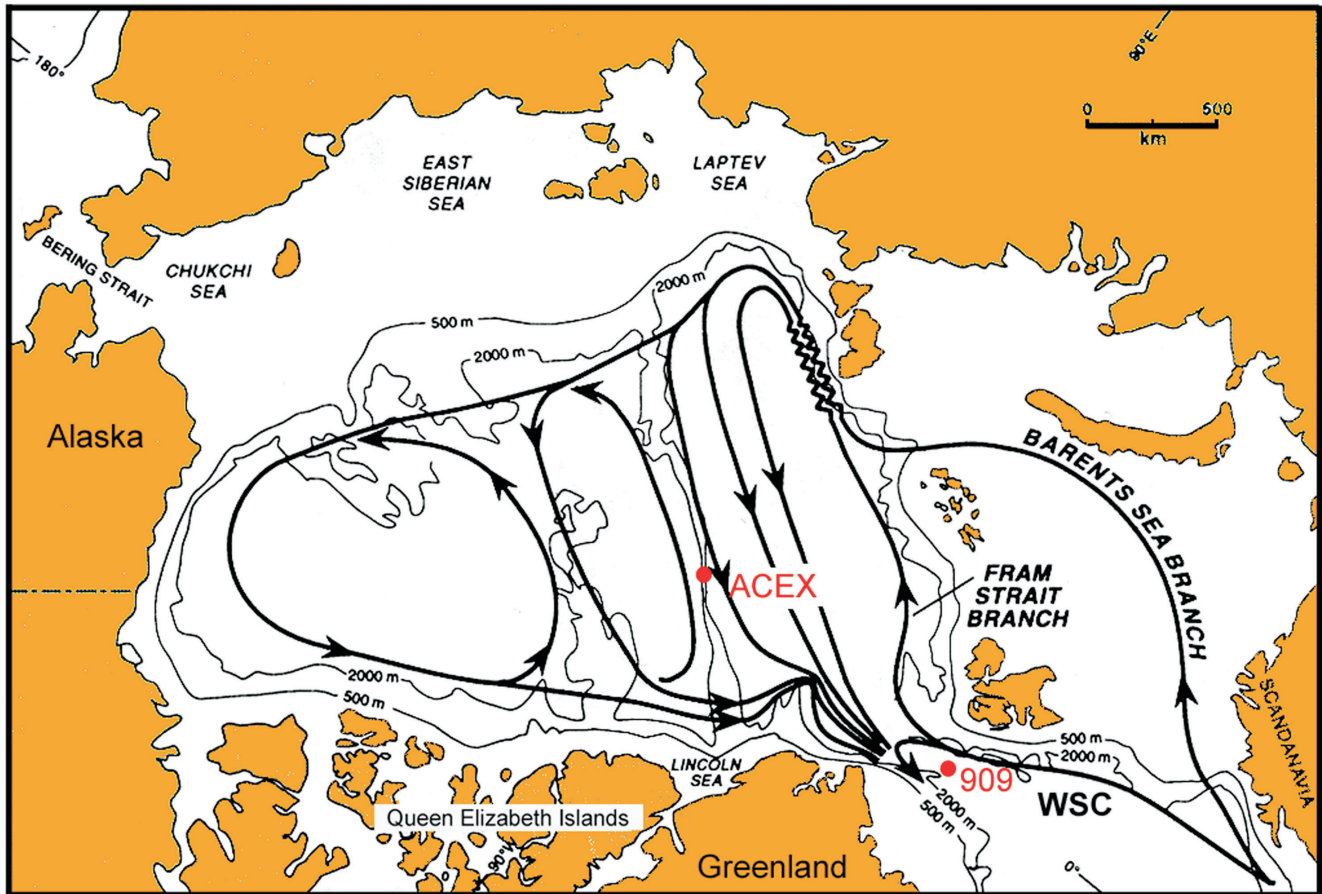
TEXT-FIGURE 2
Circulation of the WSC and Atlantic Intermediate Water in the Arctic Ocean between 200 and 1700 m, with locations of drill sites (after Rudels et al. 1994).

opening and appearance of Atlantic immigrant species in the Arctic is now much better constrained. It seems likely that the shift from the gray (sub-oxic) sediments to the brown (oxidized) sediments found near the top of Core section 302-M0002A-44X-1 is associated with improved ventilation owing to the presence of North Atlantic waters at the Lomonosov Ridge (Moore et al. 2006; Jacobsson et al. 2007). Jacobsson et al. attributed this change in oxygenation state to the opening of a deep passage in the Fram Strait at 17.5 Ma. This interpretation is further documented by the appearance of DWAF species with Atlantic/ Norwegian Sea affinities just above the color change. The blue-gray shales of Core section 302-M0002A-44X-1 to 302-M0002A-44X-3 are barren of benthic foraminifera. However in the brown sediments at the top of Core section 302-M0002A-44X-1 and in Core M0002A-43X, we recovered a relatively well-preserved fauna with a mixture of cosmopolitan DWAF species such as *Ammolagena clavata, Adercotryma agterbergi*, and *Reticulophragmium pusillum* and *R. rotundidorsatum* alongside Arctic endemics such as *Reticulophragmium projectum*. Most of the "cosmopolitan" species are known from somewhat older Miocene sediments at Site 909 in the Fram Strait (text-fig. 3), but are not known from older Paleogene sediments of the Beaufort Sea. In particular, *A. clavata* is regarded to be a deep-water indicator (Kaminski and Gradstein 2005), and its first appearance on the Lomonosov Ridge would therefore indicate the presence of deeper water of

Atlantic origin. This species is common in the Eocene at ODP Site 643 on the Vøring Slope (Kaminski et al. 1990), in the Oligocene at Site 985 on the Iceland Plateau (Kaminski and Austin 1999) and occurs in the lower Miocene at Site 909. Interestingly, a number of cosmopolitan agglutinated species of presumed Atlantic origin including *A. clavata, Ammodiscus latus, Ammomarginulina aubertae, Reticulophragmium placentum*, and *R. rotundidorsatum*, and display first occurrences with the Oligocene Kugmallit sequence of the offshore Beaufort-MacKenzie Basin (McNeil 1996). Although some intermittent shallow-water connections between the Arctic and the Atlantic/Tethys may have taken place earlier in the Paleogene over epicontinental seaways that allowed the exchange of neritic faunas (e.g., McNeil 1997; Podobina 2000), deep marine connections were only effected through the Fram Strait. The faunal record of the Beaufort-MacKenzie Basin suggests the influx of Atlantic deep-water species may have taken place as early as the mid-Oligocene, while the oldest DWAF assemblages from Site 909 and the Lomonosov Ridge reveal that these faunal connections were certainly in place by the Early Miocene.

CONCLUSIONS

The ACEX Hole M0002A on the Lomonosov Ridge recovered the oldest Neogene agglutinated foraminiferal assemblages

known thus far from the Central Arctic. Below the Lithological Subunits 1/4 – 1/5 boundary (corresponding to the color change at 95cm in Core section M0002A-44X-1), foraminifera are not preserved. Above the boundary, brownish-colored sediments contain a fully marine assemblage of DWAF that displays North Atlantic affinities. The presence of *Ammolagena clavata* and *Reticulophragmium* just above the lithological boundary in Core section M0002A-44X-1 testifies to the presence of a deep (or intermediate) water mass of Atlantic origin. The foraminifera from the lower Miocene to Pliocene marine sediments of Lithological Subunits 1/3 and 1/4 consist entirely of agglutinated benthic species, largely sparse assemblages containing *Cyclammina pusilla* and *Alveolophragmium polarensis.* Above Core M0002A-38X, preservation of DWAF is poor in much of the studied interval, owing to poor diagenetic silicification of the agglutinated foraminiferal tests.

By comparing the foraminiferal record of the new Arctic Drilling holes with our record from ODP Hole 909C in the Fram Strait, and the Beaufort-MacKenzie Basin (McNeil 1996, 1997) we now have better age constraints on the opening of the Fram Strait and the establishment of the Arctic – Atlantic faunal connections. The benthic foraminiferal evidence indicates that the onset of the current deep marine conditions at the Lomonosov Ridge took place during the later part of the early Miocene. The oldest sediments with cosmopolitan DWAF present on the Lomonosov Ridge are dated to the latest early Miocene (approx 17.5 Ma) based on the magnetostratigraphically-calibrated age model for Hole M0002A (Shipboard Scientific Party 2006; Jacobsson et al. 2007). However, the onset of deep-marine sedimentation on the Lomonosov Ridge may not equate with the opening of a deep passage in the Fram Strait, as proposed by some authors. The faunal exchange between the Arctic and the Norwegian Sea and by inference the inflow of Atlantic Intermediate Water into the Arctic began earlier, since at ODP Hole 909C in the Fram Strait DWAF-bearing sediments at the base of the cored succession are correlated to the earliest Miocene. Furthermore, the first occurrence of cosmopolitan DWAF is observed within sediments of late Oligocene age in the Beaufort-MacKenzie Basin (McNeil 1996). Consequently, since at least the Early Miocene, the Arctic Ocean has experienced open connections with the Norwegian-Greenland Sea to the south, with estuarine circulation and well-ventilated deep water appearing at the Lomonosov Ridge in the later part of the Early Miocene. It is likely that submarine erosion and current-controlled deposition in the Norwegian Sea in the Early Miocene is linked with the opening of the deep Fram Strait connection, as suggested by Stoker et al. (2005).

TAXONOMY

The taxa below are listed alphabetically by genus. Species identifications are based largely on the taxonomic work of Schröder-Adams and McNeil (1994a,b), Evans and Kaminski (1998), Kaminski and Gradstein (2005), and Kaminski et al. (2005).

Adercotryma agterbergi Gradstein and Kaminski 1989
Plate 3, figures 4–6

Adercotryma agterbergi GRADSTEIN and KAMINSKI 1989, p. 73, pl. 1, figs. 1a-5c, pl. 2, figs. 1a-3b, textfig. 1.

Remarks. The species was first described from the Oligocene of the Central North Sea (Gradstein and Kaminski 1989). We have also observed it in the Oligocene at Site 985 on the Iceland Plateau (Kaminski & Austin 1999).

Alveolophragmium polarensis O'Neill 1981
Plate 4, figures 1a–3b

Alveolophragmium polarensis O'NEILL 1981, pl. 2, figs. 15, 16.– EVANS and KAMINSKI 1998, p. 125, pl. 2, figures 5–8.

A large, rotund species with many chambers, a coarsely agglutinated wall, and clearly defined, simple alveoles that are visible on abraded specimens. The aperture is interiomarginal, with a thin upper lip. In larger specimens the aperture appears to break up and becomes multiple.

Remarks. This species was first recorded by O'Neill (1981) from the Alpha Ridge, and it is common in the site survey cores from the Lomosonov Ridge (Evans & Kaminski 1998).

Ammolagena clavata (Jones and Parker 1860)
Plate 1, figure 8

Trochammina irregularis (d'Orbigny) var. *clavata* JONES and PARKER 1860, p. 304.
Ammolagena clavata (Jones and Parker 1860).–O'NEILL 1981, p. 1158, pl. 1, fig. 17.– KAMINSKI and GRADSTEIN 2005, p. 165, pl. 21, figs. 1-6 (figure 1 is the lectotype).– KAMINSKI et al. 2005, p. 382, pl. 2, figs. 3a-4.

Remarks. Found mostly attached to sand grains, as is the case with the specimens found in the Eocene at ODP Site 643 in the Norwegian Sea (Kaminski et al. 1990) and in the modern forms recovered in piston cores from the Alpha Ridge by O'Neill (1981). It first occurs in upper Oligocene Kugmalit sequence in the offshore Beaufort-MacKenzie Basin (McNeil 1996), and in the Lower Miocene at Site 909 (Kaminski et al. 2005). This species is not known from older Paleogene sediments in the Arctic (D.H. McNeil, personal communication to MAK 2005)

?Cribrostomoides sp. 1
Plate 1, figures 13a,b

Remarks. A small species tentatively identified as *Cribrostomoides*, with a depressed umbilicus and a multiple, interiomarginal aperture with an overhanging lip. It differs from *C. subglobosus* in having more regular planispiral coiling (at least in the latter part of the test) and in possessing an aperture that is truly interiomarginal. In this respect, it is closer to the Paleogene species *Cribrostomoides trinitatensis* than it is to the type species, *C. subglobosus.*

Cyclammina cancellata Brady 1879
Cyclammina cancellata BRADY 1879, p. 62.– BRADY 1884, pl. 37, figs 8-15.– KAMINSKI and GRADSTEIN 2005, p. 476, pl. 118a, figs. 1a–4b; pl. 118b, figs. 1-6.

Remarks. The largest *Cyclammina* in our material, with sigmoidal sutures and up to 16 chambers in the final whorl. Found mostly as fragments.

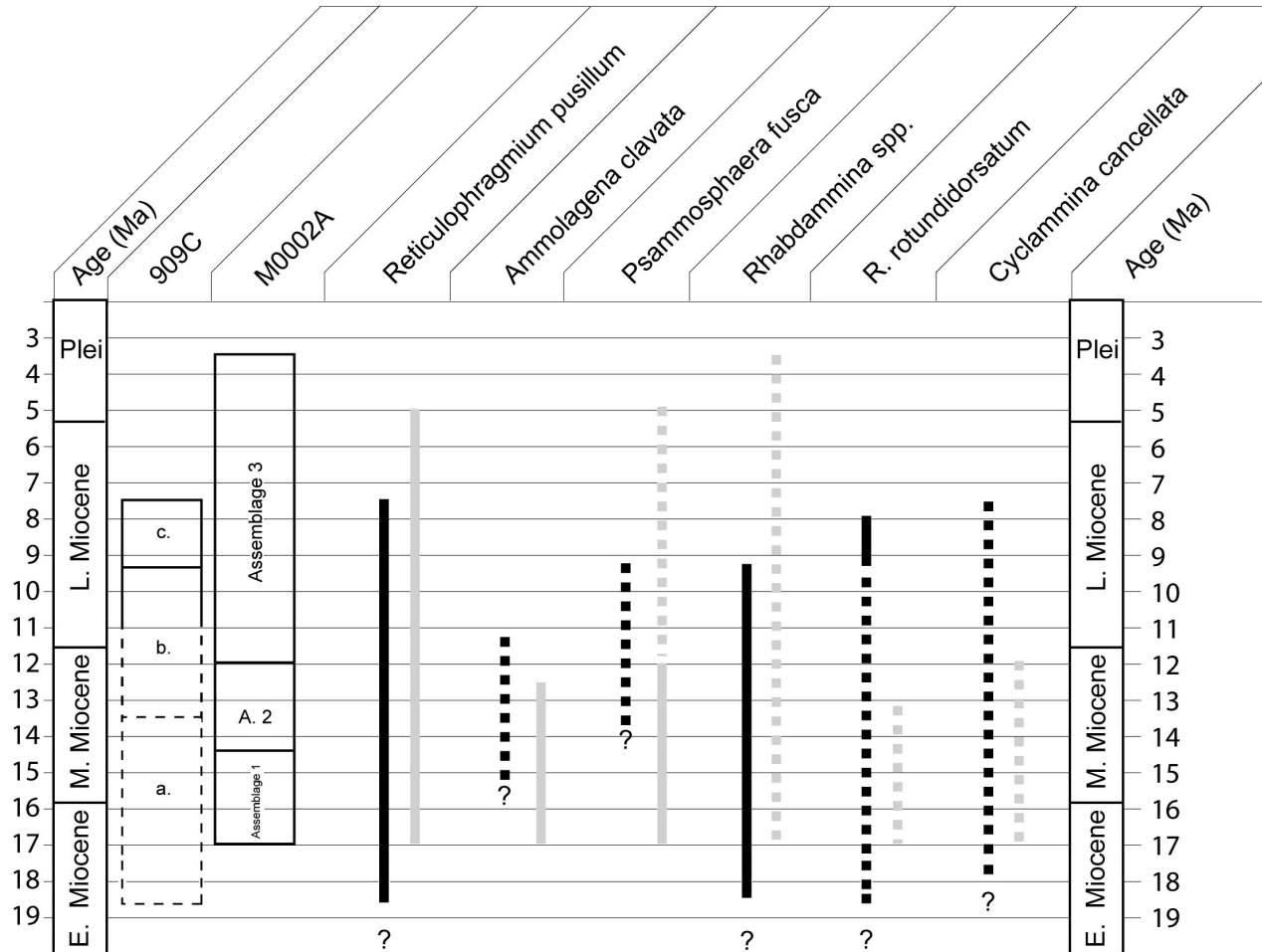***Eggerelloides scabrus*** (Williamson 1858)
Plate 3, figures 7a–8b

Bulimina scabra WILLIAMSON 1858, p. 65, pl. 5, figs. 136, 137.
Eggerelloides scabrus (Williamson).– HAYNES 1973, p. 44, pl. 2, figs. 7,8; pl. 19, figs. 10,11, textfig. 8.

Haplophragmoides sp. 1
Plate 1, figures 10a,b; 12a,b

TEXT-FIGURE 3
Comparison of stratigraphic ranges of DWAF found at ODP Site 909 (black lines) and in Hole M0002A on the Lomonosov Ridge (gray lines). Because the age of the sediment column was not well constrained in Hole 909C, question marks at the bottom of ranges indicate that the true first occurrences of species in the Fram Strait area is unknown. Assemblages in Hole 909C are after Kaminski et al. (2005): a. *Reticulophragmium amplectens – Reophanus berggreni* Assemblage; b. *R. amplectens* Assemblage; c. *Reticulophragmium rotundidorsatum* Assemblage.

A small, coarsely agglutinated, eight-chambered species of *Haplophragmoides* with a rounded periphery and an open umbilicus.

Haplophragmoides sp. 2
Plate 1, fig. 11

A species of *Haplophragmoides* with ten chambers in the final whorl, a subacute periphery, slightly sigmoidal sutures, and a thin, finely agglutinated, finely finished wall. The aperture is interiomarginal with a thin overhanging lip.

Hyperammina rugosa Verdenius and Van Hinte 1983
Plate 1, figure 9

Hyperammina rugosa VERDENIUS and VAN HINTE 1983, p. 187, fig. 16; pl. 1, figs. 12-14.– KAMINSKI and GRADSTEIN 2005, p. 143, pl. 13, figs 1-4.

Remarks. Very coarsely agglutinated specimens, proloculus not observed. First reported from the Oligocene of DSDP sites on the Icelandic Plateau (Verdenius and Van Hinte 1983).

Psammosiphonella cylindrica (Glaessner 1937)
Plate 1, figures 1–3

Rhabdammina cylindrica GLAESSNER 1937, p. 354, pl. 1, fig. 1.
Psammosiphonella cylindrica (Glaessner).– KAMINSKI and GRADSTEIN 2005, p. 119, pl. 5/6, figs. 9-13.

Remarks. Narrower than *P. discreta*, with a well-cemented wall consisting of well-sorted agglutinated grains.

Praesphaerammina sp.
Plate 2, fig. 4a,b

Remarks. A very involute species of *Praesphaerammina*, with very few chambers and a very coarsely agglutinated wall. Aperture not visible. Differs from the type species *P. subgaleata* in having fewer chambers and a coarser wall.

Psammosiphonella discreta (Brady 1881)
Plate 1, figures 4, 5

Rhabdammina discreta BRADY 1881, p. 48.– BRADY 1884, p. 268, pl. 22, figs. 11-13.

Psammosiphonella discreta (Brady).– KAMINSKI and GRADSTEIN
 2005, p. 117, pl. 4/5, figs 1-8.

Remarks. Specimens are mostly fragmentary.

Psammosphaera fusca Schultze 1875
Plate 1, figures 6, 7

Psammosphaera fusca SCHULTZE 1875, p. 113, pl. 2, fig. 8a-f. –
 O'NEILL 1981, p. 1158, pl. 1, fig. 9.– KAMINSKI and GRADSTEIN
 2005, p. 125, pl. 8, figs. 1-7.

Recurvoides brideauxi Schröder-Adams and McNeil 1994
Plate 2, figures 2a-c, 8a-c; plate 3, figures 1a-c.

Recurvoides brideauxi SCHRÖDER-ADAMS and MCNEIL 1994a, p.
 180, pl. 3, figs. 1-18.– SCHRÖDER-ADAMS and MCNEIL 1994b, p.
 40, pl. 6, figs. 5a-6b.

Test large, streptospiral, involute, with a coarsely agglutinated
wall that is only a single grain thick in places. The species ag-
glutinates large, angular quartz grains and cements them in a
masonry manner. Aperture is an areal opening that may have
upturned edges, surrounded by a thin, finely agglutinated lip.

Remarks. We identified this form as *R. brideauxi* based on the
wall texture and apertural characteristics, which Schröder-Ad-
ams and McNeil (1994a) described as "an open, oval slit,
rimmed by a narrow lip". However, the illustrations of the
types do not clearly show this feature. *Recurvoides brideauxi*
was originally described from outer neritic and bathyal facies of
the Oligocene Kugmallit and Miocene Akpak sequences of the
MacKenzie Delta.

Recurvoides spp.
Plate 2, figures 1a-b, 3,6. 5a-b.

Test streptospiral tests with a coarsely grained wall and cham-
bers that increase rapidly in size, aperture not visible.

Reticulophragmium projectum Schröder-Adams and McNeil 1994
Plate 5, figures 5a,b; 8a,b

Reticulophragmium projectus SCHRÖDER-ADAMS and McNEIL
 1994a, p. 181, pl. 3, figs. 3, 4.– SCHRÖDER-ADAMS and McNEIL
 1994b, p. 41, pl. 8, figs. 1a-4b.

Tests are large, finely agglutinated, with 13 or 14 chambers in
the final whorl and the typical sigmoidal sutures of the type
specimens from the MacKenzie Delta.

Remarks. Our specimens do not appear to present a "projecting"
final chamber as described by Schröder-Adams and McNeil
(1994), because they are slightly damaged.

Reticulophragmium pusillum (Brady 1881)
Plate 4, figures 4, 6a,b; Plate 5, figures 1a–8c

Cyclammina pusilla BRADY 1881, p. 53.– EVANS and KAMINSKI
 1998, p. 124, pl. 1, figs 8–10.
Reticulophragmium pusillum (Brady 1881).– KAMINSKI et al. 2005, p.
 390, pl. 6, figs 1a,b, 2a,b

Remarks. This species is consistently preserved in the Neogene
noncalcareous sediments, and was the most common species
found in the site survey cores from the area of the Lomonosov
Ridge (Evans & Kaminski 1998). It is also known from the
Early-Middle Miocene at ODP Site 909 (Kaminski et al. 2005)

PLATE 1
All specimens are from Hole M0002A; Scale bars are 100 or 200μm, as marked

1-3 *Psammosiphonella cylindrica* (Glaessner 1937),
 43X-3, 134-136cm

4-5 *Psammosiphonella discreta* (Brady 1881), 4. 35X-2,
 134-136cm; 5. 37X-3, 20-22cm.

6-7 *Psammosphaera fusca* Schultze 1875, 43X-3,
 134-136cm

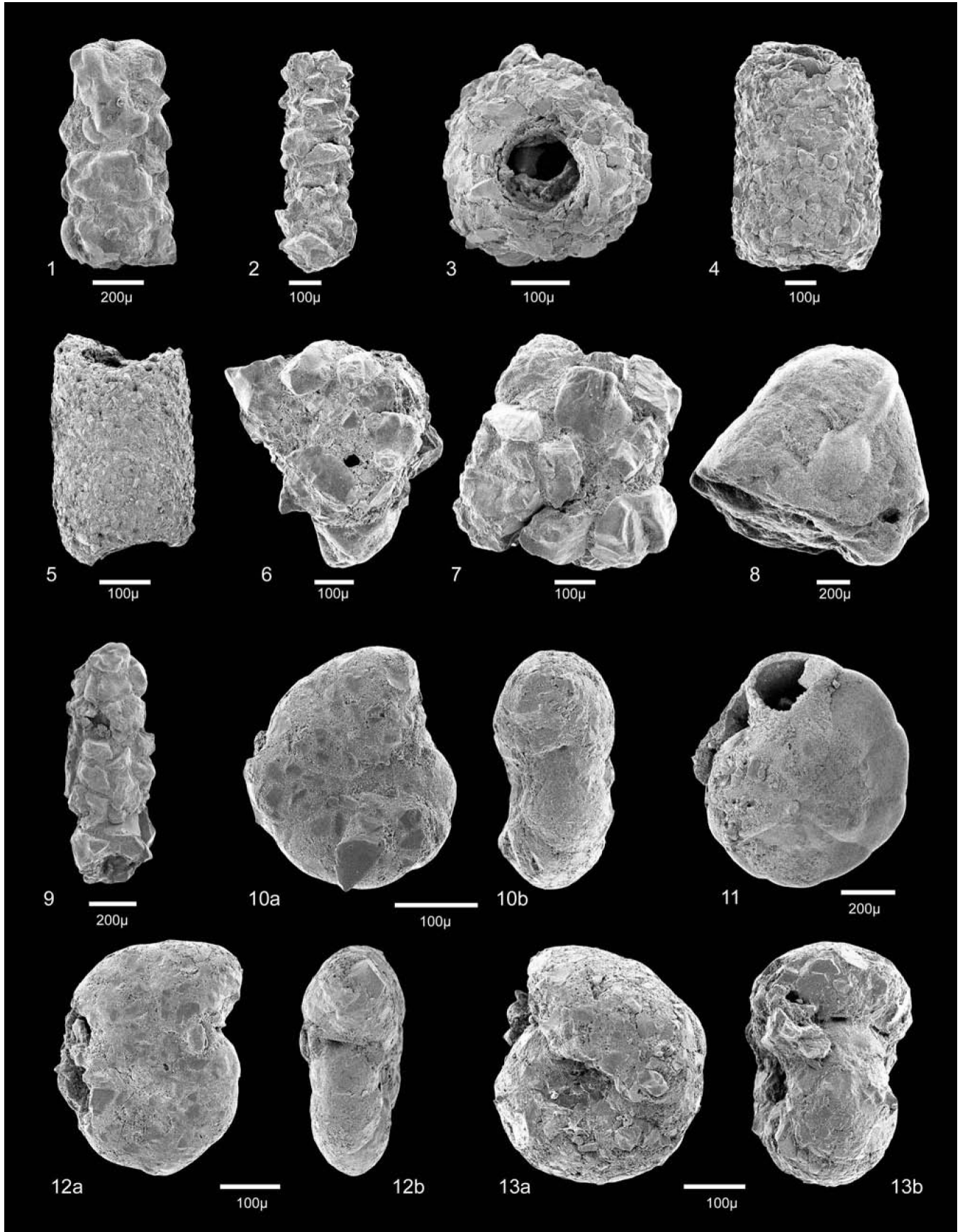8 *Ammolagena clavata* (Jones and Parker 1860), 43X-3,
 134-136cm

9 *Hyperammina rugosa* Verdenius and Van Hinte 1983,
 43X-3, 134-136cm.

10, 12 Haplophragmoides sp. 1, 43X-3, 134-136cm

11 *Haplophragmoides* sp. 2, 35X-4, 64-66cm

13 *Cribrostomoides* sp., 38X-2, 64-66cm.

and from the upper Miocene of Site 646 in the Labrador Sea (Kaminski et al. *1*989). Our specimens from the Arctic have a finely agglutinated wall, with one single alveole per chamber. The species belongs in *Reticulophragmium* because of its interiomarginal aperture.

Reticulophragmium rotundidorsatum (Hantken 1875)
Plate 4, figure 5a,b.

Haplophragmium rotundidorsatum HANTKEN 1875, p. 12, pl. 1, fig. 2.
Reticulophragmium rotundidorsatum (Hantken 1875).– HORVÁTH 2002, p. 31, pl. 2, fig. 2.– KAMINSKI et al. 2005, p. 390, pl. 6, fig. 7a,b; pl. 7, fig. 1a,b

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PLATE 2
Scale bars are 100 or 200µm, as marked

1 *Recurvoides* sp., 38X-4, 64-66cm.

2 *Recurvoides brideauxi* Schröder-Adams and McNeil 1994, 38X-4, 64-66cm. Aperture is areal with up-turned edges and surrounded by a thin lip. The circular hole on the right is where an agglutinated grain has been dislodged.

3,6 *Recurvoides* sp., 38X-4, 64-66cm

4. *?Praesphaerammina* sp., 43X-3, 64-66cm. Two views of broken specimen, showing only three chambers. Aperture is not present on this fragment.

5 *Recurvoides* sp., 43X-3, 134-136cm

7 *Recurvoides* sp., 43X-3, 134-136cm

8 *Recurvoides brideauxi* Schröder-Adams and McNeil 1994, 43X-3, 64-66cm.
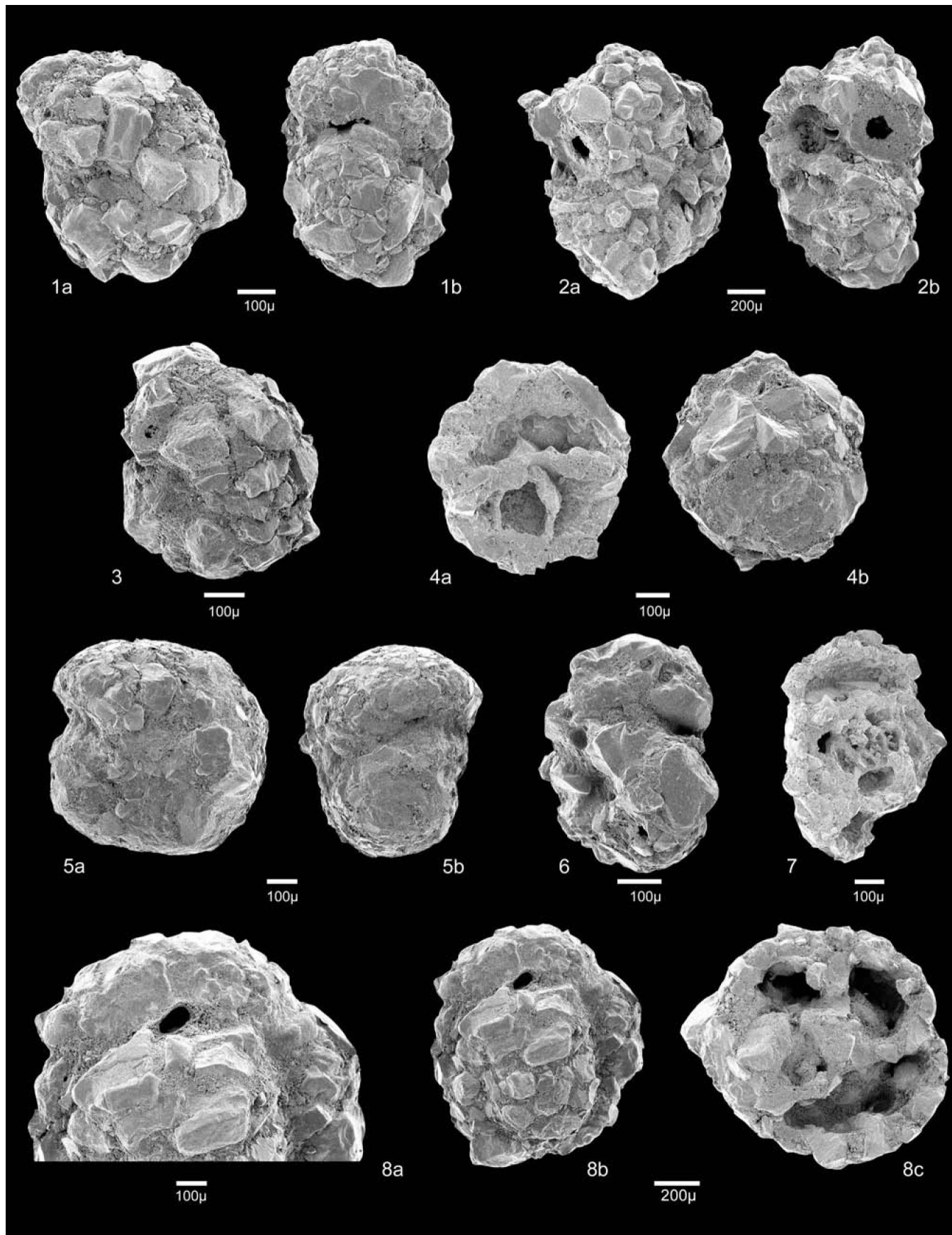
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PLATE 3
Scale bars are 100 or 200μm, as marked

1 *Recurvoides brideauxi* Schröder-Adams and McNeil 1994, 38X-4, 64-66cm

3 *Recurvoides* sp. 35X-2, 134-136cm

4-6 *Adercotryma agterbergi* Gradstein and Kaminski 1989. 3-4. 35X-4, 64-66cm. 5. 38X-2, 64-66cm

7,8 *Eggerelloides scabrus* (Williamson 1858), 7. 37X-3, 20-22cm. 8. 43X-3, 64-66cm.
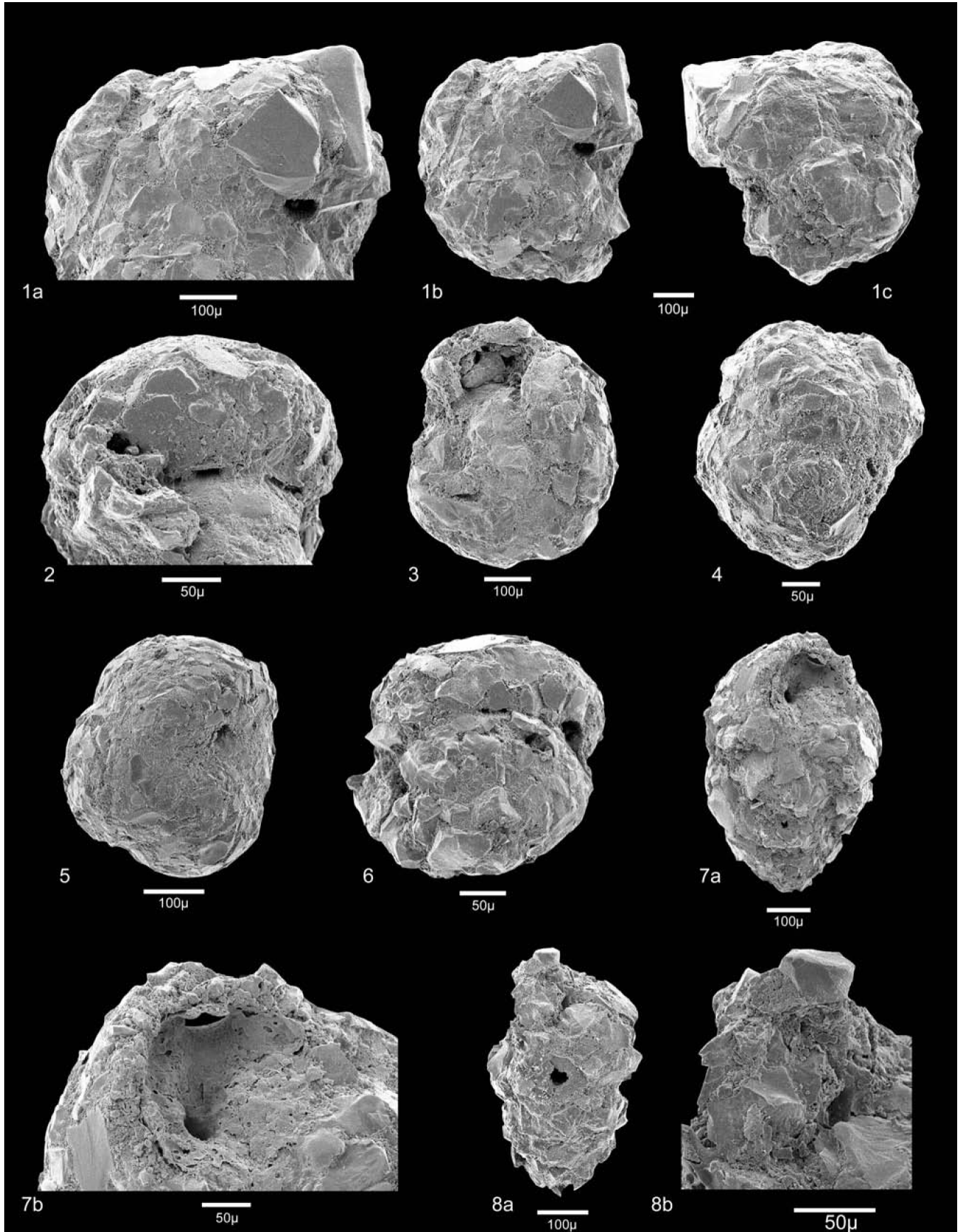
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PLATE 4
Scale bars are 100, 50 or 20µm, as marked

1-3 *Alveolophragmium polarensis* O'Neill 1981, 1. Specimen with broken last chamber and abraded wall, revealing large simple alveoles, 38X-1, 18-20cm. 2. Small specimen, 38X-4, 134-136. 3. Small specimen, 35X-2, 134-136cm

4,6 *Reticulophragmium pusillum* (Brady 1881), 42X-3, 134-136cm.

5 *Reticulophragmium rotundidorsatum* (Hantken 1875), 38X-4, 134-136cm.
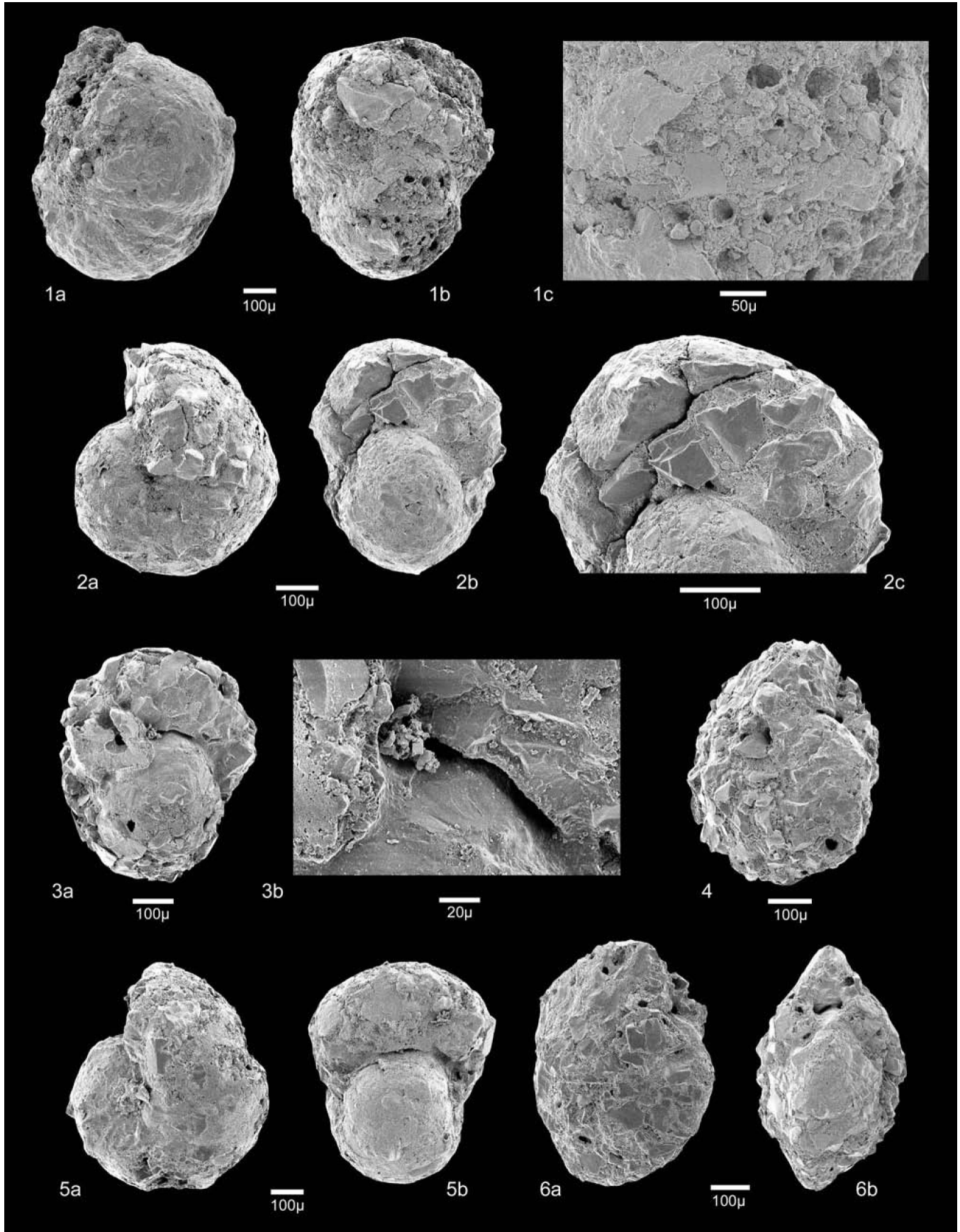
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PLATE 5
Scale bars are 200, 100, or 50µm, as marked

1 *Reticulophragmium pusillum* (Brady 1881), 42X-3, 134-136cm.

2,3 *Cyclammina cancellata* Brady 1879. 2. 38X-1, 18-20cm. 3. 35X-4, 134-136cm.

4,6,7 *Reticulophragmium pusillum* (Brady 1881), 4. 6. broken specimens showing wall structure and a single

alveole in each chamber, 35X-4, 64-66cm. 7. 35X-2, 134-136cm.

5,8 *Reticulophragmium projectum* Schröder-Adams and McNeil 1994. 43X-3, 134-136cm.
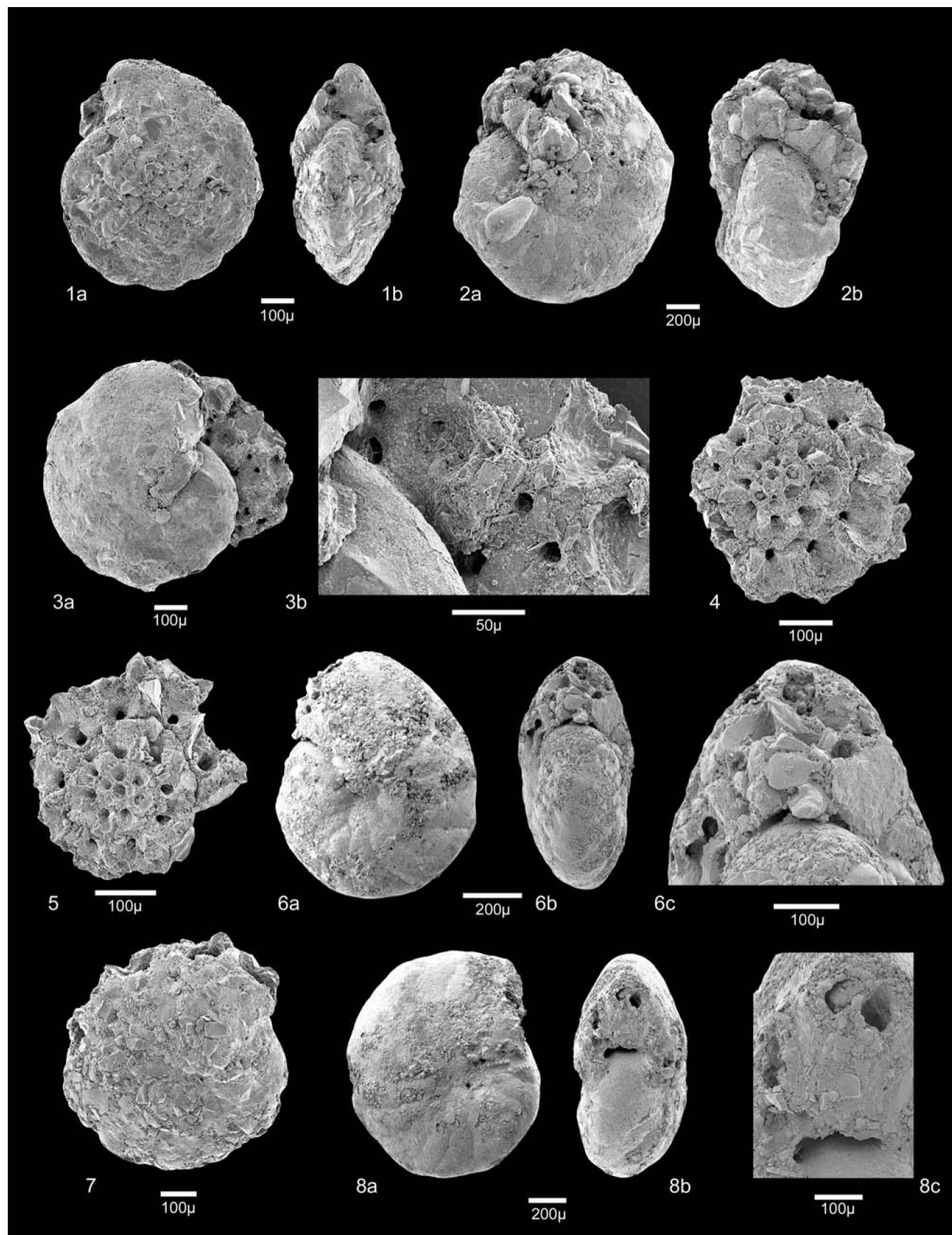
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PLATE 6
Preservation of Agglutinated Foraminifera - Scale bars are 200 or 4μm, as marked

1-2 Fragments of agglutinated foraminifera from Sample 11X-2, 64-66cm. In these specimens the intergranular space is open, and no trace of organic cement remains.

3-4 Fragments of agglutinated foraminifera from Sample 43X-3, 134-136. At this level, pore water concentrations of dissolved silica were high, and the grain faces appear to be covered with spheres of opaline silica. Cement is visible at grain contacts.