

Paleoceanographic development in Storfjorden, Svalbard, during the deglaciation and Holocene: evidence from benthic foraminiferal records

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Brines can have a profound influence on the relative abundance of calcareous and agglutinated foraminiferal faunas. Here we investigate the distribution of calcareous and agglutinated benthic foraminiferal species in four cores from a brine-enriched environment in Storfjorden, Svalbard. Stratigraphically, the cores comprise the last 15 000 years. The purpose of the study is to reconstruct changes in the paleoecology and paleoceanography of Storfjorden in relation to past climate changes, and to identify potential indicator species for brine affected environments. The benthic foraminifera in Storfjorden have all widespread occurrences in the Arctic realm. Calcareous species dominated Storfjorden during the deglaciation and early Holocene until *c.* 8200 a BP. However, agglutinated species increased in abundance whenever conditions became colder with more sea ice and stronger brine formation as during the Older Dryas, the Intra-Allerød Cold Period and the Younger Dryas. Following a moderately cold period with numerous agglutinated foraminifera from *c.* 8200–4000 a BP, conditions became more changeable from *c.* 4000 a BP with repeated shifts between warmer periods dominated by calcareous species and colder periods dominated by agglutinated species. The warmer periods show stronger influence of Atlantic Water, reduced brine formation and less corrosive conditions at the sea bottom. Conversely, the colder periods show stronger influence of Arctic water, higher brine production and more corrosive bottom water. The distribution patterns of the calcareous species are basically the same whether calculated versus the total fauna (including agglutinated specimens) or versus calcareous specimens alone. Moreover, the patterns are similar to the

patterns found elsewhere along western Svalbard in areas without influence of brines. No particular species appear to be specifically linked to brine formation. However, the most persistent agglutinated species *R. scorpiurus* and *A. glomerata* are also the most tolerant species to the acidic bottom water that normally is associated with brine formation.

Tine L. Rasmussen (tine.rasmussen@uit.no), CAGE - Centre for Arctic Gas Hydrate, Environment and Climate, Department of Geology, UiT, the Arctic University of Norway, NO-9037 Tromsø, Norway; Erik Thomsen, Department of Geoscience, Aarhus University, DK-8000 Aarhus C, Denmark: Brine formation generates about 10% of the deep water in the Arctic Ocean and the Barents Sea today (Quadfasel *et al.* 1988). Brine formation may have been even more important in the past under different climate regimes (Haley *et al.* 2008). It is, however, difficult to reconstruct the intensity of brine formation in the past as paleoceanographic proxies generally are inadequate to detect brines. Estimates of previous brine production are, therefore, indirect and normally highly uncertain. Brines are cold, salty and rich in oxygen and CO₂. They are corrosive to calcium carbonate (Steinsund & Hald 1994; Andersson *et al.* 2004, 2010) and can leave traces of dissolution in calcareous shells (Steinsund & Hald, 1994). Brines may also cause sedimentary disturbances as they can release downslope turbidity flows (Rumohr *et al.* 2001). Finally, a potential proxy that so far has only been provisionally explored is the possibility that marine organisms are affected by brines and therefore, individually, or as whole faunas, may act as indicators of brine formation.

A potential group of organisms for such studies is benthic foraminifera. They constitute a diverse and abundant group in most marine environments. Their tests are generally well preserved in the geological record, and they have been widely used as paleoenvironmental indicators, for example of bottom currents, food supply to the sea floor, oxygen level, water temperature, salinity, and pollution (Alve 1991; Gooday 1994; Kaiho 1994; Gooday & Rathburn 1999; Schönfeld 2002; Sejrup *et al.* 2004). They have also been used as indirect indicators for presence of sea ice (Schröder-

Adams *et al.* 1990; Scott & Vilks 1991; Scott *et al.* 2008; Schell *et al.* 2008; Polyak *et al.* 2013; Seidenkrantz 2013), a pre-requisite for brine formation.

Here we focus on Storfjorden, Svalbard, which today constitutes a special marine environment with intense brine formation. The brines are often dense enough to cross the shelf and reach the deep slope (Quadfasel *et al.* 1988; Schauer & Fahrbach 1999). Earlier studies from Storfjorden have showed that the ratio of agglutinated to calcareous benthic foraminifera can be used as an indicator of changes in brine formation during the Lateglacial and Holocene time period (Rasmussen *et al.* 2007; Rasmussen & Thomsen, 2009, in press). The study indicates that brine formation normally intensifies during the colder periods and weakens during the warmer.

The purpose of the present investigation is twofold. Firstly, we reconstruct the paleoenvironmental and paleoceanographical changes in Storfjorden during the Lateglacial and Holocene time period with particular reference to the distribution of water masses and food, the occurrence of glaciers and sea ice, and brine production. Secondly, we analyze the distribution patterns of the most important agglutinated and calcareous foraminiferal species. The purpose here is to analyze the reaction of the individual species to the ecological changes in a brine-influenced environment and to disclose potential indicators of brine formation. The data from Storfjorden are compared to published foraminiferal records from other areas around Svalbard.

Oceanographic and environmental setting

Storfjorden is a sound in the southeastern part of the Svalbard archipelago between the islands of Spitsbergen, Edgeøya and Barentsøya (Fig. 1). The sound is connected to the Arctic Ocean via two passages to the northeast. Storfjorden consists of a ~190 m deep inner basin bordered by less than

40 m deep shallow shelves to the north and east. To the south, a 115 m deep sill separates the basin from Storfjorden Trough. Dense brines are generated each winter filling the inner silled basin (Midttun 1985; Quadfasel *et al.* 1988; Schauer 1995; Skogseth *et al.* 2004) (Fig. 2). The brines eventually overflow the sill and cross the shelf via Storfjorden Trough. This trough was formed by an ice stream during the glacial period (e.g. Laberg & Vorren 1996). The ice-stream retreated from the outer shelf before 16 300 ¹⁴C a BP (Rasmussen *et al.* 2007). Dates from the inner basin indicate that the ice retreated from here at the beginning of the Holocene (Rasmussen & Thomsen 2009). Today, several glaciers reach Storfjorden with the largest termini located to the west and north.

Arctic surface water from the Arctic Ocean and the Barents Sea enters Storfjorden via the two passages to the northeast and continues along the inner shelf of Svalbard as a coastal current (Fig. 1). Warm Atlantic water from the West Spitsbergen Current branches off near Storfjorden and enters the eastern part of the fjord. In some years it penetrates into the inner basin, where it mixes with Arctic water (Lydersen *et al.* 2002; Skogseth *et al.* 2005a). Sea ice forms from December and stays until the beginning of July (e.g. Smedsrud *et al.* 2006). The sea ice consists of local ice and ice advected from the Arctic Ocean and the Barents Sea (e.g. Hendricks *et al.* 2011). During winter and spring, brines are produced on the eastern shelf of the inner basin (Haarpainter *et al.* 2001; Skogseth *et al.* 2008) (Fig. 1). Winds from the northeast create large polynyas in the ice cover, where continuous freezing generates cold and salty brines (-1.9°C, >34.8->35.8) (Quadfasel *et al.* 1988; Haarpainter *et al.* 2001; Schauer 1995; Anderson *et al.* 2004; Skogseth *et al.* 2004, 2005a, b). The heavy brine sinks and fills the basin eventually overflowing the sill. The overflow begins during the early spring in March-April and continues for 5–6 months (Fig. 2).

The sediments in Storfjorden contain more than 2% of organic matter including a proportionally large terrestrial component (Winkelman & Knies 2005). The productivity is high and linked to the amount of seasonal sea ice and the formation of polynyas (Winkelman & Knies 2005),

which again depends on the prevailing wind direction. In winters dominated by northeasterly winds the temperatures are low (Skogseth *et al.* 2004) and the amount of sea ice is high. The winds maintain and prolong the polynyas, intensifying the formation of brines. In winters dominated by southwesterly winds the inflow of Atlantic Water increases. The higher temperatures reduce the formation of sea ice and the generation of brines. However, the intrusion of salty Atlantic Water may increase brine production the following year (Skogseth *et al.* 2004).

The bottom water temperatures in the deeper parts of the inner basin are year-round affected by brines keeping temperatures below -1.0 – -1.5°C (Fer *et al.* 2003). In areas occasionally affected by Atlantic water, the temperatures may vary from <-1.5 to $>2^{\circ}\text{C}$ (Schauer 1995; Lydersen *et al.* 2002). The salinity in the inner brine basin varies between 34.8 and >35.8 , while the salinity of the Atlantic water is around 35 (Schauer 1995; Skogseth *et al.* 2005a). Thus, the benthic foraminiferal faunas in the brine basin and in the pathway of the overflow experience quite large seasonal and yearly changes in salinity, temperature, sea ice cover, food supply and bottom current activity. Conditions in the deeper parts of brine basin are probably more stable than on the shelf.

Material

The 350 cm long core NP05-86GC was retrieved centrally from the inner brine basin from 142 m water depth in August 2005 during a cruise with RV Lance (Plassen *et al.* 2008; Rasmussen & Thomsen 2009) (Figs 1, 2). The upper 280 cm consist of black, homogeneous mud with a smell of sulphur, while the lower 70 cm comprise a massive diamict of coarse, unsorted gravel in a matrix of clay, silt and sand and devoid of foraminifera (Fig. 3). The upper part has previously been investigated for oxygen and carbon isotopes measured in the benthic foraminifera *Nonionellina*

labradorica and *Cibicides lobatulus* (Rasmussen & Thomsen 2009). The samples used in the previous study (taken at 6 cm and 3 cm intervals) were analyzed for the content of benthic foraminiferal species.

JM10-10GC and JM10-12GC were taken in October 2010 by RV Jan Mayen. JM10-10GC was taken from 123 m water depth in a sub-basin east of the main basin below the shelf west of Edgeøya, where the brines form (Skogseth *et al.* 2008). It is 402 cm long and consists of mottled brownish and black clayey silt in the upper 360 cm. The lower part consists of a mixture of black and relatively coarse glaciomarine sediments and diamict-like material (Fig. 3). The core was sampled at 5 cm intervals. The 320 cm long core JM10-12GC was taken in the brine basin on the northern flank of the sill, which at a water depth of 146 m separates the brine basin from the shelf. The upper ~250 cm consist of mottled brownish and black clayey silt, lithologically very similar to the upper part of core JM10-10GC. The lower part consists of coarse, glaciomarine sediments and diamict-like sediments similar to the lower part of core JM10-10GC (Fig. 3). JM10-12GC was sampled at 4 cm intervals. Previously published core JM02-460GC from Storfjorden Trough was taken in the pathway of the brine overflow across the shelf from 389 m water depth (Rasmussen *et al.* 2007; Rasmussen & Thomsen 2009) (Figs 1, 2). It is 387 cm long and consists entirely of hemipelagic clayey silt (Rasmussen *et al.* 2007) (Fig. 3). The 692 cm long sister-core JM02-460PC from the same position reached a till ~500 cm below the sediment surface (Fig. 3) (Rasmussen *et al.* 2007). Samples taken at 5 cm intervals have previously been analyzed for the dominant calcareous foraminifera. For this study the agglutinated species were identified to species level.

Methods

All sediment samples were wet sieved using mesh-sizes of 63, 100 and 1000 μm . The residues were dried and weighed. A number of >300 specimens of benthic foraminifera were picked from the >100 μm size fraction, counted and identified to species level. The concentration of calcareous and agglutinated forms and the total concentration of benthic foraminifera were calculated (numbers per gram dry weight sediment). The relative abundance (percentage) of each species was calculated relative to the total number of benthic specimens. Furthermore, the relative abundance of calcareous species was also calculated relative to the number of calcareous specimens alone. In the latter calculations we only included samples with more than 50 calcareous specimens.

The agglutinated species *Spiroplectammia earlandi* and *S. biformis* were not distinguished. According to Korsun & Hald (2000), these two species are morphotypes of the same species. We refer to the species as *S. earlandi/biformis*. *Reophax* species other than *R. scorpiurus* were grouped as *Reophax* spp. The group is dominated by *R. guttifer*, *R. fusiformis*, *R. difflugiformis* and some unidentified (often broken) specimens. *Buccella frigida* and *B. tenerrima* were not distinguished. They are labelled *Buccella* spp.

The residues were subsequently dry sieved over mesh-sizes 150 μm (excluding core JM10-10GC) and 0.5 mm (excluding core JM02-460GC) and mineral grains (ice rafted debris; IRD) were counted from each size fraction. For core JM10-10GC and JM10-12GC, IRD was also counted in the >1mm size fraction. The number of IRD per gram dry weight sediment was calculated. The previously published IRD record (>1 mm) from core JM02-460GC is included (Rasmussen *et al.* 2007). Grain size distribution is expressed as percentage.

The scanning electron micrographs were taken on CamScan Maxim MX2500 scanning electron microscope.

Results

Dating and age models

Six samples from core NP05-86GC, nine samples from core JM10-10GC, five samples from core JM10-12GC and seven samples from JM02-460GC have previously been AMS ^{14}C dated (Rasmussen *et al.* 2007; Rasmussen & Thomsen 2009; Rasmussen & Thomsen in press). All AMS ^{14}C dates were calibrated to calendar ages applying the Calib7.02 and the Marine13 program (Stuiver & Reimer 1993; Reimer *et al.* 2013). An age model was constructed for each core (Fig. 4). The dates indicate continuous successions in all cores except for core JM10-10GC. The age model for this core indicates the presence a hiatus between 345.5 cm and 324.5 cm comprising the time period *c.* 6500–9500 a BP (Rasmussen & Thomsen in press) (Fig. 4).

Distribution of benthic foraminiferal species

The cores from Storfjorden contain diverse, well preserved assemblages of both calcareous and agglutinated benthic foraminifera. The most important species of both groups are illustrated by scanning electron micrographs in Figs 5, 6, 7.

Based on the distribution patterns of benthic foraminifera and IRD, we have subdivided the four records into five periods: 1, Bølling-Allerød and Younger Dryas *c.* 15 000–11 700 a BP; 2, the Younger Dryas-early Holocene transition *c.* 11 700–*c.* 10 500 a BP; 3, the early Holocene 10 500–*c.* 8200 a BP; 4, mid-Holocene *c.* 8200–4000 a BP, and 5, late Holocene 4000–Recent (Figs 8, 9, 10).

Only core JM02-460GC from the outer shelf comprises sediments older than the end of the Younger Dryas/Holocene transition (Fig. 8). The calcareous faunas from this part are dominated by

Elphidium excavatum, *Cassidulina reniforme*, *C. teretis*, *Melonis barleeanus* and *Cibicides lobatulus* (Rasmussen *et al.* 2007) (Fig. 9). The agglutinated faunas show three peaks of maximum abundance (Fig. 10). The predominant species are *Reophax scorpiurus* and *Reophax* spp. (Fig. 10).

The oldest sections of the three cores from the inner brine basin consist of a diamict (core NP05-86GC) or of a mixture of diamictic and glaciomarine deposits dated to the Younger Dryas (Figs 3, 8) (cores JM10-12GC and JM10-10GC) The deposits are characterized by generally high magnetic susceptibility, a low water content and a high concentration of coarse material (Figs 3, 8). The coarse sediments in the two latter cores contain a diverse micro- and macrofauna of benthic foraminifera, ostracods, branching and encrusting bryozoans, echinoids and shells of mollusks including pteropods. Planktonic foraminifera are present in low numbers (Fig. 8). The shell material is well preserved and in all groups both juvenile and adult specimens are present. It is therefore assumed that the faunas are autochthonous. The benthic foraminiferal faunas are dominated primarily by *E. excavatum* and *C. reniforme* (Fig. 9). Agglutinated species are absent (Fig. 10).

In all four cores, the Holocene deposits older than *c.* 8200 a BP are totally dominated by calcareous benthic species (Fig. 9). From *c.* 8200 a BP the proportion of agglutinated foraminifera increases. However, the increase is uneven and the proportion of agglutinated species becomes more and more fluctuating, in particular in the uppermost part younger than *c.* 4000 a BP (Fig. 10).

Throughout the Holocene, the calcareous faunas are dominated by *C. reniforme*, *E. excavatum*, *N. labradorica*, *Islandiella norcrossi*, *Buccella* spp. and *C. lobatulus* (Figs 5, 6, 9). *Elphidium excavatum* is most abundant in the oldest and youngest parts of the cores (before 9000–10 000 a BP and after 3000 a BP). *Cassidulina reniforme* shows a general declining trend from a maximum in the early Holocene. *Nonionellina labradorica* attains maximum relative abundance between *c.* 10 500 and *c.* 8200 a BP followed by a more or less gradual decrease towards the recent. *Cibicides lobatulus* is relatively rare except for a small peak in the middle Holocene.

Overall, agglutinated specimens are most abundant in the middle and late Holocene successions younger than *c.* 8200 a (Fig. 10). They dominate in the upper part of core NP05-86GC from the central brine basin, where they sometimes constitute more than 80% of the total benthic foraminiferal assemblages (Fig. 8). The assemblages from the brine basin are dominated by *Reophax* species (mostly *R. scorpiurus*), *Cribrostomoides crassimargo*, *Spiroplectammina earlandi/biformis*, *Recurvoides turbinatus*, *Adercotryma glomerata*, and *Ammotium cassis* (Fig. 10). Core JM02-460GC differs slightly in that the more sturdy species from the brine basin are much rarer here (except for *R. scorpiurus*), while the smaller and more fragile *R. guttifer*, *Cribrostomoides jeffreysi*, *Eggerella advena*, *Trochammina globigeriniformis*, and *Textularia torquata* are more common (Figs 6, 7, 10). In all cores, small fragile forms increase in abundance in the top layers (Figs 8, 10).

Reophax scorpiurus is the most persistent and most abundant agglutinated species in all cores. In the inner basin, *Cribrostomoides crassimargo* is important in the mid Holocene section from *c.* 8200–6000 a BP and again in the late Holocene deposits younger than 1000 a BP. *Ammotium cassis*, *R. turbinatus* and *A. glomeratum* show slightly decreasing trends throughout the Holocene, whereas the small and fragile species *S. earlandi/biformis* shows a slightly increasing trend (Fig. 10).

Species diversity is low in the early Holocene records from the brine basins. The diversity increases to about 10 species per sample between *c.* 8200 and 6000 a BP after which it has been relatively stable. In core JM02-460GC from the shelf, we see a steady increase from about 20 species per sample 15 000 years ago to about 40 species today (Fig. 8).

Discussion

The Svalbard ice sheet retreated from the outer shelf of Storfjorden before 16 300 ¹⁴C a BP (before 19 700 a BP) (Rasmussen *et al.* 2007). Similar ages for the retreat have been obtained from the shelf west and north of Svalbard (Svendsen *et al.* 1992; Landvik *et al.* 2005; Ślubowska *et al.* 2005; Ślubowska-Woldengen *et al.* 2008 and references therein; Hormes *et al.* 2013). The retreat from the outer shelf occurred about 8000 years earlier than the retreat from the inner basin, where the oldest marine sediments are assigned to the Younger Dryas-Holocene transition (Figs. 3, 8).

Interpretation and discussion of faunal distribution and IRD events

Bølling-Allerød-Younger Dryas, c. 15 000–11 700 BP. – The oldest sediments in core JM02-460GC have an estimated age of *c.* 15 000 a BP and are referred to the early Bølling (see Rasmussen *et al.* 2007). The sediments older than *c.* 14 500 a BP contain a low diversity foraminiferal fauna dominated by *E. excavatum* and *C. reniforme* (see Rasmussen *et al.* 2007) (Fig. 9). Similar poor faunas are today typically found in front of glaciers and termed ‘ice-proximal’ faunas (Hald & Korsun 1997; Korsun & Hald 1998). During the earliest deglaciation before 14 500 a BP ‘ice proximal’ faunas occurred widespread on the outer shelf of Svalbard (Cadman 1996; Lubinski *et al.* 1996; Polyak & Mikhailov 1996; Hald & Aspeli 1996; Duplessy *et al.* 2001; Hald *et al.* 2004; Ślubowska *et al.* 2005; Ślubowska-Woldengen *et al.* 2007, 2008; Klitgaard Kristensen *et al.* 2013).

The period from 14 600–11 700 a BP was unstable in Storfjorden. We can recognize three warmer intervals predominated by calcareous species interrupted by three colder intervals with higher abundances of agglutinated forms (Figs 9, 10). These colder intervals correlate in time with the Older Dryas cold event (OD) (centred at 14 600 a BP, Stanford *et al.* 2006), the Intra-Allerød

Cold Period (IACP) (13 300 a BP, Björck *et al.* 1996) and the earliest part of the Younger Dryas indicating that the periods represent cold events during the deglaciation.

The warmer intervals contain, in addition to *E. excavatum* and *C. reniforme*, numerous specimens of *C. lobatulus* and species indicative of a subsurface inflow of Atlantic Water (viz., *Cassidulina teretis* and *Melonis barleeanus*; see e.g. Ślubowska *et al.* 2005; Ślubowska-Woldengen *et al.* 2007; Rasmussen *et al.* 2007). Bottom water conditions were clearly improved as compared to the earliest period before 14 500 a BP with higher temperatures, stronger water movements and higher productivity. *Cibicides lobatulus* is normally associated with strong bottom currents (Sejrup *et al.* 1981; Mackensen *et al.* 1985; Hald & Korsun 1997; Polyak *et al.* 2002; Pogodina 2005; Lloyd 2006) (Fig. 9).

The agglutinated faunas of the three cooling events are dominated by *A. glomerata*, *R. turbinatus*, *R. scorpiurus*, *Trochammina nana* and *C. jeffreysi* (Fig. 10). Today, these species are ubiquitous around Svalbard thriving in the inner fjords as well as on the open shelf. They are typical in inner parts of fjords affected by fresh water runoff (Hald & Korsun 1997; Majewski & Zajączkowski 2007). *Reophax scorpiurus* is described as a winter species by Hald & Korsun (1997) thriving in areas with seasonal sea ice. The species is epifaunal according to Gooday (1994) and probably prefers areas with elevated bottom currents (Mackensen & Douglas 1989; Schmiedl *et al.* 1997). In Baffin Bay, *A. glomerata* seems to prefer the cold water below the carbonate compensation depth (CCD) in areas with seasonal sea ice cover and high productivity (Schröder-Adams & van Rooyen 2011). It is characterized as an epifaunal to shallow infaunal species. It has recently increased in abundance in Oslofjorden, Norway, due to a higher organic supply to the sea bottom (Nagy & Alve 1987). Around Svalbard, the species attains maximum abundance in the high productive mixing zone between the Atlantic water and the polar water (Hald & Korsun 1997; Lloyd 2006). In the St. Anna Trough east of Franz Joseph Land and in the Kara Sea the species

occurs together with *C. crassimargo* in sandy slope sediments (Korsun & Hald 1998). Both species are common in Storfjorden today (Fig. 10).

The high abundance of fine delicate species - otherwise only seen in the uppermost few centimetres of the core - indicates exceptionally good conditions for the preservation of agglutinated foraminifera. The dominance of different taxa during the three events is difficult to explain (Fig. 10). It may reflect ecological variability, but it may also be random. The calcareous faunas of the cold episodes are dominated by *E. excavatum* and *C. reniforme*, also indicating polar conditions (Fig. 9). *C. lobatulus* is relatively rare and the inflow of Atlantic Water was probably reduced as compared to the warmer periods. In the later part of the Younger Dryas, the relative abundance of *E. excavatum* decreases, whereas the relative abundance of *M. barleeanus* and *C. reniforme* increases, indicating a rejuvenation of the inflow of Atlantic Water and reduced sea ice (Rasmussen *et al.* 2007).

The moderate increase in the ratio of agglutinated to calcareous foraminifera indicates a small increase in the production of brines especially during the Older Dryas. According to Rasmussen and Thomsen (in press) a higher ratio of agglutinated to calcareous benthic foraminifera in Storfjorden can be taken as an indication of increased brine formation.

Younger Dryas-Holocene transition, 11 700–10 500 a BP. – The first indications of marine conditions in the inner basin of Storfjorden are assigned to the Younger Dryas-Holocene transition. Two foraminiferal samples from the glaciomarine deposit in the lower part of cores JM10-10GC and JM10-12GC are dated to 12 532 a BP and 12 660 a BP, respectively, indicating that the deposits belong to the Younger Dryas, *c.* 12 900–11 700 a BP (Figs 3, 8). However, the deposits are most likely younger than the calibrated ages suggests. The marine reservoir effect for the Younger Dryas is unknown for the Svalbard area, and in other inner shelf areas from the Nordic seas and

North Atlantic it has been shown to be increased by 200–600 years on top of the standard 405 years used in the Calib7.02 and Marine13 program (Bondevik *et al.* 2006; Austin *et al.* 2011). The glaciomarine layers were most likely deposited during the Younger Dryas-Holocene transition. There are no dates available of the massive diamict in core NP05-86GC, but we assume that it is of similar age or slightly younger than the glaciomarine deposits in JM10-10GC and JM10-12GC. Altogether, we conclude that diamictic and glaciomarine deposits in the three cores represent the last glacial deposit before the opening of the inner Storfjorden and that the ice retreated from the sill and the inner basin around the Younger Dryas-Holocene transition 11 700 a BP. This conclusion is in accordance with ages from raised beaches on nearby Edgeøya (Bondevik *et al.* 1995). The strong peak of very coarse IRD in the early Holocene interval indicates a short-lasting intense activity in the ice sheet probably followed by a rapid retreat (Fig. 8).

The occurrence of foraminifera in the glaciomarine deposits is surprising. The concentration is low and agglutinated forms are virtually absent. The preservation is excellent and the best observed in the present study. The presence of planktonic foraminifera (Fig. 8) and pteropods in several samples indicates that the area was isostatically overdeepened by the newly retreated ice sheet. Planktonic foraminifera are normally rare on the shelf of Svalbard (Ślubowska *et al.* 2005; Rasmussen *et al.* 2007; Ślubowska-Woldengen *et al.* 2007; Skirbekk *et al.* 2010) and generally absent from the fjords (Kubischta *et al.* 2011; Rasmussen *et al.* 2012; Jernas *et al.* 2013).

The benthic faunas from the oldest continuously marine deposits in the inner basin are dominated by calcareous species. The productivity was extremely low as indicated by the combination of low sedimentation rates and low concentrations of foraminifera (Figs 4, 8). The low diversity fauna is dominated by *C. reniforme* and *E. excavatum* and resembles the so-called “ice-proximal” fauna that dominated the outer shelf of Svalbard before 14 500 a BP (see above and Fig. 9). A similar fauna has also been described from Muchisonfjorden and the inner Isfjorden, where it

occurs under comparable circumstances and with the same timing as in the inner Storfjorden (Kubischta *et al.* 2011; Rasmussen *et al.* 2012). The fauna is thus time-transgressive following the retreat of the ice sheet.

However, the conditions in the inner basin were probably slightly improved compared to the early deglaciation as indicated by the dominance of *C. reniforme* over *E. excavatum* in most cores and by a gradual increase in the absolute abundance of benthic specimens. Dominance of *C. reniforme* over *E. excavatum* generally occurs in less stressed environments with increased food supply and reduced impact of glaciers (Korsun & Hald 1998) (Fig. 9). The glaciers must have been passive and probably retreating. This is in good agreement with the presence of *C. teretis*, *M. barleeanus*, and miliolids in core JM10-12GC (not shown) near the sill between the inner basin and the outer shelf (Fig. 1). These species are generally found more distal to glacier fronts than *E. excavatum* and *C. reniforme* and Korsun & Hald (1998) and Hald & Korsun (2000) characterize them as ‘ice-distal’ species. Nevertheless, sea ice was still abundant as indicated by the common occurrence of *Stainforthia loeblichii* in all cores. This species proliferates during winter months (Korsun & Hald 2000) and the species is used as an indicator of sea ice cover (Polyak *et al.* 2002; Ślubowska *et al.* 2005). The ice conditions were probably not very different from today, when the inner fjord is ice covered about seven months of a year. The increase in the relative abundance of *Elphidium* spp. (*Elphidium bartletti*, *E. subarcticum*, *E. orbiculare* and others) may reflect reduced salinity (e.g. Feyling-Hanssen *et al.* 1971; Madsen & Knudsen 1994; Hansen & Knudsen 1995; Korsun *et al.* 1995; Polyak *et al.* 2002; Rytter *et al.* 2002; Bauch *et al.* 2004) (Fig. 9).

The calcareous faunas inhabiting the shelf of Storfjorden during the Younger Dryas-Holocene transition are much richer than the simultaneous ‘ice proximal’ faunas in the inner basin. In JM02-460GC, the faunas are first of all characterized by high abundances of *N. labradorica*, *C. reniforme*, *Islandiella norcrossi*, and *M. barleeanus* (not shown; see Rasmussen *et al.* 2007) (Fig.

9). This fauna signifies a stronger influence of warm Atlantic Water than in the inner basin and a significantly lower impact of sea ice. The amount of sea ice was probably also lower than during the Younger Dryas (Rasmussen *et al.* 2007). The periodically higher concentration of IRD indicates that the site was still passed by a significant number of icebergs (Fig. 8).

Rasmussen & Thomsen (in press) suggests that the low ratio of agglutinated to calcareous specimens in the Storfjorden system during the earliest Holocene can be taken as an indication of reduced brine production in the inner basin.

Early Holocene 10 500–8200 a BP. – During this period the concentration of benthic specimens increases to a maximum while the concentration of IRD decreases to a minimum (Fig. 8). These changes, which occur in all four cores, indicate a further retreat of the ice front and an increase in the organic productivity. The relative abundance of agglutinated species is very low during most of the period, but it increases gradually towards the end, in particular in the inner basin, where agglutinated specimens may increase to nearly 50% of the total fauna (Fig. 10). Core JM10-10GC is incomplete due to the presence of a hiatus comprising the time period *c.* 9500–6500 a BP (Fig. 4).

The agglutinated fauna is dominated by *R. scorpiurus* on the shelf and by *A. glomerata* in the inner fjord (Fig. 10). Today, these two species occurs ubiquitously around Svalbard from the inner fjords to the open shelf (see above). Both species are often drawn to areas with freshwater runoff. *Reophax scorpiurus* also seems to prefer environments with slightly elevated bottom currents (see above).

In all cores, the most important calcareous species are *N. labradorica*, *I. norcrossi* and *Bucella* spp. (Fig. 9). Today, *N. labradorica* is flourishing under high productive conditions below oceanic front zones, where it is attracted to fresh food particles settling from the spring bloom (e.g. Cedhagen 1991; Hunt & Corliss 1993; Newton & Rowe 1995; Polyak *et al.* 2002; Pogodina 2005;

Lloyd 2006). The high relative abundance of *N. labradorica* indicates that Storfjorden in this period was under strong influence by the Arctic Front (see Hald & Steinsund 1992; Steinsund 1994; Saher *et al.* 2012). It also indicates that the sea ice cover was seasonal and less extensive than during the preceding period and probably also less extensive than today (Fig. 9). *Islandiella norcrossi* and *Buccella* spp. are also linked to the high productivity zone near ice fronts living on fresh phytodetritus (Steinsund 1994; Hald & Korsun 1997; Korsun & Hald 1998; Polyak *et al.* 2002). The high percentages of *N. labradorica*, *I. norcrossi* and *Buccella* spp. is in concordance with the overall high concentration of benthic foraminifera in the bottom sediments (Fig. 9).

Mid-Holocene c. 8200–4000 a BP. – Overall, this period is characterized by a decrease in the concentration of benthic foraminifera and increase in the proportion of agglutinated forms (Figs 8, 10). This increase is strongest in the inner basin, where agglutinated specimens from *c.* 8200–5000 a BP often make up more than 50% of the benthic foraminiferal fauna.

In all four cores, the most common agglutinated species is *R. scorpiurus* (Fig. 10). In the inner part of Storfjorden, *R. turbinatus*, *C. crassimargo*, *A. glomerata* and *A. cassis* are also common. Today, these four species are characteristic constituents of faunas in the inner fjords of Spitsbergen especially in areas affected by fresh water runoff (see above). They also occur in Baffin Bay, where they are found in the cold corrosive, deep water below the CCD in areas with seasonal sea ice cover and high food supply (*R. turbinatus* is here recorded as *R. contortus*) (Schröder-Adams & van Rooyen 2011). *Recurvoides turbinatus* and *R. scorpiurus* are characterized as winter species similar to *S. loeblichii* (Korsun & Hald 2000). *Reophax scorpiurus* probably prefers areas with elevated bottom currents (see above). The indications of stronger currents are supported by an increase in the relative abundance of the calcareous species *C. lobatulus* from *c.* 7000–4000 (5500

in JM10-12GC) a BP (Fig. 9). It is well-known that this species is attracted to areas with strong bottom currents (see above).

Altogether, we conclude that the conditions in Storfjorden became more severe after *c.* 8200 a BP. They were clearly harsher than during the previous period, 10,500–*c.* 8200 a BP and approaching the modern conditions in the area. This includes more extensive seasonal sea ice, increased polynyal activity, and higher production of brines (see Rasmussen & Thomsen (in press)). The more vigorous current activity indicated by the increase in *C. lobatulus* could partly be due to a higher brine production in the inner basin and a stronger overflow of brines over the sill. In East Greenland fjords with low saline polar water and low pH there are few calcareous species (Jennings & Helgadottir 1994). Only live specimens are found here, indicating that the tests dissolve soon after death. Despite the poorer conditions, the concentration of IRD remains very low throughout the period and it is likely that the glaciers by now had retreated from the coast (Fig. 8).

Late Holocene, the last c. 4000 years. – The concentration of benthic foraminifera is low with a slight increase during the last 1000 years (Figs 8, 9, 10). In cores JM10-10GC and NP05-86GC from the inner basin we notice an increase in the concentration of IRD (Fig. 8). The percentage of agglutinated specimens is strongly fluctuating ranging from ~5% to nearly 100% of the total benthic foraminiferal faunas (Fig. 10). The excursions are largest in the inner fjord. The maximum concentration and highest percentages of agglutinated specimens are found within the last 1000 years with highest peaks in the uppermost samples (Fig. 10).

High percentages of agglutinated foraminifera occur from *c.* 1500–1100 and *c.* 600–100 a BP, while low percentages occurs from *c.* 2500–2000 a BP and from *c.* 1100–600 a BP (Fig 10A). The timing is slightly offset in JM10-12GC probably due to problems with the age model for the uppermost part of this core (Fig. 4). The intervals dominated by agglutinated species correlate with

cold periods in the Greenland ice cores, while the intervals dominated by calcareous species correlate with warm intervals in the ice core (Rasmussen & Thomsen, in press). Some of the cold phases also correlate with well-known cold phases in the European climate history, viz. the Dark Ages Cold Period (DACP, c. 1500–1100 a BP) and the Little Ice Age (LIA, c. 600–100 a BP) (see compilation of ages in Grauel *et al.* 2013), while some of the warm phases correlate with warm phases in the European history, viz. the Roman Warm Period (RWP, c. 2500–2000 a BP), and the Medieval Warm Period (MWP, c. 1000–700 a BP).

Elphidium excavatum is the most important calcareous species in all cores (Fig. 9). The relative abundance of *E. excavatum* begins to increase from c. 5000 a BP. In cores NP05-86GC and JM10-12G from the inner basin the species becomes almost as abundant as during the early Holocene before c. 10 000 a BP (Fig. 9). This is especially conspicuous when the percentage is recalculated on an ‘agglutinated foraminifera-free’ basis (Fig. 11). In core JM02-460GC from the shelf, the relative abundance of *E. excavatum* increases to the same level as during the Younger Dryas and at the beginning of the Bølling interstadial. The increase in *E. excavatum* indicates more difficult conditions probably related to a more extensive seasonal ice cover as also indicated by the increase in the concentration of IRD (Fig. 8). The low relative abundance of *C. lobatulus* and *N. labradorica* and the higher abundance of *Elphidium* spp. in cores JM02-460GC, NP86GC and JM10-12GC may reflect weaker bottom currents, reduced seasonal surface productivity and lower salinity as compared to the preceding periods. The relatively high percentages of *C. reniforme*, *N. labradorica* and *C. lobatulus* in core JM10-10GC suggest that these changes were smaller in the eastern part of the inner basin (Fig. 9). The overall similarity between the calcareous faunas after c. 4000 a BP and the ‘ice proximal’ fauna that dominated the inner basin during the earliest Holocene before 10 500 a BP points to increased glacial activity as also indicated by the slightly higher

abundance of IRD in the inner Brine basin. The surrounding glaciers probably advanced to the fjord with glacier fronts located not very different from their present positions.

The most common agglutinated species are *R. scorpiurus*, *C. crassimargo*, *A. cassis*, *S. earlandi/biformis*, *T. nana*, and *A. glomerata*. The fauna in the uppermost samples contains, in addition, a number of small fragile species such as *R. difflugiformis*, *T. torquata*, *T. globigeriniformis*, *C. jeffreysi*, and *Eggerella advena* (Fig. 7). Most of these species have poor preservational potential and they are generally found only in the uppermost few centimetres of the sea bottom (e.g. Schröder 1988; Denne & Sen Gupta 1989). Except for core JM10-12GC, the diversity also reaches a maximum in the top layers (Fig. 4). *Spiroplectammia earlandi/biformis* has been reported from cold polar bottom water in Disco Bay, west Greenland (Lloyd 2006) and from East Greenland fjords (Jennings & Helgadottir 1994), where it occurs abundantly together with *R. difflugiformis* and *T. nana*. *Reophax difflugiformis* (as *R. atlantica*), and other fragile *Reophax* species are dominant in the Barents Sea in areas with cold bottom water and sediments with a high organic content (Hald & Steinsund 1992).

Distribution patterns of agglutinated foraminifera in relation to brine formation

Agglutinated species are rare in most Holocene records from the western and northern shelf of Svalbard (Cadman 1996; Ślubowska *et al.* 2005; Ślubowska-Woldengen *et al.* 2007; Skirbekk *et al.* 2010; Kubischta *et al.* 2011). High abundances seem restricted to Storfjorden, Isfjorden (Rasmussen *et al.* 2012) and an area northeast of Svalbard (Klitgaard Kristensen *et al.* 2013). These are all environments which to some extent are affected by brines during winters (Nilsen *et al.* 2008; Lubinski *et al.* 2001). Storfjorden is, furthermore, characterized by high organic productivity and a high content of organic material in the bottom sediments (Rasmussen & Thomsen in press).

These observations are in good agreement with modern studies. In live faunas around Svalbard and in the Barents Sea agglutinated forms typically make up around 50% of the specimens. Faunas dominated by agglutinated foraminifera (predominantly *Reophax* and *Trochammina*), are normally only found in environments where, for various reasons, the bottom water and pore water is corrosive and the calcareous tests are dissolved (Steinsund 1994; Steinsund & Hald 1994; Hald & Steinsund 1996). These can be brine influenced environments or areas promoting high organic productivity resulting in acidic conditions at the sea floor or in the pore water (Wollenburg & Mackensen 1998; Wollenburg & Kuhnt 2000). Alve & Murray (1995) state that fossil faunas dominated by agglutinated foraminifera are often the remnants after the calcareous faunas have been dissolved.

The importance of brines for the preservation of agglutinated and calcareous foraminifera is demonstrated by the different proportions of agglutinated tests in the investigated core. The highest proportions are found in core NP05-86GC from the deepest part of the inner brine basin (Fig. 10). This core is affected by brines year round (Fig. 2). JM10-12GC, which has a lower proportion of agglutinated forms, is from the sill and only affected by brine flow through spring and early summer (Fig. 2). The record with the fewest agglutinated specimens is JM02-460GC, which is the most distal record and least affected.

The changes in the ratio of agglutinated to calcareous foraminifera that characterize the late Holocene interval in the cores from Storfjorden are consistent with these general observations. The warmer phases such the Roman Warm Period (RWP; *c.* 2500–2000 a BP) and the Medieval Warm Period (MWP; *c.* 1000–700 a BP) show low ratios of agglutinated to calcareous species, whereas the cold phases show high ratios. The same pattern is evident during the cold and warm periods of the deglaciation as demonstrated in core JM02-460GC (Figs 9, 10). The main reason for these changes is considered to be related to changes in brine production. During the cold periods the

extent of sea ice, the intensity of polynyal activity and the production of brines increases causing dissolution of the calcareous tests. Furthermore, brines seem to facilitate the preservation of certain types of agglutinated tests (Schröder 1988; see Rasmussen & Thomsen in press for more references). The oxygen isotope records from Storfjorden differ slightly from records from other areas around Svalbard (Fig. 5). The values from Storfjorden are overall higher and show mostly a steeper increase towards the late Holocene than normally seen around Svalbard (see Rasmussen *et al.* 2007; Rasmussen & Thomsen 2009; Rasmussen *et al.* 2014) (Fig. 5). We attribute these differences to the cooling effect of the flow of cold brines. It is, however, noticeable that the fluctuating values, evident in the late Holocene foraminiferal data, are absent in the isotope records.

Despite the variable preservation and dissolution of the calcareous foraminifera, the species composition of the calcareous assemblages from Storfjorden over the last 12 000 a is remarkably similar to numerous other records from more normal marine environments around Svalbard (Fig. 11). The resemblance is illustrated by the distribution pattern of the three most common species, *C. reniforme*, *N. labradorica* and *E. excavatum*, in Storfjorden, which is similar to the patterns recorded from Hinlopen Strait (Ślubowska *et al.* 2005), Bellsund Høla (Ślubowska-Woldengen *et al.* 2007), and Kongsfjorden Trough (Skirbekk *et al.* 2010) (Fig. 11). Apparently the dissolution in Storfjorden did not affect the relative importance of species. It is also striking that the distribution trends are basically the same whether the calculations are based on the total number of foraminifera or on calcareous foraminifera alone (Fig. 11). Still, the relative abundance of calcareous species obviously increases if the agglutinated specimens are removed from the calculations. In Storfjorden, we notice an increase in the relative abundance of *E. excavatum* of more than 30% in core NP05-86GC, which has the highest proportion of agglutinated species (Fig. 11).

The benthic foraminiferal species discovered in Storfjorden have all widespread occurrences on the Arctic shelves across the Northern Hemisphere (see e.g. Schröder-Adams *et al.* 1990; Scott

& Vilks 1991). We have not observed additional or missing species in Storfjorden as compared to non-brine areas around Svalbard. The species diversity is also about the same.

The most persistent agglutinated species in Storfjorden in intervals affected by brine flow is *Reophax scorpiurus* followed by *A. glomerata*. The more fragile species *A. cassis*, *C. crassimargo* and *S. earlandi/biformis* are only common in the brine basin (Fig. 10). These five species may be particularly tolerant to the acidic, CO₂ rich conditions that characterize a brine-influenced environment. Together with *Reophax atlantica* (= *R. difflugiformis*), they are dominant in Isfjorden in both the living and fossil records (Hald & Korsun 1998; Rasmussen *et al.* 2012). However, they are clearly not restricted to brine influenced environments as they are among the most widespread agglutinated species today and adaptable to widely different ecological conditions (Murray & Alve 2011). They are the most important species in Lancaster Sound and Baffin Bay in areas with seasonal sea ice cover (Schröder-Adams *et al.* 1990; Schröder-Adams & van Rooyen 2011), and according to Wollenburg & Mackensen (1998) and Wollenburg & Kuhnt (2000) they occur widespread in the Arctic Ocean in areas with seasonal sea ice cover.

Altogether, we have not been able to uncover species especially adapted to brine influenced conditions.

Conclusions

Storfjorden is remarkable for the Arctic area by preserving a paleorecord of agglutinated species going back to the beginning of the deglaciation at *c.* 15 000 a BP. Both the calcareous and agglutinated assemblages are dominated by species that have widespread occurrences in the Arctic and Polar areas. The most important calcareous species are *Cassidulina reniforme*, *Elphidium excavatum*, *Nonionellina labradorica*, *Buccella* spp. and *Islandiella norcrossi*. The most important

agglutinated species are *Reophax scorpiurus*, *Adercotryma glomerata*, *Cribrostomoides crassimargo*, *Ammotium cassis*, *Recurvoides turbinatus* and *Spiroplectammina earlandi/biformis*.

During the deglaciation c. 15 000–11 700 a BP, the shelf of Storfjorden Trough experienced marine conditions, while the inner part was occupied by continental ice. The calcareous fauna on the shelf were dominated by *E. excavatum*, and *C. reniforme*. The fauna is species poor and typical for Arctic environments close to glacier fronts. During cold events of the deglaciation (Older Dryas (centred at 14 600 a BP), Intra-Allerød Cold Period (13 300 a BP) and the Younger Dryas (12 900–11 700 a BP), the proportion of agglutinated species increased. However, each cold event was dominated by a different set of agglutinated species and the conditions were clearly unstable.

The temperatures increased at the beginning of the Holocene 11 700 a BP and the ice sheet retreated from the inner basin. The earliest Holocene faunas from 11 700–c. 8200 a BP are everywhere totally dominated by calcareous species. The earliest faunas in the inner basin are ‘ice-proximal’ faunas similar to the faunas that thrived on the shelf during the deglaciation. The surface water was probably stratified and brine formation was weak. On the shelf, a diverse fauna thrived dominated by *Nonionellina labradorica* and species attracted to warm Atlantic water. From c. 8200 a BP, the proportion of agglutinated species increased indicating colder conditions and an increase in brine formation. On the shelf, the agglutinated part of the fauna was totally dominated by the robust species *Reophax scorpiurus*. From c. 5000 a BP *E. excavatum* returns in increasing quantities indicating a further cooling and return of polar conditions. In the inner basin, the content of ice rafted debris increased and the glaciers became more active. After 4000 a BP, the ratio of agglutinated to calcareous foraminifera became more fluctuating with agglutinated species attaining maxima during the colder phases (Dark Ages Cold Period, c. 1500–1100 a BP and the Little Ice Age, c. 600–100 a BP) and calcareous species attained maxima during warmer phases (Roman Warm Period, c. 2500–2000 a BP and the Medieval Warm Period, c. 1000–700 a BP).

The distribution patterns of the calcareous species show basically the same trends whether calculated on the basis of the total faunas or on the basis of the calcareous specimens alone, even though the actual percentages obviously are elevated when calculated versus calcareous specimens alone. Moreover, the distribution patterns are similar to the patterns found elsewhere along western Svalbard in areas without any influence of brines. The most persistent agglutinated species are *R. scorpiurus* and *A. glomerata*. They are probably the most tolerant species to the brine influenced acidic environment of Storfjorden. However, we have not discovered any species that could specifically be linked to the flow of brines.

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Figure text

Fig. 1. Map of Svalbard with core positions from Storfjorden marked. Line A-B indicates approximate location of bathymetric profile sketches in Fig. 2.

Fig. 2. Bathymetric profiles sketches showing seasonal formation and flow of brines in Storfjorden and Storfjorden Trough for winter, summer and fall based on Skogseth *et al.* (2005b). Core locations are indicated. For location of profile sketches and identification of core numbers see Fig. 1.

Fig. 3. Lithological logs of the investigated cores with ^{14}C dates indicated (corrected for -400 years reservoir effect). For location of cores see Figs 1 and 2.

Fig. 4. Age-depth plot of the four investigated cores.

Fig. 5. Scanning electron micrographs of important benthic foraminiferal species from Storfjorden.

All specimens are from core JM02-460GC (Bar scale = 100 µm). Calcareous species: 1, 2.

Astrononion gallowayi Loeblich and Tappan. 3, 4, 5. *Buccella frigida* (Cushman). 6, 7. *Cassidulina*

neoteretis Seidenkrantz. 8. *C. reniforme* Nørvang. 9, 10. *Cibicides lobatulus* (Walker and Jacob).

11, 12. *Elphidium excavatum* (*E. excavatum* (Terquem) f. *clavata* Cushman). 13. *Globobulimina*

auriculata (Bailey). 14. *Islandiella norcrossi* (Cushman). 15. *Lagena nebulosa* (Cushman). 16, 17,

18. *Melonis barleeanus* (Williamson). 19. *Miliolinella subrotunda* (Montagu). 20, 21, 22.

Nonionella opima digitata (Nørvang). 23, 24, 25. *Nonionellina labradorica* (Dawson).

Fig. 6. Scanning electron micrographs of important benthic foraminiferal species from Storfjorden.

All specimens are from core JM02-460GC (Bar scale = 100 µm). Calcareous species continued: 1,

2. *Pullenia bulloides* (d'Orbigny). 3. *Quinqueloculina seminulum* (Linnaeus). 4. *Q. stalker*

Loeblich and Tappan. 5, 6, 7. *Robertinoides charlottensis* (Cushman). 8, 9, 10. *Stainforthia*

loeblichii (Feyling-Hanssen). 11, 12. *Trifarina fluens* (Todd). 13. *Triloculina tricarinata*

(d'Orbigny). Agglutinated species: 14, 15, 16. *Adercotryma glomerata* (Brady). 17, 18.

Ammodiscus spp. 19, 20. *Cribrostomoides crassimargo* (Norman). 21. *Cuneata arctica* (Brady). 22.

Deuterammia ochracea (Williamson). 23. *Hyperammia elongata* Brady. 24, 25. *Recurvoides*

turbinatus (Brady).

Fig. 7. Scanning electron micrographs of important benthic foraminiferal species from Storfjorden.

All specimens are from core JM02-460GC (Bar scale = 100 µm) Agglutinated species continued: 1,

2. *Reophax difflugiformis* (Brady). 3, 4, 5, 6. *R. fusiformis* (Williamson). 7. *R. guttifera* (Brady). 8,

9, 10, 11. *R. scorpiurus* Montfort. 12. *Saccorhiza ramosa* (Brady). 13, 14, 15. *Spiroplectammina*

biformis (Parker and Jones), 'type S. *biformis*'. 16, 17. *Spiroplectammina biformis*, 'type'

Textularia earlandi Phleger. 18, 19. *Textularia torquata* Parker. 20, 21. *Trochammina globigeriniformis* (Parker and Jones). 22, 23. *T. nana* (Brady).

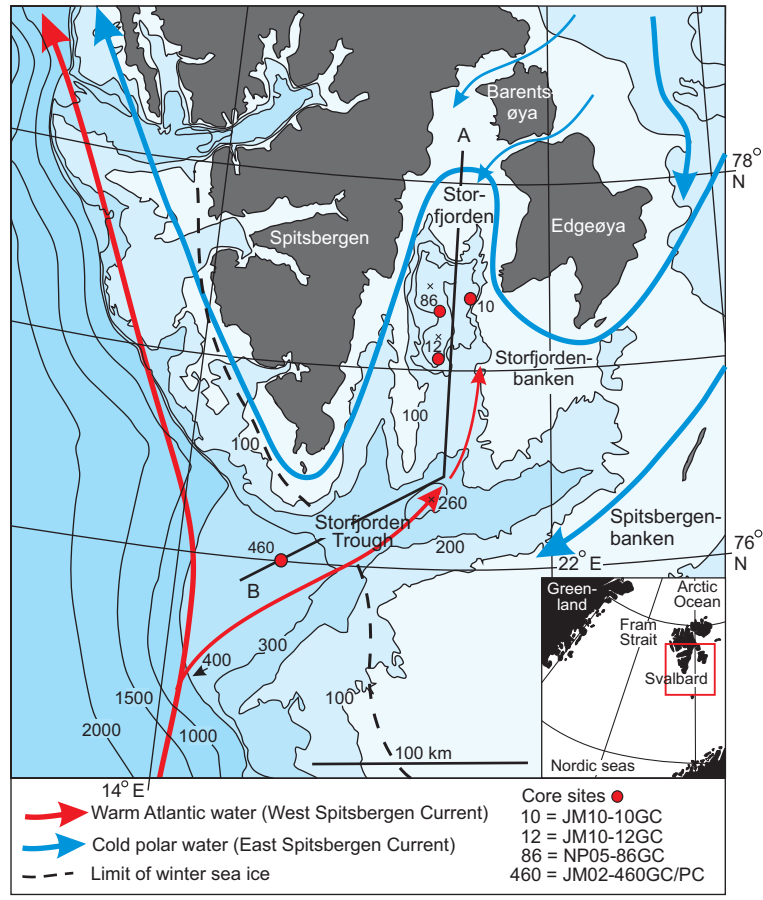
Fig. 8. Various data for each core plotted versus depth. From the left to right: Magnetic susceptibility with ^{14}C ages marked, percentage of water in sediment with calibrated ages marked, number of benthic foraminifera per gram dry weight sediment, various grain sizes and IRD parameters, total number of species per sample (black line) and number of calcareous species per sample (red line), number of planktonic foraminifera per sample (panels B, C) and per gram dry weight sediment (panel D), oxygen isotopes measured in *Nonionellina labradorica*, *Cibicides lobatulus*, *Cassidulina reniforme* and *Melonis barleeanus* (only panels A, B, D). OD = Older Dryas; IACP = Intra-Allerød Cold Period; YD = Younger Dryas.

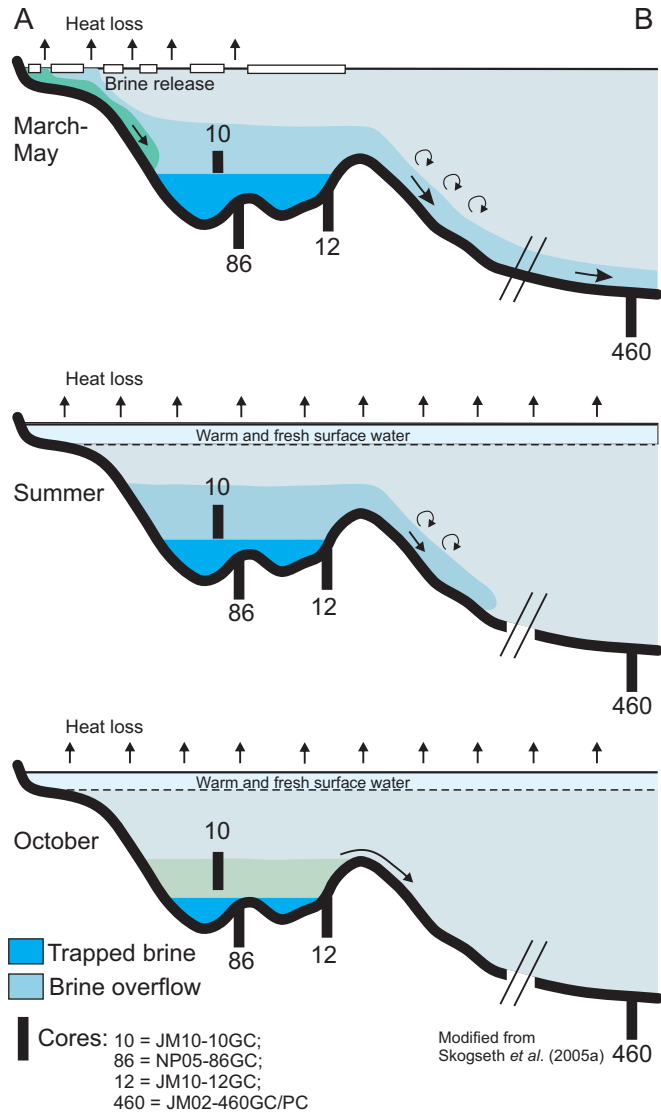
Fig. 9. Relative abundance of important calcareous benthic foraminiferal species for the investigated cores (panels A-D) plotted versus calendar years BP. For each core from the left to right: Percentage calcareous specimens of total foraminiferal fauna, number of calcareous specimens/gram dry weight sediment, relative abundance of *Elphidium excavatum*, *Cassidulina reniforme*, *Nonionellina labradorica*, *Cibicides lobatulus*, *Ephidium bartletti* (only A), *Elphidium* spp. (panels B, C, D), *Stainforthia loeblichii*, *Buccella* spp., *Islandiella norcrossi*. OD = Older Dryas; IACP = Intra-Allerød Cold Period; YD = Younger Dryas; LIA = Little Ice Age; MWP = Medieval Warm Period; DACP = Dark Ages Cold Period; RWP = Roman Warm Period.

Fig. 10. Relative abundance of important agglutinated benthic foraminiferal species for the investigated cores (panels A-D) plotted versus calendar years BP. From the left to right: Percentage

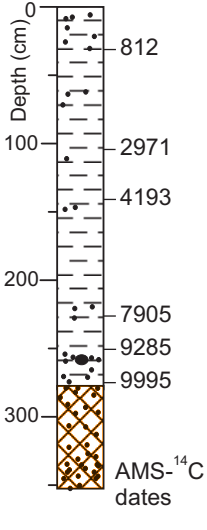
agglutinated specimens of total foraminiferal fauna, number of agglutinated specimens/gram dry weight sediment, relative abundance of *Reophax scorpiurus*, *Cibrostomoides crassimargo* (only panels A-C), *Ammotium cassis* (only A-C), *Spiroplectammina earlandi/biformis* (only A-C), *Adercotryma glomerata*, *Reophax turbinatus*, *Eggerella advena* (only D), *Trochammina nana* (only D), *Cibrostomoides jeffreysi* (only D), sum of *Textularia torquata*, *C. crassimargo*, *S. earlandi/biformis*, *Trochammina globigeriniformis*, *Ammodiscus* spp. and other agglutinated species added together (only D). OD = Older Dryas; IACP = Intra-Allerød Cold Period; YD = Younger Dryas.

Fig. 11. Plots of the relative abundance of the three most common calcareous species, *Nonionellina labradorica*, *Elphidium excavatum* and *Cassidulina reniforme*, from the Storfjorden cores compared with published records from the Svalbard margin: Core JM98-845PC (Rasmussen *et al.* 2012), core NP94-51SC (Ślubowska *et al.* 2005), core JM02-440GC/PC (Ślubowska-Woldengen *et al.* 2007) and core NP05-21GC (Skirbekk *et al.* 2010). In order to facilitate comparison with the published records where agglutinated species are not preserved, we have calculated the percentages of the three species in Storfjorden both relative to the total fauna (including agglutinated species) (black lines) and relative to the calcareous fauna alone (color lines).

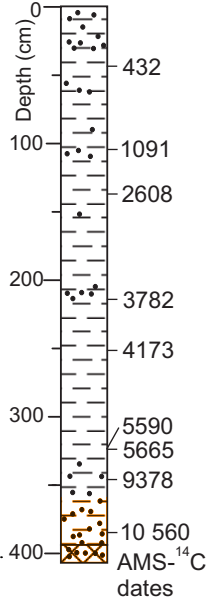




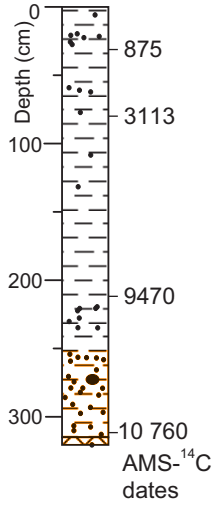
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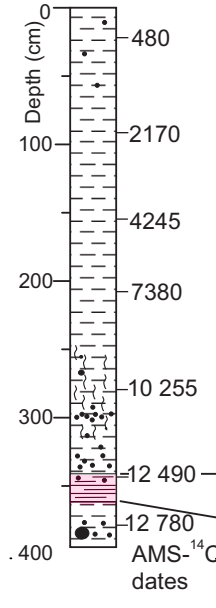
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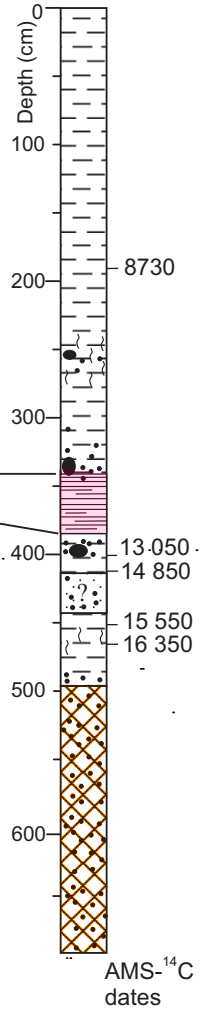
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




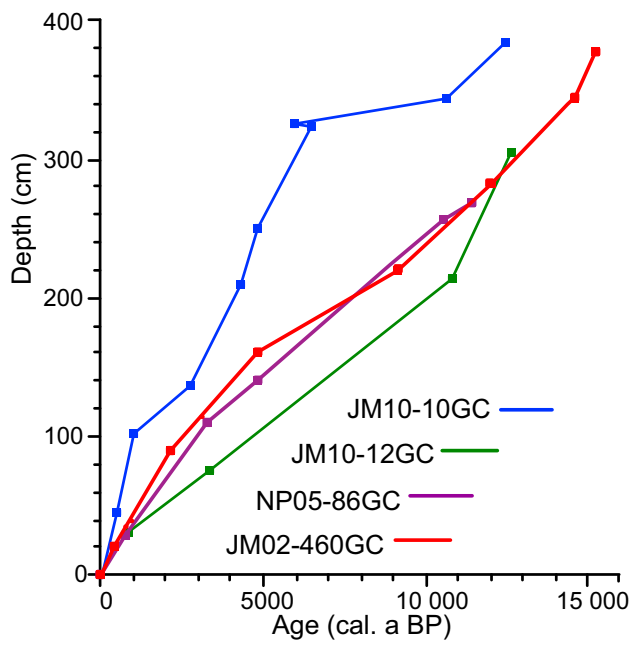
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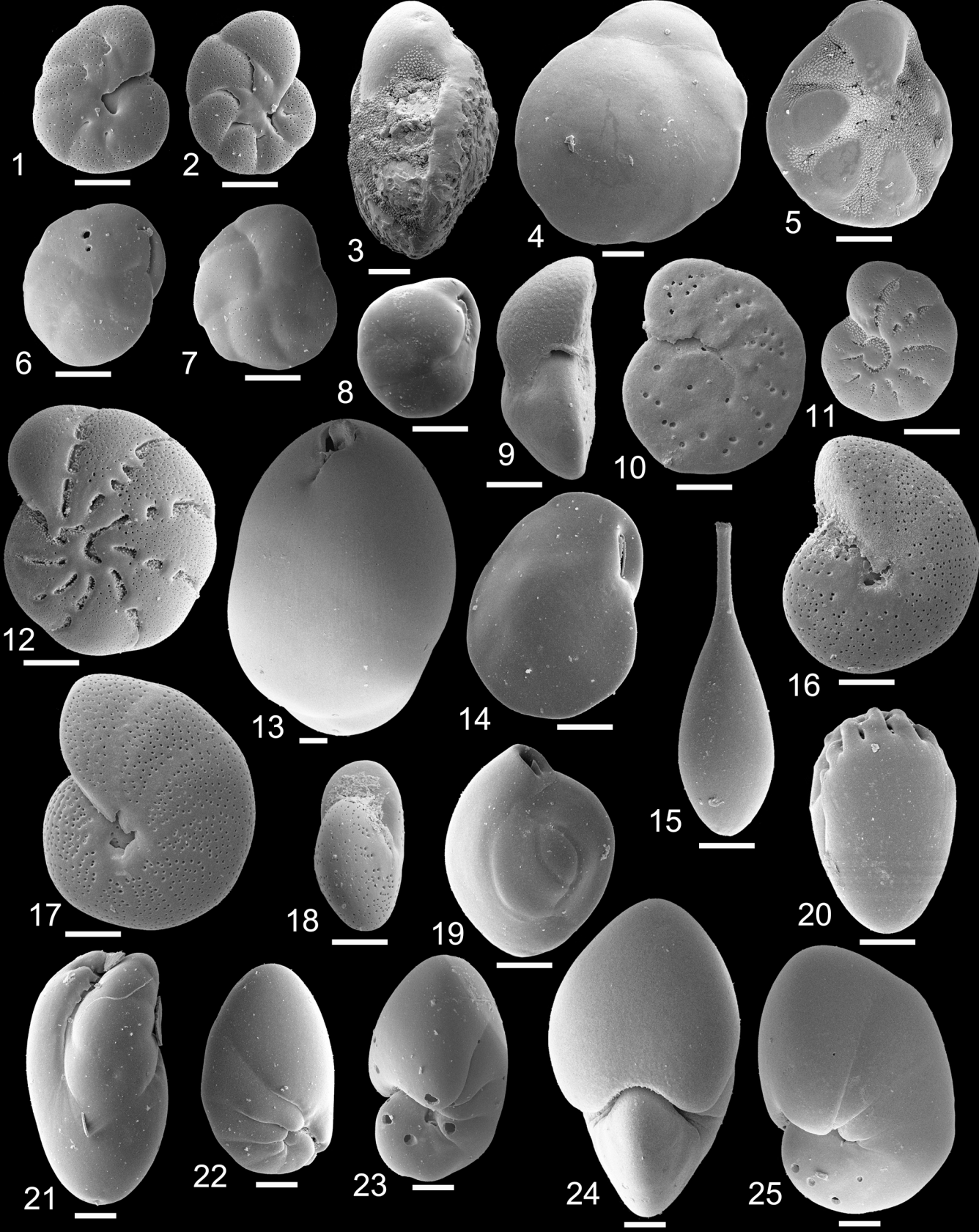


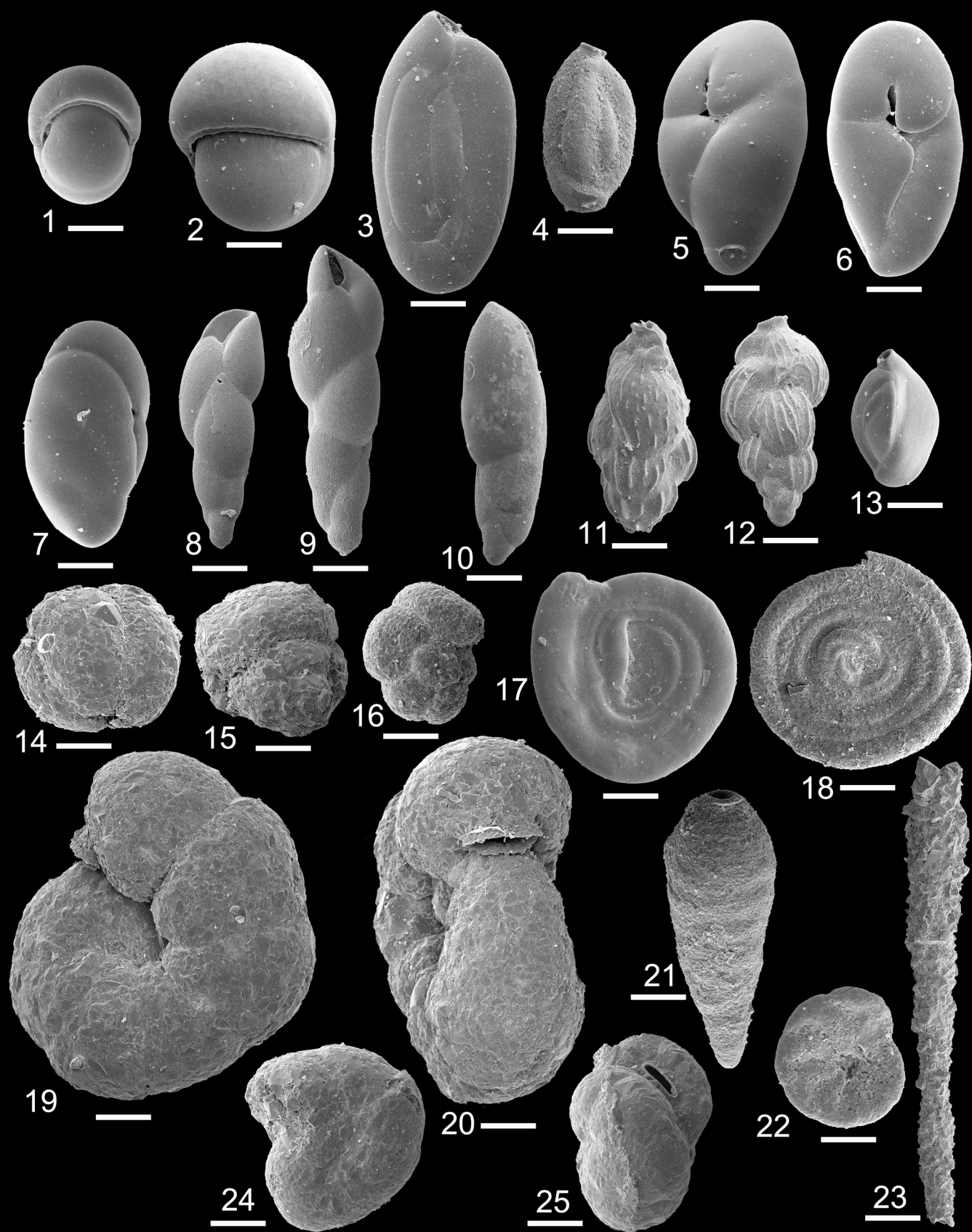
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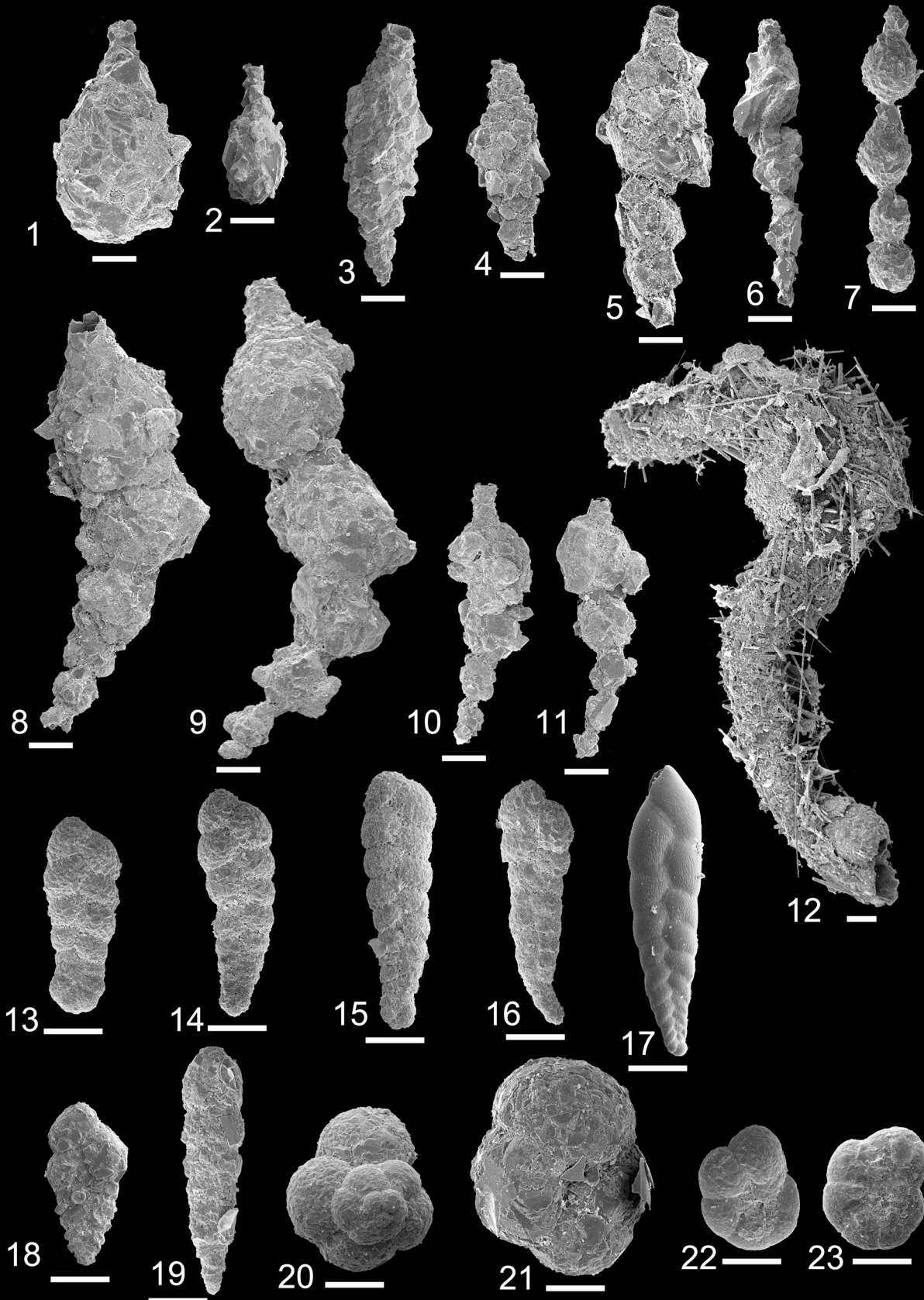


-  Hemipelagic deposits
-  Fine clay with laminations
-  Sandy mud
-  Pyritized burrows
Gravel >5 mm
-  Diamict/Glaciomarine deposits

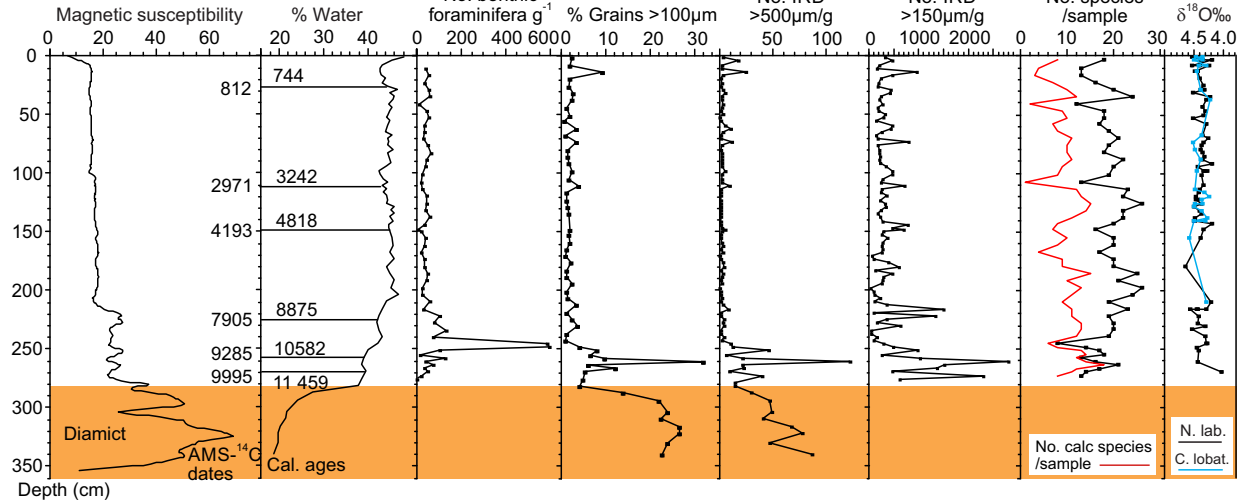




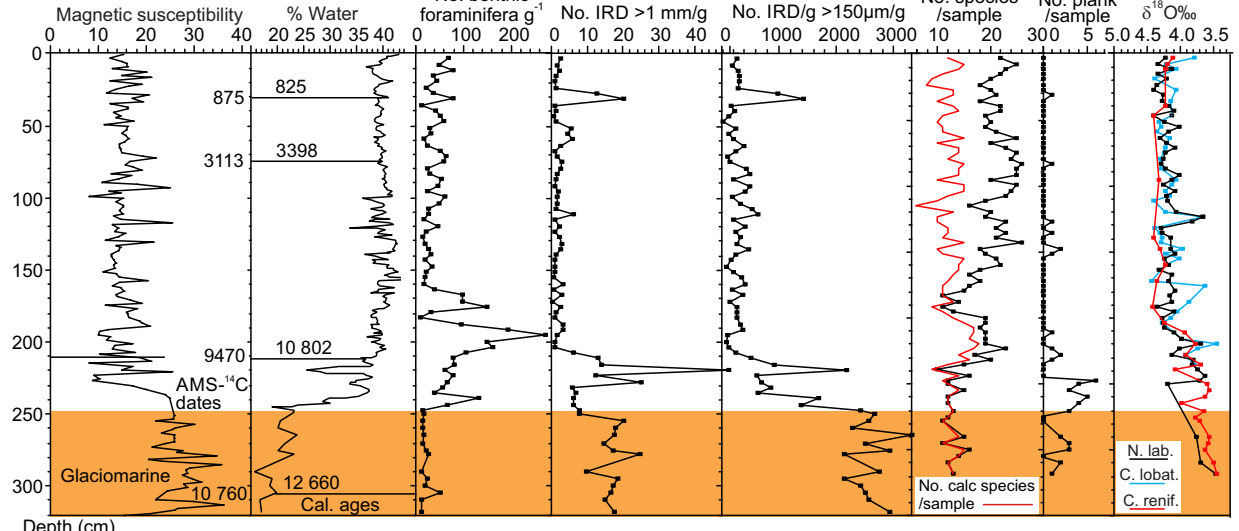




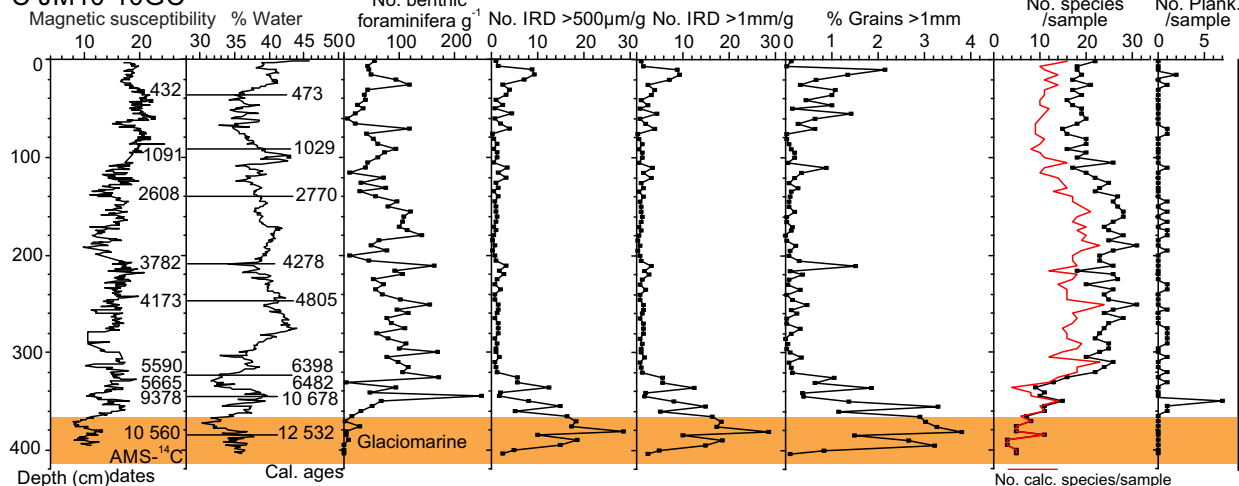
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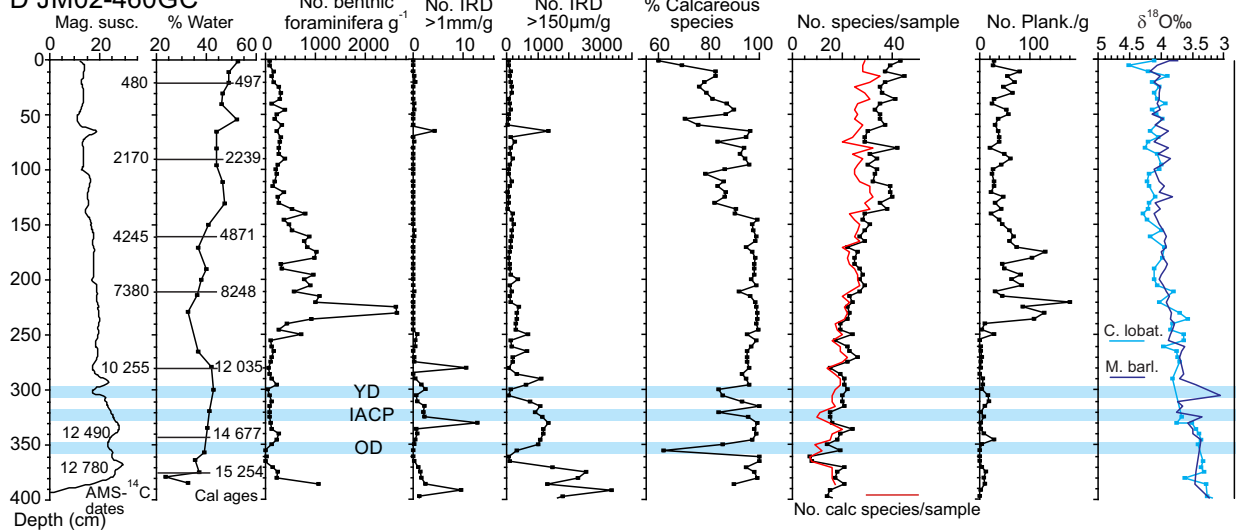
B JM10-12GC



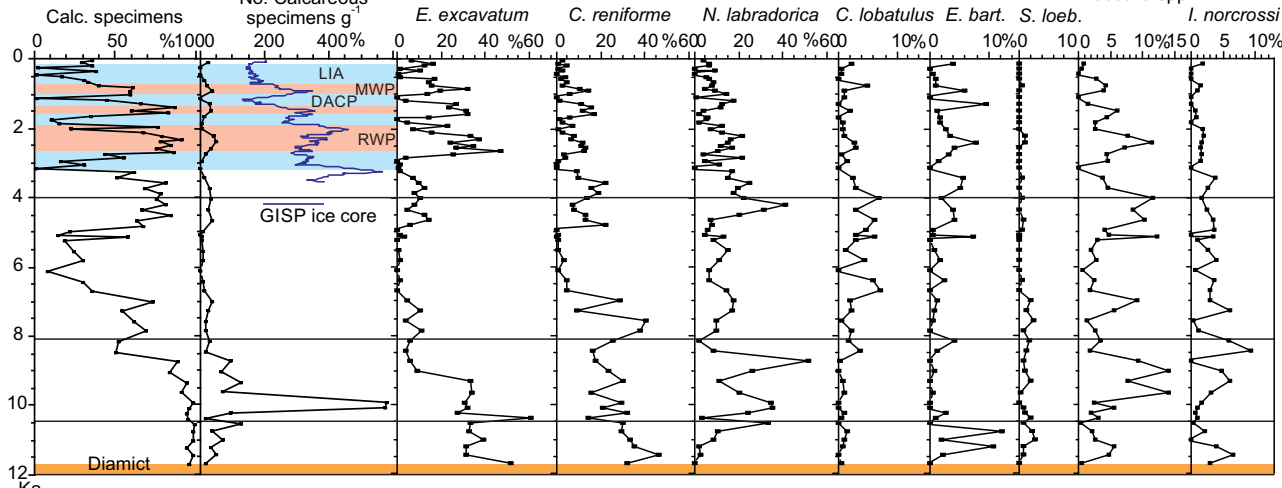
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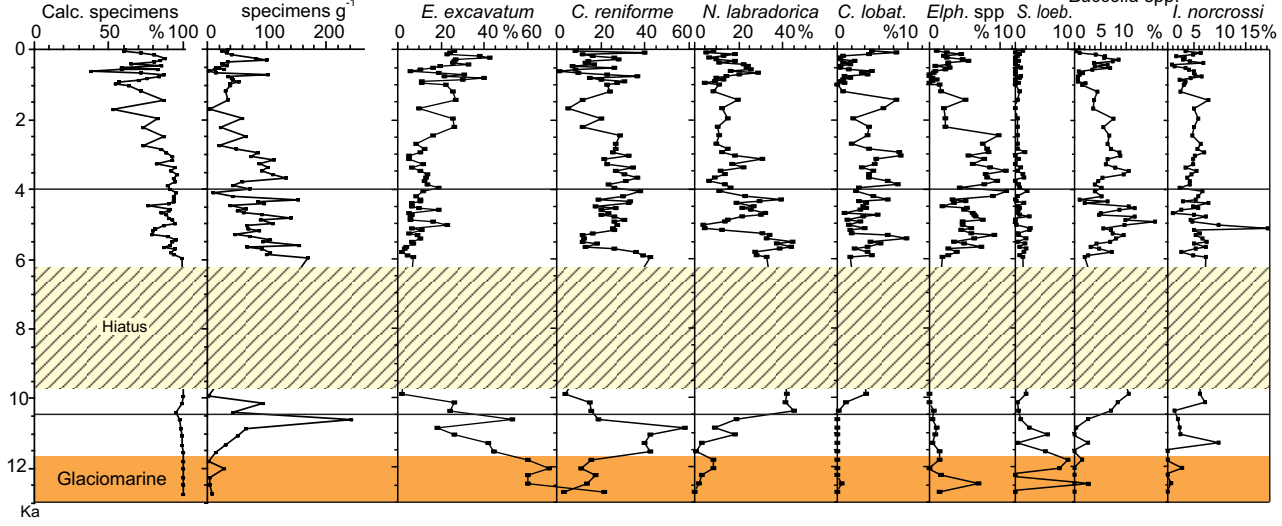
D JM02-460GC



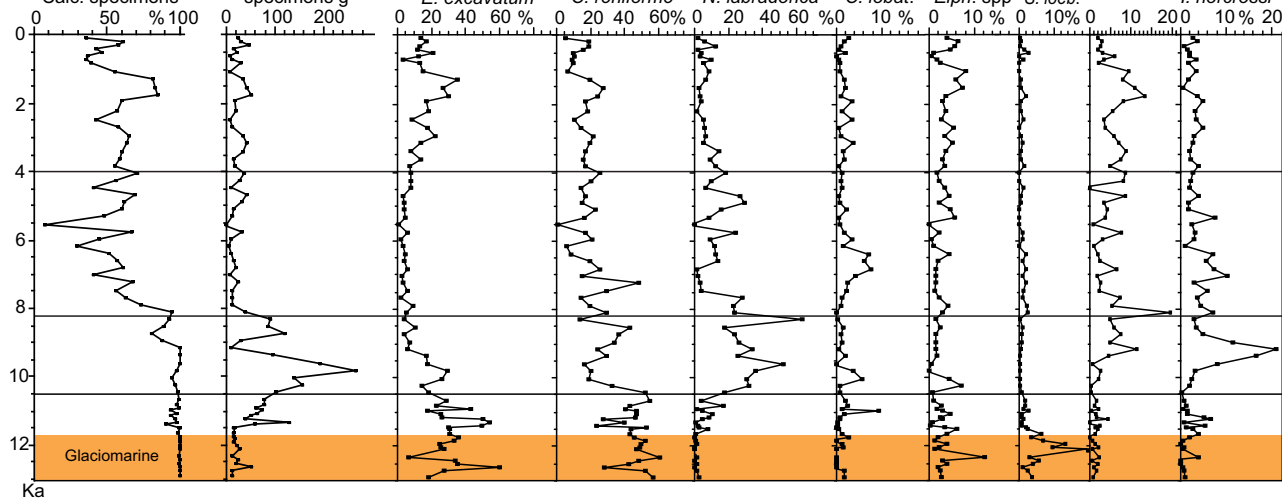
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C JM10-012GC



D JM02-460GC

