RESEARCH ARTICLE

Benthic foraminiferal investigations in Middle to Late Quaternary sections of Kongsfjordhallet, north-west Svalbard

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Abstract

Stratigraphic sites in north-west Svalbard record at least six significant glacial advances in the last 200 Ky, and sediments deposited under locally high relative sea level during intervening interstadials or interglacials contain abundant benthic foraminifera. We present a biostratigraphic record from the Kongsfjordhallet site in the Kongsfjorden area that covers five high relative sea-level events and stretches back to the Middle Pleistocene (>195 Kya). Five foraminiferal assemblages have been identified: (1) *Cassidulina reniforme – Elphidium clavatum* — *Islandiella helenae*; (2) *Cassidulina neoteretis – Cassidulina reniforme*; (3) *Cassidulina reniforme – Cibicides lobatulus – Cassidulina neoteretis*; (4) *Cibicides lobatulus – Cassidulina reniforme – Elphidium clavatum;* and (5) *Cassidulina reniforme – Elphidium clavatum* assemblages. The assemblages suggest a distal glaciomarine environment with variable influence of seasonal sea ice and nutrient availability in the Kongsfjorden region during the five deglaciation events. The foraminiferal data are also compared with foraminiferal records from other sites in Svalbard and the adjacent Arctic Ocean.

Keywords
Benthic foraminifera; glacial–interglacial cycle; palaeoenvironment; Kongsfjorden; Spitsbergen; Arctic

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Abbreviations
Ky(a): thousands of years (ago)
MIS: marine isotope stage
TFN: total foraminiferal number

To access the supplementary material, please visit the article landing page

Introduction

The worldwide significance of environmental modification in the Arctic region during the Cenozoic, such as the build-up and break-down of ice sheets and the flow of accompanying meltwater, has been studied by many researchers. Geological onshore and offshore records reveal climate and sea-level changes during Quaternary events in the Arctic and surrounding areas, including glaciation and deglaciation of Eurasian ice sheets of which the Barents Sea ice sheet is here of particular interest (Hormes et al. 2013; Jakobsson et al. 2014; Landvik et al. 2014; Hughes et al. 2016). The Svalbard archipelago (76°–80°N), situated between the North Atlantic and the Arctic Ocean and at the boundary between major surface water masses, has been the site of many palaeoclimatic and oceanographic studies (Hald et al. 1996; Cottier et al. 2010; Rasmussen et al. 2012). Sedimentary sections in different parts of Svalbard contain marine deposits that represent local high relative sea levels during periods when the global eustatic sea level was considerably lower than today (Mangerud et al. 1998; Waelbroeck et al. 2002). Today, these marine deposits are positioned above the mean sea level as a result of glacioisostatic uplift (Mangerud et al. 1998; Alexanderson et al. 2018). On the basis of relative and absolute age information, correlations between these raised marine deposits have been used to build a framework for the regional glaciation history (Miller 1982; Mangerud et al. 1998; Alexanderson et al. 2018). Key sites for this work are Kapp Ekholm in central Spitsbergen (e.g., Mangerud & Svendsen 1992; Eccleshall et al. 2016), Brøggerhalvøya in the north-west (Miller et al. 1989; Alexanderson et al. 2011), Skilvika (Landvik et al. 1992; Alexanderson & Landvik 2018) and Linnéelva (Lønne & Mangerud 1991) in the south-west, and Kongsøya in the east (Ingólfsson et al. 1995; Mangerud et al. 1998; Fig. 1a). Other notable sites with sedimentary succession containing raised marine deposits include Kongsfjordhallet (Boulton 1979; Houmark-Nielsen & Funder 1999; Alexanderson et al. 2018); Poolepynten (Andersson et al. 1999; Alexanderson et al. 2013); Forlandsundet (Forman 1989) and Nordaustlandet (Kaakinen et al. 2009).

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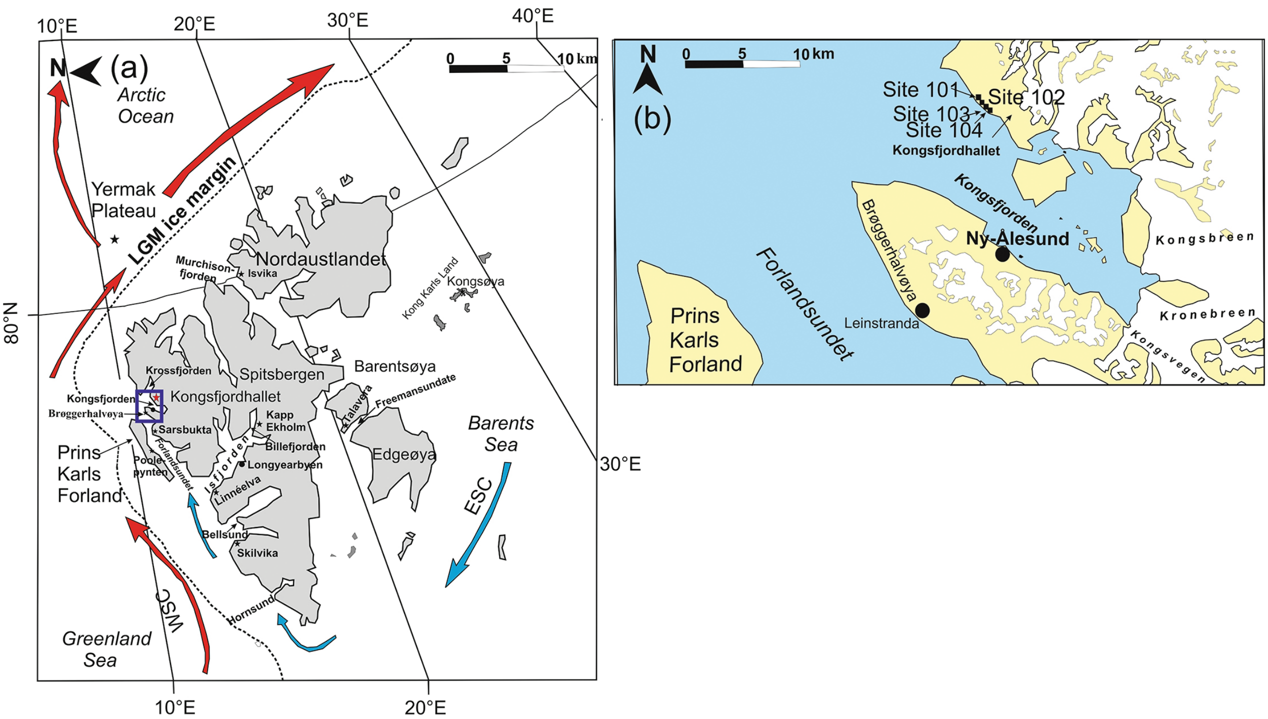

Fig. 1 (a) Map of Svalbard and the West Spitsbergen Current (WCS) and East Spitsbergen Current (ESC), which transports Arctic Water around the coast. The red star indicates the location of this study and the black stars represent other sites mentioned in this article. The dotted line indicates the Last Glacial Maximum (LGM) ice margin, in accordance with Hormes et al. (2013). (b) Close-up view of the study area of Kongsfjorden, showing the locations of the Kongsfjordhallet sites and nearby localities.

In this study, we take a biostratigraphic approach using foraminifera as a proxy to improve the palaeoenvironmental reconstruction of glacial–interglacial environmental changes as recorded in Kongsfjordhallet (Fig. 1). Foraminifera, an important group of microfossils, are unicellular protists that can survive in various marine environments. Studying the small, distinctive, well-preserved and abundant tests of foraminifera is an essential stratigraphic and palaeoecological tool. This biostratigraphic study aims to use benthic foraminifera to refine palaeoenvironmental interpretation in seven lithostratigraphic units from the uppermost ca. 20 m of the 40 m high sedimentary succession at Kongsfjordhallet and to correlate these findings with published glacial–interglacial events based on sedimentological and chronological data (Alexanderson et al. 2018). This article also evaluates to what extent foraminiferal data can aid stratigraphic correlation with similar raised marine deposits elsewhere in Svalbard and with documented MISs and global sea-level changes.

Quaternary glacial–interglacial successions in the Kongsfjorden area

In the Kongsfjorden area, several sites have been shown to contain older Quaternary sedimentary successions (Boulton 1979; Troitsky et al. 1979; Miller 1982; Miller et al. 1989; Houmark-Nielsen & Funder 1999; Alexanderson, Landvik & Ryen 2011; Alexanderson et al. 2018). The sediments are dominated by littoral gravels, glaciomarine muds or diamicton, shallow marine sands and silty tills (e.g., Troitsky 1979; Forman 1999; Houmark-Nielsen & Funder 1999; Alexanderson, Landvik & Ryen 2011). The different units have been correlated to each other and to European stratigraphy mainly on the basis of amino acid ratios (Miller 1982; Miller et al. 1989) and relatively few radiocarbon or luminescence ages (e.g., Troitsky 1979; Houmark-Nielsen & Funder 1999; Alexanderson, Landvik & Ryen 2011). Though some older (Middle and Early Pleistocene) units have been inferred on the basis of high amino acid ratios, palaeomagnetic data or mollusc fauna (Miller 1982; Houmark-Nielsen & Funder 1999), most units have been interpreted to be Late Quaternary in age. For example, at Leinstranda, on Brøggerhalvøya (Fig. 1b), four glacial–interglacial cycles with deposition at high relative sea level around 185 ± 8 Kya, 129 ± 10 Kya, 99 ± 8 Kya and 36 ± 3 Kya were identified (Alexanderson, Landvik, Molodkov et al. 2011; Alexanderson, Landvik & Ryen 2011), in addition to the Last Glacial Maximum during the Late Weichselian documented elsewhere in the area (Lehman & Forman 1992; Landvik et al. 2005; Henriksen et al. 2014).

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At Kongsfjordhallet, Houmark-Nielsen & Funder (1999) identified three primary sediment successions, each interpreted to comprise a glaciation–deglaciation event and ranging in age from the Early to the Late Pleistocene. Alexanderson et al. (2018) resolved additional events—at least five glaciations—in the upper part of the succession at the site. Including other sites in the area, Alexanderson et al. (2018) could also show that at least six glacial advances occurred in the Kongsfjorden area during the last 200 Ky. Four happened during the Late Pleistocene, with at least the Late Weichselian glaciation reaching the shelf break and filling the Kongsfjordrenna Trough with glacial deposits. Two older glacial advances occurred during the Saalian.

Previous studies of foraminiferal palaeofaunas on Svalbard

Previous palaeoclimatic, palaeoenvironmental and palaeoceanographic studies based on foraminifera assemblages in raised marine deposits have been done at different localities in Svalbard. Key studies of Quaternary Arctic foraminifera have been carried out at Sarsbukta (Feyling-Hanssen & Ulleberg 1984), Brøggerhalvøya (Miller et al. 1989), Skilvika and Linnéelva (Lycke et al. 1992), Bellsund (Landvik et al. 1992), Kongsøya (Ingólfsson et al. 1995), Poolepynten, Prins Karls Forland (Bergsten et al. 1998), Nordaustlandet (Kubischta et al. 2010), and Kapp Ekholm (Hovland 2014; Fig. 1a). Foraminifera data from the sites mentioned here have been used to interpret palaeoenvironments during Eemian and Weichselian times; key foraminifera species that have been identified are listed in Table 1.

In addition to these, a diverse range of foraminiferal studies have been carried out on marine sediments from adjacent Arctic areas where the foraminifera assemblages provide information on the region's late glacial to Holocene palaeoceanography and palaeoenvironment (e.g., Polyak & Solheim 1994; Polyak & Mikhailov 1996; Koç et al. 2002; Ślubowska et al. 2005; Ślubowska-Woldengen et al. 2007; Aagaard-Sørensen et al. 2010; Zajączkowski et al. 2010; Rasmussen et al. 2012; Chauhan et al. 2014; Groot et al. 2014).

For the Kongsfjorden area, the most significant palaeoenvironmental study using Late Pleistocene foraminiferal assemblages is the one carried out at Site 15 (Leinstranda) on Brøggerhalvøya (Miller et al. 1989). The study revealed diverse Arctic foraminifera in marine sediments deposited during the Eemian interglacial and Early Weichselian interstadials (as dated by Alexanderson, Landvik & Ryen [2011] and Alexanderson, Landvik, Molodkov et al. [2011]). An investigation of a core in the Kongsfjorden Trough by Skirbekk et al. (2010) focused on Late Weichselian and Holocene palaeoenvironments interpreted from foraminiferal fauna.

For Kongsfjordhallet, a thorough foraminiferal investigation was first carried out by Jørgen Sivertsen (1996). The samples were collected from three profiles—1304, 1305 and 1308 (designations according to Houmark-Nielsen & Funder [1999])—and the profiles were divided into foraminiferal zones. The study comprised diversity, abundance and palaeoenvironment as derived from the foraminifera zones coupled with lithology, glacial history,

Table 1 Records of key foraminifera species reported from sites in Svalbard from the Late Saalian to the Late Weichselian. For the location of sites in Svalbard, see Fig.1a; for sites other than Svalbard, see Seidenkrantz (1995).

Key foraminifera species	Locality / area	Chronology	Reference
Elphidium clavatum, *Cassidulina reniforme*	Sarsbukta	Late Saalian to Early Eemian	Feyling Hanssen & Ulleberg 1984
	Poolepynten	Eemian	Bergsten et al. 1998
	Skilvika	Eemian	Lycke et al. 1992
	Linnéelva	Eemian	Lycke et al. 1992
	Brøggerhalvøya	Eemian	Miller et al. 1989
Cibicides lobatulus	Skilvika	Early Weichselian Interstadial	Landvik et al. 1992
	Brøggerhalvøya	Eemian	Miller et al. 1989
	Eurasian Arctic	The last deglaciation 13 Kya	Hald et al. 1999
Cassidulina neoteretis	North Sea	Upper Pleistocene	Seidenkrantz 1995
	Yermak Plateau	Early Weichselian and Eemian and Last Glacial Maximum	Chauhan et al. 2014
Astrononion gallowayi	Linnéelva, Isfjorden	Eemian	Lycke et al. 1992
	Skilvika	Early Weichselian interstadial	Landvik et al. 1992
	Kongsøya	Pre-Eemian to Eemian age	Ingólfsson et al. 1995
	Sarsbukta	Eemian	Feyling Hanssen & Ulleberg 1984
Nonionella labradorica	Kapp Ekholm	Early Eemian transition	Hovland 2014

chronostratigraphic and palaeomagnetic data. The results show the existence of deposits from three glacial–interglacial periods. The age of the lower glacial–interglacial cycle is interpreted to be at least 780 Ky (MIS 21–22), from findings of the foraminifera species *Cassidulina teretis*; the age is further supported by amino acid dating of molluscs as well as palaeomagnetic dating (Houmark-Nielsen & Funder 1999). The age of the second glacial cycle could not be determined from the foraminiferal assemblages (Sivertsen 1996). Thermoluminescence dating of sediments correlated to the third event indicated an Eemian to Early Weichselian age (Houmark-Nielsen & Funder 1999), which was later supported by optically stimulated luminescence ages (Alexanderson et al. 2018).

This study adds to the unpublished research by Sivertsen (1996) by extending the foraminiferal record further up in the succession. Since the stratigraphy in the Kongsfjordhallet coastal cliffs is somewhat variable laterally (Houmark-Nielsen & Funder 1999; Alexanderson et al. 2018) and samples were not taken at the same sites, a definitive correlation between our units and the foraminiferal zones of Sivertsen's (1996) is not straightforward. However, we consider it probable that our unit 4 corresponds to Sivertsen's zone 1304-H and possibly to zone 1305-E, and that his zones 1305-D and 1304-F-G correspond to one or more of our units -1, 0 and 1.

Physical setting

Geological setting

Kongsfjordhallet (Fig. 1) is a gently sloping plain, 6 km long and 12 km wide, that terminates in steep coastal cliffs at the northern side of the Kongsfjorden fjord in north-western Spitsbergen, Svalbard. The largest portion of the Kongsfjordhallet plain is shielded by Quaternary deposits such as till and raised beach deposits. Garnet–mica schist dominates the bedrock visible at the lower parts of the coastal cliffs, which are as high as 40 m and consist of various sediments ranging from glacial, marine, alluvial, littoral to solifluction deposits (Houmark-Nielsen & Funder 1999; Alexanderson et al. 2018). The oldest sediments are of Early Pleistocene age (Houmark-Nielsen & Funder 1999), whereas the youngest succession is Late Pleistocene (Weichselian) in age (Alexanderson et al. 2018). The dominating deposits are glaciomarine diamictons and littoral gravels. In this study, the uppermost ca. 20 m of the deposits in the central 800 m of the coastal section of Kongsfjordhallet have been targeted (Fig. 2). This part of the succession contains sediment accumulation resulting from at least five glaciation–deglaciation cycles (Alexanderson et al. 2018).

Oceanographic setting

Svalbard is encircled by the Arctic Ocean to the north, the Barents Sea to the south and Fram Strait to the west. North of Scandinavia, the Norwegian Atlantic Current splits into two branches: one as the North Cape Current and another as the West Spitsbergen Current. The North Cape Current flows east to the Barents Sea, while the West Spitsbergen Current (Fig. 1) carries warm and saline Atlantic Water far north along the slope of western Svalbard. On Spitsbergen, the main island of the archipelago, west-facing fjords are adjacent to the West Spitsbergen Current and are therefore more influenced by Atlantic Water compared with Svalbard's other fjords (Cottier et al. 2010). In the southern part of Svalbard, the warm Atlantic Water meets the cold and less saline Arctic water; this Coastal Current carries Arctic surface water from the eastern Arctic shelf areas further north along western Svalbard (Skirbekk et al. 2010).

The Kongsfjorden region has two notable features: (1) tidewater glaciers, e.g., Kongsbreen and Kongsvegen in the eastern, inner part of the fjord, that generate freshwater and suspended sediment and (2) a connection to the North Atlantic Ocean through the Kongsfjordrenna Trough in the west, creating a marine environment at the outer part of the fjord system. The area is influenced by cold and warm oceanic currents (Fig. 1a). Cold and fresh Arctic Water exists on the shelf. The warm West Spitsbergen Current transports a large amount of heat and salt along the shelf break to Kongsfjorden by accommodating warm and saline Atlantic Water in the upper 600 m of the water mass. The fjord has a deep-water connection to the adjacent shelf at ca. 350 m, permitting the seasonal inflow of shelf and oceanic water masses that shape the fjord's hydrography and biological characteristics (Svendsen et al. 2002; Howe et al. 2003).

Material and methods

Fieldwork at Kongsfjordhallet was carried out at four sites, designated 101 (N79°2′00″, E11°52′0″), 102 (N 79°1′14″, E11°52′ 24″), 103 (N79°1′30″, E11°54′0″) and 104 (N 79°01′32″, E11°53′53″) in the summer months of 2014, 2016 and 2018. Numeric designations of sites and names of stratigraphic units are in accordance with Alexanderson et al. (2018). The sections were excavated, described and photographed before sediment samples were collected for microfossil analysis. A total of 20 sediment samples were collected from Kongsfjordhallet sites 101, 102, 103 and 104 in beds correlated to units -1, 1, 3, 4, 7 and 8 (Table 2). The sediment samples were washed and sieved at 63 µm to remove silt and clay particles, retaining the >63 µm residue containing the microfossils. Washed residues were then oven-dried at

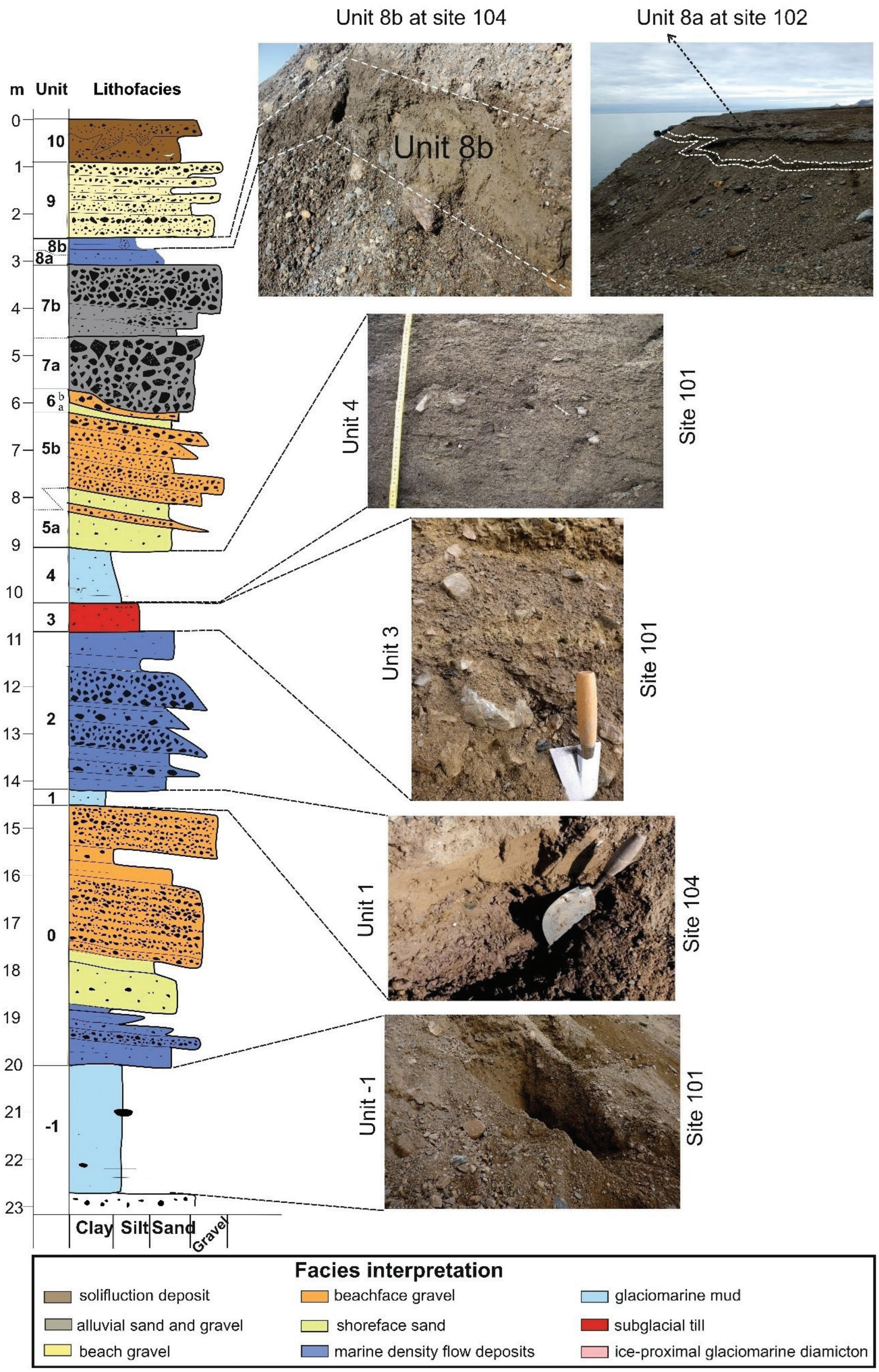

Fig. 2 Composite stratigraphy of the upper part of the Kongsfjordhallet sequence. Units 1, 3, 4, 8a and 8b are according to Alexanderson et al. (2018), while units 0 and -1 are described herein.

50°C for 2 h and weighed. The dried residue of each sample was split using a micro-splitter. The >63 µm sediment fraction of each sediment sample of 1 g was sprinkled evenly over a micropalaeontological tray and analysed under a stereo zoom microscope (Nikon SMZ 1000). Tests of benthic foraminifera were picked up with a thin

Table 2 Sample information including site and unit numbers and assigned ages (based on luminescence ages from Alexanderson et al. [2018]).

Serial no.	Sample id.	Site	Unit	Lithology	Approximate ages (Ky)
1	Kong west top	104	8b top	Marine sand and silts	17 ± 0.6
2	Kong west left	104	8b mid	Marine sand and silts	17 ± 0.6
3	Kong west bottom	104	8b base	Marine sand and silts	17 ± 0.6
4	unit 8a top	102	8a top	Marine sand and silts	60 ± 4
5	unit 8a mid	102	8a mid	Marine sand and silts	60 ± 4
6	unit 8a base	102	8a base	Marine sand and silts	60 ± 4
7	unit 7 top	103	7 top	Alluvial sand and gravel	85 ± 2
8	unit 7 mid	103	7 mid	Alluvial sand and gravel	85 ± 2
9	unit 7 base	103	7 base	Alluvial sand and gravel	85 ± 2
10	KFH14-12	101	4 top	Glaciomarine mud	132 ± 7
11	KFH14-01	101	4 mid	Glaciomarine mud	132 ± 7
12	KFH14-11	101	4 low	Glaciomarine mud	132 ± 7
13	KFH14-10	101	3 up	Subglacial till	132 ± 7
14	KFH14-09	101	3 low	Subglacial till	132 ± 7
15	Kong top	104	1 top	Glaciomarine mud	195 ± 10
16	Kong middle	104	1 mid	Glaciomarine mud	195 ± 10
17	Kong base	104	1 base	Glaciomarine mud	195 ± 10
18	KFH14-06	101	-1 top	Glaciomarine mud	>195
19	KFH14-05	101	-1 mid	Glaciomarine mud	>195
20	KFH14-04	101	-1 base	Glaciomarine mud	>195

damp brush and placed on micropalaeontological slides. The slides were covered with glass covers and were kept in the repository unit in the Micropalaeontology Laboratory, Department of Geological Sciences, Jadavpur University, Kolkata, India. The tests of benthic foraminifera were identified to species level and the best-preserved foraminifera tests were selected and photographed using a scanning electron microscope (Zeiss EVO 18).

The statistical analyses undertaken include TFN and Fisher's alpha diversity index. Species richness has been determined from the number of foraminifera species present in the sediment.

Sedimentology and stratigraphy

Most of our samples were taken from units described in detail by Alexanderson et al. (2018), and the reader is referred to that article for sedimentological information. However, this study reports two new lithological units at Kongsfjordhallet compared with Alexanderson et al. (2018). These new units are stratigraphically lower (older) than their unit 1 and are accordingly designated Units 0 and -1 (Fig. 2). Both units were documented at site 101 and are described and interpreted in the next section.

Description

Unit -1 is 2.7 m thick and consists of massive clayey silt with occasional scattered clasts (Fig. 2). Clasts become scarcer towards the top. A few shell fragments and thin sandy laminae are found in the lower part. The lower boundary to the underlying sandy gravel is sharp.

Unit 0 is ca. 5.5 m thick and dominated by 0.5–1.5 m thick, slightly dipping beds of massive or weakly stratified clast-supported gravels and massive sandy gravels (Fig. 2). Minor lithofacies include massive, silty diamicton and massive silty sand. One bed of ripple-laminated sand was also observed. This unit was not sampled for foraminifera. The lower boundary to unit -1 is sharp and erosive.

Interpretation

The clayey silt of unit -1 is interpreted as a glaciomarine mud with iceberg-rafted dropstones. Fewer dropstones towards the top suggest increased distance to glaciers or more irregular tidewater glacier margins. The stratified gravelly unit 0 is interpreted to have been deposited by a combination of marine density flows and littoral processes. Its heterogeneous nature suggests a variety of depositional processes.

Results

Twenty samples were analysed (Table 2). Two samples from unit 3 and three samples from unit 7, interpreted as subglacial till and terrestrial alluvium, respectively (Alexanderson et al. 2018), contained reworked foraminifera (Supplementary Table S1). These samples are not included in the palaeoenvironmental analysis.

Foraminifera were found in abundance in unit 1 and unit 4. The lowest quantity was in unit 8. The highest TFN is 1746 in 1 g dry sediment at the base of unit 1 (sample "Kong Base"). The occurrence and frequency of dominant foraminifera species at Kongsfjordhallet vary from one unit to another and from bottom to top in each unit. The foraminifera species dominant in all units as a whole are *Cassidulina reniforme, Cassidulina neoteretis, Elphidium clavatum, Cibicides lobatulus, Islandiella helenae, Haynesina orbiculare* and *Nonionella labradorica*. Accessory species are *Astrononion gallowayi* and *Buccella frigida*, followed by *Cribroelphidium williamsoni, Elphidium subarcticum, Elphidium albiumbilicatum, Globocassidulina* sp., *Islandiella norcrossi, Nonionella auricula, Quinqueloculina* sp., *Stainforthia loeblichi, Melonis barleeanus, Guttulina* sp., *Glandulina* sp., *Fissurina* sp., *Oolina* sp. and *Trifarina fluens.* (See Supplementary Table S2 for a full species list and Supplementary Figs. S1 and S2 for representative photographs.)

In total, 23 species have been identified in this study. The lowest species richness occurs in unit -1 (four species) and the maximum in unit 1 (15 species). There is an upwards decrease in number of species from 14 in unit 4 to 10 in Subunit 8a, and eight species in subunit 8b.

The occurrence (percentage) of benthic foraminifera in each unit is summarized here and displayed in Figs. 3–7. For actual numbers and other details of each sample see Supplementary Tables S3 and S4.

Table 3 Summary of the five foraminiferal assemblages from Kongsfjordhallet and their palaeoenvironmental interpretation. The inferred chronology is according to Alexanderson et al. (2018).

Foraminifera assemblages	Environmental interpretations	Chronology
Cassidulina reniforme – Elphidium clavatum	Glacier distal, stable, saline, glaciomarine	Late Weichselian 17 ± 0.6 Kya MIS 2
Cibicides lobatulus – Cassidulina reniforme – Elphidium clavatum	Glacier distal, higher energy, an inflow of marine waters	Middle Weichselian 60 ± 4 Kya MIS 4
Cassidulina reniforme – Cibicides lobatulus – Cassidulina neoteretis	Glacier distal, inner shelf higher energy, productivity, interglacial event	Eemian 132 ± 7 Kya MIS 5e
Cassidulina neoteretis – Cassidulina reniforme	Glacier distal, inner shelf, stable, lower energy, cold, seasonal sea ice	Saalian 195 ± 10 Kya MIS 6
Cassidulina reniforme – Elphidium clavatum – Islandiella helenae	Glacier distal, inner shelf, stable, lower energy, cold	Saalian Older than ca.195 Kya MIS 7

Foraminifera in marine sections of the Kongsfjordhallet succession

Five characteristic foraminifera assemblages were identified at Kongsfjordhallet, each corresponding to a lithostratigraphic unit or subunit (Table 3, Fig. 8). The assemblages are described next.

Unit -1 features a *Cassidulina reniforme – Elphidium clavatum – Islandiella helenae* assemblage (Fig 3). The TFNs from the base, middle and top of unit -1 are 17, 26 and 18, respectively. The assemblage is dominated by *Cassidulina reniforme* (ca. 60%) and *Elphidium clavatum* (ca. 35%), followed by subordinate species *Islandiella helenae* and *Haynesina orbiculare*, constituting 20 and 6%, respectively. The assemblage has a low TFN (<100) and contains only four foraminifera species. The Fisher's alpha index cannot be determined on account of the low TFN. Unit -1 has the lowest TFN of the units investigated here.

Unit 1 has a *Cassidulina neoteretis – Cassidulina reniforme* assemblage (Fig. 4). The highest occurrence of *Cassidulina neoteretis* (60%) occurs at the top, while it is 43% in the middle and lower parts. The second most common species is *Cassidulina reniforme* (40%). These two species constitute the bulk of the foraminiferal fauna. Accessory species include *Elphidium clavatum, Elphidium albiumbilicatum, Islandiella helenae* and *Nonionella labradorica* (Fig. 4). The foraminifera content in unit 1 is high at its base (TFN = 1746) and gradually decreases towards the middle (TFN = 614) and top (TFN = 325) and comprises 15 foraminifera species. The high diversity of this assemblage zone is revealed by Fisher's alpha index varying between 2 and 3.

Unit 4 features a *Cassidulina reniforme – Cibicides lobatulus – Cassidulina neoteretis* assemblage (Fig. 5). Foraminifera are abundant throughout the unit, with a TFN of 983 at the base, 828 in the middle and 763 at the top. It is characterized by pronounced proportions of *Cassidulina reniforme* (30%) and *Cibicides lobatulus* (33%), followed by *Cassidulina neoteretis* (19%). Accessory species are *Elphidium clavatum, Islandiella helenae, Buccella frigida, Astrononion gallowayi, Haynesina orbiculare, Elphidium subarcticum* and *M. barleeanus* (Fig. 5). The unit shows a high abundance of foraminifera specimens and 14 species, with a Fisher's alpha index between 1 and 2, i.e., the assemblage is low in diversity.

Subunit 8a has a *Cibicides lobatulus – Cassidulina reniforme – Elphidium clavatum* assemblage (Fig 6). It shows a moderate distribution of foraminifera with a TFN of 20 at the base, 25 in the middle and 26 in the top. Ten foraminifera species have been identified in subunit 8a, with a predominance of *Cassidulina reniforme, Cibicides lobatulus* and *Elphidium*

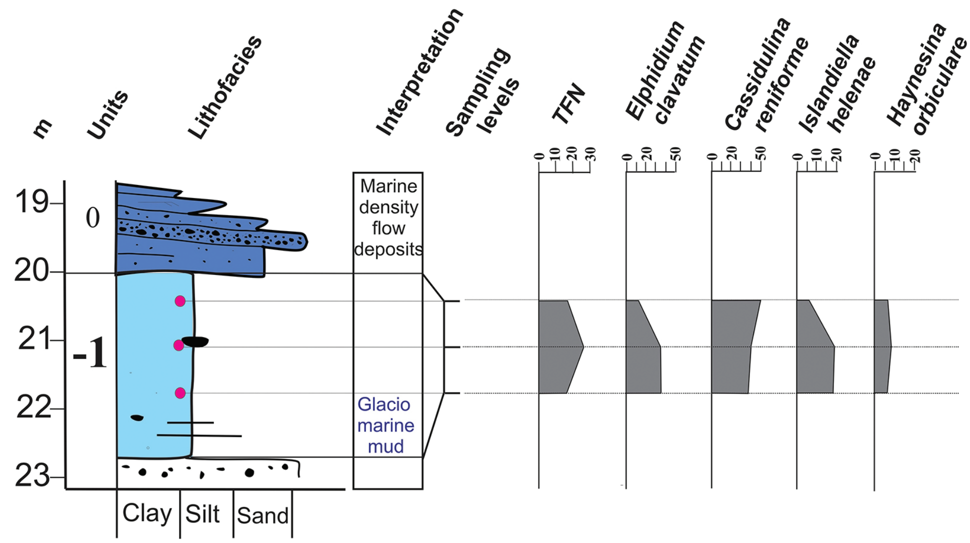

Fig. 3 Benthic foraminifera abundance (%) and TFN in unit -1. The unit is characterized by a *Cassidulina reniforme* – *Elphidium clavatum* – *Islandiella helenae* assemblage.

Table 4 Locations where foraminifera assemblages similar to those of Saalian age from Kongsfjordhallet have been documented.

Kongsfjordhallet event	Kongsfjordhallet foraminifera assemblage	Area	Location, unit, core or zone	Reference	Reported age
Event II Saalian (195 ± 10 Kya)	*Cassidulina neoteretis* — *Cassidulina reniforme* assemblage	Norwegian sea (*C. neoteretis*), northern North Atlantic	ODP core 644A	Seidenkrantz 1995	Slightly above the palaeo-magnetic Brunhes/Matuyama boundary Middle Pleistocene
		Southern Yermak Plateau	Marine core JM10-02GC	Chauhan et al. 2014	Saalian–Eemian boundary (MIS 6/5e) Early–Middle Weichselian
		Northern Barents Sea (*C. reniforme* and *C. teretis*)	Franz Josef Land	Polyak & Solheim 1994	Last deglaciation, ca. 13 Kya BP
Event I Pre-Saalian >195 Kya	*Cassidulina reniforme* – *Elphidium clavatum* – *Islandiella helenae* assemblage	Brøggerhalvøya Sarsbukta	zone F15 II zone QB	Miller et al. 1989 Feyling-Hanssen & Ulleberg 1984	Eemian and Early Weichselian
		Poolepynten	unit A	Bergsten et al. 1998	
		Skilvika	zone FS-II	Lycke et al. 1992	
		Kongsøya	unit D	Ingólfsson et al. 1995	

clavatum. Subordinate species include *Islandiella helenae, Haynesina orbiculare, Nonionella labradorica, Astrononion gallowayi* and *Buccella frigida*.

The *Cassidulina reniforme* – *Elphidium clavatum* assemblage that characterizes subunit 8b includes a minor abundance of *Islandiella helenae, Haynesina orbiculare* and *Cibicides lobatulus*. The assemblage contains eight foraminifera species and exhibits a fair amount of total foraminifera specimens at its top (TFN = 121) compared with its base (TFN = 80) and middle part (TFN = 42).

The Fisher's alpha index was not determined for subunits 8a and 8b because of the low TFN.

Discussion

Event I (Saalian age?)

The lithology and foraminifera populations from unit -1 at Kongsfjordhallet represent a glacier distal stable marine environment that is older than 195 Ky, but likely not very much older, as discussed next, and is tentatively correlated to the Saalian complex. The *Cassidulina reniforme* – *Elphidium clavatum* – *Islandiella helenae* assemblage (Fig. 3) contains the most common Arctic species, *Cassidulina reniforme* and *Elphidium clavatum*, which are found both on modern Arctic shelves and in Quaternary records that represent areas with sediment-rich waters in front of calving glaciers (Table 4), such as in Svalbard (Hald et al. 1994; Hansen & Knudsen 1995). *Cassidulina reniforme* is a typical calcareous foraminifera species abundant in Arctic shelf areas and widespread in glaciated fjords down to bathyal depths (Polyak et al. 2002). Its affinity to cold and saline waters is indicated by its recent distribution in the outer Kongsfjorden area, which is characterized by cold local water generated from strong cooling of Atlantic Water (Jernas et al. 2018). The *Cassidulina reniforme*-dominated assemblage of unit -1 typically characterizes the inner parts of fjords with less saline local intermediate waters and is often found in modern glaciomarine environments with cold water (Hald & Korsun 1997). In this study, the dominance of *Cassidulina reniforme* over *Elphidium clavatum* indicates conditions at depths not influenced by meltwater. *Islandiella helenae* is found in normal marine salinity and cold marine environment on the outer shelf and continental slope. The species is associated with high productivity in the seasonal marginal sea-ice zone (Cage et al. 2021). The higher frequency of *Islandiella helenae* indicates the presence of oceanic fronts, marginal sea-ice zones and plankton blooms. *Haynesina orbiculare* reflects relatively stable marine salinities (Polyak et al. 2002).

This environment in unit -1 belongs to succession B at Kongsfjordhallet, as described by Houmark-Nielsen & Funder (1999). The unit is older than 195 ± 10 Ky, the age of the overlying units 1 and 2 (Alexanderson et al. 2018). It represents at least one older glaciation and was deposited under high relative sea level during the deglaciation of an ice sheet preceding that recorded by units 1 and 2. If unit -1 represents one event (i.e., one glaciation–deglaciation cycle; see Alexanderson et al. [2018]), this would likely place it in MIS 7. An even older age cannot be ruled out, but, given the appearance of the sediment and the inferred Early Quaternary age of the underlying sediments (Houmark-Nielsen & Funder 1999), it is unlikely to be very much older.

The foraminifera assemblage reveals a low abundance of foraminifera specimens, and this is the least diverse of the faunas described here with both few species (four) and few specimens (17–28; Fig. 3; Supplementary Table S3). The low species count may be due to the limited yearly sea-ice cover and meltwater influx in the region at the time. The presence of ice-rafted debris in the unit implies drifting ice originating from glaciers or ice caps, i.e., a calving glacier front near the study site. No advection of Atlantic Water occurred, as envisaged from the total absence of Atlantic Water-influenced species. However, sea-ice marginal conditions with phytodetritus might have existed (Cage et al. 2021).

The dominant species are the same as those found by Sivertsen (1996) in zones 1305-DI and DII, but he found more species (9–27) and a higher diversity. Zone 1305-DI differs by the presence of *Astrononion gallowayi* and *Cibicides lobatulus* and zone 1305-DII by the presence of *Islandiella inflata*. In addition, zone 1305-D (I and II) contains *Cassidulina teretis* (1–5%) and *Elphidium albiumbilicatum*. However, according to Sivertsen (1996), these two zones cover a wide time range.

Since no absolute ages for unit -1 are currently available, the assemblage cannot be compared or correlated with those from coeval sites in Svalbard. However, it can be inferred that at least a seasonal sea-ice cover and stable salinity conditions existed during that time, and the environment was not that of a strong interglacial. Detailed investigations of Middle Pleistocene strata from other sites in Svalbard would be interesting, but few such sites are known, though there is potential, e.g., across the fjord on Brøggerhalvøya (Miller 1982).

Event II (Saalian age)

Event II at Kongsfjordhallet is dated to 195 ± 10 Kya and correlated to the Saalian (late MIS 7 or Early MIS 6 [Alexanderson et al. 2018]). It can be depicted as glacier distal, inner shelf, stable cold glaciomarine environment with periodic Atlantic Water inflow, as interpreted from the lithology and the *Cassidulina neoteretis* – *Cassidulina reniforme* foraminifera assemblage in unit 1 (Fig. 4). *Cassidulina neoteretis* is an infaunal species that typically lives in fine sediments, such as terrigenous mud, in areas characterized by cool, modified Atlantic Water with stable salinity and temperature. In the Arctic, this species is observed in abundance mainly where fresh polar water overlies chilled Atlantic Water, and where fresh phytodetritus is available (Cage et al. 2021). *Cassidulina reniforme* is an epifaunal to shallow infaunal Arctic species favouring cooled, salty Atlantic Water. It is widespread in Quaternary shelf records from Svalbard; abundance of this species along with high diversity has been considered an indicator of glacier front retreat (Miller et al. 1989). That there were tidewater glaciers in the vicinity is supported by the ice-rafted debris in unit 1 (Alexanderson et al. 2018).

Both *Cassidulina reniforme* and *Cassidulina neoteretis* are cold water indicator species (Saher et al. 2009) and reveal that deposition of unit 1 took place in a cold glaciomarine environment. *Islandiella helenae* is a shallow, sandy, infaunal Arctic Water indicator species that thrive in areas of high seasonal productivity (Polyak & Mikhailov 1996). It generally prefers areas where summer sea-ice edge-productivity generates significant amounts of organic nutrients. Therefore, its presence indicates that sea-ice marginal conditions existed during that period. *Nonionella*

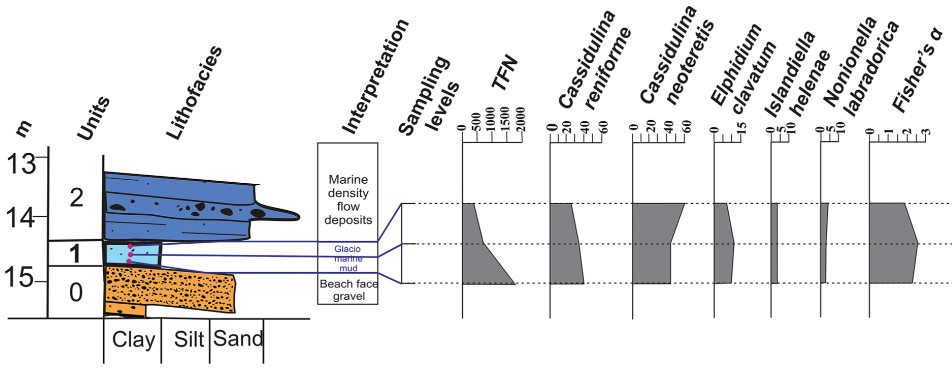

Fig. 4 Benthic foraminifera abundance (%), TFN and diversity indices in unit 1. The foraminifera make up a *Cassidulina neoteretis – Cassidulina reniforme* assemblage.

labradorica flourishes in Arctic fjords and exhibits Atlantic Water influence in an open ocean environment close to the polar front.

A cool Atlantic Water mass at the study site during the Saalian event is assumed from the presence of *Cassidulina neoteretis*. *Cassidulina neoteretis* has been found to be common during most of the cold but ice-free phases of the last deglaciation on the Norwegian continental shelves (Feyling-Hanssen 1990; Seidenkrantz 1995). In addition, at least seasonally, ice-free conditions and high productivity might have existed, as indicated by the presence of *Cassidulina neoteretis*, *Islandiella helenae* and *Nonionella labradorica*.

It can be inferred that the deposition of unit 1 occurred during a cold, seasonally ice-free phase, with a substantial influence of Atlantic Water, high diversity and the presence of North Atlantic-influenced foraminiferal faunas. This unit contains the samples with the highest TFN (1746) and the highest Fisher's alpha index (3) of all samples (Supplementary Table S3). Abundant mollusc shell fragments in unit 1 supports the interpretation of a productive glacial marine environment. The high relative sea level during this period (evidenced by the present elevation of the sediments) indicates a significant ice load preceding sediment deposition (Alexanderson et al. 2018).

Sivertsen's (1996) foraminiferal zone 1305-D could be from the same time period as unit 1, but the correlation is uncertain, and the foraminiferal assemblages are only partly similar. If they do not represent the same time, the foraminiferal record from our unit 1 at Kongsfjordhallet could be uniquely the only foraminiferal fauna of Saalian age yet documented in Svalbard. The likely coeval deposits on Kongsøya (unit B [Ingólfsson et al. 1995]) were examined for foraminifera but yielded none or only few worn specimens that could not be identified. Chronologically, Kongsfjordhallet unit 1 is comparable with event 1 of Leinstranda (Alexanderson, Landvik & Ryen 2011) and episode D of north-west Brøggerhalvøya (Miller et al. 1989), but to our knowledge the foraminiferal content of those deposits has not been studied.

Event III (Eemian age)

The Eemian or the last interglacial at Kongsfjordhallet, dated to 132 ± 7 Kya (Alexanderson et al. 2018) showed a glacier-distal, inner shelf, high-energy, productive interglacial marine environment according to the lithology and foraminifera populations of unit 4. The foraminifera make up a *Cassidulina reniforme – Cibicides lobatulus – Cassidulina neoteretis* assemblage. *Cibicides lobatulus* is an attached, epifaunal, glacier-distal living species abundant in coarse sediments on thresholds or in outer parts of fjords and is indicative of a high-energy bottom water environment (Hald & Korsun 1997). *Cassidulina reniforme*, abundant in the upper part of unit 4, commonly prefers a domain in some distance to glaciers. The dominance of *Cassidulina reniforme* reflects increased food flux and productivity and a stable glacier distal environment (Korsun & Hald 2000). *Cassidulina neoteretis* is a shallow infaunal species associated with the northern North Atlantic (Seidenkrantz 1995) and thrives in areas of cool Atlantic Water and fresh phytodetritus (Husum et al. 2015). Therefore, the presence of *Cassidulina reniforme*, *Cibicides lobatulus* and *Cassidulina neoteretis* overall reflects the deposition of unit 4 in a productive marine environment. Interaction between Arctic and Atlantic waters at a polar front could have helped to increase foraminifera species, such as *Buccella frigida* and *N. labradorica*, which depend on algal blooms at the sea-ice margin. The abundance of *Cibicides lobatulus* and *Astrononion gallowayi* found in coarse sediment areas indicates strong bottom currents. The high diversity and abundance of foraminifera was therefore likely caused by the availability of food, close to the polar front and the sea-ice edge.

Compared with Sivertsen's (1996) foraminiferal zones that may correlate to unit 4, we find the closest similarity with his zone 1305-E, which is dominated by *Elphidium clavatum* and *Cassidulina reniforme*, with a significant proportion of *Cibicides lobatulus*. Unit 4 at Kongsfjordhallet may chronologically also be correlated to episode C on nearby north-west Brøggerhalvøya (Miller et al. 1989), as is discussed further , as well as with several other sites on Svalbard that have been dated to the last interglacial: Poolepynten on Prins Karls Forland (units A1–A2 [Bergsten et al. 1998]), Kapp Ekholm (formation B [Mangerud et al. 1998]), and Skilvika (formations 3 and 4 [Lycke et al. 1992; Alexanderson & Landvik 2018]) of Svalbard, possibly also Kongsøya (unit D [Ingólfsson et al. 1995]) and Sarsbukta (zones QA and QB [Feyling-Hanssen & Ulleberg 1984]). However, the foraminiferal assemblage at Kongsfjordhallet (*Cassidulina neoteretis – Cassidulina reniforme)* differs from most of the assemblages at these other sites by the absence of *Elphidium clavatum* and *Astrononion gallowayi*. An exception is formation B at Kapp Ekholm with a *Cassidulina reniforme*-dominated assemblage, along with the thermophilous mollusc *Mytilus edulis*, which signifies the inflow of warm Atlantic Water (Mangerud et al. 1998; Hovland 2014).

The species *Cassidulina neoteretis*, one of the dominant species in the unit 4 foraminifera assemblage, has been reported from Eemian deposits on the Yermak Plateau (Chauhan et al. 2014). A relatively high abundance of *Cassidulina reniforme* and *Cassidulina neoteretis*, similar to our assemblage, has been recorded at the northern and western Svalbard continental shelf during the Bølling Allerød interstadial (Ślubowska-Woldengen et al. 2007), when an increased inflow of Atlantic Water took place.

Thus, it can be inferred that a glacier-distal productive marine environment with the influence of substantial bottom currents existed at Kongsfjordhallet during the early Eemian period.

Event IV (Middle Weichselian age)

At 60 ± 4 Kya, during the Middle Weichselian, there was a stable, distal glaciomarine, higher energy environment in Kongsfjordhallet, as evidenced by the *Cibicides lobatulus – Cassidulina reniforme – Elphidium clavatum* foraminifera assemblage. *Cassidulina reniforme* and *Elphidium clavatum* are typical foraminifera in Arctic fjords (Hansen & Knudsen 1995; Hald & Korsun 1997). *Cassidulina reniforme* is often associated with *Elphidium clavatum* in glacier-proximal areas, although *Cassidulina reniforme* appears more abundant towards the ocean. *Cassidulina reniforme* indicates that a stable, more saline marine condition prevailed at that time. The presence of *Cibicides lobatulus* at the top and base of the unit reflects the influx of saline water into an energy-rich coastal environment. The presence of the accessory species *Astrononion gallowayi* and *Buccella frigida* indicates strong bottom currents and marginal sea-ice conditions with the availability of food. The presence of *Islandiella helenae* and *Nonionella labradorica* signifies a seasonal sea-ice margin with high biological productivity (Husum et al. 2015) and an elevated concentration of food (Jernas et al. 2018), respectively. An inflow of Atlantic Water probably also occurred at the time of deposition. Together with *Cibicides lobatulus*, the assemblage reflects a pronounced effect of high energy with seasonal marginal sea-ice conditions in a glacier distal environment.

From lithological data, the unit was interpreted to have been deposited in a marine environment with currents and variable energy levels likely by different types of sediment marine density flows in a coastal setting (Alexanderson et al. 2018). This is consistent with the foraminiferal data.

A similar fauna was documented at Leinstranda on Brøggerhalvøya (*Cassidulina reniforme –Astrononion gallowayi* [F-15 II] zone [Miller et al. 1989]), though it is of Early Weichselian age (99 ± 8 Kya; Alexanderson, Landvik & Ryen 2011). Roughly contemporaneous (i.e., Middle Weichselian) foraminiferal faunas in Svalbard have been documented at Poolepynten (unit C [Bergsten et al. 1998]) and Linnéelva (zone FL-III [Lycke et al. 1992]). The foraminifera fauna in unit C at Poolepynten is characterized by uniform and high values of *Cassidulina reniforme*, which indicate primary production along an ice edge (Bergsten et al. 1998) and glaciomarine conditions. The existence of *Islandiella helenae*, *Nonionella labradorica* and *Buccella frigida* indicates algal bloom along the ice edge. The species assemblage from Linnéelva (FL-III) has been considered to record bottom currents in a glaciomarine environment (Lycke et al. 1992).

Overall, it can be inferred that there was a high-energy, productive and stable glacier distal marine environment during Middle Weichselian times at Kongsfjordhallet.

Event V (last deglaciation)

Shortly after the Last Glacial Maximum (at 17 ± 0.6 Kya), there was a stable, saline glaciomarine environment at Kongsfjordhallet. The environment is documented by the presence of a *Cassidulina reniforme – Elphidium clavatum* assemblage in subunit 8b. This type of assemblage has been found in the modern fjords of Svalbard, i.e., glaciomarine environments (Hansen & Knudsen 1995). The species *Cassidulina reniforme* reflects glacier-distal, cold-water areas, with seasonal sea-ice coverage and muddy sediments (Polyak et al. 2002). The dominance of *Cassidulina reniforme* together with *Elphidium clavatum*, coupled with glacier-distal faunas such as *Islandiella helenae*, *Nonionella labradorica*, *Astrononion gallowayi* and

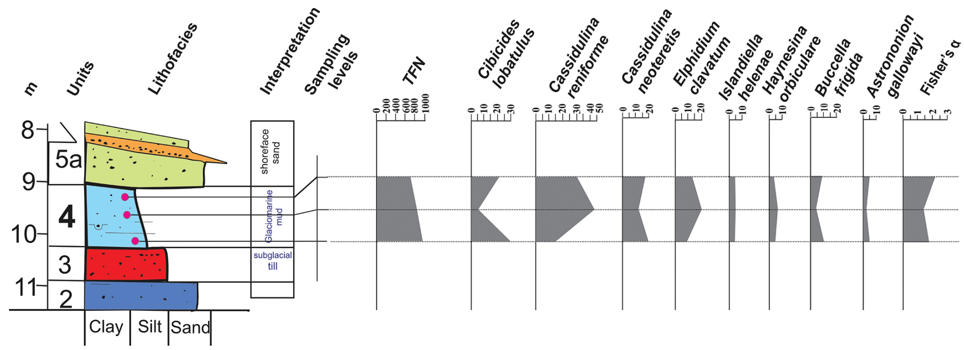

Fig. 5 Benthic foraminifera abundance (%), TFN and diversity index in unit 4. The foraminifera form a *Cassidulina reniforme – Cibicides lobatulus – Cassidulina neoteretis* assemblage.

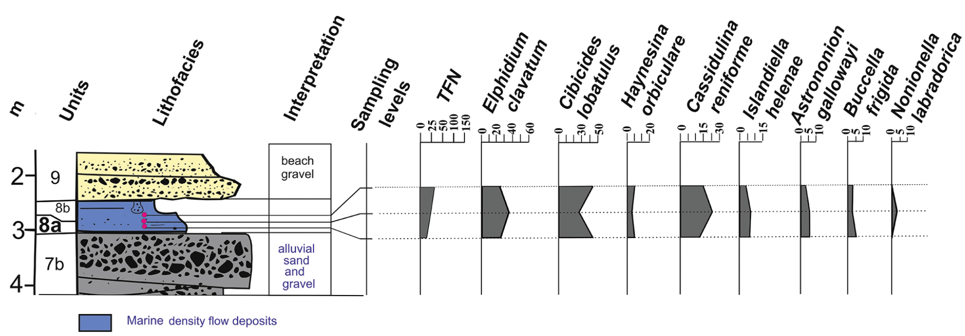

Fig. 6 Benthic foraminifera abundance (%) and TFN in subunit 8a. The subunit is characterized by a *Cibicides lobatulus – Cassidulina reniforme – Elphidium clavatum* assemblage.

Buccella frigida in the entire unit, therefore reveals a glacier-distal location with milder conditions, i.e., seasonal marginal sea-ice conditions during the deposition of the unit.

The presence of *Nonionella labradorica*, *Islandiella helenae* and *Haynesina orbiculare* indicates an occasional inflow of freshwater to Kongsfjordhallet (see Polyak et al. 2002). The palaeoenvironment and the age suggest that this occurred shortly after deglaciation. A similar *Cassidulina reniforme* dominated stable glacier-distal glaciomarine environment has been documented during the Early Holocene (11.8–11.3 Ky BP) in Kongsfjorden (Skirbekk et al. 2010) and in other raised marine sections around Svalbard and the Barents Sea during the Late Weichselian to Holocene (Hansen & Knudsen 1995; Korsun et al. 1995).

Sedimentologically, the unit is interpreted to consist of marine mass movement deposits, with debris flows dominating the lower part and turbidity currents in the upper part, along with deposition from suspension (Alexanderson et al. 2018). Dropstones show that calving glaciers were in the fjord, consistent with the interpretation from the foraminiferal assemblage in the sediment. There was therefore a stable glacier distal marine environment during both the Middle Weichselian (60 ± 4 Kya) and the last deglaciation (17 ± 0.6 Kya) at Kongsfjordhallet.

Foraminiferal data as a correlation tool

Foraminifera assemblages from Quaternary deposits can be used to reconstruct the past marine environment at a site, but the correlation between foraminiferal palaeorecords from different sites in areas such as Svalbard is hampered by occurrences at only a few contemporaneous sites, low chronological resolution (see Alexanderson et al. 2014) and variable oceanographic conditions in a fjord-dominated coastal area (e.g., Svendsen et al. 2002). The low age resolution means that even if we compare deposits that have been dated to the same time period, e.g., a certain MIS, the precision of the ages commonly leaves uncertainties of several thousand years. This, in turn, implies that we may not be examining the same phase of the deglaciation: one site may record a slightly earlier, colder phase while another one records a slightly later and warmer phase, with different foraminiferal faunas as a result of the different conditions. Using foraminifera from raised marine deposits instead of from marine cores at least provides some limitation on the possible age

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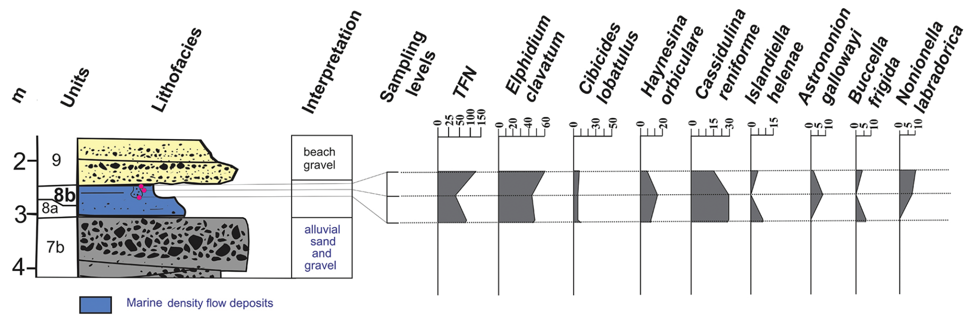

Fig. 7 Benthic foraminifera abundance (%) and TFN in subunit 8b. The foraminifera make up a *Cassidulina reniforme – Elphidium clavatum* assemblage.

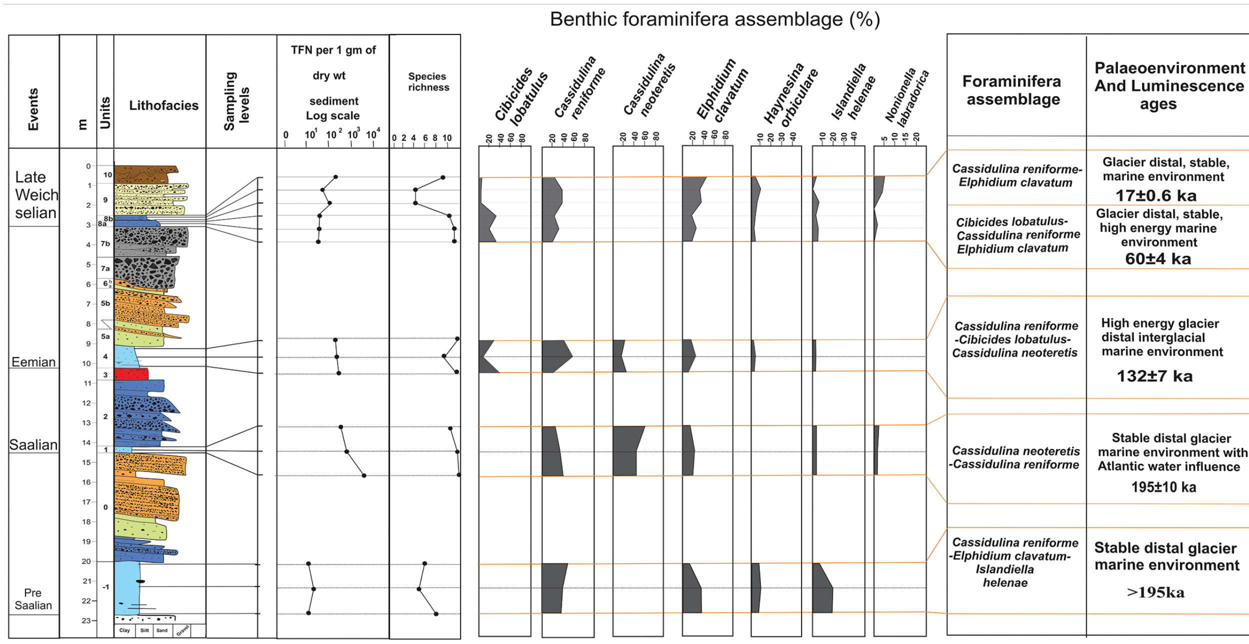

Fig. 8 Summary of palaeoenvironments of Kongsfjordhallet with key foraminiferal species, species richness, foraminifera assemblages, and interpreted environments and ages.

range, though. Raised deposits typically represent the initial phase of deglaciation at a site, before glacial isostacy had lifted the site above sea level. Comparison with the last deglaciation suggests that this would mean the first few thousand years (Alexanderson et al. 2018).

As an example, we can consider the foraminiferal faunas from the last interglacial as recorded at Kongsfjordhallet (unit 4, this study) and at nearby Leinstranda (zone F15 V, specifically unit 9 [Miller et al. 1989]). The two units/zones are dated to the same age (132 ± 7 Ky and 129 ± 10 Ky, respectively [Alexanderson, Landvik & Ryen 2011; Alexanderson et al. 2018]), but the error margins of the ages are large. The two sites are not too far apart and could be expected to have experienced similar oceanographic conditions. Nevertheless, the faunal composition differs significantly between the two sites: at Kongsfjordhallet, there was a *Cassidulina reniforme – Cibicides lobatulus – Cassidulina neoteretis* assemblage (Fig. 5), while *Elphidium excavatum*, *Astrononion gallowayi* and *Cassidulina reniforme* dominated at Leinstranda (Miller et al. 1989). Foraminifera abundance and diversity were, however, high at both sites at the time of deposition, with 5000–20 000 specimens and 35 to 40 species per 100 g sample at Leinstranda (Miller et al. 1989) and 983 specimens and 14 species per 1 g sample at Kongsfjordhallet. The species difference, which may be due to local sedimentary environment variations, makes it difficult to use the foraminiferal fauna as the sole base for correlation between the two or any other sites.

If several samples are taken from the same unit, the foraminiferal records do, however, provide important information on the local oceanographic development during an interglacial or interstadial at a site, which can then be compared with that at other roughly contemporaneous sites to get a regional picture. Also, the data can be used to identify the relative strength of interglacial/interstadial conditions (e.g., inflow of Atlantic Water) for different units in a stratigraphic succession, which then can be used to compare with, e.g., marine isotope records. For example, there are key species (such as *Cassidulina neoteretis* and *Nonionella labradorica*) that are warm-water indicators, but a high faunal diversity is also a sign of interglaciation. In our record, the assemblage dominated by *Cassidulina reniforme* and *Cassidulina neoteretis* from unit 1 is the most diverse (Fig. 8), while the most warm-loving species are found in the *Cassidulina reniforme – Cibicides lobatulus – Cassidulina neoteretis* assemblage from unit 4 (Fig. 5). While the foraminifera data from both units 1 and 4 show high average TFN, unit 4 is characterized by a high Fisher's alpha index whereas the highest species richness is in unit 1. Therefore, it appears that the foraminiferal fauna from the interglacial during late MIS 7 or MIS 6 (195 Kya) was more diverse than that during the Eemian, but conditions were not necessarily as warm.

Summary

We used benthic foraminifera assemblages, combined with sedimentological and chronological data, to reconstruct the Middle and Late Quaternary oceanographic environment at Kongsfjordhallet, north-west Svalbard. Our main conclusions are as follows.

Two new lithological units—unit -1 and unit 0—were identified and are interpreted to have a Middle Pleistocene (>195 Ky) age.

Five foraminiferal assemblages were observed in sediments from Kongsfjordhallet, all indicating distal marine environments with various degrees of productivity, sea-ice influence and energy levels. The data add new information to the palaeoenvironmental reconstruction of the Kongsfjorden area.

The pre-Saalian (>195 Kya) record from unit -1 comprises *Cassidulina reniforme, Elphidium clavatum* and *Islandiella helenae* and represents a stable glaciomarine environment with a strong influence of sea ice at the study site.

The Saalian (ca. 195 Kya) record from glaciomarine mud of unit 1 contains *Cassidulina reniforme, Cassidulina neoteretis, Islandiella helenae, Elphidium clavatum* and *Nonionella labradorica*. The unit represents a glacier distal inner shelf-stable environment and its foraminiferal assemblage is the most diverse of the documented assemblage at the site.

The Eemian (ca. 130 Kya) record contains the most warm-loving species, is characterized by *Cibicides lobatulus, Cassidulina reniforme, Cassidulina neoteretis* and *Islandiella helenae,* and indicates a high-energy glacier-distal environment. The presence of *Nonionella labradorica* and *Cassidulina neoteretis* shows the availability of fresh phytodetritus during an interglacial period.

The Middle Weichselian (ca. 60 Kya) and the last deglaciation (ca. 17 Kya) represented in subunits 8a and 8b, respectively, are represented by distal glacial environments, as evident from the occurrence of a *Cassidulina reniforme – Elphidium clavatum*-dominated assemblage. The characteristic occurrence of *Cibicides lobatulus* in subunit 8a represents relatively fast-flowing water masses.

Foraminiferal records, such as those presented here, are difficult to use on their own as a correlation tool between stratigraphic sites on Svalbard, mainly due to variable oceanographic and sedimentary conditions and deposition during different phases of an interglacial or interstadial. They, do, however, provide important information on the local oceanographic development of the early phases of an interstadial or interglacial and on the relative strength of interglacial/interstadial conditions that can be used to compare with, e.g., marine isotope records.

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Disclosure statement

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