Quaternary Biostratigraphy of Kongsfjorden region, Svalbard, High Arctic

Thesis

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Debolina Chatterjee

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Supervisor

Dr. Anupam Ghosh

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JADAVPUR UNIVERSITY
KOLKATA-700 032, INDIA

FACULTY OF SCIENCE : DEPARTMENT OF GEOLOGICAL SCIENCES

CERTIFICATE FROM THE SUPERVISOR

This is to certify that the thesis entitled **"Quaternary Biostratigraphy of Kongsfjorden region, Svalbard, High Arctic"** submitted by **Ms. Debolina Chatterjee** who got her name registered on **22.08.2016** for the award of **Ph.D. (Science) degree** of **Jadavpur University**, is absolutely based upon her own work under the supervision of **Dr. Anupam Ghosh** and neither this thesis nor any part of it has been submitted for either any degree/diploma or any other academic award anywhere before.

Anupam Ghosh

Dr. Anupam Ghosh

Dr. Anupam Ghosh
Associate Professor
Department of Geological Sciences
Jadavpur University
Kolkata-700 032,W.B. India

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Debolina Chatterjee
Signature

List of Publications

Journal Papers

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Chatterjee D., and Ghosh A. (2023). Distribution of recent Benthic foraminifera in Kongsfjorden and Krossfjorden; North-West Svalbard, High Arctic. *Journal of the Paleontological Society of India* (2023): 1-15 (in press)

Conference Papers

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Paul S., Ghosh A., and **Chatterjee D.** (2019). A study of benthic foraminifera from the Northern sector of Chilika Lake, Odisha. XXVII Indian Colloquium on Micropaleontology and Stratigraphy 2019, Vanaras Hindu University, p-105.

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Chatterjee D., Ghosh A., Alexanderson H, Henriksen M, Landvik Y. J., and Ryen T.H. (2017) Benthic foraminiferal records of the Late Pleistocene deposits of (North-western) Spitsbergen, Svalbard (2017). National seminar on the Application of Scanning Electron Microscope (SEM) in Geosciences (Geocon 2017), University of Calcutta.

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Abstract

The impact of changes that occurred due to glacial-interglacial variability in the Late Quaternary played a pivotal role in Arctic paleoceanography and paleobiology. Extensive glaciological investigations of a series of sites along the north-western coast of Svalbard, Arctic reveal that the archipelago has been glaciated four times during the Weichselian and two during Saalian. The most extensive Late Weichselian glaciation left morphological evidence from which glacial extent, movement, and deglaciation have been well documented. Despite the low preservation potential and fragmentary record of older glaciations, due to the isostatic uplift of vast areas of marine deposits caused by glacio-eustatic lowering of sea level after the Last Glacial Maximum (LGM), these are now accessible in sections along the present-day coast of Svalbard and provide glacial-interglacial history and associated sea level fluctuations over the last 200 ka.

Foraminifera are a noteworthy group of microfossils that can be well applied to delineate past environmental and paleoceanographic conditions that existed during their ontogeny; stratigraphic correlations and reconstructions. They are vital in studying climate changes in the Quaternary. The present study aims to emphasize paleoenvironmental evaluation from foraminiferal assemblages recorded in the Kongsfjorden area (North-west Svalbard).

The work investigates the modern distribution of foraminifera in the Kongsfjorden and Krossfjorden sites; those have been used as an analog to interpret the past. The proximal region of both fjords is characterized by *Cassidulina reniforme- Elphidium clavatum* assemblage pointing out a turbid, stressed, low-oxygenated environment. The region also contains abundant asymmetric agglutinated foraminifera *Textularia* spp. and *Spiroplectammina biformis*. The central and outer parts of both fjords are characterized by *Cassidulina reniforme, Nonionellina labradorica*, *Lobatula lobatula,* and agglutinated species *Adercotryma glomaratum*. The shelf region, specifically at the confluence of two fjords is entirely composed of *Nonionellina labradorica* reflecting the intrusion of Atlantic water, a productive and well-oxygenated environment. In the context of productivity, Krossfjorden appears more productive than Kongsfjorden.

Sediments have been collected from the selected Quaternary units from Kongsfjordhallet, Stuphallet, and Leinstranda. The foraminifera assemblage from unit 1 of the Kongsfjordhallet section reveals *Cassidulina neoteretis -Cassidulina reniforme* assemblage pointing out a stable, cold glaciomarine environment with an occasional inflow of Atlantic water into the site during

Saalian period (195±10 ka). The foraminifera assemblage from unit 4 and unit 3 from Kongsfjordhallet and Stuphallet represent *Cassidulina reniform- Lobatula lobatula - Cassidulina neoteretis* and *Cassidulina reniforme- Lobatula lobatula - Elphidium clavatum* respectively revealing the notable existence of Atlantic water in those particular sites during Eemian times (132±7 ka). They were scarce in the units of Leinstranda during the same period. The foraminifera assemblage from unit 7 and units 14/15 from Stuphallet and Leinstranda comprising *Cassidulina reniforme- Elphidium clavatum-Astrononion hamadaense* and *Lobatula lobatula- Elphidium clavatum-Cassidulina reniforme* respectively reflecting abundance, and noticeable temporary warm high sea-level Phantomodden interstadial event (97±5 ka) in the sites.

Contents

Chapter 1: Introduction

Chapter 2: Methodology

Chapter 3: Distribution of Recent Foraminifera in Fjords

Chapter 4: Quaternary Deposits of Kongsfjordhallet, Stuphallet and Leinstranda

Chapter 5: Discussion and Conclusion

List of Figures Pages

List of Tables Page

List of Plates Pages

Chapter 1 INTRODUCTION

1.1 General Introduction

Micropaleontology is an important discipline of paleontology that deals with fossil organisms that are microscopic in size and also with fossil organisms that may be visibly somewhat large, but in either case, the fossils are to be examined under the microscope for their proper identification. Due to abundant and wide occurrence from the Cambrian up to the Holocene and even distribution in sediments over larger fossils, microfossils are particularly useful in stratigraphic correlation and hydrocarbon exploration. They have been significantly applied to a large extent in understanding past environmental, climate, and ocean circulation changes. Benthic foraminifera respond to changes in water depth, and food availability at the sea floor and provide information on sea-level changes and benthic-pelagic coupling in the ocean.

Foraminifera are unicellular organisms belonging to Kingdom Protista; that have thread-like pseudopodia and a protoplasm-bearing test. The shells are mostly calcareous, though a few of them are pseudo-chitinous, agglutinated, or, rarely siliceous. Their size ranges from about 0.1mm to more than 10cm. Foraminifera are classified into benthic and planktonic; while benthic foraminifera can be further divided into larger and smaller. Based on the composition of the wall of the test, foraminifera can be classified as organic-walled, agglutinated, and calcareous. The organic-walled test is composed of proteinaceous matter, or tectin while the agglutinated test is formed through cementing assorted particles from the sea floor. The calcareous wall can be hyaline or porcelaneous. Most foraminifera have been found in marine environments, but they can also occur in brackish and freshwater. The organic-walled Allogromiid foraminifera live in fresh and marine waters. Agglutinated foraminifera are found in the marsh to deep marine i.e., bathyal and abyssal environments. Porcelaneous foraminifera are found from marginal marine to deep marine, while calcareous foraminifera are distributed from shallow marine to deep marine environments. Larger benthic foraminifera are shallow marine dwellers and prefer carbonate platforms and reef environments. Benthic foraminifera ingest nutrition mainly from algae and bacteria and dissolved organic matter while Planktonic foraminifera depend on copepods, diatoms, and silicoflagellets. The greater application of benthic foraminifera has been found in paleoenvironmental interpretation while planktonic foraminifera are widely used in biostratigraphy, particularly for Cretaceous and younger successions.

1.2 Origin of the problem

The Arctic region is specifically sensitive to climate changes and exerts greater influences on the global ocean circulation system. The worldwide significance of environmental modification in the Arctic region as the build-up and breakdown of ice sheets and the flow of accompanying meltwater since the Cenozoic has been widely studied by many researchers in recent years. Both geological onshore and offshore studies reveal climate and sea-level changes during Quaternary glacial and deglaciation events in the Arctic and surrounding areas, of which the Barents Sea ice sheet and Eurasian ice sheets are of particular interest (Boulton 1979; Forman et al., 1987,1989; Svendsen & Mangerud 1992; Svendsen et al., 1996; Ingólfsson 2011; Ingólfsson & Landvik 2013; Landvik et al., 1985; 1992, 2005, 2014; Jennings et al., 2000; Darby et al., 2006; Hormes et al. 2013; Jakobsson et al., 2014; Henriksen et al., 2014; Hughes et al., 2016).

Figure 1.1: Overview of the Arctic landscape

The Middle-Late Quaternary is characterized by extensive glacial-interglacial events that have been correlated with the Marine Isotope Stages (MIS) as follows: The end of Saalian (MIS 6) and Pre Saalian (MIS 7); The Last interglacial, Eemian (MIS 5e); the Early Weichselian (MIS 5d); the Middle Weichselian (MIS 4) and the Late Weichselian (MIS 2). Major glacial advances have been reported during Saalian, Early, Middle, and Late Weichselian times with intervening Eemian interglacial and Phantomodden (97 ka) and Kapp Ekholm (40 ka) interstadial events (Mangerud et al., 1984, 1987, 1991,1998; Eccleshall et al., 2016).

The eustatic sea level compared to the present-day sea level was considerably lower during glaciations (Waelbroeck et al., 2002, Mangerud et al., 1998) and also during the entire Weichselian in the case of Svalbard. Hence, accessibility of the marine deposits preserved today above the mean sea level denotes they have been vertically uplifted and that can only be done by glacial-isostasy. These raised marine deposits represent high relative sea-level events and contain interlayered glacial and marine strata providing a possibility for additional paleoenvironmental reconstruction (Mangerud et al., 1998; Alexanderson et al., 2018).

Apart from a number of relevant terrestrial and marine studies (Adler 2009; Andersson et al.,1999, 2000) numerous questions still exist about the characteristics of Arctic paleoclimate. The delineation of past environmental changes requires firm chronostratigraphic data, detailed sedimentological information, and better accessibility. However, beyond the instrumental time series paleoenvironmental interpretation requires a proxy. Benthic foraminifera can be a useful proxy since they inhabit a particular marine environment. They are highly relevant for their high abundance and diversity on shelves and in fjords of the Arctic region (Korsun et al., 1995; Hald & Korsun 1997; Korsun & Hald 1998, 2000).

In the Arctic region, previous paleoclimatic, paleoenvironmental, and paleoceanographic studies based on foraminifera assemblages in raised marine deposits have been done at different localities on Svalbard (Figure 1.2), and in marine cores from the adjacent Arctic Ocean and the Barents Sea (Feyling Hanssen and Ulleberg 1984; Feyling Hanssen 1990; Nagy et al., 1984; Miller et al., 1989; Lycke et al., 1992; Landvik et al., 1992; Ingólfsson et al., 1995; Seidenkrantz 1995, Bergsten et al., 1998; Kubischta et al., 2010; Hovland 2014, Chauhan et al., 2014). Investigations of key benthic foraminifera species characterizing interglacial and interstadial events are summarized in Table 1.1.

Figure. 1.2: Position of Svalbard archipelago (Source: https://en.wikipedia.org/wiki/Svalbard)

Key Foraminifera species	**Locality /Area**	**Chronology**	**Reference**
Elphidium clavatum and *Cassidulina reniforme*	Sarsbukta	Late Saalian to Early Eemian	Feyling Hanssen and 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
Lobatula lobatula	Skilvika	Early Weichselian Interstadial	Landvik et al. 1992
	Brøggerhalvøya	Eemian	Miller et al.1989
	Eurasian Arctic	The Last deglaciation 13ky BP	Hald et al. 1999

Cassidulina neoteretis	North Sea	Upper Pleistocene	Seidenkrantz 1995
	Yermak Plateau	Early Weichselian and Eemian times and the Last glacial maximum	Chauhan et al. 2014
Astrononion hamadaense	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	The Last Interglacial-Eemian MIS 5e	Feyling Hanssen and Ulleberg 1984
Nonionellina labradorica	Kapp Ekholm	Early Eemian transition	Hovland 2014

Table 1.1: Records of key foraminifera species from reported sites in Svalbard from Late Saalian to the Last Glacial Maximum

Apart from paleoenvironmental observations, there exist profuse significant Quaternary and Holocene paleoceanographic studies from marine cores from Svalbard fjords and the adjacent Arctic Ocean (Polyak and Solheim 1994; Wollenberg et al., 2001; Koç et al., 2002, Hald et al.,1999; Ślubowska et al., 2005; Ślubowska-Woldengen et al., 2007; S. Aagaard-Sørensen et al., 2010; Skirbekk et al., 2010; Zajączkowski et al., 2010; Rasmussen et al., 2012; Groot et al., 2014; Chauhan et al., 2014; Polyak et al., 2002). Those observations of foraminiferal data gave an overview of the variability of Atlantic water, productivity, organic matter, seasonal sea-ice cover, freshwater inflow, polar front, etc. of the region.

Besides the aforementioned studies, concurrently foraminiferal studies based on recent benthic foraminifera association with the different glacial environments, ecology, and changes in local hydrography have been carried out (e.g., Hald 1994, Korsun et. al., 1995; Hansen & Knudsen 1995; Hald & Korsun 1997; Korsun & Hald 2000; Majewski & Zajączkowski 2007; Saher et al., 2009; 2012; Forwick et al., 2010, Jernas et al., 2018, Cage et al., 2021). These illustrate insight into the environmental significance of taxa and potentially improve paleoenvironmental interpretation for fossil faunas. The notable foraminiferal studies in the Arctic near glacial environments (Hald 1994); Freemansundet (Hansen & Knudsen 1995) and Kongsfjorden areas (Jernas et al., 2018) provide information about ecological conditions.

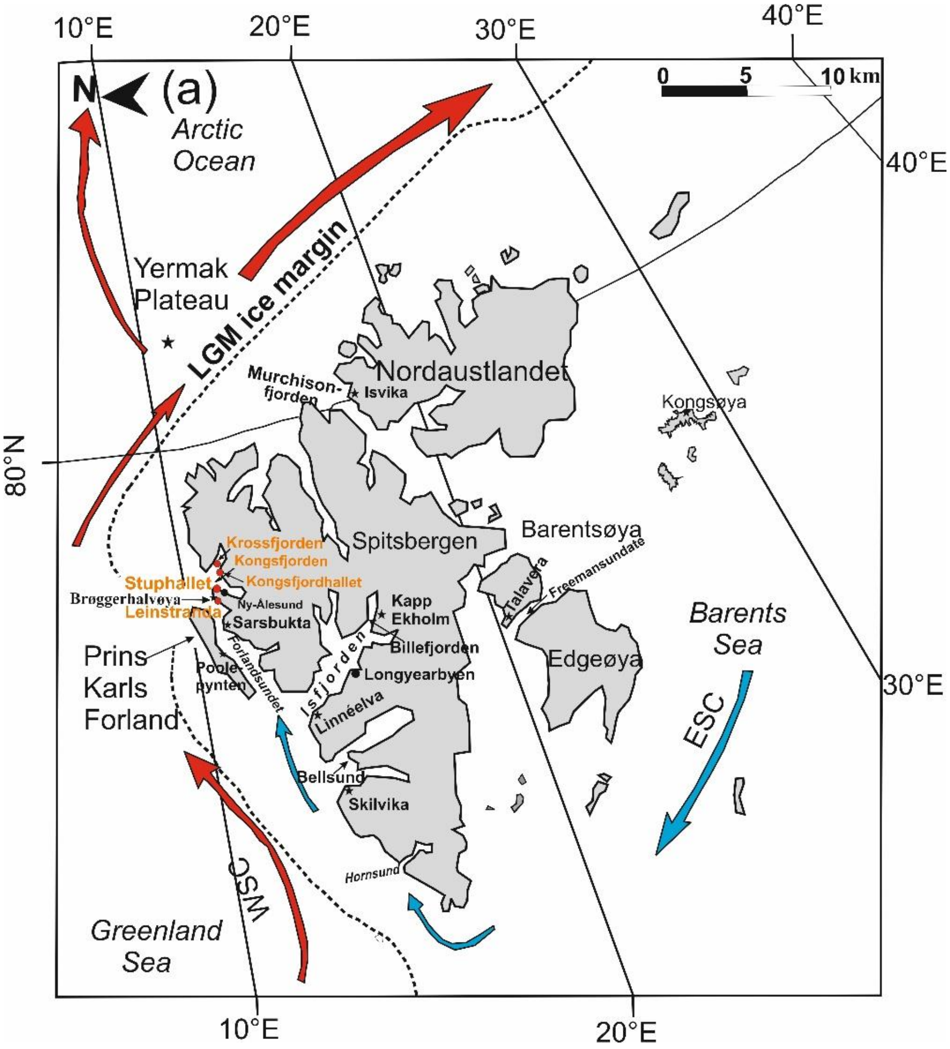


Figure 1.3: Map of Svalbard showing previously studied sites based on foraminiferal assemblages

Therefore, studying Arctic foraminifera supports the events and phases that took place during the particular glacial-interglacial times, while radiocarbon dates and OSL dating provide absolute ages for the events. Thus, a multiproxy approach using foraminifera, lithostratigraphy, and chronology will do together a better understanding of the scenario.

For the Kongsfjorden area, north-west Spitsbergen, a thorough investigation was carried out by Miller et al. 1989 which revealed foraminiferal stratigraphy of the Late Pleistocene at Brøggerhalvøya, south of Kongsfjorden. Four foraminifera zones and their corresponding paleoenvironment were established. Their study's significant contribution reveals that West Spitsbergen's glacial history was affected by regional climate changes. The most noteworthy deposit is characterized by more diverse Arctic foraminifera and interpreted to represent the Eemian interglacial (MIS 5e). Another important investigation was done by Skirbekk et al., 2010 from a core in the Kongsfjorden trough. In that study, marine sediment cores comprising foraminiferal fauna during the Late Weichselian and Holocene revealed cold proximal glaciomarine and strong Atlantic water influence respectively.

For Kongsfjordhallet, a thorough investigation was carried out by Jørgen Sivertsen (1996), which revealed Pleistocene foraminiferal stratigraphy and paleoecology in the raised coastal cliffs of Kongsfjordhallet.

Detailed sedimentation and glaciation history during the Last glacial-interglacial cycle from either side of Kongsfjorden of Svalbard has been significantly analyzed by Alexanderson et al., 2018. The present Saalian and even prior to Saalian foraminiferal study will notably refine the paleoenvironmental evolution of the area. Moreover, this study correlates well with similar foraminiferal zones of other sites of Svalbard which gave an overview of regional paleoenvironmental and paleoceanographic events of the area.

1.3 Physiography of the Kongsfjorden area

The Svalbard archipelago, high Arctic, (76°-80° N), is situated amidst significant surface water masses between the North Atlantic and the Arctic Ocean (Elverhøi et al., 1980; Hald et al., 1996; Cottier et al., 2010; Rasmussen et al., 2012). The seafloor morphology of the Svalbard margin, west and north of the archipelago is characterized by a series of deep fjord trough systems. This is caused by the actions of ice sheets and ice streams during the Pleistocene.

Spitsbergen is the largest island of the Svalbard archipelago (Figure 1.3), situated between 76º and 80ºN and bordered by the Arctic Ocean to the north, the Barents Sea to the South, and East, and the Norwegian–Greenland Sea to the west. The archipelago is dominated by Phanerozoic sedimentary rocks. The continental margin west of Spitsbergen is characterized by a relatively narrow shelf with a typical glacial morphology represented by glacial troughs with intervening shallow banks; the troughs have been found in the continuation of the east-west trending fjords. Kongsfjorden is a kind of such trough located between $78^{0}40'$ and $77^{0}30'$ N and $11^{0}3'$ and $13^{0}6'$ E on the western coast of Spitsbergen, Svalbard. It is 20 km long, 4 -10 km wide, south-east to north-west oriented fjord with a maximum depth of 394 m at the outer fjord and less than 100m at the inner fjord system. Together with Krossfjorden, another fjord located north of Kongsfjorden has produced the main submarine glacial trough Kongsfjordrenna at their seaward limits.

The region encompassing Kongsfjorden is situated on the tectonic boundary between a tertiary fold-thrust belt that extends across western Spitsbergen and the North-western basement province which lies to the Northeast. Kongsfjorden has formed in a depression produced from bedrock fracturing parallel to the thrust front (Howe et al., 2003). North of Kongsfjorden, the bedrock consists of medium-grade metamorphic marbles, mica schist, and quartzites of the middle Proterozoic age. In a north-south trending zone comprising the island Blømstrandhalvøya and islands Lovénøyane are of Devonian age, red conglomerates, and sandstones are interlayered with marbles. South of Kongsfjorden, Brøggerhalvøya represents Tertiary thrusts with Palaeozoic sediments comprising conglomerates, sandstones, carbonates, and dolomites (Husum et al., 2019). The region has two notable features 1) the existence of tidewater glaciers, i.e., Kongsbreen and Kongsvegen in the eastern, inner part of the fjord, and 2) the connection to the open ocean (the North Atlantic) through Kongsfjordrenna depression in the west. The intrusion of warm Atlantic water from the open ocean side and the discharge of fresh water from glaciers from the inner end restraining the fjord system have been found to occur simultaneously. The fjord links partially glaciated terrestrial environments with the open marine environment. This unique setting has made the area suitable to study based on climatic changes; the interaction between terrestrial and marine realms.

1.4 Oceanography

Kongsfjorden is strongly governed by the oceanic currents that flow around the Svalbard archipelago (Figure 1.4). The area is influenced by cold (blue arrow) and warm oceanic currents (red arrow). The boundary between these two water masses is called the Polar front. The position of the polar front is known to fluctuate through time causing varying inflow of Atlantic water (AW) inflow to the area (Skirbekk et al., 2010). Cold and relatively fresh Arctic water (ArW) of East Spitsbergen Current (ESC) exists on the shelf. It flows as a coastal current extending northward, then eastwards from Storfjorden, and finally rounds the southern tip of Spitsbergen (Svendsen et al., 2002).

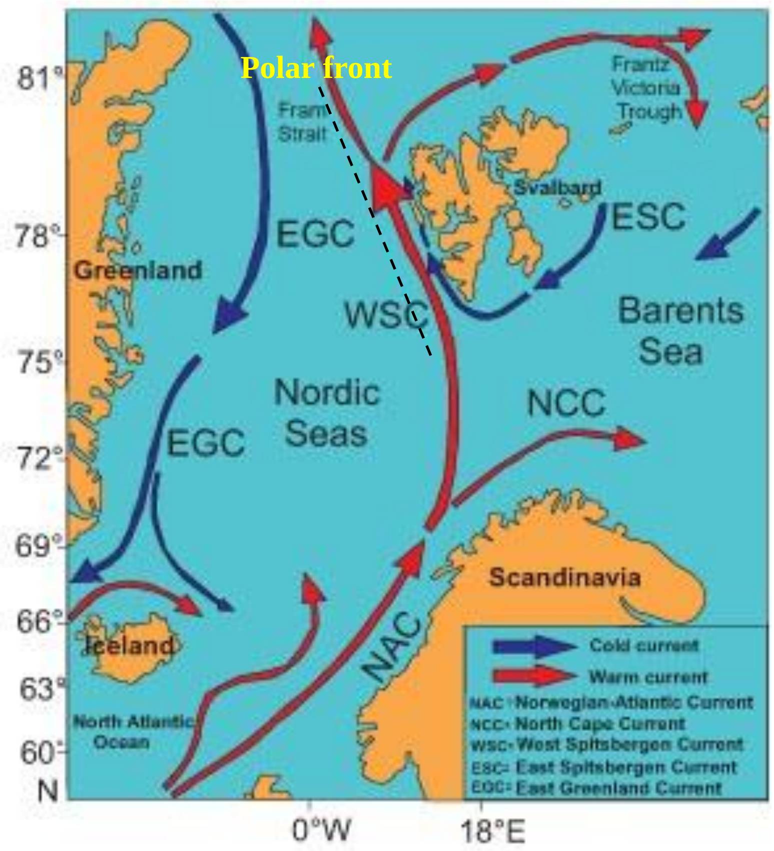


Figure 1.4: Overview of oceanic current pattern in and around Svalbard.

The West Spitsbergen Current (WSC; Figure 1.4) transports a large amount of heat and salt to the Arctic Ocean by accommodating warm and saline Atlantic water (AW) in the upper 600m and flowing northward as the Norwegian Atlantic Current (NAC) by following the continental slope of west Spitsbergen. An important aspect is that since this warm current is the primary source of productivity and nutrients, its variability in the past and present is reflected in past climate and environmental change in Arctic fjords since this current also enters the fjords (Jernas et al., 2018).

1.5 Flora & Fauna

Kongsfjorden is characterized by rich Tundra vegetation. Locally very rich vegetation is observed below bird cliffs with high biodiversity. The bird fauna is also quite rich, with a number of seabird colonies on the steep cliffs with Brunich's Guillemots, Kittywakes, Glaucous gulls, and very rarely even the Razorbill, which is only found in this part of Svalbard. Another ornithological highlight of Kongsfjorden is the Long-tailed Skua. The tundra areas are important feeding sites for geese, mostly Barnacle geese (Figure 1.5a). The islands are home to large numbers of Common Eider ducks. Reindeer (Figure 1.5b) and foxes roam over the tundra. Ny Ålesund, Kongsfjorden has a good number of species to offer, including Arctic tern (Figure 1.5c), Arctic fox, geese, Long-tailed duck, the Ivory gull, and polar bears (Figure 1.5d).

Figure 1.5: Arctic fauna- a) Barnacle geese, b) Reindeer, c) Arctic tern, and d) polar bears

1.6 Objectives of Thesis

The aim of this study is to amplify the perception of the paleoenvironmental evolution of the Kongsfjorden region by studying the glacial-interglacial cycle, sedimentation, correlation, foraminifera content, and their paleoenvironmental implications from Pre Saalian (>195ka) to Last Glacial Maximum (18ka). The major objectives are:

1. Analyzing the different glacial environments associated with foraminifera and reconstructing paleoenvironmental conditions of the Kongsfjorden region for the time frame older than Saalian to Last Glacial Maximum (LGM).

2. Stratigraphic correlation of foraminiferal data with similar raised marine deposits elsewhere on Svalbard for improving knowledge and understanding of the area's Late Pleistocene stratigraphy and chronology.

3. Study of ecology and accompanying glacial environment of recent foraminifera distribution in Kongsfjorden and Krossfjorden region; can be used as an analog to interpret the past.

1.7 Organisation of the Thesis

The thesis is divided into five chapters. Chapter 1 shows the general background, an overview of previous studies, physiography, oceanography, flora and fauna of the studied area, and objectives. Chapter 2 contains various methods and materials used during the study. Chapter 3 comprises ecology and the recent foraminifera distribution of the Kongsfjorden and Krossfjorden areas. Chapter 4 provides a detailed analysis of benthic foraminifera assemblages, and inferred paleoenvironments observed in the collected sediment samples from three Quaternary sections of the Kongsfjorden region. Chapter 5 comprises the discussion and conclusions of the study, stratigraphic correlations within the present three sites of Kongsfjorden, and similar raised marine deposits in other studied sites of Svalbard based on foraminiferal stratigraphy.

2.1 Fieldwork in the High Arctic

The field trip from India to the Arctic is sponsored by National Centre for Polar and Ocean Research (NCPOR) in 2018. The Indian Research base '***Himadri***' (Figure 2.1) set up by NCPOR (July 2008) in ***Ny-Ålesund***; a small town and an international research centre in the Arctic; has given the basic facilities for staying at Svalbard. The Norwegian Polar Institute (NPI) has provided logistic arrangements and necessary requirements for field visits in Svalbard. The Kings Bay, Marine Laboratory, Ny-Ålesund; has provided the facility i.e., Stereozoom microscopes, magnetic stirrer, hot air oven, and 63µm sieves, etc. to carry out the analysis prior to and after the field sampling. i.e., sample processing and preparation of Rose Bengal solution. The Quaternary sites; Kongsfjordhallet, Stuphallet, and Leinstranda were accessed by a small boat directly to the sections 11km, 7km, and 30km respectively from Ny-Ålesund. Samples from desired locations from Kongsfjorden and Krossfjorden fjords were accessed by an M/S Teisten boat equipped with scientific instruments.

Figure 2.1: Research base 'Himadri' in the Arctic

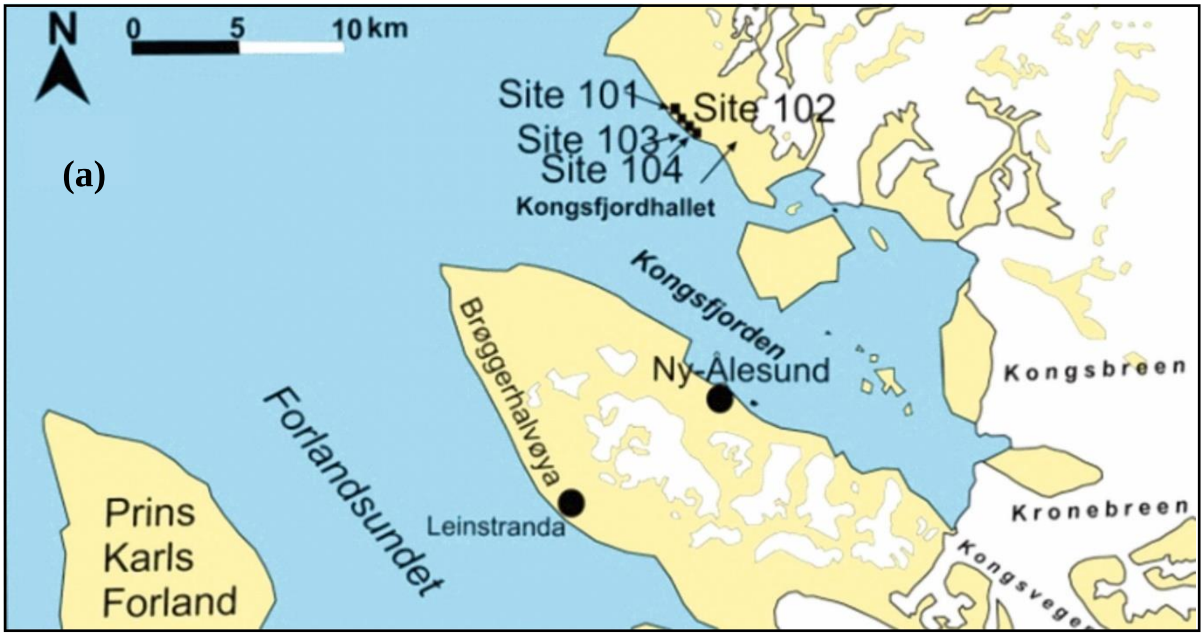


Figure 2.2: Sampling sites in Kongsfjordhallet

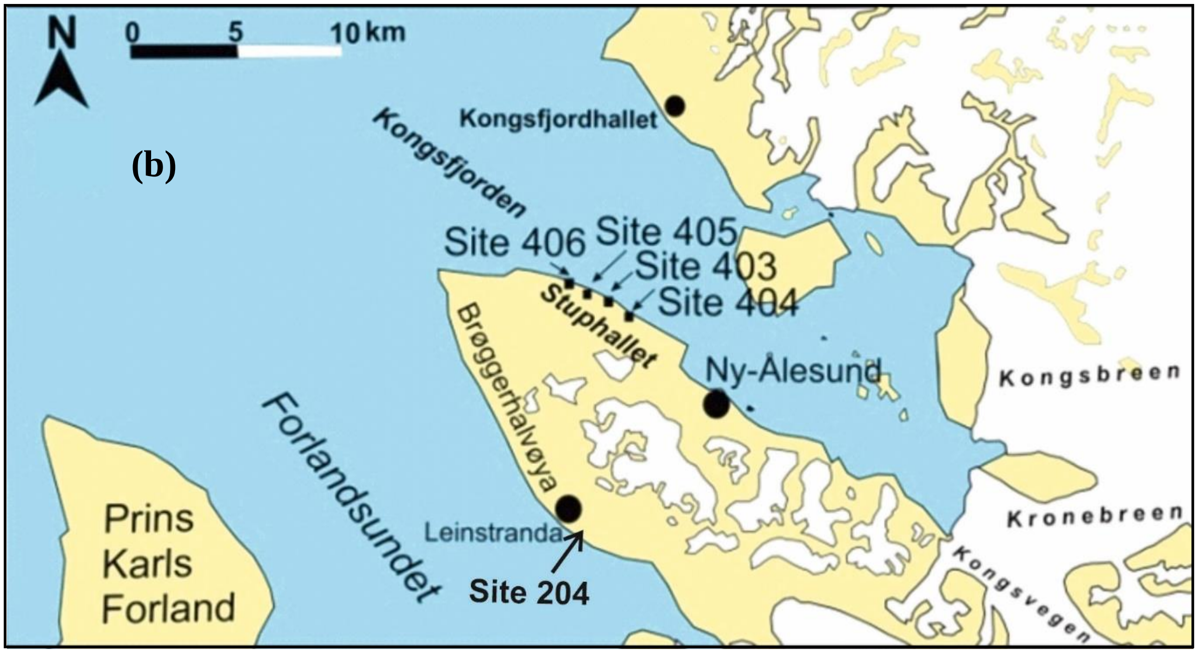


Figure 2.3: Sampling sites in Stuphallet and Leinstranda

S. No.	Field Sites	GPS Coordinates	Sample Collection	Volume of Samples
1.	Leinstranda, Brøggerhalvøya	N 78°52'53", E 11°33'23"	Sediment for microfossil	100 cm^3 for each logged unit
2.	Stuphallet, Brøggerhalvøya	N 78°57'50″, E 11°37"34″; N 78°57'54″, E11° 36'29"; N 78°58'2", E11° 34'50"; N 78°58'12", E11°32'35"	Sediment for microfossil	100 cm^3 for each logged unit Sediment for OSL Dates (Cores of D= 2” and L=8”) 25 cm^3 for one core
3.	Kongsfjordhallet, north side of Kongsfjorden	N79°2'00", E11°52'0", N 79°1'14", E11°52′24", N79°1'30", E11°54'0", N 79°01'32", E11°53'53"	Sediment for microfossil	100 cm^3 for each logged unit

Table 2.1: Sample details of Quaternary sites in Kongsfjorden

2.2 Detailed Field Documentation

Fieldwork at Kongsfjorden was carried out in the summer months (July-August) of 2018. The samples were derived from particular sites based on the knowledge of detailed sedimentological characteristics of the Kongsfjordhallet, Stuphallet, and Leinstranda areas (Alexanderson et al., 2018). According to Alexanderson et al. (2018), site numbers and stratigraphic units are named. The samples were collected from units at regular intervals i.e., top, middle, and bottom parts of each unit. The thickness and character of the strata were also noted. The sample locations were marked on the toposheet and GPS readings were noted. Graphic logs are prepared for the transverse section and stratigraphic positions of the collected samples are marked in them. The hammers and chisels were cleaned before each sample was collected to avoid contamination. Sample bags were labeled on the spot and details were entered in a field notebook.

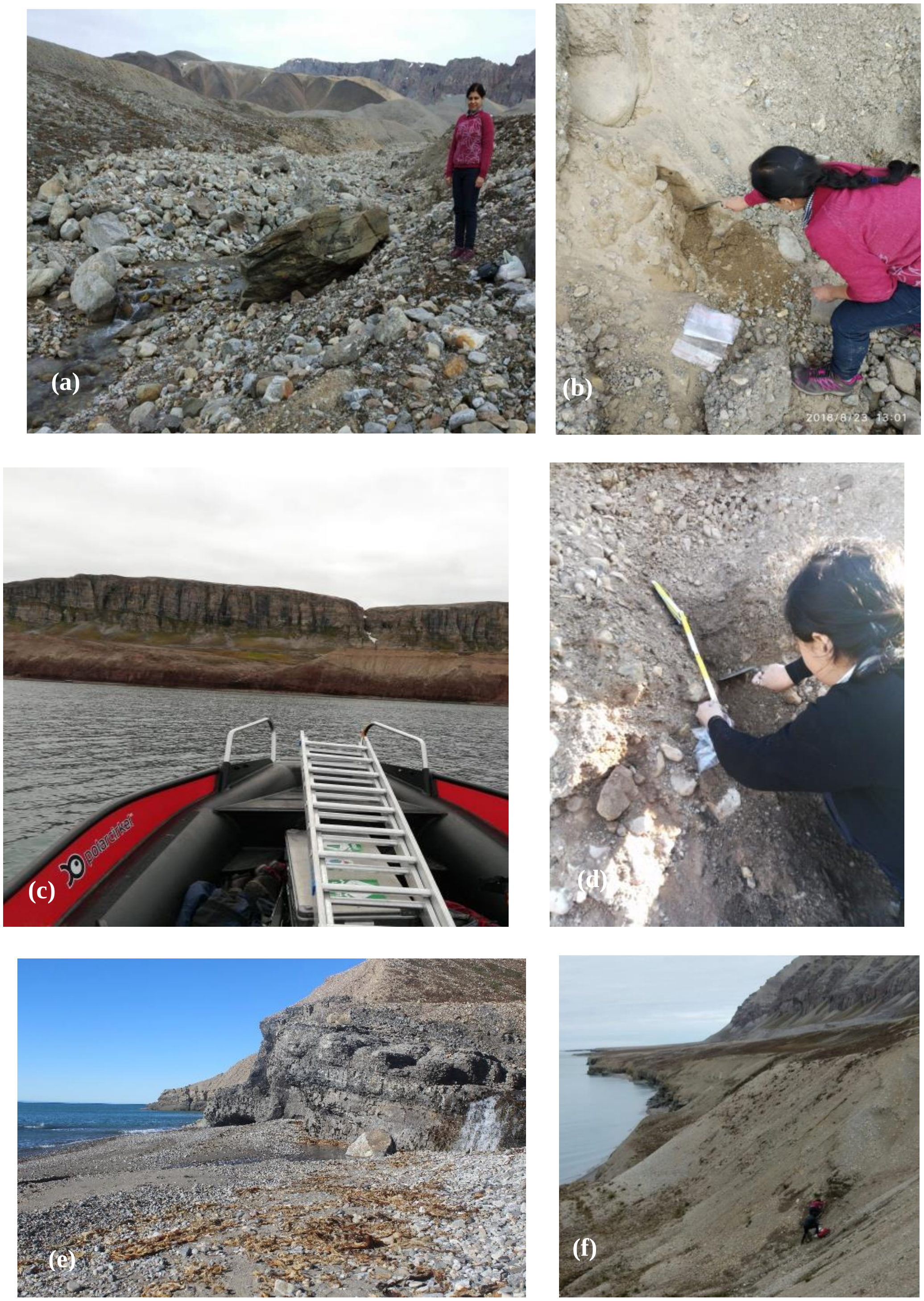


Figure 2.4: Collection of Quaternary samples; [a] Gateway at site 104 of Kongsfjordhallet, [b] collection of samples from Kongsfjordhallet; [c] Stuphallet site 404, [d] Sampling collection at Stuphallet site 404; [e] Leinstranda site 204, and [f] sample collection at site 204 of Leinstranda.

The materials examined in the present study include sediment samples from sections in the coastal cliffs of four sites of Kongsfjordhallet (Figure 2.2). They are as follows: site 101(N79°2'00", E11°52'0"), site 102 (N 79°1'14", E11°52′ 24"), site 103 (N79°1'30", E11°54'0") and site 104 (N 79°01'32", E11°53'53"). At Stuphallet (Figure 2.3) and Leinstranda (Figure 2.3); it was carried out at the field sites 403 (N 78˚57 ̍50″, E 11˚37 ̎ 34″); 404 (N 78˚57 ̍ 54″, E11˚ 36 ̍ 29 ̎), 405 (N 78 ˚ 58 ̍ 2 ̎, E11 ̍ 34 ̍ 50 ̎), 406 (N 78 ˚ 58 ̍ 12 ̎, E11˚32 ̍ 35 ̎) and site 204 (N 78˚52 ̍ 53 ̎, E 11˚33 ̍ 23 ̎) respectively. Before collection of the samples, the sections were excavated with a shovel; cleaned with a trowel; described, and photographed (Figure 2.4). The samples of fine-grained sediments were taken with a trowel and placed in plastic zip-lock bags. The plastic bags were labeled according to the respective units from where the samples were collected. The bags were sealed in sample containers for transportation back to India.

Figure 2.5: Collection of Recent Sediments : [a] CTD measurements, [b] Van Veen grab used for sampling, and [c] Collection of modern samples from Kongsfjorden fjord.

The modern samples were collected from Kongsfjorden and Krossfjorden, another fjord lying to the north of Kongsfjorden. During the process of collection, the sample locations are marked on the location map; the GPS readings and necessary field observations such as sea surface temperature, salinity, and water depth of respective stations (Figure 2.5a) were noted in a field notebook. Sediment samples from Kongsfjorden and Krossfjorden fjords were retrieved by using Van Veen grab having long arms (Figure 2.5b) attached to each bucket thus giving a better beverage for closing. The top sediment was transferred into a 250ml plastic bottle (Figure 2.5c) and stained with buffered rose

Bengal solution (2 grams of rose Bengal powder in 1-liter ethanol). The rose Bengal solution is used to differentiate living foraminifera from dead ones. During the collection of samples, a strategy was maintained that samples were taken from the glacial proximal towards the open sea.

2.3 Micropaleontological sample processing

Analysis of the foraminiferal content of sediment samples involves the separation of foraminifera from the matrix by a combination of mechanical and chemical disaggregation techniques. These processes have been referred to as sample processing techniques. For extraction of foraminifera, each sample was washed, and wet sieved through a 63µm fraction to remove silt and clay particles in the laboratory. Then the washed residue of each sample was oven-dried at 50ºC for two to three hours and weighed using a digital scientific scale. The dried residue was evenly represented using a microsplitter till to 1 gram both for Quaternary and modern samples and stored in plastic sachets. The 1-gram sediment is sprinkled evenly over micropaleontological picking trays with grid intersection lines. They were examined under a Nikon SMZ1000 Stereozoom microscope.

2.4 Sorting and Identification

The micropaleontological accessories include a picking tray, a fine brush of 000 sizes, a needle, and micropaleontological slides. Tests of benthic foraminifera were picked from 1gram of sample with a damped thin brush and placed on micropaleontological slides. The slides are made up of cardboard with glass slides and aluminium cases. The slides were subsequently covered with glass covers and were stored in the repository unit in the Micropaleontology Laboratory, Department of Geological Sciences, Jadavpur University, Kolkata, India.

The identification of Arctic foraminifera was done based on the works of Loeblich and Tappan (1987) and papers for the Arctic region. The papers comprise the pioneering work of Feyling Hanssen (1964), Feyling-Hanssen and Karre Ulleberg (1984), Feyling-Hanssen (1990), Hald and Korsun (1997), Jernas et al. (2018), Cronin et al. (2019) and Seidenkrantz et al. (1995).

For the current study, all the complete specimens of calcareous benthic foraminifera from 1 gram of sediment sample were counted. Some tests of foraminifera show a poor preservation state. It includes dissolution evidence and breakage, or abrasion due to transport. Those tests are not considered for the analysis.

Selected foraminiferal specimens were observed under a Scanning Electron Microscope (SEM) to identify characteristic morphological features and pore size. The microphotographs have been taken in the DST-FIST sponsored SEM-EDS Laboratory Facility, Department of Geological Sciences, Jadavpur University.

2.5 Statistical methods

Diversity indices: Diversity indices are a mathematical measure of species diversity in a community. It provides more information about community composition than simply species richness (i.e., the number of species present); they also take the relative abundances of different species into account.

For the present study three types of such diversity indices have been used-1) Fisher's alpha index: It is the simplest diversity index that shows the mathematical relationship between the number of species (S) and the number of individuals (N) in the species. Fisher's α, whose iterative formula is given by $S = \alpha \ln [1 + (N/\alpha)]$. The values of α become high with a high diversity of the species. 2) Shannon's – Wiener Index: The Shannon diversity index (H) is represented as p (n/N). It is defined by the proportion of individuals of one particular species found (n) divided by the total no of individuals found (N), ln is the natural log; Σ is the sum of calculation. It is expressed as Shannon's $H= -\Sigma p_i \ln (p_i)$. 3)

Total Foraminiferal Number (TFN): It is calculated as the number of specimens per gram of dry sediment.

Total species richness (S): It is the number of different species present in the collected sample.

2.6 Chronology

Optically Stimulated Luminescence Dating (OSL): This method makes use of electrons trapped between the valence and conduction bands in the crystalline structure of quartz and feldspar. The difference between radiocarbon dating and OSL is that the former is used to date organic materials, while the latter is used to date minerals. The event that can be dated using OSL is; the mineral's last exposure to sunlight. To carry out OSL dating, coarse mineral grains of 100-200 μm or fine grains of 4-11 μm have to be extracted from the sample. The trapping sites are imperfections of the lattice impurities or defects of the mineral crystal. The ionizing radiation produces electron-hole pairs: Electrons are in the conduction band and holes are in the valence band. If the centre with the hole is a luminescence centre (radiative recombination centre) emission of light will occur. The photons are detected using a photomultiplier tube. The signal from the tube is then used to calculate the dose that the material has absorbed.

For the current study, this method has been largely applied to determine the age of the different sedimentary strata of examined sections of Kongsfjordhallet; Stuphallet, and Leinstranda. One sample from Stuphallet has been collected for chronology. The sample was sent to the Department of Geology, Lund University, Sweden for OSL dating. NCPOR is acknowledged for providing financial assistance for this OSL dating.

3.1 Introduction

The Arctic Ocean plays a major role in global ocean circulation and has undergone significant climatic changes in recent decades (Racine et al., 2018). While notable investigations related to climatic changes in different parts of the Arctic region have been carried out, i.e., Mangerud et al. 1998; further studies will enhance the knowledge of the characteristics of the past environment. Studies based on the present distribution of benthic foraminifera provide a better understanding of the region's environments (Lloyd et al., 2006). Benthic foraminifera assemblages in the Arctic region have significantly been used as a valuable proxy for estimating Quaternary paleoclimatic changes (Feyling Hanssen & Ulleberg, 1984; Miller et al., 1989; Lycke et al., 1992; Bergsten et al., 1998; Kubischta et al., 2010; Hovland 2014, and Chauhan et al., 2014). Due to their greater preservation potential, abundance, and diversity in marine waters, shelf areas, and fjords (Jernas et al., 2018), they are helpful, particularly when studying long records of climate changes along with other records, i.e., sedimentology and chronology, and accessibility of certain areas around the Arctic region is challenging (Husum et al., 2015). Studying the ecology and habitat of modern benthic foraminifera assemblage denotes the characteristics of the associated marine environment and, therefore, can be used as an analog for interpreting past environments (Hald & Steinsund, 1992; Jennings & Helgadottir, 1994).

3.2 Glacier proximal assemblages

The present study shows a greater abundance of stress-tolerant species, i.e., *Elphidium clavatum* (23-25%) and *Cassidulina reniforme* (36-45%) in the glacier proximal part of the fjords of Kongsfjorden (Station KO 1, KO 2, KO 3) and Krossfjorden (Station Kr 1, Kr 2, Kr 3) (Figure 3.1). This co-dominance of *C. reniforme* and *E. clavatum* typically characterizes glacier proximal foraminifera assemblages in Svalbard fjords with low faunal diversity (Korsun et al., 1995, Hansen and Knudsen 1995). Spitsbergen fjords foraminifera assemblages dominated by *C. reniforme* have been linked to winter-cooled waters in inner parts (Bergsten et al., 1998). The species prefer temperatures below 2˚C and stable salinity (>30 ppm) (Polyak et al., 2002). The assemblage is typical in Late Pleistocene records of the Barents Sea and Norwegian shelf, indicating glacier proximity (Korsun et al., 1995).

The present distribution of *C. reniforme* in this part of Kongsfjorden goes well with temperature (~3° C), salinity (~30ppm), and depths (51-86m) (Figure 3.3). At Krossfjorden *Cassidulina reniforme* occurs mainly at the proximal part (48%), in addition to *Elphidium clavatum* (28%), *Nonionellina labradorica* (16-25%), and *Islandiella helenae* (10-20%) (Figure 3.10).

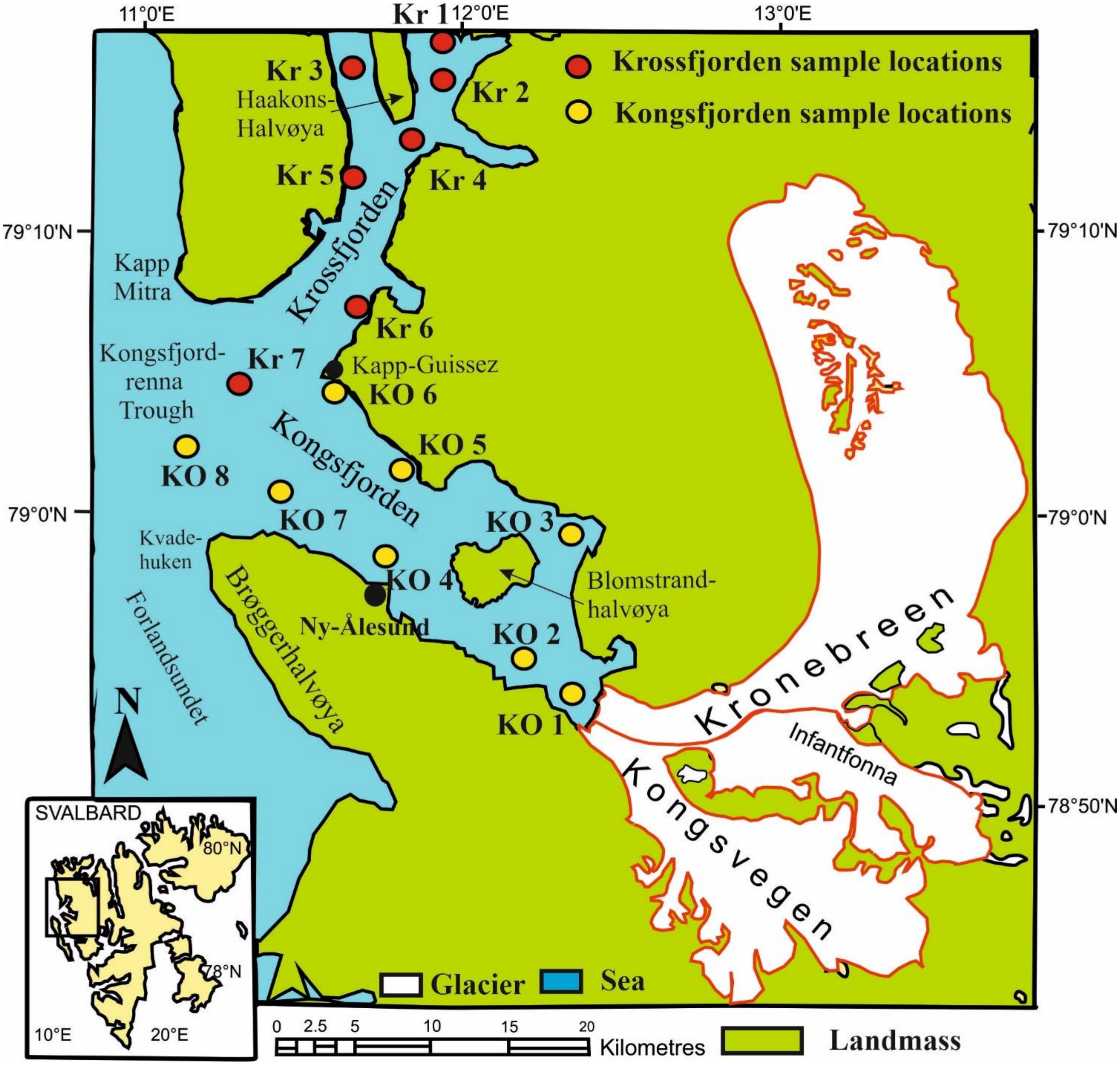


Figure 3.1: Location map of Kongsfjorden and Krossfjorden with sampling stations

One interesting observation of our study is the notable occurrence of *N. labradorica* and *Islandiella helenae* near the glaciers of Krossfjorden. *N. labradorica* is associated with temperate and saline

Transformed Atlantic Water (TAW) (Hald & Korsun, 1997). The assumption matches well with *Adercotryma* sp. (10%), which relates to Atlantic source waters (Hald & Korsun, 1997). Therefore, increased *N. labradorica* frequencies (Station Kr 2, Kr 3) in the proximal part of Krossfjorden indicate nutrient enrichment in the site (Korsun & Hald, 1998). In Kongsfjorden, the occurrence of the smaller size of foraminiferal tests (>63 µm) in the proximal part is high compared to larger tests (125µm) (Figures 3.6 and 3.7). The reason may be due to meltwater discharge and high sedimentation rate, affecting primary production in the plankton community and thereby diminishing foraminifera test sizes (Korsun et al., 1995). This result goes well with the study that has shown that the calving rate of the Kongsbreen glacier has increased in addition to increasing meltwater discharge during the melt season of 2016 (Schild et al., 2018). *Spiroplectammina biformis* and *Textularia* spp. (23%) (Figure 3.10) are the two characteristic species that dominate the agglutinated forms in this part of the fjord. *Textularia* spp. along with *S. biformis* have been identified in areas characterized by relatively cold, low-salinity Arctic water and often in glaciomarine sediments (Lloyd et al., 2006). This result matches well with cold (3° C) and less saline (20-30 ppm) environments in the proximal part of Kongsfjorden. The increased ratio of overall angular asymmetric to rounded symmetric forms (0.8) and the presence of agglutinated forms (10-20%) (Figure 3.8 and 3.9) has been attributed to the presence of cold water (>0 ° C), low salinity, low organic carbon (Jennings et al., 1994), rapid change in sea-ice cover (Rytter et al., 2002), increased sedimentation (Osterman et al., 1999), and oxygen deficiency (Saraswat et al., 2018) in the vicinity of glaciers. The abundance of agglutinated foraminifera in the proximal part has been attributed to meltwater flux and sediment load (Saraswat et al., 2018). In addition, *I. helenae* has been found in cold temperatures and range of salinities from 33-34.5 ppm in Polar Waters and flourishes with pulse productivity at sea-ice margins (Cage et al., 2021). The stable salinity (32-34ppm) and temperature (3-4° C) condition of Krossfjorden may be the reason behind this abundance of this foraminifera species. Studies have shown that benthic fauna uses macroalgal detritus as their food which also constitutes a significant source of the Arctic fjord's food web (Jernas et al., 2018). So, it can be assumed that Atlantic waters influence the fjord, and the concentration of microalgal detritus has been elevated, have made the Krossfjorden ecosystem more productive and suitable for the growth of *N. labradorica* and *Islandiella helenae*. Among the agglutinated taxa, *Textularia* sp. occurs only near glaciers (Kr 1). However, the deficiency of oxygen and low organic carbon in the proximal glacier environment cannot be ruled out, supported by the abundance of agglutinated foraminifera (Figure 3.18 and 3.19) in the proximal part and the enhanced ratio (0.2) of angular asymmetric by rounded symmetric (Figure 3.19).

Figure 3.2: Kongsfjorden glacial proximal part and tidewater glaciers

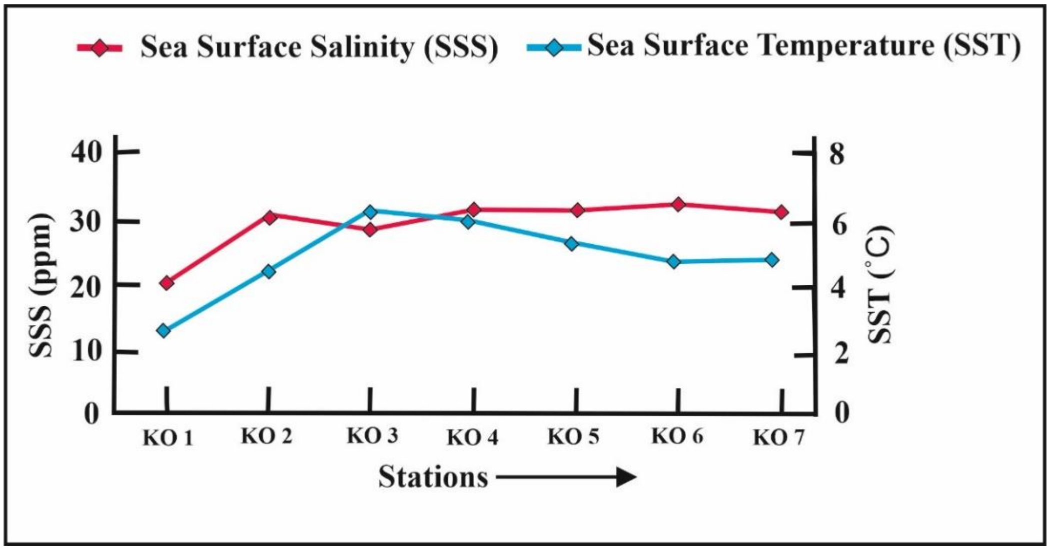


Figure 3.3: Sea surface Salinity and Sea surface temperature plot for Kongsfjorden

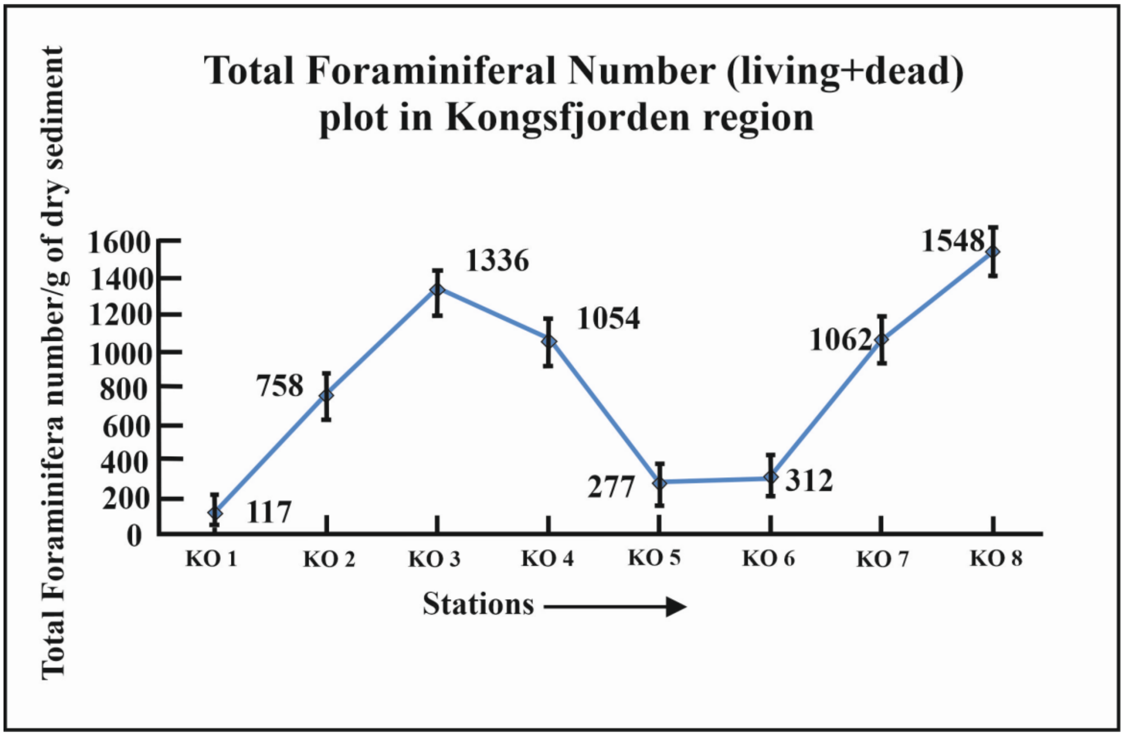


Figure 3.4: Total foraminifera number (TFN) plot for Kongsfjorden

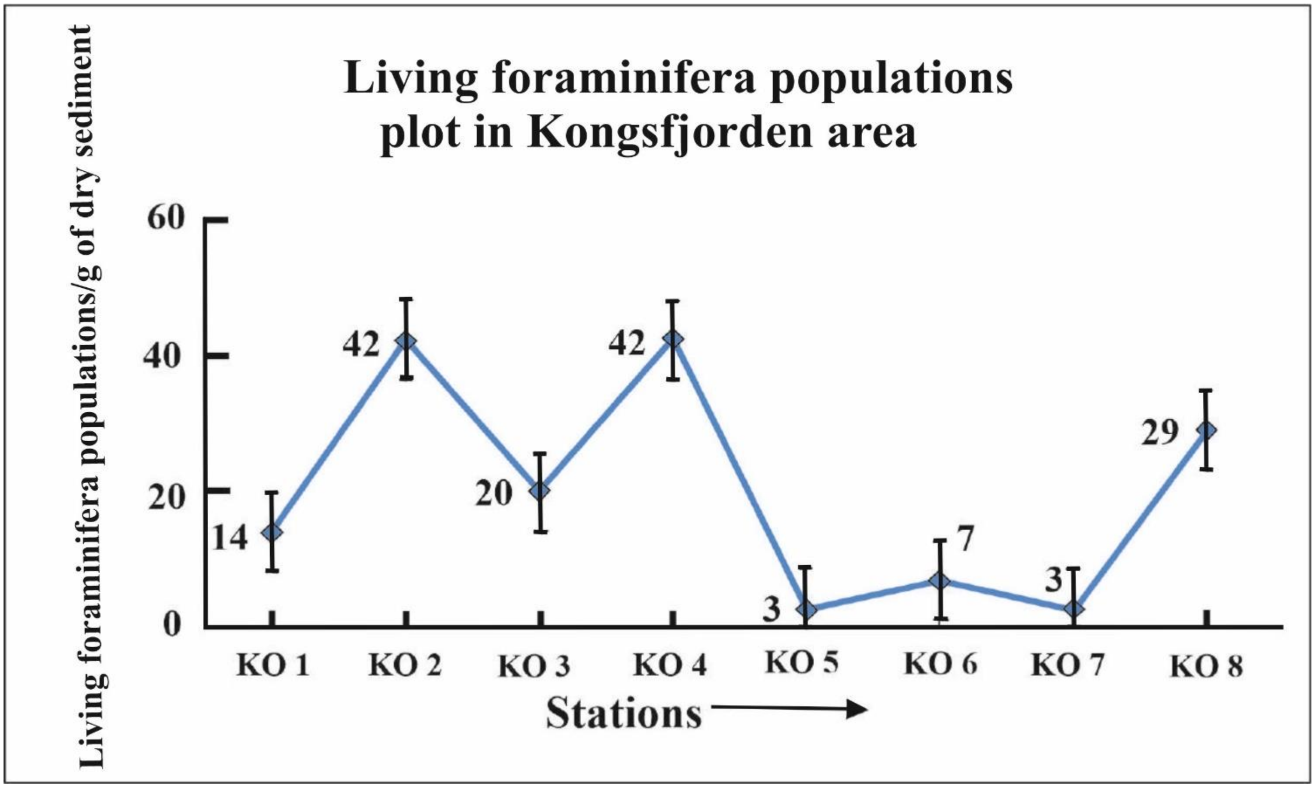


Figure 3.5: Living foraminifera plot for Kongsfjorden

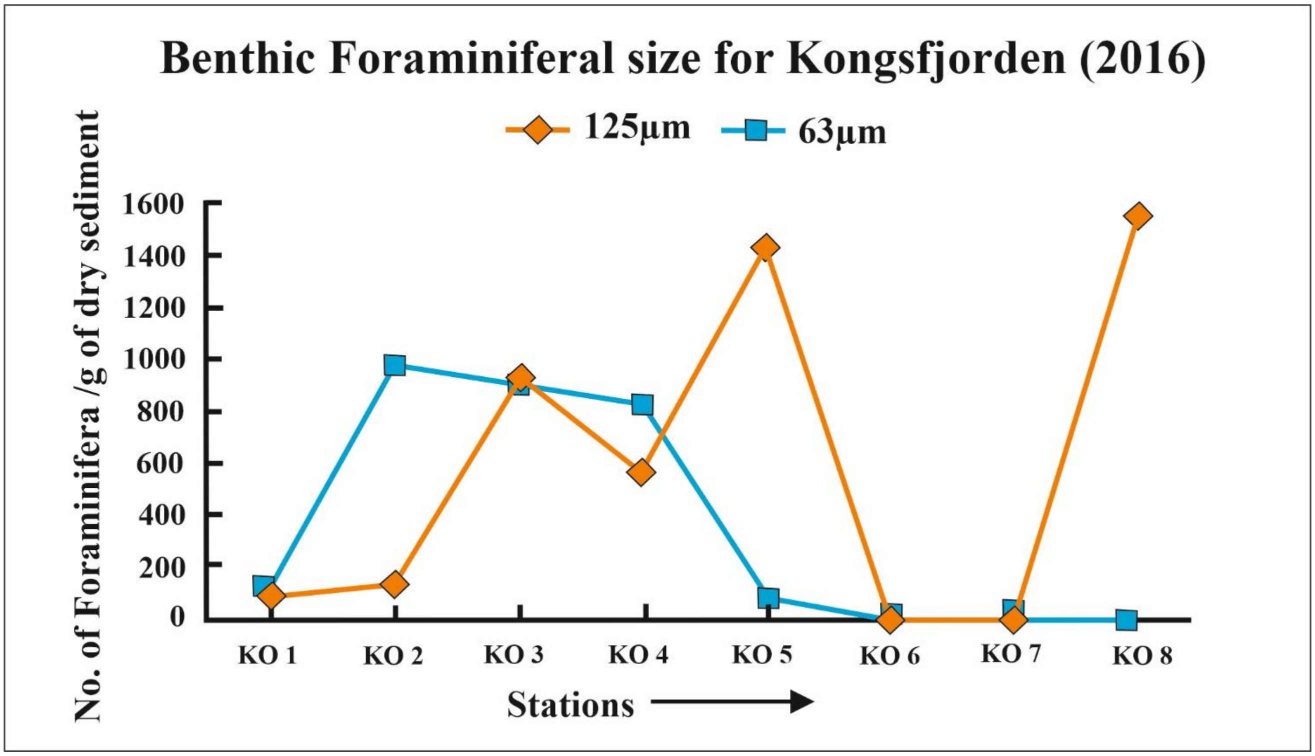


Figure 3.6: Benthic foraminifera size variation in Kongsfjorden 2016

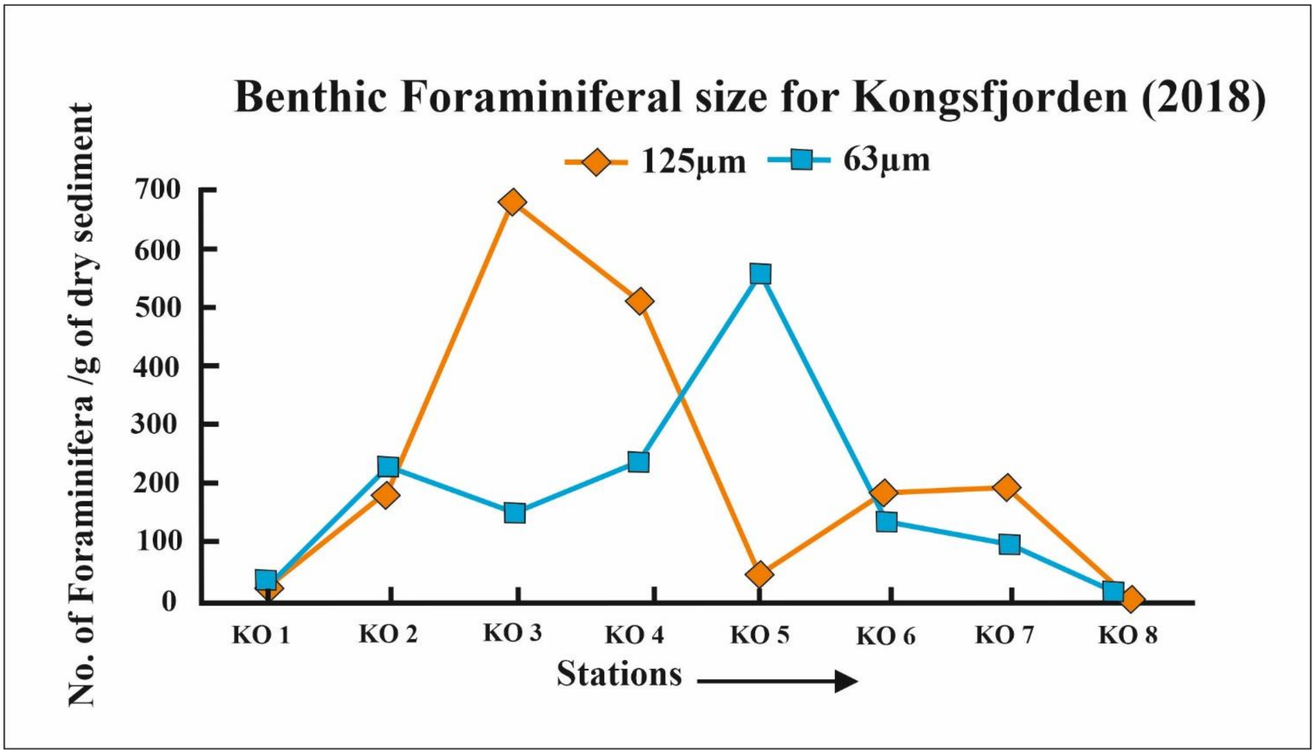


Figure 3.7: Benthic foraminifera size variation in Kongsfjorden 2018

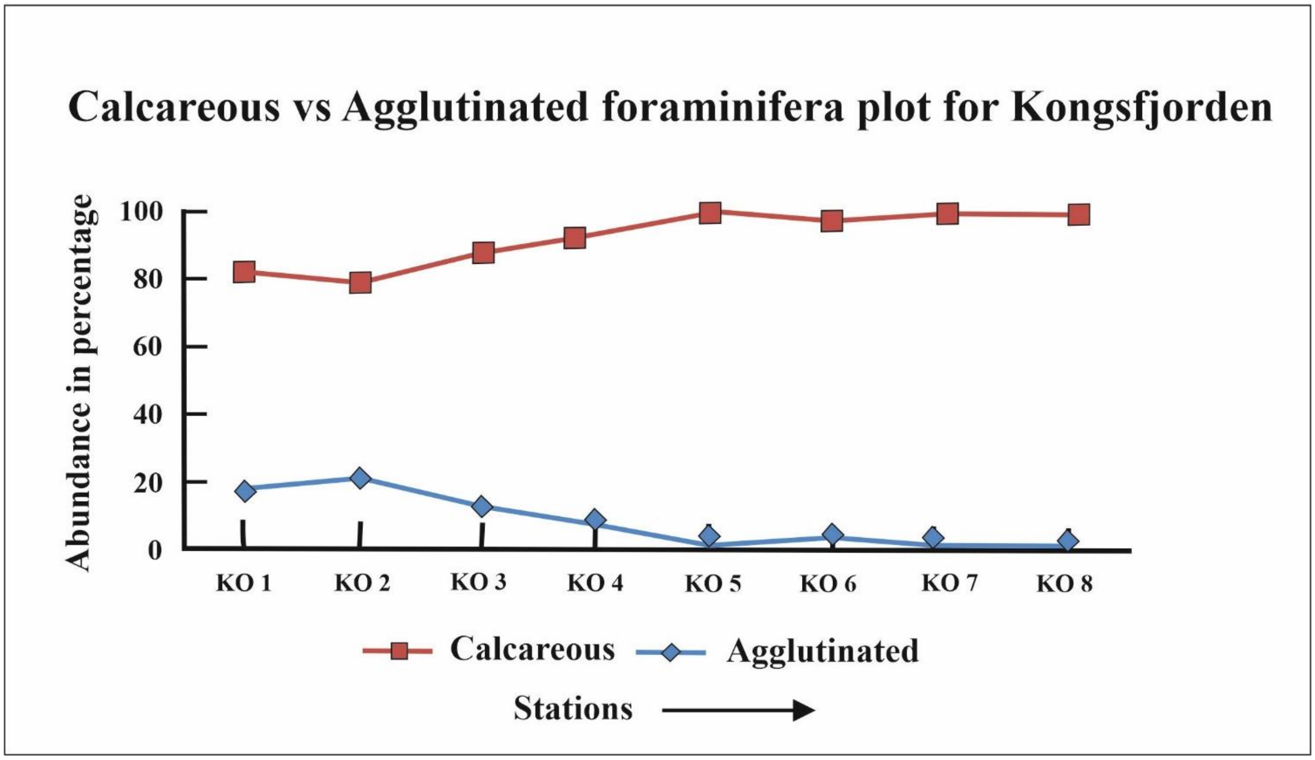


Figure 3.8: Calcareous and agglutinated foraminifera plot for Kongsfjorden

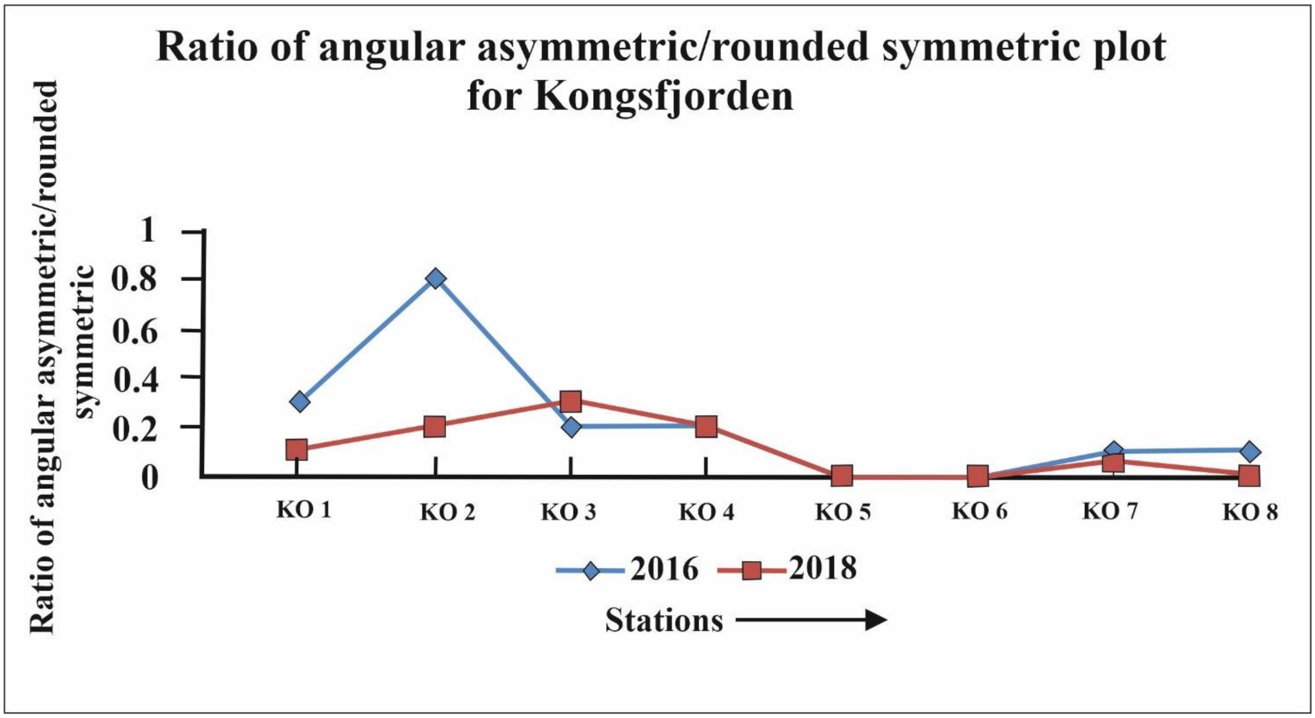


Figure 3.9: Ratio of angular asymmetric to rounded symmetric plot for Kongsfjorden

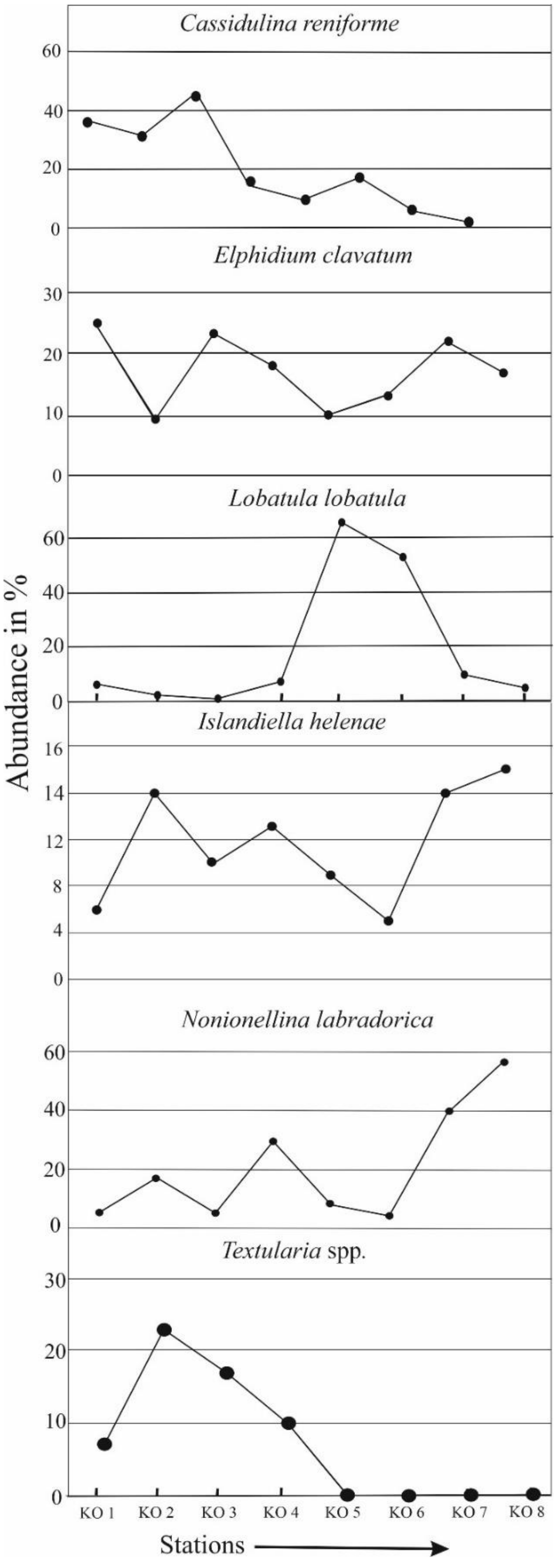


Figure 3.10: Dominant benthic foraminifera abundance percentage in Kongsfjorden

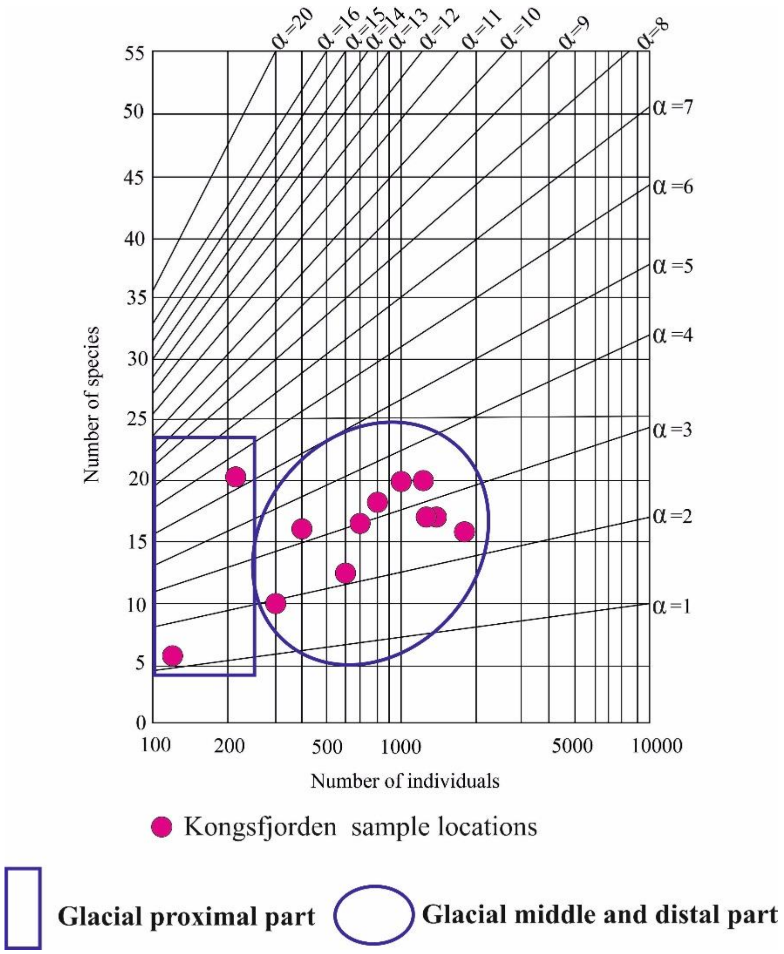


Figure 3.11: Fisher's alpha diversity index for Kongsfjorden

3.3 Glacial intermediate assemblages

The intermediate part of the fjords characterizes *Nonionellina labradorica* (31-46%), *Islandiella helenae* (12-14%), and *Lobatula lobatula* (45-60%) assemblages. A significant amount of rounded calcareous foraminifera has been found in the middle (Station KO 4 and KO 5) parts of the Kongsfjorden. This high amount of calcareous rounded benthic foraminifera in the middle indicates elevated oxygen concentration in the water, a low sedimentation rate, a greater distance from glaciers, and an increase in organic carbon (Saraswat et al., 2018). The presence of rounded agglutinated foraminifera, i.e., *Adercotryma* sp., only in the middle part relates to the presence of Transformed Atlantic Water (Hald & Korsun, 1997) at a greater distance from glaciers. This result indicates Atlantic -sourced waters influence the middle part of Kongsfjorden (Lloyd et al., 2006). However, the increase in calcareous angular foraminifera species *Stainforthia loeblichi* in the middle part (5-6%)

indicates local oxygen-reduced conditions (Saraswat et al., 2018). *Lobatula lobatula* in coarse sediments (Station KO 5) in the mid-fjord, close to the coast, indicates higher bottom currents in that region. However, this assemblage may vary in the fjords of Svalbard; i.e., the co-occurrence of *Cassidulina reniforme*, *Elphidium excavatum*, *Nonionellina labradorica* and *Islandiella helenae* assemblage in Krossfjorden (Station Kr 4, Kr 5). The assemblage indicates less glacial activity, regular saline, a cold environment with high organic carbon and phytoplankton density (Korsun & Hald, 1998). This assumption is consistent with the abundance of angular calcareous foraminifera *Stainforthia loeblichi* (12%) (Figure 3.21) in local oxygen restricted with a high organic carbon zone in the middle part (Saraswat et al., 2018). This causes a high angular asymmetric to the rounded symmetric ratio observed in 2016 (Figure 3.19). However, a sudden decrease in the foraminiferal population is observed in the middle part, which denotes low food availability and depleted oxygen concentration. The notable presence of distal glacial species *Lobatula lobatula* reflects a higher energy environment due to suspended organic carbon enrichment (Korsun & Hald, 1998).

Figure 3.12 : Krossfjorden glacial proximal region and tidewater glaciers

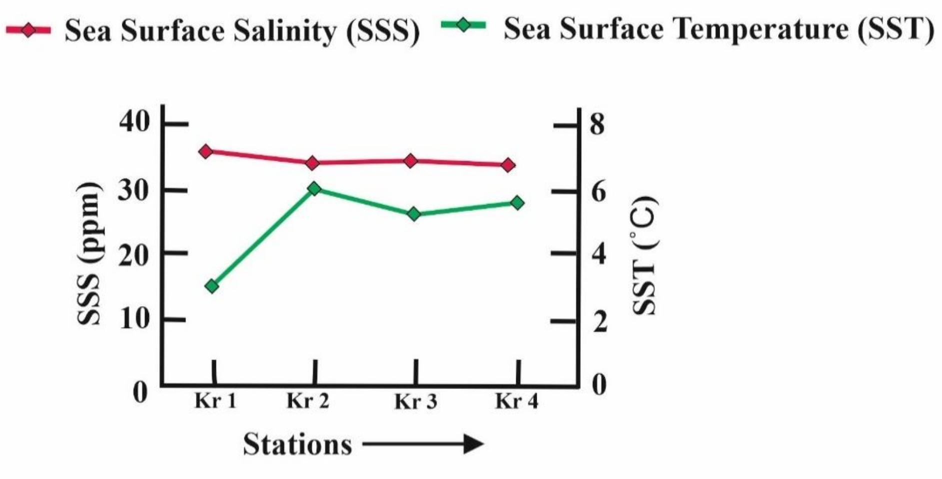


Figure 3.13: Sea surface salinity and Sea surface temperature plot for Krossfjorden

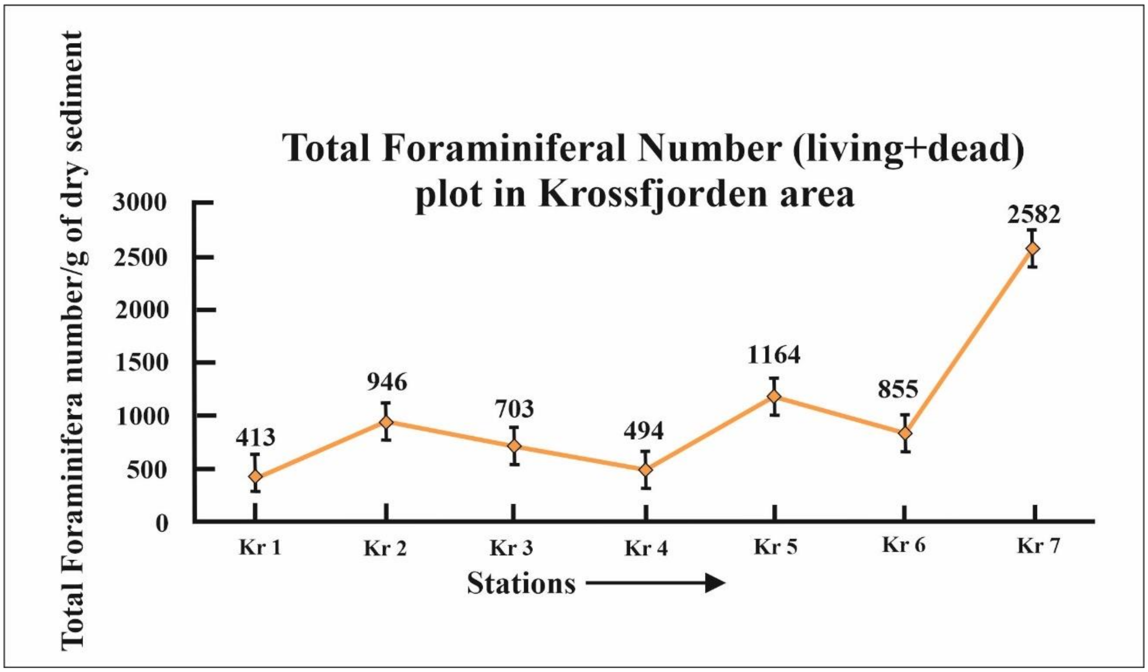


Figure 3.14: Total foraminifera number (TFN) plot for Krossfjorden

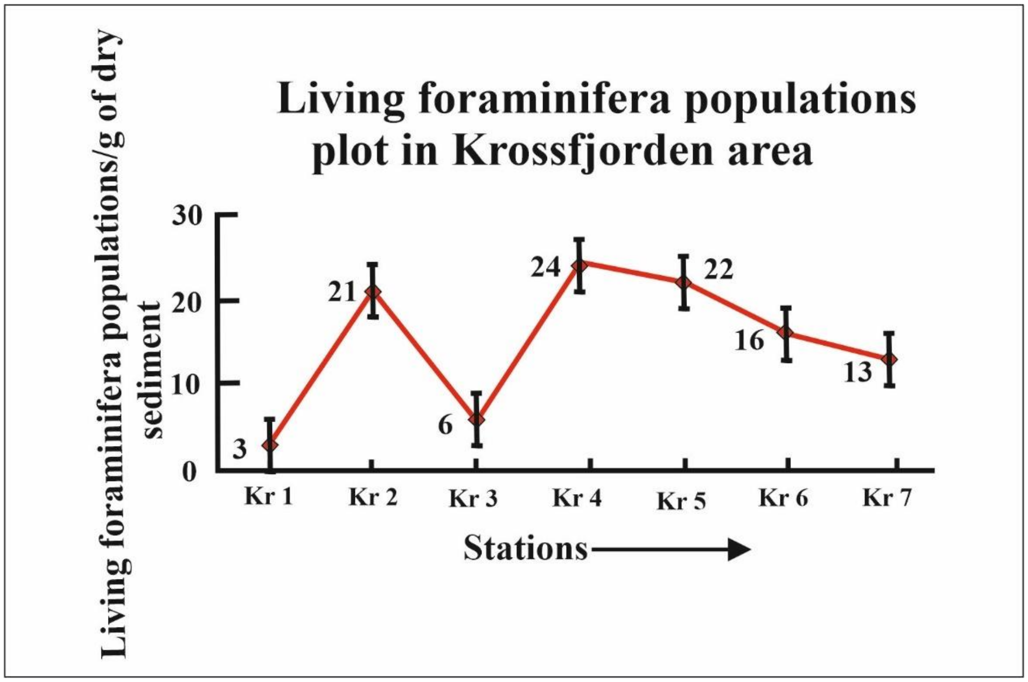


Figure 3.15: Living foraminifera plot for Krossfjorden

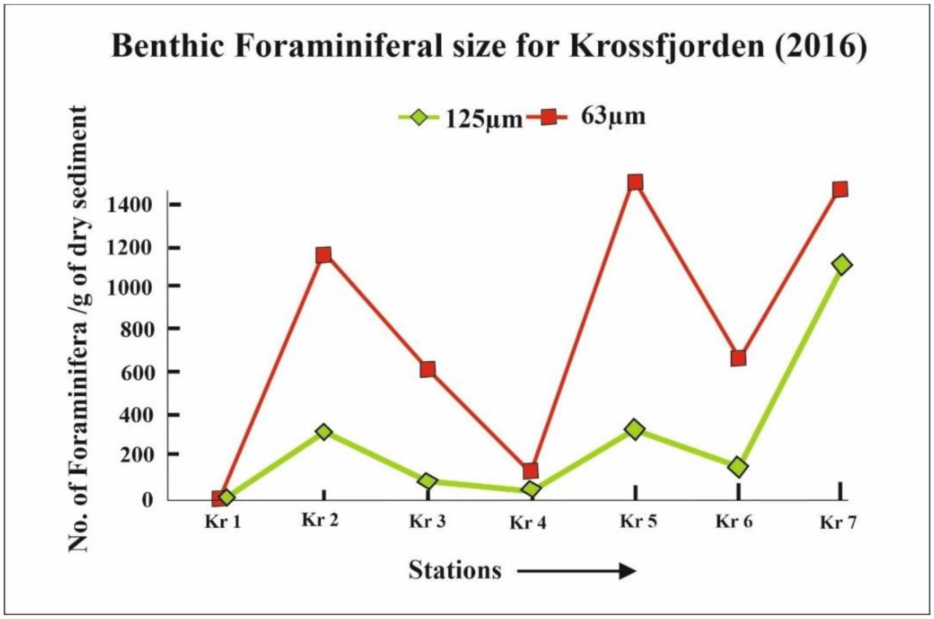


Figure 3.16: Benthic foraminifera size variation in Krossfjorden (2016)

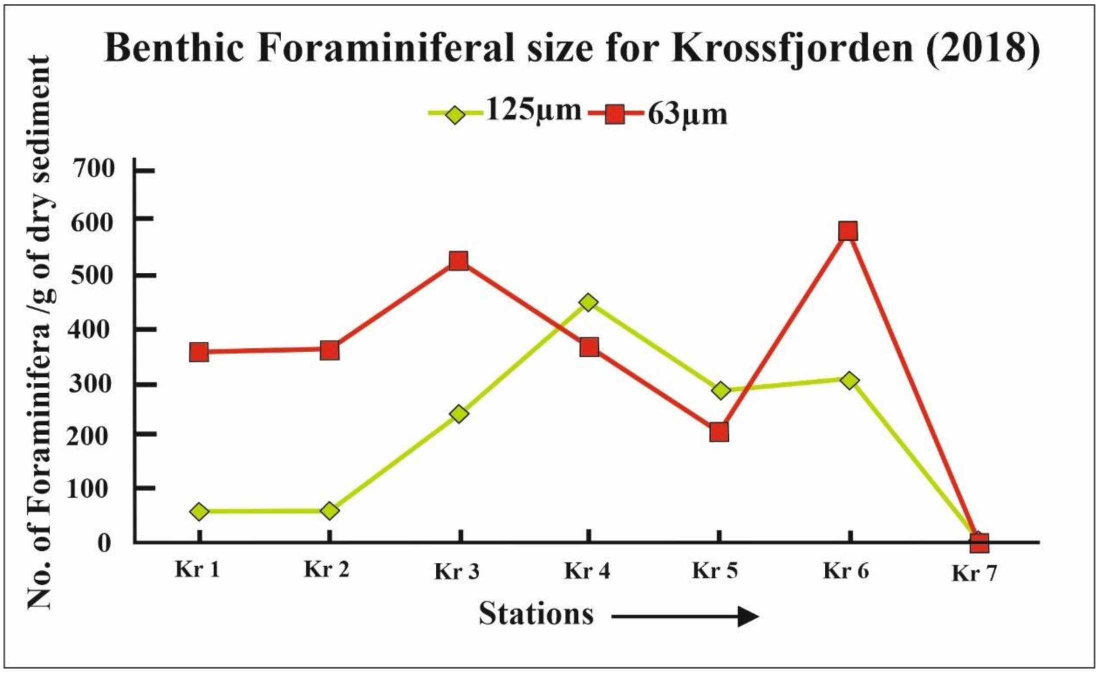


Figure 3.17: Benthic foraminifera size variation in Krossfjorden (2018)

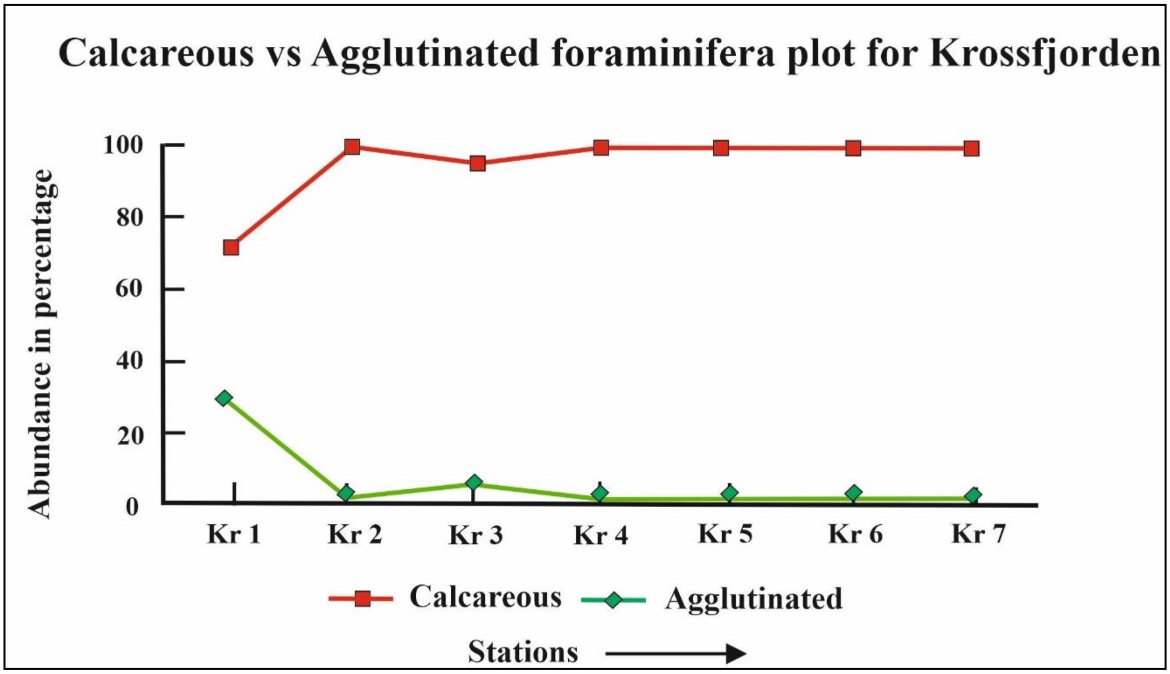


Figure 3.18: Calcareous and agglutinated foraminifera plot for Krossfjorden

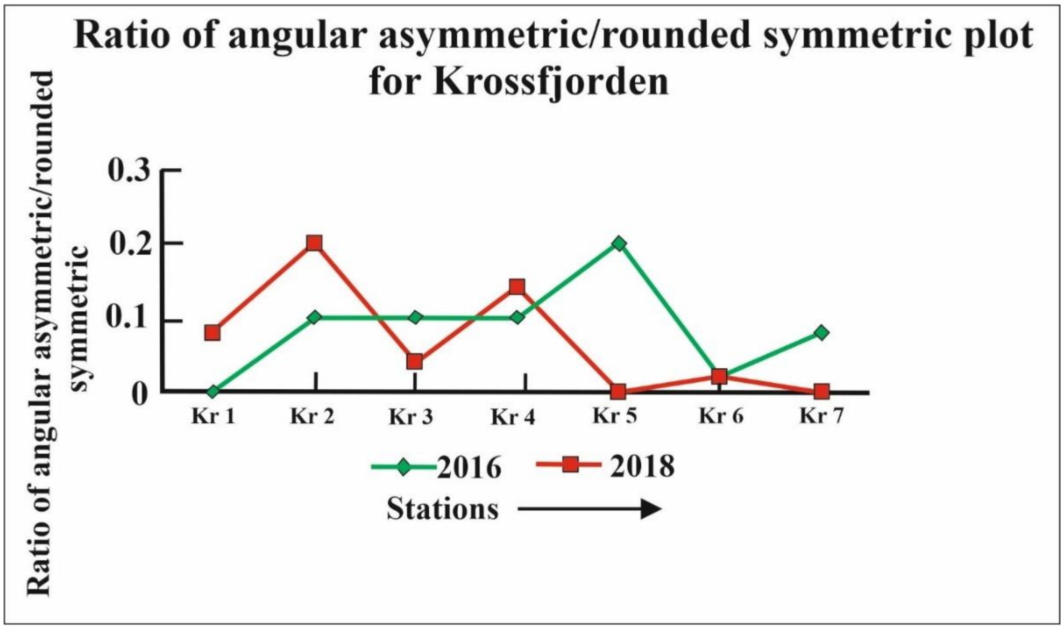


Figure 3.19: Angular asymmetric to rounded symmetric plot for Krossfjorden

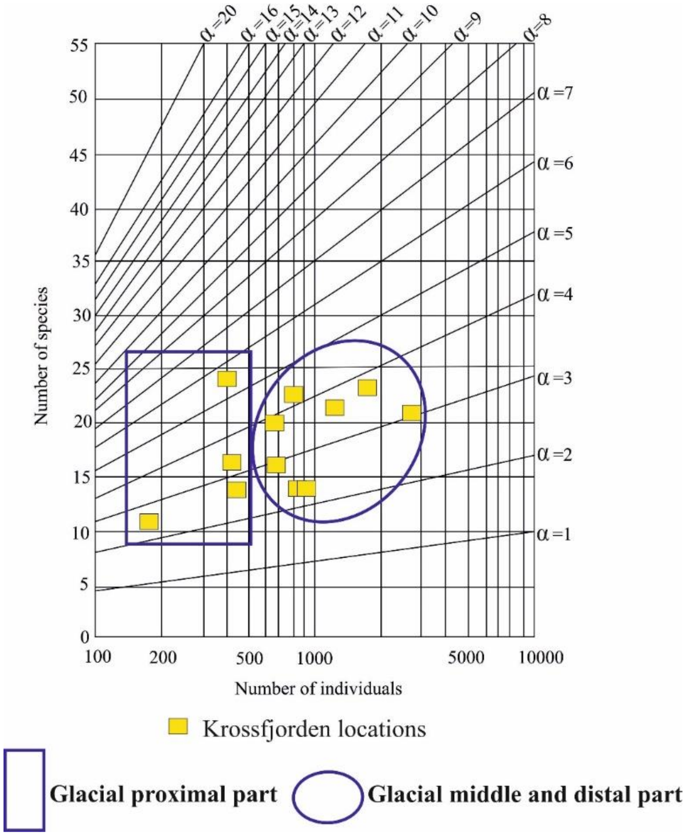


Figure 3.20: Fisher's alpha diversity plot for Krossfjorden

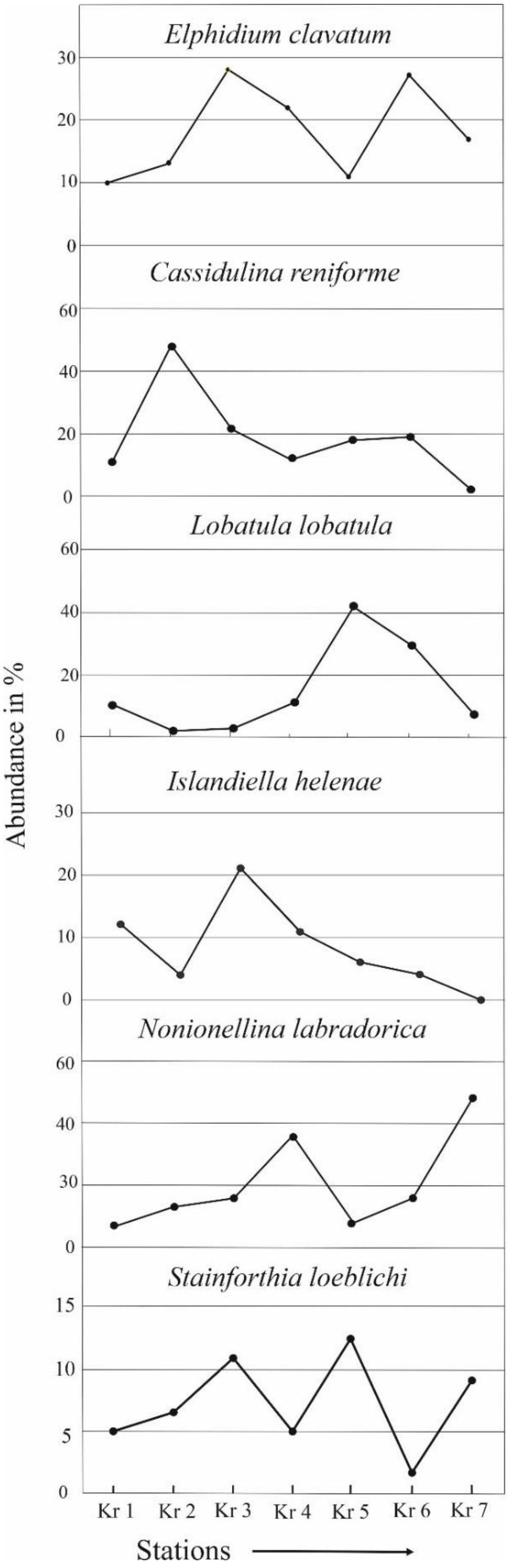


Figure 3.21: Dominant benthic foraminifera abundance in Krossfjorden

3.4 Glacier distal and shelf assemblages

Islandiella helenae, one of the characteristic foraminifera species, in the distal part of the fjord (KO 6, KO 7, KO 8) relates to high, stable salinity and summer ice-age productivity, while the presence of *Nonionellina labradorica* indicates increased food availability (Polyak et al., 2002). The presence of *N. labradorica* constitutes the bulk of the foraminiferal population at the distal sediment (Kr 6, Kr 7), along with rounded symmetric calcareous forms, i.e., *Islandiella helenae* and *Lobatula lobatula* indicates a well-productive, oxygenated and nutrient-rich environment. The high diversity and abundance of well-rounded calcareous foraminifera towards the distal part of the fjords represent the presence of well-oxygenated water (Saraswat et al., 2018). The wide occurrence of *N. labradorica* (Figure 3.10) in the sediment is ascribed to the connection between the outer basin and shelf at a deeper level that causes a significant exchange of water masses and intrusion of Atlantic water (AW) for Kongsfjorden. This interaction enhances the availability of nutrients and food concentration that helps to proliferate *N. labradorica*, which is not frequent in other fjords (Jernas et al., 2018). The result indicates elevated food concentration at least seasonally in the sediment in this part of Kongsfjorden (Polyak et al., 2002).

This preference to proliferate towards the distal glacier of *N. labradorica* significantly differs from its ubiquitous distribution in Kongsfjorden observed by Jernas et al., 2018. Based on the cumulative distribution of the most dominant benthic foraminifera, they concluded that from 2005 to 2008, the fjord was characterized by single benthic foraminifera *N. labradorica* that occupies significant proportions, strikingly different from other northern and southern fjords of Svalbard. In the context of morpho groups, the rounded calcareous symmetrical groups are more widespread in the distal to the Kongsfjorden than in the study by Saraswat et al., 2018, which have shown calcareous rounded symmetrical forms are absent in distal Kongsfjorden, while they are maximum at the confluence of two fjords and inner part of the Kongsfjorden. In this study, angular agglutinated foraminifera, i.e., *Textularia* spp., are dominant compared to the previous study by (Jernas et al., 2018), where rounded agglutinated foraminifera *Adercotryma glomeratum*, *Recurvoides* spp., and *Labrospira crassimargo* have been reported as the dominant group. The present study shows rounded agglutinated foraminifera are considerable (4-5%) in the middle and scarce (1%) in the distal part. The more significant amount of calcareous benthic foraminifera in the current study matches well with a notable preceding study by (Hald & Korsun, 1997) at Krossfjorden, which showed the presence of more than

75% of calcareous benthic foraminifera assemblage throughout the fjord. *N. labradorica* (36-48%) and *E. clavatum* (28%) in the present study resemble the previous one and differ in the presence of *Cassidulina reniforme* (22-48%); followed by *Islandiella helenae* (21%) and *Stainforthia loeblichi* (12%). *S. loeblichi* has been found to occur in less than 10% of the previous study. *Adercotryma glomeratum*, *Recurvoides* sp., and *Labrospira crassimargo* were recorded in the distal part. The present study includes *L. crassimargo* and *Recurvoides* sp. less than 1%. The present study matches the dominance of calcareous fauna and rounded agglutinated forms.

3.5 Summary

So, in summary, the environment of fjords can be divided into three parts. The abundance of agglutinated foraminifera and stress-tolerant species in the glacier proximal part indicates high turbidity, low salinity, low organic carbon, oxygen-restricted zone, meltwater runoff, sedimentation, high ratio of angular asymmetric to rounded symmetric forms, and low count of total benthic foraminifera. The environment gradually changes to increased organic productivity and oxygen concentration in the middle part by accommodating increased concentrations of rounded calcareous. It characterizes as a more productive, nutrient-enriched zone with the occurrence of *N. labradorica* and *I. helenae*. The environment experiences the local oxygen-depleted zone characterized by a sudden decrease in total foraminifera number and angular asymmetric forms increase in abundance in the middle part. Towards the distal part, the environment experiences high surface primary productivity, nutrient, and food availability, diatoms concentrations (Jernas et al., 2018), well-oxygenated waters, and high organic carbon, which is reflected by the presence of diverse (Figure 3.11,3.20) rounded calcareous specimens along with *Nonionellina labradorica* and the scarcity of agglutinated fauna.

Foraminifera assemblages	**Region of the Kongsfjorden**	**Characteristic Environment**
Cassidulina reniforme-*Elphidium clavatum*-*Textularina* spp. and *Spiroplectammina biformis*	The glacial proximal region, close to Kongsvegen and Kronebreen glacier	Turbid, low saline, increased nutrients, high angular to rounded foraminifera ratio, low total foraminifera number, and living foraminifera specimens
Nonionellina labradorica, *Islandiella helenae* *Cassidulina reniforme* *Elphidium clavatum* *Textularia* spp., *Alveolophragmium crassimargo,* and *Adercotryma glomeratum*	Glacial central region	Presence of Transformed Atlantic water, higher oxygen concentration, High total foraminifera, and living foraminifera specimens, high diversity
Lobatula lobatula, C. reniforme and *Elphidium clavatum*	Glacial distal and coastal region	Higher bottom currents, low total organic carbon (TOC), elevated oxygen concentration, absence of agglutinated fauna, medium to high diversity
Nonionellina labradorica and *Islandiella helenae*	Glacial distal (Fjord end) and shelf areas	High surface primary productivity, well-oxygenated water, high diversity, and an abundance of calcareous rounded forms.

Table 3.1: Summary of foraminifera assemblages and marine environments of Kongsfjorden

Foraminifera assemblages	**Region of the Krossfjorden**	**Characteristic Environment**
Cassidulina reniforme, *Elphidium clavatum*, and *Nonionellina. Labradorica*, *Textularia* sp.	Glacier proximal region	Less glacial activity, a less saline, cold, and turbid environment, increased nutrients, high angular to rounded foraminifera ratio, a Lesser number of total foraminifera
Nonionellina labradorica, *Islandiella helenae*, *Stainforthia loeblichi*, and *Adercotryma* sp.	Glacier central region	Temperate and saline Transformed Atlantic water, the concentration of microalgal detritus, significant angular to rounded ratio, high total foraminifera specimens
N. labradorica, *Islandiella helenae, Lobatula lobatula*	Glacial distal and shelf region	Well-productive, oxygenated, and nutrient-rich environment, high diversity, high abundance of total foraminifera number, and rounded specimens

Table 3.2: Summary of foraminifera assemblages and marine environments of Krossfjorden

Taxa	**References**
Labrospira crassimargo	Norman, 1892
Adercotryma glomeratum	Brady, 1878
Ammotium cassis	Parker, 1870
Astrononion hamadaense	Asano, 1950
Buccella frigida	Cushman, 1922
Bolivinellina pseudopunctata	Höglund, 1947
Cassidulina reniforme	Nørvang, 1945
Lobatula lobatula	Walker and Jacob, 1798
Dentalina sp.	Cushman, 1923
Elphidium clavatum	Cushman, 1930
Elphidium bartletti	Cushman, 1933
Cribroelphidium sp.	Cushman and Brönnimann, 1948
Elphidium subarcticum	Cushman, 1944
Eggerella sp.	Cushman, 1922
Fissurina sp.	Fée, 1825
Globobulimina sp.	Bailey, 1984
Globocassidulina sp.	Voloshinova, 1960
Glandulina sp.	d'Orbigny,1839
Haynesina orbiculare	Brady, 1881
Islandiella helenae	Feyling Hanssen& Buzas,1976

Taxa	**References**
Islandiella norcrossi	Cushman, 1933
Melonis affinis	Reuss,1851
Nonionellina labradorica	Dawson, 1860
Lagena sp.	Röding, 1798
Pyrgo sp.	Defrance, 1824
Quinqueloculina sp.	d'Orbigny, 1826
Recurvoides turbinatus	Brady, 1881
Reophax scorpiurus	Montfort, 1808
Robertina sp.	d'Orbigny, 1846
Spiroplectammina biformis	Parker & Jones, 1865
Stainforthia loeblichi	Feyling-Hanssen, 1954
Textularia earlandi	Parker, 1952
Textularia torquata	Parker, 1952
Trifarina fluens	Todd in Cushman and McCulloch,1948
Uvigerina sp.	d'Orbigny, 1826

Table 3.3 Foraminiferal list of recent fjord sediments, High Arctic with the original reference.

SCANNING ELECTRON MICROSCOPE IMAGES OF ARCTIC FORAMINIFERA

(DESCRIPTION OF PLATE 1)

Figure 1. *Labrospira crassimargo* (S)

Figure 2. *Adercotryma glomeratum* (S)

Figure 3. *Astrononion hamadaense* (S)

Figure 4. *Buccella frigida* (U)

Figure 5. *Buccella frigida* (Sp)

Figure 6. *Cassidulina reniforme* (S)

Figure 7. *Lobatula lobatula* (U)

Figure 8. *Lobatula lobatula* (Sp)

Figure 9. *Dentalina* sp. (S)

Figure 10. *Elphidium clavatum* (S)

Figure 11. *Fissurina* sp. (S)

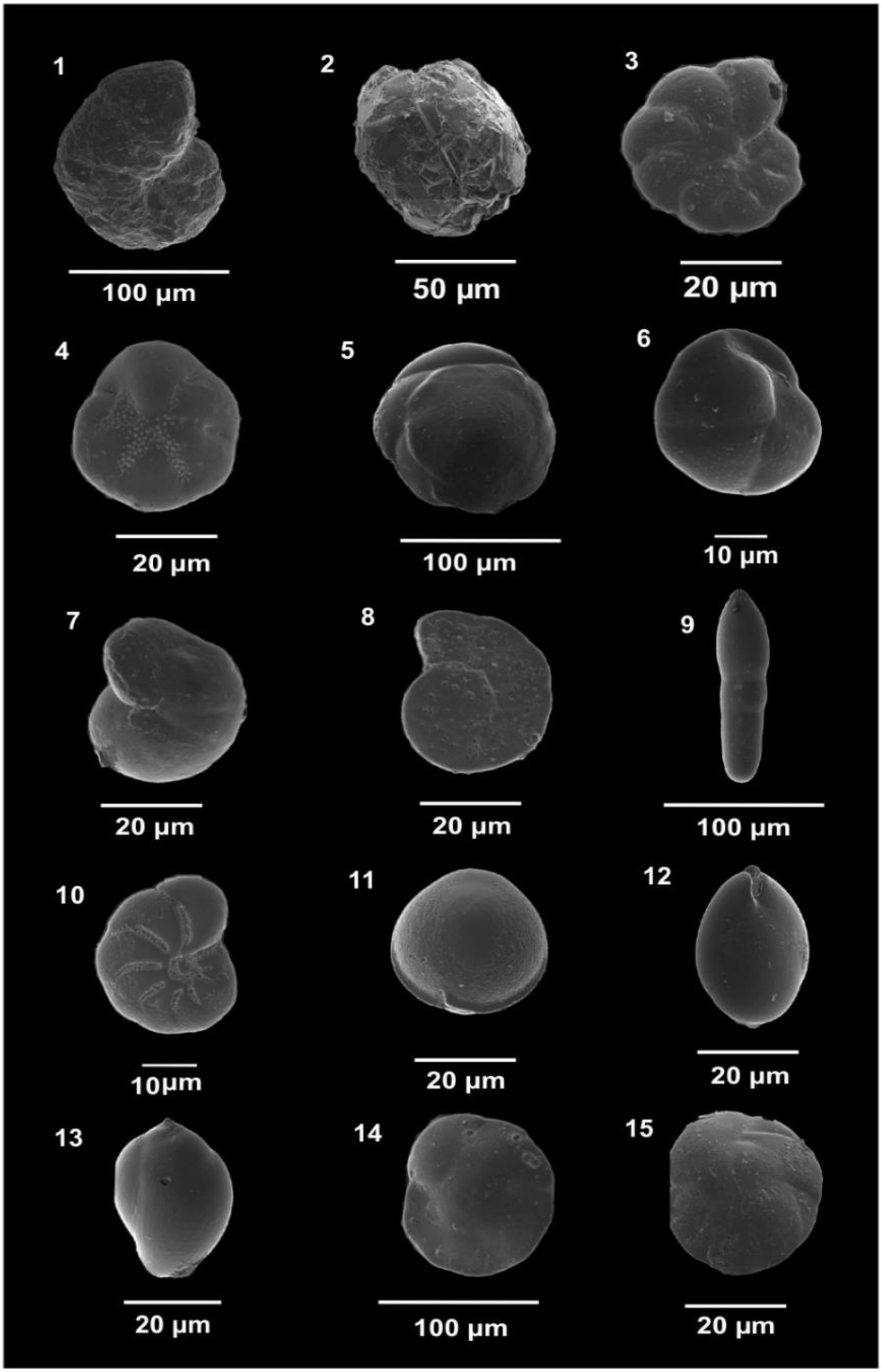
Figure 12. *Globobulimina* sp. (Ap)

Figure 13. *Globobulimina* sp. (S)

Figure 14. *Islandiella norcrossi* (Sp)

Figure 15. *Islandiella helenae* (Sp)

U-Umbilical view, Ap-Apertural view, Sp-Spiral view, S-side view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(DESCRIPTION OF PLATE 2)

Figure 1. *Haynesina orbicularis* (S)

Figure 2. *Lagena* sp. 1 (S)

Figure 3. *Lagena* sp. 2 (S)

Figure 4. *Melonis affinis* (S)

Figure 5. *Nonionellina labradorica* (S)

Figure 6. *Nonionellina labradorica* (Ap)

Figure 7. *Portatrochammina* sp. (S)

Figure 8. *Quinqueloculina* sp. (S)

Figure 9. *Recurvoides turbinatus* (S)

Figure 10. *Recurvoides turbinatus* (Ap)

Figure 11. *Stainforthia loeblichi* (Ap)

Figure 12. *Spiroplectammina biformis* (S)

Figure 13. *Textularia earlandi* (S)

Figure 14. *Trifarina fluens* (S)

Figure 15. *Bolivinellina* sp. (S)

Figure 16. *Uvigerina* sp. (S)

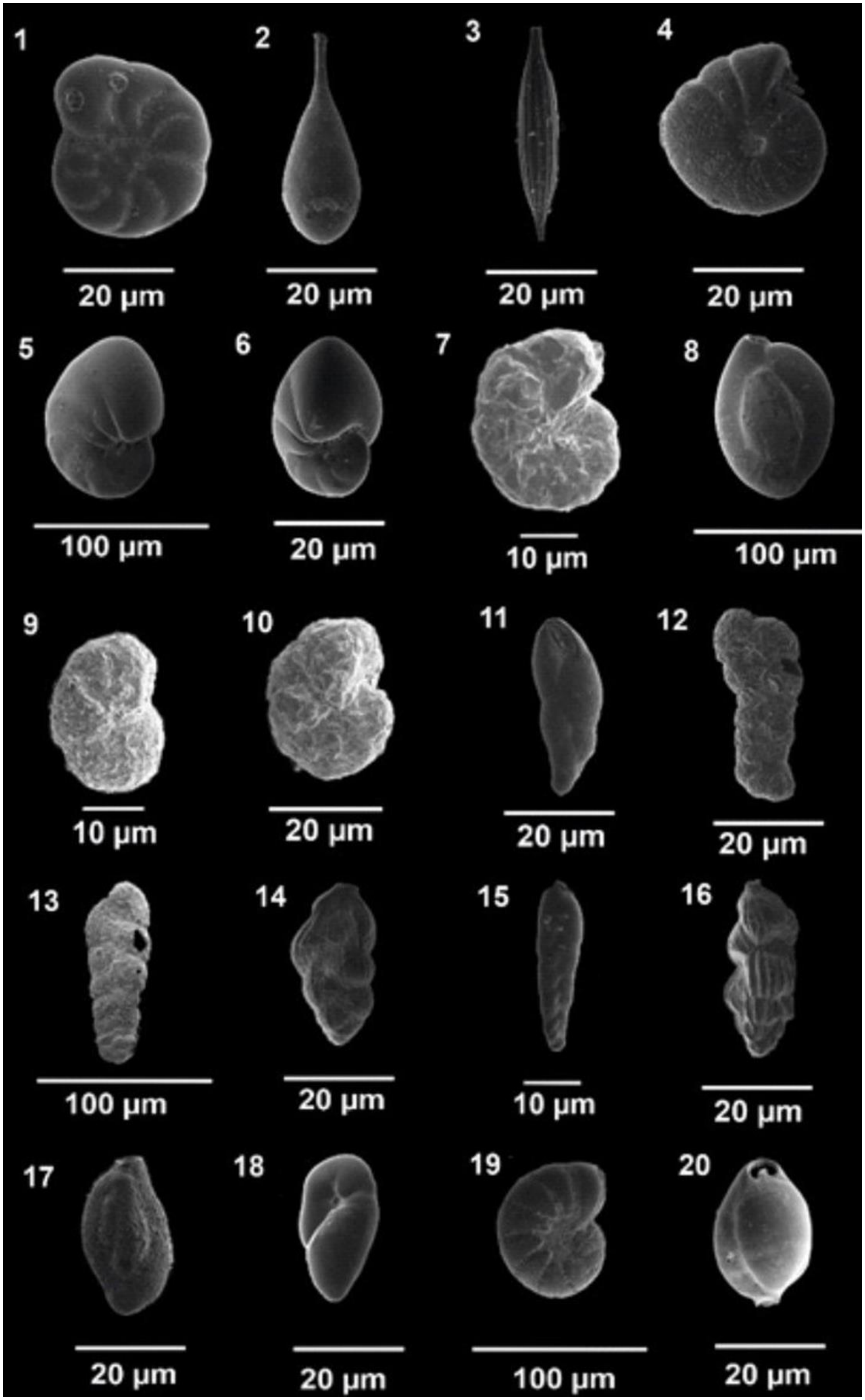
Figure 17. *Miliammina fusca* (S)

Figure 18. *Robertina* sp. (S)

Figure 19. *Elphidium bartletti* (S)

Figure 20. *Pyrgo* (S)

U-Umbilical view, Ap-Apertural view, Sp-Spiral view, S-side view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DESCRIPTION OF PLATE 3

Figure 1. *Reophax* sp 1. (S)

Figure 2. *Reophax* sp 2. (S)

Figure 3. Reophax sp 3. (S)

Figure 4. *Portatrochammina bipolaris* (S)

Figure 5. *Ammotium* sp. (S)

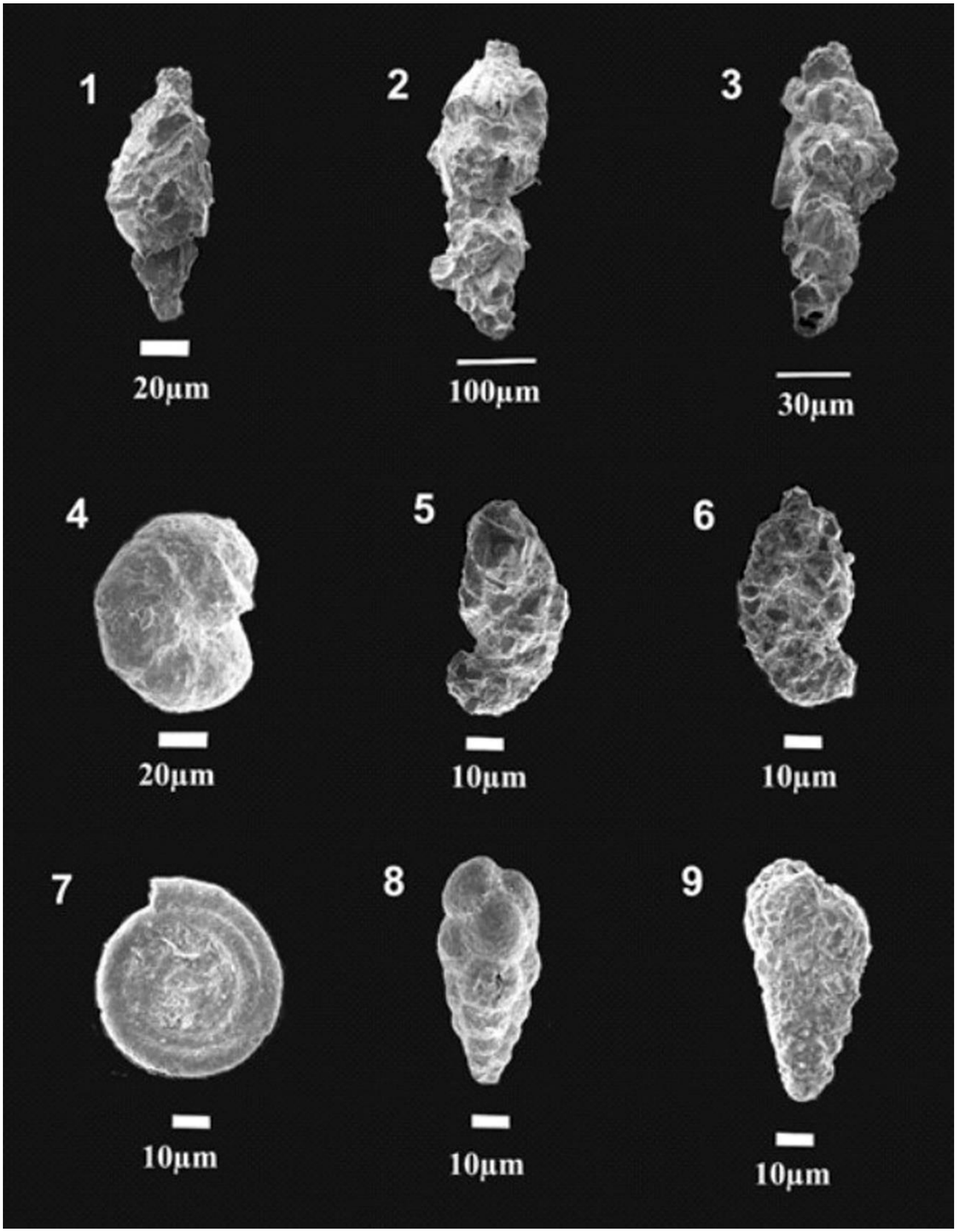
Figure 6. *Ammotium* sp. (S)

Figure 7. *Ammodiscus* sp. (S)

Figure 8. *Eggerella* sp. (S)

Figure 9. *Textularia torquata* (S)

U-Umbilical view, Ap-Apertural view, Sp-Spiral view, S-side view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Chapter 4 Quaternary Deposits of Kongsfjordhallet, Stuphallet and Leinstranda

4.1 Introduction

Kongsfjordhallet is a 6 km long and 12 km wide gently sloping plain terminated by steep coastal cliffs at the northern side of the Kongsfjorden fjord in the north-western part of Spitsbergen, Svalbard archipelago (74°-81° N; 10°-35° E). The largest portion of the Kongsfjordhallet plain is shielded by Quaternary deposits such as till and raised beach deposits. The oldest sediments are of the Early Pleistocene age (Houmark-Nielsen & Funder 1999) whereas the youngest succession is of the Weichselian age (Alexanderson et al., 2018). The dominating deposits are glaciomarine diamictites and littoral gravels.

Figure 4.1: Quaternary outcrop at Kongsfjordhallet (site 104)

4.1.1 Quaternary sections of Kongsfjordhallet

At Kongsfjordhallet, Houmark-Nielsen & Funder (1999) identified three primary successions comprising glaciations-deglaciations events from the Early to Late Pleistocene. Alexanderson et al. (2018) resolved additional events – at least five glaciations – in the upper part of the stratigraphy. Including other stratigraphic sites in the area, Alexanderson et al. (2018) could show that at least six glacial advances took place in the Kongsfjorden area during the last 200 ka. Four of these occurred 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.

Ten successive sedimentary units of Kongsfjordhallet described by Alexanderson et al. (2018) and two new units (Figure 4.2) have been identified about which six units were sampled for foraminifera and are discussed in detail. These two new units are stratigraphically older than their Unit 1 and are accordingly designated Unit 0 and Unit -1. Both units were documented at site 101. A total of twenty sediment samples were collected from Kongsfjordhallet sites 101, 102,103,104 in beds correlated to Units -1, 1, 3, 4, 7and 8 (Figure 4.2).

Unit -1 is 2.7 m thick and consists of massive clayey silt with occasional scattered clasts (Figure 4.2). Clasts become rarer 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. Sedimentologically, the clayey silt of Unit -1 is interpreted as a glaciomarine mud with iceberg rafted dropstones. Fewer dropstones towards the top may suggest increased distance to glaciers or irregular tidewater glacier margins in the area.

Unit 0 is c. 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 (Figure 4.2). Minor lithofacies include massive, silty diamicton and massive silty sand. One bed of ripple-laminated sand was also observed.The lower boundary to unit -1 is sharp and erosive.The stratified gravelly Unit 0 is interpreted to have been deposited by a combination of marine density flows and littoral processes. The unit's heterogeneous nature suggests a variety of depositional processes. This unit was not sampled for foraminifera.

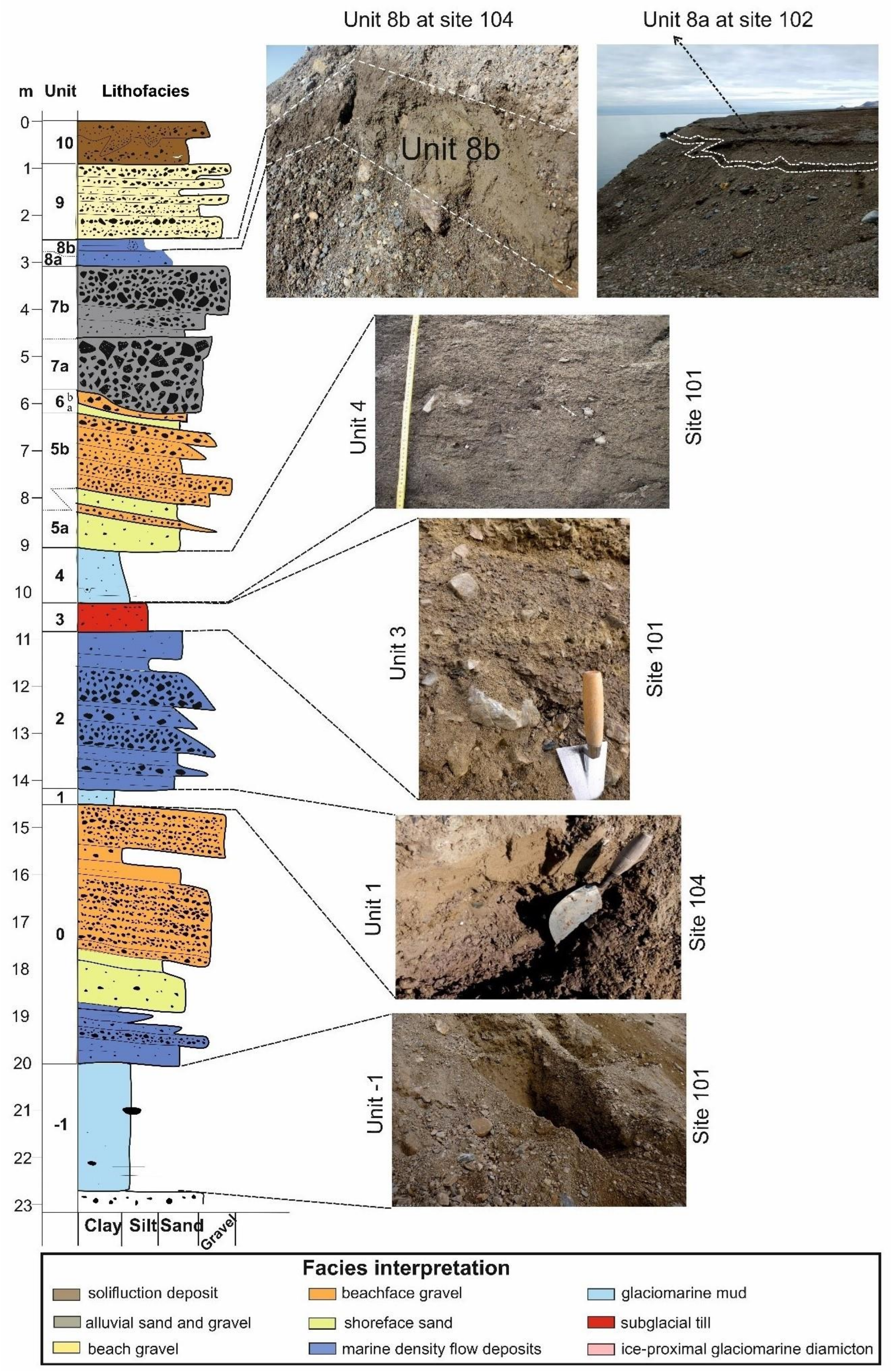
Unit 0 and unit -1 belong to succession B at Kongsfjordhallet as described by (Houmark-Nielsen and Funder (1999). They are older than 195±10 ka, the age of the overlying Units 1 and 2 (Alexanderson et al., 2018). They are one glaciation older and deposited under high relative sea level during the deglaciation of an ice sheet preceding recorded by Units 1 and 2. These two units (-1 and 0) represent one event (i.e. one glaciation-deglaciation cycle; cf. Alexanderson et al., 2018), that would likely took place in marine isotope stage MIS 7. For detail sedimentological descriptions readers are requested to see Alexanderson et al. 2018.

4.1.2 Benthic foraminiferal assemblage zones

A total of twenty samples have been analysed. High abundance of foraminifera has been found in unit 1 and unit 4 and the lowest abundance in unit 7. The highest total foraminiferal number is 1746 in 1-gram dry sediment at the base of in Unit 1. The stratigraphic occurrence and frequency of dominant foraminifera species at Kongsfjordhallet varies from one unit to another and from base to top in each unit. Dominant foraminifera species in all units as a whole are *Cassidulina reniforme*, *Cassidulina neoteretis*, *Elphidium clavatum*, *Lobatula lobatula*, *Islandiella helenae, Haynesina orbiculare* and *Nonionellina labradorica*. Accessory species are *Astrononion hamadaense*, *Buccella frigida* , *Cribroelphidium williamsoni.*, *Elphidium subarcticum*, *Elphidium albiumbilicatum, Globocassidulina* sp., *Islandiella norcrossi*, *Nonionellina auricula*, *Quinqueloculina* sp., *Stainforthia loeblichi*, *Melonis affinis*, *Guttulina* sp., *Glandulina* sp., *Fissurina* sp., *Oolina* sp., and *Trifarina fluens*. The maximum species richness occurs in unit 1 (15 species); it decreases in unit 4 by 14 species and 10 species in Unit 8a and 8 species in Unit 8b. In total, 23 species have been identified in this present study.

Five characteristic foraminifera assemblages have been identified at Kongsfjordhallet each corresponding to a lithostratigraphic unit or subunit (Table 3). The assemblages are described below.

Cassidulina reniforme-Elphidium clavatum-Islandiella helenae assemblage; occurs within the sediment of **Unit -1** (Figure 4.3). The total foraminifera numbers from the base, middle, and top of unit -1 are 17, 26, and 18 respectively. The assemblage is dominated by *Cassidulina reniforme* (c. 60%) and *Elphidium clavatum* (c.35%), followed by subordinate species *Islandiella helenae* and *Haynesina orbiculare* constituting 20% and 6%, respectively. The assemblage represents a low total foraminifera number (TFN < 100) and contains only four foraminifera species. The Fisher's alpha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Sand
Gravel
Unit 4
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Unit 3
Site 101
Unit 1
Site 104
Unit -1
Site 101
Facies interpretation
solifluction deposit
alluvial sand and gravel
beach gravel
beachface gravel
shoreface sand
marine density flow deposits
glaciomarine mud
subglacial till
ice-proximal glaciomarine diamicton

Figure 4.2: 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.

index cannot be determined due to low content of total foraminiferal number. Unit -1 has the lowest TFN of the units investigated here.

Cassidulina reniforme-Elphidium clavatum-Islandiella helenae assemblage; occurs within the sediment of **Unit -1** (Figure 4.3). The total foraminifera numbers from the base, middle, and top of unit -1 are 17, 26, and 18 respectively. The assemblage is dominated by *Cassidulina reniforme* (c. 60%) and *Elphidium clavatum* (c.35%), followed by subordinate species *Islandiella helenae* and *Haynesina orbiculare* constituting 20% and 6%, respectively. The assemblage represents a low total foraminifera number (TFN < 100) and contains only four foraminifera species. The Fisher's alpha index cannot be determined due to low content of total foraminiferal number. Unit -1 has the lowest TFN of the units investigated here.

Cassidulina neoteretis-Cassidulina reniforme assemblage was observed in **Unit 1**, and is characterised by *Cassidulina reniforme* and *Cassidulina neoteretis* (Figure 4.4). The highest occurrence of *Cassidulina neoteretis* (60%) occurs at the top, while it is 43% in the base, and middle. 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 *Nonionellina labradorica* (Figure 4.3). 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 contains fifteen foraminifera species. The high diversity of this assemblage zone is revealed by Fisher's alpha index varying between 2 and 3.

Cassidulina reniforme-Lobatula lobatula-Cassidulina neoteretis assemblage identified in **Unit 4** contains *Lobatula lobatula, Cassidulina reniforme,* and *Cassidulina neoteretis* as dominant foraminifera (Figure 4.5). The assemblage exhibits abundant foraminifera throughout with a total foraminifera number 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 *Lobatula lobatula* (33%) followed by *Cassidulina neoteretis* (19%). Accessory species are *Elphidium clavatum, Islandiella helenae, Buccella frigida, Astrononion hamadaense, Haynesina orbiculare, Elphidium subarcticum,* and *Melonis affinis* (Figure 4.3). The unit shows a high abundance of foraminifera specimens and fourteen species, with a Fisher's alpha index between 1and 2, i.e., a low diverse assemblage.

Lobatula lobatula-Cassidulina reniforme-Elphidium clavatum assemblage reported from Subunit **Unit 8a** constitutes *Lobatula lobatula*, *Elphidium clavatum* and *Cassidulina reniforme* as dominant foraminifera species (Figure 4.6). 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 dominance of *Lobatula lobatula* and *Elphidium clavatum*. Subordinate species include *Islandiella helenae*, *Haynesina orbiculare*, *Nonionellina labradorica*, *Astrononion hamadaense,* and *Buccella frigida*.

Cassidulina reniforme-Elphidium clavatum assemblage of **Subunit 8b** is characterised by two dominant species - *Cassidulina reniforme* and *Elphidium clavatum*, with a minor abundance of *Islandiella helenae*, *Haynesina orbiculare* and *Lobatula lobatula*. The assemblage contains eight foraminifera species and exhibit a fair amount of total foraminifera specimens at its top (TFN=121) compared to its base (TFN=80) and middle part (TFN=42).

The Fisher's alpha index is not determined for Subunit 8a and 8b due to the low total foraminiferal number.

4.1.3 Paleoenvironment

Event I (Saalian age?)

The lithology and foraminifera populations from Unit -1 at Kongsfjordhallet represent a glacial distal stable marine environment that is older than 195ka, but likely not very much older, as discussed below, and is tentatively correlated to the Saalian. The *Cassidulina reniforme-Elphidium clavatum-Islandiella helenae* assemblage contains the most common Arctic species, *C. reniforme* and *E. 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, such as in Svalbard (Hald et al., 1994, Hansen & Knudsen 1995). *C. 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 characterised by cold local water (LW) generated from strong cooling of Atlantic Water (AW; Jernas et al., 2018). The *C. reniforme*-dominated assemblage typically characterises 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 the present study, the dominance of *C. reniforme* over *E. clavatum* indicates conditions at depths not influenced by meltwater. *I. helenae* is

Foraminifera Assemblages	**Environmental interpretations**	**Chronology**
Cassidulina reniforme-Elphidium clavatum	Glacier distal, stable, saline, glaciomarine	Late Weichselian 17 ± 0.6 ka MIS-2
Lobatula lobatula-Cassidulina reniforme-Elphidium clavatum	Glacier distal, higher energy, an inflow of marine waters	Middle Weichselian 60 ± 4 ka MIS-4
Cassidulina reniforme-Lobatula lobatula-Cassidulina neoteretis	Glacier distal, inner shelf higher energy, productivity, interglacial event	Eemian 132±7 ka MIS-5e
Cassidulina neoteretis - Cassidulina reniforme	Glacier distal, inner shelf, stable, lower energy, cold, seasonal sea-ice	Saalian 195±10 ka MIS-6
Cassidulina reniforme-Elphidium clavatum-Islandiella helenae	Glacier distal, inner shelf, stable, lower energy, cold	Saalian Older than ~195ka MIS-7

Table 4.1**:** Summary of the five foraminiferal assemblages from Kongsfjordhallet, and their paleoenvironmental interpretation. The inferred chronology is according to Alexanderson et al., (2018). MIS=Marine Isotope Stage

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 *I. 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 ka, 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; cf. Alexanderson et al. 2018), this would likely place it in marine isotope stage (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 that it is 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 (4) and few specimens (17-28). Low species count may be due to limited yearly sea ice cover and meltwater influx in the region. The presence of ice-rafted debris (IRD) 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 available nutrients 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 hamadaense* and *Lobatula lobatula* and zone 1305-DII by the presence of *Islandiella inflata*. In addition, the zone 1305-D overall contain *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 other coeval sites on 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 on Svalbard would be interesting, but so far, few such sites are known, though there is potential e.g., across the fjord on Brøggerhalvøya (Miller 1982).

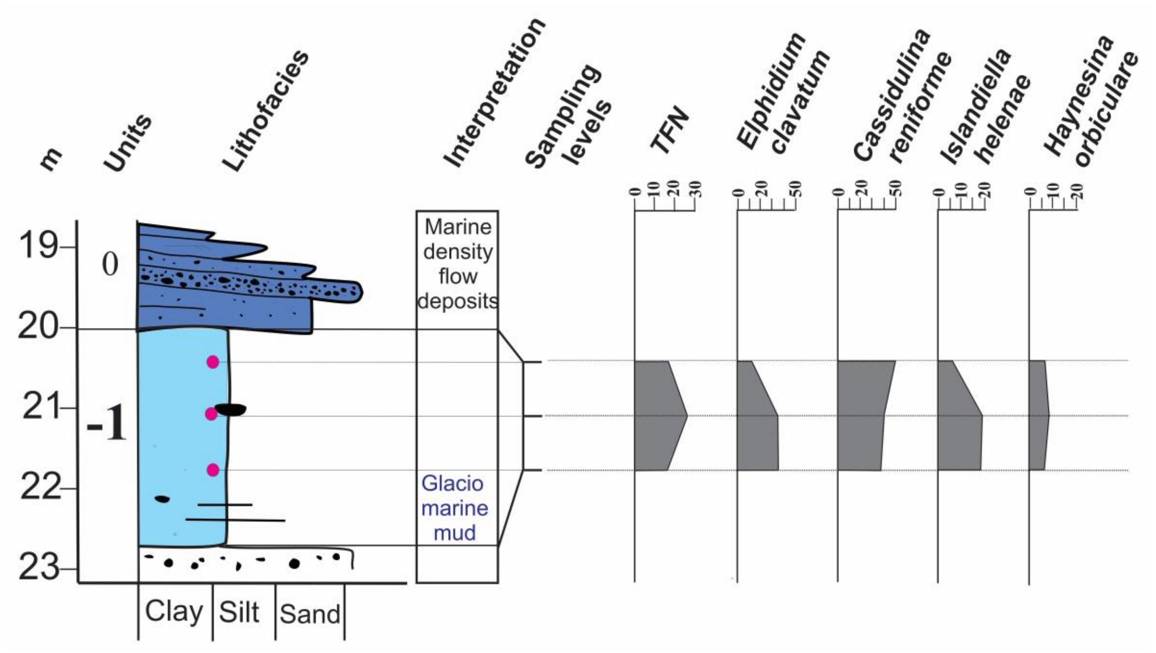

Figure 4.3: Benthic foraminifera abundance (%) in Unit -1

Event II (Saalian age)

Event II at Kongsfjordhallet is dated to 195±10 ka 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. *C. 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 phyto detritus is available (Cage et al., 2021). *C. 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 tidewater glaciers existed in the vicinity is supported by the existence of IRD in Unit 1 (Alexanderson et al., 2018).

Both *C. reniforme* and *C. neoteretis* are cold water indicator species (Saher et al. 2009) and reveal that deposition of Unit 1 took place in a cold glaciomarine environment. *I. 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 significant amounts of organic nutrients are produced due to summer sea-ice edge-productivity. Therefore, its presence indicates that sea-ice marginal conditions existed during that period. *N. 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 *C. neoteretis*. *C. neoteretis* has been found common during most of the cold but ice-free phases of the last deglaciation on the Norwegian continental shelves (Seidenkrantz 1995). In addition, at least seasonally, ice-free conditions and high productivity might have existed as indicated by the presence of *C. neoteretis*, *I. helenae* and *N. 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 waters, high diversity and 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. The presence of 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).

The Foraminiferal zone 1305-D of Sivertsen (1996) 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 are not representing the same time, the foraminiferal record from our Unit 1 at Kongsfjordhallet could be unique for Svalbard, as the only documented foraminiferal fauna of Saalian age yet. 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 NW Brøggerhalvøya (Miller et al., 1989), but to our knowledge, the foraminiferal content of those deposits has not been studied.

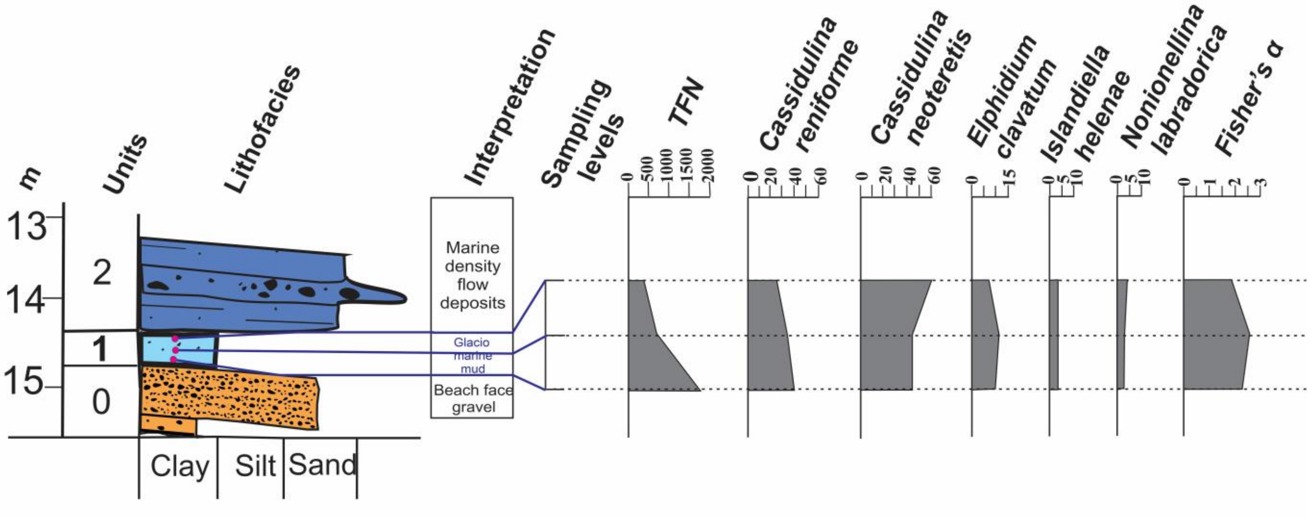

Figure 4.4: Benthic foraminifera abundance (%) and diversity in Unit 1

Event III (Eemian age)

The Eemian or the last interglacial at Kongsfjordhallet (dated to 132±7 ka by 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- Lobatula lobatula-Cassidulina neoteretis* assemblage. *Lobatula lobatula* 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). *C. reniforme*, abundant in the upper part of Unit 4, commonly prefers a domain in some distance to glacier. The dominance of *C. reniforme* reflects increased food flux and productivity and a stable glacier distal environment (Korsun & Hald 2000). *C. 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 *C. reniforme*, *L. lobatula* and *C. 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, *B. frigida*, and *N. labradorica*, which depend on algal blooms at the sea ice margin. The abundance of *L. lobatula* and *Astrononion hamadaense* 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. Comparing to Sivertsen's (1996) foraminiferal zones that may correlate to Unit 4, we find the highest similarity with his zone 1305-E, which is dominated by *E. clavatum* and *C. reniforme* with a significant proportion of *L. lobatula.* Unit 4 at Kongsfjordhallet may chronologically also be correlated to episode C on nearby NW Brøggerhalvøya (Miller et al., 1989); as is discussed further below, 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 (units 3-4; Lycke et al., 1992, Alexanderson and 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 (*C. neoteretis- C. reniforme)* differs from most of the assemblages at these other sites by the absence of *E. clavatum* and *A. gallowayi*. An exception is Formation B at Kapp Ekholm with a *C.reniforme* dominated assemblage, along with the thermophilous mollusc *Mytilus edulis*, which signifies the inflow of warm Atlantic Water (Mangerud et al. 1998; Hovland 2014).

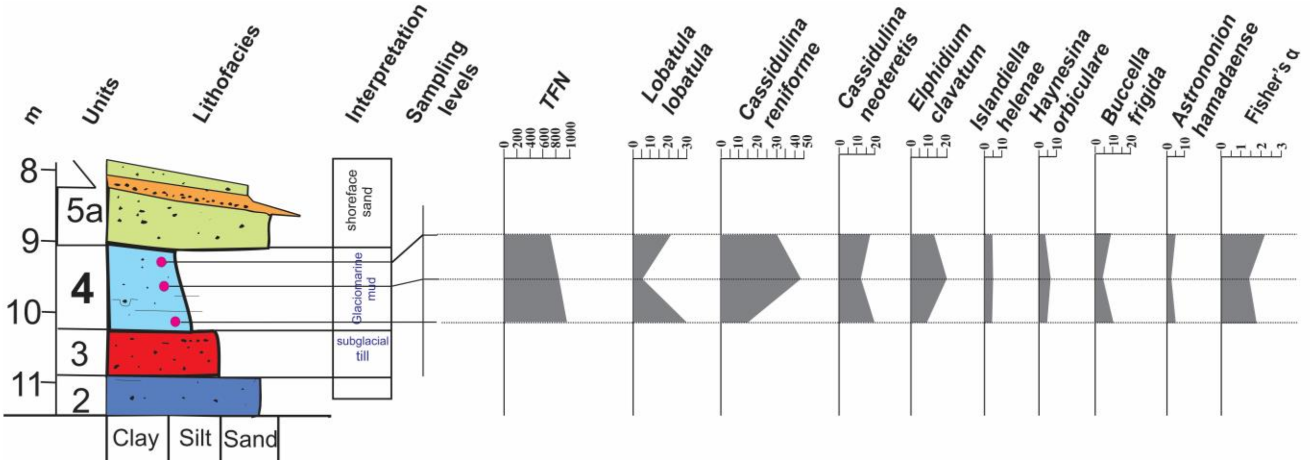

Figure 4.5: Benthic foraminifera abundance (%) and diversity in Unit 4

The species *C. neoteretis*, one of the dominant species in the Unit 4 foraminifera assemblage, was on the other hand reported from Eemian deposits on the Yermak Plateau (Chauhan et al., 2014). A relatively high abundance of *C. reniforme*- and *C. 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 the increased inflow of Atlantic waters 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)

The Middle Weichselian (60±4 ka) there was a stable, distal glaciomarine, higher energy environment in Kongsfjordhallet as evidenced by the *Lobatula lobatula- Cassidulina reniforme-Elphidium clavatum* foraminifera assemblage. *C. reniforme* and *E. clavatum* are typical foraminifera in Arctic fjords (Hansen and Knudsen, 1995; Hald and Korsun, 1997). *C. reniforme* is often associated with *E. clavatum* in glacier proximal areas, although the appearance of *C. reniforme* appears more abundant towards the ocean. *C. reniforme* indicates that a stable, more saline marine condition prevailed at that time. The presence of *L. lobatula* 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 hamadaense* and *Buccella frigida* indicates strong bottom currents and marginal sea ice conditions with the availability of food. The presence of *Islandiella helenae* and *Nonionellina 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 *L. lobatula*, 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 (*C. reniforme-Astrononion hamadaense* (F-15 II) zone, Miller et al., 1989), though it is of Early Weichselian age (99±8 ka; Alexanderson, Landvik & Ryen 2011). Roughly contemporaneous (i.e., Middle Weichselian) foraminiferal faunas on Svalbard have on the other hand been documented at Poolepynten (Unit C; Bergsten et al. 1998) and Linnéelva (FL-III, Lycke et al. 1992). The foraminifera fauna in Unit C at Poolepynten is characterized by uniform and high values of *C. reniforme* which indicates the existence of primary production along an ice edge (Bergsten et al. 1998) and glaciomarine conditions. The existence of *I. helenae*, *N. labradorica*, and *B. frigida* indicates the presence of 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 a high-energy, productive, and stable glacier distal marine environment existed during Middle Weichselian times at Kongsfjordhallet.

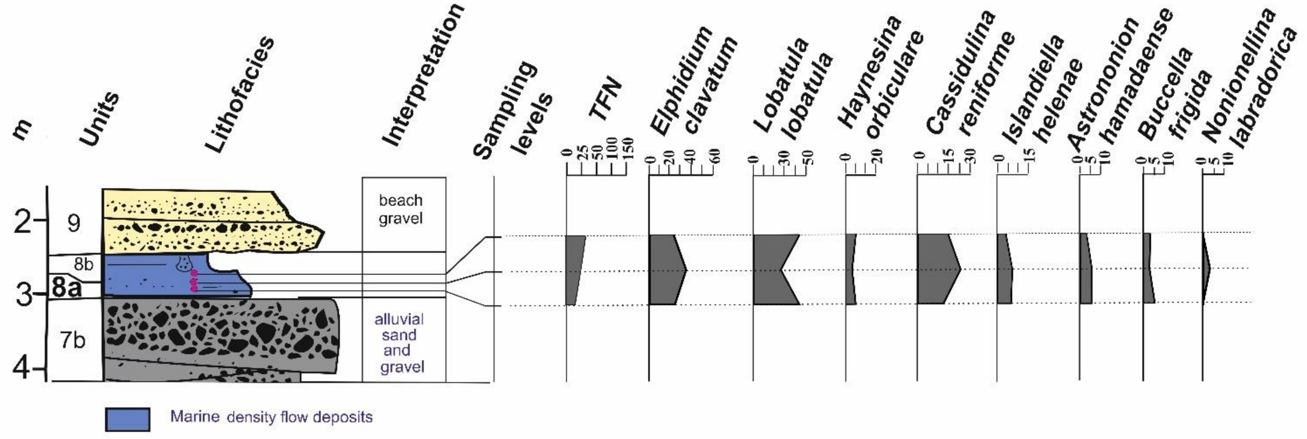

Figure 4.6: Benthic foraminifera abundance (%) Unit 8a

Event V (Last deglaciation)

Shortly after the Last Glacial Maximum (at 17±0.6 ka), 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 *C. reniforme* reflects glacier distal, cold-water areas, with seasonal sea-ice coverage and muddy sediments (Polyak et al., 2002). The dominance of *C. reniforme* together with *E. clavatum* coupled with glacier distal faunas such as *I. helenae, N. labradorica*, *A. gallowayi,* and *B. frigida* in the entire unit, therefore, reveals glacier distal location with milder conditions, i.e., seasonal marginal sea ice conditions that existed during the deposition of the unit.

The presence of *N. labradorica*, *I. helenae* and *H. orbiculare* indicates an occasional inflow of fresh water to Kongsfjordhallet (cf. Polyak et al., 2002). The paleoenvironment and the age suggest that this occurred shortly after deglaciation. A similar *C. reniforme* dominated stable glacier-distal glaciomarine environment has been documented during the Early Holocene (11.8-11.3 ka 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 (Korsun et al., 1995; Hansen and Knudsen 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 present in the fjord, consistent with the interpretation from the foraminiferal assemblage in the sediment. Thus, a stable glacier distal marine environment existed both during the Middle Weichselian (60 ± 4 ka) and during the last deglaciation (17± 0.6 ka) at Kongsfjordhallet.

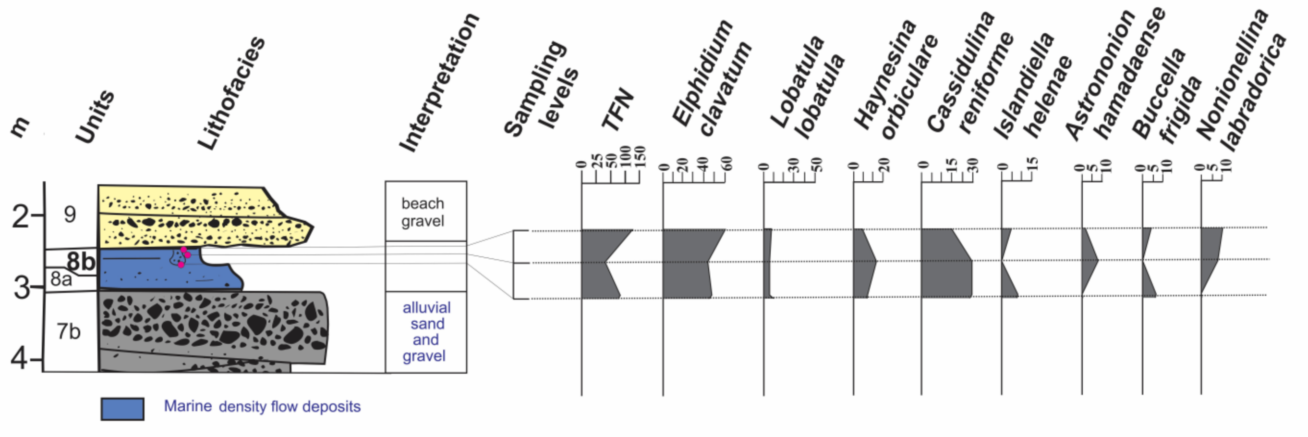

Figure 4.7: Benthic foraminifera abundance (%) in Unit 8b

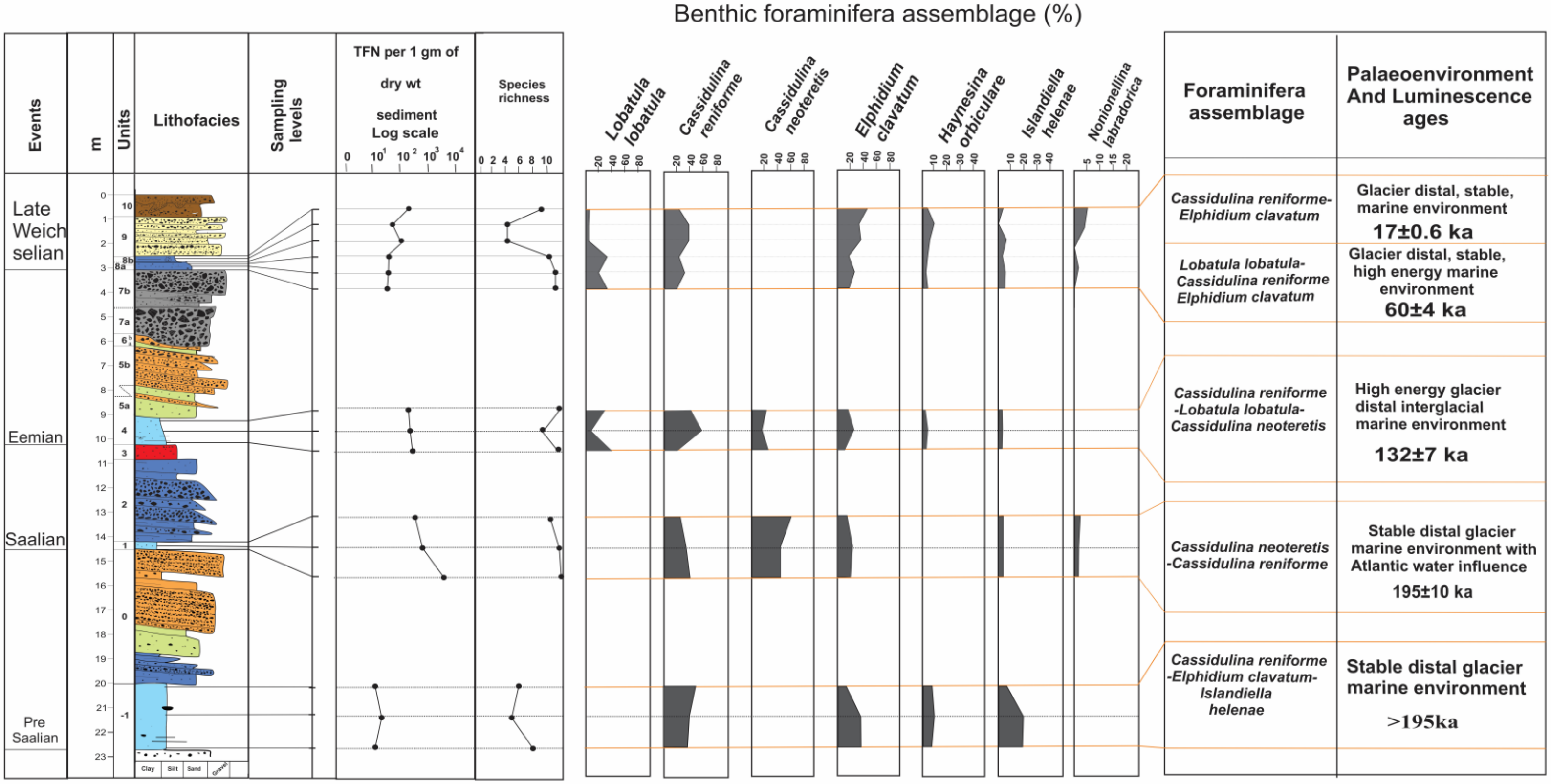

Figure 4.8 : Summary of Paleoenvironments of Kongsfjordhallet with key foraminiferal species, species richness, foraminifera assemblages and interpreted environment and ages.

4.2 Quaternary sections of Stuphallet

Stuphallet is positioned as the exposed beach cliffs approximately 30 m high from mean sea level on the northern part of Brøgger peninsula located on the west coast of Spitsbergen. Stuphallet is about 7 km from Ny-Ålesund, a small town in Svalbard; the site consists of two streams flowing in a direction from east to west bounded by a bank and a bird nesting cliff (Figure 4.9). Sediments deposited on the slope generally belong to the glaciogenic and biogenic origin of the Quaternary period and are transported by turbidity currents that were more active during glacial periods. The sediments deposited in the section represent transgression-regression cycles ranging from before the Last Interglacial (~130 ka) through Late Weichselian interstadial (~97 ka) up to Early Holocene. Interglacial and interstadial deposits constitute glaciomarine mud indicative of transgressive marine cycles, whereas beach gravels and subglacial till signify regressive cycles. The present investigation comprises foraminiferal analysis from a total of ten sediment samples that were collected from Stuphallet site 404 corresponding to Unit-2, 3, 4,6,7,8 and 9.

Figure 4.9: View of coastal cliffs at site 404 of Stuphallet

The Stuphallet stratigraphic succession (Figure 4.11) deposits exhibit ten sedimentary units labelled 1-10. The sedimentary succession starts with unit 1, comprising ice proximal glaciomarine diamicton accommodating marine mass deposit. Sedimentologically, Unit 2 serve as a reddish coloured 1.5m thick subglacial till containing a very low abundance of foraminifera. Unit 3, comprising glaciomarine mud and Unit 4, comprising shoreface sand, revealed good abundance and species of foraminifera. After deposition of unit 4, a sedimentary unit containing beach face gravel encompassed by Unit 5 has been found to occur above it. These 2, 3, 4 units have made a coarsening upward sequence.

Another coarsening upward sequence starts from the glaciomarine diamicton of unit 5 and ends with the solifluction deposit of unit 10. It houses a sedimentary unit of beach face gravel overlain by subglacial till of unit 6. Unit 6 is 90 cm thick brownish colored sediment characterized by subglacial till with scarce foraminifera. Unit 7 is a 50 cm thick glaciomarine mud unit containing abundant, diverse foraminifera and fragmented mollusc shell. The boundary between unit 6 and unit 7 has been notably identified in site 404 (Figure 4.10) and laterally extend to site 403. It is followed by shoreface sand of unit 8, beach gravel and beach face gravel of unit 9 and solifluction deposit of unit 10 on the top of the site.

These two sequences represent deposits of glaciation before the last interglacial succeeded by deglaciation of the last interglacial-Eemian interglacial events (129±7 ka) through deposits of interstadial-Phantomodden interstadial events (97± 5 ka) followed by Holocene deposits.

Figure 4.10: Site 404 of Stuphallet

4.2.1 Benthic foraminifera assemblage zones

The stratigraphic occurrence and frequency of dominant foraminifera species in Stuphallet are noteworthy. It varies from one unit to another i.e. from unit 2 to unit 8. In total, 22 species have been identified from the entire sedimentary units. The highest occurrence of foraminifera specimens in one gram of dry sediment of >63 µm has been encountered in unit 7 base (TFN-3404), followed by unit 7 middle (TFN-1596) and unit 7 top (TFN-170). After unit 7, the abundance has been observed at the boundary between unit 3 and 4, unit 3 and unit 4 are 48, 34 and 17 respectively. Although foraminifera specimens have been identified in unit 6 and unit 2; being characterized by subglacial till they are not considered for paleoenvironmental interpretation. The foraminifera count in unit 8 is 40 and total absence of foraminifera in unit 9. The units 2,6, and 9 are all reworked and not considered for analysis. The maximum no of foraminifera species has been identified in entire Unit 7 that corresponds to 18,16 and 12 in base, middle and top. Five, six and eight foraminifera species have been identified in unit 3, boundary between 3 and 4, unit 4, and unit 8 respectively. The dominant foraminifera species which have been reported from this site are *Cassidulina reniforme* and *Elphidium clavatum*, *Astrononion hamadaense*, *Lobatula lobatula*, *Buccella frigida*, *Nonionellina labradorica and Islandiella helenae.*

The foraminiferal assemblages from Stuphallet represent two distinct interglacial and interstadial assemblage (A1-A2), one that consists of *C. reniforme* and *Lobatula lobatula* indicative of open ocean condition with glacially intermediate to distal facies and fluvial influence and another characterised by *Nonionellina labradorica* and *Astrononion hamadaense* with glacially proximal facies and Atlantic water mass respectively (Figures 4.12, 4.13).

4.2.2 Paleoenvironment

Each assemblage zone is represented by dominant foraminifera species. These are described and interpreted in terms of paleoenvironments below.

Assemblage zone A1: *Cassidulina reniforme–Lobatula lobatula-Elphidium clavatum* assemblage

This assemblage zone occurs within sediments of units 3 and 4. The study of foraminifera in the units mentioned above, particularly with unit 3, is noteworthy as the unit has been assigned to the Last interglacial event of the Eemian age (129±7 ka).

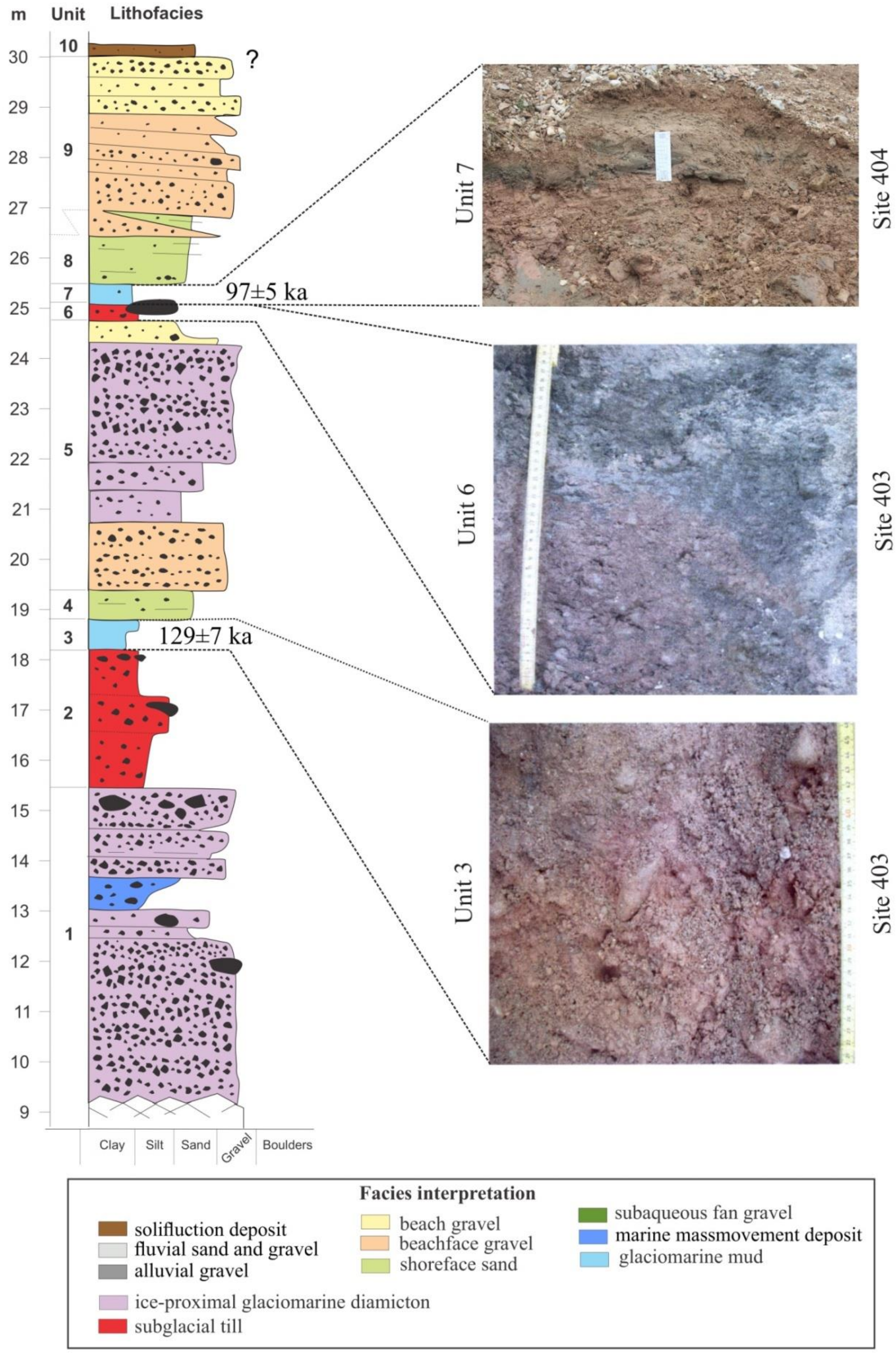

Figure 4.11: The composite stratigraphy of Stuphallet showing Units 3, 4 and 6. Units 1-10 are according to Alexanderson et al., 2017.

The assemblage zone is characterized by *Cassidulina reniforme*, *Lobatula lobatula*, and *Elphidium clavatum*. Other associated species include *Haynesina orbiculare* and *Islandiella helenae* (Figure 4.8). *Cassidulina reniforme* is a typical Arctic foraminifera species (Hald & Korsun 1997) associated with winter-cooled waters in the inner part of Svalbard fjords distally following *Elphidium clavatum* dominated areas (Bergsten et al., 1998). The great abundance of this species reflects an off-the-meltwater-plume environment where normal marine condition with high productivity persists (Guilbault et al., 2003). *C. reniforme* is more often found associated with *Elphidium clavatum*. But its presence over *E. clavatum* indicates a glacial intermediate to the distal environment. *Lobatula lobatula* is an attached species found in water with high salinity, strong bottom current velocity, and thereby higher energy environment in the fjords of Svalbard (Hansen & Knudsen 1995) and is also considered an Atlantic water group species. So, its presence signifies a glacially distal environment. The dominance of *E. clavatum* indicates glacial front areas of less stable conditions and declines towards the open ocean areas. *Haynesina orbiculare* generally prefers to live in river-influenced areas where sedimentation rate is low, and strongly correlated with a brackish environment (Bergsten et al., 1998). *Islandiella helenae* is associated with highly productive areas where nutrient availability is good (Kubischta et al., 2010), with a warm inflow of Atlantic water. It generally prefers areas where the organic nutrient is significantly high due to summer sea-ice edge productivity (Bergsten et al., 1998). So, this species, when present, always indicates a distal glacial environment. So, in summary, this assemblage mirrored by units 3 and 4 of Stuphallet represents a high-energy glacial intermediate to a distal environment (Figure 4.12).

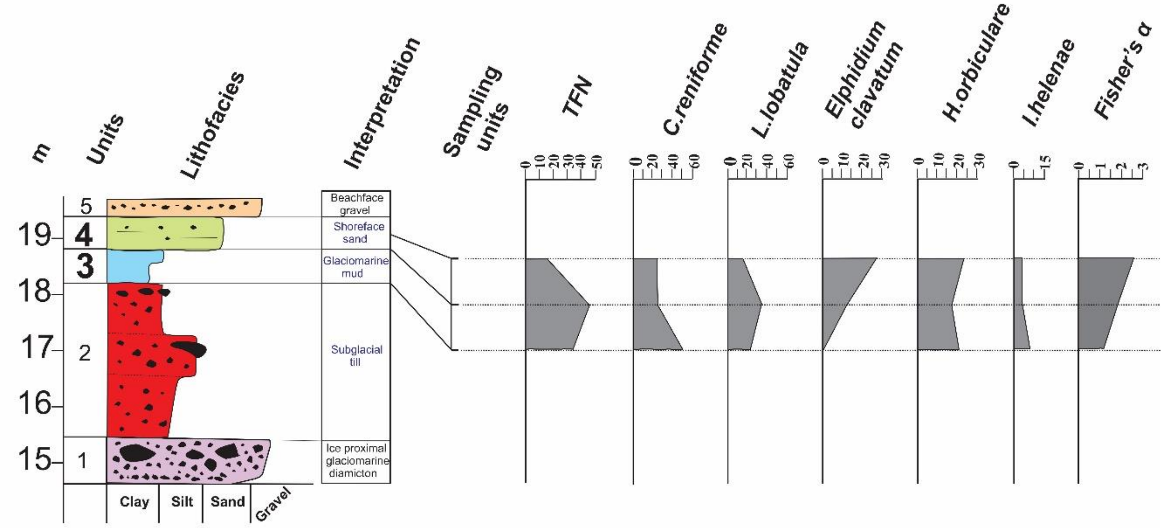

Figure 4.12: Benthic foraminifera abundance (%) and diversity in Units 3 and unit 4

Assemblage zone A2: *Cassidulina reniforme-Elphidium clavatum–Astrononion hamadaense* -assemblage- Sediments of units 7 and 8 exemplify this assemblage zone. The unit is characterized by *Cassidulina reniforme, Elphidium clavatum*, and *Astrononion hamadaense*. Other associated species include *Islandiella helenae*, *Lobatula lobatula*, and *Buccella frigida* (Figure 4.13). Unit 7 has been dated and found to be 97±5 ka representing a temporary warm high sea-level event among the units above.

The assemblage represents a well-preserved high abundance and diverse foraminifera species. The great abundance and presence of *Cassidulina reniforme* indicate the glacier front retreat (Lycke et al., 1992) and more stable hydrological conditions. *Elphidium clavatum* is a cold-loving species mainly associated with glacial termini where turbidity is high, salinity is low, and fluctuating (Korsun et al., 1995, Koç et al., 2002). *Astrononion hamadaense* is considered the bottom current indicator group (Pawlowska et al., 2015) and often occurs with *E. clavatum* as subordinate species. Still, its presence is symbolic since it is found associated with high diverse interglacial (Eemian) and interstadial assemblage reported from other onshore sections of Svalbard (Lycke et al., 1992). Increased diversity, together with the presence of *A. hamadaense*, marks a connection to the inflow of marine waters. The occurrence of *Lobatula lobatula* suggests the presence of powerful bottom currents. Both *Buccella frigida* and *Lobatula lobatula* prefer a distal glacial environment. *Nonionellina labradorica*, another most important foraminifera species, when present, always indicates the presence of warm Atlantic water mass and the existence of a polar front nearby (Koç et al., 2002). *Buccella frigida* is preferably seen as associated with highly productive areas with greater food and nutrient availability. It reflects the inflow of warm water of the Atlantic that was intense during interstadials and interglacial. So, in summary, the assemblage comprising all the species above with high diversity represents a distal glacial environment with an intermittent connection to warm Atlantic water (Figure 4.14).

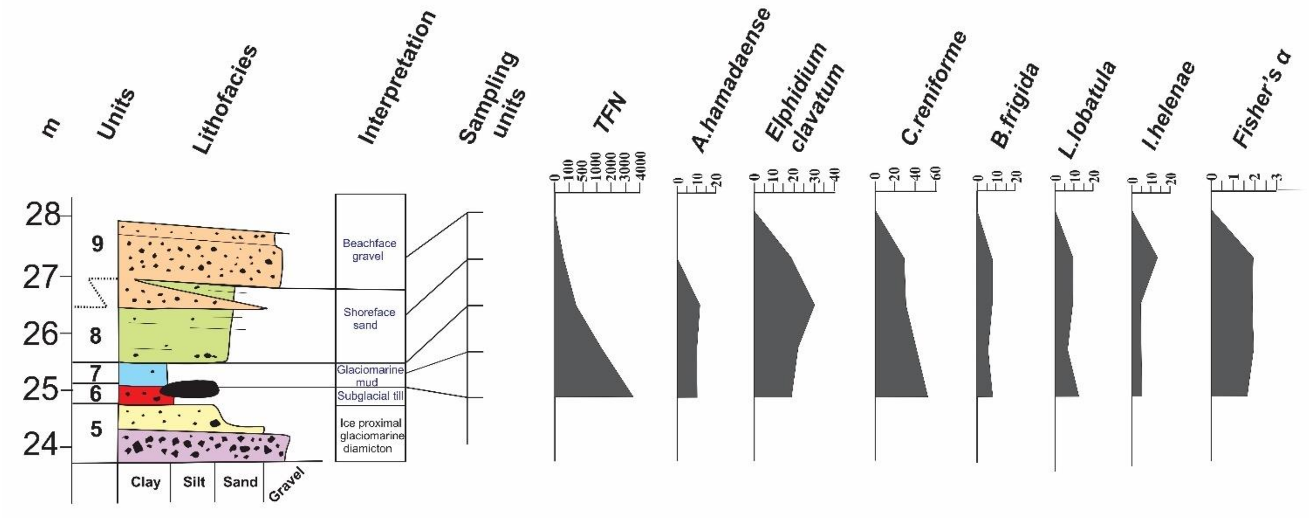

Figure 4.13: Benthic foraminifera abundance (%) and diversity in Units 7,8, and 9

Assemblage zone	Characteristic foraminiferal assemblages	Paleoenvironment	Age
A2	*Cassidulina reniforme-Elphidium clavatum-Astrononion hamadaense*	Glacial distal, stable salinity, inner shelf, bottom current, productivity, and warm Atlantic water	Phantomodden interstadial 97±5 ka MIS-5c
A1	*Cassidulina reniforme-Lobatula lobatula-Elphidium clavatum*	Glacial distal, inner shelf, higher energy, productivity, fluvial influence, brackish marginal marine	Eemian Interglacial 129±7 ka MIS-5e

Table 4.2: Summary of foraminifera assemblages from Stuphallet and their paleoenvironmental interpretation. The inferred chronology is according to Alexanderson et al. 2017

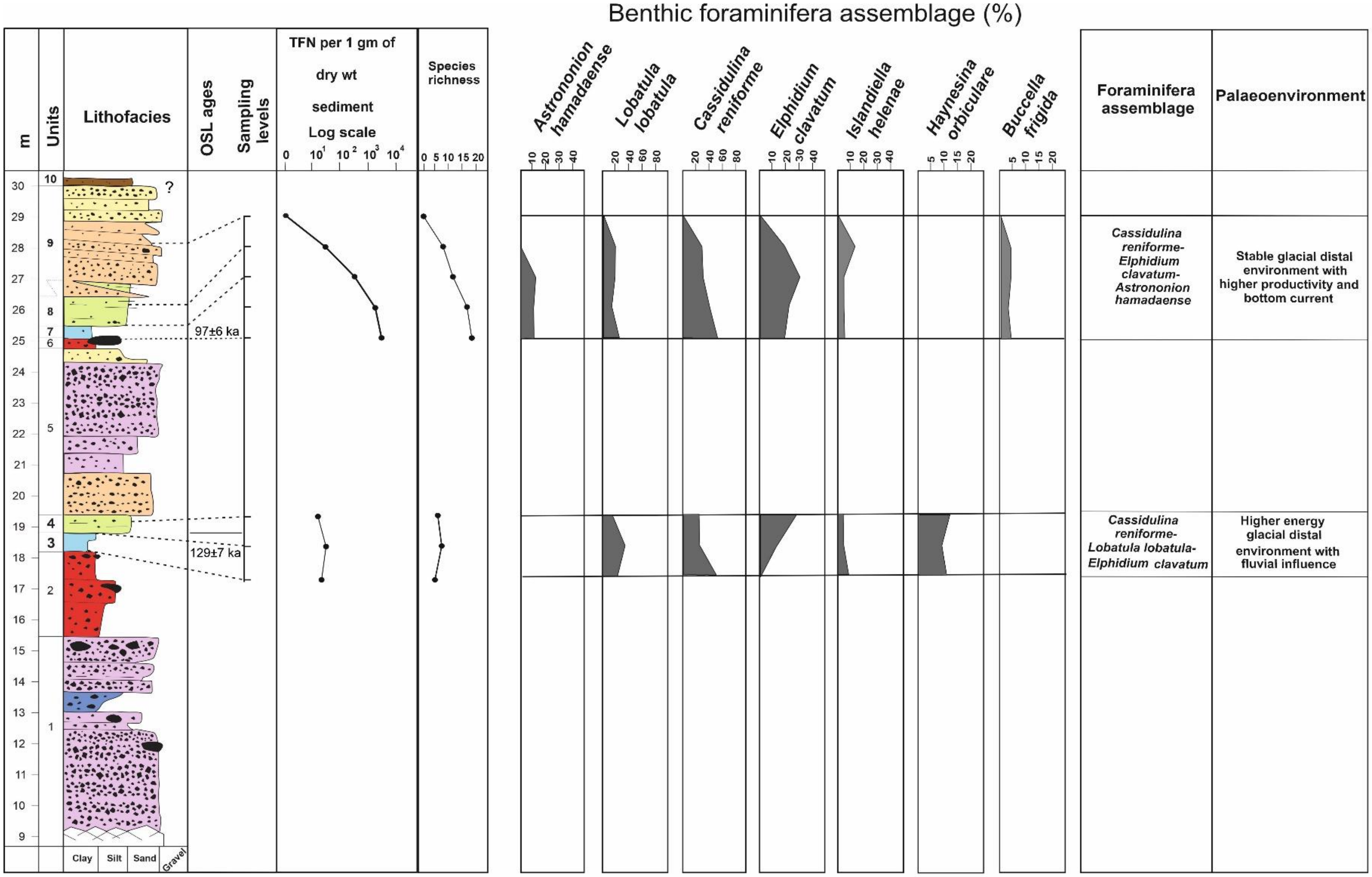

Figure 4.14: Summary of paleoenvironments of Stuphallet with key foraminiferal species, species richness, foraminifera assemblages and interpreted environments and ages

4.3 Quaternary sections of Leinstranda

Leinstranda, is the one of the sites, that preserves good records of Pleistocene events. The coastal cliffs of Leinstranda are at most ~33 m high, of which only the lowest~6 m is bedrock. The main exposures (Site 204, 207) are within 100 m of each other north of the large ravine, with supplementary exposures ~180m further inland of the ravine (205) and 40-60 m south of the ravine (204, 207). Two pairs of prominent marker beds (Units 8/9 and 14/15), were used for lateral correlations. The sections of Leinstranda are described by Alexanderson et al., 2011, including previous investigations by Troitsky et al., (1979), Miller et al., (1982, 1989). Major glaciations occurred in the parts of Late Saalian and Early Weichselian times. Two deglacial events (140±20) ka and (80±10) ka have been identified equivalent to Miller's amino acid episode C and B respectively.

Figure 4.15: (a) Site 204 of Leinstranda and (b) folded strata present at the site

Twenty sedimentary units (Figure 4.17) have been recognized and described by Alexanderson et al., 2011. The underlying bedrock of units 0-4 consists of carbonate rocks and sandstones of the Palaeozoic formation. It is heavily folded and later eroded to a flat level~6m m.s.a.l. Its surface is commonly cracked and shattered but in places it is glacially polished. For detailed sedimentological description of each unit see Alexanderson et al., 2011, Alexanderson et al., 2014.

4.3.1 Benthic foraminifera assemblage zones

In this present study two boundary between units 8 and 9 and unit 14/15 have been investigated for distribution of benthic foraminifera assemblages of which only 14/15 contain notable foraminifera specimens. Unit 8/9 contains only ten foraminifera specimens while unit 14/15 contains 200 specimens and only seven foraminifera species. The foraminifera assemblages reflect low diversity and abundance with respect of total foraminifera number (TFN).

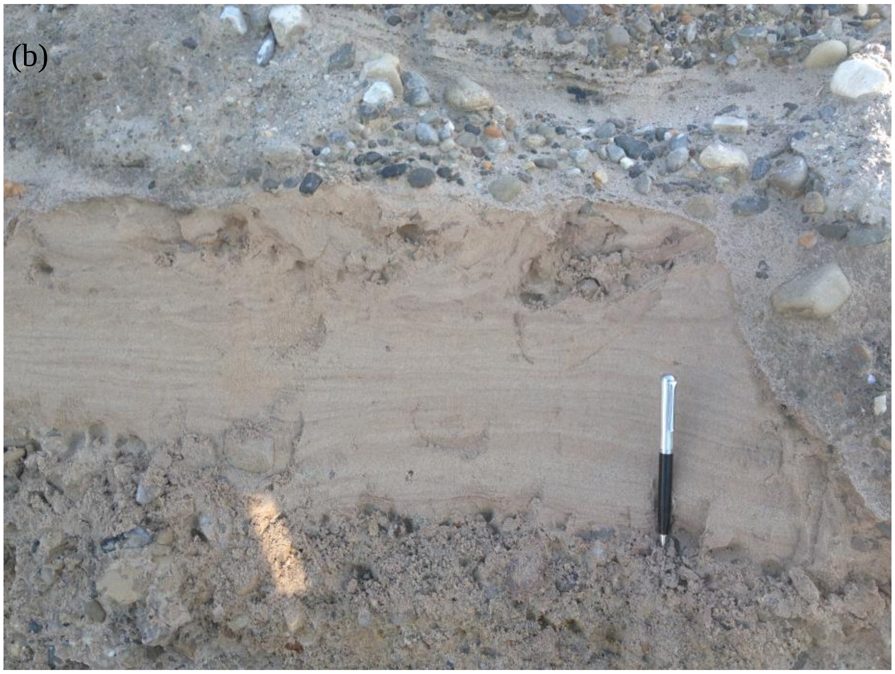

Figure 4.16: a) Close up view of Unit 8/9 top, b) Close up view of Unit 14/15 of Leinstranda

The benthic foraminifera assemblage recognized at 14/15 represents *Elphidium clavatum* - *Lobatula lobatula* - *Cassidulina reniforme* assemblage (A1) (Figure 4.17).

4.3.2 Paleoenvironment

Assemblage zone A1: *Elphidium clavatum - Lobatula lobatula- Cassidulina reniforme*

The foraminifera assemblage reflects dominant occurrence of *Elphidium clavatum* and *Lobatula lobatula*. They include significant presence of *Cassidulina reniforme, Haynesina orbiculare, Buccella frigida, Islandiella norcrossi* and *Astrononion hamadaense* in the decreasing order of abundance. *E. clavatum* is glacier turbid melt water typical Arctic foraminifera found in Arctic fjords comprising high turbidity, low salinity areas which define the glacier proximity with enriched action of melt water plume. Greater abundance denotes glacier proximal environment. *Lobatula lobatula* is an attached, epifaunal, glacially distal species and being a suspension feeder, found to be proliferate in areas of elevated microhabitat that contains rocks, seaweed, corals with strong bottom current activity and sustainable in higher energy condition. *Cassidulina reniforme* commonly prefers glacial intermediate environment. *Haynesina orbiculare* is commonly associated with riverine sedimentation. Both *Islandiella norcrossi* and *Buccella frigida* depends on nutrients derived by sea ice productivity and therefore glacial distal facies. *Astrononion hamadaense* represents presence of strong current and can be used as an indicator species of interglacial or interstadial events. From foraminifera assemblage this units reveals glacial proximal environment with inflow of warm Atlantic water as indicated from presence of glacial distal, higher energy and productivity dependent foraminifera species. The chronology of this event denotes an interstadial event (99±8 ka) consistent with paleoenvironments as depicted from foraminifera specimens (Figure 4.17, 4.18).

Characteristic foraminiferal assemblages	Paleoenvironment	Age
Elphidium clavatum - Lobatula lobatula- Cassidulina reniforme-	Glacial proximal, melt water influenced environment	Phantomodden interstadial 99± 8 ka MIS-5c

Table 4.3: Summary of foraminiferal assemblages from Leinstranda and their paleoenvironmental interpretation. The inferred chronology is according to Alexanderson et al. 2011

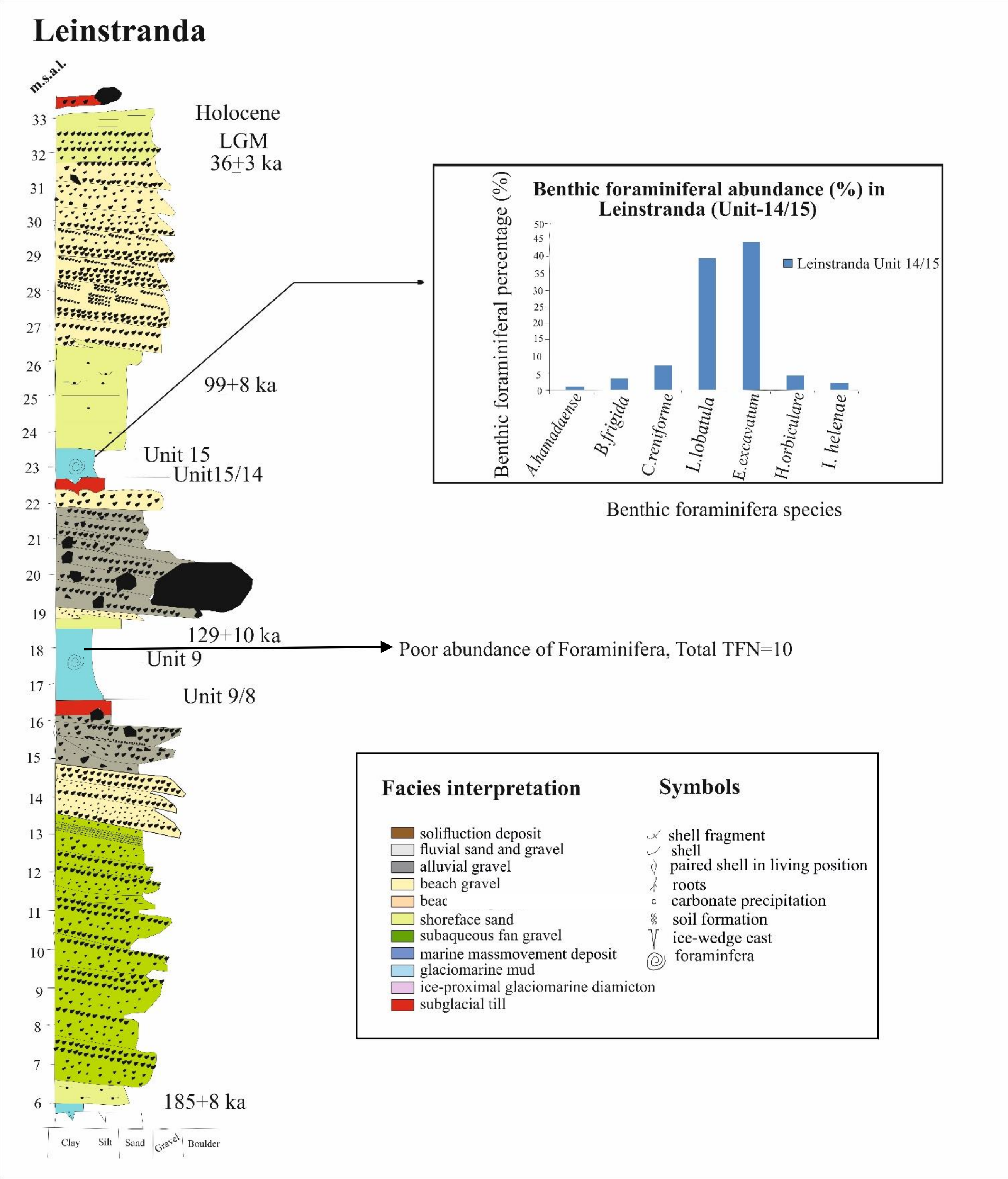

Figure 4.17: The composite stratigraphy of Leinstranda and benthic foraminifera abundance (%) in Units 8/9 and 14/15. Units 1-20 (Alexanderson et al., 2011, 2014)

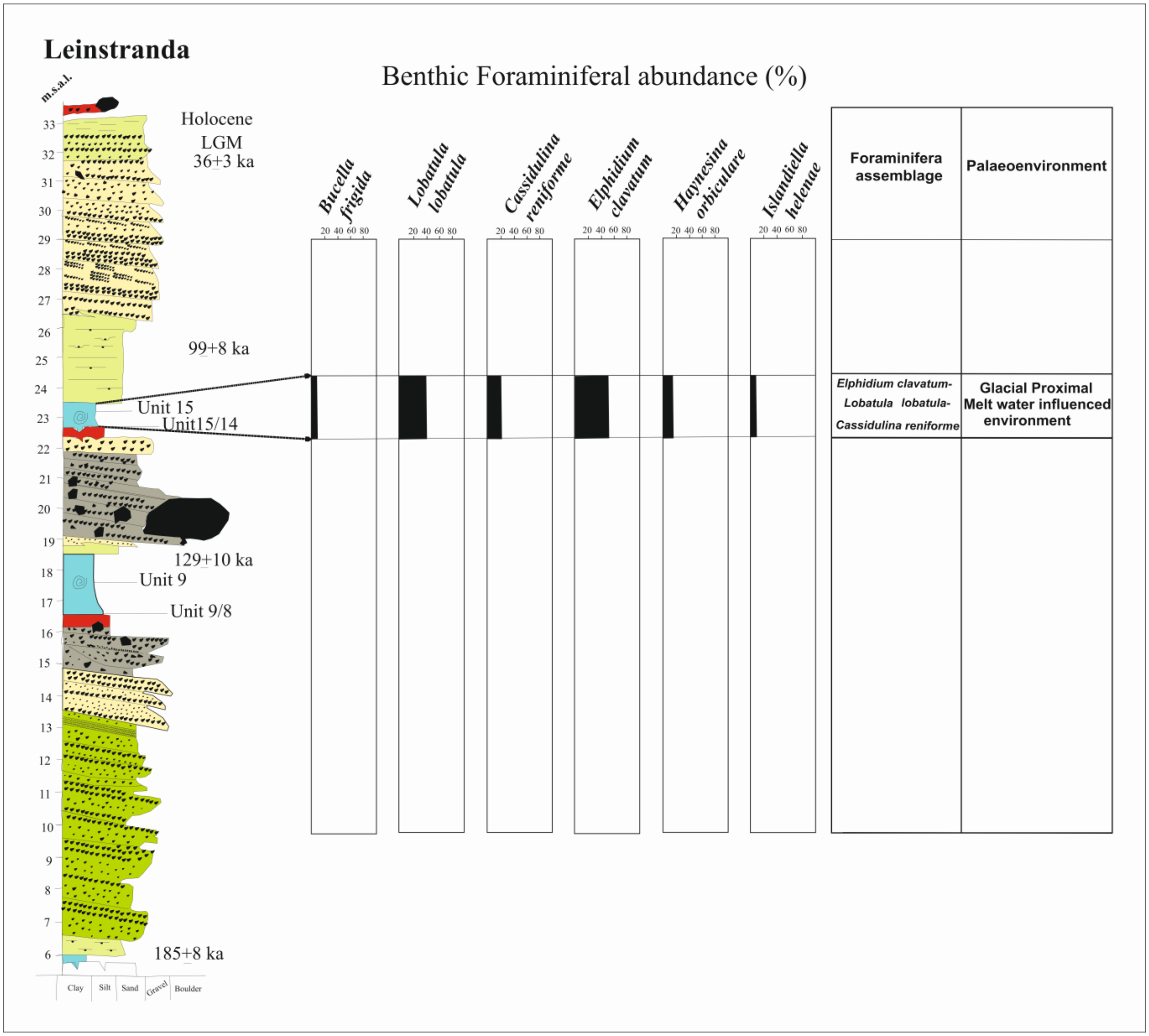

Figure 4.18: Paleoenvironment as depicted from benthic foraminifera at Leinstranda

Taxa	**References**
Astrononion hamadaense	Asano, 1950
Buccella frigida	Cushman, 1922
Cassidulina reniforme	Nørvang, 1945
Cassidulina neoteretis	Tappan 1951, Seidenkrantz 1995
Lobatula lobatula	Walker and Jacob, 1798
Elphidium clavatum	Cushman, 1930
Cribroelphidium williamsoni	Haynes,1973
Cribroelphidium sp.	Cushman and Brönnimann, 1948
Elphidium subarcticum	Cushman, 1944
Elphidium albiumbilicatum	Weiss, 1954
Fissurina sp.	Fée, 1825
Globocassidulina sp.	Voloshinova, 1960
Glandulina sp.	d'Orbigny,1839
Guttulina sp.	d'Orbigny,1839
Haynesina orbiculare	Brady, 1881
Islandiella helenae	Feyling Hanssen & Buzas, 1976
Islandiella norcrossi	Cushman, 1933
Melonis affinis	Reuss, 1851
Nonionellina labradorica	Dawson, 1860

Genus species	**References**
Nonionellina auricula	Heron-Allen and Earland, 1930
Oolina sp.	d'Orbigny, 1839
Quinqueloculina sp.	d'Orbigny, 1826
Stainforthia loeblichi	Feyling-Hanssen 1954
Trifarina fluens	Todd in Cushman and McCulloch, 1948

Table 4.4: Foraminiferal list of Kongsfjorden sections with the original reference

SCANNING ELECTRON MICROSCOPE IMAGES OF ARCTIC FORAMINIFERA

(DESCRIPTION OF PLATE 1)

Figure 1. *Astrononion hamadaense* (U)

Figure 2. *Buccella frigida* (Si)

Figure 3. *Buccella frigida* (U)

Figure 4. *Cassidulina reniforme* (U)

Figure 5. *Cassidulina reniforme* (Si)

Figure 6. *Lobatula lobatula* (Si)

Figure 7. *Lobatula lobatula* (U)

Figure 8. *Elphidium clavatum* (S)

Figure 9. *Cribroelphidium williamsoni* (S)

Figure 10. *Elphidium subarcticum* (S)

Figure 11. *Elphidium albiumbilicatum* (S)

Figure 12. *Globocassidulina* sp. (Si)

Figure 13. *Globocassidulina* sp. (A)

Figure 14. *Cassidulina neoteretis* (Si)

Figure 15. *Cassidulina neoteretis* (A)

A-Apertural view, U-Umbilical view; Si-Spiral view, S-Side view

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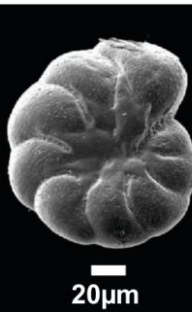

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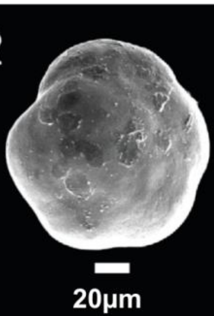

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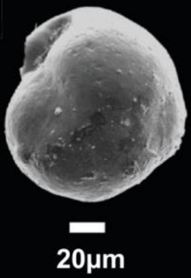

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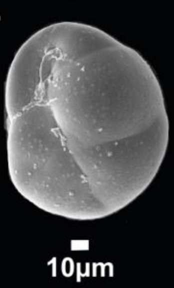

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SCANNING ELECTRON MICROSCOPE IMAGES OF ARCTIC FORAMINIFERA

Description of Plate 2

Figure 1. *Haynesina orbiculare* (S)

Figure 2. *Islandiella helenae* (A)

Figure 3. *Islandiella helenae* (Si)

Figure 4. *Islandiella norcrossi* (A)

Figure 5. *Nonionellina auricula* (S)

Figure 6. *Nonionellina labradorica* (S)

Figure 7. *Melonis affinis* (S)

Figure 8. *Fissurina* sp. (S)

Figure 9. *Stainforthia loeblichi* (S)

Figure 10. *Guttulina* sp. (S)

Figure 11. *Oolina* sp. (S)

Figure 12. *Quinqueloculina* sp. (S)

Figure 13. *Glandulina* sp. (S)

Figure 14. *Trifarina fluens* (S)

A-Apertural view, U-Umbilical view; Si-Spiral view, S-Side view

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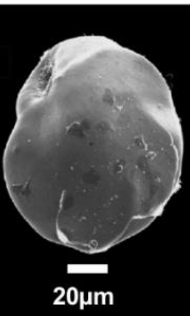

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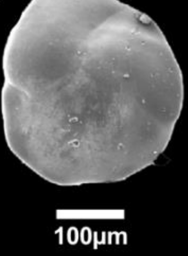

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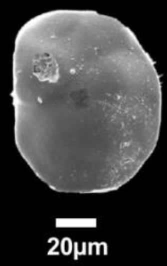

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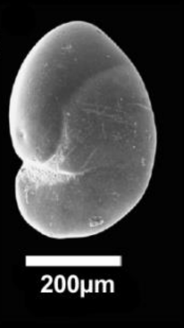

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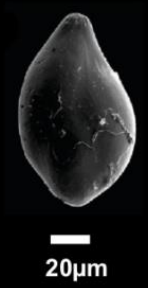

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Chapter 5 Discussion and Conclusion

5.1 Recent foraminiferal assemblages

In the context of the recent distribution of foraminifera, our study reveals significant outcomes which show specific foraminifera assemblages of the different sections of the Kongsfjorden fjord. In addition, this study includes another fjord of Svalbard, Krossfjorden, that extends the knowledge about the distribution of foraminifera.

The proximal region of Kongsfjorden contains *Cassidulina reniforme* and *Elphidium clavatum* as characteristic foraminifera species. These two species have been found widespread in the Svalbard fjords characterizing high turbidity, low salinity, and stressed water column in front of glaciers. The region is dominated by a high abundance of agglutinated foraminifera i.e., *Textularia sp*. and *Spiroplectammina biformis* assemblages. These two species denote lower oxygen conditions, low pH, and high organic matter input. The area overall is characterized by low total foraminifera numbers and living foraminifera numbers, except for a certain area representing a higher proportion of total and living fauna.

The central part of the fjord comprises a greater abundance of *Cassidulina reniforme*, *Nonionellina labradorica* followed by *Islandiella helenae*. This higher increment of these particular species denotes a more favored condition for replenishment. The conditions include the presence of well-oxygenated water, availability of food and nutrients, lesser activity of glacier meltwater, and the presence of a stratified water column. The region shows a greater abundance of agglutinated taxa *Adercotryma glomeratum* that is linked to Transformed Atlantic water. However, the local oxygen minimum zone occurs as evidenced by the presence of asymmetric calcareous taxa *Stainforthia loeblichi*. The region includes a higher total foraminifera number and living fauna.

The outer part of the fjord is made up of a greater abundance of *Nonionellina labradorica* along with *Islandiella helenae*, in addition to the exceptional proliferation of *Nonionellina labradorica* at the shelf region. This expansion of this taxa has been ascribed to the circulation of Atlantic water, which carries abundant nutrients and food particles in the region. Extreme high foraminifera numbers and the development of symmetric taxa indicate well-productive, oxygenated marine conditions. An increased population of *I. helenae* particularly indicates productive and sea-ice marginal conditions.

Apart from Kongsfjorden, Krossfjorden characterizes throughout the distribution of *Nonionellina labradorica*, *Islandiella helenae,* and *Cassidulina reniforme*. This abundant occurrence of these taxa indicates the presence of microdetritus algal blooms in the fjord. This greater proliferation is indicative of higher productivity in the surrounding area. This event eventually points out a more productive Krossfjorden compared to Kongsfjorden. However, in the glacial proximal region dominance of *E. clavatum* and *C. reniforme* has been observed along with the dominance of agglutinated foraminifera i.e., *Textularia* sp. and *Spiroplectammina* at the extreme close to the glacier.

So, from investigations from the recent distribution of foraminifera in the fjords, it can be assumed that the presence of *C. reniforme* and *E. clavatum* exclusively indicate proximal glacial condition. The abundance of *C. reniforme* over *Elphidium*, however, indicates more stable distal glacier conditions while the abundance of *Elphidium* is more confined close to the glacier front. Conversely, the presence of *Nonionellina labradorica* and *Islandiella helenae* restricted to more productive, well-oxygenated conditions of the ambient realm. This specific association in the recent records reflects equivalent marine conditions in the past.

5.2 Quaternary foraminiferal assemblages

Three Quaternary sections ***Kongsfjordhallet***, ***Stuphallet***, and ***Leinstranda*** on the north-western section of the Svalbard archipelago for the current study have been chosen for paleoenvironmental evaluation. The foraminifera assemblages of these three sites are significant in terms of the glacial and interglacial environment. The results are consistent with the sedimentary and glacial environments and can be compared with other Quaternary sections of Svalbard.

The oldest foraminifera record of this current study is of Pre Saalian ages >195 ka reported from the Kongsfjordhallet section. The foraminifera assemblages have been found in Unit -1 of the section. It comprises *Cassidulina reniforme-Elphidium clavatum* assemblage reflecting a stable, cold inner shelf glacial distal environment with at least seasonal productivity as evident from taxa *Islandiella helenae.* However, no record of intrusion of Atlantic water has been found during that time period which represents a glacial-interglacial cycle older than 195 ka. The unavailability of this particular record needs further documentation of the similar kind of strata in other sections.

The foraminifera assemblages of Saalian ages (195± 10 ka) have been found in Unit 1 of the Kongsfjordhallet section. It contains *Cassidulina reniforme-Cassidulina neoteretis* assemblage pointing out a stable, cold glaciomarine environment with an occasional inflow of Atlantic water into the site during that time. It is inferred from the presence of taxa *C. neoteretis*, *N. labradorica*, *Buccella frigida,* and *Islandiella helenae*. No such foraminiferal records have been found in Stuphallet and Leinstranda sections, although similar sedimentary strata of equivalent ages exist.

The foraminifera assemblages prior to the Last Glacial Maximum (60±4 ka) and during the Last glacial maximum (17±0.6 ka) have been documented from Kongsfjordhallet in Unit 8a and Unit 8b respectively. It characterizes *Lobatula lobatula- Cassidulina reniforme- Elphidium clavatum* and *Cassidulina reniforme- Elphidium clavatum* assemblages revealing a glacier-distal location with milder conditions, i.e., seasonal marginal sea-ice conditions during the deposition of the units. No such records have been found in Stuphallet and Leinstranda sections.

The foraminifera assemblages during the Eemian interglacial event at 132±7 ka are important and have been found present in all three sections. For Kongsfjordhallet, the foraminifera assemblages contain *Cassidulina reniforme--Cassidulina neoteretis* assemblage reflecting higher energy, glacial distal marine environment with a notable inflow of Atlantic water into the site. The foraminiferal record of Stuphallet during Eemian times represents *Cassidulina reniforme- Lobatula lobatula- Elphidium clavatum* assemblage. It differs from Kongsfjordhallet by having *Elphidium clavatum* in the assemblage along with a low abundance of foraminifera specimens. On the contrary, Kongsfjordhallet shows a more elevated concentration of foraminifera specimens. The Leinstranda section significantly differs from the above two sites by a scarcity of foraminifera specimens. The study shows, the foraminiferal records during Eemian times vividly vary with sites in a small region. This is ascribed probably due to the surrounding sedimentary environment. Kongsfjordhallet shows a more pronounced effect i.e., the vigorous effect of Atlantic water compared to Stuphallet and Leinstranda. However, intrusion of Atlantic water took place in the Stuphallet section as evidenced by *C. reniforme* and the presence of Atlantic water-influenced species i.e., *Lobatula lobatula* (Landvik et al., 1992, Hald et al.,1999). Evaluating environmental prediction at Leinstranda requires further documentation and analysis of strata for foraminifera records.

The foraminifera record during the interstadial event, Phantomodden interstadial event (97± 5 ka, 99±8 ka) has been significantly found in Stuphallet and Leinstranda sections. The foraminifera assemblages of Stuphallet comprises *Cassidulina reniforme- Elphidium clavatum-Astrononion hamadaense* assemblage reflecting higher bottom currents, productivity, glacial distal environments with notable abundance and diversity. The foraminifera assemblage from Leinstranda in the interstadial event represents *Lobatula lobatula-Elphidium clavatum-Cassidulina reniforme* reflecting high energy proximal glacier environment but low abundance compared to Stuphallet. This scenario is completely different in the case of Kongsfjordhallet by foraminifera barren units. This difference has been attributed to the presence of a fluvial environment on the site.

5.3 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 paleorecords from different sites in areas such as Svalbard is hampered by occurrences at only few contemporaneous sites, low chronological resolution (cf. 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 marine isotope stage, the precision of the ages commonly leaves uncertainties of several thousand years. This in turn implies that we may not examine 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. Using foraminifera from raised marine deposits instead of from marine cores at least provides some limitation on the possible age 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 at 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 ka and 129±10 ka, respectively; Alexanderson, Landvik & Ryen 2011, Alexanderson et al., 2018), but the error margins of the ages are large. The two sites are located not too far apart and could be expected to have experience similar oceanographic conditions. Nevertheless, the faunal composition differs significantly between both sites: At Kongsfjordhallet a *Cassidulina reniforme-Lobatula lobatula-Cassidulina neoteretis* assemblage existed (Fig. 5), while *Elphidium excavatum*, *Astrononion hamadaense* and *C. 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 only as the base for correlation between the two or any other sites. The specific environment of Kongsfjordhallet containing *Lobatula lobatula* and *Cassidulina neoteretis* resembles Holocene interstadial events i.e., Bølling-Allerød interstadials greatly recorded in the Svalbard fjords (Ślubowska-Woldengen et al., 2007).

In the current study, glacial events in the Kongsfjordhallet, Stuphallet and Leinstranda sites have been compared and correlated in terms of glacial, sedimentary, foraminiferal composition, and paleoenvironments.

The foraminifera assemblages *Cassidulina reniforme-Lobatula lobatula-Elphidium clavatum* from Stuphallet closely resemble Eemian assemblages from Sarsbukta (QB zone) (Feyling –Hanssen et al. 1984) and Middle Weichselian interstadial foraminifera assemblages of Isvika, Murchisonfjorden (Kubischta et al., 2010). The assemblage differs from most of the other sites of Svalbard having *Astrononion hamadaense* as a major component in those Eemian deposits i.e., the Eemian and Early Weichselian interglacial deposits of NW Brøggerhalvøya, Zone FS-I and FL-III from Skilvika and Linnéelva (Lycke et al., 1992), and Poolepynten (unit A, Bergsten et al., 1998). The assemblage represents a stable, higher energetic environment during Eemian compared to much-mitigated conditions i.e., the higher advection of Atlantic water and abundant foraminifera specimens in the Kongsfjordhallet section. This framework has been found different in the case of Leinstranda with similar lithology but few foraminifera specimens. The deposits of Unit 4, Unit 3, and Unit 8/9 of the Kongsfjordhallet, Stuphallet, and Leinstranda sites respectively have been therefore correlated in the present study (Figure 5.1) based on uniform lithology i.e., glaciomarine mud, chronology i.e., Eemian interglacial period 132±7 ka and more or less similar foraminifera assemblages and inferred paleoenvironments.

The significant outcome of the present study is the presence of foraminifera *Cassidulina neoteretis* in the Kongsfjordhallet section. However, this particular species was not reported in the adjacent areas during pre-Saalian times where its documentation only extends up to Eemian times in the adjacent Yermak Plateau (Chauhan et al., 2014). The presence of *C. neoteretis* (Seidenkrantz 1995) indicates chill Atlantic water mass existed during the pre-Saalian time in Kongsfjordhallet. The assemblage represented that, the interglacial during late MIS 7 or MIS 6 (195±10 ka) was more diverse than that during the Eemian, but conditions were not necessarily as warm. These particular assemblages have not been identified in the surrounding regions. The Saalian and Pre-Saalian assemblages are not currently found in the Stuphallet and Leinstranda in the present study which denotes different sedimentological and glacial environment which requires further study and availability of similar strata of the same age.

The Phantomodden interstadial events (97±5 ka) of Stuphallet in unit 7 represents diverse and abundant foraminifera specimens. The foraminifera assemblage *Cassidulina reniforme- Elphidium clavatum-Astrononion hamadaense* reflects short transportation and deposition in the coastal environment. The assemblage can be compared to the rich and diverse interglacial assemblage from Sarsbukta (Feyling-Hanssen and Ulleberg, 1984), and correlated to the Early Weichselian interstadial faunal zones F-S-I of Skilvika and F-L-III of Linnéelva by the presence of characteristic fauna *A. gallowayi* (Lycke et al., 1992). The interstadial deposit from Leinstranda (99±8 ka) in 14/15 unit contains *Lobatula lobatula-Elphidium clavatum-Cassidulina reniforme* assemblage. The unit reveals glacial distal, higher energy, and productivity-dependent foraminifera species i.e., *Islandiella helenae* and *Buccella frigida,* and interglacial or interstadial indicator species *A. hamadaense*. These two interstadial deposits of Stuphallet and Leinstranda have been correlated (Figure 5.1) based on identical lithology i.e., thick glaciomarine mud, chronology, foraminifera assemblage, and interpreted paleoenvironments. This interstadial assemblage (97±5 ka) is not currently found in Kongsfjordhallet section.

Therefore, 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 to 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 *Nonionellina labradorica*) that are warm-water indicators, but a high faunal diversity is also a sign of interglaciation. In our record, the assemblage dominated by *C. reniforme* and *C. neoteretis* from Unit 1 from Kongsfjordhallet is the most diverse, while the most warm-loving species are found in the *Cassidulina reniforme-Lobatula lobatula-Cassidulina neoteretis* assemblage from Unit 4 of Kongsfjordhallet. While the foraminifera data from both units 1 and 4 show high average TFN, Unit 4 is characterized by high Fisher's alpha index; although the highest species richness is in Unit 1.

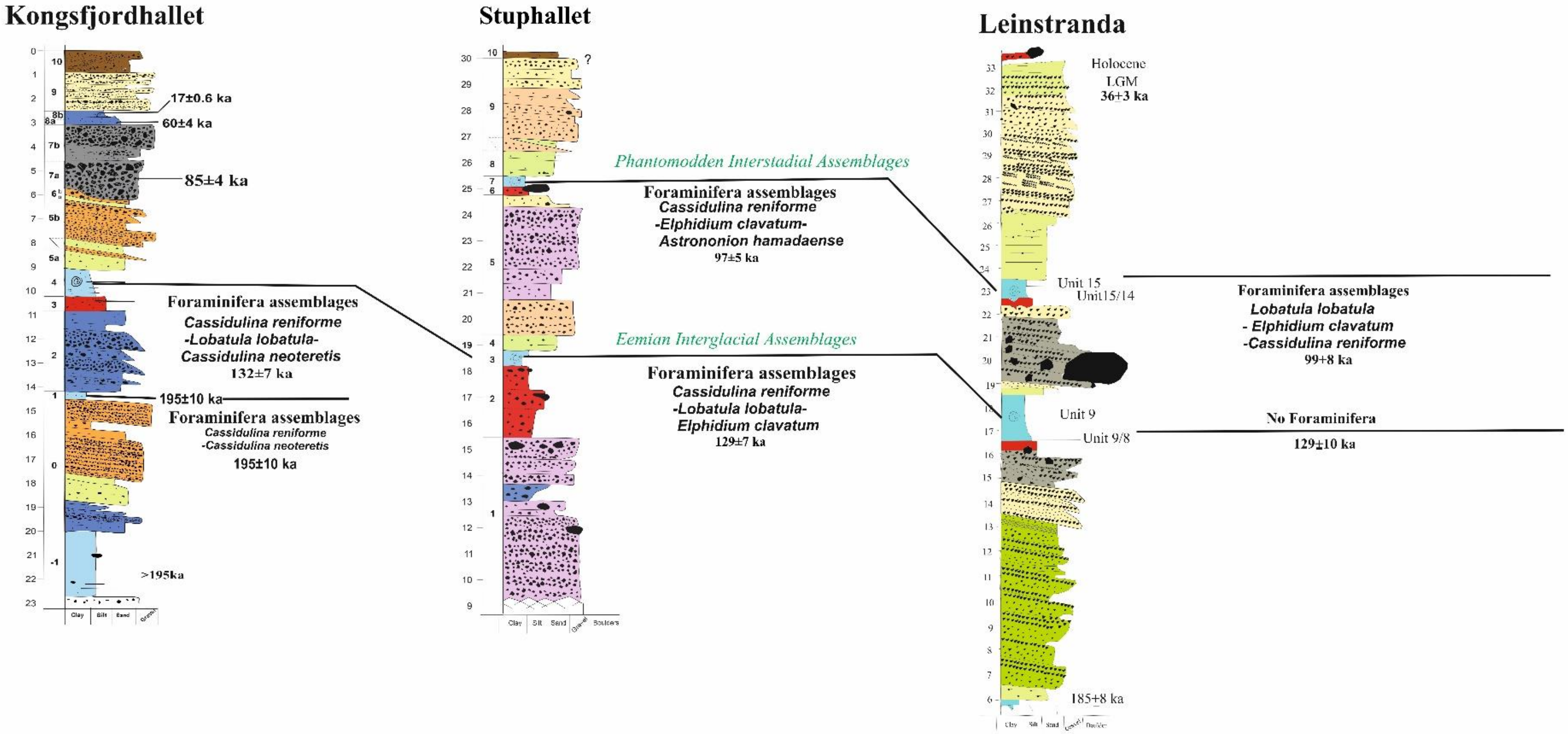

Figure 5.1: Correlation Between Kongsfjordhallet, Stuphallet and Leinstranda sites

5.4 Conclusion

The important findings of the present study are

- The pre-Saalian deposits that represent a significant glacial-interglacial cycle older than popularly studied Saalian glacial cycles in and around Svalbard i.e., older than 195 ka have been identified only in Unit -1 of Kongsfjordhallet section. The foraminifera assemblage *Cassidulina reniforme- Elphidium clavatum* represents a stable cold, inner shelf glaciomarine environment during that period concomitantly follows the distribution of aforementioned taxa in the modern marine realm of Kongsfjorden-Krossfjorden system.
- The Saalian deposits documented in Unit 1 of Kongsfjordhallet are one of the exclusive sites which record the presence of Atlantic water during that time. The foraminifera *Cassidulina neoteretis -Cassidulina reniforme* assemblage reflects a productive marine environment that existed in the interim of Saalian at 195±10 ka.
- The Eemian deposits recorded in Unit 4 of Kongsfjordhallet at 132±7 ka is significant in terms of foraminifera assemblage i.e. *Cassidulina reniforme-Lobatula lobatula-Cassidulina neoteretis* representing a more favored condition for the development of foraminiferal taxa compared to nearby sites. The Eemian deposits documented at Stuphallet represent *Cassidulina reniforme-Lobatula lobatula-Elphidium clavatum* revealing the notable existence of Atlantic water in that particular site. The Eemian deposits of Leinstranda show scarce foraminifera. These three deposits have been correlated based on uniform lithology, chronology, and foraminifera composition.
- The interstadial deposits recorded in Unit 7 of Stuphallet at 97±5 ka representing Phantomodden interstadial exhibit well productive marine environment with the intrusion of Atlantic water in the site. The foraminifera composition comprising *Cassidulina reniforme-Elphidium clavatum-Astrononion hamadaense* represents much diversified, abundant, noticeable temporary warm high sea-level events not even found in the surrounding sites. These interstadial deposits have been found in Unit 14/15 of Leinstranda (99±8 ka) showing *Lobatula lobatula-Elphidium clavatum-Cassidulina reniforme* assemblage showing good abundance and the marine environment through that specific time. These two deposits have been correlated.

- The proximal part of Kongsfjorden and Krossfjorden constitutes *E. clavatum* and *C. reniforme* assemblage. Abundant angular asymmetric agglutinated forms characterize the area of Kongsfjorden, i.e., *Textularia* sp. and *Spiroplectammina biformis*. In addition, Krossfjorden contains *Adercotryma glomaratum*. The assemblage indicates the low saline, increased sedimentation, and meltwater runoff environment.

- The middle and distal parts constitute *N. labradorica, L. lobatula,* and *I. helenae* assemblage. The agglutinated foraminifera mainly comprise *Adercotryma glomaratum*. The foraminiferal populations indicate well-oxygenated, low sedimentation rate, and high surface primary productivity and influence of Atlantic waters.

- Krossfjorden appears more enriched in productivity and phytodetritus than Kongsfjorden from abundant *N. labradorica* in the proximal and distal part, followed by *I. helenae* and a more rounded calcareous fauna.

- The presence of *Stainforthia loeblichi* in the middle part of the Krossfjorden shows the occurrence of low oxygen conditions.

Therefore, this current study has shown when modern foraminiferal assemblages are translated into fossil assemblages; with sedimentology and chronology; it can create new insights into past environments i.e., reconstruction of the Middle and Late Quaternary paleoenvironment in the Kongsfjorden area.

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