Late Quaternary environmental reconstruction using foraminifera and sedimentary stratigraphy from Kapp Ekholm, Svalbard

Department of Geography

University in Bergen

Department of Arctic Geology

The University Centre in Svalbard

By Alexander Hovland

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SUMMARY

The Kapp Ekholm sedimentary sections is a key location for our present understanding of the two last glacial cycles on western Svalbard. Its long sedimentary history (MIS 6 to present) and its position almost at the center of the Spitsbergen island distinguishes the site from other localities on Svalbard. At least four regional glacial advances are recorded in the sections and are separated by marine intervals deposited during relatively high sea level. The marine intervals show a regressive trend shallowing up-section. This stratigraphical trend is in places interrupted by deposits from slope-processes and fluvial-influence.

The foraminiferal stratigraphy of the sublittoral intervals of Formation B (Eemian interglacial), Formation F (Kapp Ekholm interstadial) and Formation H (Holocene interglacial) is described and interpreted from Section II. The fauna generally shows a moderate to distal glacial influence as indicated by high ratios and frequencies of *C.* reniforme and *E.* excavatum. There no consistent up-section trend for any of the formations in terms of glacial influence.

The fauna from the lower half of Formation B is interpreted to indicate inflow of Atlantic Water. The main indication of Atlantic Water masses are high frequencies of *N. auricula* and *N. labradorica* that suggest a seasonal inflow. It is suggested that this period is associated with increased Atlantic Meridional Overturning Circulation (AMOC) at the transition between MIS 6/5e or at the beginning of MIS 5e. In the upper half, the inflow is shut down, and *I. norcrossi* replaces both *N. labradorica* and *I. norcrossi*. This suggests a stratified hydrological environment where cold and saline water dominate like today.

The foraminiferal fauna of Formation F (MIS 5a/b) and Formation H (c. 10-8 cal ka BP) shows no indiciation of warm-water inflow and local water masses probably dominated. Formations F and H differ from Formation B by having more species that are generally associated with fluvial influenced environments including *A. gallowayi, E. subarcticum*, *H. orbiculare* and. This may suggest a depositional environment closer to the coast than what is the case for Formation B.

PREFACE

This thesis is the end product after two and a half year of work on my Master in Physical Geography. Most of the fieldwork was conducted already by the end of July 2012, during two beautiful Svalbard-weeks. A full year was then spent on taking courses both at the University of Bergen (UiB) and the University Centre on Svalbard (UNIS).

A second round of fieldwork was conducted in July 2013 with strong winds, sleet, and rain, but was a beautiful week nonetheless. Lab-work started at UNIS in the fall 2013, but was interrupted by an accident involving a Shiba Inu, about 12 Alaskan huskies and my hand. The rest of the fall was spent travelling between Longyearbyen and Tromsø resulting in a delay of the thesis-work. Lab work was finalized in May 2014 and writing in September.

The thesis starts with an introduction that outlines the project, the study site and the methods. Introduciton is followed by the results. This chapter is divided into a part on sedimentary stratigraphy and another part on the foraminiferal stratigraphy. The results chapter focuses on presenting the data and the environmental constraints. The discussion parts focuses on putting these environmental constraints into a larger framework before conclusions are drawn. References and Appendix follow at the end.

ACKNOWLEDGEMENTS

I would like to use this opportunity to express my gratitude to everyone who have supported me throughout the course of the project.

Dr. Anne Hormes. You have been my supervisor, but also a good friend throughout my years at UNIS. I am deeply grateful for the adventures we have shared and your continuous support and trust as a supervisor. Also to my supervisor from Bergen, Prof. Svein Olaf Dahl who have supported and challenged me since I began my bachelor in Geography. You have always met me with a smile and I deeply appreciate our many conversations and discussions.

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1. INTRODUCTION

A series of glaciations characterize the Quaternary geological period (2.588 Ma to present). On the Arctic archipelago Svalbard (74°-81° N, 10°-35° E) there is evidence of several regional sized ice-sheets forming over Spitsbergen and extending to its western shelf during the Middle- to Late Pleistocene (Landvik et al., 1992; Mangerud et al., 1998; Svendsen et al., 2004; Ottesen et al., 2008; Ingolfsson and Landvik, 2013). In-between have been periods of considerable warming. So far our insight into climatic change on Svalbard is focused mostly on variability within the Holocene-interglacial (e.g. Svendsen and Mangerud, 1997; Ślubowska et al., 2005; Hald et al., 2007; Baeten et al., 2010; Rasmussen et al., 2012) and to some degree interstadials within the last glaciation (e.g. Landvik et al., 1992; Lycke et al., 1992; Kubischta et al., 2010). Much more limited is our knowledge of environmental conditions that existed during the last interglacial (MiS 5e - Eemian) as very few natural archives have been preserved. Sediments from the western coast of Svalbard, correlated to the Eemian-interglacial, is so far only known from Poolepynten (Bergstrøm et al., 2001; Alexanderson et al., 2013), Leinstranda (Alexanderson et al., 2010) and from Kapp Ekholm (Mangerud et al., 1998). Kapp Ekholm is considered a major key-site in understanding the last glacial cycle on Svalbard. It is located at the center of Spitsbergen and was until recently the only site that recorded both the last and penultimate interglacial, as well as marine sediments from two interstadial periods during the last glacial period.

Contemporary northwestern Europe and the Northern Atlantic have a climate that is 5-10 °C warmer than the zonal mean (Hald et al., 2007). This pattern corresponds with areas influenced by the North Atlantic Current and Spitsbergen Current where the flow of warm water from the Gulf of Mexico represents an important source of heat (Figure 1). These currents are major components of the Atlantic Meridional Overturning Circulation (AMOC), a system which has a profound effect on the earth's climatic system. According to Risebrobakken et al. (2006) changes in the intensity and the extent of AMOC may be important casual factors for explaining climatic changes observed in Arctic. On Svalbard, it has been shown that periods of glacial retreat during

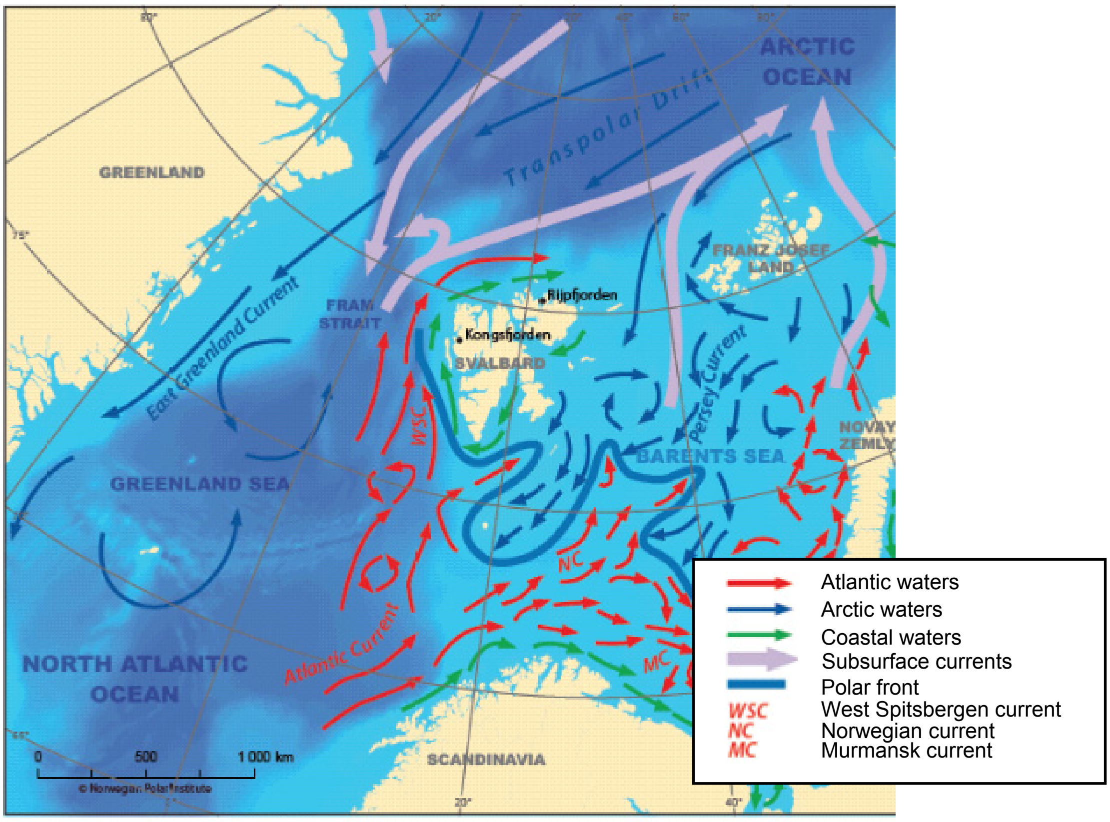


Figure 1: Main ocean currents around Svalbard. The northward flow of Atlantic Water represents an important agent in this system and is an important source of heat transport to Svalbard. (NPI, 2014)

the Eemian- and Holocene interglacials corresponds with periods of increased AMOC (Risebrobakken et al., 2006; Hald et al., 2007; Rasmussen et al., 2012; Chauhan et al., 2014).

At present, there is a general consensus by the Intergovenmental Panel on Climate Change (IPCC) that the world today is undergoing anthropogenically driven climate change (Masson-Delmotte et al., 2013). One of the major uncertainties highlighted by the IPCC is the future behavior of AMO*C.* Svalbard is already experiencing an increased warming of the fjords during summer (Berge et al., 2005; Nilsen et al., 2008; Pavlov et al., 2013). This has allowed for the introduction of non-native warm-water species into the fjord ecosystems along the western coast. In order to better understand and predict future behavior of AMOC and climate change, it is important to understand antecedent environmental and climatic change. Assessment of past environmental conditions beyond the instrumental record can only be estimated using proxies. One key proxy for palaeoenvironmental reconstructions in the Arctic is benthic foraminifera (Murray, 2006a). These microorganisms may provide us with information

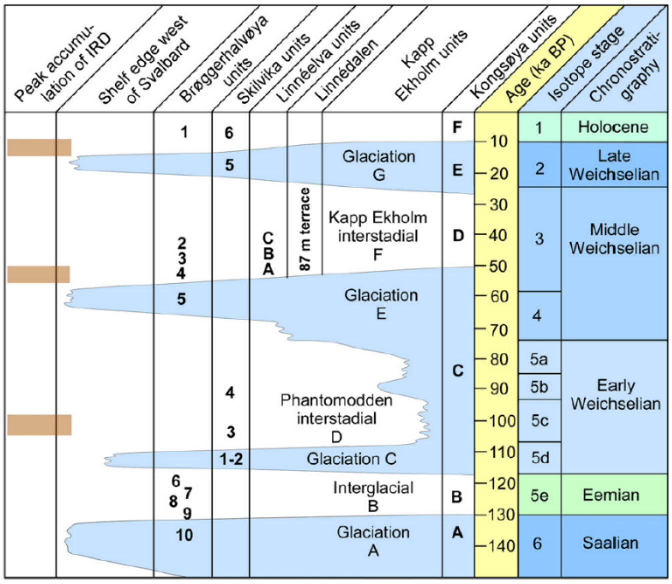
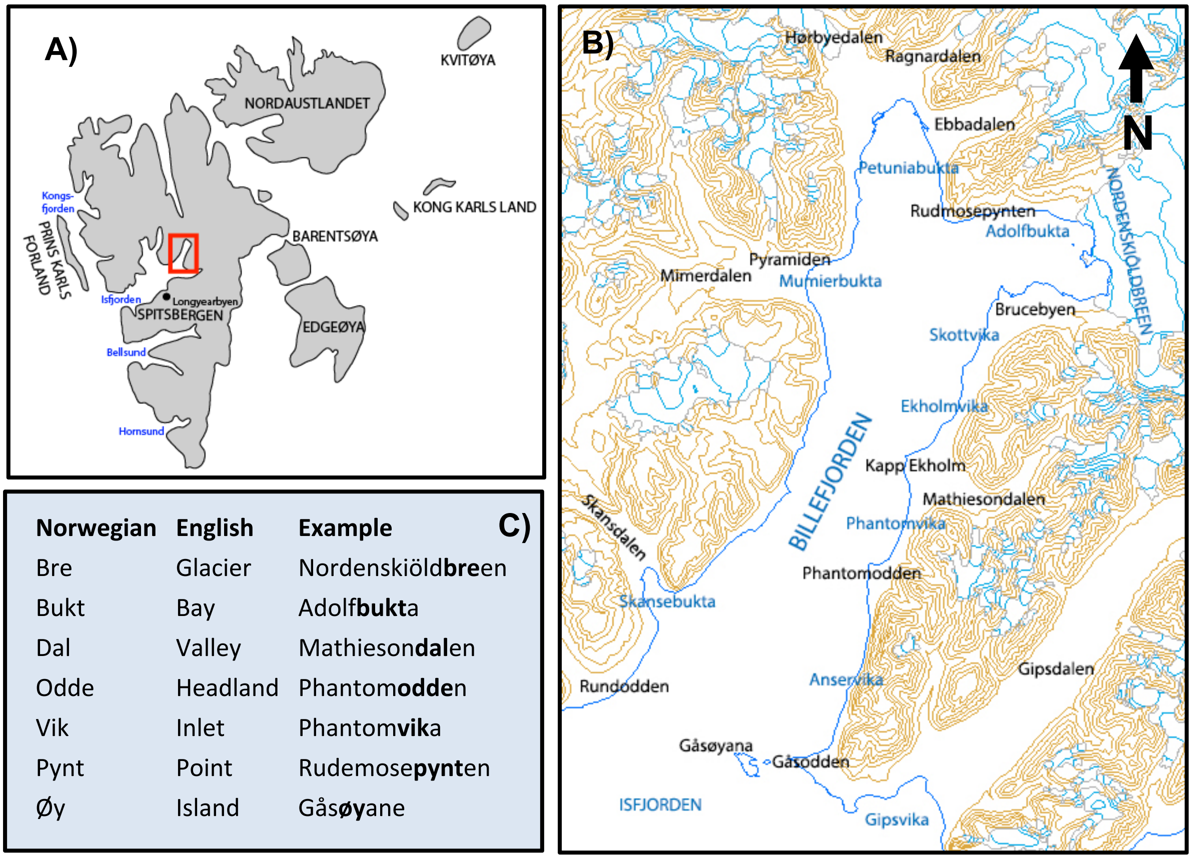


Figure 2: Our current understanding of Late Quaternary glaciations on Svalbard as presented by Ingolfsson and Landvik (2013) based on initial work by Mangerud et al. (1998)

on the regarding the hydrological conditions that existed during their lifetime – in particular, the composition of their host water mass. Foraminifera are common organisms in marine, brackish and even in some fresh-water environments. The evolutionary history of the Foraminifera extends back to the Cambrian and they are widely used as biomarkers, dating, correlation of sediments and for palaeoenvironmental interpretation. On Svalbard they have been used in studies of recent environments (Hald and Korsun, 1997; Pogodina, 2005; Zajączkowski et al., 2010), Holocene environments, (Ślubowska et al., 2005; Rasmussen et al., 2012) Pleistocene xenvironments, (Feyling-Hanssen, 1955, 1965; Feyling-Hanssen and Ulleberg, 1984; Lycke et al., 1992; Bergsten et al., 1998) and pre Quaternary environments (Edwards et al., 1979; Løfaldli and Nagy, 1980; Nagy et al., 2009; Nagy et al., 2010; Reolid et al., 2010; Reolid et al., 2012)

Marine sediments deposited during periods of higher relative sea level are today preserved on land at several locations on Svalbard. Through description, dating, interpretation and correlation of these sites, Mangerud et al. (1998) sconstructed a temporal framework as well as a record of large-scale climatic fluctuations on Svalbard. The most reason revision to this is presented in (Figure 2). One of the most important key sites is the Kapp Ekholm sections in Billefjorden in Central Spitsbergen (Figure 3). Repeating sequences of basal till, overlain by regressive marine sediments, indicate at least four large glacial advances within Billefjorden since the onset of the Saalian (MiS 6). Several authors have worked with dating and inter-site correlation of these



Norwegian	**English**	**Example**
Bre	Glacier	Nordenskiöld**bre**en
Bukt	Bay	Adolf**bukt**a
Dal	Valley	Mathieson**dal**en
Odde	Headland	Phantom**odde**n
Vik	Inlet	Phantom**vik**a
Pynt	Point	Rudemose**pynt**en
Øy	Island	Gås**øy**ane

Figure 3: Maps of Svalbard and Billefjorden. A) Location of Billefjorden within the Svalbard archipelago (Bjørnøya is not on map); B) Topographical map over Billefjorden; C) English translations of some relevant topographical nouns. (Maps made with data from Norwegian Polar Institute, 2013)

sediments (Feyling-Hanssen, 1955; Mangerud and Salvigsen, 1984; Mangerud and Svendsen, 1992; Mangerud et al., 1998; Forman, 1999; Linge et al., 2008; Eccleshall, 2013). However, so far the only paleo-environmental description from the site has been a simplified description and interpsretation of mollusk-taxa presented in Mangerud and Svendsen (1992). Most notable has been the finding of shells belonging to the boreal taxa *Mytilus edulis* that has been interpreted to indicate inflow of warm Atlantic-Water to Billefjorden. This would suggest conditions very different from today where Atlantic water is more or less absent from the fjord system.

1.1. Research aims

The main objective of this thesis is to contribute to our understanding of the climatic history on Svalbard throughout the Late Quaternary. Fjords represent an important link between the marine- and terrestrial environment and is a crucial component in understanding both local and regional climate change. Billefjorden is in this regard of particular interest because of its position at the center of Spitsbergen.

1. **What is the Late Quaternary palaeoenvironmental history of Billefjorden as recorded by sedimentary deposits and foraminiferal assemblages at Kapp Ekholm?**
2. **Is there foraminiferal evidence for past inflow of Atlantic Water to Billefjorden during marine intervals at Kapp Ekholm?**

These questions will be answered using a combination of sedimentary observation and an analysis of the foraminiferal fauna from marine formations B, F and H (*sensu* Mangerud and Svendsen (1992).

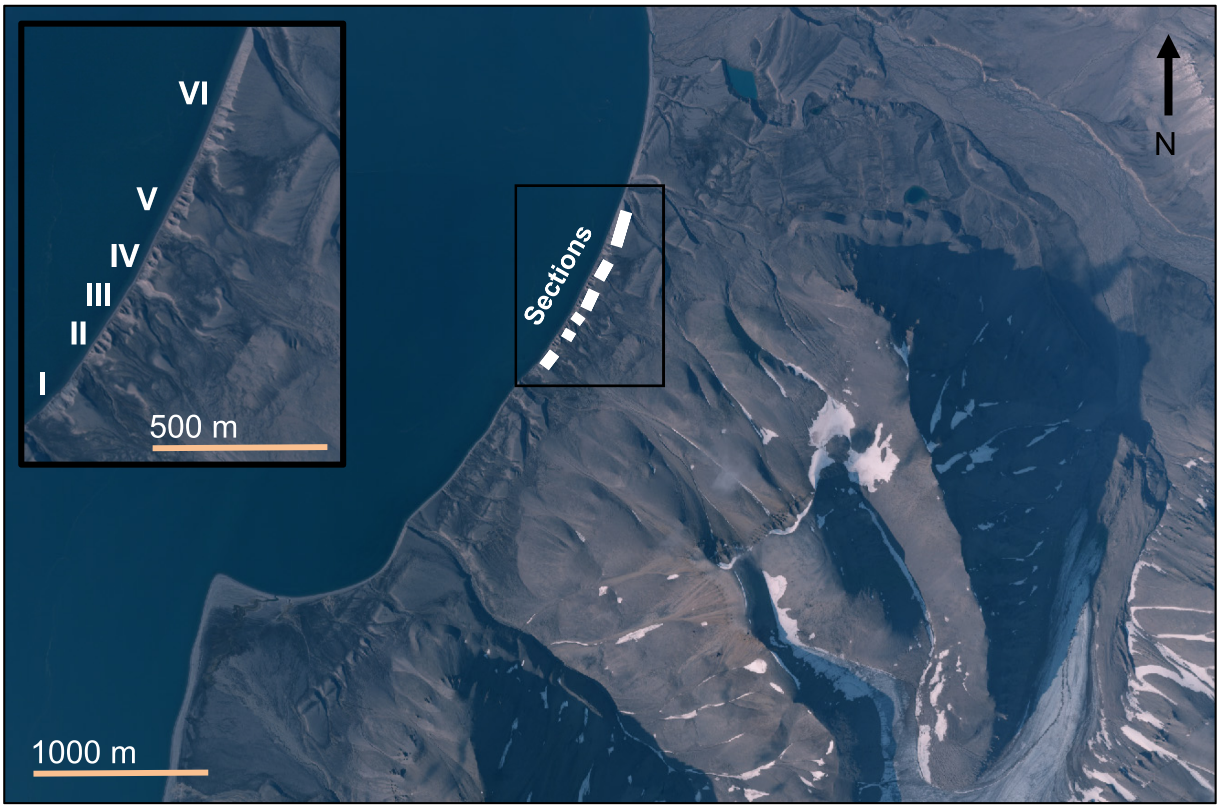


Figure 4: Aerial photo of the area surrounding the Kapp Ekholm sections. (Aerial photo from Norsk Polarinstitutt)

2. STUDY AREA

The study site consists primarily of the Kapp Ekholm sections (Figure 4 and Figure 5) exposed as beach cliffs (between 33X E34380 and N8721460 - E33430 and N8718790) between the Kapp Ekholm delta and Phantomodden headland aslong the western coast of Billefjorden.

Figure 5: Photo from Section II and Section III: (Left) Top surface of sections; (Right) Section II and III seen from the front with a view of alluvial fans in the background.

Billefjorden is a 32 km long, north trending (c. 27° N) tributary to Isfjorden (Figure 3) which is the largest fjord-system within the Svalbard archipelago. It is up to 8 km wide in the outermost part, whereas the inner part of the fjord splits into the two bays Petuniabukta and Adolfbukta. At present, the only glacier to reach the fjord is Nordenskiöldbreen which forms an ice-cliff front in Adolfsbukta. The glacier is presently retreating however and during the summer 2014 its front was observed almost entirely on land.

The catchment area of the fjord covers a total area of 907 km2 following the highest mountain crests, or the ice-divide as in the case of Nordenskiöldbreen (Baeten et al., 2010). Most of the valleys surrounding the fjord are presently characterised by paraglacial river-landscapes originating from glaciers further up-valley. Glacial coverage of this area is 43.8 per cent, somewhat less than the overall coverage of Svalbard (60 per cent).

2.1. Geology

In terms of structural geology the fjord follows the south to north trending Billefjorden Fault Zone (BFZ) which has been active with various intensity since the Precambrian (Braathen et al., 2011). The fjord has been interpreted as a rift basin in the shape of a half-graben structure, with its footwall paralleling the western coast of Billefjorden. Precambrian rocks (Figure 6) includes various types of intrusive rocks such as gabbro and lamprophyres, and metamorphic rocks (e.g. gneisses quartzites, amphibolites, schists and marbles). These are mostly located towards the northwest part of the fjord, but also crop out at the front of Nordenskiöldbreen. Devonian strata are mostly exposed in the western part of the Billefjorden area and consists of siliciclastic post-orogenic molasse. These strata are sometimes referred to as “Old Red” owing to the strikingly red color of its sandstones. Dominating most of the Billefjorden area however is Carboniferous, to Permian sedimentary rocks that ranges from siliciclastic, coal bearing strata, to various carbonate lithologies. Gypsum-anhydrite conversions, as well as an overall high porosity, provides favourable conditions for the occurrence of karst. This is a characteristical morphological feature of the bedrock at Fortet, as well as within Mathiesondalen (Mangerud and Svendsen, 1992). Mesozoic schizts, siltstones

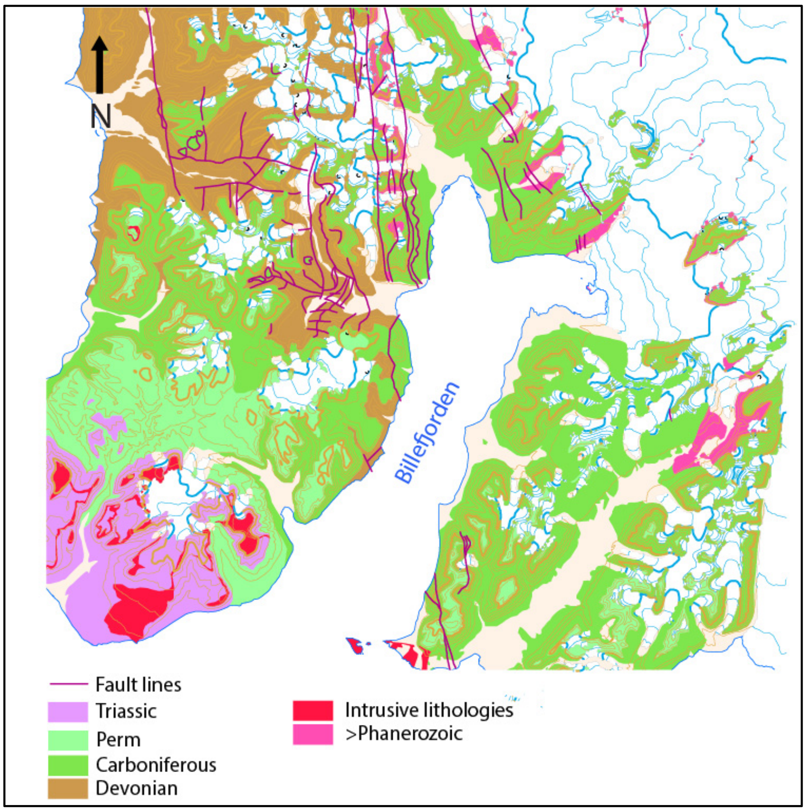
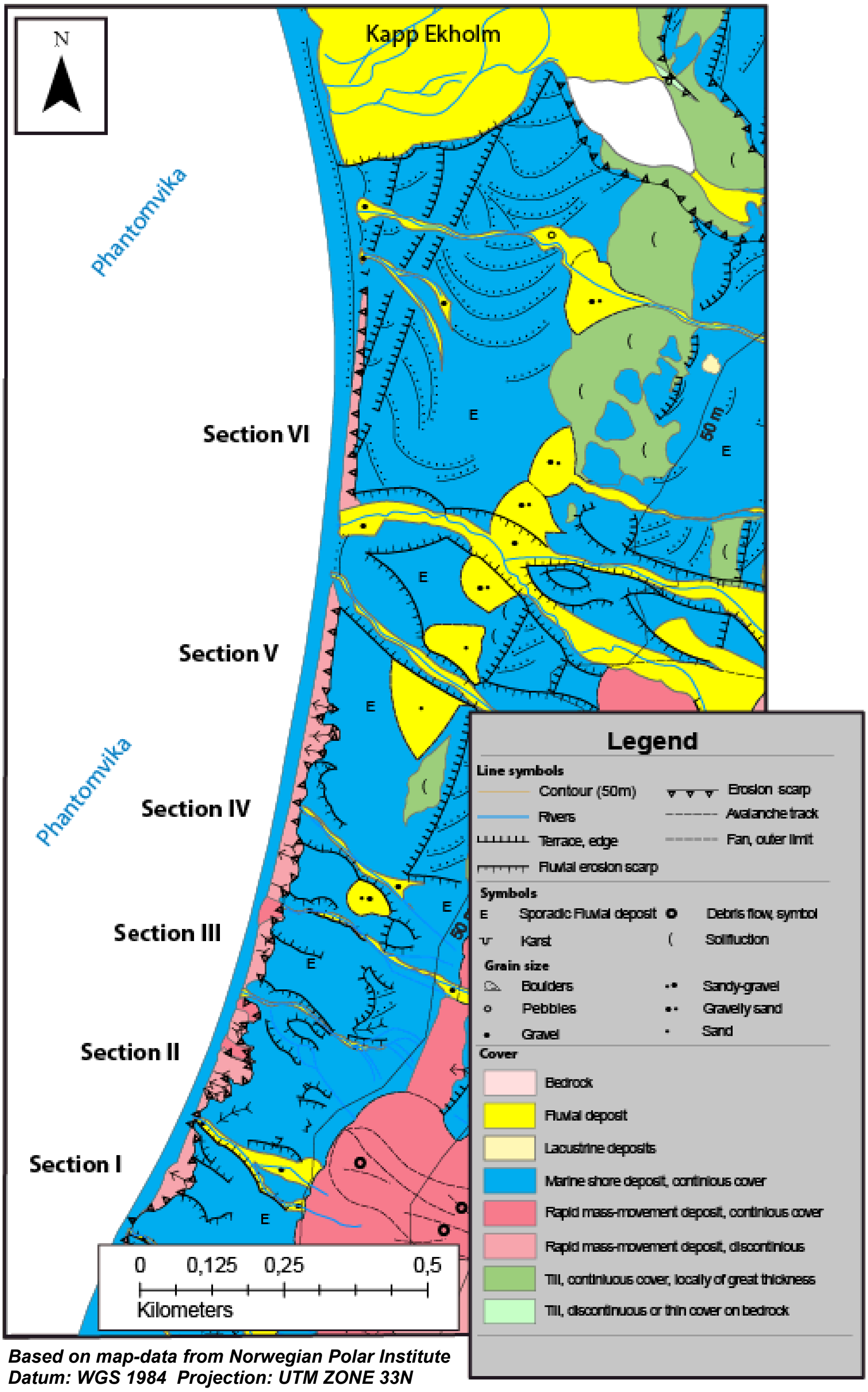


Figure 6: Chronostratigraphical bedrock map over the Billefjorden area. (Made with data from Norwegian Polar Institute, 2013)

and sandstones form the youngest bedrock found only in the southernmost part of the Billefjorden. Rocks of Holocene age are also found within Mathiesondalen, where glaciofluvial material is consolidated into conglomerates by carbonate cementation (Lauritzen and Salvigsen, 1983).

Unconsolidated marine sediments of Quaternary age makes up a large part of the eastern coastline as a continuous cover with varying thickness (Figure 7). The sedimentary sections are located in the steep coastal cliffs (up to 30 m in height)and are continuously modified by coastal erosion and various slope processes. The cliffs are intersected by ravines and gullies where rivers and creeks drain melt-water from the hinterland. Marine terraces dominate the surface morphology with distinct paleo-shore platforms at several levels that give a step-wise appearance of the coastline towards the mountainside. The isostatic rebound following the last glaciation (Weichselian) is known to have been substantial (Forman et al., 2004). Raised marine terraces indicates a relative sea-level rise in Billefjorden of up to 90 m (Figure 8) and of this, the eustatic sea level during the early Holocene may have accounted for about 40 m.



Based on map-data from Norwegian Polar Institute
Datum: WGS 1984 Projection: UTM ZONE 33N

Figure 7: Quaternary map for Kapp Ekholm – Phantomvika. The surface is dominated by marine sedimentation overayling older glacial deposits. Fluvial- and coastal erosion are important processes today in modifying the morpohology.

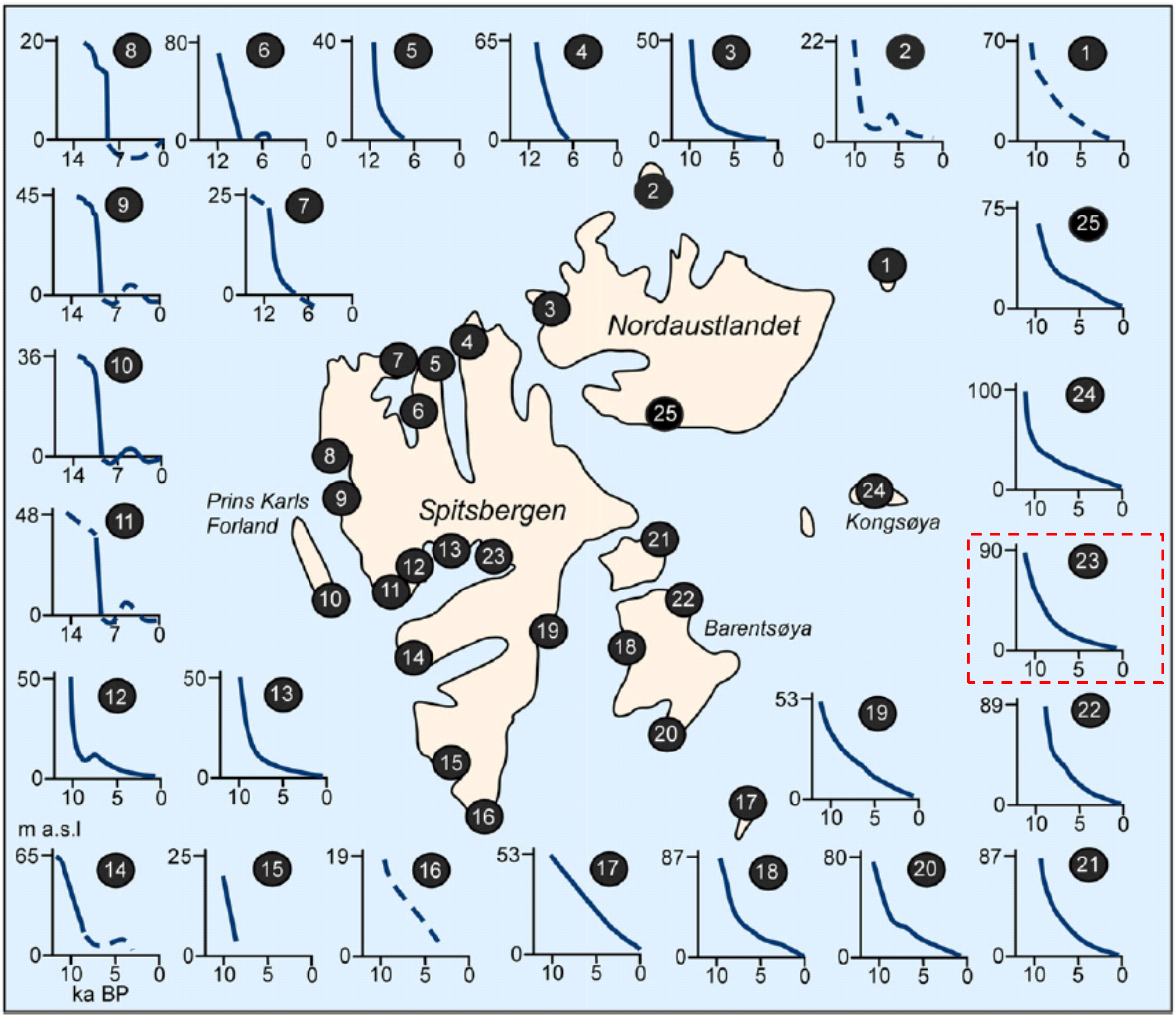


Figure 8: Post-glacial emergence curves for Svalbard. The most relevant curve for Billefjorden (nr. 23) is marked with a red rectangle. Figure is modified from Ingólfsson and Landvik (2013).

The paleo-shore platforms associated with these terraces show a distinct tilt up-fjord, with a weaker dip axis towards the center of the fjord. On top of the terraces, especially in areas unaffected by solifluction and fluvial-action, are preserved beach ridges with fragments of shells and occasionally whalebones. The marine terraces are probably superimposed onto an older moraine system as it is underlain by diamict containing frequently striated clasts resting directly on top of the striated bedrock. Several circle shaped lakes are also present in the area and associated with karst-processes (Lauritzen and Salvigsen, 1983).

The main basin of the fjord is located in the inner and central parts of the fjord, just west of Kapp Ekholm (Figure 9). The fjord basin have maximum measured depth of 211 m, whereas in Petuniabukta, Adolfbukta and Mimerbukta the water depth is

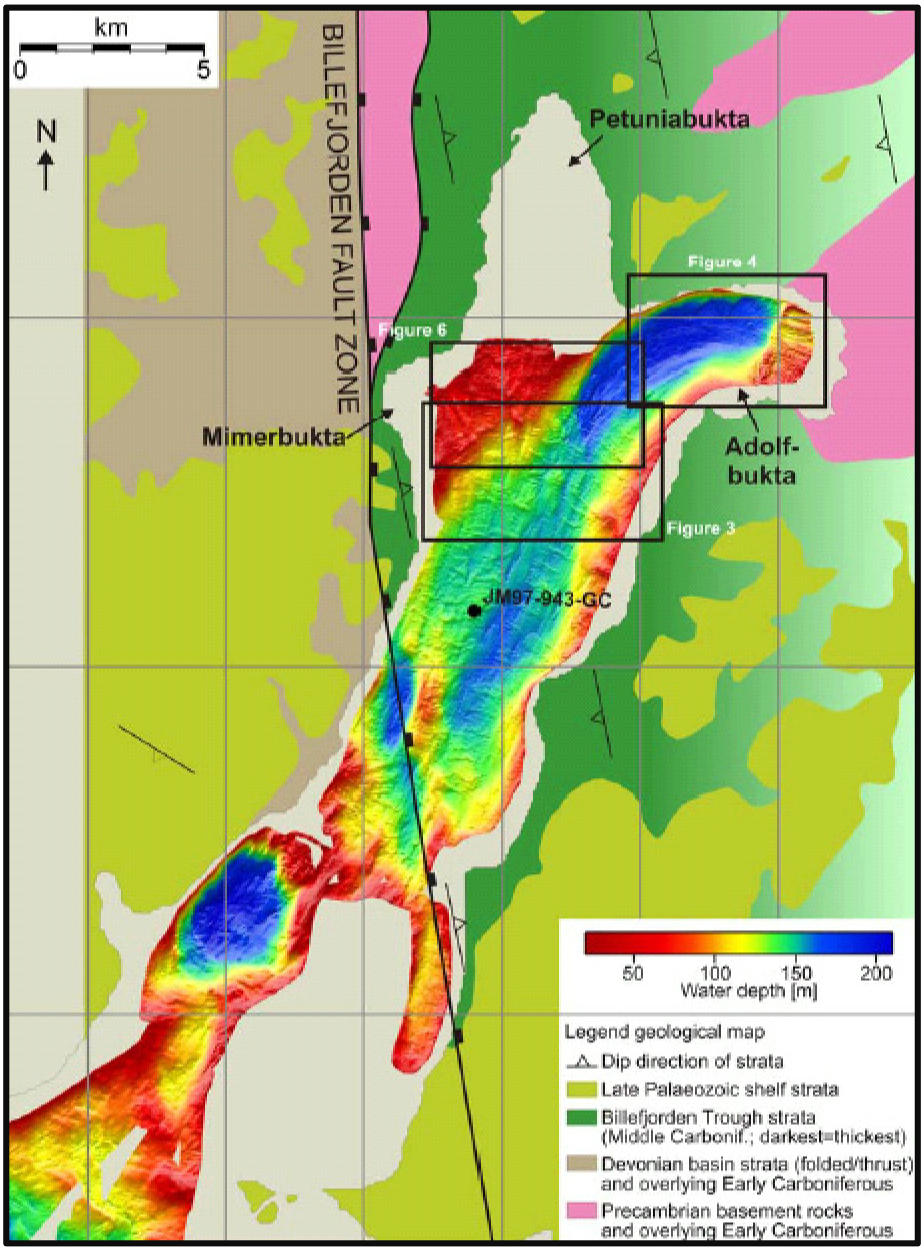


Figure 9: Bathymetric map of Billefjorden. According to Baaeten et al. (2010) the threshold in the outer part corresponds to an area of more erosion resistant Late Paleozoic bedrock (Figure from Baaeten et al. 2010).

generally less than 100 m. Basal till and glacial landforms (lineations, moraines and ice-berg scourmarks) dominate the seafloor and is ascribed to the Weichselian glaciation (Baeten et al., 2010). Marine sediments on top indicate the glacier retreated from the central- to the inner parts around 11.2 ± 0.13 cal ka BP (Hormes et al., 2013)

The fjord show a restricted bathemetry in the outer part between Isfjorden and the main Basin. H a two-sill morphological system with a minimum depth of between 30 to 50 m. The sills are separated by a small basin just east of Skansebukta with a maximum depth of up to 226m. The sill-area is investigated in detail by Baeten et al. (2010) who concluded that the morphology reflect bedrock structures of the Billefjorden Fault Zone, rather than sedimentary deposition. It is therefore more precise to refer to these structures as shoals and not sills.

2.2. Climate

The regional climate of Spitsbergen is strongly influenced by the West Spitsbergen Current, a northern branch of the Norwegian Atlantic Current that brings huge volumes of warm Atlantic Water to the archipelago. As a consequence the climate is mild considering the latitude with an a Mean Annual Air Temperature (MAAT) of c. -6 °C for the time-interval 1961-1990 (Winther et al., 1998) at Longyearbyen Airport. This is warm, when compared to measuring stations at similar latitudes (70° -80° N) which will usually fall in between -9 to -15 °C (Eckerstorfer and Christiansen, 2011). The warmest months are usually July and August in which the mean temperature is + 5 °C The annual mean precipitation is 200 mm and Spitsbergen may be described as having a polar desert climate. There is no permanent metrological station in Billefjorden. Temperatures measured at the head of Billefjorden suggest however that there may be a higher seasonal contrast when compared to Longyearbyen Airport, with temperatures c. 3.3 °C lower in winter, and 1.3 °C higher in summer (Rachlewicz, 2009).

The summer lasts from the end of June to September where temperatures are typically above 0°C with continuous daylight. In the autumn, temperatures will fall below freezing and most rivers will dry out or be completely frozen.

Winter which lasts from December to March is characterized by the lowest temperatures, polar night and with sea-ice developing in most of the fjords by the beginning of January. The sea-ice will last through spring despite daylight gradually returning with increasing temperatures and enhanced melting. Maximum melting rates is achieved in late spring (May).

2.3. Hydrography

Both the local- and regional climate, as well as the marine hydrology on Svalbard is strongly influenced by the West Spitsbergen Current (Skogseth et al., 2005). This current transports warm Atlantic Water (AW; T <3°C ; S >34.9 psu) from the Norwegian Atlantic (Figure 1). At the shelf it converges and mix with colder and less saline Arctic Water (ArW; T >0°C; S 34.3 – 34.8 psu) as well as surface-melt water (SW; T > 1°C;) producing Transformed Atlantic Water (TAW; <1 °C; S <34.7 psu). In the following the acronym AtW (T <1 °C; <34.7 psu) is used as a collectively term to describe both untransformed Atlantic Water (AT) and Transformed Atlantic Water (TAW).

Isfjorden is a broad and open fjord and is directly linked to the shelf-slope with no distinct shallow-water threshold at the mouth (Nilsen et al., 2008). ArW is openly exchanged between Isfjorden and the shelf, following in along the southern coast and eventually exiting out in the northern part of Isfjorden. AW is normally present on the shelf all year, but do not penetrate into Isfjorden before summer with water-volumes showing an inter-annual variability. Nilsen et al. (2008) argues that brine rejection and consequently the formation of dense winter-cooled water (WCW; T < 0 °C; S > 35 psu) represent an important hydraulic mechanism for AW-inflow during the following summer. Isfjorden can be regarded as a polynya in years where conditions are favorable for sea ice-growth. The continuous production of sea-ice throughout the winter causes large volumes of dense WCW to form. This increases the hydraulic gradient between Isfjorden and causes WCW to flow out on the shelf, allowing AW to enter Isfjorden.

Billefjorden, as opposed to Isfjorden, have a much more restricted hydrological exchange. The water exchange is greatly influenced by the shallow-water sill in the outermost part of the fjord that retain the seasonally produced WCW (Figure 10). Only locally produced water types are present, even in years where AW dominate in Isfjorden. This inhibited outflow weakens the hydraulic gradient between Billefjorden and Isfjorden preventing the subsequent inflow of AW. In the summer and spring the uppermost part of the water column is usually dominated by SW (>1 °C) formed by glacial melt and river runoff, and gradually thins as a wedge towards the mouth of the

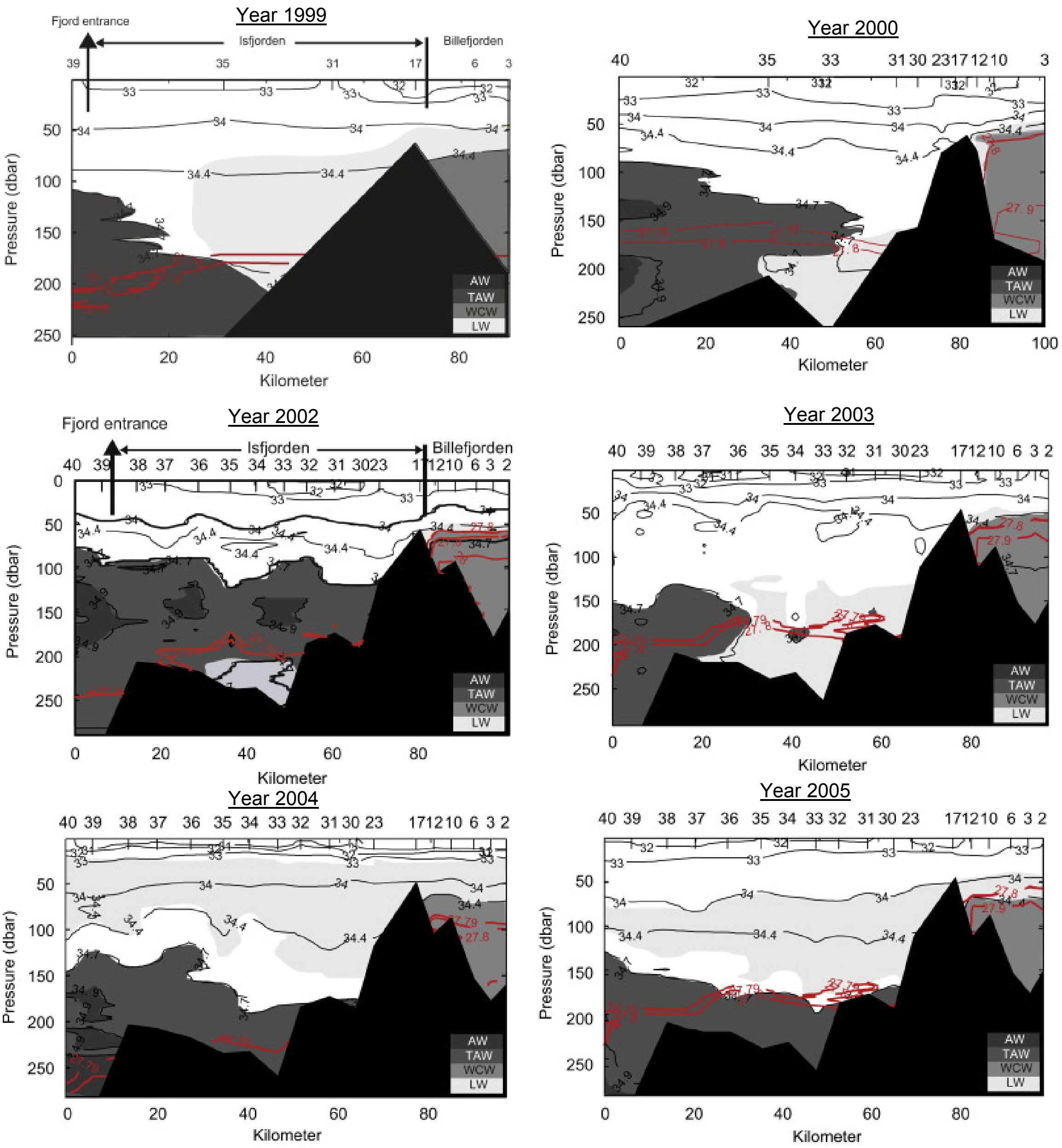
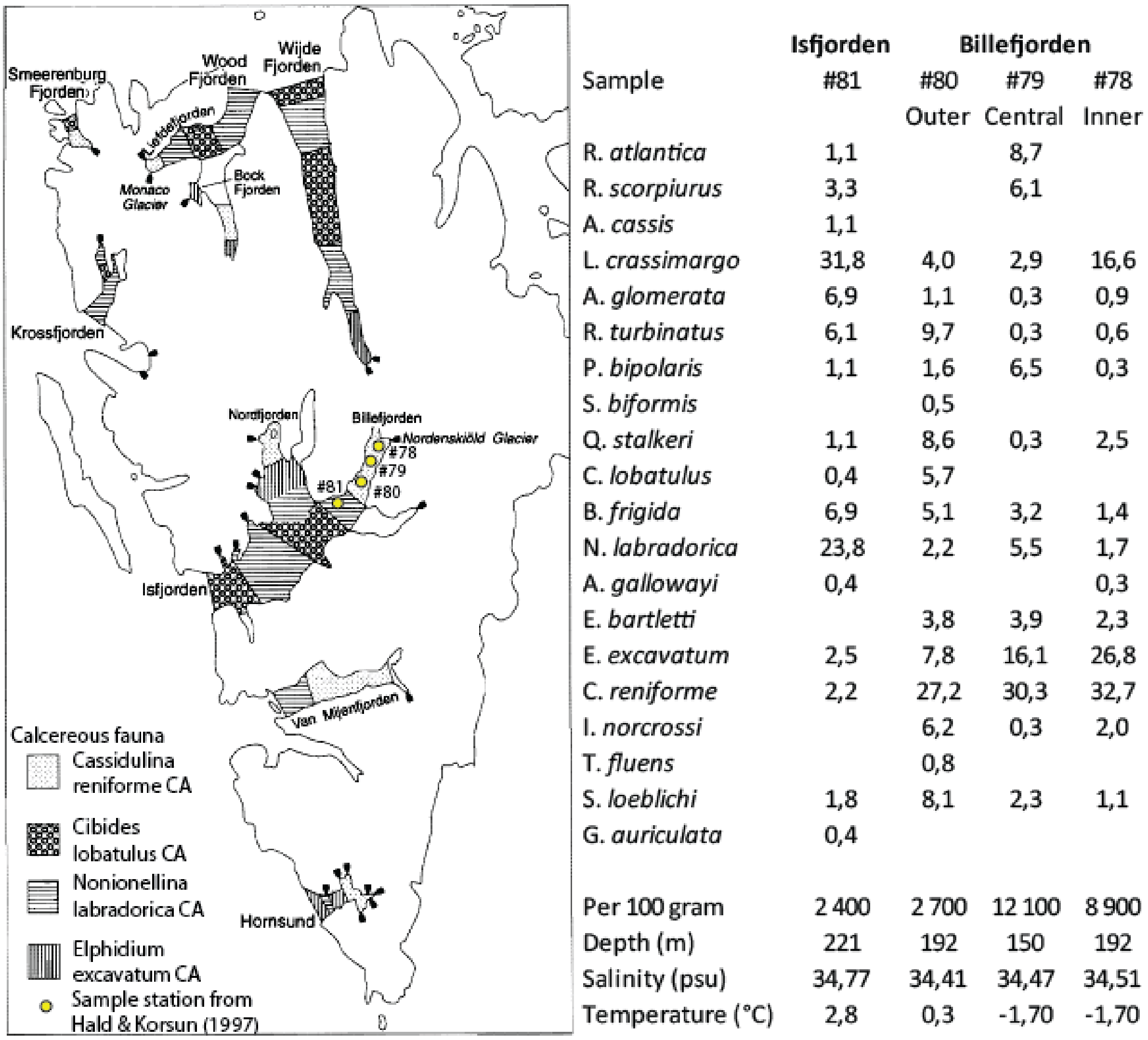


Figure 10: CTD-sections from Isfjorden-Billefjorden showing different modes of Atlantic Water (AW and TAW) influx to Isfjorden. Note how the changing presence of warm water masses in Isfjorden have little influence on ater masses in Billefjorden. (Modified from Nilsen et al. (2008))

fjord. Close to a glacier front, the salinity rapidly decreases and there SW can be regarded as brackish-water. SW also has a wide positive temperature range because of the high particulate content that promotes warming by insolation. In the summer 2014 surface water temperatures of 9 °C was measured in Billefjorden (Eirik, 2014). During the autumn and winter SW will cool, producing either LW (<1°C) and/or WCW which in the following year will be flowing below the SW-layer.



	Isfjorden	**Billefjorden**		
Sample	#81	#80	#79	#78
		Outer	Central	Inner
R. *atlantica*	1,1		8,7	
R. *scorpiurus*	3,3		6,1	
A. *cassis*	1,1			
L. *crassimargo*	31,8	4,0	2,9	16,6
A. *glomerata*	6,9	1,1	0,3	0,9
R. *turbinatus*	6,1	9,7	0,3	0,6
P. *bipolaris*	1,1	1,6	6,5	0,3
S. *biformis*		0,5		
Q. *stalkeri*	1,1	8,6	0,3	2,5
C. *lobatulus*	0,4	5,7		
B. *frigida*	6,9	5,1	3,2	1,4
N. *labradorica*	23,8	2,2	5,5	1,7
A. *gallowayi*	0,4			0,3
E. *bartletti*		3,8	3,9	2,3
E. *excavatum*	2,5	7,8	16,1	26,8
C. *reniforme*	2,2	27,2	30,3	32,7
I. *norcrossi*		6,2	0,3	2,0
T. *fluens*		0,8		
S. *loeblichi*	1,8	8,1	2,3	1,1
G. *auriculata*	0,4			
Per 100 gram	2 400	2 700	12 100	8 900
Depth (m)	221	192	150	192
Salinity (psu)	34,77	34,41	34,47	34,51
Temperature (°C)	2,8	0,3	-1,70	-1,70

Figure 11: Map and table shows the results of Hald and Korsun (1997). Note the difference in modern fauna between Isfjorden (influenced by Atlantic Water) and Billefjorden (With only local water masses). The Kapp Ekholm sections are situated between #80 and #79 (Modified from Hald and Korsun (1997))

2.4. Foraminiferal fauna

The contempoary foraminiferal fauna of Isfjorden and Billefjorden (Figure 11) have been described by Hald and Korsun (1997). In general, the fjord has a fauna assemblage that is characteristic of glacially influenced fjords dominated by cold water with somewhat reduced salinity. The two Arctic species *Cassidulina reniforme (*Nørvang*)* (27.2 – 32.7 %) and *Elphidium excavatum (*Terquem*) (7.8 – 26.8 %)* dominate throughout, but the latter show a clear increase towards the tidewater front of Nordenskiöldbreen. Both are typical for glaciomarine environments, but *E. excavatum* usually replaces *C.* reniforme as the most dominant taxa in front of glaciers. The fauna is almost exclusively calcareous, with exception of an increased occurrence of the agglutinated species L. crassimargo which occurs in higher frequencies in front of the glacier in Adolfsbukta.

The fauna in Isfjorden, just outside the mouth of Billefjorden, is dominated by the species *Alveolophragmium crassimargo* (Norman) (31.8 %) and *Nonionellina labradorica* (Dawson) (23.8 %)(Hald and Korsun, 1997). *C. reniforme* and *E. excavatum* only show up in very low frequencies (c. 2-2.5 %). According to Hald and Korsun (1997) the change in fauna is explained geographically by the presence versus absence of Atlantic Water.

2.5. Previous relevant studies

Several authors have described and discussed the sedimentary stratigraphy of the Kapp Ekholm sections (Feyling-Hanssen, 1955; Lavrushin, 1967, 1969; Boulton and Rhodes, 1974; Boulton, 1979; Troitsky et al., 1979; Mangerud and Salvigsen, 1984; Mangerud and Svendsen, 1992; Mangerud et al., 1998; Forman, 1999; Linge et al., 2008; Ingólfsson and Landvik, 2013; Eccleshall et al., in prep.).

The most detailed and supported description of the sections so far, is found in Mangerud and Svendsen (1992). The site is here divided into six sections (I-VI) and by correlating units laterally, they describe and interpret four different till-beds, separated by marine sediments (Formations A – H; see Figure 12 and Figure 13). The

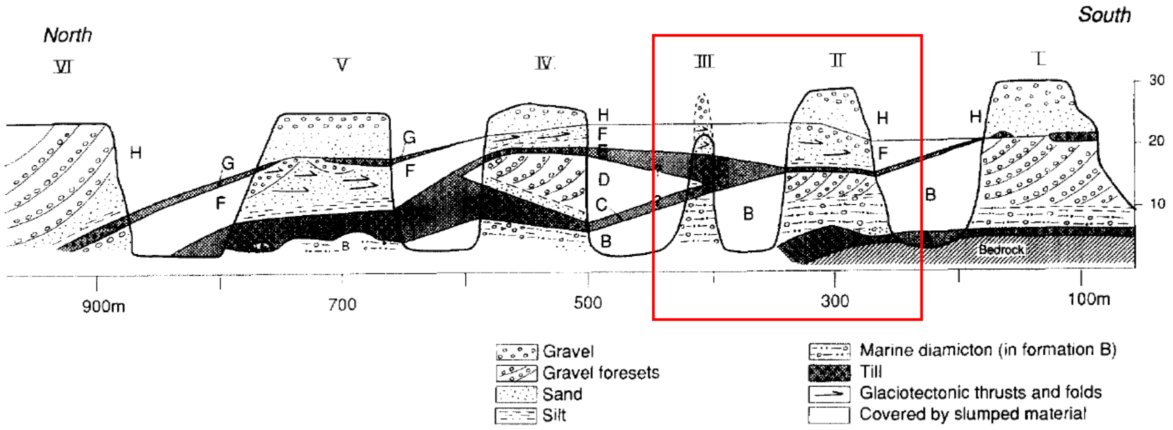
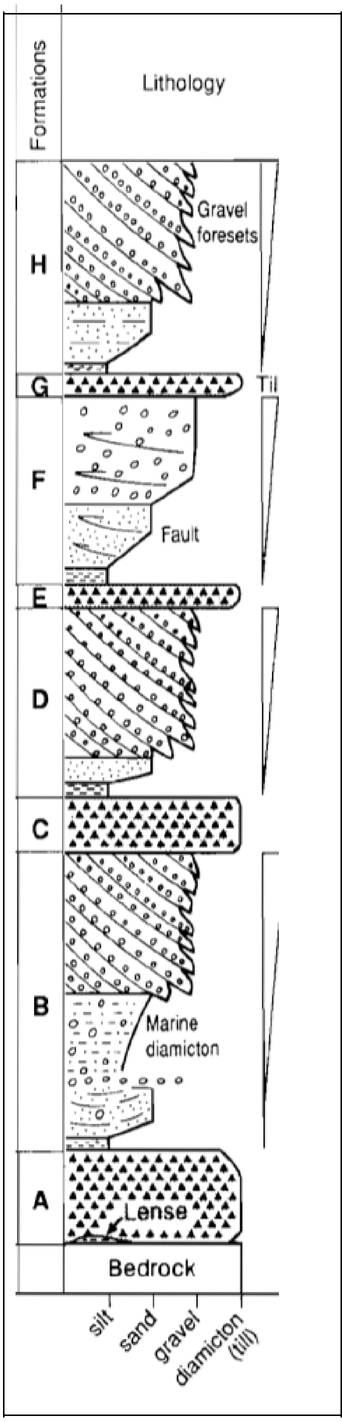


Figure 12: Division of sections (I-VI) and formations. Focus here is on sections II and III (Mangerud et al. (1998) modified from Mangerud and Svendsen (1992))



Radiocarbon dates (ka)	TL dates (ka)	IRSL and OSL dates (ka)	
9.6[1], 9.7[1], 9.7[1], 9.7[1], 9.8[1], 9.9[1], 11.0[1]		9.5[1], 16.0[1], 19.0[1] 10.0± 1[2], 12.6± 1[2], 10.5± 1[2], 12.7±1[2], 11.9± 1[2], 10.7± 1[2], , 11.6± 1[2], 9.7± 1[2], 12.5± 1[2], 10.6± 1[2], 10.3± 1[2], 11.3± 1.1[2] 12.6± 1[2]	Q - SARA FK - SARA
36.5[1], 37[1], 42[1], 44[1], 45[1], 45.9[1], 46.1[1], 48.1[1], >45.4[1]	38[1], 44[1], 44[1], 53[1], 104[1] 35±3[2], 40±4[2], 85±8[2], 98±10[2], 43±4[2]	80[1], 50[1], 59[1] 72±7[2], , 39±4[2], 45±4[2], 112±10[2], 63±25[2], 68±7[2] 72±10[3], 42±5[3], 32±5[3] 68±7[3] 76± 10[3], 71± 8[3], 65± 7[3] 56± 7[3], 63± 9[3], 52± 8[3]	Q-SARA FK – SARA PM – IRSL PM – IRSL RSL
	107[1], 122[1], 139±14[2], 106±10[2]	76[1], 93[1], 99[1], 103[1] 144±14[2], 106±10[2]	OSL
43.8[1], 49.0[1], >48.9[1], >49.0[1], >50.4[1], >60.9[1]	76[1], 104[1], 114[1] 126± 10[2]	89[1] 116± 10[2], 129± 10[2] 113± 10[2], 117± 10[2], 115± 10[2], 220± 25[3], 235± 32[3], 223± 25[3] 102±12[3], 138± 19[3], 115± 16[3]	OSL Q-SARA FK-SARA PM- IRSL PM-IRSL

Figure 13: Summary of previous dating at Kapp Ekholm from (Eccleshall, 2013) modified from (Mangerud et al., 1998)

[1] Mangerud and Svendsen (1992)

[2] Mangerud et al. (1998)

[3] Forman (1999)

PM-IRSL = Polymineral IRSL measurement; Q = Quarts; F = feldspar; SARA = Single aliquot, regenerative and addeed dose method; RSL = Red-stimulation luminescense; FK = Potassium feldspar marine intervals are described as coarsening upward sequences of shallow-marine to littoral units, caused by glacio-isostatic rebound.

Formation A is interpreted as a grey colored glacial till (Lavrushin, 1969; Boulton, 1979; Mangerud and Svendsen, 1992; Mangerud et al., 1998). The first marine interval is

Formation *B.* Mangerud and Svendsen (1992) describes the lower boundary as sharp, followed by a thin unit of red-brown diamicton that subsequently grades into silt. The authors state that the genesis of the red-brown diamicton is diffuse, but primarily marine, on the premise of shells and shell fragments. Boulton (1979) previously

interpreted the same diamicton as a basal till, but do not describe any marine fauna from the unit. On top follows a marine diamicton, that grades into a marine silt. In Section II, Mangerud and Svendsen (1992) and Lavrushin (1969) also describe a laterally limited, sandy channel-fill is described and interpreted as gravity-flow-depositions. On top of this channel is a gravel-rich zone that contain dominantly fragments, but also intact shells of the warm-water indicator *Mytiluls edulis (*Linnaeus). This is the only species recorded from Formation B that at the time was not occurring on Svalbard (Mangerud et al., 1998). In 2004 however, it was re-discovered at the mouth of Isfjorden after being absent for almost 1000 years (Berge et al., 2005). Its re-occurrence has been explained by an increasing inflow of Atlantic Water to the fjords on Svalbard. On top follows a marine diamicton. According to Mangerud and Svendsen (1992) quiet water conditions must have prevailed to explain the high content of mud in the unit, with depths of at least 15 to 20m. Outsized gravel- and pebble sized clasts are of local lithologies and is explained either as rolling down from the shore, transported by sea-ice or kelp.

In Section II, the upper half of Formation B is described as gravelly fjord-dipping strata. Boulton (1979) interprets these deposits as proglacial outwash, relating it directly to the superimposed glacial till (Formation C or E). This is dismissed by Mangerud and

Svendsen (1992) who describes both shell-fragments and seaweed from the same deposits. These foresets, they argue, also appear to interfinger with the marine diamicton below. Following this, the authors argue that these deposits represent shoreface deposits that are more proximal to the coastline than the marine diamicton below.

The subsequent marine sequences are all divided by grey, compact diamictons which are interpreted as glacial tills. Sedimentologically, Formation F, D and H are described as overall very similar to that of Formation B, except that sandy units replaces its marine diamicton. In addition, Formation F has sedimentary structures that indicate post-depositional deformation.

According to Mangerud et al. (1998) the mollusk fauna from both Formation B and F is overall rich in species and they argue that this suggest open communication of Atlantic Water between Billefjorden and Isfjorden. Formation D however, has very few species, indicating a more restricted circulation, although the sediment exposure of this unit is thin, compared to that of formations B and F. Formation H contains a rich mollusk-fauna. Species such as M. *edulis* and Zirphea *crispate* indicates inflow of warm water and that the hydrological environment was much warmer than that of today.

Boulton (1979) used Amino-Acid D/L-ratios to estimate that shells incorporated into the lowermost till (Formation A) belonged to the Eemian-interglacial. Consequently Formation B would represent an interstadial within the Weichselian glaciation. This was later disputed by Mangerud and Svendsen (1992) who argued that the discovery of M. *edulis* would indicate that Formation B is of Eemian age. This was later supported by luminescene-ages (Thermoluminescene (TL) and single aliquot, regeneration and added dose (SARA)) from Mangerud et al. (1998). Consequently Formation A is of Saalian age, or older. Discussion was sparked however, when Forman (1999) using Infrared Stimulated Luminescence (IRSL), concluded that Formation B had an age closer towards 195±13 ka (MiS 7) implicating an even older age for Formation A. This was later not supported however by Eccleshall (2013) and (Eccleshall et al., in prep.)

who obtained an average age of 122.46 ka for Formation B using IRSL and Optically stimulated luminescence (OSL).

The next ice-free period is represented by Formation D (Phantomodden interstadial). Mangerud and Svendsen (1992), and later Mangerud et al. (1998), argue that these sediments were deposited at an interstadial during marine isotope stage 5 and concluded with an age around *c.* 100 ka using OSL, TL and SARA.

Sediments belonging to Formation F (Kapp Ekholm interstadial) was originally interpreted by Boulton (1979) as being of Holocene age. Mangerud and Svendsen (1992) however, describes a new regression cycle occurring on top of formation F, thus these sediments had to be older and were ascribed to another interstadial within the Weichselian glaciation. TL-ages supported this interpretation with 30 and 50 ka. Somewhat older ages were reported by Mangerud et al. (1998) (40-60 ka) using TL, OSL and SARA. With the further development of luminescence dating techniques increasingly older ages were assigned by Forman (1999), Eccleshall (2013) and Eccleshall et al. (in prep.) who later concluded with ages of between 60 to 80 ka.

The final deglaciation (Holocene) is represented by Formation *H.* Radiocarbon ages suggest that Kapp Ekholm was de-glaciated at, or shortly before, 11 ka BP (Mangerud and Svendsen, 1992; Mangerud et al., 1998; Baeten et al., 2010). Glacio-isostatic rebound during the Holocene probably occurred faster in the outer part of the fjord, compared to that of the fjord head and is used as an explanation for the increasing thickness of Holocene sediments up the fjord.

3. MATERIAL AND METHODS

3.1. Quaternary mapping

The area between the Mathiesondalen river and Phantomodden headland was mapped using aerial photos, topographical maps and in-field survey. A handheld GPS (GARMIN C60CSX; WGS84) was used in this work to mark points of interest. The aim was to identify the areal extension of landforms and gain an understanding of potential processes that could influence the sedimentary stratigraphy and environmental history of the site. The map was produced using ESRI ArcGIS 10.1. with a modified nomenclature for Quaternary mapping from Norges Geologiske Undersøkelser (Bergstrøm et al., 2001).

3.2. Sedimentology

This project has focused on the two beach-cliff sections described by Mangerud and Svendsen (1992) as Section II and Section III. Section I was surveyed but not described in detail due to a thick cover of scree. Sections III-V were part of another investigation by (Håkansson et al., In prep.).

The cliffs were investigated and described in terms of sub-sections. Where needed, the subsections were correlated laterally in a staircase-like pattern. Sedimentation was assumed to having occurred horizontally when not guided by other sediment structures. This can be problematic however when sediment-layers are steeply inclined (Figure 14)

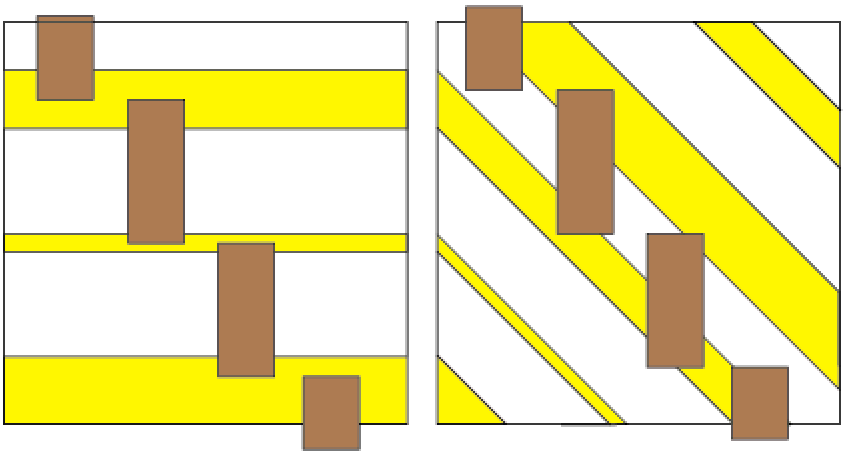


Figure 14: Relationship between sub-sections and dip of bedding A significant difference in time-coverage occurs when bedding is horizontal, compared to when it I dipping.

The sediments were described in field using conventional sedimentological techniques such as colour, grain size, sorting, structures, lithologies and so on. Grain size was described using the Wentworth-scale. Units are named following the nomenclature of Mangerud and Svendsen (1992), but are further subdivided into members (E.g. “B-3” refers to “Formation B, unit 3”) and beds (E.g. B-3a). Symbols are modified from Alexanderson et al. (2013) and Benn and Evans (2010)

3.3. Numerical chronology

11 samples were collected for Luminescence-dating as a part of the project. Procedures and techniques related to this are described and discussed by Eccleshall (2013) as a part of her Master of Science and later submitted as Eccleshall et al. (in prep.). Because of statistical uncertainties related to the numerical ages and sedimentation rate changes it was advised not to produce an age-depth model.

3.4. Collection and identification of foraminifera

Foraminifera (plural of foraminifer) is an order (Foraminiferida) within the phylum Protista and can a specimen is defined as a “*Cycloplasmic body enclosed in a test or shell of one or more inter-connected chambers*” (Murray, 2006a p. 1). Further they are divided into genera and most commonly into species. The taxonomy of foraminifera is based on the morphology of their tests and they are in the strict sense morphospecies rather than biological species.

The foraminifera discussed in this thesis are all identified from the remains of past living specimens. These are referred to as fossils (or fossil assemblages) throughout, but are technically considered fossils due to the lack of lithification. Although this has little relevance for the results here, it do carry significance in terms of using these remains for radiocarbon dating osr amino acid racemization.

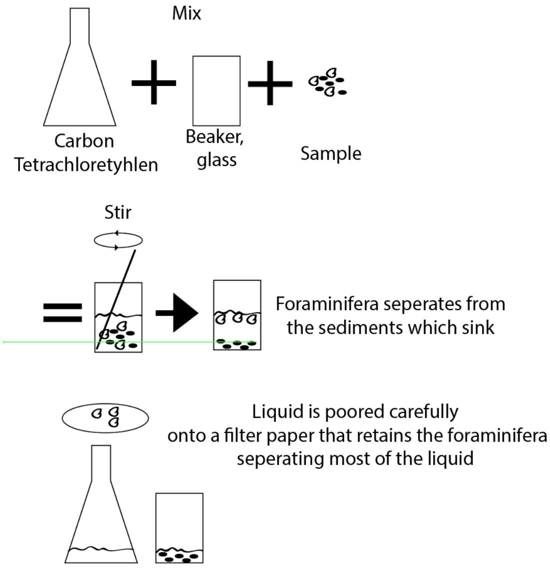


Figure 15: Procedure for seperating tests of foraminifera from sediments in a sample using the heavy liquid seperation method.

Sediment samples were collected using a spatula and transferred into a plastic zip-bag. Each sample was about 10 cm^3 and later subsampled to fill a plastic beaker. The sample was than dried at a low temperature (50 ^{o}C) for 48 hours to avoid thermal cracking of the tests. Each sample was than weighted using a digital scientific scale and subtracting the weight of the beaker to get the total weight of the dry sample. Each sample was then sieved to subtract the 125 µm fraction. This fraction was choosen to facilitate correlation with other studies from Svalbard that use primarily 125 µm. Density separation (Figure 15 was used to separate the foraminiferal tests from the minerogenic material samples following the procedures described in Feyling-Hanssen (1980); Knudsen (1998) as well as through correspondence with Karen Luise Knudsen (*Personal communication*, August 2013). Each sample was carefully mixed with carbon tetrachloroethylene (C_2CL_4), a heavy liquid with a relative density of 1.62 g/cm^3, separating the heavier sediments from the lighter foraminiferal tests. The entire process is conducted under a fume cupboard, as the chemical is considered highly toxic. The liquid was decanted onto a filter (No. 413) with particle retention of 5-13 µm and thereafter allowed to dry out for a minimum of 2 hours. Tests of benthic foraminifera were than picked directly from the filter until a minimum of 300 specimens was achieved or, the sample depleted. Planktonic foraminifera were counted separately as a ratio x to the counted number of benthic.

A binocular light microscope (Leica MZ95 8x-77x) was used when identifying and sorting individual foraminifera onto slides. A Leica MC170HD camera, attached onto a Leica M20C microscope was used to take pictures of the most important species. Individuals were identified to the rank of species whenever possible, or denoted as ".spp" when identified to the rank of genus only. Foraminifera are reported as frequencies (n/total) which evaluates the ratio of species and relative abundance.and per 100g.

3.5. Diversity indices

In biology the term diversity refers to the number and/or the variety of species found within a specified unit. This unit can be a geographical area, within an assemblage, an ecosystem or even within a temporal unit. There is not a set standard for which diversity measures should be applied in a study, this rather varies with the purpose as well as the data of the study. In this project *species richness* and *fisher's α are used to quantify the diversity.*

Species richness (SR.) is simply the total number of different taxa at a specific taxonomic rank within a given sample. To simplify and reduce the amount of noise (e.g. re-destributed specimens) then only species occurring in frequencies of at least 2 % within at least one sample is used in the analysis and subsequent discussion.

Fisher's alpha is a diversity index and is one of several methods that relates the number of species to the number of individuals (Murray, 2006b). It assumes that the abundance of species follow a log series distribution. This is based on an observation that in most communities, only a few species tend to be abundant, whereas the rest occurs only in small numbers (Fisher et al., 1943). A higher alpha value indicate a higher number of abundant species whereas a lower number indicate a higher number of species in low frequencies. The diversity option in the statistical software Primer (V6.1.16) from Primer-E is used to calculate the Fisher's Alpha Diversity. Statistically fisher's alpha is defined implicitly by the following expression:

$$S = a \times \ln(1 + \frac{n}{a})$$

Where S is the number of taxa, n is the number of individuals and a is the fisher's alpha.

Abundance is expressed as the number of specimens per 100 gram of sediment. It is calculated by dividing the number of specimens with the total size of the sample multiplied by 100. This may give an indication on the abundance of foraminifera at a given time, however, because there is no temporal scale, this may also reflect changes in sedimentation rate. A lowering of the sedimentation rate will increase burial time and also increase the number of tests at a given horizon.

3.6. Biofacies

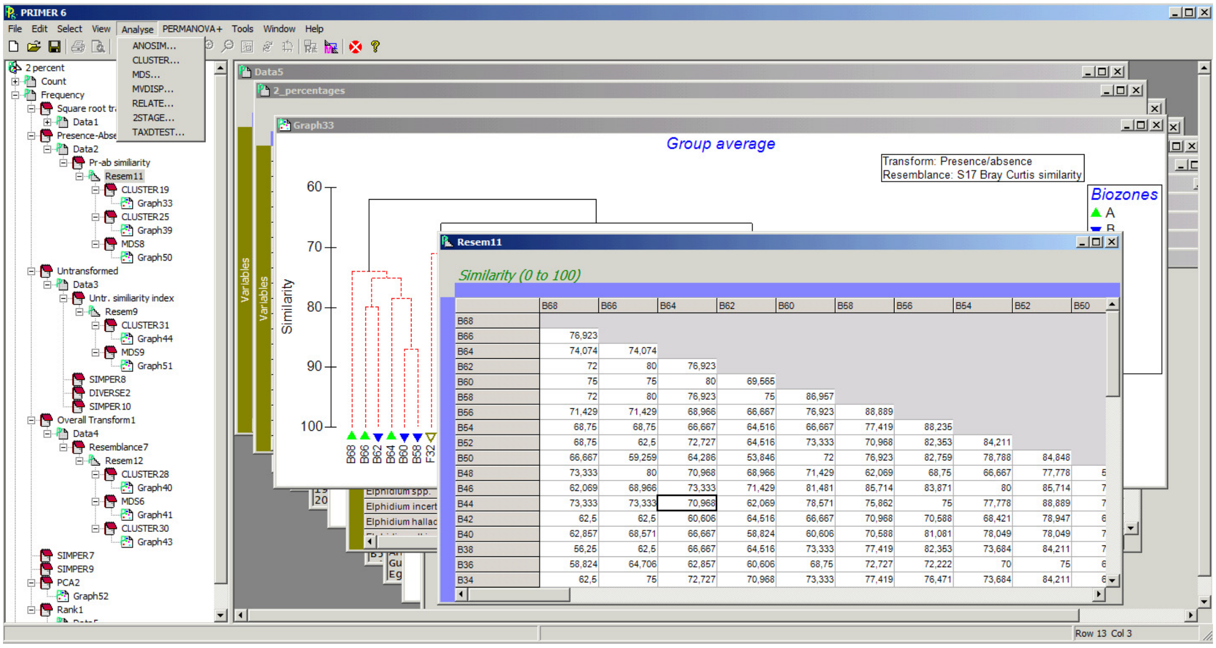
Paleoecology is the study of past environments using data from fossils and subfossils. A key concept in paleoecology is that species and groups of species are related to different environmental conditions. These may be divided into biostratigraphic units that according to Murphy and Salvador (1999) are bodies of strata defined or characterized on the basis of their contained fossils (*sensu lato*). A Biofacies (also plural) is a type of biostratigraphic unit where the fauna (or flora) differs significantly from that found elsewhere in the same unit. It is instrumental in the sense that it is diagnostic for a type of environment or some environmental condition. An important difference between a biofacies and other types of stratigraphical units (e.g. Zones/Assemblages) is that a biofacies is temporally diachronous. This means that the same facies may re-occur multiple times throughout time.

The data was analyzed statistically for clustering of samples (Q-mode analysis) and quantifying the between-group relationships in terms of their similarity and significance (Sen Gupta, 2002a). Common for the statistical approaches to clustering is the assumption that natural distinct groupings (clusters) exist and that these groupings naturally relate to specific environmental conditions.

The first step was to construct an index that indicate the relationship between all the samples. A Bray-Curtis similarity index (also known as Czekanowski similarity (Somerfield, 2008)) was constructed using the statistical software package Primer 6 (V. 6.1.16) & Permanova+ (V. 1.0.6) from PRIMER-E (Figure 16). It does so, using the following expression:

$$S_{jk} = 100\frac{\sum_{i=1}^{p} 2\min(Y_{ij}, Y_{ik})}{\sum_{i=1}^{p}(Y_{ij}, Y_{ik})}$$

Where Y_{ij} represents the entry in the *i*-th row and *j*-th column of the matrix for the *i*-th species in the *j*-th sample. Y_{ik} is the count for the *i*-th species in the *k*-th sample. The min(.,.) term is the minimum of the 2 counts. The seperate sums in the numerator and denominator are both over all rows (species in the matrix). Bray-Curtis similarity is used here because it is an index that operate with frequencies as opposed to Euclidian distance, which is influenced by the numerical size of its entities (the numerical count of each taxa).



Transform: Presence/absence
Resemblance: S17 Bray Curtis similarity

Similarity (0 to 100)

	B68	B66	B64	B62	B60	B58	B56	B54	B52	B50
B68										
B66	76,923									
B64	74,074	74,074								
B62	72	80	76,923							
B60	75	75	80	69,565						
B58	72	80	76,923	75	86,957					
B56	71,429	71,429	68,966	66,667	76,923	88,889				
B54	68,75	68,75	66,667	64,516	66,667	77,419	88,235			
B52	68,75	62,5	72,727	64,516	73,333	70,968	82,353	84,211		
B50	66,667	59,259	64,286	53,846	72	76,923	82,759	78,788	84,848	
B48	73,333	80	70,968	68,966	71,429	62,069	68,75	66,667	77,778	5
B46	62,069	68,966	73,333	71,429	81,481	85,714	83,871	80	85,714	7
B44	73,333	73,333	70,968	62,069	78,571	75,862	75	77,778	88,889	7
B42	62,5	62,5	60,606	64,516	66,667	70,968	70,588	68,421	78,947	6
B40	62,857	68,571	66,667	58,824	60,606	70,588	81,081	78,049	78,049	7
B38	56,25	62,5	66,667	64,516	73,333	77,419	82,353	73,684	84,211	7
B36	58,824	64,706	62,857	60,606	68,75	72,727	72,222	70	75	6
B34	62,5	75	72,727	70,968	73,333	77,419	76,471	73,684	84,211	6

Figure 16: Screenshot from Primer-E. Statistical operations are here performed by selected the data in the index to the left and choosing the statistic from the menu.

Only species that had at least 2 %, in at least one sample were used. Many authors transform their data (e.g. by applying a square root to each variable) to enhance or downplay certain aspects of their data. By using untransformed data the results are more strongly shaped by the dominant taxa (Kindt and Coe, 2005; Włodarska-Kowalczuk et al., 2013). This is preferable for environments characterized mainly by a few taxa, and where taxa that are more abundant are also assumed to have a more valid representation (e.g. not re-distributed) within the sample. Sen Gupta (2002c) recommend trying out different methods and compare the results and rule out or at least distrust results that are fundamentally different. Following this, untransformed, square-root-transformed and fourth-root-transformed data is used and compared in order to view the data from different perspectives.

Most statistical approaches for clustering foraminifera into biostratigraphic units (Facies/Assemblages/Zones) arse based on constructing hierarchical agglomerates (Sen Gupta, 2002c). In Primer-E a similarity-dendrogram can be produced using a similarity-index (constructed previously). All entities (stratigraphic samples) are initially constructed as individual clusters. Entitites are than grouped iteratively on the next step of similarity/distance, creating a hierarchy of samples, until all entities are merged into a single entity at a resulting similarity-level. The results are presented as a dendrogram which show at which similarity level samples cluster and then draped over a Multidimensional Scaling (MDS) plot to assess the similarity between clusters.

The different biofacies are interpreted using modern day analogues and previously published results that document the modern environmental preferences of foraminifera. From Svalbard, the most comprehensive study so is that conducted by Hald and Korsun (1997) who documents both the fauna and environmental conditions in several of the fjords around Svalbard.

A SIMPROF-analysis is applied from within Primer-E to test for any evidence (at a 1 % significance level) of structure between sample-clusters. It does so by constructing and running a null-hypothesis model multiple times before comparing results with the original similarity profile.

4. RESULTS

4.1. Sedimentary stratigraphy

Sedimentary descriptions are divided into formations following the nomenclature introduced by Mangerud and Svendsen (1992). Formations are further divided into members. Interpretation of units follows for each formation. An overview of the sections and the composite log are shown in Figure 17 and in Figure 18.

4.1.1. Bedrock (0)

Laterally continuous bedrock exposures are present at the base of Sections II and III. A combination of limestone and dolomite characterize all visible bedrock. The upper bedrock boundary is characterized by a sharp transition to the non-lithified sediments. This transition dips 1.8° up-fjord, towards the north-northeast (c. 25°). The bedrock exposure is heavily cracked and shattered, especially in its vertical exposure towards the beach. The rockhead is smoothly polished with crosscutting striae (oriented between 223° and 243°) roughly parallel to the fjord-axis (Figure 18).

Interpretation

These bedrock exposures are part of the Late Carboniferous Minkinfjellet Formation (Dallmann et al., 2004). Characteristics of the rockhead indicates glacial erosional from a glacier moving parallel to the long axis of the fjord. Today the rockhead is protected from weathering by superimposed sediments. However, vertical bedrock exposures are being continuously undercut by waves and disintegrated by various weathering processes (e.g. frost-shattering and salt-precipitate). The upfjord dip probably reflect the uneven glacio-isostatic rebound caused both by differences in past glacial thickness, and differences in the age of deglaciation (Forman et al., 2004).

4.1.2. Formation A

Formation A is the lowermost unit of non-lithified sediments in both Sections II and III. It is described primarily from Section II.C and is overall characterized as a clast-supported diamicton sequence (Figure 19). The formation varies between 2 m and 5 m. It dips down towards the north however and disappear below present sea level

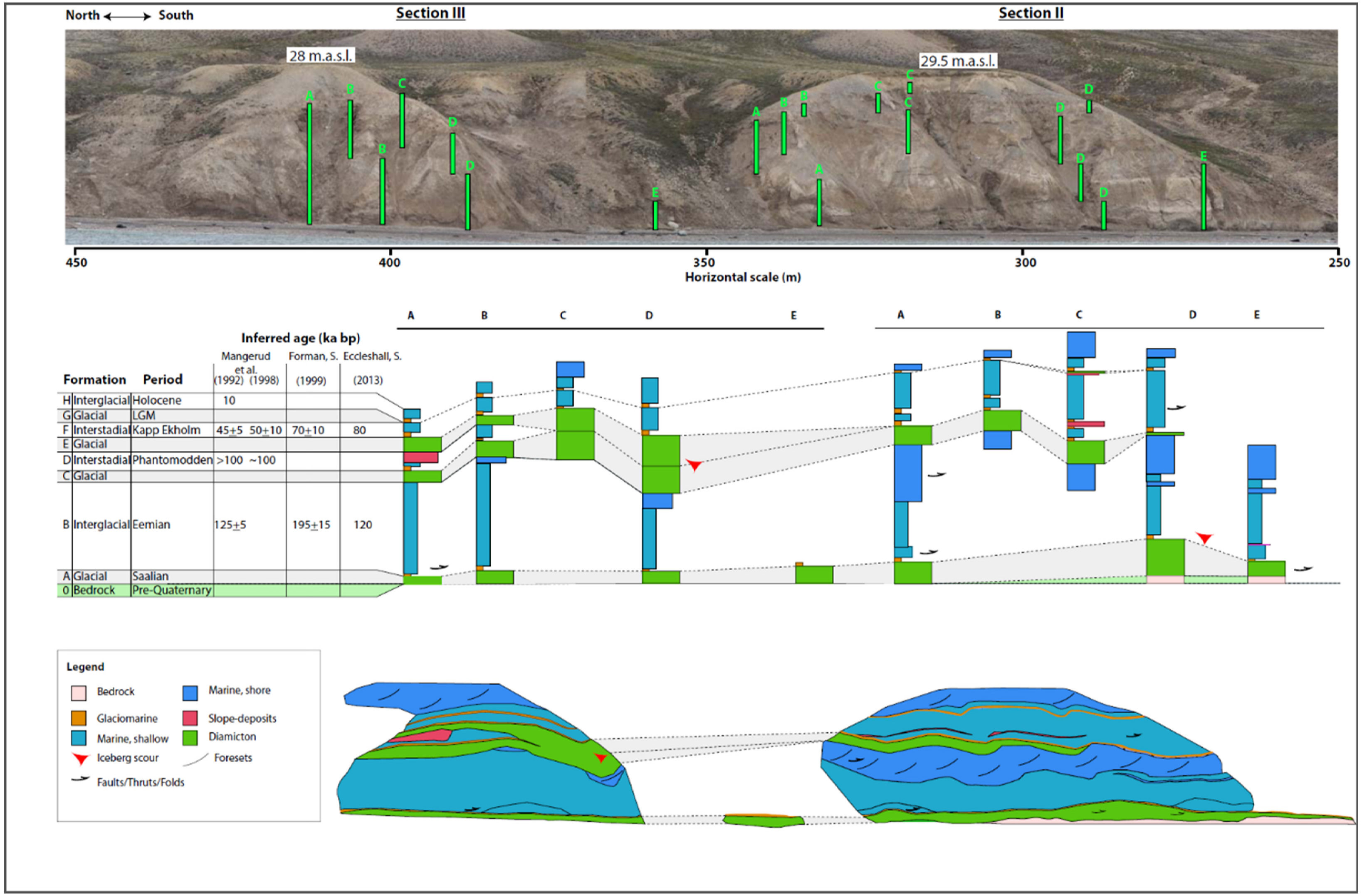


Figure 17: Stratigraphical overview of Section II and III with depositional environments

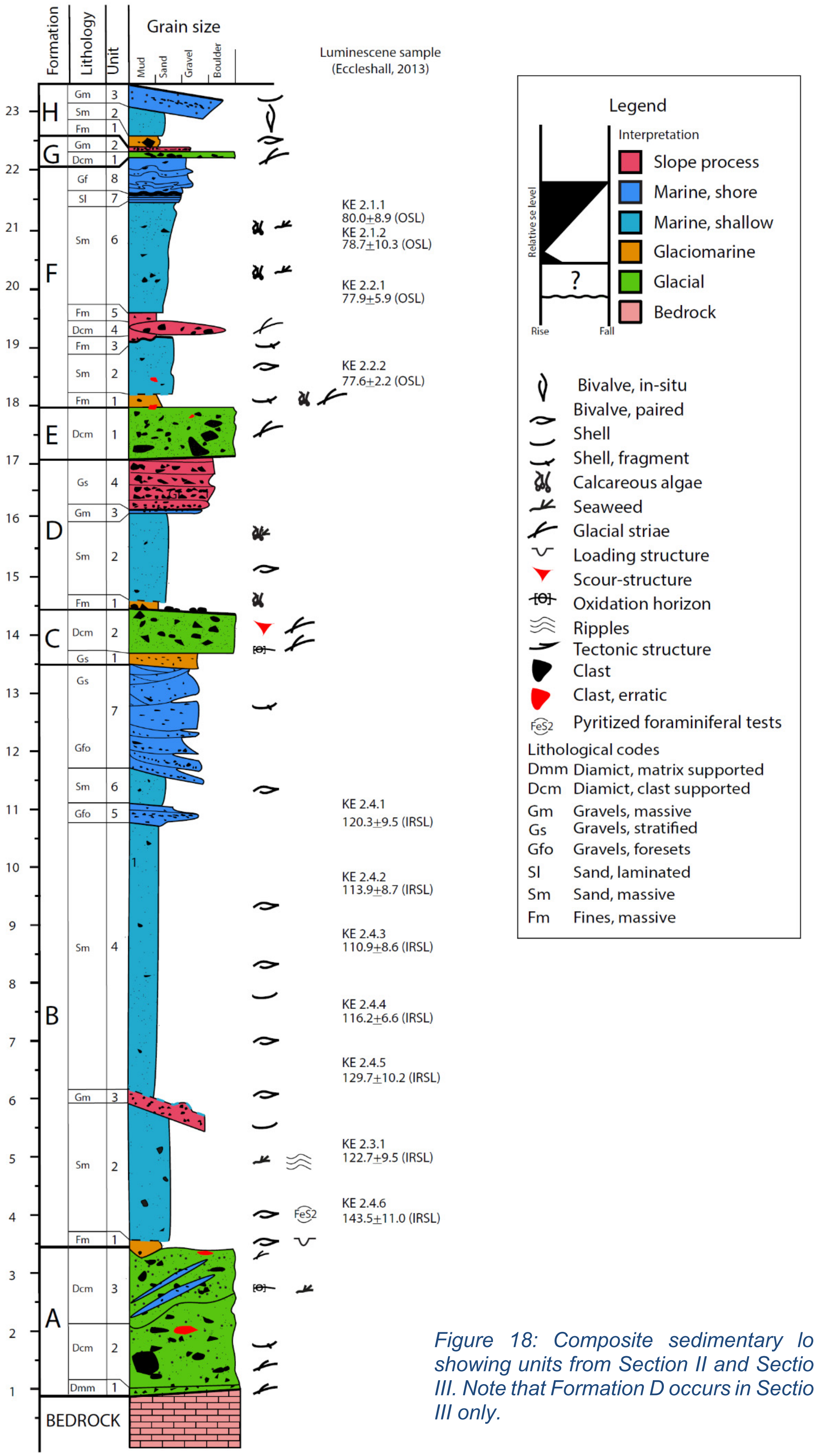


Figure 18: Composite sedimentary log showing units from Section II and Section III. Note that Formation D occurs in Section III only.

between Section IV and III. On the basis of changes in clast content this formation has been subdivided into three members (A1 – A3) which are described below.

Member A-1 (Dmm)

Massive, matrix-supported diamicton. The matrix consists of sandy mud with angular, medium- to coarse-grained gravel. Clasts appear mostly of the same limestone lithology as the underlying bedrock and frequently show striations.

Figure 19: Details from Formation A: A) Polished and striated limestone-clast retrieved from the bedrock below; B) Close-up photo of Member A-2 where Striated rounded to subrounded clasts dominate.

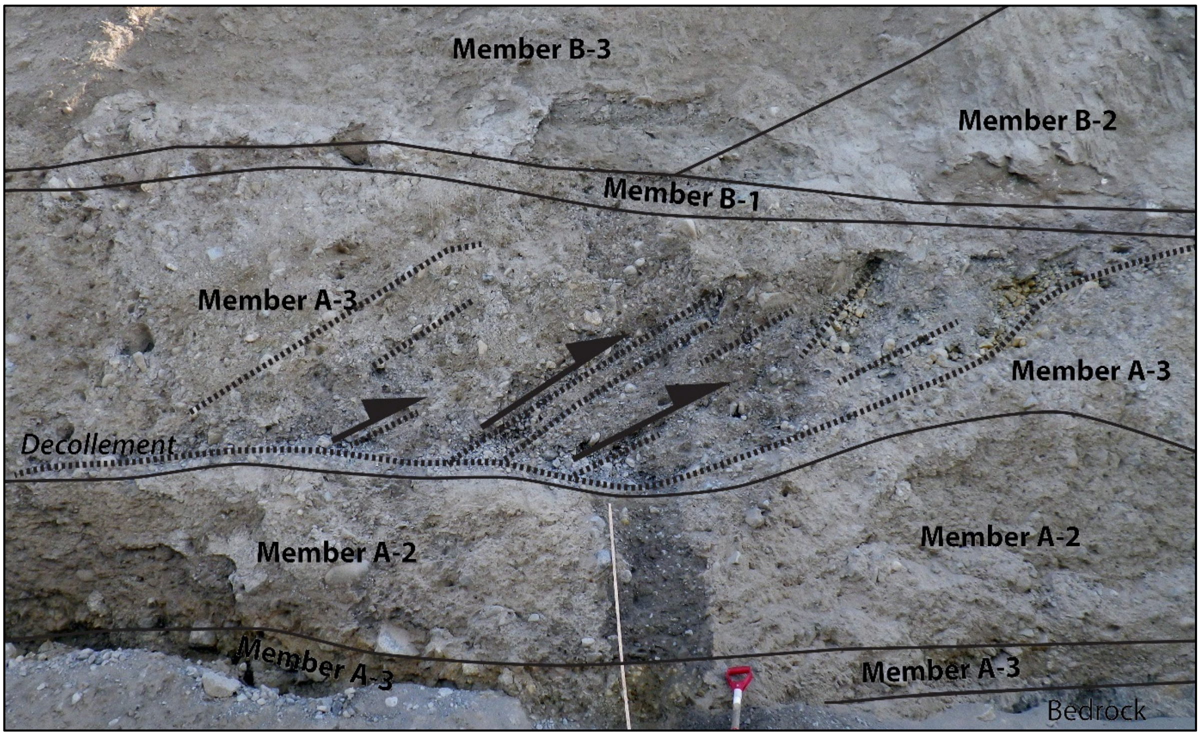


Figure 20: Fault planes indicating sub-glacial shear from Section II D-E at around 280 m)

The member occurs only discontinuously at the base of formation A with a thickness not greater than 15 cm. It follows a sharp and regular boundary to the underlying bedrock.

Member A-2 (Dcm)

Massive, clast supported diamicton with a silty-sand matrix.The color of the matrix is grey-brown as opposed to the more yellow-brown colored matrix of the underlying member (**A-1**). Clasts range from sub-angular- to sub-rounded- gravels, pebbles and occasionally boulders. Striae is common. Clasts include siliciclastic- (mudstones, sandstones), carbonate- (limestone and/or dolomite) and intrusive lithologies (granite). Small shell fragments also occur, but appears very rare. In section II.D-E (Figure 17) It is observed with a thickness of up to 130 cm. The lower boundary is diffuse where it overlay Member A-1, but sharp where it follows directly on top of the bedrock. It appears laterally continuous throughout section II, but it is unclear whether it also occurs in Section III.

Member A-3 (Dcm)

White-grey, clast-supported diamicton without any form of stratification. The matrix consists mostly of silty-sand, although the sand fraction appears more prominent than for the member below (**A-2**). Clasts are gravel to pebble sized and mostly sub-rounded. Thickness varies laterally, from 60 to 95cm where measured (Section II.A, see Figure 17). The lower boundary is diffuse, although in places defined by an irregular oxidation horizon towards Member **A-2**. This member is described from Section II.C, but a similar division is seen in Section II.A. It was not practically possible however, to follow the unit continuously between the subsections.

Several lenses occur within Formation A in section II. A contorted series of openwork gravel beds occur in Member A-3 between 275 and 250 m (Figure 20). They consists of rounded coarse gravels and small pebbles with a sandy, partially openwork matrix. A few shell fragments and sea-weed-remains are observed within the matrix. Overall, the color of the clasts is yellow-white, contrasting the surrounding grey-brown diamicton with a sharp, but irregular boundary. The lowermost bed consists of a horizontal wedge with a width of 4 meters and a maximum thickness of 30cm. Towards the south, are multiple upward arching extensions of this bed with a length of up to 3 meter. These extensions show a decreasing angle (30-20°) from left to right, cross cutting the superimposed diamicton-member with sharp boundaries.

Interpretation

The three members (A1-A3) that details this formation are all interpreted as glacial tills. This is based on their large lateral extent, high degree of compaction, the unsorted material and high content of striated clats. An indication of subglacial movement is also the striated and polished surface of the rockhead below.

The angular and seemingly autochthonous clasts of the lowermost member (**A-1**) is explained by glacial abrasion and quarrying of the underlying bedrock. This member is interpreted as a lodgement till where deposition occurred when friction between the bedrock and the sub-glacial material exceeded the drag of the ice. The member on top (**A-2**) also show subglacial characteristics such as compaction and a high ratio of striated clasts. The clast material indicates a longer transportation however, including the degree of clast-rounding, and the mix of both local and regional lithologies. Most are found within Billefjorden, but the closest source of granite is the Chydeniusbreen Granitoid Suite at Newtontoppen (<50km, NE) (Dallmann et al., 2004). Member **A-3** show similar characteristcs. An interesting feature of this unit is the various inclusions that occur. Kelp and shell fragments suggests a marine origin, possible a coarse-grained beach. Similar inclusions are mentioned by Mangerud and Svendsen (1992), but not discussed further. The upthrusted appearance of these units suggest deformation as a dominant mechanism for their host-member (**A-3**) which is therefore interpreted as a deformation till. This implies that Formation A represent at least two glacial events and that these advances are separated by a marine interval of unknown duration.

4.1.3. Formation B

The lower part consists primarily of sandy members, whereas the upper part is dominated by gravelly sequences. This coarsening upward sequence is divided into seven members based on pronounced changes in grain size. The formation is laterally continuous across Section II and Section III, although the upper gravelly part appear to be mostly missing in Section III. The formation is described primarily from Section II.C.

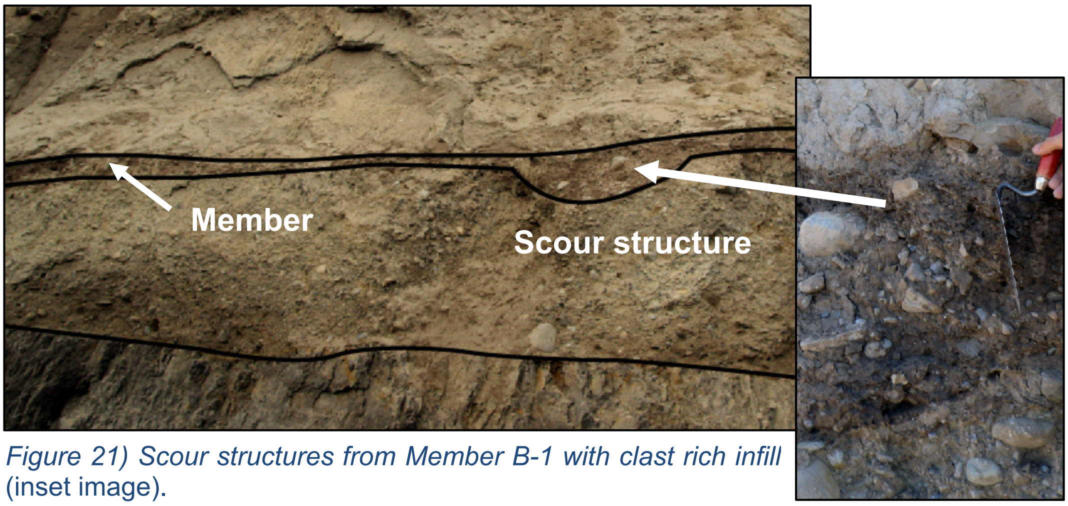


Figure 21) Scour structures from Member B-1 with clast rich infill (inset image).

Member B-1 (Fm)

The lowermost member is a massive, red-brown-colored, clayey-silt (Member **B-1**). Angular to sub-rounded gravel-sized clasts occur throughout. Pebbles and small boulders occur, but are not common.The member follows conformably on top of the underlying diamicton (Formation A) with a mostly uniform thickness (c. 30 cm). The lower boundary varies between gradual and sharp. In places, this member forms troughs, cut into the underlying diamict (Figure 21). These troughs are characterized a clast-rich fill and a more irregular lower boundary characterized by deformed lenses of grey and red-colored mud. In Section II Member **A-1** is overlain (Figure 22) by either a grey sand body (Member **B-2**), or a brown clayey sand (Member **B-4**).

Member B-2 (Sm)

This unit consists of white-grey, well sorted, fine grained sand. Granules and gravels are widely scattered throughout, ranging from rounded to angular. Pebbles are observed, but less common. Bivalve shells appear frequently many of them paired.The member is laterally finite between c. 268 – 280m. It has a plano-convex shape and appear as a lense within Member **B-3.** It varies thickness, but was measured with a height of up to 210 cm. A similar sand body was observed between 308 and 315 m in section II, but appears much smaller.

Member B-3 (Gf)

This sandy gravel unit shows a fining upward trend from clast supported in the lower part to matrix supported in the upper part. Rounded gravel sized clasts dominate in a

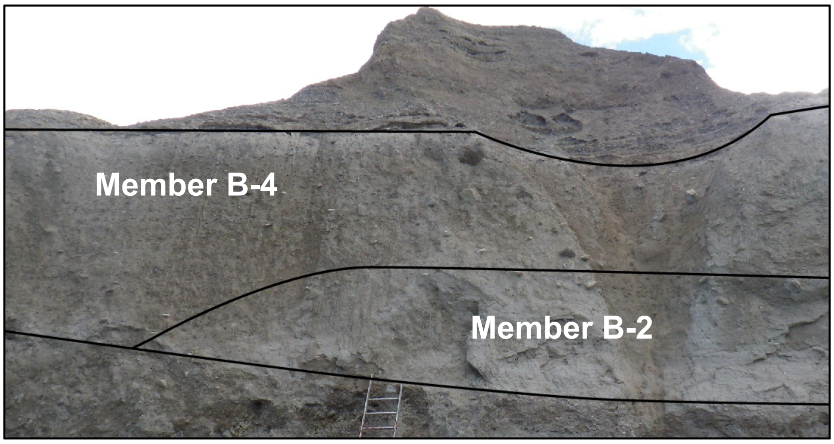


Figure 22: Formation B seen in southern part of Section II. Note the bar shape of Member B-2. Laterally, the lower boundary of this member and Member B-4 are assumed to be time-synchronous.

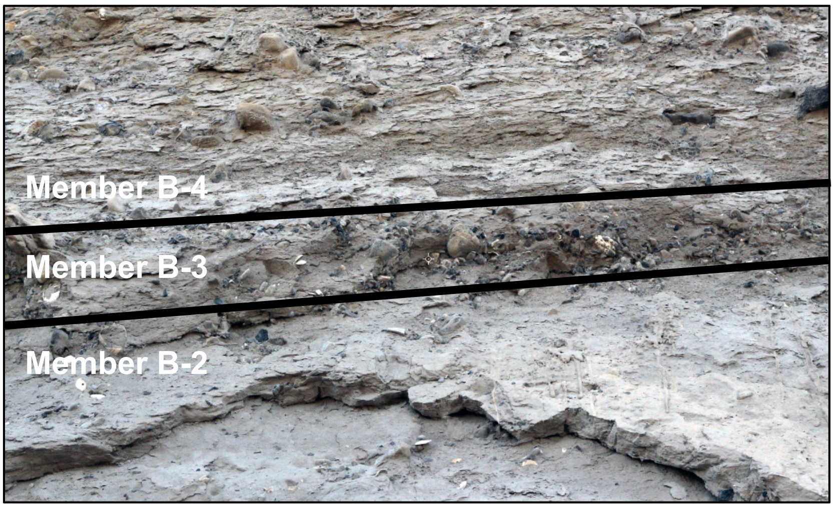


Figure 23: A gravel rich horizon (Member B-3) follows at the boundary between Member B-2 an d Member B-3

yellow-brown, medium to coarse-grained matrix. Shells occur, many of them fragmented, although some are also better preserved. It is up to 30 cm thick, although in the upper part the boundary appears irregular and diffuse with a gradual reduction of clasts up-section. The member is laterally finite and follows conformably on top of member B-2 in the southern part of Section II.

Member B-4 (Sm)

A yellow-brown, silty sand with a weak, but steeply fjord-dipping bedding (<20-30°). The matrix consists of silty, medium-grained sand, coarsening somewhat up-section. Coarser, but more sorted sand lenses are sometimes observed. Clasts are scattered throughout and range from gravel to larger pebbles that vary from sub-angular to rounded. Clasts are occasionally covered by remains of calcareous marine moss animals (*Bryozoa)* and/or seaweed. Bivalved shells are also frequent, many of which are paired. The unit is latereally continuous and observed both in Section II and in Section III.

Member B-5 (Gfo)

This member is grey-yellow, stratified gravel member. It is coarsening upward from mainly coarse-grained sand, into a medium-to coarse grained clast supported gravel in the upper part. Many of the clasts also appear disc-shaped and imbricated. It is up to 40 cm thick with a sharp and planar lower boundary. The unit is observed only in Section II, and is laterally finite between 285 m and 265 m.

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Member B-6 (Sm)

Medium- to coarse grained sand appearing with a yellow-brown color. Subangular to subrounded gravels appear throughout as do paired bivalve shells. It is up to 60 cm thick and follows only on top of the gravelly member **B-5** with a sharp, planar boundary.

Member B-6 (Gfo-Gs)

Alternating layers of gravelly sand and clast supported gravel that dips towards northwest. The member overall appear moderately, to well sorted. In the lower part the stratification is alternating, whereas in the upper part it appears more cross-cutting. Shell fragments occur, but are rare and small. The member is measured up to 180 cm and is laterally continuous in Section II. In Section III it is only sporadically observed.

Interpretation

Marine remains appear common to most of the units in Formation B suggesting the formation was deposited in a marine setting. The high mud content of the lowermost member (**B-1**) indicates a low energy environment. This imply that sea level was relatively high and that there were some distance to the shore. At present, muddy sediments dominate in the middle parts of Billefjorden and have been shown to originate from glacial melt-water (Szczuciński and Zajączkowski, 2012). A glaciomarine origin is supported by the red-brown color of the mud, which is likely to be linked to the erosion of red siliciclastic strata which are found only on the western side of the fjord. Troughs within the lower boundary probably relate to large icebergs scouring the seabed with subsequent melt out of coarse grained material in the mud.

The glacial influence diminishes up section. The shape of Member **B-2** suggests this to be a local process. Together with the sorted sand, it probably represent a distal

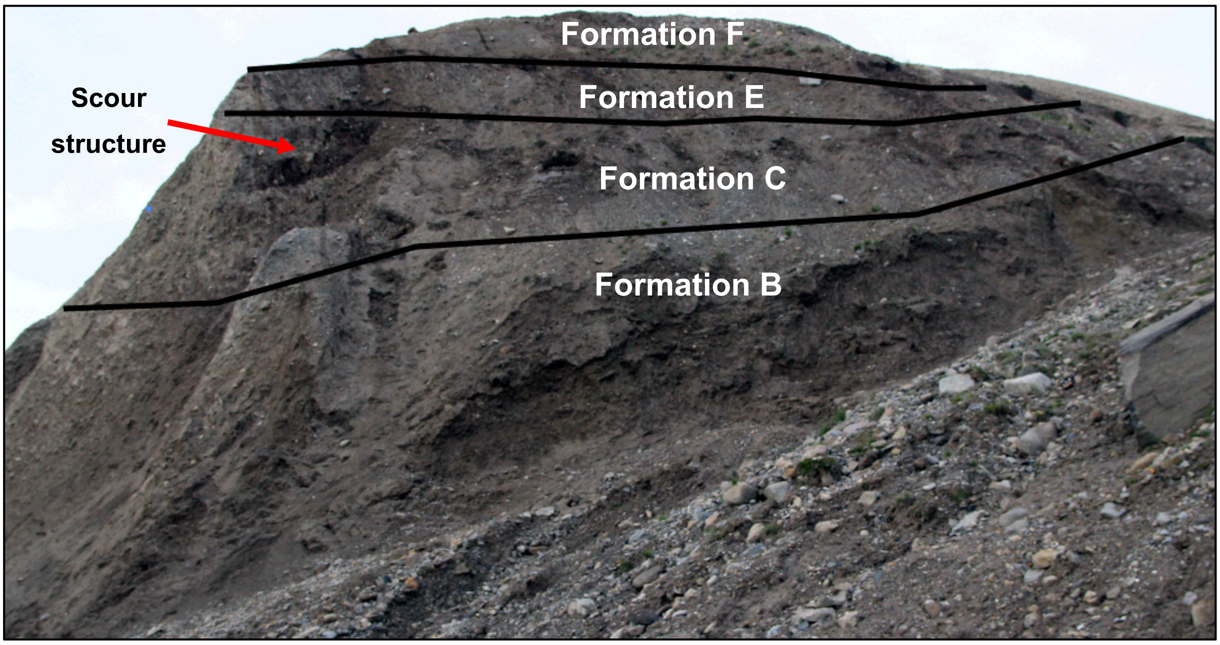

Figure 24: Southern exposure of Section III. The diamictons described as Formation C and Formation E merges leaving out Formation D which is only exposed towards the north.

fluviomarine facies. The gravelly member on top (**B-3**) was probably a gravity flow spreading out over the fan. The lower boundary of **B-2** is assumed to be laterally time-synchronous with the lower boundary of **B-4** which is interpreted as a sub-littoral deposit based on its grain size. Sporadic sand lenses probably indicate temporal increases in discharge from a nearby river-system. Some of the outsized clasts were probably kelp-rafted, but other transport mechanisms such as IRD cannot be ruled out. A sub-littoral setting is also given for member **B-6** occuring on top of the gravelly member **B-5** interpreted. The latter is here interpreted as a littoral deposit, possible from spit development, based on its finite lateral occurrence and position between two sub-littoral units. Spits represent a coastal landform also observed on Kapp Ekholm today. The alternating beds of sand and gravel towards the top of Formation B indicates an increase in energy from below and is interpreted as a littoral, probably intertidal deposition.

4.1.4. Formation C

This formation is recognized from Section III only. Based on a marked change in sorting and mud content it is divided into two members.

Member C-1 (Gs)

A Stratified gravel within a grey and compact sandy-mud-matrix. Clasts are dominantly rounded gravels. It appears poorly to moderately sorted with a weak fjord-dipping stratification of the clasts. Shell fragments occur, but are rare and poorly preserved. The member appear as sporadic pockets no more than 30 cm thick. It follows a sharp and erosive boundary that form an angular unconformity to the dipping, gravelly beds below **(B-6)**.

Member C-2 (Dcm)

This member is a compact, grey-colored and dominantly clast-supported silty diamicton. Clasts range in size from gravel to boulders that are dominantly sub-rounded. Striations are common, but only local lithologies were observed (mudstone, sandstone and limestone). Maximum thickness was measured to 80 cm, but it merges with Formation E in the southern part of Section III.

Interpretation

The high mud content of both units composing this formation is characteristic for glacial environments. The stratified appearance of the lowermost member suggest an environment with changing energy. The high degree of rounding is not consistent with distant glacial transport, but rather re-deposition of fluvial- or beach material. This may suggest that the deposit occurred close to the glacier front pushing up the the gravelly sediments at the top of Formation *B.* The diamict on top is interpreted as glacial till and indicates glacial overriding of the site. Members C-1 and C-2 is interpreted as part of the same glacial advance and thus implies that it occurred during high relative sea level.

4.1.5. Formation D

Sediments associated with Formation D are only found in northern part of Section III. The formation is divided into 4 members based on characteristic changes in grain size.

Member D-1 (Fm)

The member is a massive and brown silt unit. Gravel sized clasts are frequent throughout with a dominance of rounded to sub-rounded clasts. Paired bivalve shells

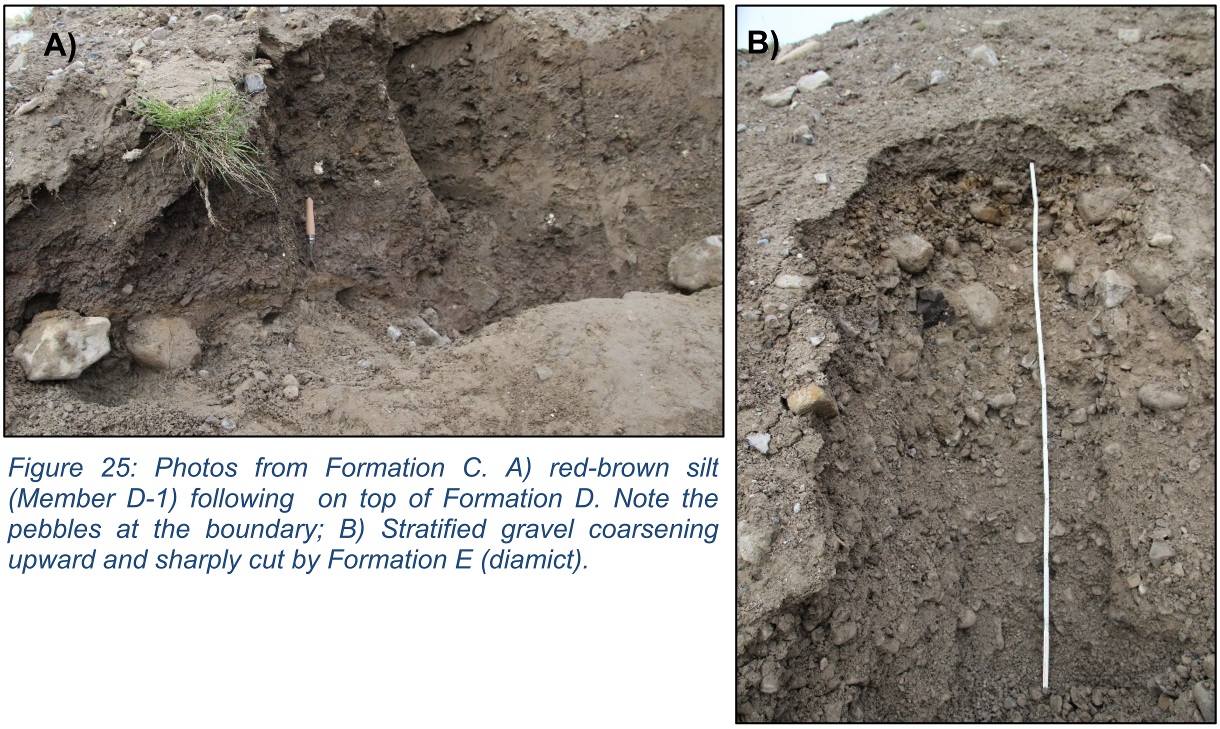

Figure 25: Photos from Formation C. A) red-brown silt (Member D-1) following on top of Formation D. Note the pebbles at the boundary; B) Stratified gravel coarsening upward and sharply cut by Formation E (diamict).

occurs infrequently throughout. The member has a sharp and planar lower boundary and show a thickness of up to 30 cm. A lag of pebbles and boulders also occur as a discontinuous horizon at the base of the member.

Member D-2 (Sm)

Fining upward sequence from mostly fine, to medium-grained sand. It is massive and show a yellow-brown color. Gravel sized clasts are common, but less frequent than below. Only local lithologies are observed and clasts are rounded to subangular in shape. Paired bivalve shells are common, but not abundant. The lower boundary is gradual towards Member D-1 and the member has a measured thickness of 53 cm.

Member D-3 (Fm)

Rounded gravels dominate and the member appears well sorted. It is clast supported and partially openwork, although some sand is also seen within the matrix. The lower boundary is sharp and regular. The member overall is very discontinuous and too thin to determine any structure. At its thickest it is about 9 cm but varies greatly,

Member D-4 (Gs)

Stratified sandy gravel. The member is coarsening upward from dominantly fine to medium grained gravel with pebbles on top. A sandy, partially openwork matrix characterizes the member with little to no compaction. It follows on top of a sharp, but irregular boundary and is measured with a thickness of up to 187 cm.

Interpretation

The lowermost red-brown member (D-1) is interpreted as a glaciomarine mud (Similar to Member B-1). The clast-lag at the lower boundary is most likely the result of winnowing and indicates an erosional phase prior to deposition of Member-D1. Member D-2 show less glacial influence, although the environment remains marine. Based on this it is interpreted as a sub-littoral deposition. The rounded gravels of Member D-3 may the remains of littoral sediments that have been eroded. The stratified appearance of the gravel described as Member D-4 is consistent with that of coarse-grained mass-movement deposits (Blikra and Nemec, 1998). The angularity of the material in the upper part suggest little reworking of the material. There is no evidence to pinpoint this sequence to a marine setting, rather it appear more as a terrestrial process due to its openwork structure. If so, it could be argued that this member should be separated into a new formation. Because this member is not described in much detail, it seems redundant to

4.1.6. Formation E

Member E-1 (Dcm)

This formation consists of a compact silty-clay diamicton with no visible structure. It contains frequent striated clasts that vary in size from gravels to boulders. In addition to local lithologies are also regional lithologies including schist and granite. In section II it is measured with up to 90 cm of thickness. It occurs continuously in both Section II and in Section III.

Interpretation

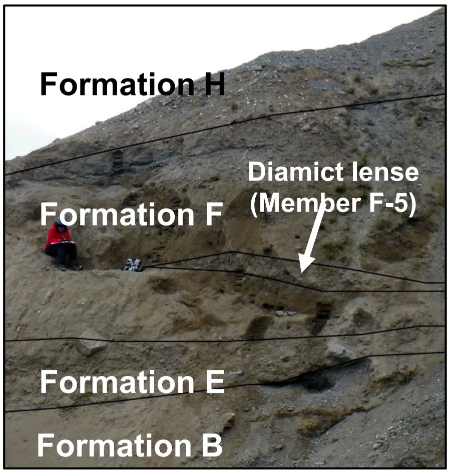

Figure 26: Diamict lense in Formation F. Photo s taken from the upper part of Section II at c. 325 m. This lense is surrounded by a red-brown silt. This silt continuous to ther northern end of Section II and is shown in Figure 27.

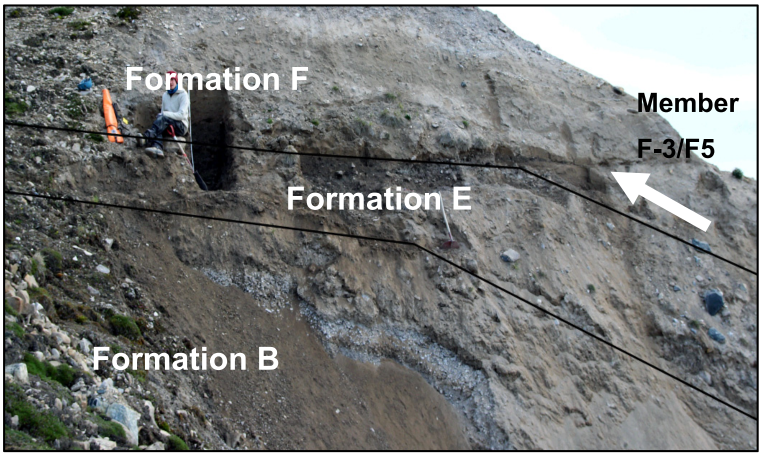

Figure 27:Slumping-contact between Formation E and F. Arrow marks the lateral continiouation of the red-brown silt which surrounds the diamict lense towards the south.

The formation have characteristics similar to that of Formation A and is accordingly interpreted as a glacial till. Towards the south depositions was very thin and/or eroded subsequently to deposition. This formation is here referred to as Formation E following the nomenclature for Section II by Mangerud and Svendsen (1992) defined from Section IV where Formations A-H are all represented in superimposition. Stratigraphically this implies that a significant hiatus exists at the lower boundary of Formation E. Formation E could however, also be C, in which a hiatus should exist at the lower boundary of Formation F.

4.1.7. Formation F

This formation is observed continuously throughout both Section II and Section III. It is overall a coarsening upward sequence of fines to stratified gravel. It is at its thickest in Section II (c. 4-5m) and thins towards Section III (c. 3 m). It is divided into 7 members reflecting mostly sharp changes in grain size.

Member F-1 (Fm)

The lowermost member of Formation F is a reddish-brown clayey-silt. There is no visible structure and characterized as massive. Sub-angular gravel sized are frequent, although pebbles are also observed in the lower part. Paired bivalve shells occurs but are not abundant. It follows a sharp, regular boundary and is mostly uniform in thickness (c. 20 cm). It is observed at Formation F in both Section II and III.

Member F-2 (Sm)

This sequence is an upward coarsening sequence of silty sand. It is dominantly massive, although a weak, subhorizontal bedding occasionally occurs. Gravel sized clasts are scattered throughout. Many of the clasts have seaweed or remains of moss animals (*Bryoza)* attached to the surface. Bivalve shells, many of them paired are common throughout, but not abundant. It is up to 90 cm thick and follows on top of a gradual boundary to the underlying Member F-1. The member is laterally continuous and found on top of the previous member (F-1) in both Section II and in Section III. In Section II it is about 90 cm thick. In Section III (Figure 17) it appears as the uppermost unit of Formation F and is up to 180 cm thick.

Member F-3 (Fm)

This red-brown clayey silt is very similar to Member F-1.The silt contains sub-angular to sub-rounded granule to gravel sized casts. This unit is traced laterally between 290 m and 340 m in Section II (See Figure 24 and Figure 27). At 340 m it shows a landward contact to the lower diamicton (Formation E) and its superimposed red-brown clayey-silt (F-1). The contact between these units are irregular and turbulent with deformed lense-like structures. There is a marked decrease in clasts seaward from this contact with no clasts appearing in the outermost part. Here the lower boundary is planar and sharp.

Member F-4 (Dcm)

This member is a grey and massive silty diamict. It is mostly clast supported with sub-angular gravels being most common. Striae on the surface of the clasts is also frequent. The lower boundary is sharp and the member has a thickness up to 30 cm.

The unit is laterally finite occurring as a 210 wide lense between Member F-3 and F-5 in Section II.C (Figure 17).

Member F-5 (Fm)

Red-brown silt member that is massive with infrequent gravel sized clasts that are mostly sub-angular. A few shells and shell fragments are observed. The member is up to 15 cm thick with a sharp regular boundary. The unit is laterally finite, observed only on top of the wedge described previously (Member F-4). It is very similar to Member F-3 and it also merges with this unit on the sides with no discernable boundary in-between.

Member F-6 (Sm)

On top follows a brown-colored, sandy sequence (**Member F-6**). The sand is fine- to medium grained. A weak, horizontal bedding is observed at irregularly spaced intervals, but with no marked grange in lithology. Towards the top the number of clasts increase, mostly gravel sized. Many of them are covered by remains of moss animals (bryoza) and/or seaweed. The lower boundary is planar and sharp where seen.

Member F-7 (Sl)

Inversely graded, planarly laminated, well-sorted, medium-grained sand unit (Figure 28). The laminae is made from light and dark colored bands, but with no detectable change in grain size. The member has been eroded subsequently to deposition as the horizontal lamina is cut by subsequent channel incision. Moving from the coast, towards the fjord, the laminae becomes increasingly deformed over the 3 meter wide exposure. Primary structure are more or less completely lost in the outermost part. The lower boundary is planar and sharp and the unit is up to 33 cm thick. This unit is only seen in Section II.C

Member F-7 (Gs)

The uppermost member of Formation F is a stratified gravelly sand which has been strongly deformed. The gravel is mostly fine to medium-grained, although larger gravels and sometimes pebbles occur. Most of the clasts appear to be subrounded,

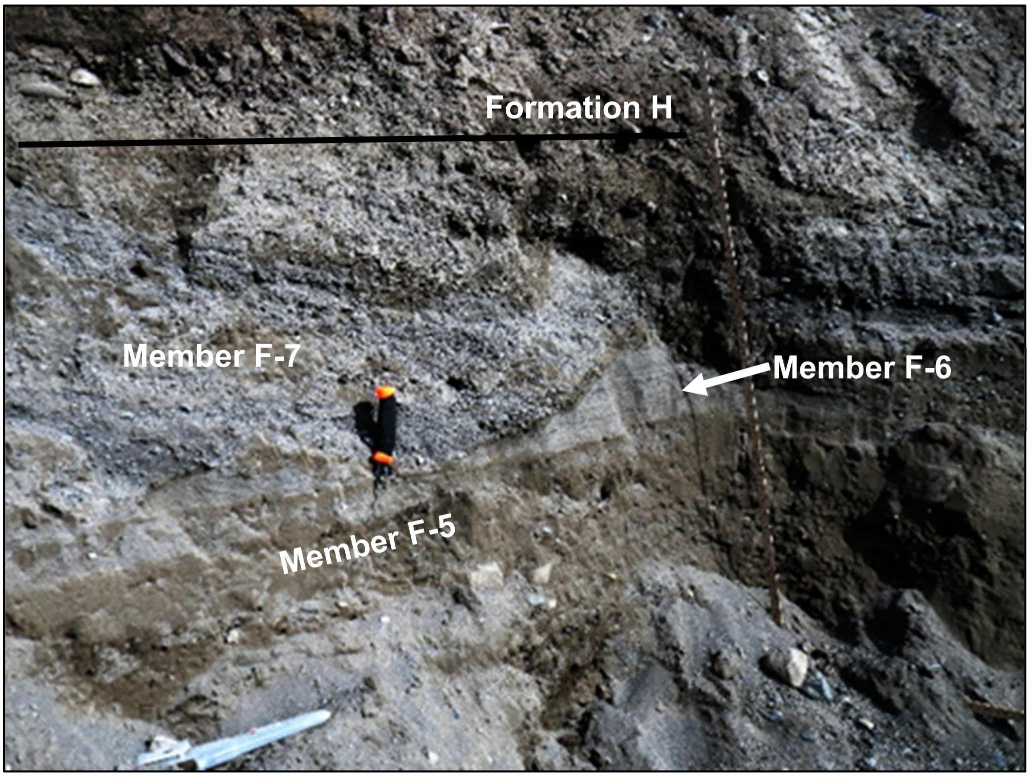

Figure 28: Uppermost part of Formation F in section II. Line marks boundary between Member F5 and Member F6. Note the disformed appearance of Member F7. Formation H follows on top with sporadic diamict lenses.

although sub-angular and angular clasts also occurs. Unpaired shells are seen, but not frequent and fragments dominate. The member is up to 65 cm thick. The lower boundary is sharp and erosive forming channel incisions into the underlying laminated sand (member F-6).

Interpretation

The high frequency of shells and other marine remains suggest the formation as a whole was deposited in a marine setting. The red-brown silt unit (Member F-1) is interpreted as a marine unit dominated by glaciomarine mud deposition, similar to Member B-1 and D-1. As the glacial influence weakens, the environment becomes dominated by more sandy, sub-littoral deposition. Outsized clasts may be explained by several forms of transport, but at least some of the clasts were kelp-rafted. Others may have rolled down the slope as originally suggested by Mangerud and Svendsen (1992).

A similar origin is suggested for the red-brown units that occur in Section II (F-3 and F-5). The geoemetry, including the “turbulent” contact between F-3 and F-1 in the northern part of Section II suggests that these units represents a re-deposition (slumping) of unit F-1 and Formation *E.* Horizontal fining seaward may be explained by an increasing ratio of suspended material being deposited.

Sandy, planar-lamination may occur under fast and shallow unidirectional water flows where there is high transport of bed load and suspended material (John, 2003). Deposition on upper-stage plane beds can here give rise to a planar lamination. A unidirectional flow would implicate a fluvial origin for these sediments. This is contradicted by the high content of foraminifera found in this unit (see also chapter on foraminifera). Upper-stage plane sand beds may also develop in sandy beaches under high velocity water currents that reverse in direction. The swash and backwash associated with wave breaking may sometimes gives rise to planar laminae with characteristic concentrations of minerals. Because of differences in mineral density, this may result in light and dark colored laminae and make it appear more sorted. The deformed character of the unit on top makes it hard to interpret. Its channel geometry indicates a fluvial genesis. Marine remains (molluscs and foraminifera) suggest a relation to the marine environment however, and it may be part of a fluvial system entering the marine environment (i.e. a type of estuary). The units appear to be deformed by pressure from the front of the sections and may have been caused by the subsequent glacial advance.

4.1.8. Formation G

Member G-1 (Dcm)

This formation **(G)** occurs only as a thin (<9 cm) discontinuous layer of clast supported diamicton. The lower boundary is sharp and erosive. Clasts are gravel sized, angular to sub-rounded, commonly with striae, in a clayey silt matrix.

Interpretation

The material associated with Formation G is of glacial origin. The thin, discontinuous appearance in Section II and Section III makes it difficult to rule out that these

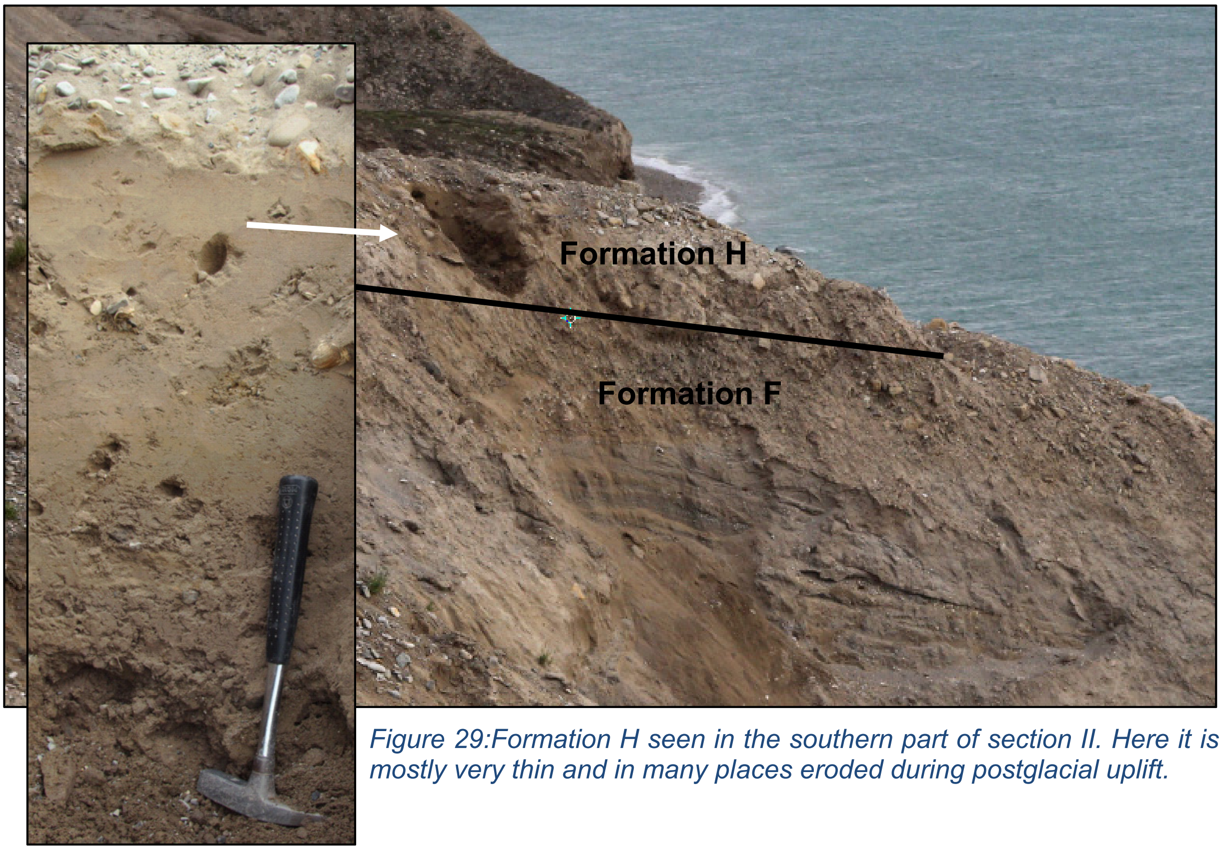

Figure 29:Formation H seen in the southern part of section II. Here it is mostly very thin and in many places eroded during postglacial uplift.

sediments may have been re-deposited. Formation G, is known however, to be much thicker and better exposed in Section V and VI (Mangerud and Svendsen, 1992).

4.1.9. Formation H

Formation H is relatively thin in Section II, increasing in thickness towards Section III. It represents a coarsening upward sequence with silt and sand in the lower part, and sandy gravel in the uppermost part.

Member H-1 (Fm)

A brown silt forms the base of Formation *H.* Sub-angular gravel to pebble sized clasts occurs with a few clasts showing striae on the surface (Figure 29). Striations was observed on a few clasts, but is not common for the unit. The lower boundary is planar and sharp, and it dips gently towards the fjord. The member is up to 13 cm thick in Section II.D. Bivalve shells, some of which are paired occurs throughout, but are not frequent.

Member H-2 (Sm)

This member is a massive, yellow-white sand sequence. The sand is moderately sorted with gravels, mostly rounded, occurring throughout. Shells are abundant, including the easily recognizable *Hiatella arctica* (Linnaeus)*,* which occurs in living position. It follows on top of a planar but gradual boundary and the unit is up to 40 cm thick in the southern part of Section II.

Member H-3 (Gs)

A sandy gravel occurs in the uppermost part of Formation *H.* The gravel is rounded and the member appears as clast supported with a medium-grained sand matrix. Shell fragments and unpaired shells occurs frequently. The unit is up to a meter thick in Section II.D, but is clearly much thicker towards the north and in the range of meters. The lower boundary is irreguler and appear to interfinger with the sand in member H-2. On top, the gravel appear to be eroded by a relict channel incision into the surface.

Interpretation

Although thinner, this formation represent the same sequence of events as previous deglaciation-cycles. A glaciomarine depositional environment follows the glacial retreat with sporadic deposition of IRD from the calving glacier front. The glacial influence eventually diminishes with sub-littoral conditions prevailing. Deposition eventually shifts into the intertidal zone with deposition of more coarse-grained material as the coast shifts seaward. As sea-level drops, the coast also shifts from net deposition to the present regime with overall erosion.

4.2. FORAMINIFERAL STRATIGRAPHY

4.2.1. Summary sample statistics

In total 21 482 specimens of foraminifera was counted and identifed from 55 samples giving an average of 391 specimens per sample(. None of the samples was barren, although a single sample (# F2) did not meet the minimum 300. Most of the tests were in good condition or with minor defects. The quality was a little lower in Formation F, especially in the upper part, but in total was still a negligible component of the total.

Many of the foraminifera in the lower part of Formation B, as well as in the middle part of Formation F were black or brass-coloured (Figure 30). These were mostly concentrated in the heavy residue. Further up-section these specimens disappeared and were at best sporadic. In addition, abnormal forms of recognizable taxa were also sometimes encountered, including morphologic distortions such as cysts, twisted coiling and aberrant chamber shapes. No systematic increase or above naturally occurring population-values occurred however (2 %; Yanko et al., 1998).

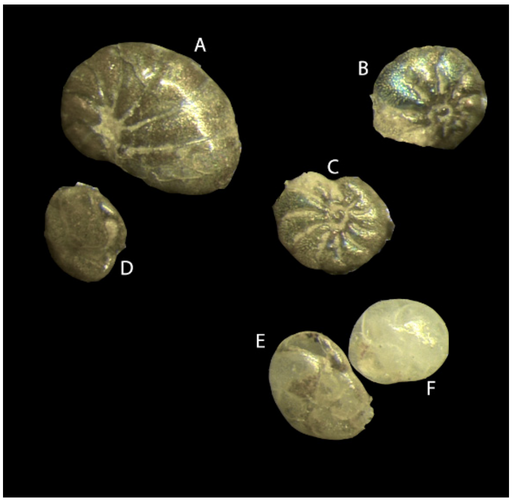

Figure 30: (A-D) Brass-coloured specimens. Note the blue shine on B; (E) Partially brass-coloured specimen; (F) Normal white-coloured specimen.

98 different taxa were identified with only one species identified as planktonic. 19 taxa was identified only to the level of genus (1.6 %), excluding 0.5% which was not identified further than to the rank of phylum (foraminiferida). 34 taxa meet a value minimum of 2 % occurring in at least one sample (Table 2). Of these 9 taxa were *Elphidiums* including *Elphidium albiumbilicatum* (Weiss)*, Elphidium bartletti* (Cushman)*, E. excavatum, Elphidium hallandense* (Brotzen)*, Elphidium incertum (*Williamson)*, Elphidium magellicum (*Fichtel & Moll*), Elphidium selseyense (Heron-Allen & Earland)* and *Elphidium subarcticum (*Cushman*)*.

Only 8 specimens were identified as planktonic foraminifera (Only Neogloboquadrina *pachyderma)*, the remainder being benthic species.

Table 1 lists the most important species identified together with their minimum, maximum and average values. These were selected based on having a distinct and continuous presence throughout. Out of these, *Cassidulina reniforme* and *Elphidium excavatum* are the most common species for the fauna overall. Especially in Formation F and H these two species usually accounts for more than half of the fauna. In the lower half of Formation B these two are usually followed by *Nonionella auricula*, whereas in the upper half *Islandiella norcrossi* appear to replace this species. *Haynesina orbiculare* (Brady) is a species that is uncommon throughout, except in the uppermost part of Formation F where it appears in high frequencies.

Table 1: Statistical overview of the most frequently (%) occurring species throughout.

Species	Average	Minimum	Maximumm
Astrononion gallowayi	0,04	0,00	0,11
Buccella frigida	0,05	0,00	0,19
Cassidulina reniforme	0,34	0,09	0,72
Cibicides lobatulus	0,02	0,00	0,13
Elphidium excavatum	0,15	0,02	0,46
Elphidium subarcticum	0,02	0,00	0,11
Haynesina orbiculare	0,03	0,00	0,27
Islandiella norcrossi	0,08	0,00	0,35
Nonionella auricula	0,06	0,00	0,34
Nonionellina labradorica	0,02	0,00	0,13
Quinqueloculina stalkeri	0,07	0,00	0,55

Table 2: List of taxa occurring with more than 2 percent in at least one sample, with the main reference for identification

Genus species (Authority)	**Reference**
Anomalina globulosa (Chapman and Parr)	Feyling-Hanssen et al. (1971 p. 258; Plate 9, fig. 1-3)
Astrononion gallowayi (Loeblich and Tappan)	Scott and Schafer. (2001a p. 135; Plate 1, fig 10a-b)
Buccella frigida (Cushman)	Feyling-Hanssen et al. (1971 p. 253; Plate 8, fig. 253)
Cassidulina reniforme (Nørvang)	Narayan et al. (2005 p. 25; Plate 3, fig. 2-3); (Rodrigues et al., 1980 p. 58; Plate 2, fig. 2,4,6; Plate 3, fig. 3,6,9,11,12; Plate 5, fig. 10-12)
Cibicides lobatulus(Walker and Jakob)	Feyling-Hanssen et al. (1971 p. 260; Plate 9, fig. 9-14)
Eggerella scabra (Williamson)	Feyling-Hanssen et al. (1971p. 192; Plate 1, fig. 13)
Elphidium albiumbilicatum (Weiss)	Feyling-Hanssen et al. (1971 p. 268; Plate 10, fig. 15-19)
Elphidium bartletti (Cushman)	Feyling-Hanssen et al. (1971 p. 271; Plate 11, fig. 6-9; Plate 20, fig 1-4)
Elphidium excavatum (Terquem)	Feyling-Hanssen (1972); Wilkinson (1979)
Elphidium hallandense (Brotzen)	Riverios and Patterson (2008p. 34; Fig. 15.3a-c)
Elphidium incertum (Williamson)	Feyling-Hanssen (1972 p. 277; Plate 12, fig. 11-12; Plate 21, fig. 8-9)
Elphidium lidoensis (Cushman)	Feyling-Hanssen (1972 p. 344; Plate 6, fig. 1-7); (Alexanderson et al., 2013)
Elphidium macellum (Fichtel and Moll)	Feyling-Hanssen (1972 p. 278; Plate 22, fig. 1-4)
Elphidium selseyensis (Heron-Allen and Earland)	Feyling-Hanssen (1972p. 341; Plate 4, fig 1-7; Plate 5, fig. 1-7)
Elphidium spp. (de Montfort)	Loeblich and Tappan (1988 p. 674; Plate 786, fig. 6-9; Plate 787, fig. 1-7)
Elphidium subarcticum (Cushman)	Feyling-Hanssen et al. (1971 p. 280; Plate 13, fig. 3-7; Plate 22, fig. 9)
Elphidium subclavatum (Nørvang)	Wilkinson (1979 p. 637; Plate 1, fig. 3; Plate 2, fig. 7)
Guttulina spp. (d'Orbigny)	Loeblich and Tappan (1988 p. 419; Plate 458, fig. 1-7)
Haynesina orbiculare (Brady)	Scott and Schafer. (2001ap. 139; Plate 11, fig. 10a-b); Protoelphidium *orbiculare* - Feyling-Hanssen et al. (1971 p. 289; Plate 14, fig. 8-11)
Islandiella islandica (Nørvang)	Rodrigues et al. (1980 p. 49; Plate 1, fig. 2,4,6; Plate 3, fig. 2,5,8)
Islandiella norcrossi (Cushman)	Rodrigues et al. (1980 p. 49; Plate 4, fig. 1,4,7,10; Plate 6, fig. 8,9)
Melonis barleeanus (Williamson)	Murray (2003 p. 24; Figure 8.11-8.14)
Nonion umbilicatulum (Walker & Jacob)	Feyling-Hanssen et al. (1971 p. 263; Plate 10, fig. 3-4)
Nonionella auricula (Heron-Allen and Earland)	Feyling-Hanssen et al. (1971 p. 265; Plate 10, fig. 7-9)
Nonionella labradorica (Dawson)	Scott and Schafer. (2001ap. 140; Plate 11, fig. 17a-b); Nonion *labradoricum* - Feyling-Hanssen et al. (1971 p. 262; Plate 10, fig. 1-2)
Protoelphidium anglicum (Murray)	Feyling-Hanssen et al. (1971 p. 286; Plate 14, fig. 2-5)
Protoelphidium nivuem (Lafrenz)	Feyling-Hanssen et al. (1971 p. 286; Plate 14, fig. 6-7)
Quinqueloculina agglutinata (Cushman)	Feyling-Hanssen et al. (1971 p. 193; Plate 1, fig. 15)
Quinqueloculina arctica (Cushman)	Lukina (2001Fig. 61); (Scott and Schafer., 2001a)
Quinqueloculina seminulum (Linné)	Feyling-Hanssen et al. (1971 p. 193; Plate 1, fig. 18-20)
Quinqueloculina stalkeri (Loeblich and Tappan)	Feyling-Hanssen et al. (1971 p. 194; Plate 2, fig. 1-3)
Triloculina trigonula (Lamarck)	Feyling-Hanssen et al. (1971 p. 196; Plate 2, fig. 4-6)
Triloculina trihedra (Loeblich and Tappan)	Feyling-Hanssen et al. (1971 p. 196; Plate 2, fig.7)

Table 1: *List of taxa occurring with more than 2 percent in at*

Reference

Table 3: Frequencies for foraminiferal taxa (>2 %) that occur in samples B68 to B30 in Formation B.

Taxa	**B68**	**B66**	**B64**	**B62**	**B60**	**B58**	**B56**	**B54**	**B52**	**B50**	**B48**	**B46**	**B44**	**B42**	**B40**	**B38**	**B36**	**B34**	**B32**	**B30**
.spp	0	0	0	1	0	2	0	0	0	0	0	1	0	0	0	3	2	1	0	0
Anomalina globulosa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
Astrononion gallowayi	0	0	0	0	0	0	0	0	0	0	7	5	5	4	0	6	7	3	3	5
Buccella frigida	1	1	4	3	10	10	8	7	6	6	2	1	3	1	2	2	1	2	4	4
Cassidulina reniforme	29	29	16	25	33	28	20	9	16	12	12	19	18	27	29	28	33	48	35	25
Cibicides lobatulus	0	0	0	0	2	2	1	1	0	1	0	2	13	4	1	1	1	2	0	0
Eggerella scabra	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
Elphidium albiumbilicatum	0	0	2	0	7	8	3	1	1	1	0	1	1	0	2	1	2	2	1	0
Elphidium bartletti	1	0	1	11	0	0	0	1	0	0	2	0	1	0	0	0	0	1	0	0
Elphidium excavatum	20	26	7	5	7	15	22	42	34	46	21	12	6	6	7	14	6	6	10	14
Elphidium halladense	0	0	0	0	0	0	0	0	1	0	0	0	3	4	3	5	6	3	2	1
Elphidium incertum	0	1	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	1	0	0
Elphidium lidoensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium magellicum	0	0	0	0	0	0	1	0	0	1	0	3	1	0	3	2	1	1	0	0
Elphidium selseyensis	2	0	0	0	0	0	3	2	4	1	2	0	0	0	0	0	0	0	0	0
Elphidium spp.	1	1	0	2	4	2	2	2	3	0	1	2	1	4	2	1	2	1	0	2
Elphidium subarcticum	0	0	0	0	0	0	1	0	2	0	1	7	5	1	0	2	11	1	4	3
Elphidium subclavatum	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	1
Guttulina spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haynesina orbiculare	0	0	0	0	0	0	1	0	2	1	0	0	0	0	1	1	0	0	1	4
Islandiella islandica	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Islandiella norcrossi	10	10	7	2	0	2	8	6	6	6	4	4	3	1	1	0	2	2	10	16
Melonis barleeanus	0	0	0	0	0	0	0	2	1	0	0	1	0	0	0	0	0	0	0	0
Nonion umbilicatulum	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Nonionella auricula	5	1	1	16	18	16	11	11	18	14	34	22	14	13	34	15	8	7	5	6
Nonionella labradorica	11	13	4	9	3	4	5	9	3	6	3	6	2	2	1	3	1	1	0	0
Protoelphidium anglicum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Protoelphidium Nivuem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Quinqueloculina agglutinata	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Quinqueloculina arctica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina seminulum	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	2	0
Quinqueloculina stalkeri	12	10	55	24	16	7	9	1	2	2	4	12	21	16	4	9	8	9	18	13
Triloculina trigonula	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Triloculina trihedra	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Weight																				
Sample weight (gram)	15	11	6	14	6	9	6	6	5	3	3	4	22	23	11	28	51	55	46	17
Per 100g	2276	6164	5166	2194	4889	3884	6117	8349	11568	14028	10921	7384	1357	1289	2776	1569	727	567	1363	1780
Diversity indices																				
Species richness	26	27	17	15	13	22	22	31	25	21	21	20	22	26	30	28	26	26	31	27
Species richness (>2%)	13	13	14	12	11	12	15	19	19	14	17	16	17	19	22	19	21	19	20	18
Number of specimens	331	684	311	307	308	333	362	517	607	410	303	295	304	296	307	438	372	310	628	308
Fisher	6,61	5,61	3,86	3,30	2,75	5,29	5,16	7,24	5,25	4,68	5,13	4,85	5,45	6,87	8,23	6,67	6,37	6,76	6,84	7,13

Table 4: Frequencies for foraminiferal taxa (>2 %) that occur in samples B32 to B0 in Formation B.

Taxa	B28	B26	B24	B22	B20	B18	B16	B14	B12	B10	B8	B6	B4	B2	B0
.spp	0	0	0	0	0	0	0	1	1	0	0	0	2	1	0
Anomalina globulosa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Astrononion gallowayi	1	1	5	3	3	6	5	4	2	2	1	2	6	6	4
Buccella frigida	6	5	4	9	7	5	4	6	8	19	11	4	4	8	6
Cassidulina reniforme	28	27	27	25	31	38	23	22	27	25	10	33	52	40	69
Cibicides lobatulus	0	0	0	0	0	0	0	1	0	1	0	1	0	2	0
Eggerella scabra	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium albiumbilicatum	1	0	0	1	0	1	1	1	1	1	1	0	0	2	3
Elphidium bartletti	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Elphidium excavatum	17	32	8	23	19	9	2	3	6	5	41	2	5	15	8
Elphidium halladense	1	0	3	0	0	1	0	1	0	0	1	0	1	3	1
Elphidium incertum	2	0	3	1	0	1	1	1	0	0	0	1	4	0	1
Elphidium lidoensis	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Elphidium magellicum	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Elphidium selseyensis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Elphidium spp.	1	1	1	0	0	0	0	1	0	0	0	0	0	1	1
Elphidium subarcticum	2	1	2	2	2	0	0	1	4	3	1	4	6	2	2
Elphidium subclavatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guttulina spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haynesina orbiculare	3	0	3	2	1	1	3	3	3	3	0	2	2	3	1
Islandiella islandica	0	0	0	0	1	0	1	0	0	0	0	0	0	2	0
Islandiella norcrossi	14	13	22	13	16	13	32	29	21	22	5	35	4	7	2
Melonis barleeanus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nonion umbilicatulum	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Nonionella auricula	4	1	3	1	2	0	6	4	3	3	20	2	1	0	0
Nonionella labradorica	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0
Protoelphidium anglicum	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Protoelphidium Nivuem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina agglutinata	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina arctica	0	0	0	0	0	3	4	4	10	3	0	0	0	0	1
Quinqueloculina seminulum	0	0	1	0	1	1	1	0	1	0	0	0	0	0	0
Quinqueloculina stalkeri	14	12	14	17	14	18	13	14	9	9	3	12	9	0	0
Triloculina trigonula	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Triloculina trihedra	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Weight															
Sample weight (gram)	23	35	11	35	20	17	12	12	11	11	12	17	12	11	12
Per 100g	2017	1183	3838	2331	4488	2031	2626	2625	2651	2835	5638	1959	2497	2582	3208
Diversity indices															
Species richness	26	24	22	25	25	21	19	23	24	21	25	15	20	23	17
Species richness (>2%)	16	17	16	18	18	13	15	20	17	14	18	13	15	18	14
Number of specimens	472	416	436	812	911	343	323	313	304	321	675	337	299	296	369
Fisher	5,92	5,54	4,89	4,88	4,75	4,93	4,41	5,72	6,11	5,04	5,11	3,22	4,83	5,83	3,68

Table 5: Frequencies for foraminiferal taxa (>2 %) for samples from Formation F and Formation H. A full list is given in the appendix.

Taxa	**F3**	**F3**	**F3**	**F2**	**F2**	**F2**	**F2**	**F2**	**F1**	**F1**	**F1**	**F1**	**F1**	**F8**	**F6**	**F4**	**F2**	**H2**	**H4**	**H6**
.spp	0	0	0	0	1	0	0	2	1	2	0	2	1	2	0	2	2	0	0	0
Anomalina globulosa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Astrononion gallowayi	2	6	9	10	6	4	6	6	10	8	4	4	11	8	7	4	1	3	5	1
Buccella frigida	5	6	5	5	8	6	8	7	4	7	5	5	4	2	3	2	2	2	1	0
Cassidulina reniforme	72	42	48	47	40	55	42	42	44	43	39	42	51	37	32	13	22	50	64	37
Cibicides lobatulus	1	4	3	2	2	10	1	2	4	3	1	1	2	3	4	5	7	5	2	0
Eggerella scabra	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium albiumbilicatum	1	2	0	3	2	3	1	2	0	2	1	3	1	1	1	0	1	0	4	4
Elphidium bartletti	0	1	1	0	0	0	0	0	1	1	4	1	1	0	0	0	2	0	0	0
Elphidium excavatum	5	19	16	20	15	5	15	15	9	9	11	9	16	15	19	12	13	22	15	40
Elphidium halladense	0	0	1	1	0	1	0	0	0	0	1	1	3	3	6	1	7	3	1	0
Elphidium incertum	0	5	1	1	3	1	3	1	4	2	2	1	0	4	0	5	1	0	1	0
Elphidium lidoensis	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Elphidium magellicum	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Elphidium selseyensis	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium spp.	0	0	1	1	1	1	2	1	1	2	1	3	1	1	0	2	5	3	1	1
Elphidium subarcticum	2	0	0	0	2	2	4	4	1	2	3	4	1	1	3	3	0	2	1	7
Elphidium subclavatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guttulina spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Haynesina orbiculare	1	3	1	3	3	1	4	4	4	4	10	6	2	4	12	25	27	0	0	0
Islandiella islandica	0	0	0	0	2	0	2	0	0	0	2	0	1	2	1	2	3	0	0	0
Islandiella norcrossi	7	4	7	3	7	2	6	6	5	8	8	10	2	4	7	4	0	2	0	1
Melonis barleeanus	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nonion umbilicatulum	0	0	0	0	1	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Nonionella auricula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nonionella labradorica	0	2	2	0	2	0	1	1	2	2	2	3	0	1	0	0	0	2	3	3
Protoelphidium anglicum	0	0	0	1	0	0	0	0	0	0	0	0	0	4	0	16	0	0	0	0
Protoelphidium Nivuem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina agglutinata	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Quinqueloculina arctica	0	0	0	1	0	1	0	1	2	2	0	1	0	0	0	0	0	0	1	1
Quinqueloculina seminulum	0	0	0	0	0	0	1	0	3	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina stalkeri	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Triloculina trigonula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Triloculina trihedra	0	0	1	0	0	0	1	0	3	2	1	1	0	0	0	0	0	0	0	0
Weight																				
Sample weight (gram)	2	12	12	6	6	3	6	5	21	20	6	6	9	10	40	58	58	7	11	17
Per 100g	18979	2676	2515	5436	5030	12809	6189	5980	1456	1625	4610	5358	7512	3195	2266	453	149	6662	2849	1869
Diversity indices																				
Species richness	19	24	25	21	23	17	24	22	24	22	25	24	25	26	20	21	16	23	18	20
Species richness (>2%)	15	17	19	15	18	14	19	18	19	18	18	20	17	18	14	14	15	16	15	18
Number of specimens	331	311	293	316	296	318	341	313	304	327	254	312	684	321	914	262	86	319	312	458
Fisher	4,38	6,07	6,54	5,06	5,83	3,84	5,89	5,40	6,11	5,32	6,88	6,06	5,10	6,68	3,61	5,38	5,79	5,69	4,16	4,27

4.2.2. Key species

Astrononion galloway

This infaunal calcareous species is planispirally coiled, involute and compressed with a lobulated periphery (Figure 31). It has a chracteristic star-shaped umbilical area where supplementary wedge shaped chambers surround the umbilicus (Scott and Schafer., 2001b).

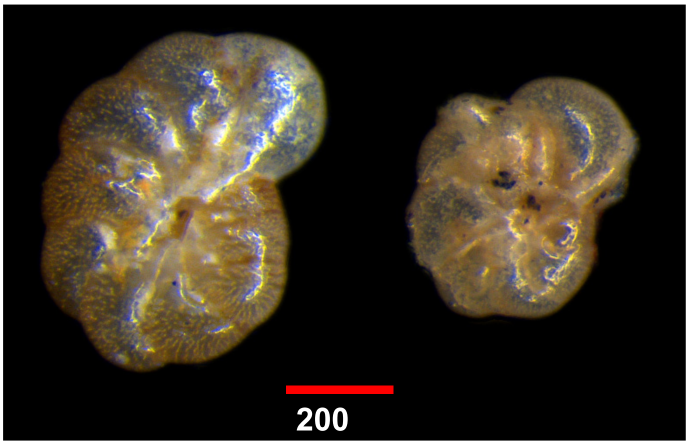

Figure 31: C. Side view (10.3x) of A. gallowayi (Both pictures). It is easily recognizable by its star shaped umbilical area which has also given its name (Greek: Astro = Star).

It often occurs in small frequencies, but is a common accessory species of faunas on Svalbard and generally on inner shelf- and outer estuary environments in the Arctic (Hald and Korsun, 1997). Polyak et al. (2002) classifies *A. gallowayi* as a river distal taxon associated with elevated current activity and coarser sediments in the shallow parts of the Barents Sea. As pointed out by Hald and Korsun (1997) its association with coarser sediments may be the result of winnowing. Steinsund et al. (1994) found this species in environments with water temperatures below 1°C and with salinities of mostly 33 psu, but no higher. It generally follows the distributions of *L. lobatulus*, but requires a higher, and more steady supply of nutrients (Rasmussen et al., 2012).

- River distal
- High food availability
- Elevated current activity

Buccella frigida

The test of *B. frigida* (Figure 32) is calcareous and trochospirally coiled (Scott and Schafer., 2001b). *B. frigida* is the most common of the *Buccella* species within the

Arctic, but due to taxonomic difficulties, it may also incorporate other species belonging to the Buccella genus (e.g. *B. tenerrima*).

According to Polyak et al. (2002) *B. frigida* prefers river influenced environments. Several authors consider it as an indicator of high seasonal productivity and also suggest a relation to seasonal sea-ice edge-production (Ślubowska et al., 2005). Steinsund (1994) argues that B. *frigida* prefer water temperatures between 0 °C and 1 °C with salinities around 33-34 ‰

- Sea-ice indicator
- River-influenced areas

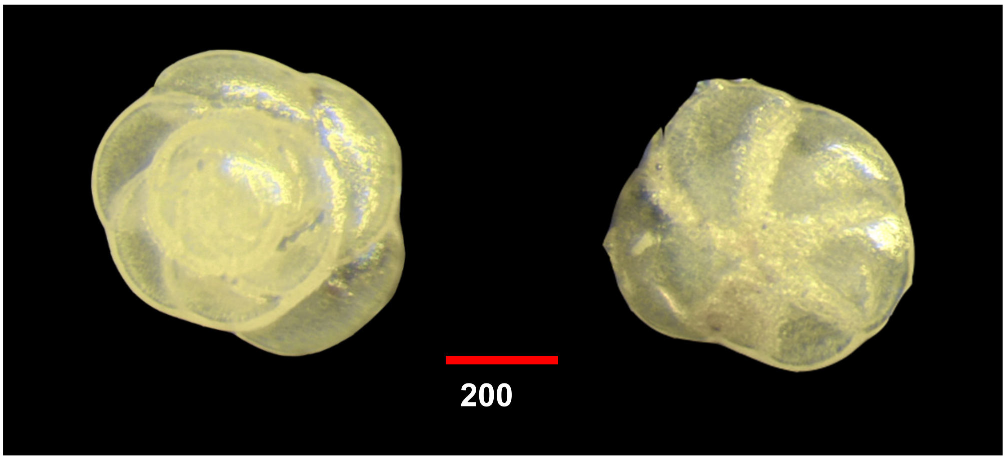

Figure 32: (To the left) Dorsal view (9.37x) of B. frigida; (To the right) Ventral view (9.37x)of same specimen

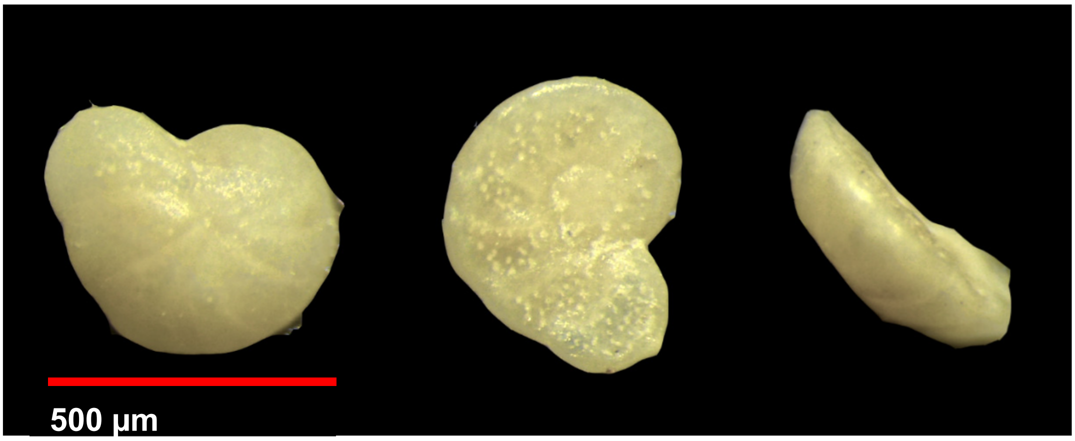

Figure 33: (Left) Dorsal view (4.68x) of C. lobatulus); (Middle) Ventral view (4.68x) of the same specimen; (right) Side-view (4.68x) showing the planoconvex shape of the test

Cibicides lobatula

Calcareous species with a characteristic plano-convex test (Figure 33)(Scott and Schafer., 2001a). Its spiral side is coarsely perforate and flat to irregular. The aperture extends from its convex side along the suture of the first few chambers.

It is a passive epifaunal suspension feeder that lives on elevated microhabitats, including rocks, pebbles, algae and the hard parts of macrobenthos such as corals, and seaweed (Linke and Lutze, 1993; Steinsund et al., 1994; Polyak et al., 2002). It is further associated with elevated current activity and shallow waters (Wollenburg and Mackensen, 1998). It prefers water salinities >32‰ (Steinsund et al., 1994)

- High Salinity
- Current-indicator
- Shallow water

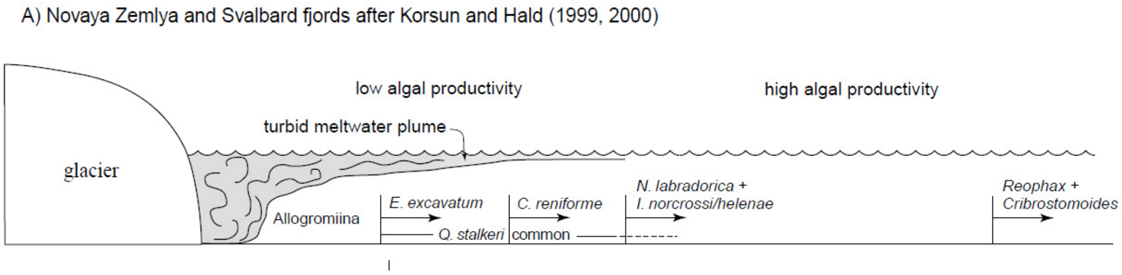

Figure 34: Generalized distribution of modern foraminifera on Novaya Zemlya and Svalbard in relation to glacial fronts.(Guilbault et al., 2003)

Cassidulina *reniforme*

This species has a calcareous, hyaline and lightly perforated test with a circular, biconvex shape (Figure 35). It has a characteristic aperture described as a narrow, arched, elongate slit, parallel to periphery, at base of final chamber, nearly closed by a broad apertural flap (Nørvang, 1958). Its aperture separates Cassidulina from species of Islandiella that in some cases show a high resemblance.

.It is often abundant in fjords influenced by cold (<2 °C) saline Water (> 30psu) (Polyak et al., 2002; Rasmussen et al., 2012). *C. reniforme* is frequent in many modern glacimarine environments. On Svalbard it is commonly found together with *E.*

excavatum in low diversity assemblages close to glacier fronts (Figure 34) (Korsun et al., 1995; Hald and Korsun, 1997; Korsun and Hald, 1998; Polyak et al., 2002; Hald et al., 2004).

- Glaciomarine
- Stress-tolerant
- Avoids low salinities

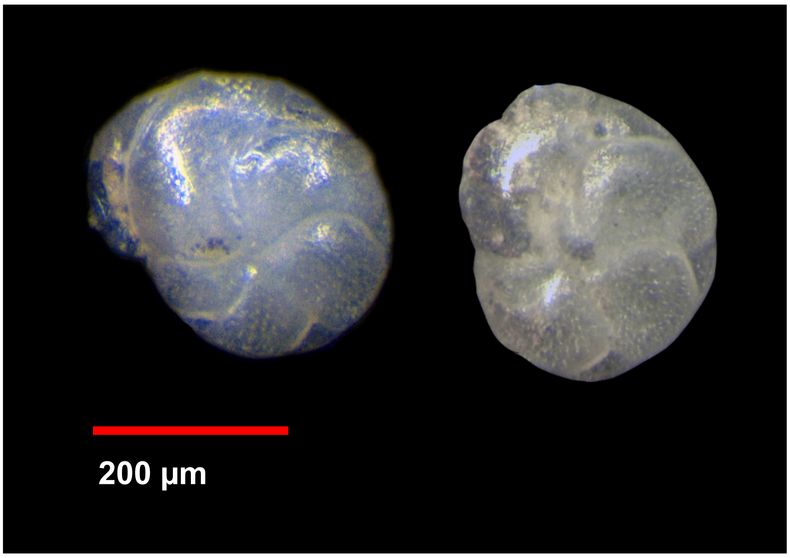

Figure 35: C. reniforme. (Left) Dorsal view (14.3x) with aperture barely visible as a lip on the left side. (Right) Ventral view (11.2x) of the same species, but different specimen.

Elphidium excavatum

This *Elphidium* species has a calcareous lenticular, planispirally enrolled test (Figure 35) that is involute or partially evolute. It may have an umbilical plug on each side. Deeply incised sutures form interlobular spaces that communicate with umbilical spiral canals leading from the spiral canal to the surface of umbilical plug with retral processes (backward extensions from the chamber lumen along the sutures). The exact geographical distribution, as well as its environmental preferences, is somewhat obscured however because of taxonomic difficulties in distinguishing between its many subspecies/morphotypes and also from other species of Elphidium (Feyling-Hanssen, 1972; Wilkinson, 1979). Adding to this is differences in the taxonomic rank of the same taxon that range from morphotype or subspecies to the rank of species. Many authors prefer to group subspecies together under *E. excavatum* or just as Elphidium spp. to avoid taxonomic challenges.

The *E. excavatum* is a widespread species in the Arctic. It often dominate in areas with strongly fluctuating conditions such as close to the termini of tidewater glaciers. It is an opportunistic species with high nutritional- and habitat versatility. Linke and Lutze (1993) found that the *E. excavatum* can be found in elevated microhabitats, on the sediment surface or within the uppermost sediment layer depending on food availability and/or changing environmental conditions.

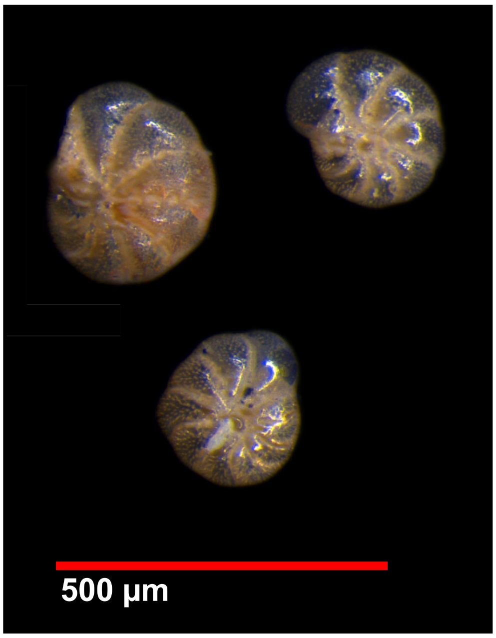

Figure 36: Side view (6.75x) of tree specimens of *E. excavatum*

E. excavatum is sometimes also reported in hifh frequencies from the southern Barents Sea. Sejrup et al. (2004) however explains this as the result of *E. excavatum* f. selseyensis and *excavatum f.* clavata being grouped together. The latter has a southern distribution in the Barents sea limited by water temperatures above c. 4 °C and/or by the the winter sea-ice boundary (Polyak et al., 2002) and more commonly found in Arctic water-masses and common to modern fjords on Svalbard (Feyling-Hanssen, 1972; Wilkinson, 1979; Hald and Korsun, 1997).

- Glaciomarine
- Dominant in glacioproximal environments
- Stress tolerant

Elphidium subarcticum

The calcareous test is planispiral and involute (Scott and Schafer., 2001b). Chambers moderately inflated and sutures slightly depressed. It has a row of sutural pores and a wide opaque band (Figure 37). Aperture is a row of pores at the base of apertural face of the last chamber.

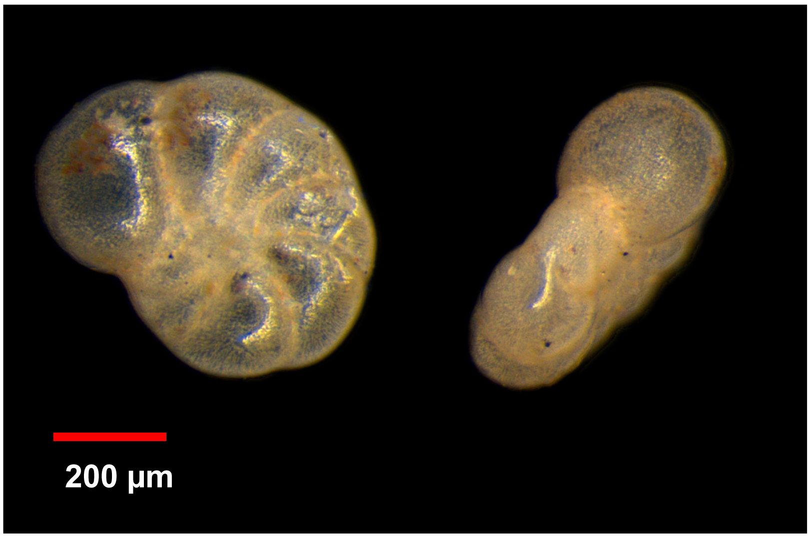

Figure 37: E. subarcticum. (Left) Side view (9.34x); (Right) Apertural view (8.8x) of same specimen.

Often found in areas with coarse sediments, attached to immobile benthic organisms (Steinsund et al., 1994; Polyak et al., 2002). It seems to prefer low temperatures (<1°C), lowered salinities (33-34‰) and is sometimes associated to sea-ice cover. Polyak et al. (2002) found it to dominate in river-distal environments. Epifaunal taxa generally avoid river-proximal environments which has a faster burial rate, a higher redox boundary and relatively low-quality organic matter when compared to organic matter of marine origin (Mojtahid et al., 2010)

Taxonomical uncertainty and/or errors in identifying the *E. subarcticum* to some degree challenges our knowledge of this taxon as noted by (Polyak et al., 2002). Throughout its life-cycle it may resemble other Elphidiids such as *E.* albiumbilicatum, *E. incertum*, *E. frigidum*, *E. halladense*, and Cribroelphidium *magellanicum*.

Haynesina orbiculare

Test is planispirally coiled bilaterally symmetrical and involute (Figure 38: H. orbiculare (Left) Side view; (Right) Apertural view.). Wall is calcareous and usually transparent with fine perforation (Michelsen, 1967). Margin is rounded, smooth to slightly lobulate. The last whorl has 6-8 not inflated chambers, increasing only slowly in size. Sutures slightly depressed, backward-curved. Umbilicus not depressed, usually covered by a granular secondary coating.

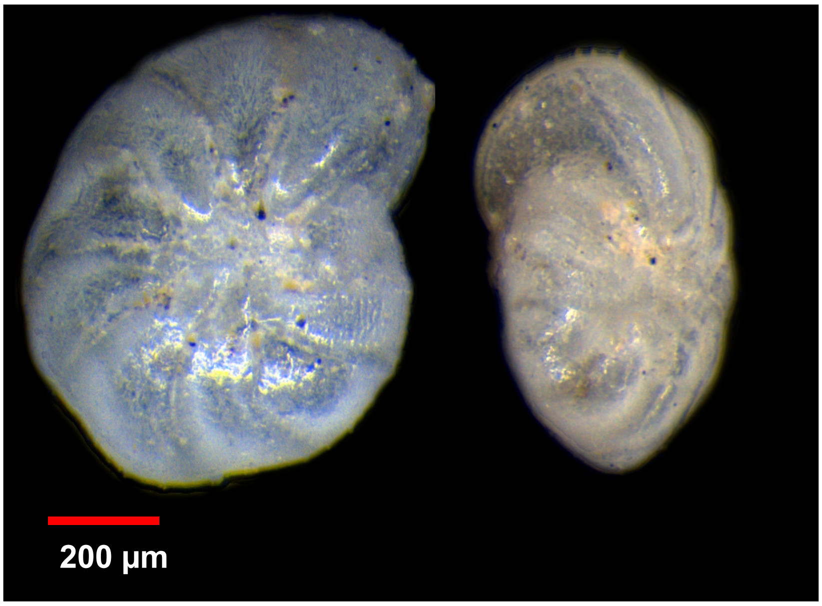

Figure 38: H. orbiculare (Left) Side view; (Right) Apertural view.

This species may live both infaunal or epifaunal (Polyak et al., 2003). According to Polyak et al. (2002) the *H. orbiculare* is an important indicator of river-proximal environments showing a clear decreasing trend in frequency towards the river-distal areas.*H. orbiculare* normally do not occur in the vicinity of melting glaciers (Hald and Korsun, 1997; Anjar et al., 2012), but is considered an important species in river proximal enviornments (Polyak et al., 2002). It proliferate in brackish water (Salinity of 22-26 psu) with low temperatures (-1 to +1 °C), although it has been shown to adapt to temperatures as high as 20 °C (Steinsund et al., 1994; Anjar et al., 2012).

- Brackwater-indicator
- River-proximal

Islandiella norcrossi

This species has a calcareous, hyaline test that is biconvex and lenticular. It appears strongly compressed with its periphery slightly keeled and evolute. Its umbilical region is transparent with previous whorls visible inside. Chambers consists of four to five pairs and are planispirally enrolled. Sutures are distinct and slightly curved.

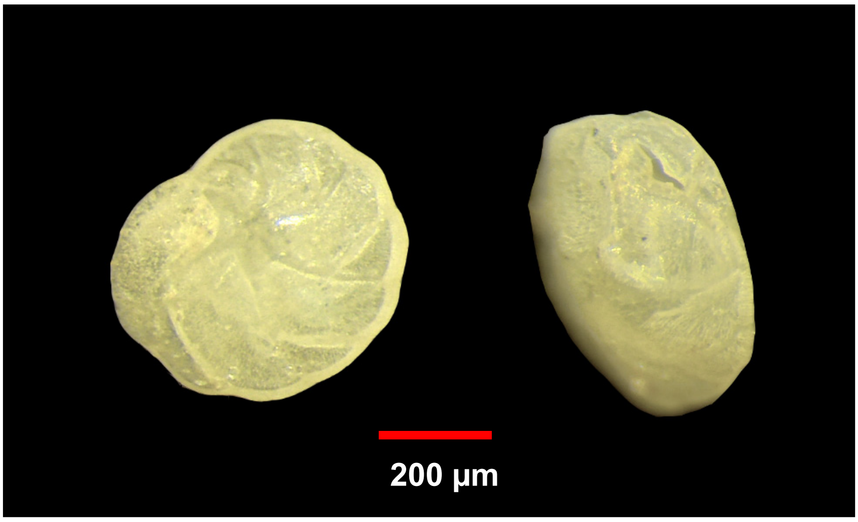

Figure 39: (Left) Dorsal view of I. norcrossi ; (Right) Side-view showing aperture of I. norcrossi

I. norcrossi is a common Arctic taxon that also occur on Svalbard today (Hald and Korsun, 1997). It thrives in environments characterized by high and stable bottom salinities and is considered a distal glacimarine taxon (Korsun and Hald, 1998) and/or distal to river-dominated environments (Polyak et al., 2002). This may be explained by its low tolerance to high sedimentation rates (Zajaczkowski et al., 2010). In the Barents Sea, populations of *I. norcrossi* show their maxima in areas with seasonal sea-ice and high organic nutrient content possible linked to summer sea-ice edge-productivity (Hald and Steinsund, 1996; Korsun and Hald, 1998; Saher et al., 2012).

- Glacially dital
- Sea ice-indicator
- Seasonal food productivity
- High and stable salinity

Nonionella auricula

Test ovate in outline (Figure 40), coiled and slightly trochoid (Loeblich and Tappan, 1955). Periphery rounded with chambers slightly inflated and increasing rapidly in size as added. 5 or 6 of the previous whorl is visible dorsally where the test is partially evolute, only the 9 to 10 chambers of the final whorl visible ventrally. Final chamber is somewhat inflated and comparatively higher than the preceding chambers, extending farther over the ventral side when seen in edge view. Sutures are distinct and gently cursved. Walls are calcareous, thin, hyaline, finely perforate and smooth; aperture at

Figure 40: N. auricula. The N. auricula has an assymetric arrangement of the chamber as opposed to N. labradorica

the base of the apertural face extending from the periphery a short distance on the ventral side

The *N. auricula* is a species not commonly occuring on Svalbard today. Living specimens of *N. auricula* from Svalbard is reported only in low concentrations (<3 %) from Bellsund by Lycke et al. (1992). In addition Feyling-Hanssen (1965) reports a small occurrence (<1 %) of *N. auricula* from Barentsøya in sediments of uncertain, but probably Holocene age. Another pre-recent occurrence <3 % is described by Lycke et al. (1992) from the Linnéelva-sections in sediments correlated to the Kapp Ekholm interstadial (Mangerud et al., 1998).

On Greenland the *N. auricula* is found in several units correlated to the Eemian interglacial (Feyling-Hanssen and Funder, 1990; Bennike et al., 1994; Kelly et al., 1999). In higher frequencies, it is almost exclusively found in faunas of high diversity and is interpreted as an indiator of warm-water influx and overall ameliorated conditions (Gudina and Evzerov, 1981). Hald and Steinsund (1996) states that many authors have previously mistaken this species for *N.* labradorica and advised combing the two for their foraminiferal-database for the Barents- and Kara seas. Saher et al. (2012) warns against this, stating that these two taxa seem to have profoundly different environmental preferences. This is also supported by Karen Luise Knudsen who points out that *N.* labradorica and *N. auricula* do not seem to proliferate together (Personal communication, 5th of June, 2014). The *N. auricula* might prefer warm water, or is just better adapted to warmer water, than the *N. labradorica* (Margot Heelen Saher,

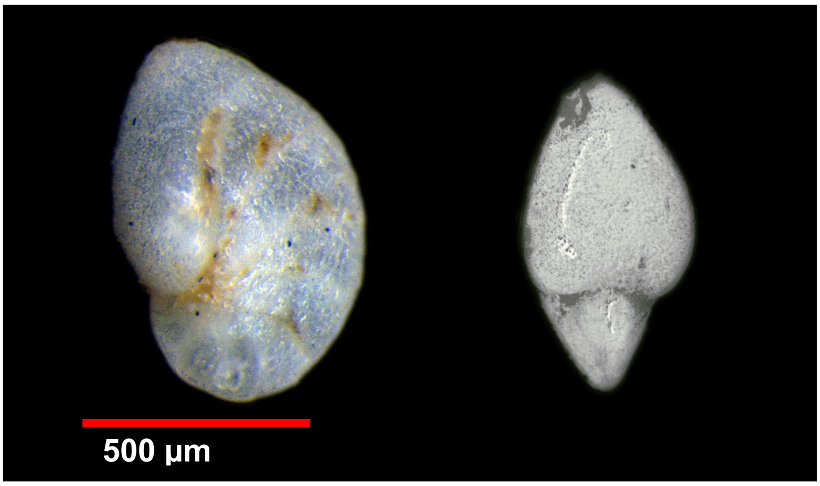

Figure 41: N. labradorica. A species that generally is easy to identify on the basis of its final chamber and symmetric apperaence.

personal communication, 4th of June, 2014). *N. auricula* is reported with high living frequencies (0-17 %) from the Central – Southern Barents Sea (Saher et al., 2012 with additional unpublished data). In this limited sample-set (*n.* 29) *N. auricula* shows its highest abundances of 20-35 % where temperatures range between 5-8 °*C.* According to Sejrup et al. (2004) the maximum abundance of *N.* labradorica in the Barents sea, is found where bottom waters are colder than 2°C.

In terms of interpretation *N.* auricula is believed to show the same preferences as *N.* labradorica in terms of food availability, but may indicate overall warmer bottom water conditions (See also *N. labradorica*)

- Non-native to Svalbard
- Food indicator
- Warm water indicator
- Glacially distal

Nonionellina labradorica

This calcareous species has a planispiral test (Figure 41)that is ovate to auriculate in outline (Loeblich and Tappan, 1955). It is involute and bilaterally symmetrical, biconvex and biumbiliate. Its most characteristic feature is its chambers that increase in size, whereas the final chamber is almost twice the size of the preceding chamber.

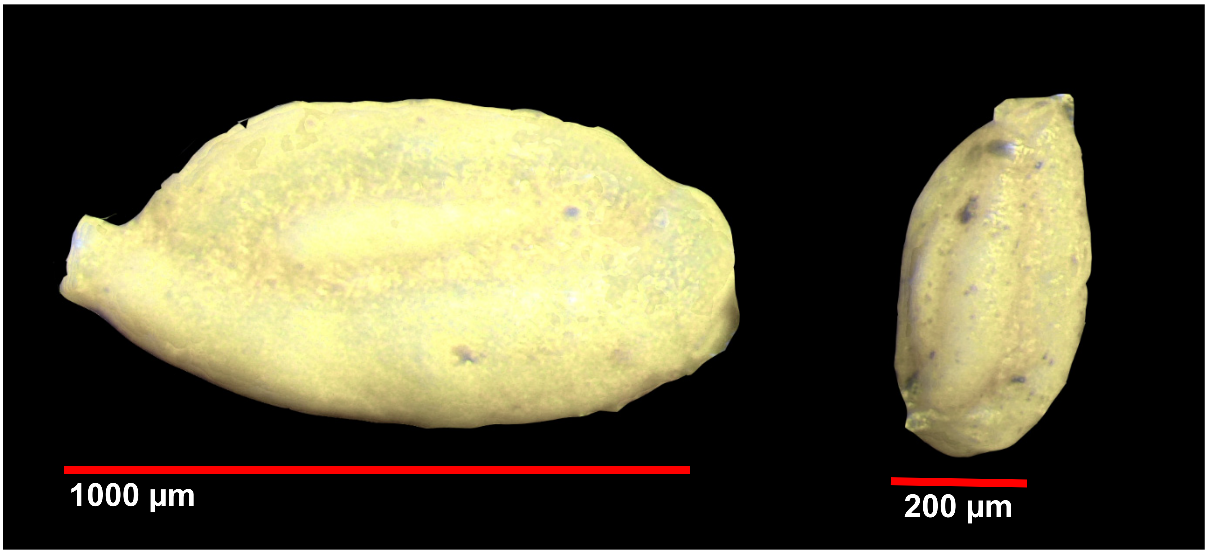

Figure 42: The Q. stalkeri is recognized form other milioids by its "stalky" aperture. Although sediment grains are usually attached to the outer part of its wall, it is not considered an agglutinated species.

The *N. labradorica* is common in areas of high productivity with a preference for fresh phytodetritus and often co-occur with *I. norcrossi* and *Bucc*ella Spp. in the Barents Sea (Stein, 1996; Polyak et al., 2002). According to Steinsund et al. (1994) its maximum concentrations are found on the slopes or banks in areas with high organic production, along the oceanic polar front or at the mouth of glaciated fjords as shown by Hald and Korsun (1997). According to Sejrup et al. (2004) the maximum abundance of *N. labradorica* in the Barents Sea, is found where bottom waters are colder than 2°C.

- Food indicator
- Warm-water indicator
- Glacially distal

Quinqueloculina stalkeri

This *Milliodae* has a test that is small and ovate in outline (Nørvang, 1957). Chambers are quinqueloculine in plan with distinct sutures. It is calcareous, but has very finely grained agglutinated surface. Aperture is ovate to rounded, somewhat elevated, on a short neck and surrounded by a distinct lip.

Q. stalkeri (Figure 42)is described as an Arctic, opertunistic species, occupying mostly shallow waters and being extremely rare in the open Barents- and Kara seas (Feyling-Hanssen, 1964; Feyling-Hanssen et al., 1971; Barmawidjaja et al., 1995; Korsun et al., 1995). Korsun and Hald (1998) found that the presence of *Q. stalkeri* in the Kara Sea was limited to areas with glaciomarine-clay occurring as an accessory species in samples with high frequencies of *C. reniforme* and *E. excavatum*. A similar pattern is also seen in the Vendsyssel sections in Denmark (Feyling-Hanssen et al., 1971); Korsun and Hald (1998), referring to data from Feyling-Hanssen (1964),states that the *Q. stalkeri* is mostly found in water depths of less than 50m. However in the data from Hald and Korsun (1997) it shows up in higher frequencies in much deeper water (80-192m).

- Glaciomarine, intermediate
- Stress tolerant

4.2.3. Cluster analysis

The foraminiferal data was treated statistically by constructing a Bray-Curtis similiarity index using untransformed, square-root transformed and fourth-root transformed data. Each incremental step of transformation also resulted in increasing similiarity

Samples overall show a high degree of similiarity and increases with the strength of the transformation function (Untransformed < Square root < Fourth root). This is an indication that the type of taxa occuring within the samples are the same. Dissimilarity between samples are to a large degree explained by different frequencies of the same taxa.

Figure 43, Figure 44 and Figure 45 shows the result of the clustering analyses and how results vary by using different transformation functions. The untransformed data results in 19 significant clusters (Sig. 0.01) where 8 clusters consist of only a single sample only. A square root transformation reduces the number of clusters to 10 where 4 clusters consist of a single sample only. A fourth root transformation reduces the number of clusters to 8 with only 2 samples consisting of a single sample.

Samples from Formation B show a significant dissimiliarity with samples from Formation F and H at a similarity score of 65 (Using square-root transformed data). Two principal clusters are formed which overall divide the lower from the upper half of Formation *B.* Formation F is also divided into two clusters at a similarity score of 65, altough most samples fall into a larger cluster mixed with samples from Formation H.

Biofacies were constructed from these clusters using primarily the results of the square-root transformed. Deviations from this are noted in the description of the individual facies and is done when a single species apper to occur in abnormally high frequencies.

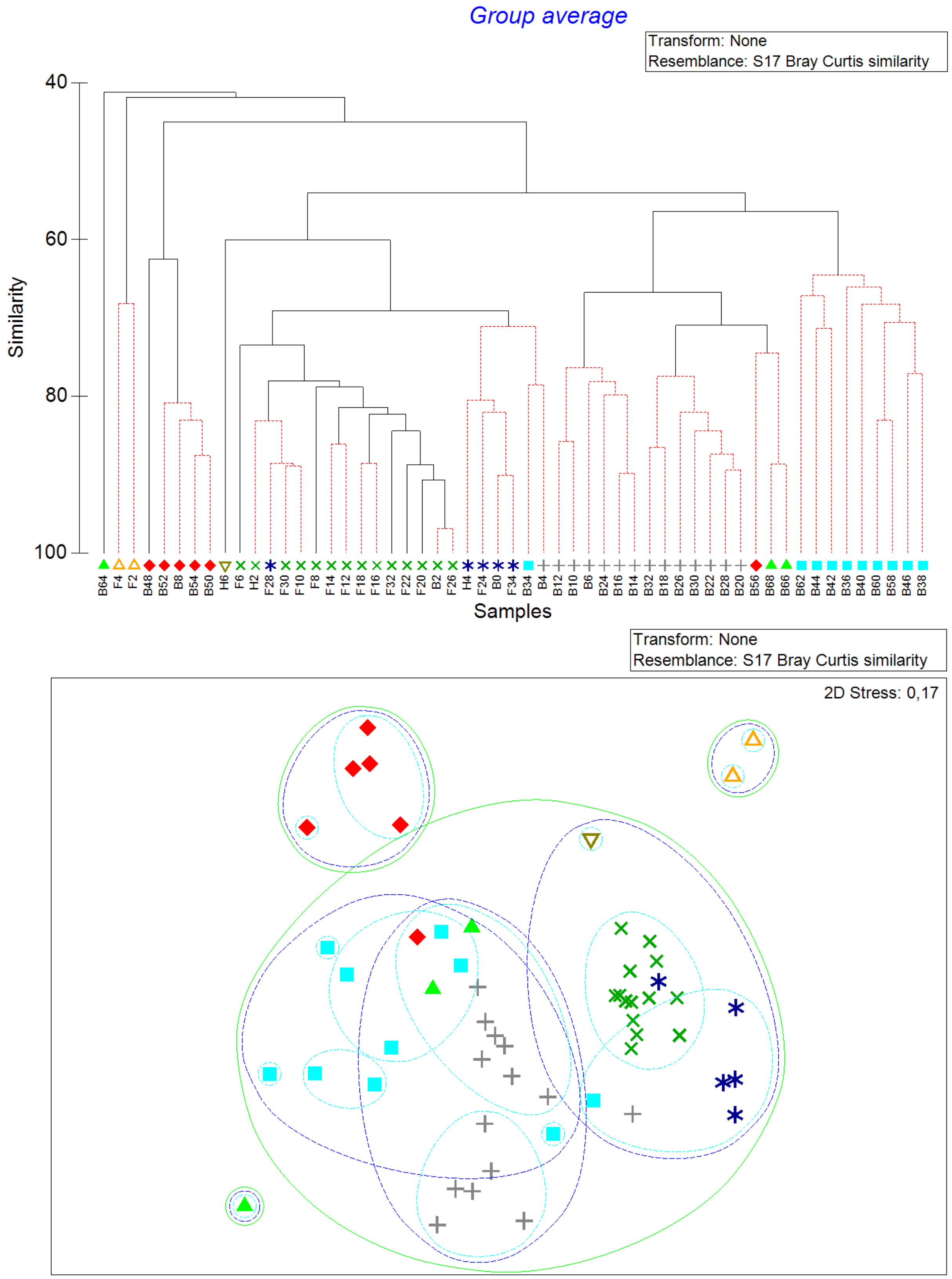

Figure 43: (Upper) A similarity dendrogram based on hierarchical agglomeration of clusters using square root transformed data. Stipled lines mark clusters that show no significant difference. (Lower) MDS-plot visualizing the same similarity index, but without hierarchical agglomeration.

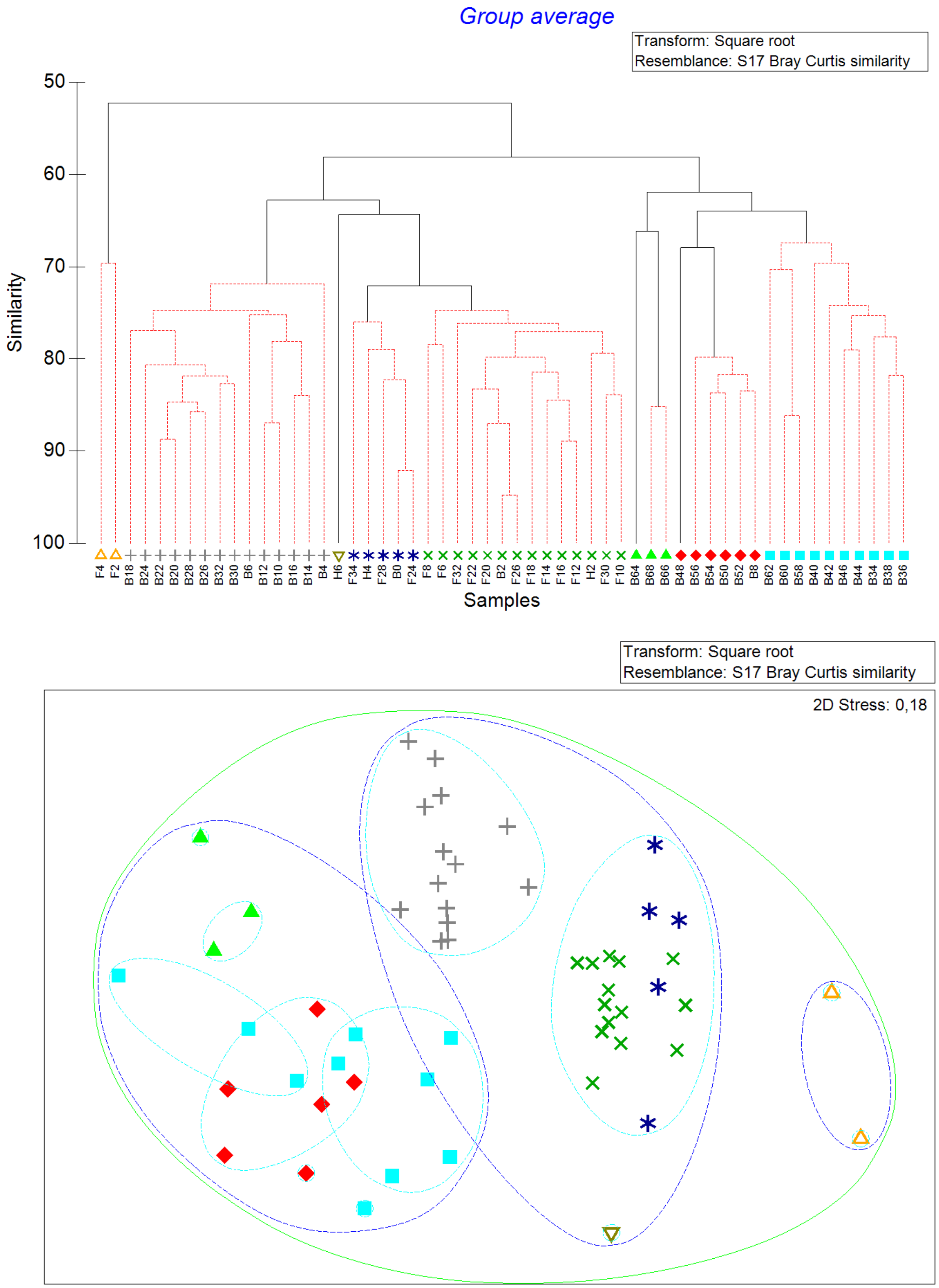

Figure 44:(Upper) A similarity dendrogram based on hierarchical agglomeration of clusters using fourth-root transformed data Stipled lines mark clusters that show no significant difference. (Lower) MDS-plot visualizing the same similarity index, but without hierarchical agglomeration.

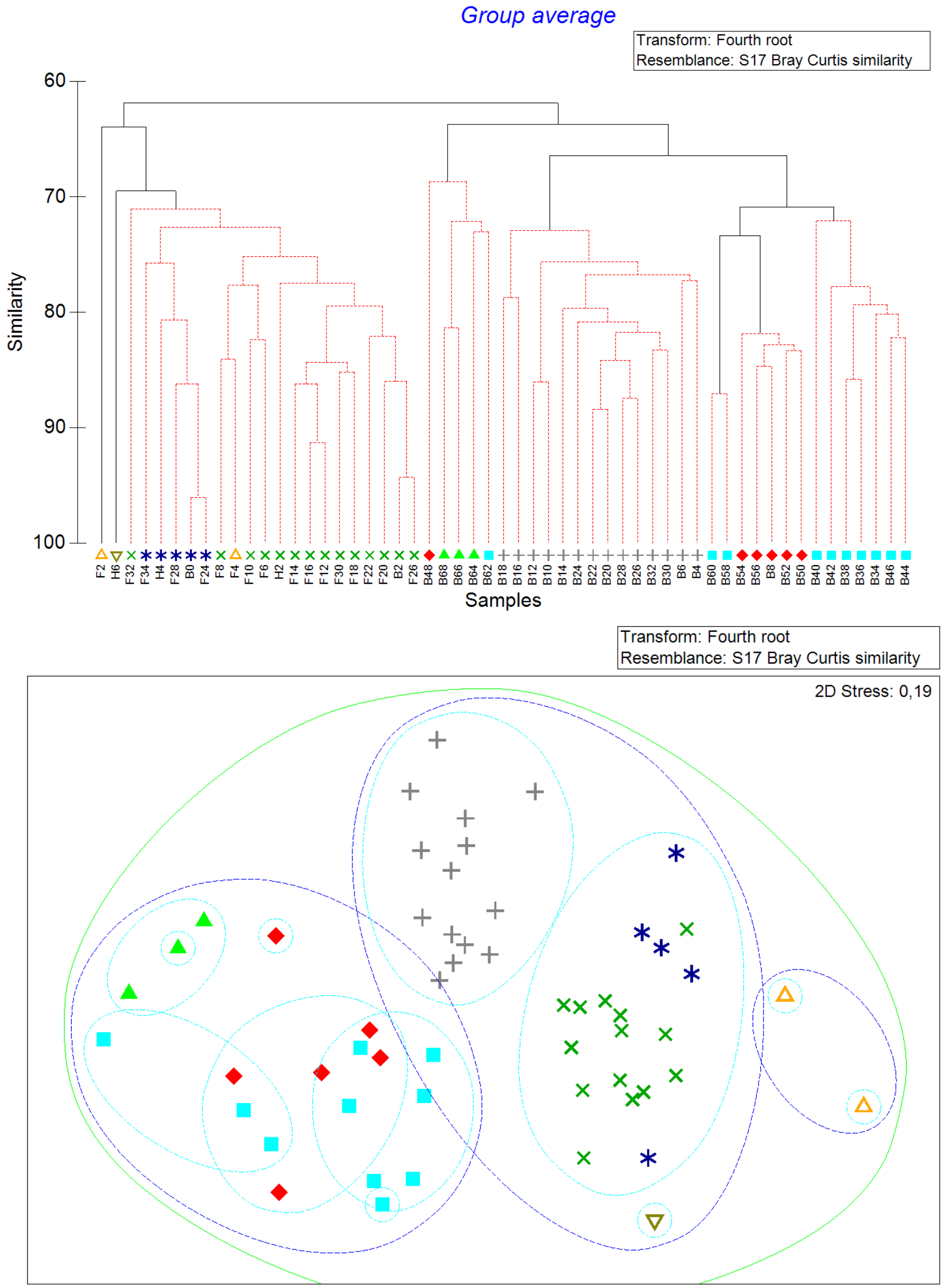

Figure 45: (Upper) A similiarty dendrogram based on hierarchical agglomeration of clusters using untransformed data. Stipled lines mark clusters that show no significant difference. (Lower) MDS-plot visualizing the same similarity index, but without hierarchical agglomeration.

4.2.4. Biofacies

Facies A

Three samples from the lowermost part of Formation B are included in this facies (B68-B64). SIMPROF-results show no significant difference between samples B68 and B66. Sample B64 shows a lower degree of similarity, but is still included under this facies as dissimilarity appears primarily to be the result of abnormally high frequencies of *Q. stalkeri* (see also interpretation).

C. reniforme (avg. 24 %) and *E. excavatum* (avg. 18 %) occurs in near-equal frequencies and accounts for about half of the sampled population. In high frequencies are also the species *N. labradorica* (avg 12 %), *Q. stalkeri* (avg. 11 %) and *I. norcrossi* (10 %). *N. auricula* is present, but considered a minor species

On average each sample has a raw species richness of 27, but contains only 6 species that occur with frequencies above 2 %. Faunal diversity, as indicated by fisher's alpha, is low (avg 2.42) with abundances averaging at 4212 specimens per 100 gram.

Interpretation

All species occurring in high frequencies are common on Svalbard today (Hald and Korsun, 1997). Both *C. reniforme* and *E. excavatum* are stress-tolerant species that usually dominate in glaciomarine environments. According to Korsun et al. (1995) these two taxa will occur in near-equal frequencies where glacial impact is moderate and/or the distance to glacier fronts is intermediate. Similar frequencies and ratios of these two species is today found just south of Rudmosepynten (Figure 3 and Figure 11). This suggest glacial impact was higher than today. Another indication of glacial influence is the species *Q. stalkeri*. High frequencies of this species is associated with proximal glacial environments where algae-production is inhibited by glacial melt-water. *N. labradorica* and I. *norcrossi* are both considered indicators of at least seasonally high algae-productivity. *N. labradorica* usually proliferate in areas characterized by upwelling of relatively warm and nutrient-rich water. *I. norcrossi* on

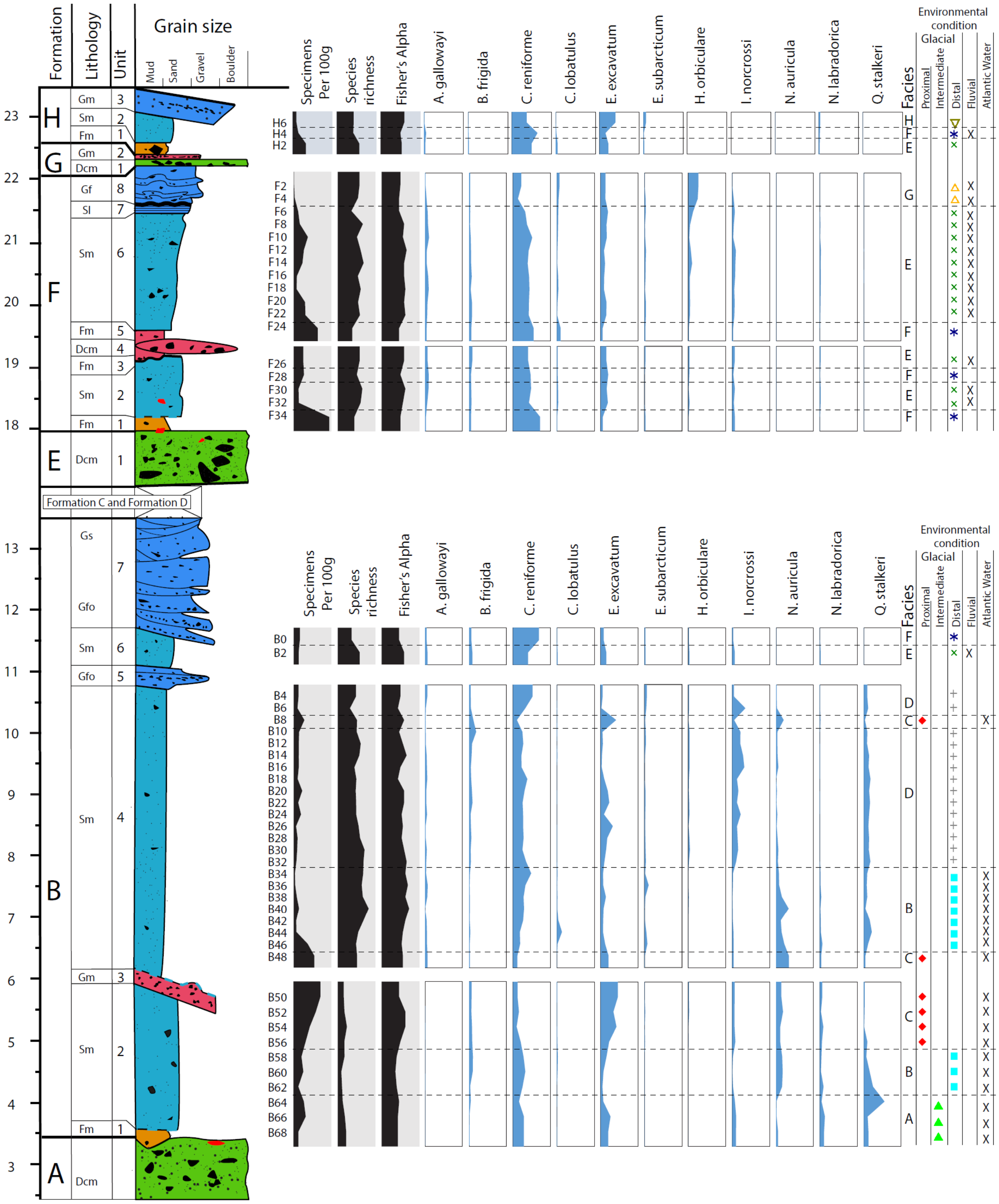

Figure 46: Foraminiferal stratigraphy showing distribution of key species

the other hand profits from algae-productivity at the sea-ice edge and proliferate in late spring.

Facies B

Ten samples (B62-B58 and B46-B34), all from the lower half of Formation B, detail this facies. None of the samples shows any significant variability following the results of the SIMPROF-analysis.

C. reniforme dominates the fauna (avg. 29 %) and generally occurs in much higher frequencies than *E. excavatum* (avg. 8 %). The two species *N. auricula* (avg. 16 %) and *Q. stalkeri* (avg. 13 %) also occurs in high frequencies. Minor species with low frequencies are *B. frigida, I. norcrossi, C. lobatulus, N. labradorica, E. subarcticum, A. gallowayi, E. albiumbilicatum and E. halladense.*

This facies has an average species richness of 23 with 9 species having a frequency above 2 %. Fisher's alpha indicate a faunal diversity of 3.6. Each sample has about 2663 specimens per 100 gram.

Interpretation

The dominance of *C. reniforme* suggest more stable hydrological conditions then what is the case for *E. excavatum* dominated faunas. The high frequency of *C. reniforme* to *E. excavatum* suggest a distal glacial influence, perhaps similar to that of today (Hald and Korsun, 1997). Sediment-laden melt-water still appear to have been present in area however as indicated by high frequencies of *Q. stalkeri*.

The most peculiar species for this facies is *N. auricula* which do not occur on Svalbard today. It is interpreted as an indicator for ameliorated conditions and may reflect a seasonal inflow of warm water masses and subsequently increased overall productivity.

.

Facies C

This facies is described from five samples in the lower half of Formation B (B56-B48), as well as a single sample from the upper half (B8). One sample (B48) show significant variability following results of the SIMPROF-test. The main difference appear to be a higher, but not dominant frequency of *A. gallowayi* and slightly lower frequencies of *B. frigida than the average.*

E. excavatum (Avg. 34 %) dominates. In high frequencies is also *N. auricula* (avg. 18 %) and *C.* reniforme (Avg. 13 %). Other frequent taxa are *B. frigida* (7 %), *I. norcrossi* (avg. 6 %), *N. labradorica* (avg. 5 %) and *Q. stalkeri* (avg. 4 %). *E. selseyense* is recoreded as a minor species.

On average each sample contain 24 species, in which 8 species occur with frequencies above 2 %. Faunal diversity as indicated by Fisher's alpha is 3.3 and there is 943 speciems recorded per 100 gram.

Interpretation

Dominance of *E. excavatum* is characteristic for glacial-proximal environments with highly variable hydrological conditions (e.g. salinity, sedimentation). *C. reniforme* is also frequent in glacimarine environments, but require more stable conditions (especially salinity) than *E. excavatum*. The higher ratio of *E. excavatum* may indicate a more proximal glacial influence than for example today (Hald and Korsun, 1997). This is also supported by high frequencies of *Q. stalkeri*, a species associated with glacial proximity and sediment laden-meltwater. On the other hand are the species *B. frigida, I. norcrossi, N. auricula* and *N. labradorica* that are all typical of environments distally influenced by glaciers. *N. labradorica* and *N. auricula* are both associated with warm-water-inflow, whereas I. *norcrossi* and *B. frigida* are related to seasonal sea-ice edge productivity.

Facies D

This cluster consists of 14 samples (B32 – B10 and B6 – B4) from the middle- to upper half of Formation *B.* All samples detailing this facies sshow non-significant variance according to results of the SIMPROF-test. Overall, this facies show a higher degree of similiarty to samples from Formation F and H, than with samples from Formation B.

C. reniforme (avg. 30 %) is followed by high frequencies of I. *norcrossi* (avg. 19 %). Frequent are the species *Q. stalkeri* (avg. 13 %), *E. excavatum* (avg. 11 %) and *B. frigida* (avg. 6 %) with A. *gallowayi*, *E. subarcticum*, *H. orbiculare* and *N. auricula* as minor species.

20 species on average occurs in each sample where nine species occurs in frequencies above 2 %. Faunal diversity has a fisher's alpha of 3.6. On average each sample contains 2532 specimens per 100 gram.

Interpretation

All species occurring in prominent frequencies are also commonly occurring species on Svalbard today (Hald and Korsun, 1997). *C.* reniforme, *E.* excavatum and *Q.* stalkeri are all considered species typical for glaciomarine environments. The dominance of *C. reniforme* over *E. excavatum* indicates a more distal glacial influence, perhaps more similar to today. Both species are stress tolerant, but high frequencies of *C.* reniforme usually require more stable hydrological conditions than those found in front of a glacier where sediment flux and melt-water often show high variability. *Q.* stalkeri on the other hand is considered more proximal than *C.* reniforme*.* High frequencies of this species is associated with sediment-laden meltwater plumes that inhibit algae productivity.

Glacial distal species are I. *norcrossi* and *B. frigida.* These are considered seasonal food indicators and are often associated with increased algae-productivity at the sea-ice edge. Overall, the fauna appears glaciomarine, but with a distal to intermediate influence. There's no indication of warm water inflow, rather, the water masses were probably stratified like today with a dominance of local water masses.

Facies E

Fourteen samples form this facies (B2; F34-F30; F26; F22-F6; H2) which describe large parts of Formation F, in addition to a single sample from Formation B and one sampe from Formation *H.* Results of the SIMPROF-test using square-root transformed data indicate only non-significant variability within the clusters.

Dominating the fauna is *C.* reniforme (avg. 42 %), followed by *E. excavatum* (avg. 15). The species A. *gallowayi* (avg. 7 %), *B. frigida* (avg 6 %), I. *norcrossi* (avg. 6 %) and *H. orbiculare* (avg. 5 %) are also frequent. Minor species include L. lobatulus and *E. subarcticum*.

On average, each sample contains 23 species where 9 occurs in frequencies above 2 %. Faunal diversity has a fisher's alpha score of 3,8 with 4998 species per 100 gram.

Interpretation

All of the prominent species are commonly occurring on Svalbard today. The high ratio of *C.* reniforme to *E. excavatum* suggest a distal glacial influence, somewhat similar to today. *B. frigida* and I. *norcrossi* are both food indicators associated with seasonal sea-ice edge productivity. A. *gallowayi* and *H. orbiculare* is associated with river-influenced environments with low sedimentation-rates due to their epifaunal mode of life. Overall the fauna appear similar to what could occur around Kapp Ekholm today with some distance to the glacier front(s). In addition, this facies appear more influenced by fluvial outflow than some other facies.

Facies *F*

Samples belonging to formations B (B0), F (F34, F28 and F24) Formation H (H4) constitute this facies. Only non-significant variability is indicated by the results of the SIMPROF-test. This cluster, together with Facies E detail most of Formation F and Formation H and show significantly less similarity with samples from Formation B.

C. reniforme (avg. 62 %) accounts for more than half of the fauna. *E. excavatum* (avg. 11 %) is usually second in frequency, but considerably less common. In lower frequencies are A. *gallowayi* (avg. 4 %), *B. frigida* (avg. 4 %) and I. *norcrossi* (avg 4 %), Minor species include *E.* albiumbilicatum, and L. lobatulus.

The facies have a species richness of 23 with 9 species on average having a frequency above 2 %. Faunal diversity scores 3,8 with average abundance of 3922 specimens per 100 gram.

Interpretation

A distal glacial influence is suggested by the dominance of *C.* reniforme and the high ratio of this species over *E. excavatum*. The high dominance of *C.* reniforme suggest that cold and relatively saline water dominate. A. gallowayi, *B.* frigida and I. norcrossi are all species related to seasonally high nutrient availability where the latter two are usually associated with sea-ice growth and decay. Again, this fauna could occur around Kapp Ekholm today. Compared to the fauna described for facies E, this facies seem to show less fluvial influence and with higher salinity, allowing *C.* reniforme to replace *H.* orbiculare.

Facies *G*

Two units from the uppermost part of Formation F (F2 and F4) detail this facies. Variability between these two sample is non-significant following results of the SIMPROF test. This cluster have the highest dissimiliarity to other clusters branching at a similiarity level of < 55.

The most frequent species in this fauna is H *orbiculare* (Avg. 26 %). Frequencies of *C.* reniforme (avg. 18) is slightly higher than frequencies of *E. excavatum* (avg. 13 %). L.

lobatulus (avg. 6 %) *E.* halladense (avg. 4 %) also occur frequently, but not in high numbers. *B. frigida* is considered a minor species.

The facies on average has 19 species out of which 6 occur in frequencies above 2 %. Fisher's alpha is 5,58 and the average number of foraminifera is 8656 specimens per 100 gram.

Interpretation

H. orbiculare is a species that thrive in river-influenced areas with brackish water and tends to avoid glacially influenced areas. This may explain the relatively low frequencies of *C.* reniforme and *E.* excavatum although their presence still suggest a glacial influence. The near equal ratios between these two may indicate an intermediate glacial influence. The presence of *C.* reniforme and absence of I. norcrossi may be explained by reduced salinity as indicated by *H.* orbiculare. Supporting a river-influenced marine environment is also the species L. lobatulus and *E.* halladense. Both are associated with strong currents. Together with *H.* orbiculare these species are all considered epifaunal species suggesting a low sedimentation-rate. Overall, this facies differ from other facies by having a marked fluvial influence. It is interesting to note that the fisher's alpha is relatively high for this fauna when compared to that of other facies. While this may suggest ameliorated conditions, there is no indication of warm-water inflow.

Facies H

This facies is described from a single sample only (H6) occurring at the top of Formation *H.* Overall, it shows a higher similarity to cold-water facies (Facies E and F) than those associated with warm-water inflow (Facies A, B an d C).

C. reniforme (avg. 37 %) and *E. excavatum* (avg. 40 %). *E. subarcticum* (avg. 7 %), *E.* albiumbilicatum (avg. 4 %), *N.* labradorica (avg. 3 %) are also frequent, but not in large numbers.

There are 23 species out of which 5 occurs in frequencies above 2 %. Faunal diversity scores 3,3 on fisher's alpha. The sample has 1869 specimens per 100 gram.

Interpretation

The near-equal ratio of *C.* reniforme and *E. excavatum* suggest a moderate glacial influence. Both species are stress tolerant and their combined dominance is indicative of relatively cold, but saline water. Frequent *E. subarcticum* may be an indication of seasonal sea ice cover and/or river-influenced areas, but its environment preferences appear somewhat diffuse.. This environment appear similar to today, but with less stable and lower bottom water salinity as indicated by an absence of I. norcrossi. In addition, *E.* albiumbilicatum and *N.* labradorica are both species associated with warm water inflow which may suggest that at least some circulation occurs between the Isfjorden system and Billefjorden.

5. DISCUSSION

5.1. Sedimentary stratigraphy

The sedimentary stratigraphy as described from Section II and Section III is overall in agreement with the stratigraphy presented by Mangerud and Svendsen (1992). In Section III all formations (A-H) occur in a stacked order, although Formation G was only sporadically observed.

In Section II it is still argued that formations C and D are missing or were never deposited. A new glacial diamicton (Member F-4) was described from Section II, but is interpreted as a re-deposition of either Formation C or Formation *E.* The same diamict is described and interpreted by Eccleshall (2013). In this thesis, the sequence of glaciomarine clay and glacial diamicton is interpreted as an ice-rafted deposit. It is now clear however, that these units are much wider in extent and that there is a contact between these units and similar units below. This interpretation is further supported by a similar foraminiferal fauna occurring below (Member F-2) and on top (Member F-6) of this sequence.

5.2. Absence of agglutinated forms

Agglutinated foraminiferal forms are almost completely absent in the fossil assemblages described. Hald and Korsun (1997) however, found several forms in Billefjorden with relatively high frequencies including:

- *Reophax* spp. *(6.1–8.7 %)*
- *Alveolophragmium crassimargo (4–16.6 %)*
- *Recurvoides turbinatus (6–9.7 %)*
- *Portatrochammina bipolaris* (0.3- 1.6 %)
- *Adercotryma glomerata* (0.9–1.1 %)

Wollenburg and Kuhnt (2000) argue that the number of agglutinated forms in a fossil-assemblage are likely to be underestimated in fossil assemblages. This is because they readily disintegrate post-mortem. The heavy liquid separation method which is applied here, is known for favoring the selection of intact, multi-chambered forms (Austin and Cage, 2010), while other forms, including agglutinated tests will usually sink into the “heavier fraction”. Neither of these explanations can readily be dismissed. On the other hand, some studies of living foraminifera show that agglutinated forms are strongly reduced or even absent in some environments. In both Adventfjorden and in Hornsund it has been found that the number of agglutinated forms are reduced or absent in areas with high water turbidity (Majewski and Zajaczkowski, 2007; Zajaczkowski et al., 2010). This may partially explain the results seen here, however, it seem unlikely that this is the case throughout.

5.3. Pyritization of foraminiferal tests

A striking number of the foraminiferal tests from the lower part of Formation B was black, or brass colored indicating that they are in-filled with pyrite. According to Sen Gupta (2002b) the environmental significance of pyritization is not fully understood, although it is clearly related to redox conditions and concentration of H_2S. Pyrite precipitation is most commonly confined to deep-water environments, euxinic shallow-water environments however, may also lead to formation of pyrite (Larsen and Chilingar, 1979). The same process is not observed in Formation F, nor in Formation *H.* This may indicate some difference in redox conditions of the different formations although it remain unclear what exactly causes this.

The gradual reduction of this phenomena up-section may be related to a gradual reduction of these conditions. More problematic however, is the aspect that it could indicate re-deposition of older foraminiferal tests. Re-deposition of older foraminiferal tests in coastal environments is not uncommon. As noted earlier however, most of the tests were of high quality which may also be used as an argument of the contrary.

5.4. Indications of Atlantic Water Masses

Inflow of Atlantic Water Masses into Arctic fjords is usually associated with increased productivity, higher biodiversity and immigration of extralimital species (Hald and Korsun, 1997). The most consistent indicator of warm water-inflow to Billefjorden is the high and consistent presence of *N. auricula* in the lower half of Formation *B.* Although little appear to be known about its environmental preference, it is a species associated with warm water inflow and high productivity environments. *N.* labradorica, which is very similar in appearance, is also associated with Atlantic-Water influenced environments, but has been shown to prefer colder water than *N. auricula (Saher et al., 2012)*.

Despite the strong occurrence of these two indicator species, there is little else to support any prominent warm water inflow. Facies (A-C) associated with these species do not show any characteristic increase in faunal diversity and/or species richness. A similar remark is also given about the mollusk fauna from Formation B by Mangerud et al. (1998, p.20):

> *"even though Mytilus edulis indicates that sea surface*
> *temperatures were warmer than at present, it is so far the only*
> *'extralimital' species recorded from the Eemian beds"*.

This may be an indication that some environmental stressor is still present, inhibiting immigration of other warm-water taxa. It is known from Svalbard fjords today, that inflow of Atlantic Water in many fjords is seasonal. The proliferation of *N.* labradorica has been shown to coincide with summer inflow of warm water masses(Haakon et al., 2002; Jernas, 2012). Just as important however, has been its ability to tolerate and survive unfavorable conditions during winter. A similar ability is also seen in M. *eduis* which is known for being able to also tolerate and survive periods of low temperature (Williams, 1970).

NAW is found along the western shelf of Spitsbergen today, but is normally restricted by hydrological barriers, in its inflow to the Isfjorden-system as discussed by Nilsen et al. (2008). Occasionally NAW manages to penetrate into Isfjorden and may even dominate the water column, except in Billefjorden, where hydrological communication is still physically restricted by its shallow-water-threshold. Following this, the mere presence of NAW in Isfjorden may not be enough to explain an inflow of such water masses to Billefjorden. Higher relative sea level may have had an important influence by diminishing the relative effect of the Billefjorden shoal on the water column. Another important, but unknown factor, is to which extent the Billefjorden bathymetry has been modified during the latest glaciation. There is clear evidence that Billefjorden during the LGM was filled by a large warm-based glacier that advanced beyond Gåsøyane and probably merged with a larger glacier system draining out Isfjorden (Baeten et al., 2010):

5.5. Chronological environmental history

5.5.1. Formation A - Glacial overriding

The first preserved Quaternary event in the Kapp Ekholm Sections is a glacier overriding the bedrock. The distance to both the present, and Little Ice Age position of Nordenskiöldbreen is about 20 km (Rachlewicz et al., 2007). It is therefore postulated that any glacier advancing beyond the Kapp Ekholm sections must represent a significant glacial advance compared to today.

The erosive lower boundary of Formation A implicates warm based ice. The bedrock is overlain by two glacial tills that in places are separated by glacially deformed marine shoreface material. This may be an indication that Formation A represents two glacial advances, and not just one, as proposed previously (Mangerud and Svendsen, 1992; Mangerud et al., 1998). On the other hand, while these advances may be separated by a longer duration of time, it is also possible that they represents smaller fluctuations within the same glacial period.

The maximum age of Formation A is not confidently constrained. The only attempt so far, has been through the use of Amino-Acid-dating and suggests that deposition of the glacial tills occured shortly before deposition of Formation B (Mangerud et al., 1998). It follows parsimoniously however that Formation A is associated with the Saalian-glaciation if the sediments following directly on top represent interglacial sediments of Eemian age (MIS 5e). This is also the conclusion of Mangerud and Svendsen (1992),Mangerud et al. (1998) and Eccleshall (2013). In a review paper by Svendsen et al. (2004) it is argued that a huge ice-sheet complex formed over Northern Eurasia (Svalbard included) during the Late Saalian (160-130 ka). Also Boulton (1979) concludes that the lowermost formation is a glacial diamict, but argue that shells incorporated into the tills are of Eemian-age on the basis of Amino-Acid-racemization. Amino Acid dating was a popular method in the 70 and 80s (before the advance of Luminescense dating), but is today generally recognized as being notoriously unreliable when it comes to numerical dating (Miller et al., 2013). Especially in the Arctic, the rate of racemization is variable and may cease almost completely in very low temperatures. This was also pointed out by Mangerud and Svendsen (1992) and Mangerud et al. (1998). Forman (1999) who also dated the sections argued that Formation B was much older, concluding on an age of 185±13 ka. This necessitates that Formation A is older (E.g. MIS 8). While it is beyond the scope of this project to discuss technicalities of dating methods, it should be noted that the uncertainty-range of Steve Forman’s paper is wide and do not exclude an Eemian age beyond the uncertainty expressed by the author.

5.5.2. Formation B – High relative sea level, seasonal inflow of Atlantic Water

The lowermost unit (Member B-1) in Formation B is interpreted as a glaciomarine deposit. This is in agreement with Mangerud and Svendsen (1992) who interpret the same unit as marine. Boulton (1979), who do not describe any observations of marine remains, inferred this unit to be a second glacial diamicton occurring on top of Formation A. This interpretation is confidently rejected based on the relatively high and well-preserved foraminiferal content and mollusks of this unit.

There is no indication of a terrestrial phase, or hiatus, between Formation A and *B.* Deglaciation is therefore assumed to having occurred during high relative sea level. The Saalian ice-sheet over Northern Europe was probably far bigger and more long-lasting than during the Late Glacial Maximum (Svendsen et al., 2004; Colleoni et al., 2011). Following this, the glacial isoatic depression from the Saalian Ice-sheet must have been immense and possible of greater amplitude than that of the LGM.

Iceberg-scours at the base of Formation B suggest that at least one glacier had a marine front within the fjord during deposition of the lowermost unit. The red coloring of the sediments is associated to erosion of red-colored Devonian, or Early Carboniferous strata. Post-depositional oxidation could also lead to a red-brown discoloring, but this seems unlikely. Today, the sediment-plume associated with drainage in Petuniabukta show a distinct red-stained coloring of the water-surface, whereas meltwater in front of the Nordenskiöld glacier have a yellow-brown coloring (Szczuciński and Zajączkowski, 2012). Following this, it is reasonable to conclude that sedimentation was influenced more by sediment discharge from Petuniabukta and/or western coast of Billefjorden. At present the melt-water plume in Petuniabukta do not extend more than a few hundred meters. This is because of the shallow tidal flat that enhances water-mixing and consequently flocculation close to the coast. In front of the Nordenskiöld glacier, the melt-water plume may extend several kilometers away from the glacier front before mixing and subsequently settling. According to Szczuciński and Zajączkowski (2012) this represent the present dominate mode of deposition in the middle- parts of Billefjorden, with sedimentation rates decreasing significantly with distance to the glacier and the coast. The abrupt change (also repeated in Formation

D, F and H) may indicate that glaciers on the eastern side of Billefjorden retreated more quickly on land than on the western side of the fjord.

The grain size is overall coarsening upward in Formation *B.* This trend is consistent with observation from the most recent deglaciation. Maximum relative sea level is attained shortly after deglaciation and then gradually falls due to post-glacial isotactic rebound (Forman, 1999). Local progradation may in some cases interrupt this trend, which is the case for unit B-2, interpreted as a distal fluvio-marine facies building out from the side of the fjord. Laterally however, there is a direct succession between the glaciomarine (Member B-1) and marine (Member B-4) environment. Maximum regression is recorded and preserved by littoral-, to supralittoral sediments on top.

The foraminiferal fauna in formation B largely consists of species common in fjords around Svalbard today (Hald and Korsun, 1997). *C.* reniforme together with *E. excavatum* indicates a glacially influenced fjord. The ratio between these two have been is as an indicator of glacial influence (E.g. sedimentation, salinity and temperature) and suggest a moderate to more proximal influence. More important however is the relatively high and consistent frequency of *N. auricula* (Facies B and C) and *N.* labradorica (Facies A) in the lower half of Formation *B. N.* auricula do not occur on Svalbard today. Together with *N.* labradorica it is interpreted to indicate inflow of Atlantic Water as they require relatively warm and nutrient-rich water masses to proliferate.

In the upper half of Formation B, *N.* labradorica and *N. auricula* both disappear and indicate that NAW inflow from Isfjorden was terminated. Facies D is associated with environment conditions very similar to today where the inhibited circulation causes the ocean water to stratify and provide favorable conditions for seasonal sea-ice growth as indicated by I. *norcrossi*.

Previously published marine evidence shows that deglaciation of the Saalian Ice-sheet (also known as Termination II) occurred in a stepwise manner, following periods of enhanced Atlantic meridional overturning circulation (AMOC) (Risebrobakken et al., 2006; Chauhan et al., 2014). These periods were followed by melt-water events linked to enhanced melting of the ice-sheet, with subsequent weakening of AMO*C.* Risebrobakken et al. (2006) shows evidence for a persistent increased influence of Atlantic Water masses along the eastern Nordic Seas towards the north, at 135-34 ka and at 130.5 to 126 ka, just above the MIS 6/5e boundary. (Hald and Korsun, 1997; Nilsen et al., 2008). It is assumed that similar bathymetrical conditions existed during deposition of Formation B and during subsequent marine-intervals. However, as shown by Baeten et al. (2010), there is bathymetrical evidence of warm and erosive glacier-movement during LGM that may have altered the fjord-profile.

5.5.3. Formation C – Glacial overriding

A glacier overrides Kapp Ekholm. The age of the formation is bracketed by the age of the subjacent Formation B, and the overlying age for Formation D which points at an early stadial within the Weichselian glaciation. As for any glacier reacing the Kapp Ekholm site it indicates a significant regional advance.

5.5.4. Formation D – High relative sea level, local water masses like today

Lithologically Formation D is similar to Formation *B.* It is interpreted as a regressional trend where the environmental change from glaciomarine, to sub-littoral and littoral deposition is documented. High relatively sea level is again interpreted as the result of glacio-isostatic depression. The most noticeable change between Formation D and Formation B is that the units are thinner, and overall the sand is coarser. It is possible that Formation D represents a more coast-proximal deposition than Formation B and/or that deposition occurred during shorter time-intervals than for the latter. The more sandy lithology of Formation D also provides an argument that Formation D is not just a glaciotectonically upthrusted floe of Formation B as discussed by Mangerud and Svendsen (1992).

Formation D has been dated using OSL, TL and SARA from Section VI suggesting an average inferred age of c. 100 ka (Mangerud et al., 1998). Forman (1999) also attempted to date the formation using IRSL and RSL, but failed to render statistically reliable estimates. He pointed out that either the sediments were close to saturation of the luminescense signal, in which case they would be older than c. 150 ka, or contained a large amount of inherited luminescene. Eccleshall (2013) also report ages for Formation D, but appear to have confused the nomenclature, as her samples were taken from Formation F in Section II (Mangerud and Svendsen, 1992).

The foraminiferal fauna was not identified for Formation D. According to (Mangerud et al., 1998) the diversity of mollusk-taxa is low indicating restricted circulation within the fjord which is similar to the situation today.

5.5.5. Formation E – glacial overriding

Glaciers again advances through Billefjorden and overrides Kapp Ekholm. In Section III the two diamicts from Formation E and C merge. The geometry of the units is here consistent with the notion that Formation D in section II is replaced by a hiatus at the lower boundary of Formation *E.*

Again, the age of the formation is bracketed only by the maximum age of the subjacent formation, and the minimum age of the superimposed formation indicating a stadial within the Weichselian.

5.5.6. Formation F – High relative sea level, local water masses

The third regression cycle was termed the Kapp Ekholm interstadial by Mangerud and Svendsen (1992). . Formation F is thicker in total however than Formation D and possibly reflect a longer depositional time-window. The lowermost unit of Formation F is interpreted to reflect dominantly a glaciomarine deposition under similar conditions as for Formation B and D. The regressional trend is in section II interrupted by a slump event causing a local re-deposition of Formation E and Member F-1. This interpretation is also supported by the foraminiferal fauna that is largely similar both on top and beneath (Facies E and Facies F describing most of the sub-littoral sequence of Formation F). The slump is also bracketed by luminescence ages produced by

{Eccleshall, in prep. #572@@author-year} which indicates only short time interval occurring in-between (See also the composite log, Figure 18)

The foraminiferal fauna of Formation F reflects overall a glacially influenced fjord like today with seasonally ice-free conditions. The water column appears stratified with cold and saline water at the bottom. There is no indication of warm water being present in the fjord and water-exchange between Isfjorden and Billefjorden was most likely restricted. This is in contrast to Mangerud et al. (1998) who concluded that the mollusk fauna in Fomration F indicates a more open circulation with Isfjorden. Variations in fauna up-section appear to reflect dominantly change in fluvial influence (e.g. frequencies of species such as *H. orbiculare, A. gallowayi and E. subarcticum).*

The age and subsequently the correlation of Formation F to the marine isotope record is disputed. Mangerud and Svendsen (1992) argued for an age of between 40 to 50 ka using radiocarbon-dating and luminescence-dating-methods. Some additional samples were obtained using luminescence by Mangerud et al. (1998) who argued for a somewhat higher age-interval of 40 and 60 ka. Ages of between 60-80 ka have later been concluded by Forman (1999), Eccleshall (2013) and Eccleshall et al. (in prep.).

5.5.7. Formation G – glacial overriding

The uppermost glacial till in the sediment-sections is only sporadically preserved along the sections. While occurring only sporadically here, it is known to occur as much thicker diamicton in section further north (Mangerud and Svendsen, 1992). Its age is bracketed by the minimum and maximum ages of the marine sediments on top and below. Overall it is associated with the period around the Late Glacial Maximum where the Barents-Sea ice-sheet is believed to have extended all the way to the western shelf of Spitsbergen (Ingolfsson and Landvik, 2013).

5.5.8. Formation H – high relative sea level, local water masses

The last regression-sequence is very thin in Section II compared to exposures further north. Again it progresses from a glacimarine environment, to sublittoral and finally littoral sedimentation.

Formation H has been dated using both radiocarbon and luminescense-dating-methods. A minimum age for the ultimate deglaciation is provided by radiocarbon ages, suggesting it occurred somewhere shortly before 11.2 cal ka BP (Mangerud and Svendsen, 1992; Mangerud et al., 1998).

The foraminiferal fauna from the sample investigated in Formation H indicates a hydrological environment very similar to today with distal to intermediate glacial influence. The low diversity fauna and the near absence of warm-water indicator species (except very low frequencies of *N.* labradorica) suggest that there was no inflow of NAW to Billefjorden and/or that circulation with Isfjorden was limited. According to Mangerud and Svendsen (1992) the mollusk-fauna in Formation H is more diverse and several warm-water mollusk-taxa (i.e. *Arctica islandica* and *M. edulis*, *Zirphea crispata*). This is not consistent with the interpretation of the foraminiferal fauna as indicating a relatively cold environment. One possible explanation is that Formation H in section II represents only a short period at the onset of the Holocene. It is apparent that the sub-littoral sediments in Formation H are not younger than c. 7-8000 years from the radiocarbon ages (Mangerud and Svendsen, 1992) in addition to the elevation of the sediments compared to the Holocene sea level curve (Forman et al., 2004) The onset of the Holocene Climatic Optimum is on Svalbard delimited between 8-5000 years (Hjort et al., 1995). It might be that in Section II this warmer period is not preserved, as opposed to in the much thicker sediment sections IV and V upfjord.

5.6. Correlation to other key sites

Miller et al. (1989) have described the foraminiferal fauna for the Leinstranda/Site 15 sections on Western Spitsbergen. His foraminiferal Zone F15 V may be correlated on the basis of numerical-dating to Formation B assuming an Eemian age (Alexanderson et al., 2010; Ingólfsson and Landvik, 2013). Compared to the other foraminiferal zones this fauna is described as having a high diversity of species, with several unique boreal taxa. Miller argued that this reflected a period of more vigorous NAW-influx than at present. In addition, the author also concludes that NAW was present at deglaciation, something also observed in Formation *B.* Increased influx of NAW was also concluded by Bergsten et al. (1998) for the lower part of unit A at Poolepynten on Prins Karls Forland. This unit was later subdivided into A1 and A2, in which A2 was correlated to the Eemian-interglacial (Alexanderson et al., 2013). It wa Es also noted that the fauna during the early Holocene and also from recent samples was less meliorate than the Eemian-fauna.

Foraminifera Zone F15 II and I at Leinstranda have been correlated to Formation F by Mangerud et al. (1998) and Ingólfsson and Landvik (2013). According to Miller et al. (1989) the foraminiferal fauna show some influence of NAW, but is overall similar to today. A similar conclusion was also made by Lycke et al. (1992) who failed to find any evidence for marked increase in NAW-influx during Weichselian interstadials at the Linnéelva sections.

6. SUMMARY AND CONCLUSION

The sedimentary stratigraphy from section II and III of the Kapp Ekholm have been re-investigated. In summary four diamicton sequences (Formation A, C, E and F) have been identified and suggest periods where glaciers were significantly larger than today. These advances are associated with a pre-Eemian advance (most likely Saalian) and three stadial-advances during the last glacial period (Weichselian). The latest glacial advance is associated with the LGM advance although in section II and Section III it is only represented by a thin, discontinuous diamicton.

Glacial periods are followed by periods of high relative sea level and marine sedimentation above present sea level. The marine sequences are overall regressive explained by falling sea-level and/or coastal progradation. The regressive pattern of the stratigraphy is in places interrupted by local slope-processes (including gravity flows and slumping) and also fluvial-progradation and spit-development. These are also contemporary processes that can be observed in the area today. Overall the sedimentary investigations confirm the original descriptions and interpretations by Mangerud and Svendsen (1992) of four preserved glacial-deglaciation cycles. The most conspicuous finding was a new clast-rich diamicton in Section II within sediments described as Formation F. The sediments, which is most likely glacial in origin, could provide a candidate for the “missing” glacial-deglacial cycle in section II. However, sedimentary observations suggest that this is a re-deposition of the glacial diamicton occurring below. This is supported by the foraminiferal fauna that do not change significantly in addition to age constrains leaving little room for another stadial advance in-between.

The foraminiferal fauna from Formation B, Formation F and Formation H have been described and interpreted. Most of the species identified also occur in Billefjorden today and the fauna is generally of low diversity with 2 or 3 species dominating. This is consistent with a fjord that is overall dominated by cold, and often sediment-laden, glacial melt-water. An inhibited exchange of water-masses with Isfjorden results in a restricted circulation within the fjord and the hydrology is characterized by stratified water masses.

The most notable exception to this is the lower half of Formation B which have high and consistent frequencies of the warm-water indicators *N. auricula* and *N.* labradorica. Their environmental preferences suggest that there was a significant exchange of Atlantic Water masses to Billefjorden. This inflow however, is not associated with any notable increase in diversity or other warm-water species and may suggest that inflow was seasonal. *N. auricula* and *N.* labradorica more or less disappear in the upper half of Formation B and is replaced by high frequencies of I. *norcrossi*. This species also occur in Billefjorden today and is associated with high and stable bottom-water salinity and is an indication that warm-water exchange between Isfjorden and Billefjorden has shut down. Also in Formation F and in Formation H there is no indication of increased Atlantic-Water exchange throughout.It is suggested here that Formation B, based on changes in the foraminiferal fauna, may be correlated to the early Eemian transission. A period characterized by increased flow of warm water to the arctic regions due to enhanced AMOC.

The Kapp Ekholm sections remain an important brick in the puzzle to resolve forcing factors on the disintegration of marine based ice sheets. The presence of NAW in the innermost fjord of Billefjorden was demonstrated with an integrated study of sediment and foraminifera environmental change during the deglaciation of the penultimate glaciation in the very early stage of the Eemian interglacial.

7. APPENDIX

The following files are available on a compact disc (CD) attached to the paper version of this thesis. It contains the following files:

1. **Raw_count.xls**

Raw specimen count of foraminifera for each sample

2. **Species_list.xls**

List of genus and species of foraminifera identified

3. **Similarity_index_untrans.xls**

Bray-curtis similarity index for untransformed data

4. **Similarity_index_2root.xls**

Bray-curtis similarity index for square-root transformed data

5. **Similarity_index_4root.xls**

Bray-curtis similarity index for fourth-root transformed data

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