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Early and Mid-Holocene environments in Isfjorden, Svalbard - what does the foraminifera and molluscs tell?

Master's thesis in Geography

Supervisor: Chantel Nixon

Co-supervisor: Mark Furze

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Abstract

This thesis aims to investigate foraminifera and molluscs from early- and mid-Holocene in Svalbard and their paleoenvironmental implications. Raised marine sediments have been sampled for foraminifera and mollusc bivalves from four different field sites around Isfjorden, western Spitsbergen, in fall 2020. Earlier observations of thermophilous molluscs extinct in Svalbard today is seen as an indicator of significant warmth in early phases of the Holocene, known as the Holocene Thermal Maximum (HTM). Knowledge about the last phase with warmer-than-present conditions is crucial to evaluate effects of human-induced warming and environmental change.

A target number of 300 foraminifera specimens were identified in 12 samples from Bogebecken and five from Erdmannflya. At two sites, Hiorthhamn and Bolterdalen, no foraminifera were seen in the samples. A total of 21 individuals of the mollusc bivalve *Arctica islandica* have been radiocarbon dated, 15 from Bogebecken and six from Erdmannflya. The radiocarbon dates from both sites reveal younger dates than previously reported *A. islandica* from Svalbard and indicate warm conditions and inflow of Atlantic water at least until ~8.5 ka BP. Further interpretations from the yet scarce dataset remain speculations, but a potential hiatus of *A. islandica* 8.5 ka BP – 7.9 ka BP may be linked with the 8.2 ka – event and reduced ocean heat transport to Svalbard. Only calcareous benthic foraminifera species were observed, with a relatively low species diversity. Foraminifera assemblages on both sites are strongly dominated by *Lobatula lobatula*, which indicates a high-energy regime, strong currents and/or coarse sediments. *Criboelphidium excavatum* and *Cassidulina reniforme* also occur >10% relative abundance in one or more samples. Lack of distinct stratigraphy limits the paleoenvironmental interpretations from Bogebecken. More studies of foraminifera from raised marine sediments in Svalbard and the use of e.g. $\delta^{18}\text{O}$ -analysis may increase the comparability and quantitative paleoenvironmental interpretations. The known spatial and temporal distribution of thermophilous molluscs is still limited and calls for further investigations of the mollusc fauna. The occurrence of *A. islandica* confirms Arctic amplification of warming, while also confirming earlier studies indicating that different pattern of warming makes HTM a bad analogue for the current and future Arctic warming.

Sammendrag

Denne oppgaven tar for seg foraminiferer (poredyr) og muslinger fra tidlig Holocen (11 700 – 8200 år før nåtid) og mid-Holocen (8200-4200 år før nåtid) i Svalbard, og hva disse kan fortelle om klima og miljø i den perioden. Sedimentprøver og muslingskjell har blitt samlet inn på fire ulike lokasjoner rundt Isfjorden, vestlige Spitsbergen, høsten 2020. Tidligere observasjoner av termofile (varmeelskende) muslinger som ikke lever på Svalbard i dag har blitt sett som en indikator på et betydelig varmere klima på Svalbard i denne perioden, kjent som «Holocene Thermal Maximum» (HTM). Kunnskap om tidligere faser med klimatiske forhold varmere enn de nåværende er viktig for å evaluere konsekvensene av menneskeskapte klimaendringer.

Et antall på 300 individer av foraminiferer per prøve ble forsøkt registrert i 12 prøver fra Bogebecken og fem fra Erdmannflya. I prøvene fra Hiorthhamn og Bolterdalen ble ingen foraminifera observert. Totalt 21 skjell av *Arctica islandica* (kuskjell) har blitt radiokarbondatert, hvorav 15 fra Bogebecken og seks fra Erdmannflya.

Radiokarbondateringene viser at skjellene fra begge prøvesteder er betydelig yngre enn tidligere daterte *A. islandica* fra Svalbard, og kan indikere varme forhold med innstrømming av varmt atlantisk vann i hvert fall frem til ca. 8500 år før nåtid. Grunnet et begrenset datasett av skjell er ytterligere tolkninger for det meste spekulasjoner – men et mulig fravær av *A. islandica* frem til 7900 år før nåtid kan potensielt tolkes som en respons på den såkalte «8.2 ka BP-hendelsen» med redusert varmetransport til Svalbard. Kun kalkdannende, bentiske (bunnlevende) foraminiferarter ble observert i prøvene, og et relativt lavt antall arter. Den dominerende arten i både Bogebecken og på Erdmannflya er *Lobatula lobatula*, en art som kan indikere et energirikt miljø, betydelige strømminger og/eller grove sedimenter.

Criboelphidium excavatum og *Cassidulina reniforme* opptrer også med en andel over 10 % i én eller flere prøver. Fravær av distinkt stratigrafi begrenser de miljømessige tolkningene fra Bogebecken. Flere studier av foraminiferer i hevede marine sedimenter på Svalbard og bruk av f.eks. stabile oksygen isotoper ($\delta^{18}\text{O}$) – analyser er anbefalt. Den nåværende kunnskapen om utbredelsen til termofile muslinger er begrenset og vitner om behovet for flere undersøkelser. *A. islandica* bekrefter polar amplifikasjon i Holocen, men bekrefter også at ulike mønstre i temperaturendring gjør HTM til en mindre god sammenligning for den menneskeskapte pågående og fremtidige globale oppvarmingen.

Preface

At one time in my childhood, I dreamt about digging for dinosaurs, being a palaeontologist. Maybe it was the remaining crumb of that childish thought that were set on fire when I now, 15-20 years later, was offered to dig for microfossils in the high Arctic, because saying no was harder than the frozen ground in Bolterdalen. It may have been foolish for a broad-oriented geography student with more credits on human migration and landscape identity than sediments and glaciers to enter the Arctic world of hardcore geologists and biologists, suddenly referring to myself as a micropaleontologist (I still don't do so without an utterly ironic tone. I was and still am no more than a geographer, which in my view surely is the highest title among them all). Forgive my stupidity, but maybe the fact that I hadn't even heard the word foraminifera until a few weeks before the fieldwork was a trigger in itself to me. Thankfully, despite being a seemingly narrow and literally microscopic topic this thesis touches several branches of nature science, thus somehow offering the same kind of variety and broadness as I find appealing within geography.

In case this thesis now sounds like the poop of your dog or an outcome of a creativity lesson in kindergarten, it may calm you down to know that there have been adults in the room as well, guiding me through the scientific jungle (or in this case, the scientific polar desert). These people deserve a great thanks.

I would like to thank my supervisor Chantel Nixon (NTNU) and my co-supervisor Mark Furze (UNIS) for all your help throughout the year and for offering this topic when Covid put a sudden end to my original thesis plans. Your planning, enthusiasm and scientific guidance has been essential for me right from the beginning. And Chantel, although you won't admit it and insist that your workload is not too heavy, I bet you've worked overtime to guide me in the final phase. That is maybe more than I deserve. Thanks a lot!

A great thanks also goes to Katrine Husum and Anna Pienkowski, who taught me about foraminifera and assisted me through weeks of identification and microscope work at UNIS. I would also like to thank Vendela Hergot and Magnus Brenden, who looked out for polar bears and overfed reindeers in the field while I had my nose sniffing some dipping sandy-silty sediment layers or whatever. You risked your life in the name of science. Simply outstanding.

Last, but not least, a final thanks to all great peeps at NTNU and UNIS who got my spirit going through the long and dark winter in Longyearbyen and Trondheim. Thank you all!

Table of contents

Figures.....	VIII
Tables.....	IX
1. Introduction and thesis aim.....	1
2. Background and theory.....	5
2.1 Svalbard.....	5
2.1.1. Isfjorden.....	7
2.1.2. Deglaciation.....	7
2.1.3 Postglacial sea-level change.....	9
2.2 Thermophilous molluscs.....	11
2.2.1. <i>Zirfaea crispata</i>	12
2.2.2. <i>Arctica islandica</i>	13
2.2.3. <i>Modiolus modiolus</i>	13
2.2.4. <i>Mytilus</i> spp.	13
2.3 Holocene climate in Svalbard.....	16
2.3.1 Warm early Holocene.....	16
2.3.2 Cooling towards ~8 ka cal. BP.....	18
2.3.3 The 8.2 ka cal. BP cold event.....	18
2.3.4 Short warming phase ~8 ka cal. BP.....	20
2.4 Isfjorden and the shallow water environment.....	20
2.5 Projected future climate.....	23
2.6 Field Areas.....	24
2.6.1 Hiorthhamn.....	24
2.6.2 Bogebecken.....	25
2.6.3 Erdmannflya.....	26
2.6.4 Bolterdalen.....	26
2.7 Foraminifera.....	27
2.7.1 Ecology and characteristics.....	27
2.7.2 Classification of foraminifera.....	28
2.7.3 Preservation and taphonomic processes.....	28

2.7.4	Foraminifera as a paleoenvironmental tool.....	31
2.7.5	Key species in Svalbard fjords.....	32
3.	Methods.....	34
3.1	Fieldwork.....	34
3.1.1.	Hiorthhamn (78.245°N, 15.72°E).....	35
3.1.2	Erdmannflya (78.314°N, 14.15°E).....	37
3.1.3	Bogebekken (78.10°N, 14.40°E).....	38
3.1.4	Bolterdalen (78.175°N, 15.945°E).....	39
3.2	Processing of the samples.....	39
3.2.1	Wet sieving.....	40
3.2.2	Drying and dry sieving.....	41
3.2.3	Fraction size and counting of foraminifera.....	41
3.3	Radiocarbon dating and calibration.....	43
3.4.1	Dated material.....	46
3.5	SEM photography of specimens.....	47
4.	Results.....	47
4.1	Sampling sites – sediments, stratigraphy and shells.....	47
4.2.1	Hiorthhamn.....	47
4.2.2	Bogebekken.....	47
4.2.3	Erdmannflya.....	51
4.2.4	Bolterdalen.....	51
4.3	Radiocarbon dates.....	52
4.3.1	Bogebekken.....	54
4.3.2	Erdmannflya.....	54
4.4	Foraminifera.....	55
4.3.1.	Hiorthhamn.....	55
4.3.2.	Bogebekken.....	55
4.3.3.	Erdmannflya.....	55
4.3.4.	Bolterdalen.....	56
5	Discussion.....	56
5.1	Bogebekken.....	56
5.1.2.	Foraminifera.....	60
5.2	Erdmannflya.....	62

5.2.2. Foraminifera.....	65
5.3 General discussion for Bogebeekken and Erdmannflya.....	66
5.4 Bolterdalen and Hiorthhamn – no foraminifera observed.....	67
5.5 Relevance for future climate change.....	68
5.6 Limitations.....	68
5.6.1. Limitations in method.....	68
5.6.1.1. Number of samples.....	68
5.6.1.2. Processing of samples.....	69
5.6.1.3. Identification of specimens.....	69
5.6.2. Interpretation of the results.....	70
5.6.3. Future work.....	71
6 Summary and conclusions.....	72
Reference list.....	75
Appendix.....	89
1. List over observed species.....	89
2. Foraminifera data tables.....	91
3. Foraminifera statistics.....	98
4. SEM-photos.....	105

List of figures

Figure 1. Map of Svalbard with input-map showing the locations for field work and sampling around Isfjorden in fall 2020.	4
Figure 2. General ocean circulation pattern in the north Atlantic, from Mangerud et al., 2006.....	6
Figure 3. Sea currents around the head of Isfjorden, from Fraser et al., 2018.	6
Figure 4. Terrain map of Svalbard with places referred to in the thesis: Hakluytvatnet, Hajeren, Dicksonfjorden, Linnédalen, Van Mijenfjorden and Hornsund. Map from toposvalbard.npolar.no.....	9
Figure 5. Sea-level curves from Svalbard. Figure from Forman et al., 2004, modified from Forman, 1990a.....	11
Figure 6. Distribution of subfossil and living <i>Mytilus</i> spp. in the the north Atlantic and Arctic. Figures from Leopold et al., 2019, with subfossil findings based on Salvigsen (2002) and Mangerud and Svendsen (2018), recent livings are based on observations 2004–2016 (Leopold et al., 2019).	14
Figure 7. Number of samples per 100 years of dated thermophilous molluscs from Svalbard through the Holocene. Figure from Mangerud and Svendsen (2018), which merged all published radiocarbon dates of these four species.....	15
Figure 8. Mean august sea-surface temperature for the period 1900-2012, with the present-day northern/eastern distribution limits for the thermophilous mollusks mentioned in this thesis. Figure from Mangerud and Svendsen, 2018, modified from Korablev et al., 2014.....	15
Figure 9. Combined figure from Mangerud & Svendsen (2018): Different temperature curves from Svalbard in the Holocene.....	22
Figure 10. Projected mean annual temperature changes from 1961–90 to 2071–2100 (°C). Figure from Førland et al., 2011.....	24
Figure 11-13. Hiorthhamn, pictures of sampling section.....	36-37
Figure 14-15. Erdmannflya, pictures of sampling and sampling location.....	38

Figure 16. Bogebecken, picture of sampling section.....	39
Figure 17. Bolterdalen, picture of sampling section.....	40
Figure 18. ΔR values for molluscs and whale populations in the north Atlantic. Figure from Mangerud et al., 2006.....	45
Figure 19. Examples of <i>A. islandica</i> sent for radiocarbon dating.....	48-49
Figure 20. Sediment log Bogebecken.....	50
Figure 21. Frost-sorted ground near sampling site at Erdmannflya.....	51
Figure 22. <i>A. islandica</i> from Svalbard in the Holocene, with recalibrations of Sharin et al., 2014 and Beierlein et al., 2015.....	54
Figure 23. Recalibration of the <i>A. islandica</i> from Sharin et al. (2014) and Beierlein et al. (2015).....	55
Figure 24. Sea-level curve for Erdmannflya/Bohemanflya, from Salvigsen et al., 1990. This curve is also to be seen in figure 5.....	65

List of tables:

Table 1. Overview over water masses mentioned in this thesis and its characteristics. Table modified from Fraser et al., 2018.....	5
Table 2. Samples sent to LARA in Bern, Switzerland for radiocarbon dating.....	52
Table 3. Radiocarbon dates from Bogebecken and Erdmannflya. BB means Bogebecken and EmF means Erdmannflya. All samples are <i>A. islandica</i> . Colors are an indication of elevation; samples with the same color were collected at the same elevation.....	53

1. Introduction and thesis aim

When having a look on a broad timescale, the earth's climate and environment are far from stable. Today, much attention is drawn towards anthropogenic forced change of the earth's environment, which is happening with a complexity, magnitude and rate of change which already has a dramatic impact on the environment as we have known it (IPCC, 2018). Since pre-industrial time (mid-18th century), the global average temperature has already rose more than 1°C. International agreements (e.g. The Paris Agreement) aims to keep the increase in global average temperature below two degrees, optimally below one and a half.

Arctic regions are in no sense excluded from this warming. Actually, the warming that is both observed and predicted for high latitudes are larger than elsewhere on the globe due to the “arctic amplification”, feedback effects such as albedo-change due to less ice- and snow cover causing polar regions to warm more than the global average (e.g. Folland et al., 2001; Holland and Bitz, 2003). Likely, surface air temperature has over the last two decades increased more than the double of the global average (IPCC, 2018). Similar patterns with amplified warming have occurred in high latitudes before, and knowledge about these warmer-than present phases can be valuable to understand and predict future climate change.

Around 11 700 years ago (from now on written 11.7 ka BP), the last ice age came to an end, when the cold period of Younger Dryas was followed by significantly warmer climates, marking the end of Pleistocene and beginning of Holocene. The peak of this warmer period is what's known as the Holocene Thermal Maximum (HTM). On a general basis, the ice caps covering sea- and landmasses retreated, the temperature rose on land and in the oceans, but the distribution, timing and magnitude of this warming was not uniform.

In the Arctic Archipelago of Svalbard, located between mainland Norway and the North Pole at 76-80 degrees north, observations of thermophilous mollusks extinct in the islands today found in sediments from the early Holocene give indications on warm conditions in this period. From the first observations in the early 1900's, through the observations of Feyling-Hanssen (Feyling-Hanssen & Jørstad, 1950; Feyling-Hanssen, 1955), the findings of species as *Mytilus* spp (Linnaeus, 1758), *Arctica islandica* (Linnaeus, 1767), *Zirfaea crispata* (Linnaeus, 1758) and *Modiolus modiolus* (Linnaeus, 1758) (names given according to the World Register of Marine Species (2020)) in deposits from the early Holocene indicates that this period at its warmest was several degrees warmer than the pre-industrial late Holocene.

The Holocene Therman Maximum (HTM) has through various studies been reconstructed spatially and chronologically in the Arctic. HTM is likely to have occurred at different times between 11000 and 5000 years B.P., with substantially variations between regions both in timing and magnitude (Renssen et al., 2009; Kaplan et al., 2006). While a major cause of the HTM is believed to be increased summer insolation associated with the earth's orbit, other feedback effects such as albedo and sea currents are likely to have contributed to regional variations. The assumed drivers for this exceptionally warming in the archipelago of Svalbard were likely increased insolation and inflow of "warm" atlantic water (Mangerud and Svendsen, 2018). When *Z. Crispata*, the most warmth-demanding bivalve of this four is found 10.2 -9.2 cal. ka BP, the august sea surface and shallow water temperature is believed to have been 6 °C warmer the 1900-2012 average (Mangerud and Svendsen, 2018).

Despite the mollusc's contribution to the understanding of paleoclimate in Svalbard, less attention has been drawn on other parts of the biota, and for this thesis in particular: on the foraminifera. These single-celled protists have been widely used for paleoenvironmental purposes for decades, still, foraminifera in Svalbard from the early Holocene is not well described, and so are their paleoenvironmental implications. Foraminifera are for good reasons a popular tool for paleoenvironmental analysis worldwide and might serve additional understanding of the early Holocene climate in Svalbard and its drivers. Today, as we face human-induced climate warming, knowing the environment of past warm periods and the environmental responses are utterly important to project and understand future climatic and environmental changes, and the effects this will have on both protists such as foraminifera and on ourselves, human beings causing today's global warming and ecological crisis. At the end of the day, we are all connected.

Therefore, this thesis aims to search knowledge about the foraminiferal and mollusc fauna which lived in shallow-water environments in Svalbard, in an attempt to evaluate and provide additional knowledge about the early Holocene warmth period in Svalbard and the environmental drivers behind it. Further, this thesis also aims to address whether the HTM serves as a good analogue to anthropogenic climate warming in Svalbard, with our present knowledge about the projected future warming and the past HTM. In order to do this, the thesis will be based on fieldwork done in Svalbard, investigating foraminiferal assemblages in deposits from the early Holocene. From four different sites containing raised marine sediments, samples have been excavated and counted for foraminifera, and thermophilous molluscs have been collected.

The aim of this thesis can be summarized with the following research questions:

- What does the foraminifera and molluscs tell us about climate and environment in Svalbard in the early and mid-Holocene, and the drivers behind it?
- To which degree may the early and mid-Holocene be used as an analogue for ongoing and future projected warming in the Arctic?

Field work and lab work dealing with foraminifera assemblages from the early Holocene in Svalbard have been performed in the fall of 2020 and spring of 2021. At four locations around Isfjorden in central western Spitsbergen (figure 1), sediment samples have been taken from layers dating back to this period, and thereafter being counted for foraminiferal record. In addition, mollusc bivalves from the same sediment beds and pits have been collected and radiocarbon dated. Although preservation factors may over time lead to mismatch between the once living foraminiferal assemblage and the now fossil assemblage, our findings will at least show part of the foraminiferal fauna in particular environmental settings around Isfjorden in the early Holocene, hence leading to environmental indications.

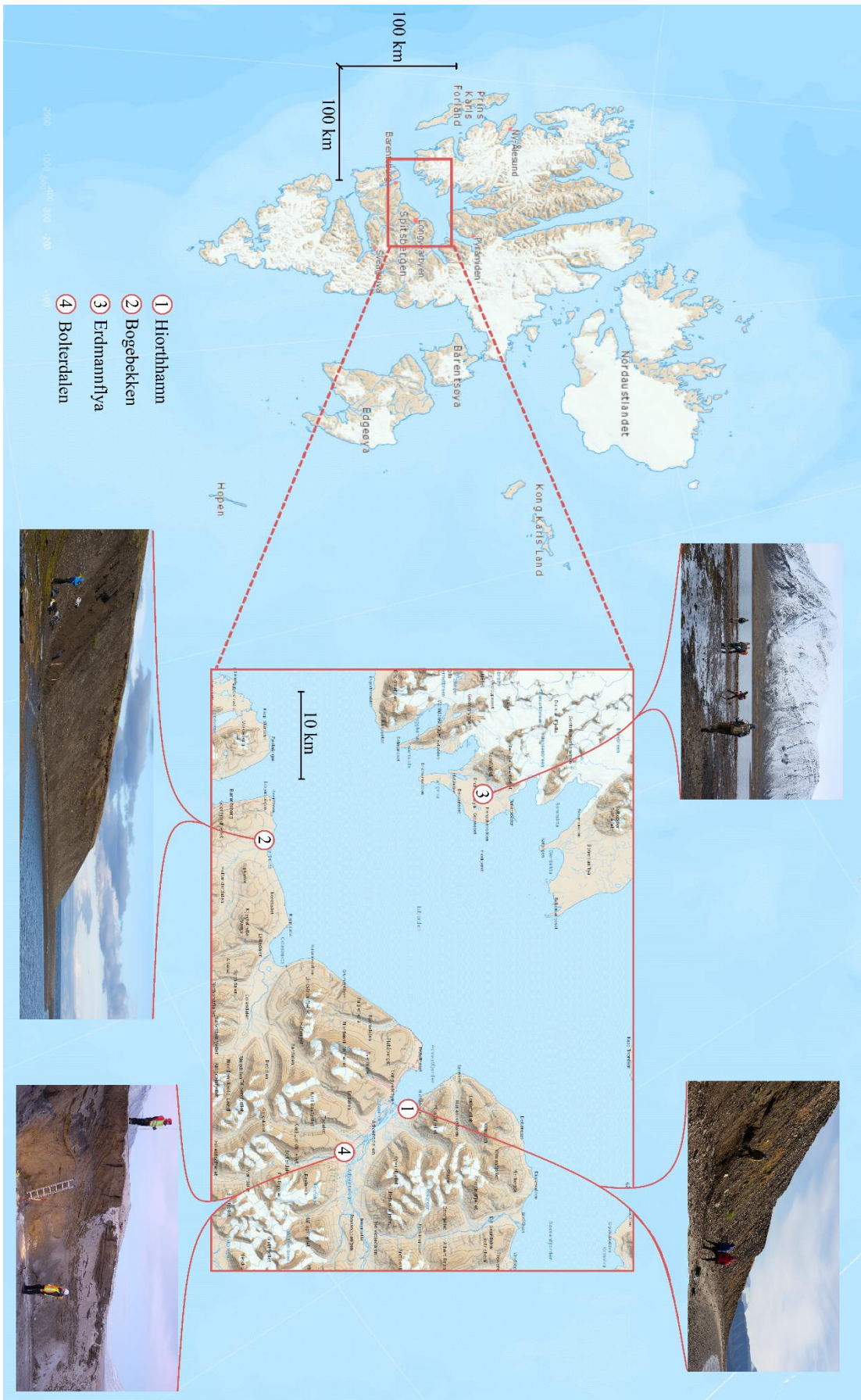


Figure 1 Input-map showing the locations for field work and sampling around Isfjorden in fall 2020.

2. Background and Theory

2.1 Svalbard

Svalbard is a mountainous, glaciated, Arctic archipelago located in the northwestern Barents Sea, spanning 76-81 °N and 10-33° E. Isfjorden, where most of the main settlements are located, is a fjord system situated on the western side of Spitsbergen, the largest island of Svalbard. The continental shelf off western Spitsbergen is narrow, and characteristically glacial, with troughs in between shallow banks, and has a steep continental slope of 4-5 ° (Hald et al., 2004). For its high latitude Svalbard has a relatively mild climate due to heat transported by the West Spitsbergen Current (WSC), which bring brings mild (>3°C) and saline (>34.9 ppm?) water (Atlantic Water, AW) from the Atlantic ocean to western and northern Svalbard along the shelf (Figure 2; Figure 3; Bensi et al., 2019; Farnsworth et al., 2020; Swift and Aagard, 1981). The WSC is an extension of the north Atlantic current, drifting at around 0.25 m s⁻¹ and underneath its AW lies the Norwegian Sea Deep Water (NSDW, Bensi et al., 2019). The WSC is an important oceanographic feature of Svalbard, which, together with cold sea currents in the Arctic waters makes Svalbard sensitive to oceanographic changes.

Flowing southwards along eastern Svalbard and around its southern tip, cold Arctic Water (ArW) named Spitsbergen Polar Current (SPC) flows parrallell to the WSC (Fraser et al., 2018). While this general flows nearer the shore and shallower than the WSC, the parts of WSC interfering and penetrating the fjord mouth and into the fjords are named Spitsbergen Trough Current (STC, Nilsen et al., 2016).

The following table shows an overview of the mentioned water masses (from Fraser et al., 2018):

Table 1 Overview over water masses mentioned in this thesis and its characteristics.

Water mass	Abbreviation	Temperature (°C)	Absolute salinity (g/kg)	Practical salinity
Atlantic water	AW	3.0 – 7.0	35.1 – 35.4	34.9 – 35.2
Transformed Atlantic water	TAW	1.0 – 3.0	34.9 – 35.1	34.7 – 34.9
Arctic water	ArW	<1.0	34.5 - 35.0	34.3 – 34.8

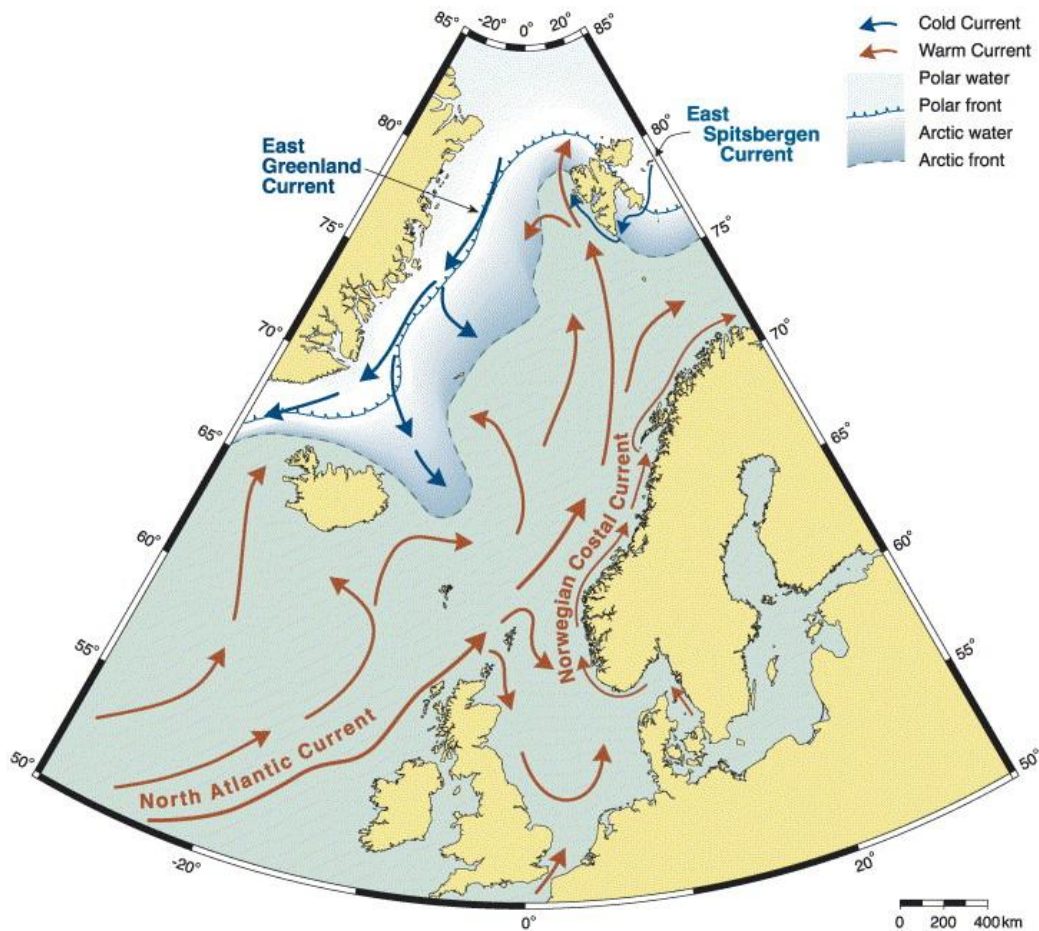


Figure 2. General ocean circulation pattern in the north Atlantic. “Warm” Atlantic water is brought northward (red arrows), making the regional climate in Svalbard warm for its latitude. Figure from Mangerud et al., 2006.

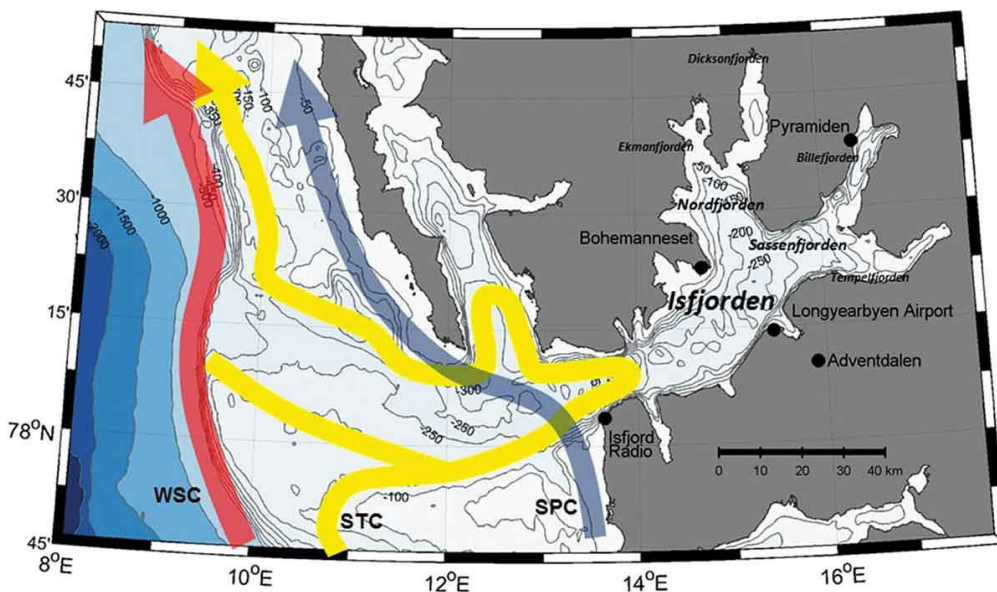


Figure 3. Sea currents around the head of Isfjorden. Red: Western Spitsbergen Current (WSC) bringing Atlantic Water (AW) along the shelf. Yellow: STC derived from WSC. Blue: SPC bringing cold Arctic Water (ArW). Figure from Fraser et al., 2018.

The prominent patterns of ocean circulation play a key role in the regional climate of Svalbard, which experiences higher marine and terrestrial temperatures in the west and south than in the east. Humidity from the main oceanic currents also causes more precipitation in southern and western areas, whereas areas further east see fewer clouds and have less precipitation (Førland et al., 2011).

2.1.1. Isfjorden

Isfjorden is Spitsbergen's largest fjord, situated on the western side of the island (Figure 1), approximately 70 kms long and with a maximum depth of 425 meters (Rasmussen et al., 2012). Being a broad fjord with no distinct sill, Isfjorden is linked to the shelf and fjord area which allows for inflow of warm Atlantic water (Berge et al., 2005; Slubowska-Woldengen et al., 2007; Nilsen et al., 2008; Fraser et al., 2018). Isfjordrenna, a 250 meters trough from the fjord mouth to the shelf, allows for further inflow of Atlantic water (Fraser et al., 2018). This flow has been shown to have a seasonal variation, with colder and less saline conditions during winter, as well as inter-annual variation (Svendsen et al., 2002; Rasmussen et al., 2012; Nilsen et al., 2008).

2.1.2 Deglaciation

Before, during and after the Last Glacial Maximum, measured by the peak in global ice-volume estimated to have occurred 23-21 ka BP (Clark et al., 2009), Svalbard was completely glaciated by the Svalbard–Barents–Kara Ice Sheet (SBKIS, Hughes et al., 2016). Initial deglaciation began at ca. 19 ka BP (Hughes et al. 2016). Following initial deglaciation, but prior to the Younger Dryas (YD) / Holocene transition 11.7 ka BP, several periods of ice-sheet re-advance and retreat occurred (ref). The edge of the continental shelf off western Spitsbergen was deglaciated ~15 ka BP (Mangerud et al., 1992; Elverhøi et al., 1995; Landvik et al, 1998). During the mild Bølling interstadial, 15.2 – 14.2 ka BP, deglaciation progressed through a number of fjord mouths and outer fjords, including Isfjorden (Hormes et al., 2013). High concentrations of ice-rafted debris (IRD) have been associated with this period of Bølling deglaciation. The radiocarbon age difference between the inner shelf and fjord mouths is small – this suggest an almost collapse and rapid retreat of ice (Hormes et al., 2013). In addition to warmer temperatures during the Bølling and possibly into the early Holocene, rising sea levels might have contributed to basal melting and disintegration of Svalbard ice shelves (Hormes et al., 2013).

While the Younger Dryas cold period (YD; 12.8 – 11.7 ka BP) resulted in glacial re-advances elsewhere in mainland Europe, glaciers and ice-sheets in Svalbard show less readvance and total extent during the YD than during the little ice age, probably due to less precipitation during this time (Mangerud & Landvik, 2007). Overall ice sheet retreat continued through YD, although at a slower pace (Mangerud & Landvik, 2007). According to Ślubowska-Woldengen et al. (2007), seasonal open water still occurred during YD, although sea-ice became closer to perennial.

Farnsworth et al. (2020) proposed that remains of the SBKIS at the onset of the Holocene (11.7 ka BP) was less extensive than previous reconstructions (e.g. Mangerud et al., 1992); a view which is supported by Kristensen et al. (2013). Already at 12.0 ka BP, deglaciation had begun at fjord mouths on western Spitsbergen. Mangerud et al. (1992) reported that Linnédalen, near the mouth of Isfjorden (figure 4) was ice-free before 12 ka BP; however, due to a lack of dateable material, the authors of this study were not able to determine the timing of retreat of the main fjord glacier occupying Isfjorden. Rapid retreat of glaciers occupying the fjord systems is likely to have taken place in the first half of the early Holocene (12.0 – 10.5 ka BP) suggesting a very warm early Holocene or rapid sea-level rise.

Mangerud et al. (1992) have suggested that inner parts of Isfjorden were ice-free by 9.9 – 9.7 ka BP, while Farnsworth et al. (2020) suggests ice-free inner fjords slightly earlier, between 11.5 – 9.1 ka BP. According to the Farnsworth et al. (2020), Svalbard fjords were half-way deglaciated by 11.6 ± 0.2 ka BP. Fjord heads on western Spitsbergen became ice-free around 10 ka BP, which is around the same time as those in eastern and northern Svalbard deglaciated. Rapid and extensive glacier retreat around 10 ka BP agrees with increasing rates of glacioisostatic uplift (Mangerud et al., 1992) and climate proxies for the Holocene Thermal Maximum.

Glacier retreat in the earliest Holocene seems to have been periodically interrupted by short-lived re-advances of cirque, outlet, and valley glaciers (e.g. Lønne, 2005; Farnsworth et al., 2020). It should be noted that these re-advances were not part of a general increase in ice volume; tributary ice advanced despite a general decline in total ice volume. Instead, the readvances highlight the complex glacial response to climatic and environmental shifts.

The ages of the reported glacial re-advances follow a geographic pattern, where older re-advances generally occurred around the outer fjords, and later readvances closer to the fjord heads (Farnsworth et al., 2020).



Figure 4. Terrain map of Svalbard with places referred to in the thesis: Hakluytvatnet, Hajeren, Dicksonfjorden, Linnédalen, Van Mijenfjorden and Hornsund. Map from toposvalbard.npolar.no

2.1.3 Post-glacial sea level change

As the ice sheet volume started to decrease after the LGM, global sea level started to rise. When the ice sheets rapidly decayed in late Pleistocene / early Holocene global sea-level rise accelerated, causing a ~ 60 m rise in global average sea level (Smith et al., 2011). Meanwhile, as the ice sheet melted and crustal loading decreased on Svalbard, glacioisostatic adjustment ensued in the form of crustal uplift. The rate and magnitude of crustal rebound is related to former ice sheet thickness and duration of the ice cover. Hence, since areas in central and eastern Svalbard in general have been more extensively glaciated than the western and southern margins of the archipelago (Hughes et al., 2016), postglacial emergence has been

greater in these areas (figure 5). Because of the variable rates of uplift, the altitude at which we can trace the maximum postglacial sea-level (marine limit) varies across the archipelago, from around and above 100 m (e.g. Kongsøya (Salvigsen, 1981)) to 20 m or less (e.g. Mitrahalvøya (Forman, 1990a)). The scatter of net postglacial isostatic uplift is in other words great, and varies on a local scale. Inner Isfjorden experienced a significantly greater uplift than outer Isfjorden (as seen in figure 5). Local estimates of marine limits are given in chapters on each sample location, 2.6.1 - 2.6.4.

In figure 5, relative sea-level (RSL) curves for various locations around the archipelago are presented, showing the general pattern of rapid uplift after deglaciation followed by declining rates of uplift towards present. At Kongsøya, outer eastern Svalbard, the rate of emergence is estimated to have been 4m/century for the first thousand years following deglaciation, and 0,3m/century for the last thousand years (Salvigsen, 1981). Consequently, the majority of terrain between marine limit and modern sea level was already subaerially exposed in the early Holocene. A mid Holocene marine transgression of up to 7 m can be seen in some areas on western Svalbard (approximately 6 – 4 ka BP; Forman et al., 1987).

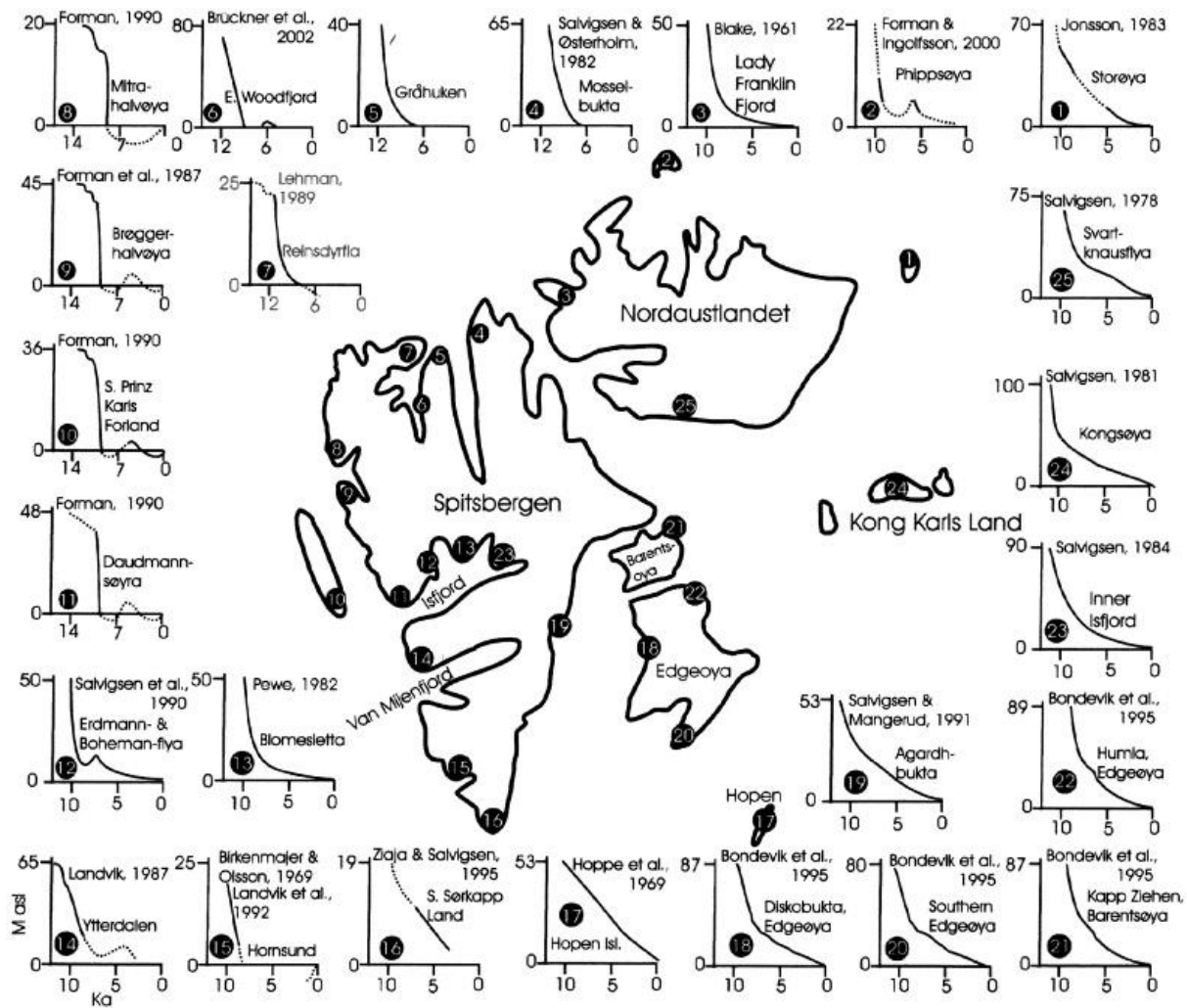


Figure 5 Sea-level curves from Svalbard. The general pattern of is a rapid fall in sea-level / rapid land-lift soon after deglaciation, in central Isfjorden ~10 ka BP. Relevant numbers: 12 is Erdmannfløya/Bohemanfløya, 23 is Inner Isfjorden. Note the marine transgression in some locations, e.g. Erdmannfløya/Bohemanfløya. Figure from Forman et al., 2004, modified from Forman, 1990a

2.2 Thermophilous molluscs

An important proxy for Holocene climate change in Svalbard was the discovery of several species of thermophilous mollusc shells preserved in raised marine sediments that do not live in the coastal waters of Svalbard today (or have only very recently re-colonised the archipelago). Observations of such mollusks, among them *Mytilus* spp, indicate a climate milder than present, known as the “Mytilus-period” (e.g. Knipowitsch, 1903). While these first observations of *Mytilus* spp were restricted to raised marine sediments <25 m.a.s.l., the “Mytilus-period” has been widely extended by later investigations that document both *Mytilus* spp and other thermophilous species of molluscs at higher elevations.

The most extensive mapping of thermophilous mollusks on Svalbard was done by Feyling-Hanssen (Feyling-Hanssen & Jørstad, 1950; Feyling-Hanssen, 1955), who mapped the mollusk fauna around parts of Isfjorden. A total of nine species of thermophilous mollusks currently absent from Svalbard or only having recently recolonized Svalbard were reported; four bivalve species and five gastropod species. Temperature interpretations from thermophilous mollusks are done by comparing their present spatial/temperature limitations. By comparing earlier species distributions in Svalbard with their present temperature/northern limit, paleotemperatures have been reconstructed. Since summer temperatures is seen as a critical parameter for these molluscs to spawn, the summer (august) sea surface temperature is used by Mangerud & Svendsen (2018) to define the distribution limits. The surface temperature map and the 10-m depth map from Korablev et al. (2014) show that the temperatures are very similar – consequently dated molluscs, at least individuals living relatively shallow, can be seen as a proxy also for sea surface temperature. The shells can also be radiocarbon dated to determine the ages of the molluscs and the sediments they were discovered in. Stable isotope analyses of *A. islandica* from raised marine beached in Dicksonfjord have been used to infer palaeosalinity (hence, dominance of Atlantic water versus meltwater input) and temperature (Beierlein et al., 2015).

In recent studies, particularly the following four bivalve mollusk species have been used as proxies for paleotemperature in the early and mid-Holocene in Svalbard (e. g. Salvigsen et al., 1992; Mangerud and Svendsen, 2018) (names are given according to WoRMS (World Register of Marine Species)):

- **2.2.1 *Zirfaea crispata* (Linnaeus, 1758) (Norwegian: Strutseskjell)**

Z. crispata is the most warm-water-demanding species of the nine different thermophilous mollusks documented from the early Holocene in Svalbard. *Z. crispata* is a filter feeder that lives in shallow water, and is today, commonly found around Trondheimsfjorden (Mangerud and Svendsen, 2018). Unconfirmed observations through the 20th century have been reported farther north and along Russia's Barents Sea coast, although living individuals have never been found there (S. Denidenko, written communication 2016 in Mangerud & Svendsen, 2018). Recent, unvalidated observations reported in Artsdatabanken from 2020-2021 in Honningsvåg, Tromsø and Rolla may indicate an ongoing northward migration (Artsdatabanken, 2021). *Z. Crispata* was only documented in one area in early Holocene sediments on Svalbard,

coinciding with the peak of the Holocene thermal maximum (Mangerud and Svendsen, 2018).

- **2.2.2 *Arctica islandica* (Linnaeus, 1767) (Norwegian: Kuskjell)**

Less warmth-demanding than *Z. crispata*, *A. islandica* is today found along the entire coast of mainland Norway as well as the Kola peninsula in Russia. In 1999, *A. islandica* were reported from Svalbard, interpreted by Dahlgren et al. (2000) as re-immigration. The species typically live between 30-60 m water depth; however, they have been observed living in shallower water at higher latitudes and as shallow as 10 m below sea level (Thompson et al., 1980). The species is known to be especially long-lived, with a maximum lifespan of ~500 years (Butler et al., 2013; Gruber et al., 2015).

- **2.2.3 *Modiolus modiolus* (Linnaeus, 1758) (Norwegian: O-skjell / Hesteskjell)**

Considered to be approximately as warmth-demanding as *A. islandica*. The modern distribution of *M. modiolus* spans the Norwegian mainland coast and extends to Russia. Although it is morphologically similar to *Mytilus* spp, *M. modiolus* belongs to a different genus and prefers slightly deeper water. Modern observations of *M. modiolus* have not been reported from Svalbard.

- **2.2.4 *Mytilus* spp (Linnaeus, 1758) (Norwegian: Blåskjell)**

Three species of *Mytilus* are known to occur in the North Atlantic and in Svalbard: *Mytilus edulis* Linnaeus 1758, *Mytilus trossulus* Gould 1850, *Mytilus galloprovincialis* Lmk. 1819 (Mathiesen et al. 2017). While recent studies (Mathiesen et al., 2017) have revealed a complex distribution pattern including hybridization of these species, and that at least *M. edulis* and *M. galloprovincialis* are found in Svalbard, earlier studies have not distinguished these species, only referring to *M. edulis* (e.g. Feyling-Hanssen & Jørstad, 1950; Salvigsen, 2002; Mangerud & Svendsen, 2018). All *Mytilus* bivalves will therefore be referred to as *Mytilus* spp. henceforth. *Mytilus* spp. is considered the least warmth-demanding compared to the other early Holocene thermophilous bivalves recorded from Svalbard. Similar to *Z. crispata* is *Mytilus* spp, a shallow-water filter feeder, living in the intertidal zone, or, in the Arctic, below the depth at which sea ice reaches (Mangerud and Svendsen, 2018). *Mytilus* spp. lives along the entire Norwegian coast at present, and recent observations from Bjørnøya (Gulliksen et al., 1999) and Sagaskjæret at the mouth of Isfjorden (figure 6; Berge et al., 2005), indicate a very recent re-colonisation of Svalbard. Sagaskjæret holds an abundant population of *Mytilus* spp. from the early Holocene, and has been regularly

sampled by UNIS students (Berge et al., 2005), sharpening the estimate of the re-immigration. Modern *Mytilus* spp. has been observed now in multiple locations around the archipelago (Leopold et al., 2019). On the basis of the larvae's known ability to be transported over time in cold water, Berge et al. (2005) suggests that the re-colonisation only found place in 2002, when there were a favorable combination of factors such as high summer surface temperature, increased heat transport by WSC and a favorable wind direction. On the other hand, Leopold et al. (2019) argues that the re-immigration is an annual event, while also suggesting that *Mytilus* spp. has been introduced by human activity, e.g. ship traffic, in addition to natural advection. As the least warmth-demanding species among the four bivalves listed so far, the high number of *Mytilus* spp. found in sediments from the early Holocene (figure 7) provides insight in the temporal and spatial climatic variability throughout the period. The recent immigration can therefore be a valuable comparison.

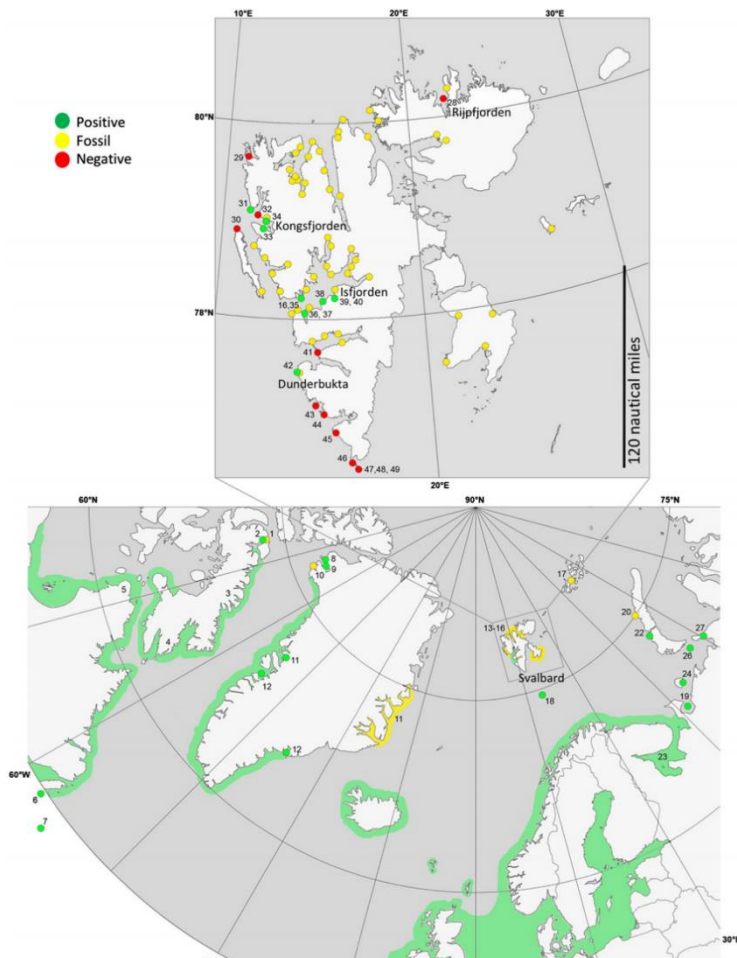


Figure 6 Lower map: Distribution of subfossil (yellow) and living (green) *Mytilus* spp. in the the north Atlantic and Arctic. Upper map: locations on Svalbard with subfossi (yellow), recent living (green) and negative findings (red) of *Mytilus* spp. Subfossil findings are based on Salvigsen (2002) and Mangerud and Svendsen (2018), recent livings are based on observations 2004–2016 (Leopold et al., 2019). Negative findings (red) are dive sites specifically surveyed for *Mytilus* spp. during this period without finding it. Figures from Leopold et al., 2019.

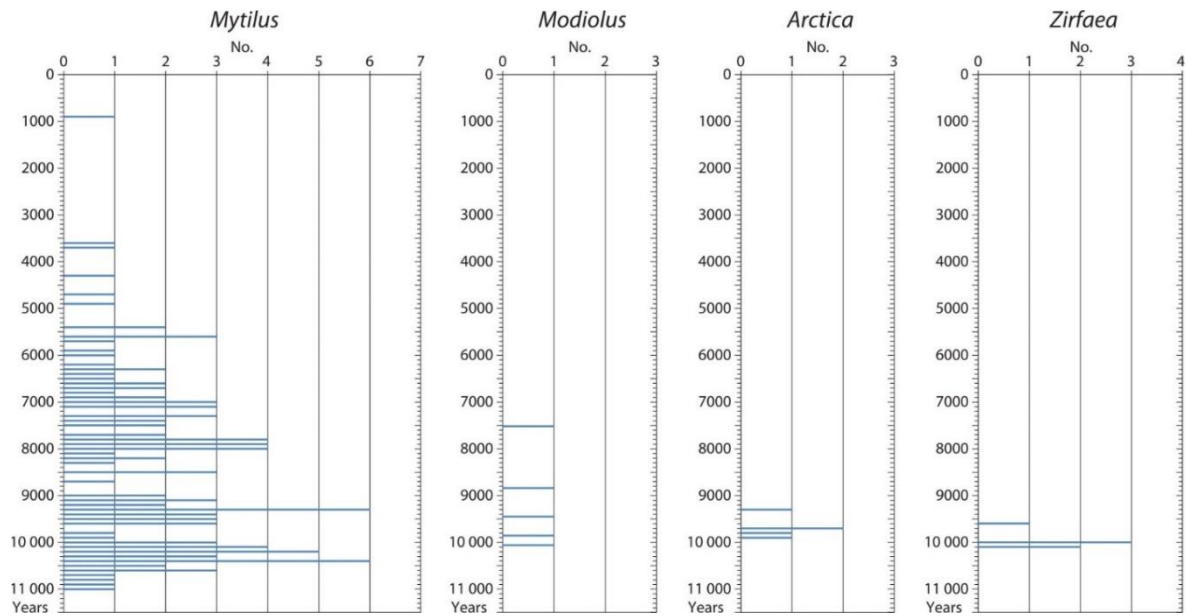


Figure 7. Number of samples per 100 years of dated molluscs from Svalbard. Only the midpoint age of the 68% confidence interval is used for each sample, and they are counted as, for example, from 9100 to 9199 and then plotted at 9100 (Mangerud and Svendsen, 2018). From this figure *Mytilus* spp. appears the least warmth-demanding specie, and *Z. crispata* the most. Figure from Mangerud and Svendsen (2018), which merged all published radiocarbon dates of these four species. Thus, dates from the following are included: Beierlein et al., 2015; Blake, 1961, 2006; Brückner, 1996; Brückner et al., 2002; Elgersma and Helliksen, 1986; Feyling-Hanssen and Olsson, 1960; Forman, 1990a, 1990b; Hansen et al., 2011; Hjort et al., 1995; Klysz et al., 1988; Landvik et al., 1987; Lønne and Nemeč, 2004; Olsson, 1960; Olsson and Piyani, 1965; Salvigsen, 1984, 2002; Salvigsen and Høgvard, 2005; Salvigsen and Österholm, 1982; Salvigsen et al., 1990, 1992; Sharin et al., 2014

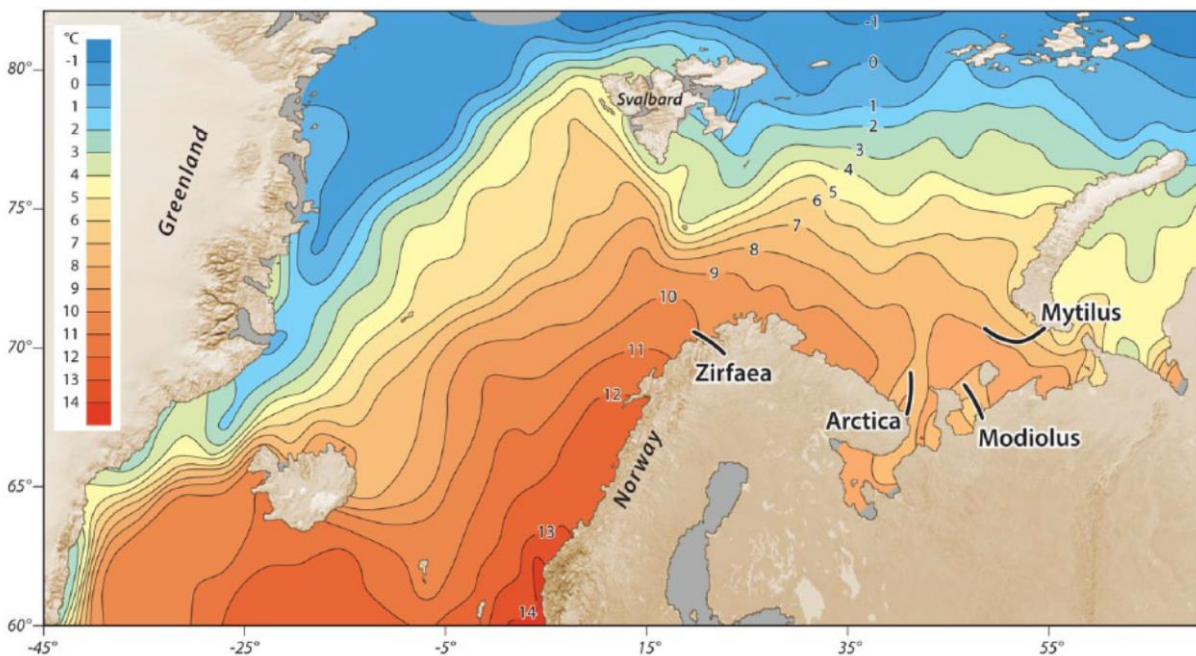


Figure 8. Mean august sea-surface temperature for the period 1900-2012, with the present-day northern/eastern distribution limits for the thermophilous mollusks mentioned in this thesis. Figure from Mangerud and Svendsen, 2018, modified from Korablev et al., 2014

2.3 Holocene climate in Svalbard

While the general picture of the Holocene climate in northern latitudes is a warm early phase followed by a gradual cooling in mid- and late-Holocene, various studies suggest differences in the timing and magnitude of these climatic swings throughout the Holocene. Several studies suggest that Svalbard experienced a period with temperatures warmer than present soon after YD, followed by a temperature decline before a new period of warming approximately 8 ka cal. BP (e.g. Ebbesen et al., 2007; van der Bilt et al., 2018; Mangerud and Svendsen, 2018). The decline in temperatures on Svalbard from this temperature peak might have happened stepwise, but with a general pattern of being significantly colder than the early temperature peak.

Referring to “present” temperatures might be an inaccurate term, both because modern-day temperature measures are relatively scarce and because the temperatures are currently rapidly increasing. On the basis of recent sources measuring fjord water temperatures in western Spitsbergen, Beierlein et al. (2015) applies “present” mean summer water temperature of 5-6°C and winter temperatures of about -1°C. While this is mostly based on measures after year 2000, the 1900-2012 average referred to by Mangerud & Svendsen gives a slightly lower summer surface temperature (figure 8). Ideally all temperature variations should have referred to the same baseline, for instance pre-industrial conditions. This is, however, hard to obtain, and temperature variations and comparisons are therefore given with reference to the baseline in each case, while trying to avoid referring to “present” temperature.

2.3.1 Warm early Holocene

Numerous observations indicate that the climate of the early Holocene was significantly warmer than present, in both marine and terrestrial environments, across Svalbard. The first documented appearance of *Mytilus* spp in western Spitsbergen was 11 ka cal. BP, suggesting that the climate was warmer than 1900-2012 average already at this point (Mangerud and Svendsen, 2018). The presence of *Mytilus* spp found on the northern coast indicates that summer temperatures in shallow water were around 2°C warmer than 1900-2012 average.

Terrestrial temperature reconstructions based on alkenone paleo-thermometry (U_{37}^k) from lake sediments in northwestern Spitsbergen suggests that lake water temperatures have varied by 6-8 °C in the Holocene (figure 9; van der Bilt et al., 2018); a range which is backed up by U_{37}^k data from other Arctic lakes (D’Andrea et al., 2011). Alkenone data from lake Hajeren

(figure 4) might indicate an exceptionally early Holocene warming, peaking 10.5 ka cal. BP and 8-9 °C above mean Holocene temperatures (van der Bilt et al., 2018). This is also indicated by sediment records from Linnévatnet (Fig. 4) showing melting glaciers 11-10 ka cal. BP as well as glacial retreat around Billefjorden (Svendsen and Mangerud, 1997).

Appearance of the thermophilous mollusk *Z. crispata*, which is found only within a narrow time window 10.2 – 9.7 ka cal. BP, marks the peak of the Holocene thermal maximum according to Mangerud and Svendsen (2018). The presence of this species of mollusk points towards summer water temperatures down to ~25-30 m depth 6°C warmer than the 1900-2012 average (figure 8). *Z. crispata* has only been found at Kapp Ekholm in Billefjorden (Fig. 4), where today, there is less cloud cover, with more continental conditions and stronger seasonal influence of insolation than in the outer fjord. This exemplifies the effect of local conditions; in certain shallow and sheltered environments in the inner fjord without nearby sources of meltwater input the conditions seemed to have been favorable enough for *Z. crispata* to survive. Today, such conditions are assumed to be comparable to those ca. 1000 km to the south along the coast of mainland Norway. Although not continental in any way, this is the approximate northern limit at present (yet a northbound migration is both seen and expected). The number of radiocarbon dated *Z. crispata* shells is, however, limited, introducing some uncertainties about the warm period they represent. In general the temperature interpretation from the mollusk fauna is relatively consistent with van der Bilt et al. (2018), yet the mollusks points to a slightly later HTM than the alkenone data, with cooling starting at 10.5 ka cal. BP in contrast to the mollusk showing greatest warmth around 10.0 ka cal. BP.

Other material offering evidence for an warm early Holocene include a marine core west of Isfjorden, indicating that the Atlantic Water at western Spitsbergen between 10.8 and 8.8 ka cal. BP was warmer than today (Ebbesen et al., 2007). By 8.8 ka cal. BP, proxy data (e.g. ice rafted debris, planktonic foraminifera incl. their stable oxygen and carbon isotopic) from this core indicates an abrupt cooling of 2°C within nine years, which does not fit together with the alkenone data but might coincide with the apparent disappearance of *Mytilus* spp around 9 ka cal. BP (van der Bilt et al., 2018; Mangerud and Svendsen, 2018).

Strong insolation was likely one of the drivers behind the HTM, as this period coincided with maximum summer insolation at 80 °N in terms of orbital changes (Huybers, 2006). Van der Bilt et al. (2018) also argues that the early Holocene summer temperatures must be seen partly as a consequence of increased insolation. Furthermore, the exceptional rise in early Holocene temperature has also been explained by the Atlantic Meridional Overturning Circulation,

which strengthened as the sea ice retreated (Risebrobakken et al., 2011; Carlson et al., 2008). Climate model simulations which includes ice sheets and meltwater as well as orbital forcing predicts a thermal maximum after 8 ka cal. BP, however, northward heat transport might have been earlier and stronger than projected by the models (Mangerud and Svendsen, 2018). The uneven distribution of thermophilous mollusks between Isfjorden and Van Mijenfjorden, located south of Isfjorden on the western side of Spitsbergen, but with its mouth and water exchange almost blocked by Akseløya, indicates that inflow of warm Atlantic water played an important role in the warming (Mangerud and Svendsen, 2018).

2.3.2 Cooling towards ~8 ka cal. BP

From 10.5 ka cal. BP to 8.3 ka cal. BP, sediments lacking alkenones from Hajeren on northwestern Svalbard (Fig. x) were interpreted by van der Bilt et al. (2018) to reflect glacial re-advance and climate deterioration. This cooling agrees with a decline in AMOC and increased freshwater input to the north Atlantic. $\delta^{18}\text{O}$ values from planktic foraminifera in a marine core from Reykjanes Ridge southeast of Iceland (61°N, 25°W, 1648 m depth) suggests cold and fresh surface waters in the North Atlantic from 10 to 8 ka cal. BP (Came et al., 2007) caused by influx from retreating ice sheets in the northern hemisphere. Simulations from the LOVECLIM model (Zhang et al., 2016) show that disrupted heat transport from the AMOC could indeed reduce summer temperatures in the Arctic, as well as suggesting that the Greenland Ice Sheet may have had an especially great impact (Zhang et al., 2016). Simulations by Lecavalier et al. (2014) shows an accelerated melting of the Greenland Ice Sheet after 10.5 ka cal. BP and a 25% volume loss before 8 ka cal. BP, which would have fed the Nordic Seas with fresh and cold water in this period, eventually leading to cooling. In the period 9 – 8.2 ka cal. BP, *Mytilus* spp is scarce, and only found in a few favorable locations in Isfjorden (Mangerud and Svendsen, 2018).

2.3.3 The 8.2 ka cal. BP cold event

One “prominent and widespread” (Alley et al., 1997) anomaly has been dated ~8.4-8.0 ka BP, peaking 8.2 ka BP based on a range of studies and proxies (e.g. loss-on-ignition (LOI) profiles in southern Norway by Nesje and Dahl (2001); diatom assemblages in Denmark by Hede et al. (2010); stable isotopes from north atlantic by Daley et al. (2011); pollen and microfossils in Ireland by Ghilardi and Connell. (2013)). This event is often referred to as the “8.2k” or “8k-event”. It brought dry and cold conditions especially to the northern hemisphere in

wintertime (e.g. Alley and Ágústsdóttir, 2005). The southern hemisphere, as well as pacific regions, seem to have experienced less impact (Ghilardi and Connell, 2013). While seemingly having a similar pattern to the Younger Dryas, its duration is way shorter, slowly resuming to warmer conditions without stabilizing in a cold state. Based on ice-cores from Greenland, the cooling had an amplitude of c. 6°C lasting for 160 years (Thomas et al., 2007).

This significant and abrupt climate anomaly has been linked with the sudden drainage of ice-dammed lakes created with the retreat of the Laurentide Ice Sheet (Barber et al., 1999). As one of the largest of these ice-marginal lakes, Lake Agassiz, drained catastrophically within a few hundred years, the magnitude of the freshwater-input caused this major anomaly in north Atlantic regions (Clarke et al., 2004). Freshwater reached the deep water convection cells in the North Atlantic, hence lowering salinity and hampering the overturning circulation (Clarke et al., 2004). Affected regions are generally reconstructed to have experienced colder, drier and windier conditions during the event. Likely, this increased freshening reduced the effect of the North Atlantic overturning circulation which in turn caused less heat and humidity to be transported to high latitudes. However, according to Klitgaard-Kristensen et al. (1998) salinity didn't lower upstream in the north sea, indicating that the meltwater pulse itself was not able to travel as far as from Lake Agassiz to Svalbard.

In Svalbard, Hald and Korsun (2008) have found throughout indications for an abrupt cooling related to the 8.2 ka event by investigating sediment cores from Van Mijenfjorden in southwestern Spitsbergen. Two steps of significant steps are observed; at 8.45 ka cal. BP and 8.2 ka cal. BP (Hald and Korsun, 2008). Although salinity didn't lower, studies (e.g. Klitgaard-Kristensen et al. (1998)) clearly shows an abrupt cooling of 2-3°C, interpreted as reduced transport of Atlantic water northward. Such a setting will move the oceanic Arctic front further south, and the inflow of water to the fjords would be more dominated by Arctic water. In turn, the Arctic water will have lower temperature, salinity and $\delta^{18}\text{O}$ -values, thus being considered by Hald and Korsun (2008) as the main explanation in the fjord water regime in Svalbard during the 8.2 ka event. Reduced intensity in the meridional overturning circulation in the North Atlantic is supported also by model predictions (e.g. Bauer et al., 2004), using a magnitude of freshwater release as estimated by Clarke et al. (2004). On the other hand, Ellison et al. (2006) argues on the basis of a separate cooling 8.5 ka BP that the 8.2 ka event was a culmination of the change initiated centuries earlier during the most rapid release of freshwater.

Despite an accumulation of recent studies regarding the 8.2 ka event, there are still large uncertainties about distribution, causes and implications from it. As a past anomaly linked to the freshening of the north Atlantic, the 8.2 ka event can be an important analogue for future environmental changes in the north Atlantic, given the increased freshwater input from a melting Greenland ice cap. Hence, broadening our understanding of this event can provide insight in future climatic response in Arctic and elsewhere.

2.3.4 Short warming phase ~8 ka cal. BP

Alkenone-based temperature reconstructions from lakes in northwestern Spitsbergen show a resumed warming period from 8.3 ka cal. BP – 7.8 ka cal. BP, when the cooling effect from ice-sheet melting decayed and strong insolation linked to orbit angles were still in place (van der Bilt., 2018). This is highly consistent with a resumed spatial spreading of *Mytilus* spp, which occupied its easternmost location during the entire Holocene at this time. *A. islandica* and *Z. crispata* have not been observed in this period (Mangerud & Svendsen, 2018), which might indicate that the temperatures were lower than in the earlier warm peak (~10 - 9 ka cal. BP).

2.4 Isfjorden and the shallow water environment

Stable oxygen isotope analysis, $\delta^{18}\text{O}$, from the two species of foraminifera, *Nonionellina labradorica* and *Lobatula lobatula*, shows a greater offset in $\delta^{18}\text{O}$ -values between the two prior to 8.2 ka cal. BP (Rasmussen et al., 2012). The former species is linked to cold bottom water and thrives in spring, and the latter in summer (Ivanova et al., 2008). As $\delta^{18}\text{O}$ -values are influenced by temperature and salinity, greater offsets between these two species can be explained by greater seasonal variation in bottom water temperature and salinity prior to 8.2 ka cal. BP (Nilsen et al., 2008), with inflow of warm bottom water on the fjord bottom. Stable oxygen isotope studies of *A. islandica* from raised marine sediments in Dicksonfjorden (Fig. 4) suggests seasonal variations in water temperatures of 12.4 °C, in contrast to the present seasonal amplitude of 6 °C (Beierlein et al., 2015). The average maximum bottom water temperature, as observed from *A. islandica*, is 15.2 °C, which is 8-10°C warmer than present. On average, the temperature was 9,1 °C, 6° warmer than present. Although mixing of water masses with different salinities also can influence $\delta^{18}\text{O}$ -values, the interpreted temperatures agree with current temperature preferences for *A. islandica* in terms of absolute temperature

and temperature seasonality (Schöne et al., 2004), as well as other reconstructions of the HTM from the North Atlantic (e.g. Sarntheim et al., 2003; Hald et al., 2004). Furthermore, the assumption that the $\delta^{18}\text{O}$ -values mainly reflect variations in temperature rather than salinity agrees with various studies suggesting stratified water masses in Isfjorden and the western Svalbard shelf area throughout the Holocene. The general idea is of a late-spring development of a pycnocline, separating warm, Atlantic water on the bottom from the upper, low-salinity meltwater. Influence of Atlantic bottom water was more prominent in summer, which coincides with the growing season of *A. islandica*. However, while Rasmussen et al. (2014) describes this strong pycnocline before 9600 yr BP, reduced sea ice cover and freshwater input from smaller or absent glaciers tilted this towards a situation dominated by Atlantic Water 9000 – 6000 yr BP.

The exact depth of the thermocline in Isfjorden is challenging to reconstruct, as it is dependent on both seasonal variations and local conditions. Present-day measures show the thermocline in Kongsfjorden to be ~5 m depth in September (MacLachlan et al., 2007), and 10-20 m depth in Dicksonfjorden in August (Forwick, 2005).

According to Rasmussen et al. (2012), the cooling at 8.2 ka cal. BP was followed by cooling steps also at 7.4 ka cal. BP and 4.0 ka cal. BP, while the period 4.0-2.0 ka cal. BP represents the temperature minimum during the Holocene. The cold period at 7.4 ka cal. BP is mirrored by growing glaciers (Forwick and Vorren, 2007) as well as temperature reconstructions from other Arctic regions (Knudsen et al., 2008). The cooling step at 4.0 ka cal. BP also coincides with growing glaciers (Svendsen and Mangerud, 1997) and the absent of planktic foraminifera when the polar front advanced. This latter cooling step seemed to be more notable also on lower latitudes.

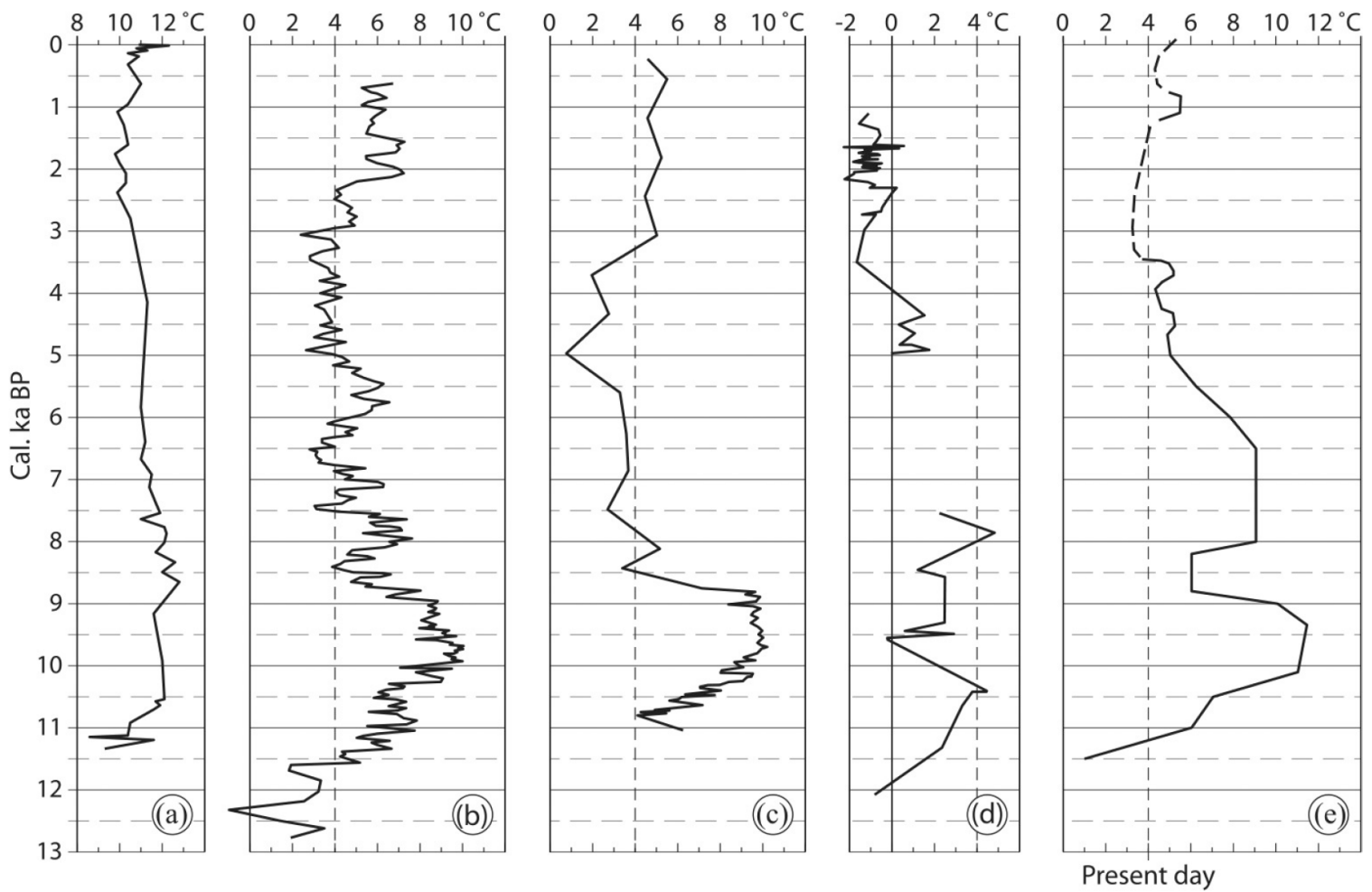


Figure 9. Combined figure from Mangerud & Svendsen (2018): Different temperature curves from Svalbard in the Holocene: (a) alkenone-based sea-surface temperature reconstruction from core PSH-5159H from the SW Barents Sea from Risebrobakken et al. (2011); (b) sea-surface temperature reconstruction based on planktic foraminifera from core 23258 from north-western Barents Sea (Hald et al., 2007); (c) sea-surface temperature reconstruction based on planktic foraminifera from core MD99-2304 from the margin west of Svalbard (Hald et al., 2007); and (d) alkenone-based, lake-water temperatures for Hakluytvatnet, located at the north-western corner of Svalbard (figure 4). The scale is relative to mean Holocene values. From Van der Bilt et al. (2018). (e) temperature-curve based on findings of thermophilous molluscs by Mangerud & Svendsen, 2018

2.5 Projected future climate

Due to Arctic amplification of warming, the near-surface temperature in the Arctic has in recent decades rose twice as fast as the global average (Screen and Simmonds, 2010). In particular the rise in winter temperatures has been remarkable. Fjørland et al. (2011) report a rapid increase of 2-3 °C per decade measured at Longyearbyen airport. This ongoing and projected Arctic amplification is caused by positive feedback effects, which adds to the global effect of greenhouse gas emissions, such as increased heat absorption due to lowered albedo and increased heat exchange from the ocean to the atmosphere, especially in winter, with less ice cover.

Despite the complexity of climate models and the fact that projections are loaded with uncertainties regarding both human emission patterns and environmental response, there are clear indications of a warm future for the Arctic. Fjørland et al. (2011) downscaled global climate models, atmosphere ocean general circulation models (AOGCMs), finding larger variability in model results than simulations on lower latitudes. Such results are not unexpected given Svalbards sensitive location along the Arctic front (Fig. 2). By running a regional climate model (RCM) tuned for the Svalbard region with a spatial resolution of 25 x 25 km, simulations project a significantly more amplified warming in northeastern Svalbard and the areas between Svalbard and Novaya Zelmya. This coincides with areas with the greatest projected decrease in sea-ice. Regionally reduced sea-ice cover will have a large impact on low-atmosphere temperature, and likely a main cause of this southwest-northeast temperature gradient (Fjørland et al., 2011). The smallest projected temperature change is expected for the mean summer temperature (Fjørland et al., 2011). In other words, the offset between mean summer temperature and mean winter temperature will decrease in the future on Svalbard. This is in contrast to the early Holocene, where seasonal temperature variations seem to have been greater than present (Beierlein et al., 2015).

Projections for the ongoing century forecast a that the warming until 2100 may be up to three times stronger than in the last 100 years in Svalbard (figure 10; Fjørland et al., 2011). For the winter temperature in particular is the projected increase strong; 10°C higher than at present, according to Fjørland et al., 2011. The already observed increase in precipitation is projected to increase further up to 2100 (Fjørland et al., 2011).

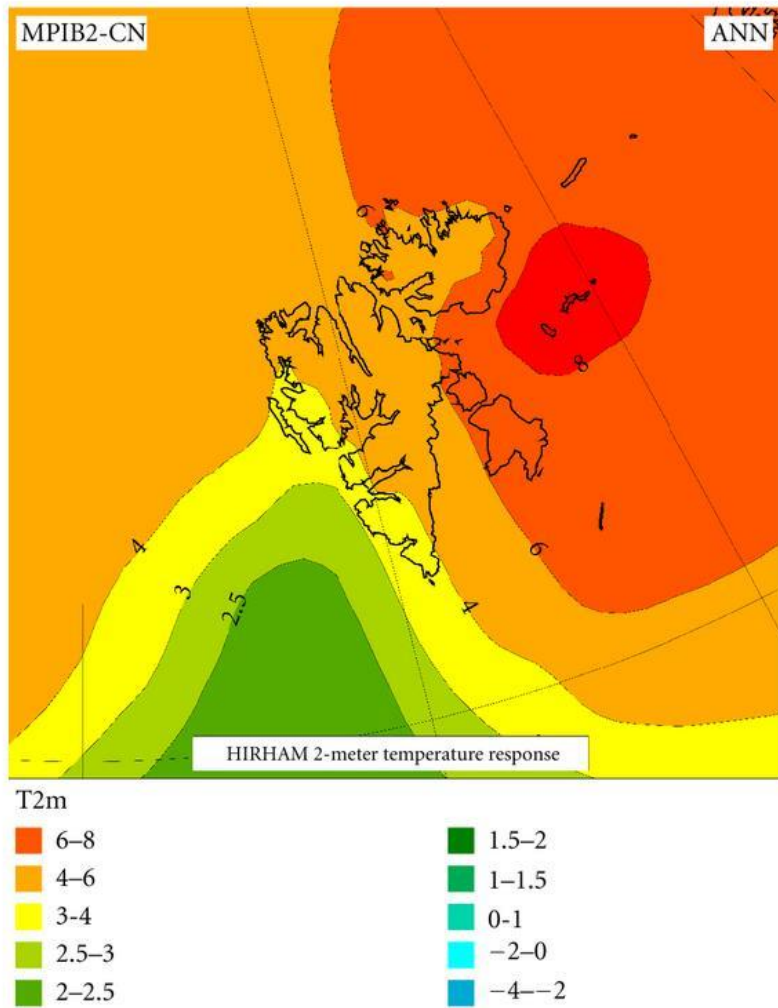


Figure 10. Projected mean annual temperature changes from 1961–90 to 2071–2100 (°C). Simulations done with the regional climate model HIRHAM2/NorACIA. Figure from Førland et al., 2011

2.6 Field Areas

2.6.1 Hiorthhamn

Hiorthhamn is the area seen from Longyearbyen right across Adventfjorden. Situated below Hiorthfjellet, there are numerous cabins and signs of earlier anthropogenic activity, and southeast of these lies a raised fan delta with a present radius of approximately . Both the fan delta and the fan delta foreset, where the samples in this thesis are taken, are comprehensive described by Lønne and Nemeč (2004). The local marine limit is ~ 70 m.a.s.l. and was established around 10 ka BP, as the fjord heads and inner fjords rapidly became deglaciated (e.g. Farnsworth et al., 2020). Although deglaciation was rapid, a small cirque glacier above

the fan delta survived (Lønne & Nemec, 2004), providing sediments for delta formation. The seasonal input of sediments lasted until 6 ka BP, when the cirque glacier melted away. The radius of the fan delta was approximately 1 km at 6 ka BP, and marine regression continued while longshore sediment drift and marine processes modified the delta foreset beds (Lønne and Nemec, 2004). Then, from 5.4 ka BP to 4.5 ka BP, Lønne and Nemec (2004) found evidence for a marine transgression of approximately 4 meters, which shrunk the radius of the fan delta plain to 0.72 km. Resumed regression gradually leading to present-day sea level (Lønne and Nemec, 2004). The delta foreset beds, which occur up to 10 m above mean sea level, have been comprehensively investigated by Lønne and Nemec (2004). Around the sampling location for this thesis, in the proximal/medial part of the fan delta, Lønne and Nemec (2004) describes a strongly wave-influenced layers and beach deposits underneath a 3-4 m coarse alluvial layer.

2.6.2 Bogebebben

Bogebebben (bekk= stream) is located in Hollendarbukta on the southern shore of Isfjorden, running west of the valley's main river Hollendarelva. These sediments are interpreted by Sharin et al (2014) as raised marine terrace, and in which fluvial erosion from Bogebebben has cut through the marine terrace eroding an excavated valley. Sampling was conducted from the western side of this excavated valley. The same sediment face has previously been sampled by Sharin et al. (2014) for marine mollusks, dating a total of five individuals of *Mya truncata* and *A. islandica*. Except the Cyrillic paper by Sharin et al. (2014), the site is not described in articles or literature. Marine limit in the area is ~ 70 m.a.s.l. and, according to Sharin et al. (2014) relative sea-level was higher than present by ~12 ka BP and stayed so until ~ 6.5 ka BP. Relative sea-level was lower than present until ~1 ka BP (Sharin et al., 2014). Sea-level lower than present for parts of mid- and late-Holocene is also interpreted from western side of Grønfjord, where 10 mollusks from altitude 0.5 – 20 m are dated between 8.5 – 11.8 ka BP (Sharin et al., 2014). The marine terraces in Bogebebben, as well as in the rest of the area, is likely to have accumulated between 12 ka BP and 6.5 ka BP, which is until sea level were lower than present (Sharin et al., 2014).

According to Sharin et al. (2014), there are three main stratigraphic units, described from top to bottom: one layer of sandy gravel, one silty-sandy layer (with mollusks), and a silty layer at the bottom.

2.6.3 Erdmannflya

Erdmannflya is a low-altitude peninsula in the northern part of Isfjorden (Fig. 1). The western part is characterized by the moraine Esmarkmorena linked to Esmarkbreen (Eskmark glacier). The final deglaciation and retreat of Esmarkbreen is estimated to have taken place 10 ka BP, which also marked the beginning of rapid isostatic uplift (Salvigsen et al., 1990). This agrees with Mangerud et al. (1992) estimate of the onset of sea-level rise and isostatic rebound in the area. Raised beaches in Erdmannflya and the neighbouring Bohemenflya are found up to ~ 60 m.a.s.l. and are dated to 10 ka BP. The following uplift occurred at a rate of ~ 3 m/century until 8.5 ka BP, based on radiocarbon dated shell material from raised beaches (Salvigsen et al., 1990). Based on the distribution of *M. truncata*, its depth requirements and content of silt and gravel, a transgression of at least 5 meters occurred between 8 and 7 ka BP (Salvigsen et al., 1990). The timing of the reported marine transgression at Erdmannflya and northwestern Isfjorden is early compared to other reported transgressions occurring between 6 – 4 ka BP (e.g. Forman et al., 2004). Esmarkbreen to the west of Erdmannflya appears to have readvanced around 9.5 ka BP, which as with other glacial readvances in the early Holocene probably were a shortlasting event (Salvigsen et al., 1990). The rate of isostatic uplift slowed down in the mid-Holocene, and already 5 ka BP the sea-level were only 3-4 meters above present. During the last centuries, sea-level have remained close to present (Salvigsen et al., 1990).

The sampling site is at the modern southeastern lakeshore of Straumsjøen (surface 1.5 m.a.s.l.) in gently sloping terrain at ~2.5 m.a.s.l.

2.6.4 Bolterdalen

Bolterdalen is a side-valley to Adventdalen, with the sampling location located approximately 9 km southeast of Longyearbyen. Raised marine beaches mark marine limit at 62 m.a.s.l. and were constructed around 10 ka BP, once the area became deglaciated. Evidence for glacier readvance at ~ 9.6 ka BP into shallow water at 58 m.a.s.l. is described by Lønne (2005). The advancing glacier overrode the frozen surface and deposited a wave-influenced ice-contact delta as well as submarine fan foreset beds. Although thin, the advancing glacier likely deformed sediments to ~1 m depth (Lønne, 2005). Abundant mollusks, especially *M. Truncata* dated ~ 9.6-9.8 14C ka BP, are found at the sampling location for this thesis, as well as a whalebone dated ~ 10 14C ka BP.

2.7 Foraminifera

Foraminifera are single-celled organisms inhabiting marine environments spanning from the deepest parts of the oceans to the high-water level (Cushman, 2013; Scott et al., 2007). While known to be mainly marine organisms, recent studies based on rDNA sequences have also revealed a higher number of forams in freshwater and soils than previously observed (e.g. Pawlowski & Holzmann, 2002; Lejzerowicz et al. 2010). Their abundance often exceeds 1000 specimens per 10 cm³, demonstrating their importance in trophic mechanisms as well as their role in the carbon cycle. Fully grown individuals typically reach a size of > 100 µm, while a few species have been reported at over 14 cm (Grell, 1973 in Gupta, 1999)

2.7.1 Ecology and characteristics

Foraminifera, or forams for short, are typically characterized by having an enclosing test of interconnected chambers (Loeblich and Tappan, 1987). Naked forms, without a test, are also argued to exist (Pawlowski et al., 1998), however, these are not preserved in the fossil. Despite being unicellular, foraminifera perform fundamental tasks similar to multicellular animals, such as moving, eating, growing, defecating and reproducing (Gupta, 1999). They respond to environmental changes; hence evolution has led to foraminifera targeting basically all marine environmental niches.

Species are normally defined and distinguished from each other by their ability to reproduce sexual, however, within foraminifera taxonomy, species are defined by their test morphology (Murray, 2006). As the life cycle is known for only 30 foraminifera species (Murray, 2006), and the known life cycles show asexual and sexual reproduction alternating between generations, the chamber and wall structure and the shape of the test form the basis for defining and differentiating species. This is particularly true when identifying dead assemblages, as the cytoplasmic body is not preserved in the fossil record.

In general, two main morphological characteristics differentiate foraminifera from other protists; the pseudopodia and the test. The pseudopodia is the “arm” that reaches out of the test and that all foraminifera possess (Gupta, 1999). The morphology is granular and so-called anastomosing; it splits and re-joins. It has proved essential for many aspects of the foraminiferal life, from feeding to movement and physical attachment (Gupta, 1999).

The other main morphological feature is the test, shell or “external skeleton” that nearly all foraminifera species possess (Gupta, 1999; Scott et al., 2007). This test can be build up in

different ways. It can be agglutinated, which means it's formed by cementing detrital material. Some species have an organic test, and in some cases the test is build of silica and in some cases the test can be organic (Gupta, 1999; Hald, 1994).

However, the most common way to form a foraminifera test is to build a calcareous (calcium carbonate - CaCO_3) test or shell (Gupta, 1999; Hald, 1994). Out of the 15 extant orders of foraminifera, 11 orders are characterized by calcareous tests (Gupta, 1999). This is also the most relevant orders for paleoenvironmental analysis, since the tests leave a fossil record and can be radiocarbon dating and stable isotopes analysis. Agglutinated tests can also be preserved. The calcareous tests can be further distinguished into three types:

- Porcelaneous, non-laminated wall with three layer (Hald, 1994)
- Microgranular, with an inner layer of regular packed grains and an outer layer of irregular packed grains (Hald, 1994)
- Hyaline, with calcite crystals either radial, oblique, intermediate or compound oriented (Scott, 2007)

2.7.2 Classification

Historically, the taxonomy of foraminifera has varied over time and has been revised several times (e.g. Cavalier-Smith, 1993; Cavalier-Smith, 1998; Gupta, 1999; Hald, 1994; Murray, 2006). The following classification is based on Armstrong & Brasier (2004), however, recent progress in molecular and DNA analysis partly challenge the classification based on wall structure and composition (Holzmann & Pawlowski, 2017):

Kingdom PROTOZA

Phylum SARCODINA

Class RHIZOPODA

Order FORAMINIFERIDA

2.7.3 Preservation and taphonomic processes

Foraminifera are useful in paleoenvironmental reconstructions when they leave a fossil record we can observe; hence, only forams with a hard calcareous or in some cases agglutinated, which are preserved over time, are used this way. Taphonomy is also important when interpreting fossil or sub-fossil foraminiferal assemblages to reconstruct palaeoenvironmental change for various applications. For example, foraminifera tests can be transported from their

living position, destructed or dissolved, changing the composing of the once living assemblage. These taphonomic processes must be evaluated carefully when making paleoenvironmental interpretations based on fossil assemblages (Murray, 2006). Still, this doesn't mean that a fossil record will give unreliable results, but to recognize taphonomic processes is of urgent importance when interpretations are made.

A vital aspect to consider is that comparing the relative abundance between dead and living assemblage relies on the rates of reproduction and lifetime for individuals of a certain specie; a higher turn-over of one specie may lead to higher accumulation of dead and fossil tests than a specie with lower turn-over (Murray, 2006).

The preservation of a given test is dependent on a number of factors, which can be both chemical, biological and physical, some of which is described below:

Transport of dead and living tests can have multiple causes. As a sediment, the empty test itself is hollow and lighter compared to most other similar-sized sediment grains, and can be transported as bed load or suspended load, often caused by waves or tidal currents in shallow waters (Murray, 2006). The variety in shape among foraminifera species makes the threshold to transport them different; some are transported by weaker forces than others, hence can parts of an assemblage be transported while other species remain *in situ*. The magnitude and distance of this form of transportation can vary greatly, from locally within the same environment to tens or hundreds of kilometres, to a completely different environment. Suspended load typically involves species with small adult size as well as juvenile individuals (Murray, 2006).

Foraminifera can also be transported with turbidity currents, where mass flow of sediments for instance can lead to alternating transport and deposition in a downward slope. Also, foraminifera can be frozen into overlaying ice, which in turn can move and redeposit the foraminifera (Murray, 2006). Foraminifera living epiphytically on sea plants will be transported with the plants when their roots are lifted in, for instance, a storm, and may accumulate together with the plants in certain areas when being moved either to the shore, along the shore or out at sea (Bock & Moore, 1968). Further, onshore winds can pick up dry sediment grains, including foraminifera, and transport them to the sand dunes. Abundant *Lobatula lobatula* have been reported from sand dunes in Ireland, and foraminifera have been reported 800 km from the sea in Thar Desert in India (Murray, 1970; Goudie & Sperling, 1977).

Another possible source of transportation is bioturbation caused by both epifaunal organisms and infaunal organisms moving within or over the sediments, moving sediments around chronologically and chorological, as well as opening new circulation ways for pore water (Murray, 2006). In turn, this may change the chemistry of the sediments, and the general result for paleoenvironmental investigations is a blurred picture of the sediments, where sediments of different age are mixed together. The depth where these biogeochemical and physical short-term postmortem processes are effective is by some interpreted to be roughly 1 meter (Murray, 2006), the so-called taphonomically active zone (TAZ). Below this depth, sediments are considered to be more undisturbed and effectively fossilised (Douglas et al., 1980; Murray, 2006). However, there have been observations of species bioturbating to greater depths. A shrimp species was by Pemberton et al. (1976) reported to burrow down to > 3 meters depth, moving through sediments representing a time interval of 300 years despite high sedimentation rates. From the shrimp species *Axius serratus*, a population density of only 18 specimens/m² have been estimated to, within twenty years, rework roughly 30 % of the sediments down to two meters depth (Risk et al., 1978).

Even though the forams might resist every force mentioned above, and manages to remain *in situ* waiting for the micropaleontologist to appear, destruction over time through mechanical, chemical and/or biological mechanisms is still a threat. Calcareous dissolution is a major consideration from living to fossil assemblage, but the nature and causes of calcareous dissolution is still subject to various understanding (Murray, 2006). While the understanding of calcite dissolution is linked to its narrow pH window hence being challenging to reconstruct in laboratory experiments (Morse & Arvidson, 2002), some general patterns have been drawn (Scott et al., 2007). Anoxic conditions often offer enhanced potential for preservation, exceptions include salt marshes where low oxygen can lead to low pH and sulphide production (Phleger & Bradshaw, 1966). In estuaries, preservation of fossils with secreted calcareous skeletons have been inversely linked with the abundance of organic matter. This is perhaps more important than sedimentation rates (Simon et al., 1994), on the other hand, a high sedimentation rate may quickly bury the foraminifera so that they are affected by destructive mechanisms in the sediment/water interface for a shorter time-span. Also, the inversely relation linked to dissolved organic matter is believed to be lesser in shallow, high-energy settings (Scott et al., 2007).

Also agglutinated tests may be destroyed or dissolved. Agglutinated tests may be destroyed or teared down by either chemical or bacterial decay of the organic cement, or through predation (Murray, 2006).

2.7.4 Foraminifera as a paleoenvironmental tool

Since Alcide d'Orbigny first came up with the word foraminifera in 1826, the numbers of species discovered and their scientific applications have been widely expanded. From the 1920's foraminifera gained attraction as a stratigraphic tool with especial interest from petroleum consultants (Hald, 1994), while the applications within paleoenvironmental reconstructions started off in the 1950's, represented with the deep-sea sediment cores from Phleger et al. (1953) and Ericson & Wollin (1956). The pioneer work on oxygen isotopes measured in forams, and stratigraphy linked to this, also started off in this decade.

In a Norwegian setting, a number of foraminiferal studies were done from the mid 1800's, and with respect to Svalbard foraminiferal studies were done, among others, by Goës (1894). However, the broad work of Feyling-Hanssen in the 1950's and 60's built a foundation for modern-day application of foraminifera taxonomy, stratigraphy and environmental reconstructions in Norway (Hald, 1994). As mentioned in further detail in chapter 2.2, Feyling-Hanssen is also central in the description of the "Mytilus-horizon" and findings of thermophilous molluscs in Svalbard, which acts as a central part of the theoretical background for this thesis.

There are a number of reasons why foraminifera have gained popularity as a tool for environmental monitoring and paleoenvironmental reconstructions. Here are a few of their advantages:

- Foraminifera typically occur in large numbers over a certain area or volume, unlike most invertebrates. Often, they are represented with a magnitude of 100 to 10000 individuals $>63 \mu\text{m}$ on 100 cm^2 (Murray, 2006), a magnitude meaning that even with a small sample volume a large and statistical significant number of individuals can be counted (Scott, 2007). Even though a number of replicates is needed to strengthen the data material, their distribution compared to most macrofauna give foraminifera a huge advantage.

- Since foraminifera are one of, or the only, organisms represented in statistically valid numbers in small volume cores and samples, they are highly cost-efficient and time-efficient, and easily accessible in many environments.
- Per 300 individuals, as much as 20 to 50 species can be expected, which means a highly variable benthic foraminiferal fauna. As each species has its niche, the existence and abundance of the species might serve broad environmental information (Schönfeld et al., 2012)
- The short life cycle of foraminifera compared to higher trophic organisms means they respond quickly when the environment is changing.
- Changes in proportions or absolute numbers of foraminiferal assemblages can therefore be indicators for environmental changes to which larger fauna will respond slower (Schönfeld et al., 2012; Armstrong & Brasier, 2004).

2.7.5 Key foraminifera species in Svalbard fjords

Modern investigations of the foraminifera fauna in Svalbard fjords (e.g. Hald & Korsun, 1997) have documented the main calcareous benthic species thriving in the fjords today, as well as fossil records from the early Holocene (e.g. Rasmussen et al., 2012).

According to Szczuciński et al. (2009), the fjords in Svalbard can be good sites for obtaining high-resolution assemblages and changes due to relatively high sediment rates. Even though subdecadal resolution has been obtained in Adventfjorden (Zajączkowski et al. 2004), too high sedimentation rates may lead to low concentrations, as well as being very fluctuating, hence reflecting local and short-lived variables.

Unlike the thermophilous molluscs, which have been extinct in Svalbard through parts of the Holocene, the key foraminiferal species found in fossil records are all present in Svalbard fjords today (e.g. Hald & Korsun, 1997). Although foraminifera species can provide valuable paleoenvironmental information, this may be an argument that the foraminifera occurrence itself, at least in a Svalbard setting, is perhaps a less sensitive indicator of AW and the HTM.

Key species in present and fossil foraminifera records from Svalbard fjords include the following:

Lobatula lobatula prefers to live on coarse-grained sediments, typically thriving on sandy seabeds, and in high-energy settings with high turbidity (e.g. Sejrup and others, 1981; Hald

and Vorren, 1984; Husum and Hald, 2004b). Jennings et al. (2004) note preferences for low sedimentation rates while Hald and Korsun (1997) noted a positive correlation with gravelly seabeds.

Astrononion hamadaense, like *L. lobatula*, prefers high-energy environments (Polyak et al., 2002), and often occurs together with *L. lobatula* (Wollenburg and Mackensen, 1998a). These two species are together known to dominate environments with strong currents (e.g. Sejrup et al., 1981; Hald and Vorren., 1984; Polyak et al., 2002).

Cassidulina reniforme is a common arctic species typically found on continental shelves and fjords and associated with normal marine salinities, cold bottom temperatures and muddy substrates (e.g. Mackensen et al., 1985). Hald and Korsun (1997) linked this species more specifically with the cold, low-salinity waters of inner fjord environments. Other studies have however, found *C. reniforme* to be dominant in 5 °C bottom waters with 34.7‰ salinity in Iceland (Jennings et al., 2004) and as warm as 6.-6.9°C in Malangen fjord, Norway (Husum, 2002).

In the transect made throughout Isfjorden and Billefjorden by Hald and Korsun (1997) *C. reniforme* were found, together with *C. excavatum*, to increase in abundance towards and in the inner fjords. Inverted proportional to this trend were the abundance of *L. lobatula* and *N. labradorica*; both species decreased in abundance from the outer to the inner fjords (Hald and Korsun, 1997). This pattern was not restricted to Isfjorden-Billefjorden – the inner parts of Hornsund (figure 4) and Van Mijenfjorden (figure 4) are both classified as *C. reniforme* – dominated assemblages (Hald and Korsun, 1997). *C. reniforme* is commonly found to thrive in various glaciomarine environments (e.g. Hald and Vorren, 1987).

Another common Arctic species is *Cribroelphidium excavatum*. It's known as an opportunistic species, often abundant in environments with fluctuating conditions (e.g. fast changes in sediments supply and salinity), and is typically abundant in glacial-proximal places (Hald et al., 1994). Their conclusion was that *C. excavatum* is linked to “something” characteristic for glacial-proximal sites, revealing the species's ability to cope with rapid shifts that might occur close to a glacier, such as various salinity and sediment flux. As mentioned, *C. excavatum* have the present tendency to increase in abundance towards the inner fjords in Svalbard together with *C. reniforme*. Hald et al (1994) found it at around 10 % abundance in outer areas of Svalbard fjords in various assemblages. It is known for living infaunally, 6-10 cm below the sediment surface.

In terms of thermal regime controlling the species, data from Kara sea and Barents sea show that *C. excavatum* is nearly absent in water temperatures above 2.5 °C, in other words several degrees colder than mean and even minimum bottom water temperatures derived from other temperature proxies (e.g. *A. islandica* showing 9.1 °C average bottom water temperature in Dicksonfjord prior to 8.2 ka BP), and the known thermal threshold for *A. islandica*. Further, Hald et al. (1994) found the highest values of *C. excavatum* in slightly low salinities around 33 ‰, although this also coincides with low temperatures.

Nonionellina labradorica. According to Hald & Korsun (1997), the present distribution of *N. labradorica* in Svalbard fjords shows a positive correlation with temperature, depth and salinity, and is therefore in general more common in outer and deeper parts of the fjords due to the bottom flow of Atlantic water. There are exceptions; in Krossfjorden, characterized by depths 200-400 meters, no sill and relatively warm bottom water during summer (Hald & Korsun, 1997), *N. labradorica* is at present the dominating species, with 20-40% abundance, throughout the whole fjord. From Wijdefjorden, the highest abundance of *N. labradorica* coincides with maximum abundance of total foraminifera (but low abundance of living foraminifera) and coarse sediments, attesting to a high-energy environment.

3. Methods

3.1 Fieldwork

The fieldwork for this project was conducted at four different locations around Isfjorden in the western part of Spitsbergen in the fall of 2020 (Figure 1). Three field sites were reached by boat from Longyearbyen, namely Hiorthhamn (08. September 2020), Bogebecken (10. September 2020) and Erdmannflya (18. September 2020), while Bolterdalen was reached by car on 30. October 2020. A hand-held Garmin GPSMAP 65 Series GPS was used to record the locations of the field sites. In order to register the heights and altitudes of the stratigraphic sections in Bogebecken and Hiorthhamn, and the height of the section at Bolterdalen, a hand-held altimeter, 230-M202 Handheld Digital Barometer-Altimeter, by Nova Lynx was used. To determine the vertical spacing between samples in the different stratigraphic sections, a wooden folding ruler was used. Hand-drawn sketches and photographs were also taken at each section.

Due to different field settings and access to the sediments, methods used to excavate the sediments differed between the field sites, in particular between Erdmannflya and the rest. At Hiorthhamn, Bogebeekken and Bolterdalen, stratigraphic sections were exposed and cleaned up via digging into the cliff face with shovels and trowels, removing younger debris that had slumped down the cliff, and preparing as vertical as possible, cross-section. Samples for foraminiferal analysis were then collected from the exposed strata. Fine-grained beds containing thermophilous molluscs were favoured over coarser-grained beds as benthic foraminifera are more likely to inhabit lower-energy, fine-grained seabed environments over high-energy sandy or gravelly seabed environments (Katrine Husum & Anna Pienkowski, personal communication 2020). Erdmannflya does not offer the same possibility, and thus, here, samples were excavated from pits dug vertically down into the raised marine sediments.

At all sites, sediments were collected with the aid of a trowel or spoon and put directly in individual, labelled plastic bags. Approximately 200 grams of sediments were collected per sample if possible, in order to have spare material in case of failure or additional analysis required later. In the frozen ground of Bolterdalen, fewer grams of sediment were collected due to difficult digging conditions (namely frozen ground). Shovels and/or spoons were cleaned with freshwater and dried between each sample, in order to minimize the risk of contamination and not influencing the water level in the samples unnecessarily. In Erdmannflya, one challenge when taking the samples from the holes was to perform this task quickly; if not the holes tended to either fill up with water or collapse. If required, further digging was done to make sure the samples were taken from freshly exposed sediments.

However, retrospectively it must be admitted that the number of samples and replicates taken are neither optimal or in accordance with initiated standards (e.g. Foraminiferal BIO Monitoring, known as the FOBIMO-initiative (Schönfeld et al., 2012)). This is a limitation of the study and is discussed in chapter 5.6. At the same time, it can be argued that a higher number of samples and replicate samples could be taken since the nature of this fieldwork was less time-consuming and expensive than deep-sea sampling, which is true, however that would eventually have exceeded the magnitude and available time of this master thesis.

3.1.1 Hiorthhamn (78.245°N, 15.72°E)

Samples were taken from a section in the delta foreset running parallel to the shoreline, described by Lønne & Nemec (2004). A layer of redeposited sediments were removed in order to reach the inner sediments with its stratigraphy. Below the coarser upper layer which

occupies the upper 3-4 meters of the foreset, a total of 11 samples were taken. One sample were taken from the coarse top layer. Samples were targeted from the seemingly finer layer of sediments between the mostly sandy-silty material. Observed fragments of *Mytilus* spp appeared thin and fragile. *Mytilus* spp were also found and radiocarbon dated by Lønne & Nemec (2004).



Figure 11. Hiorthhamn: cleaned stratigraphic section. Two steps are dug out and visible in the picture, the uppermost reaching the contact with the overlying coarse alluvial top-set beds, which are up to 4 m thick (Lønne et al., 2004). The underlying sandy-silty sediment layers are parallel and dipping towards the south at 20-25 degrees from horizontal.



Figure 12. Hiorthhamn, looking south-southeast: dipping beds at the delta foreset,



Figure 13. Delta foreset at Hiorthhamn where samples were taken. Picture taken towards southeast.

3.1.2 Erdmannflya (78.314°N, 14.15°E)

At Erdmannflya (Figure 1), the excavation of the sampled sediments differed compared to the other sites, as there are no cliff faces to excavate stratigraphic cross sections from. Instead, samples were taken from the relatively flat, gently sloping hill on the south shore of Lake Straumsjøen (Figure 14), underlain by silty-muddy sediments, surrounded by small streams. Here, five pits were dug vertically, reaching depths ranging from 25 to 45 cm (figure 15). The five pits were dug so that they together formed a cross; one pit in the middle and the four others in different directions away from the middle. The distance from the middle pit to each of the other pits was approximately three meters, meaning the five pits covered an area of 18 square meters if a quadrat were drawn around the outer four.

The distance between the holes, and the area the samples cover is important because, although foraminifera are relatively abundant, with a typical density between 100 and 10,000 living individuals $>63 \mu\text{m}$ per 100 cm^2 , their distribution and abundance can vary greatly over short distances due to local conditions and different environmental preferences. Therefore, by taking several across a larger area helps to capture some of the local variation, painting a clearer picture of the site's foraminiferal assemblage(s) and providing a better foundation for palaeoenvironmental analysis.

In addition to the sediment samples, molluscs were collected, from both the pits and from the surface, which in some areas had a remarkably high density of molluscs, particularly specie *M. truncata*.



Figure 14 Erdmannflya. Rings mark where samples are taken. Picture taken towards north.



Figure 15. Pit 2 from Erdmannflya, in which foraminifera sample were taken. Silty mud with high water content.

3.1.3 Bogebecken (78.10°N, 14.40°E)

At Bogebecken, samples were taken from surficial sediments forming the western slope of the excavated river valley. The sediment face, with a steepness of 35 – 40 degrees, was covered in reworked debris that required removal in order to expose a clean stratigraphic section.

Shovels were used to clear away the reworked debris and create a section with vertical steps, from which samples could be taken (Figure 16). The steps were excavated in order to be able to dig the entire section without it collapsing on itself, and to be able to reach and sample from all parts of the section.

Samples were taken from the marine terrace (interpreted by Sharin et al. (2014), see section 2.6.2), spanning from 0.9 masl. to 8.5 masl. As described in 2.6.2 there are three main units; of these middle sandy-silty unit is dominating. This spans from 1.0 m.a.s.l. to 7.0 m.a.s.l.,

with the coarser layer on top and the silty layer beneath (figure 16). The lowermost silty layer spans only 10-15 cm before reaching the groundwater-filled zone. Ten of the twelve samples were located within the sandy unit, which made up most of the section. Within this unit, few or none fine-grained layers were seen. In addition to the sediment samples, several mollusks were collected. When possible, mollusks were collected from the same stratigraphic layer as the foraminifera samples, and close also in terms of horizontal distance. Mollusks were also collected from the uppermost debris above the excavated section. The mollusks collected included species of *M. Truncata*, *A. Islandica* and *Mytilus* spp. Whole shells and paired valves were collected.



Figure 16. Cleaned sediment section in Bogebecken. Picture taken towards west-northwest (left picture) and northwest (right picture)

3.1.4 Bolterdalen (78.175°N, 15.945°E)

In Bolterdalen, samples were taken from the well-described “whale-bone site” (Lønne, 2005), which also is frequently visited by UNIS-students (Mark Furze, oral communication 2020). The section in Bolterdalen were sampled in the beginning of the dark season on October 30th, 2020, which meant an additional challenge with frozen ground. This aspect made it harder to dig in the sediments.

Like in Bogebeekken and Hiorthhamn, samples were taken from an excavated cliff face (i.e. younger, redeposited, overlying sediments were manually removed prior to sampling) (figure 17). This, as well as acquiring enough sediments per sample was challenging with the frozen ground. Because of this, chunks of sediment were broken out of the section and collected in sample bags at different elevations. Abundant *M. truncata* were seen, including paired valves. A total of 20 samples were taken from two vertical transects with ten samples from each.

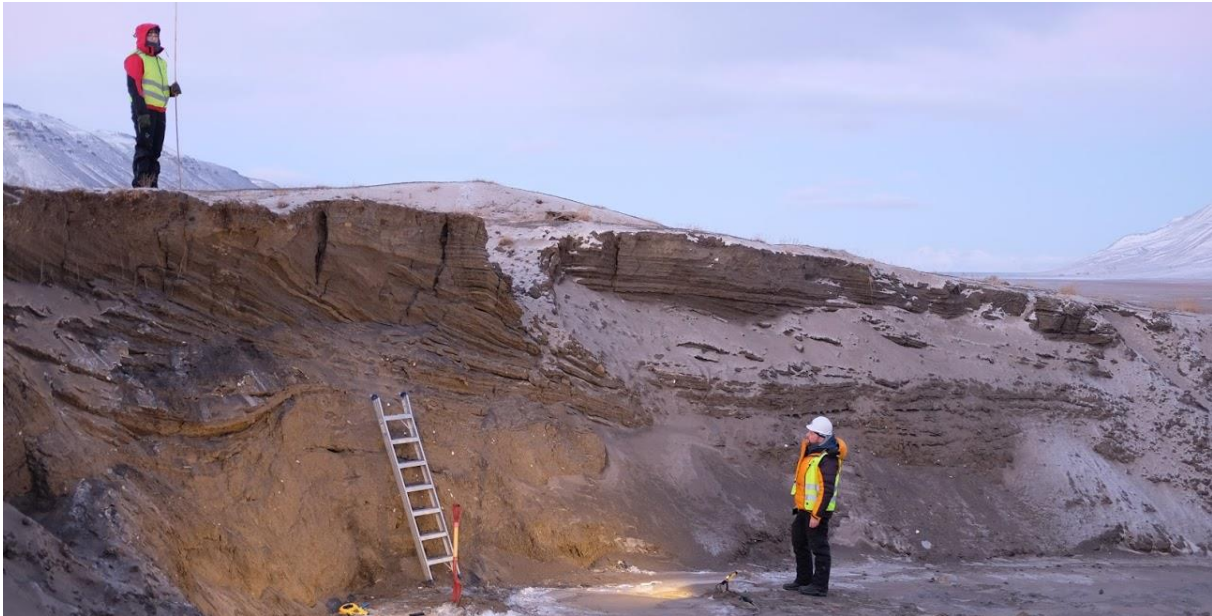


Figure 17. Bolterdalen. Samples were taken from the sediment face seen. Picture is taken towards northwest.

3.2 Processing of the samples

In the time span from field work to sieving of the samples, all samples were stored in a fridge, to prevent the growth of microbial organisms. Storing samples in a preservative between sampling and processing is also advised when dealing with living foraminifera, in order to prevent decay of the foraminiferal cells (Schönfeld et al. (2012)), however this was not considered necessary for the purposes of this study, since we only have dead foraminiferal assemblages.

3.2.1 Wet sieving

From each sample, 20 ml of sediments were placed into a graduated cylinder containing 40 ml distilled water, allowing for an estimate of sample volume by eradicating air volume between grains (Mark Furze, personal communication 2020). The mixture was then poured through a sieve with a 63 μm mesh. Here, the sediments were wet sieved with a gentle hand to make sure no foraminifera were crushed in the process. The remaining sediments were brought to a

bowl with the help of flowing water. These bowls, containing water and sieved sediments, were set to dry (see 3.2.2). The following rinsing process was then followed to thoroughly clean the 63 μm sieve to prevent contamination of the next sample:

- Rinsing with tap water from both sides
- 1-2 minutes sonic bath in tap water
- Staining of 63 μm sieve with methyl blue. If there are any remaining sediments or foraminifera on the sieve, the methyl blue will stick to these and make them stand out from the next sample. By doing so, eventual contamination tracing from the previous sample will be easily seen.
- Rinsing of the sieve to with tap water again from both sides to remove any residual sample or methyl blue, prior to sieving the next sample.

3.2.2 Drying and dry sieving

Following sieving, samples were dried in an oven at 45°C for a minimum of 48hrs. Dried samples were sieved again with a 100 μm mesh sieve. The samples were then split in two sediment fractions: >63 – 100 μm and > 100 μm .

3.2.3 Fraction size and counting of foraminifera

If all foraminifera should remain in the sample – including all juvenile individuals that can be difficult to identify taxonomically – the recommended mesh size should be around 20 μm (Schröder et al., 1987). A consequence of using such a small mesh size is that silt and clay will also be trapped together with any foraminifera, which leads to a labour-intense study and difficult taxonomy. Most foraminifera studies use sieve mesh sizes of between 63 μm , 125 μm and 150 μm . The preferred sieve size should reflect the purpose of the study and the amount of work and costs that are needed and available, and thus vary between studies.

A number of studies highlight the impact of sieve mesh sizes on species and specimens observed in a sample, and to which degree studies using different sieve sizes can be compared to each other. For example, half of all specimens and one third of all species were not observed when using 125 μm instead of 63 μm (Schönfeld et al. (2012). Storz (2006) showed that in some environments, the fraction between 125 μm and 150 μm can contain up to 80 % of the planktonic foraminifera, however, since benthic foraminifera generally speaking are larger (Armstrong and Brasier, 2005), the effect is likely to be lesser with benthic

foraminifera. Both Schönfeld et al. (2012) and Hermelin (2012) indicates a decline of about 28 % in observed numbers of foraminifera when using 125 μ instead of 63 μ . Weinkauf and Miller (2018) concludes that already small changes in mesh size, in their particular study 25 μ from 125 μ to 150 μ , make comparisons between assemblages and studies very challenging due to lack of genus and species in either of the fractions. In fact, they conclude that the different fractions can be used to monitor general biodiversity trend, but since the differences between the fractions show lack of consistency in magnitude, and neither in time nor space, the two fraction sizes are highly incomparable (Weinkauf and Miller, 2018). Further, for past environment construction studies, and other studies where errors tend to be rather large, comparisons between these and similar differences in size fractions can still be useful. Schönfeld et al. (2012) offer a clear suggestion to use 125 μ as a standard, based on the additional work associated with smaller sieve opening compared to the additional value it might offer.

In arctic environments, however, adult foraminifera often are smaller in size while at the same time being easy to identify (Schröder et al., 1987). Therefore, the choice to use 100 μ in this study, should avoid an unacceptable high loss of species, specimens and maximize the potential for accurate paleoenvironmental interpretation.

In order to be within a 95 % confidence interval, high-abundance species require lower counts than species which are less abundant in an assemblage. This means that the number of specimens that should be counted in order to be within a 95% confidence interval will vary. Patterson and Fishbein (1989) suggest that for a species with 50 % or higher fractional abundance, as few as 50 individuals are enough, while this number increases to 300 for a species for 10% fractional abundance. For species making up 5% of the assemblage, 500-1000 individuals are required, while they suggest that several thousand individuals should be counted for species with an abundance of only 1%. In other words, if the study was dependent on species with low fractional abundance, a high number of individuals would need to be counted; on the other hand, if the study only focussed on the most abundant species and neglected species with abundances <5%, reliable statistics could be made, even with relatively low specimen counts.

The main issue with counting of species is illustrated by Fatela and Taborda (2002), who noted that in samples where at least 100 individuals were counted, all species with an abundance of 5% or more would be probably represented, with a probability of only 0.7% of not being present at all. Nonetheless, the binominal error of species abundance in such a

sample would be unacceptably large for use in most analyses. The paleoenvironmental indications from a species is not only coming from its presence, but also its abundance, and so it follows that statistics itself cannot determine how many specimens should be counted in a sample.

For decades many foraminiferal studies have aimed for 300 counted individuals in each sample (Fatela and Taborda, 2002; Patterson and Fishbein, 1989), and this is also the general recommended target value made by the FOBIMO-initiative (Schönfeld et al., 2012). Even though Svalbard can be seen as a marginal marine environment and it can be argued that 100 specimens per sample is enough to assess the diversity (Fatela and Taborda, 2002), a target value of 300 specimens was chosen for this study, both to have the possibility of seeing the abundance of more species, and to contribute to building a common scientific platform of foraminiferal methods.

All samples were initially scanned under a stereo microscope to get a sense of approximate abundances of foraminifera in order to determine the split fraction. Samples with the most foraminifera were first split into smaller size fractions than what was expected to be required to give counts of 300; since the whole split fraction must be counted, this was determined to be the most efficient method and would help avoid counting for instance, 1000-2000 individuals per split if the chosen fraction was too big. This contradicts the recommendation of using the same split size in all samples (Schönfeld et al., 2012), but since the density of foraminifera varied so greatly between the sampling sites, from >300 specimens in 1/64 of a sample to <300 in entire samples, this was determined to be a necessary step. Otherwise, samples were split to target 300 specimens and species were identified and counted using a Nikon SMZ1270i microscope.

3.3 Radiocarbon dating and calibration

Carbon-14 (^{14}C), or radiocarbon, is a radioactive isotope of carbon with 8 neutrons and 6 protons, and which occurs naturally in all living organisms. The ratio between C12 and C14 varies in space and time, and the C12:C14 ratio in an organism reflects that of its environment at that time. When the organism dies and is no longer taking up radiocarbon, the C14 starts to decay at a rate according to its half-life of $5,730 \pm 40$ years. This offers the possibility to date

carbonaceous material up to approximately 50 000 years back, by determining the remaining amount of carbon-14.

When dating marine organic matter, the difference in abundance of ^{14}C in the ocean versus in the atmosphere requires a reservoir correction. The ^{14}C -age-difference between samples which got their carbon from the ocean and samples which got the carbon from the atmosphere, is known as the marine reservoir correction, ΔR (Stuiver et al., 1986). However, the age of the marine reservoir is not uniform – it varies in space and time and because of ocean circulation and ventilation (Stuiver and Braziunas, 1985; Coulthard et al., 2010). In today's surface water, the marine reservoir age is known to vary between 350 and 1500 years (Reimer & Reimer, 2001).

Marine calibration can be challenging when going back to the early Holocene, where fluctuations in sea-ice and air-sea gas exchange may be unknown. It might be argued that building on the database from Mangerud et al. (2006) is worth using in this thesis, following the logic to have the same ΔR value from coastal Norway to west Spitsbergen, since this is the same water mass / water current. This is argued for with the following words in Mangerud et al. (2006): “*The volume of Atlantic Water that enters the Norwegian Sea between Scotland and Iceland is huge, and the water mass travels all the way to Svalbard within a year without entraining significant amounts of additional water with different reservoir ages. We therefore maintain that the Atlantic Water has nearly the same marine reservoir age along the entire stretch from Scotland to Svalbard*”. This might as well make sense with respect to the early Holocene, when the thermophilous molluscs were migrating northbound. According to this logic it follows a suggested ΔR value of 20 ± 30 yr relative to the global average Marine04-curve (Mangerud et al. (2006).

On the other hand, it can be argued that there are regional and local differences from coastal Norway to Spitsbergen, and that the assumptions above from Mangerud et al. (2006) overlooks this. In fact, the very same paper highlights this different view: there is an “alternative discussion” from Bondevik and Gulliksen (Mangerud et al., 2006), which argues that the non-uniform influence of Atlantic water and run-off from mainland Norway to Svalbard requires different ΔR - values. Their mollusks and whales from which they postulate this view is shown in figure 18. The trend of increased ΔR value northward is seen as a result of increased influence of Atlantic water. It must therefore be stressed that, in an ideal world, each water mass got its own ΔR , and on a local scale this northward trend might be an oversimplification. Freshwater-input from rivers and glaciers may strongly disturb this on a

local scale, hence it follows that there might be differences between locations in Isfjorden as well as a difference between Isfjorden in general and the outer shelf. However, such a resolution can't be accounted for with neither of these two approaches. Mangerud and Svendsen (2018) who follows the approach of keeping the same ΔR -value from mainland Norway to Svalbard, consider run-off from land to have only minor influence.

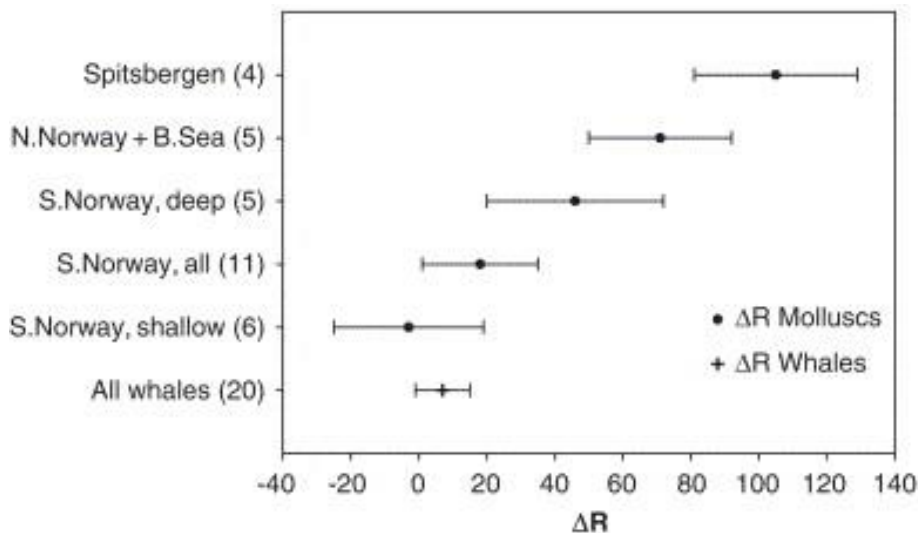


Figure 18. Bondevik and Gulliksen's view in Mangerud et al., 2006: ΔR values for different populations show a clear trend with increasing values towards North. Whales are younger than most of the different groups of molluscs. No. of samples within each group are in parantheses.

A new, yet unpublished ΔR - value for western Spitsbergen have been calculated on the basis of Bondevik and Gulliksens's view (Mark Furze and Anna Pienkowski, written communication 2021). In practical terms, it takes use of the same four datapoints from Svalbard, but is recalculated with the new global calibration curve MARINE20.

This new ΔR - value for western Spitsbergen, -66 ± 35 yr relative to MARINE20, is the approach and value chosen for this thesis. As seen from Bondevik and Gulliksen in Mangerud et al. (2006) there are differences in reservoir age both along the coast of mainland Norway and in the waters between Svalbard and the mainland, and from that it follows that a greater regional accuracy can be achieved by implementing regional and local ΔR - values along these waters. There are at present more knowledge about oceanic circulation and characteristics around Svalbard than it was when Mangerud et al. (2006) was written (Mark Furze, written communication 2021) which makes a regional approach more rigorous now. It can therefore be argued that this approach gives a better and more nuanced value – still, it must be admitted that local offset from this regional value might be of greater impact than the difference between the two main approaches described.

One issue which must be addressed is the nature of the marine calibration curve MARINE20. The MARINE20 curve is not intentionally made for use in polar regions – it is in fact intended for calibrating marine samples approximately 40°S-40/50°N (Heaton et al., 2020). In polar regions the Marine Reservoir Age (MRA) value and its fluctuations will eventually be larger (Heaton et al., 2020). MARINE20 is explicitly described as being non-suitable for polar regions, due to various extent of sea ice, ocean upwelling and air-sea gas exchange, which all influence the concentration of marine radiocarbon (Heaton et al., 2020). In fact, 40/50 °N is around the latitude of Spain, far south of what's commonly described as polar regions. This reflects the known extent of sea ice during LGM, hence unknown fluctuations in marine radiocarbon concentrations at that time. Simulations of different past climate scenarios and associated MRAs have shown a difference >1000 ^{14}C yr. between a present-day climate and during a glacial period, showing that the offset from using MARINE0 on glacial periods is likely to be greater (Heaton et al., 2020).

However, being aware of this issue, the calibration curve may still be used. This is exactly the aid of using a regional ΔR ; within this value, all the regional offsets from the calibration curve is incorporated. Therefore, since we already have a new calibrated ΔR -value with respect to the MARINE20 calibration curve, the offset is part of the ΔR -value – and we can use it despite the described limitations of MARINE20.

3.3.1 Dated material

21 bivalve shells, all *A. islandica*, were sent to Keck Carbon Cycle AMS Laboratory, University of California, Irvine, US (table 3). Out of these, 15 were collected in Bogebecken and the remaining six in Erdmannflya. These 21 molluscs were rinsed with tap water but received otherwise minimal pre-treatment before they underwent Accelerator Mass Spectrometry (AMS). Some shells were from paired valves (these are labelled “a” an/or “b”).

19 bivalve shells were to LARA in Bern, Switzerland (table 2). Out of these, six were collected in Bogebecken and 13 in Erdmannflya. Among the molluscs, individuals of *Mytilus* spp, *M. truncata*, *A. islandica*, *Hiatella arctica* and *Serripes groenlandicus* were represented. Pre-treatment was the same as for molluscs sent to Keck Carbon Cycle AMS Laboratory, University of California, Irvine, US.

3.4 SEM photography of specimens

In order to present the foraminifera identified in this thesis, a Scanning Electron Microscope (SEM) was used to photograph the different species. The specimens were gold-coated and photographed. Gold-coating was done at the Department of Materials Science and Engineering, NTNU, while SEM-photographs were taken in the Department of Geoscience and Petroleum, NTNU. Both procedures were done in April 2021. A total of 16 specimens (8 species, 2 specimens from each) were chosen for photographing (Appendix 4). Due to funding restrictions and weeks of technical failure for all SEMs at NTNU in the spring of 2021, all species could not be photographed. The selected species include the key species that are discussed in this thesis. Key species mean in this sense the species which occur with the highest abundances and therefore often the most valuable for interpreting paleoenvironment.

4. Results

4.1 Sampling sites – sediments, stratigraphy and shells

4.1.1 Hiorthhamn

Sandy-silty sediment layers dipping towards the south at 20-25 degrees makes up the vertical span in which samples were taken. These stratigraphic layers reach contact with the overlying coarse alluvial top-set beds, which are up to 4 m thick (Lønne et al., 2004). Grain sizes of the samples were generally in the sandy silt range.

High abundance of organic matter were seen in all samples. Only fragments of mollusc shells were observed – these appeared thin, fragile and decayed.

4.1.2 Bogebecken

As described from Sharin et al. (2014) consists the site of three main units, with a dominating sandy unit (Figure 20, Unit B) between upper gravel (Unit C) and underneath silt and mud (Unit A). Unit B sees few distinct layers within, but is getting slightly coarser towards the top. The border towards the upper coarse layer is distinct (figure 20). This upper layer contains gravel, cobbles and coarse sand. The lowermost layer sees cobbles between silty mud.

Shells are found throughout the sandy and silty-muddy units, with *A. islandica* occurring between abundant *M. truncata*. Up to approximately 3,5 m.a.s.l. whole shells were observed; above this elevation mostly fragments of shells were seen. Paired valves were found on all sampling elevations 1.0 -4.1 m.a.s.l. (paired valves are labelled “a” and “b” in table 3). Periostracum are partly intact on some valves (see pictures in figure 19).

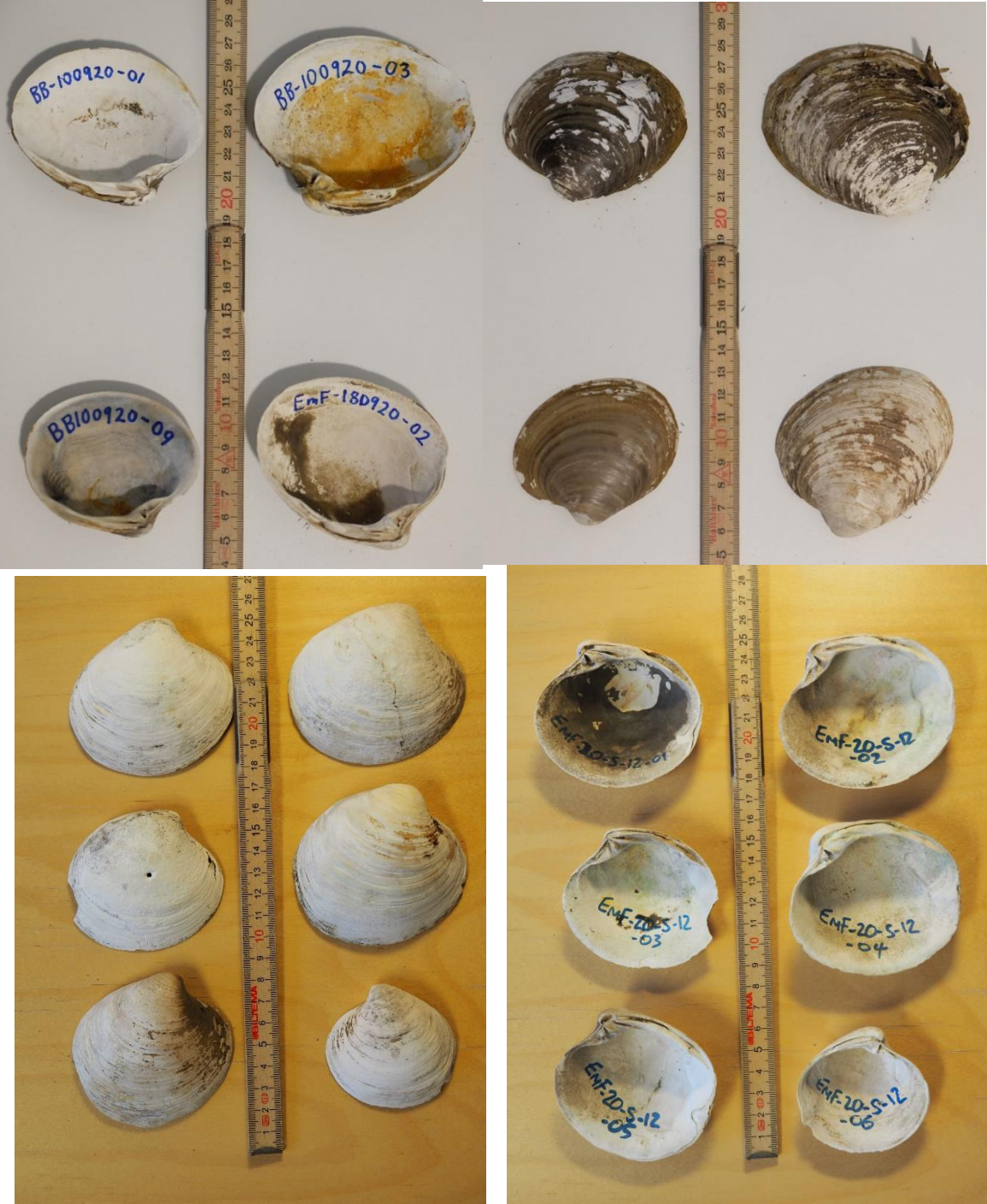




Figure 19 Examples of *A. islandica*. These individuals are all collected during the fieldwork at Erdmannflya and Bogebecken fall 2020, of which some have been sent for radiocarbon dating (table 2, table 3). Periostracum is partly intact at some shells. Shells named “a” and “b” are paired valves.

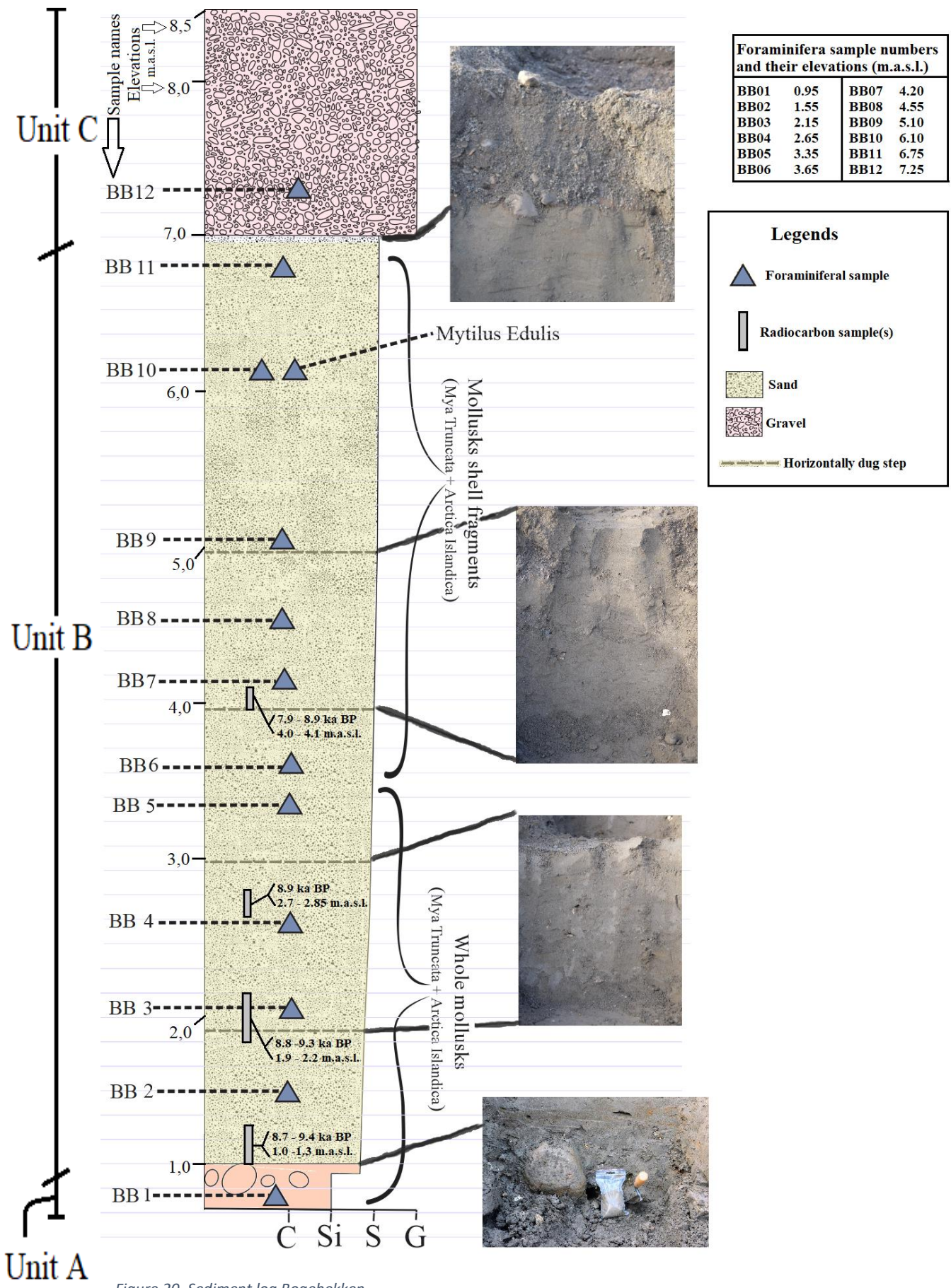


Figure 20. Sediment log Bogebecken

4.1.3 Erdmannflya

The sampling site and the pits all showed muddy-silty sediments, with no observable stratigraphy and with a high level of water. A rich molluscan fauna including whole valves of *A. islandica*, *M. truncata*, *Macoma calcarea*, *Hiatella arctica*, and several *Astarte* species (Mark Furze, personal communication) were observed on the surface, with fragments seen in the pits. One whole valve of *A. islandica* was also found in a pit. Molluscs shells were in general in good condition, with many whole shells to be seen. Low degree of decay were seen, however periostracum was to a low degree intact.

Nearby the sampling site, there seems to be periglacial features and frost-oriented ground (figure 21). Clear signs of these were not seen on the sampled area itself, although frost sorting might be a factor redistributing sediments here as well.



Figure 21. Frost-sorted ground nearby sampling site in Erdmannflya

4.1.4 Bolterdalen

Sediments are slightly coarsening upwards spanning from mud to gravel, although with laminated layers dipping in the upper part of the sediment face. This is what Lønne (2005) described as unit 3 and interpreted as a delta. Abundant *M. truncata* are seen – appearing well preserved and, with occurrence of paired valves indicating that they are in growth position, a view that is confirmed by Lønne (2005).

4.1 Radiocarbon dates

Radiocarbon dating have been received from Keck Carbon Cycle AMS Laboratory, University of California, Irvine, US, but unfortunately the dates from LARA in Bern, Switzerland haven't been received yet in may 2021 (table 2). Results here are therefore the 15 dates from Bogebekken and five from Erdmannflya, all 21 *A. islandica* (figure 19; table 3). All radiocarbon dates in this study were calibrated (or recalibrated to facilitate comparison to previously published dates) with MARINE20 and ΔR - value -66+/-35.

Sample ID	Site	Specie	Fraction	Weight (mg)
BB100920-10	Bogebekken	Mytilus Edulis	near whole valve	5998.7
BB100920-07	Bogebekken	Mya Truncata	shell fragment	5708.7
BB100920-04	Bogebekken	Mya Truncata	whole valve	10156.8
BB100920-02	Bogebekken	Arctica Islandica	whole valve	67075.3
BB100920-01	Bogebekken	Arctica Islandica	whole valve	33242.4
BB100920-09	Bogebekken	Arctica Islandica	whole valve	26434.4
EmF180920-04	Erdmannflya	Arctica Islandica	shell fragment	16842.0
EmF-20-S-01	Erdmannflya	Hiatella Arctica	whole valve	8157
EmF-20-S-02	Erdmannflya	Mytilus Edulis	2xfragments	5282.2
EmF-20-S-03	Erdmannflya	Mya Truncata	whole valve	9820.6
EmF-20-S-04	Erdmannflya	Hiatella Arctica	whole valve	3086.8
EmF-20-S-06	Erdmannflya	Hiatella Arctica	whole valve	4028.3
EmF-20-S-07	Erdmannflya	Unknown	3xfragments	213.7
EmF-20-S-12-08	Erdmannflya	Hiatella Arctica	whole valve	9611.3
EmF-20-S-09	Erdmannflya	Mytilus Edulis	whole valve	7677.1
EmF-20-S-10	Erdmannflya	Mya Truncata	2xfragments	2242.2
EmF-20-S-12-07	Erdmannflya	Serripes Groenlandicus	whole valve	9433.3
EmF-20-S-14	Erdmannflya	Hiatella Arctica	whole valve	7349.5
EmF-20-S-15	Erdmannflya	Mytilus Edulis	near whole valve	1753.9

Table 2. Samples sent to LARA in Bern, Switzerland

Table 3:		Radiocarbon dates (raw + calibrated) from Bogebecken and Erdmannflya)			Dates are calibrated with global marine calibration curve Marine20 (Heaton et al., 2020) and a ΔR value of -66 ± 35						
^{14}C results		Retrieved from KECK CARBON AMS FACILITY, EARTH SYSTEM SCIENCE DEPT, UC IRVINE			These results are low precision measurements on samples that have received minimal cleaning and pretreatment						
Sample ID	Elevation (m.a.s.l.)	Length (mm) (beak to margin)	fraction Modern	\pm	D^{14}C (%)	\pm	^{14}C raw AMS (BP)	\pm	cal. BP (median prob.)	1 σ (68.3 % prob.)	2 σ (95.4 % prob.)
BB-20-S-01-01a	1.0-1.3	75.25	0.3326	0.0064	-667.4	6.4	8840	160	9410 (9183 - 9614)	8988 - 9880	
BB-20-S-01-02a	1.0-1.3	76.6	0.3568	0.0059	-643.2	5.9	8280	140	8713 (8521 - 8923)	8344 - 9105	
BB-20-S-01-03	1.0-1.3	81	0.3584	0.0068	-641.6	6.8	8240	160	8668 (8440 - 8879)	8263 - 9113	
BB-20-S-01-04	1.0-1.3	88.57	0.3413	0.0076	-658.7	7.6	8640	180	9165 (8963 - 9423)	8628 - 9590	
BB-20-S-02-01	1.9-2.2	75.7	0.3367	0.0081	-663.3	8.1	8750	200	9297 (9023 - 9527)	8741 - 9868	
BB-20-S-02-02a	1.9-2.2	82.9	0.3478	0.0057	-652.2	5.7	8480	140	8968 (8759 - 9191)	8566 - 9372	
BB-20-S-03-01	2.7-2.85	84.07	0.3495	0.0065	-650.5	6.5	8440	150	8912 (8677 - 9126)	8486 - 9333	
BB-20-S-04-01a	4.0-4.1	87.19	0.3917	0.0055	-608.3	5.5	7530	120	7873 (7724 - 8007)	7599 - 8162	
BB-20-S-04-02	4.0-4.1	85.88	0.3494	0.0064	-650.6	6.4	8450	150	8925 (8688 - 9139)	8509 - 9355	
BB-20-S-05-1a	All surface collection	66.16	0.3559	0.0071	-644.1	7.1	8300	170	8741 (8514 - 8974)	8319 - 9218	
BB-20-S-05-04		81.39	0.3362	0.0059	-663.8	5.9	8760	140	9311 (9129 - 9485)	8934 - 9689	
BB-20-S-05-05		85.9	0.3586	0.0059	-641.4	5.9	8240	140	8665 (8454 - 8856)	8306 - 9060	
BB-20-S-05-10		90.55	0.3385	0.0066	-661.5	6.6	8700	160	9239 (9037 - 9439)	8773 - 9647	
BB-20-S-05-11		89.04	0.3534	0.0072	-646.6	7.2	8360	170	8812 (8555 - 9025)	8375 - 9275	
BB-100920-03	1.9-2.0	87.26	0.3518	0.0056	-648.2	5.6	8390	130	8846 (8629 - 9021)	8473 - 9240	
EmF-20-S-12-01	All surface collection 2.5 m.a.s.l.	76.96	0.3634	0.0055	-636.6	5.5	8130	130	8526 (8340 - 8697)	8194 - 8921	
EmF-20-S-12-02		77	0.3636	0.0056	-636.4	5.6	8130	130	8526 (8340 - 8697)	8194 - 8921	
EmF-20-S-12-04		78.07	0.3610	0.0057	-639.0	5.7	8180	130	8588 (8390 - 8759)	8267 - 8979	
EmF-20-S-12-05		71.94	0.3554	0.0056	-644.6	5.6	8310	130	8748 (8567 - 8947)	8385 - 9115	
EMF-20-S-12-06		-	-	-	-	-	-	8770	50	9338 (9256 - 9442)	9130 - 9506
EmF-180920-02	2.10 m.a.s.l. (down in pit)	79	0.3569	0.0069	-643.1	6.9	8280	160	8716 (8503 - 8944)	8307 - 9159	

Table 3. Radiocarbon dates from Bogebecken and Erdmannflya. BB means Bogebecken and EmF means Erdmannflya. All samples are *A.islandica*. Colors are an indication of elevation; samples with the same color were collected at the same elevation

4.1.1 Bogeбекken

Most radiocarbon dated *A. islandica* specimens from Bogeбекken have median probability calibrated age ranges spanning 8.67 – 9.41 ka cal. BP, although one individual is clearly younger at approximately 7.87 ka cal. BP (BB-20-S-04-01a; Table 3). Although collected from different elevations in the section, the mollusks show no clear trend of elevation-dependent ages. A weak trend of slightly younger ages upwards could be interpreted (Fig. 20), however considering the low number of samples, the age scatter is too broad to infer a distinct trend. Shells from the same altitude reveal a variety in ages overlapping with the age of shells from different elevations. In general, the age differences within the section appears unsystematic. These dated mollusks are shown together with earlier dated mollusks from this site by Sharin et al. (2014) and Beierlein et al. (2015), which were recalibrated with a $\Delta R = -66 \pm 35$ (Figure 22).

4.1.2 Erdmannflya

A. islandica from Erdmannflya have median probability calibrated age ranges spanning 8.5 – 8.7 ka cal. BP (Table 3). The new calibrated radiocarbon dates are plotted together with earlier dated mollusks on the site from Sharin et al. (2014) and Beierlein et al. (2015) in figure 22. All of the older dates have been recalibrated with MARINE20 and a ΔR value of -66 ± 35 (figure 22).

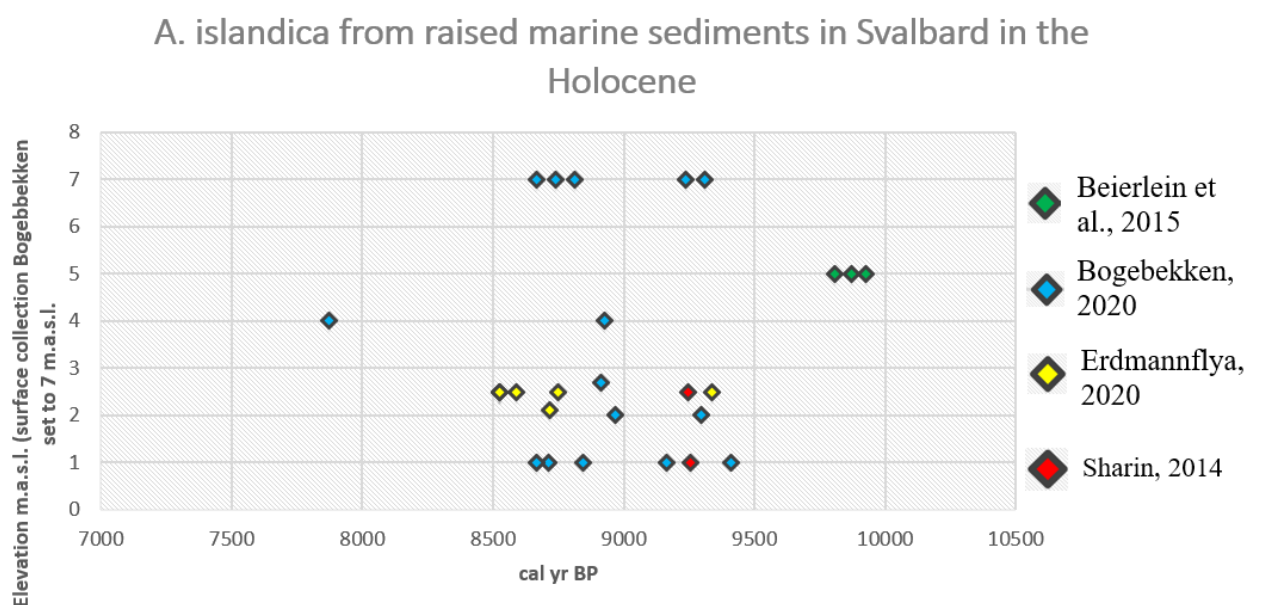


Figure 22. *A. islandica* from Svalbard in the Holocene, with recalibrations of Sharin et al., 2014 and Beierlein et al., 2015

Recalibrations of *A. islandica* from Sharin et al. (2014) and Beierlein et al. (2015) with Marine20 and ΔR : -66+/-35

Lab ID or Shell ID	Elevation (m.a.s.l.)	¹⁴ C raw AMS (BP)	±	cal. BP (median prob.)	1 σ (68.3 % prob.)	2 σ (95.4 % prob.)		Calibrated age in original paper ($\pm 1 \sigma$)	
ГИИ-14735	1.0	8700	50	9257	9151 - 9370	9038 - 9441		9670 \pm 80	Sharin et al., 2014
ЛТ-6992	2.5	8700	120	9245	9093 - 9414	8915 - 9537		9780 \pm 180	Sharin et al., 2014
AI-DiFj-02	~5	9240	70	9928	9795 - 10092	9643 - 10182		9954 \pm 139	Beierlein et al., 2015
AI-DiFj-03	~5	9200	50	9870	9730 - 10007	9617 - 10125		9838 \pm 118	Beierlein et al., 2015
AI-DiFj-04	~5	9160	50	9807	9665 - 9935	9557 - 10072		9782 \pm 105	Beierlein et al., 2015

Figure 23. Recalibration of the *A. islandica* from Sharin et al. (2014) and Beierlein et al. (2015)

4.3 Foraminifera

4.3.1 Hiorthhamn

No foraminifera were observed in sediment samples from Hiorthhamn.

4.3.2 Bogeбекken

Foraminifera were observed in nine out of twelve samples. The three non-foraminiferous samples were sampled from the highest elevations in the section (BB10-BB12; figure 20; appendix 2). Abundance ranged from 138 – 502 counted foraminifera per sample. In general, the preservation of the foraminifera allowed for most specimens to be identified, although some signs of deterioration were noted. Between 0 and 13.6% of specimens per sample could not be identified to genus or species. The most dominant specie in all samples was by far *L. lobatula*, with 51 – 89 % relative abundance (Appendix 2; appendix 3). *C. excavatum* is also seen above 10 % abundance in some samples, while no other species are represented above 5 % in any sample (appendix 2; appendix 3). Only calcareous benthic foraminifera were observed.

4.3.3 Erdmannflya

Foraminifera were abundant in all five samples from Erdmannflya (appendix 2: appendix 3), with no more than 1/32 of the sieved and dried volume per sample requiring counting. Between 293 and 427 individuals were counted per sample. The excellent preservation of the foraminifera generally allowed for a high degree of identification. Damaged specimens were uncommon. Between 3.0% and 8.1% of individuals per sample were unidentifiable. No agglutinated foraminifera and only one planktonic foraminifera were observed. *L. lobatula* is

the most abundant specie in all sample (52-61% abundance), while both *C. reniforme* and *C. excavatum* occur with more than 10 % abundance in at least one sample. Major assemblage differences between samples were not seen.

4.3.4 Bolterdalen

No foraminifera were observed in any of the 20 samples collected from Bolterdalen.

5. Discussion

5.1. Bogebecken

The dated individuals of *A. islandica* show no clear age-elevation trend within the stratigraphic section at Bogebecken (see figure 20). From the base of the sandy unit to the top, ages of the dated mollusks are overlapping and unsystematic. Such a distribution agrees with radiocarbon dated molluscs from Bogebecken by Sharin et al. (2014), who also present a blurry stratigraphy based on mollusk ages. This mixing of shell ages could be interpreted as reworked sediments in a high-energy environment. Still, paired valves, which are occurring at various elevations, is an indicator that the shells are in growth position; hence not being transported post-mortem. Various degree of intact periostracum (a few individuals with periostracum almost intact) is also an indicator that shells might be in situ. The conditions of the shells may therefore not attest to a high-energy regime only – it might have been periods of both high and low energy. As glacioisostatic adjustment progressed following deglaciation of this area around 10 ka BP (Sharin et al., 2014), shallowing coastal waters would have resulted in higher and higher energy conditions, depending on seasonal sea-ice conditions, although the coarse sediments of the raised beaches capping this site suggest that there was seasonally open water with enough wave energy to build them. Shallower and shallower conditions are reflected in the inverse grading (coarsening upwards) of unit B and between unit B and unit C (Figure 20; finer to coarser sand and shells in unit 2 overlain by cobble, gravel, and sand above). The coarse gravel and sandy sediments of the uppermost unit have been interpreted as raised beach deposits (Sharin et al., 2014), reflecting a typical emergent coastal stratigraphy from shallow water to beach sediments. In such an environment, shells of different ages are constantly reworked in the active coastal zone (from where the wave base intersects the seabed to the beach). Together with longshore drift, a process which erodes, transports, and redeposits sediments down shore, Bogebecken was likely a relatively high-energy environment during summer in the early Holocene.

Bioturbation by infaunal organisms may also have played a role in blurring much of the chronostratigraphic signal; certain species are known to rework sediments to an even greater depth than the defined taphonomically-active zone of 1 meter (Risk et al., 1978). The weak trend of younger dates up-section, might indicate the scale of reworking and time averaging; it is possible to track trends for the unit as a whole, but reworking effective on centimeter to decimeter scales blur fine variations. On the other hand, the occurrence of paired valves and a few, finer-grained sandy-silty layers attest to at least some degree of intact stratigraphy.

As the preferred water depth of *A. islandica* is >10 m, and the marine limit at Bogebecken is 60 m.a.s.l. (Sharin et al., 2014), the rapid uplift which occurred soon after deglaciation at 10 ka BP, implies that *A. islandica* must have been living towards its shallow limit at this time. Given that sea level was lower than today only until 6.5 ka BP (Sharin et al. 2014), sample BB-20-04-01a (7.9 ka BP) must have been living in shallow water. This molluscs was paired, thus an indication of it being in growth position or at least not being transported far after it died. However, an eventual redistribution mean that the growth position would have been at even higher altitude. An eventual redistribution from greater water depth is possible, although unlikely below wave base.

The radiocarbon dates of *A. islandica* from Bogebecken are significantly younger than those reported by Mangerud and Svendsen (2018): 10.0 – 9.0 ka BP. However, recalibration with MARINE20 and $\Delta R = -66 \pm 35$ of the Mangerud and Svendsen (2018) dates suggest younger ages for some of their specimens (figure 23). Nevertheless, the occurrence of younger individuals indicates that conditions were favorable for *A. islandica* to thrive over a longer time period than previously interpreted for Svalbard. This implies that the inflow of warm Atlantic water along west Spitsbergen in the early Holocene may have continued into the middle Holocene, and in any case longer than suggested by Mangerud and Svendsen. (2018). The new radiocarbon dates on *A. islandica* from Bogebecken extend the temporal range for when this species thrived in outer/middle Isfjorden to 8.5 ka, suggesting inflow of Atlantic water through at least this time. This is significantly longer than what has been suggested by Mangerud & Svendsen (2018). While it can be concluded that this temporal span now is extended, the dataset is too limited to interpret the duration of these period. While this dataset itself may seem to reveal a hiatus in the population of *A. islandica* until 7.9 ka BP, it must be stressed that the dataset is too scarce, and all discussion made on the basis of the known distribution of *A. islandica* remain speculations. Further investigations of the mollusk fauna are needed, and hence, the following paragraphs are speculations:

According to Mangerud and Svendsen (2018) *A. islandica* requires slightly warmer water than *M. modiolus*, while others describe the two species as having a similar temperature threshold (Farnsworth 2020, written communication). With these new dates, the temporal pattern of occurrence is now very similar, both with one very young date ~7.8 ka BP and remaining dates up to ~10 ka BP. This suggests that the temporal range of the two species of bivalves overlap, or that there are still gaps in the known distribution of both species due to limited material, especially from *Modiolus*. It may also be the case that if the temperature of coastal waters in Isfjorden changed around 8.5 ka BP, the time when *A. Islandica* may seem to temporarily disappear from Bogebeekken, it happened so abruptly that the time window when only *M. modiolus* and not *A. islandica* could thrive were narrow, hence being dismissed in the current datasets.

Aside from the shell dating to ca. 7.8 cal ka BP, there appears to be a relatively abrupt end to the population of *A. Islandica* at Bogebeekken, which could be related to the 8.2 ka BP event. Cooling at this time might have been stepwise and started earlier, as described by for instance Ellison et al. (2006), with a first prominent drop around 8.4 ka BP. Hald & Korsun (2008), arguing for a cooling step 8.45 ka BP seem consistent with our data as well. The absence of *M. Modiolus* after 8.2 ka BP, although observations are definitely too scarce to conclude, attests to a decline in temperature, since this species is considered to have a temperature threshold equal or slightly colder than *A. Islandica*. With the awareness of some degree of geographic variation in the timing of climate anomalies and variations in radiocarbon calibrations, a temporarily disappearance of *A. arctica* from Isfjorden at this time could be linked to this widespread cooling event. The 8.2 ka event have been observed in a relatively uniform temporal pattern in the northern hemisphere, also in Svalbard (Hald and Korsun, 2008), thus meaning that a climatic anomaly seen at this time in Svalbard can be interpreted as the response to the 8.2 ka event.

It must be accounted for that *A. Islandica* prefer to live at least 10 meters below sea level (Thompsom et al., 1980). At some time during postglacial uplift, the environment sampled at Bogebeekken became too shallow for *A. Islandica* to thrive, even while it was still below contemporaneous sea level. With a marine limit of 60 m.a.s.l. (Sharin et al., 2014) and the onset of a rapid, but declining crustal rebound from 10 ka BP, it can be assumed that the coastal sediments at Bogebeekken were lifted to < 30 m depth within 1-2 ka. Sharin et al. (2014) also show that relative sea-level was higher than today only until 6.5 ka BP, which seems early, but perhaps reasonable when we observe that the depth was tolerable for *A.*

Islandica until 7.9 ka BP. Since eventual individuals living 7.9 – 6.5 ka BP must have therefore lived in deeper water, redeposition from higher altitude is not a possibility. This individual (BB-20-S-04-01a, table 3) was found 4.0-4.1 m.a.s.l., which requires an uplift of ~14 meters between 7.9 ka BP and 6.5 ka BP given a required living depth of at least 10 m. Given estimates in both Sharin et al. (2014) and this study, this pattern of uplift might be correct. Or, it can be assumed that the sea-level estimates from Sharin et al. (2014) and/or the tolerated range of water depths for *A. islandica* are unprecise. However, the dating indicates the age since the individual died; the depth in which the molluscs can survive may differ from the depth in which they successfully reproduce and colonize, and, since *A. Islandica* has proven to be long-lived in cold environments, it's perhaps plausible to assume a shallowing even within the lifespan of an individual. With respect to the RSL-assumptions it seems likely that shallowing conditions may have prevented individuals younger than 7.9 ka BP. Again, the data material is too scarce for any conclusions, and on the basis of this site alone it can't be concluded whether younger individuals of *A. islandica* were not observed due to the thermal regime or due to water depth at the site.

Sharin et al. (2014) concluded from their dated mollusks from Bogebecken that HTM occurred no later than 9.6 ka BP, based on their youngest dated thermophilus molluscs (i.e. *A. islandica* and *Mytilus* spp). Following recalibration with MARINE20 (Heaton et al., 2020) this becomes 9.3 - 9.2 ka BP (figure 23). Although new, younger radiocarbon dates on *A. islandica* from Bogebecken extend the period of time when AW flowed into Isfjorden, the accepted temperature range for *A. islandica* is too large and the dataset too spatially limited to allow for any meaningful commentary on the timing of the HTM in this region.

The single *A. islandica* dated 7.9 ka BP (sample BB-20-4-01a; Table 3) stands out from the entire dataset from Svalbard, although it must be remarked that its 95 % confidence interval almost overlaps the youngest among the other dates. While this new observation attests to warm conditions and shallow water temperature of at least 8.5 °C at 7.9 ka BP, it also calls for further investigations of the mollusk fauna. Based on the observations in this thesis alone, it seems obvious that there are big gaps in the knowledge of distribution of thermophilus mollusks around Svalbard, preventing us from seeing the whole and nuanced picture of distribution and its paleoenvironmental implications.

It may be argued that the pattern of occurrence of *A. islandica* attests to the position that inflow of Atlantic water played a major role in the amplified water temperatures in the early and mid-Holocene, as argued by Mangerud and Svendsen (2018). While higher insolation in

general is seen as a key driver to the warmth at high latitudes, Mangerud and Svendsen argue that the differences in mollusk species distribution between fjords highlights the role of the strengthened flow of AW. In Van Mijenfjorden, south of Isfjorden (figure 4), for example, only *M. edulis* have been observed in raised marine sediments. The entrance to Van Mijenfjorden had in the early Holocene a shallow (and shallowing, today this sill has emerged and named Akseløya, blocking the fjord entrance almost entirely) sill, which impedes water mass exchange, and may explain why *M. edulis* is the only species of thermophilous mollusc observed here. Local factors impacting water mass exchange, such as palaeobathymetry, history of glacier melt, etc., in addition to regional and global factors such as large-scale circulation changes and insolation, must be considered when comparing the early Holocene thermophilous mollusc populations on Svalbard.

Nonetheless, it is interesting to note that Hald and Korsun (2008) observed two clear steps of temperature decline at 8.45 ka BP and 8.2 ka BP in a study of marine sediment cores from Van Mijenfjorden. This finding supports the view that, in spite of local conditions, AW extended into a high Arctic fjord with limited water exchange during the early Holocene.

5.1.2. Foraminifera

The foraminiferal assemblages documented in the sandy unit at Bogebecken are strongly dominated by *L. lobatula* (77- 90% relative abundance in 8 out of 9 foraminiferous samples) with *A. hamadaense*, *C. reniforme*, *C. excavatum*, and *N. labradorica* present in lower relative abundances (appendix 2, appendix 3) The dominance of *L. lobatula* thus, supports interpretations made based on the *A. islandica*, grain-size, and stratigraphic data from Bogebecken; that is, an early Holocene high-energy shoreface with seasonally-open water. Sediments here were deposited under shallowing conditions, potentially impacted by strong longshore drift currents and reworking of sediments. A slight increase in relative abundance of *L. lobatulata* was also observed moving upwards through Unit B at Bogebecken, (Fig. 20; Appendix 2; appendix 3), coinciding with the inverse grading.

The occurrence of *A. hamadaense* in the lowermost sample (BB01, Unit A) at 2,7 % relative abundance fits the interpretation of a high-energy environment. Its absence in 5 samples above BB01 (appendix 2; appendix 3) is thus surprising, given that it is known for preferring strong-currents environments together with *L. lobatula*. Possibly the seabed at Bogebecken at this time was too coarse-grained for *A. hamadaense* and other foraminiferal spp to thrive even though other environmental requirements were in place. Hence, the coarseness of the

sediments at Bogebekken, which became coarser with shallowing water depths over time, may have reduced the overall abundance and diversity of foraminifera and thus also the complexity of the paleoenvironmental signal.

Cassidulina reniforme is present in all foraminiferal assemblages from Bogebekken with a low relative abundance ranging from 0.7 % to 1.2 % (appendix 2; appendix 3). Although these low concentrations are within the error estimate (appendix 3), this species is present in all samples. *Cassidulina reniforme* is a common arctic species at present and its low abundance during the early Holocene at Bogebekken may reflect water temperatures approaching an uppermost threshold for *C. reniforme*. The association of *C. reniforme* with Arctic Water (Jennings et al. 2004) and its low abundance in Bogebekken, probably reflects higher bottom water temperatures at its location in the outer fjord, where there was likely greater exposure to Atlantic Water.

The observed abundances of *C. excavatum* in outer Svalbard fjords in Hald et al. (1994) is in relative agreement with the abundances in Bogebekken with its abundances 2.9 -14.8 % in the sandy unit. Due to the scale of reworking observed in Bogebekken, distinguishing between infaunal and epifaunal species does not influence the stratigraphic accuracy and interpretations. Given the clearly higher abundance of *C. excavatum* in the lowermost sample compared to all other samples, the following interpretation might be assumed: the lowermost sample attests to an environmental regime with either fluctuating or low salinity, turbidity, or ice-covered and cold waters. If a trend is to be seen through the sandy section, the abundance is at least not increasing upwards. Stratigraphic samples with *C. excavatum* have earlier showed a strong decrease with the inflow of warmer Atlantic water in the early Holocene (Hald et al., 1994). Several aspects limit the possibility to eventually confirm this: the limited temporal span of the unit, which spans the late early Holocene, the reworked sediments, and the limited number of samples with only one sample at each elevation. It must be noted that only one sample from the lowermost unit makes the data uncertain, as it might be accumulated by reworking.

The almost absent of *C. excavatum* > 2.5°C water bottom temperature across Kara sea and Barents sea (Hald et al., 1994) doesn't fit well with the assumed inflow of warm Atlantic water throughout the early Holocene in Svalbard fjords. However, Jennings et al. (2004) found *C. excavatum* (together with *C. reniforme*) to dominate the assemblages in an Icelandic fjord with stable 5°C bottom water temperature and 34.7‰ salinity, and Husum (2002) found *C. excavatum* present in 6-6.9°C temperatures in Malangen fjord in mainland Norway. It may

therefore either be assumed that *C. excavatum* accepts relatively warm water, and that other factors than the temperature limits its distribution in Hald et al. (1994). Or, its presence and abundance in Bogebecken indicates that local conditions overprint the regional signals, with cool and fresh water due to freshwater input. On the other hand, this is contradictive to the temperature derived from *A. islandica* on the site.

The relatively high abundance of *C. excavatum* in the lowermost sample of Unit B (31%; appendix 2; appendix 3) may attest to fluctuating conditions prior to these sediments age – and at this stage opportunistic species still had a high abundance, which decreased, in terms of percentages, over time. It also attests to relatively stable conditions in terms of salinity and temperature over time when the sandy unit was deposited – despite longshore drift and reworking. Using the assumption that the thermal maximum occurred early in the Holocene and was followed by a general decline, the abundance drop of *C. excavatum* cannot be explained by the known thermal regime.

The abundance of *N. labradorica* is low in all samples. The relative abundance is higher in the lowermost sample (> 4 %), but with the span of the error estimate this cannot be claimed for sure. It nevertheless follow the pattern where the statistical significant decrease of *L. Lobatula* is replaced, percentage-wise, by other species. Comparing to Wijdefjorden however, coarse sediments and high-energy environment in Bogebecken doesn't seem to coincide with the high abundance of *N. labradorica*. But rather with the opposite (highest abundance in the lowermost sample with the fines sediments).

The low abundance of *N. labradorica* is therefore likely linked to either of the other associated factors mentioned: temperature, depth and salinity, which all show a positive correlation with the species's abundance. This assumption strengthens the interpretation of such conditions being at Bogebecken - it may be assumed that the shallow environment with freshwater input, hence relatively cool waters and low salinity, were conditions unfavourable for *N. labradorica*.

5.2 Erdmannflya

Calibrated radiocarbon dates on *A. islandica* collected from the Erdmannflya site (Fig. 1) represent a relatively narrow time period from 8.5-8.7 ka BP (Table 3). In general, these dates are younger than most dates from Bogebecken, and younger than those reported by Sharin et

al. (2014; also from Bogebeekken) and Beierlein et al. (2015; from Dicksonfjord; Fig. 4). Unlike at Bogebeekken, where radiocarbon dates could be placed within a stratigraphic section, *A. islandica* from Erdmannflya were all surface-collected samples at 2.5 m.a.s.l. (except for one excavated from a pit, 2.1 m.a.s.l.) and not stratigraphically distinct. The clustering of dates 8.5-8.7 ka BP is therefore not overly surprising.

The finer-grained sediments indicates a lower-energy environment than the sediments in Bogebeekken. However, while whole shells are seen, paired valves are fewer than in Bogebeekken, and periostracum is, if a generalization can be done on these shells alone, in worse or in best case similar conditions as in Bogebeekken. Hence, the sediments and shells may lead do different interpretations regarding the energy regime in Erdmannflya.

The rapid uplift, up to 3m/century 10.0 – 8.5 ka BP, at Erdmannflya and Straumsjøen (figure 24) and concomitant shallowing conditions may have led to stronger tidal currents between 8.1 – 8.3 ka BP, prior to the lowstand and estimated onset of the transgression at 8.0 ka BP (Salvigsen et al., 1990). Based on the relative sea-level curve from Salvigsen et al. (1990), marine limit was ca. 6-7 m above sea level before the transgression (figure 24). Even though it should be accounted for a potential inaccurate estimate of the onset of marine transgression, it means that the sampling site at Straumsjøen may have been as shallow as 3-4-meter depth approximately at the time that's is represented in the sampled material. The depth at onset of marine transgression was therefore likely to have been too shallow for *A. islandica*; a possible speculation is therefore that no younger dates than 8.5 ka BP is seem due to shallowing.

Altogether, the radiocarbon dates on *A. islandica* from Erdmannflya compare favourably to those from Bogebeekken, suggesting that inflow of Atlantic Water continued throughout most of the early Holocene until at least 8.5 ka BP. Without major gaps, there are now dated *A. islandica* from Isfjorden from 9.9 ka BP (recalibrated from Beierlein et al. 2015; figure 22) to 8.5 ka BP (this study; table 3). This means that water temperatures at the living depth of *A. islandica* must have been (seasonally) warm enough for its existence throughout this early Holocene time period. From Mangerud and Svendsen (2018), it follows that mean August sea-surface temperatures must have been at least 8.5 °C until 8.5 ka BP. This inferred minimum temperature of surface waters during the HTM is compatible with $\delta^{18}\text{O}$ -analyses of *A. islandica* from Beierlein et al. (2015). Both Mangerud and Svendsen (2018) and Beierlein et al (2015) concluded that both the sea surface temperature and bottom water >30 m, were 6 °C higher, despite the pycnocline typically formed at <30 m depth. Surface water, including cool freshwater runoff, is not the same water mass as below the pycnocline, hence, applying

this temperature match in other settings should not be done without further consideration. As mentioned previously, Rasmussen et al. (2014) demonstrated that reduced sea ice cover and less freshwater input led to the dominance of Atlantic Water between 6.0-9.0 ka BP, however, a springtime pycnocline is assumed to have developed throughout the Holocene. Building on the results from Beierlein et al. (2015) and Mangerud and Svendsen. (2018), we therefore interpret both warmer surface water and Atlantic bottom water from Erdmannflya and Bogebekken during this period of the early Holocene.

In contrast to today's 6°C seasonal variety, Beierlein et al. (2015) describes a great seasonal variety of 12,4°C in the early Holocene and a summer temperature 8-10°C higher than present. At the same time, the stable isotopes analyses from Rasmussen et al. (2012) suggest a narrowed seasonal variety around 8.2 ka BP. Together, this points towards a temperature drop, and in particular a drop in summer bottom temperatures, around this time.

While conditions undoubtably were warm enough for *A. islandica* to thrive until 8.5 ka BP, the dataset is simply too scarce to say if *A. islandica* didn't thrive in Erdmannflya after 8.5 ka BP. Although the dates from Bogebekken and Erdmannflya both indicate disappearance and / or hiatus from 8.5 ka BP comparisons of these two seemingly simultaneous anomalies should be done with care, as their causes might be different. Based on the RSL-from Erdmannflya it may be argued that the site became too shallow for *A.islandica*, preventing younger dates independent from the thermal regime.

5.2.2 Foraminifera

L. lobatula is dominant in all samples from Erdmannflya, with relative abundances ranging from 51% to 60%. While not quite as abundant as at Bogebekken, it is still clearly the dominant species, but here in the early Holocene it has inhabited a lower-energy environment, as indicated by the finer-grained sediments. *A. hamadaense* are higher in relative abundance at Erdmannflya compared to Bogebekken, ranging from 4.4% and 7.2 % (appendix 2; appendix 3), although *C. reniforme* is the second most abundant species, with relative abundances of between 9.6 % and 12.4 %. *C. excavatum* occurs with relative abundances of between 9.6 % and 12.9 % in four out of five samples, while the fifth sample show an abundance of 5.4 %. Hence, *C. excavatum* is among the most abundant species on the site, roughly as abundant as at Bogebekken. The abundance of *N. labradorica* is low in all

samples, varying from 0.7 % to 2.3 %. This is not surprising, given known environmental preferences of this species, for example a coarse seabed (Hald & Korsun, 1997).

The higher abundances of *A. hamadaense* agrees with what's been described in the literature (e.g. Sejrup et al., 1981; Hald and Vorren., 1984; Polyak et al., 2002), where the two species dominate strong-current environments. From this assumption, which back up the interpretation from *L. lobatula*, it follows that Erdmannflya was had relatively strong currents and high energy – this is in accordance with the shallow conditions seen from the RSL-curve (figure 24).

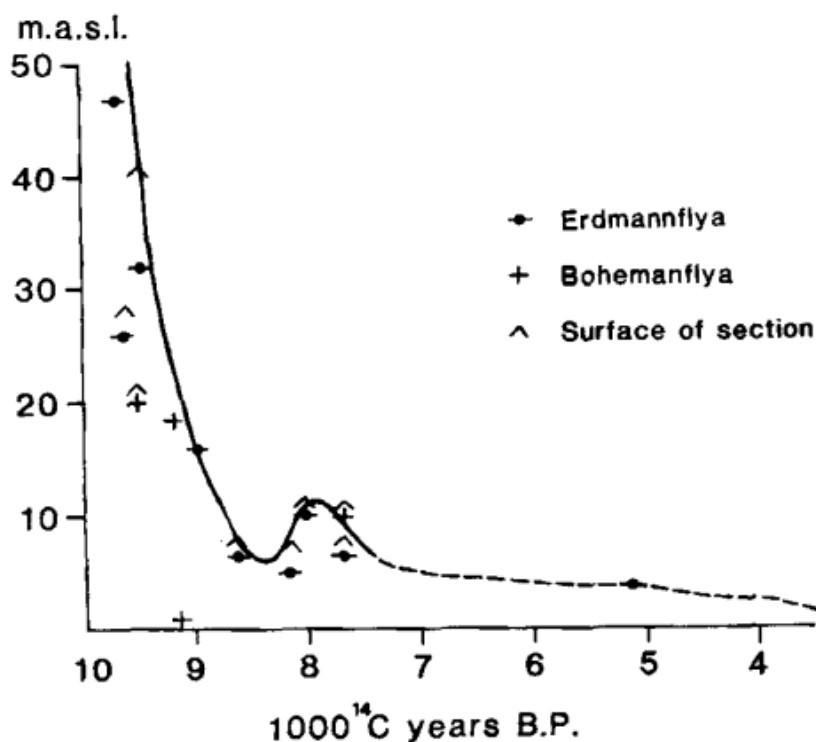


Figure 24 Shoreline displacement curve from Erdmannflya and Bohemanflya. Time/elevation of dated samples are also marked. The assumed marine transgression is seen occurring around 8 ka BP. Figure from Salvigsen et al., 1990

The relative abundance of *C. reniforme* is clearly higher than in Bøgebekken. This makes it together with *C. excavatum* the most abundant species beside *L. lobatula*. With the known pattern of abundance described by Hald & Korsun (1997), it's interesting to observe the species is significantly more abundant than in Bøgebekken, given that both locations are approximately the same distance from the fjord mouth (figure 1). There may be effects from the general circulation pattern in Isfjorden, but superficial to this it can be assumed that there are local environmental factors which influence the abundance. Firstly, the sampled sediments were muddy, which is known for being favorable for the species (e.g. Mackensen et al.,

1985). Further, the low-altitude peninsula proximal to mountains and, during parts of the Holocene, glaciers, raises the potential for freshwater input of a magnitude which could be of great influence, given the shallow depth. The re-advance of Esmarkbreen is estimated to 9.5 ka BP, hence, glacial meltwater was probably of minor importance when the foraminifera sampled for this thesis were alive. As mentioned, *C. reniforme* has shown to thrive in glaciomarine environments (Hald and Vorren, 1987), leading to colder and less saline waters. Still, even without glacial input the freshwater to the peninsula may have been strong enough to create a favorable environment for *C. reniforme*.

The relative abundance of *C. excavatum* at ~10% can, just like Bogebeekken, lead to two different assumptions: either that *C. excavatum* tolerates relatively warm water, or, that the conditions on the site held colder and fresher water than the mean and minimum bottom water temperatures derived from *A. Islandica*. Given previous interpretations, the latter assumption is likely to be the case to some degree, without ruling out the former.

The abundance of *N. labradorica* is low in all samples, varying from 0.7 % to 2.3 %. This is somehow not surprising, looking on the described preferences of the species. Neither its coincident with coarse sediments (Hald & Korsun, 1997) nor the positive correlation with depth or salinity indicates a high abundance of *N. labradorica* in Erdmannflya, given our preliminary interpretations, which in turn is strengthened by these low abundances.

5.3 General discussion for Bogebeekken and Erdmannflya

In general, the foraminifera assemblages observed in the raised marine sediments fits with the paleoenvironmental interpretations seen from both the molluscs and sediments – all mirroring aspects associated with the shallowing conditions such as current regime. However, while the thermophilus molluscs are temperature indications by their occurrence, all key foraminifera species observed in this study are also present in Svalbard fjords, thus not being a direct proxy for warmer conditions. This implies that the forams are, in this setting, a less sensitive indicators for AW (or warmer coastal water temperatures) compared to the molluscs.

The new radiocarbon dates on *A. islandica* from Erdmannflya and Bogebeekken do not agree with a cooler period between 8.2-9.0 ka BP put forward by Mangerud and Svendsen (2018), described as having summer temperatures close to those of the present. With a higher temperature threshold, the spatial distribution and ages of *A. islandica* indicate that temperatures were significantly higher than present at least until 8.5 ka BP.

While speculations on the limited shell material and a potential hiatus fits well with studies on the timespan of the 8.2 ka event (e.g. Rasmussen et al., 2012), these speculations contradict other studies as well. The suggested warming 8.3 ka cal. BP – 7.8 ka cal. BP by Van der Bilt et al. (2018), arguing that cooling effect from ice-sheet melting decayed and strong insolation linked to orbit angles were still in place, is not consistent with e.g. Ellison et al. (2006) or Hald & Korsun (2008), and neither is the spatial spreading of *Mytilus* spp (Mangerud & Svendsen, 2018) around the same time as the *A. islandica* hiatus can be speculated from the preliminary dataset. Further studies are required.

5.4 Bolterdalen and Hiorthhamn – no foraminifera observed

No foraminifera were observed at Bolterdalen and Hiorthhamn (Fig. 2). This is unfortunate, as these sites could potentially have provided valuable comparisons to Bøgebekken and Erdmannflya, thus offering the potential to strengthen palaeoenvironmental interpretations. For example, comparing foraminiferal assemblages between Bolterdalen, where abundant *M. truncata* have been observed, but no thermophilus bivalves such as *A. islandica*, with Bøgebekken and Erdmannflya, where *A. islandica* is observed, would have been interesting.

In Hiorthhamn, both the characteristics of the sediments and the presence of *M. edulis* suggest that that foraminifera should also be present. However, the observed fragments of *M. edulis* were thin and fragile, likely a result of calcium carbonate dissolution. If the leaching and corrosion of CaCO₃ on the surface of the bivalve shells is visible to the human eye, the dissolution may have been strong enough to dissolve the small foraminifera tests completely. It can therefore be assumed that the lack of foraminifera seen today is a result of the dissolution of calcium carbonate, possibly linked to the high content of organic matter observed in the samples, indicating low pH and potentially anoxic conditions in pore waters. On the other hand, coarse-grained sediments should allow for relatively free movement of water, thus preventing anoxic conditions.

In Bolterdalen, the relatively high productivity attested by the abundant molluscs may be seen as an indication that foraminifera should have been able to thrive here as well. Molluscs are in better condition than at Hiorthhamn, hence calcareous dissolution is unlikely to be the reason for the absence of foraminifera. It is possible that this site had a very high sedimentation rates in the early Holocene, limiting foraminiferal populations. If they existed, abundances may

have been very low and/or were affected by taphonomic processes that has made it difficult to impossible to find them today. If assemblages were dominated by agglutinated species rather than calcareous, drying of the samples would have caused their disintegration.

5.5 Relevance for future climate change

The results and occurrence of *A. islandica* attests to the already widely documented early and exceptional warmth of the early Holocene in Svalbard, which exceeds mean global values for reconstructed warming during this time. Hence, it highlights the phenomena of amplified warming in polar regions – an effect that is already observable in polar regions today due to anthropogenic warming. As the most recent phase with a significantly warmer-than-present climate in Svalbard, the early Holocene might provide insight to how the future will be for Arctic environments and its impact on nature and societies.

An important aspect regarding the pattern of warming and seasonal change may limit the value of the early and mid-Holocene as an analogue for anthropogenic warming; a strong increase in summer temperatures and increased seasonality versus strong increase in winter temperature and seasonality. Although this study confirm Arctic amplification in the early Holocene (*A. islandica* indicates summer temperatures lasted ~4°C warmer until 8.5 ka BP, following the logic from Mangerud & Svendsen (2018)), the unknown future of the global greenhouse gas mitigation makes, together with model limitations, the absolute warming to be expected in the future unknown. Nevertheless, it highlights the fact that high latitudes warm more than the global average, and that increased knowledge about earlier warm phases may better our ability to project future climate response through models.

5.6 Limitations of the study

5.6.1 Limitations in method

5.6.1.1 Number of samples

Retrospectively, having a greater number of samples from each site could have strengthened the interpretations by providing a more statistically robust dataset. The FOBIMO-initiative by Schönfeld et al. (2012), aiming to build a common platform for foraminiferal studies within the field of biomonitoring, has suggested that a minimum of three replicate samples should be taken for each benthic station. This suggestion is aimed at deep-sea benthic sampling of living foraminifera, which is both time-consuming and costly, but while three is seen by the FOBIMO-initiative as a compromise between cost and gain, the same issue with foraminiferal

distribution at a local scale also applies in this thesis. Erdmannflya is in one sense similar to sea-bottom sampling, as the samples are spread horizontally. In fact, we do have five different “stations” at Erdmannflya with only one sample from each. While this might seem to contradict the suggestions by the FOBIMO-initiative, their suggestions are aimed at moving vessels often with hundreds of meters between each sampling station, which can obviously lead to completely different environments from one station to another. At Erdmannflya, on the other hand, it is only a few meters between our stations, in a fairly uniform environment.

While guidelines for replicate samples from the FOBIMO-initiative (Schönfeld et al., 2012) are aimed for marine samples, the principles behind are relevant also for the other sites. On the sections of Hiorthhamn, Bogebeekken and Bolterdalen, the number of samples were a result of both available time and knowledge; at Bogebeekken there simply wasn't enough time to sample another parallel section due to unfortunate weather, while in Bolterdalen understanding of replicate samples led to two parallel sections being sampled. In that sense it was extra unfortunate that the samples in Bolterdalen turned out to contain no foraminifera.

In Bogebeekken, sampling parallel sections would have been valuable to see whether foraminiferal changes were “random” results of reworking or if there was a recurring pattern in the assemblages. Without this comparable data it is difficult to interpret palaeoenvironments from the foraminifera data with a high degree of uncertainty, however, the presence of *A. islandica* supports the evidence from the foraminifera.

5.6.1.2. Processing of samples

Dry picking of foraminifera requires dried samples. This process might have an influence on the foraminiferal assemblages itself. According to Scott et al. (2007), drying the samples takes away the possibility to see organic inner linings, which can be a marker for dissolution of calcareous foraminifera, as well as breakdown of any agglutinated foraminifera that cannot survive the drying process.

5.6.1.3. Identification of specimens

As there are a high number of species which may be found in the samples, many of them very similar, even to a trained eye, the risk of incorrect species identification is ever present. Identifying dead assemblages adds to the challenge – even though most specimens were well preserved, deformed or cracked tests were also observed.

Some species, like *L. lobatula*, is quite distinct and the risk of misidentification is low. Other species, such as *I. helenae* and *I. norcrossi*, for example look very similar and are often incorrectly identified in the literature (Cage et al., 2021). Misidentification of such species can have important consequences for palaeoenvironmental interpretations as they have different environmental preferences and are therefore important to differentiate.

One might argue that the use of spp. (multiple species grouped together within a genus, for instance *Cassidulina* spp. or *Islandiella* spp.) could have been implemented more in the identification. While this would have eased the identification and dramatically reduced the risk of misidentification, it would also limit the possibilities for palaeoenvironmental interpretation, because species in the same genus can thrive in different environments. Because of that, aiming for an identification as accurate as possible is the optimal choice when the goal is to do environmental interpretations.

5.6.2 Interpretation of the results

Lack of foraminiferal investigations from other shallow water environments both present and throughout the Holocene on Svalbard limits comparisons and interpretations – it is difficult to compare bottom-water assemblages from, for example, fjord transects (Hald & Korsun, 1997) to shallow water assemblages. Hence, we can interpret certain characteristics based on the species present, but with limited knowledge for comparison it becomes difficult to quantify or interpret how our results differ from similar sites today. The key foraminiferal species found in the samples are all present in Svalbard fjords today (e.g. Hald & Korsun, 1997); a specific temperature interpretation based on a temperature threshold similar to the thermophilus molluscs is therefore not possible. However, the blurry stratigraphy seen in Bogebecken would have made any such interpretation inaccurate.

The scope of which interpretations from shallow water sites can be applied must also be addressed. It's likely that the investigated assemblages to a large degree represent very local conditions, for instance reflecting the local variations in freshwater input, which causes cooling and freshening on a local scale (this issue is discussed by e.g. Quillmann et al., 2012). Hence, they reflect local/regional terrestrial signals, for instance the melting or growth of a glacier, rather than the large-scale oceanography. While the possibility of being a proxy for both marine and terrestrial climatic aspects in itself is valuable, a strong overprint of local

factors limits the possibility to see large-scale oceanographic features like the general inflow of Atlantic water in the fjord.

Again, the unsystematic distribution of sediments in Bogebeekken limits the interpretation of local terrestrial factors as well – with a strict stratigraphy, for instance variations in freshwater supply linked to glacial regimes could easier have been traced. This highlights two of the limitations of this study; disturbed sediments limiting the accuracy of local marine and terrestrial signals, while at the same time local signals overprinting large-scale variations.

This thesis refers to many studies using calibrated radiocarbon dates. As described, the calibration of marine radiocarbon dates can be done with different calibration curves and ΔR -values. For this thesis a brand new ΔR -value for western Spitsbergen, -66 ± 35 has been applied together with MARINE20, and consequently, it differs at least slightly from all previous calibrations. Recalibrations with this approach have been performed for *A. islandica* radiocarbon dates published in Sharin et al. (2014) and Beierlein et al. (2015) since these are extensively compared with this study, however this was not possible to do for all studies cited in this thesis. Therefore, dates which have been referred to might have looked different with a recalibration, which leads to offsets and inaccuracies when interpreting on the basis of radiocarbon dates.

5.6.3 Future work

Stable isotope analyses, particularly $\delta^{18}\text{O}$, have been used on both foraminifera and molluscs in Svalbard previously to interpret palaeo-water temperature and salinity (Rasmussen et al., 2012; Beierlein et al., 2015), and such analyses could have been of great value for this thesis. Especially when we see that Rasmussen et al. (2012) used $\delta^{18}\text{O}$ to observe seasonal variation around the 8.2 ka BP – event, and Beierlein used $\delta^{18}\text{O}$ to interpret seasonal temperature cycle from *A. islandica*. Our individuals of *A. islandica* are younger than in Beierlein et al. (2015); $\delta^{18}\text{O}$ – values of these would complement the data on temperature and seasonality to build a picture of how it changed throughout the early Holocene, and, with the 7.9 ka BP specimen from Bogebeekken, pass the 8.2 ka BP – event and into the mid- Holocene. The same goes for the foraminifera, which could then be comparative and complementary data to Rasmussen et al. (2012).

Although stable oxygen isotopes clearly could have offered valuable data, it was considered to be outside of the scope of this thesis. However, such analyses may form the basis of a future separate bachelor- or master thesis on the institute of Geography, NTNU.

Other analyses which could have been included were grain size analyses. Given its size, foraminifera are vulnerable for being washed or sieved out together with fine-grained sediments, and different species have different thresholds for this. Also, some species thrive in finer or coarser sediments compared with others. Thus, a quantitative sediment composition for each sample (rather than the qualitative assessment included) could have provided a better basis for comparison between sites.

Future studies of foraminifera in raised marine sediments in Svalbard may want to target sampling sites with distinct stratigraphy and a temporal span in order to make stronger interpretations and track assemblage changes over time. Replicate sampling sections are recommended. Valuable comparisons can perhaps be done by sampling sites both with and without thermophilous molluscs observed.

6. Summary and conclusions

Sediment samples with raised marine sediments have been collected from four different locations around Isfjorden, Svalbard, to study foraminifera and molluscs from the early- and mid-Holocene.

From the results of this study, the following key points can be summarized:

- Individuals of *A. islandica* from both Bogebeekken and Erdmannflya date younger than all previously radiocarbon dated *A. islandica* from Svalbard. Recurring samples through the early Holocene show that the species occupied coastal waters here from ~10.0 ka BP to at least as late as 8.5 ka BP.
- The occurrence of *A. islandica* show that temperatures stayed significantly above pre-industrial levels until at least ~8.5 ka BP.
- No hard conclusions can be done regarding the lack of dates 8.5 ka BP – 7.9 ka BP seen in this study. A real hiatus can't be concluded on the basis of these few shells. The following two points are speculations:

- The absence of *A. islandica* 8.5 ka BP – 7.9 ka BP might be an indicator of the so-called 8.2 ka BP – event as well as an indicator that increased inflow of Atlantic water played a major role in the regional temperatures in Svalbard in the early and mid-Holocene.
- One single individual of *A. islandica* dated 7.9 ka BP indicates that the early Holocene warm period may be extended even later. Shallowing conditions might have prevented younger shells.
- The dataset is too scarce and calls for further investigations of the mollusc fauna - more studies are required to improve the known accuracy of the temporal and spatial distribution in which both *A. islandica* and other thermophilous molluscs occur.
- The foraminifera are paleoenvironmentally consistent with the molluscs and sediment, but do not on their own indicate warmer conditions since all key species are present in Isfjorden today. Local conditions are important and might overprint regional environmental aspects. More sampling for foraminifera in raised marine sediments in Svalbard is recommended.
- Seasonal temperature variations in the early Holocene indicates that the pattern of warming differs from ongoing and projected future warming at high latitudes, hence, the warm early Holocene in Svalbard is not a good analogue for the pattern of anthropogenic warming, and neither a re-immigration of thermophilous molluscs other than *Mytilus* spp nor changes in foraminiferal assemblages is therefore directly comparable to the early Holocene.
- Anthropogenic warming combined with Arctic amplification cause a rapid increase in both marine and terrestrial temperatures in Svalbard with major and unknown consequences for ecosystems and societies. Even if not being a good analogue for future warming, increased knowledge about the last period with significant warmer conditions than present is still valuable to test and evaluate climate models for future modelling.

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Appendix 1. List over observed species

Species name	Original description
<i>Astrononion hamadaense</i>	Asano, K. (1950). Part 1. Nonionidae. In: Stach, L.W. (Editor), Illustrated Catalogue of Japanese Tertiary smaller Foraminifera. <i>Hosokawa Printing Co, Tokyo</i> . page(s): p. 6 fig. 29-31
<i>Bolivinellina pseudopunctata</i>	Höglund, H. (1947). Foraminifera in the Gullmar Fjord and the Skagerak. <i>Zoologiska bidrag från Uppsala</i> . 26: 1-328.
<i>Buccella frigida</i>	Cushman, J. A. (1922). Results of the Hudson Bay Expedition. I. The Foraminifera. <i>Contributions to Canadian Biology</i> . 1921(9): 133-147
<i>Cassidulina reniforme</i>	Nørvang, A. (1945). The Zoology of Iceland, Foraminifera. <i>Copenhagen & Reykjavik: Ejnar Munksgaard</i> . v. 2, Part 2: 1-79. page(s): p. 41, text-figs. 6e—6h
<i>Cassidulina spp</i>	Orbigny, A. D. d'. (1826). Tableau méthodique de la classe des Céphalopodes. <i>Annales des Sciences Naturelles</i> . vol. 7: 96-169, 245-314., available online at http://biodiversitylibrary.org/page/5753959 page(s): p. 282
<i>Criboelphidium albumbilicatum</i>	Weiss, L. (1954). Foraminifera and origin of the Gardiners clay (Pleistocene), eastern Long Island, New York. <i>United States Geological Survey Professional Papers</i> . 254- G: 143-163.
<i>Criboelphidium excavatum</i>	Terquem, O. (1875). Essai sur le classement des animaux qui vivent sur le plage et dans les environs de Dunkerque (premier fascicule). Paris.
<i>Criboelphidium magellanicum</i>	Heron-Allen, E.; Earland, A. (1932). Foraminifera: Part I. The ice-free area of the Falkland Islands and adjacent seas. <i>Discovery Reports Vol. IV</i> , Cambridge, University Press. pp. 291-460.
<i>Criboelphidium subarcticum</i>	Cushman, J.A. 1944. Foraminifera from the shallow water of the New England coast. Special Publ. No. 12, Cushman Lab. Foram. Res.: 1-37.
<i>Criboelphidium williamsoni</i>	Haynes, J. R. (1973). Cardigan Bay Recent Foraminifera (Cruises of the R. V. Antur, 1962-1964). <i>Bulletin of the British Museum (Natural History), Zoology</i> . Supplement 4, pp. 1-245.
<i>Elphidium asklundi</i>	Brotzen, F. 1943. Appendix, p. 267-269. In Hessland, I. (ed.), <i>Marine Schalenablagerungen Nord-Bohusläns</i> . Bulletin of the Geological Institute of the University of Uppsala, vol. 31.

<i>Elphidium bartletti</i>	Cushman, J. A. (1933). New Arctic Foraminifera collected by Capt R. A. Bartlett from Fox Basin and off the northeast coast of Greenland. <i>Smithsonian Miscellaneous Collections</i> . 89 (9): 1-8.
<i>Haynesina orbicularis</i>	Brady, H. B. (1881). XL.—On some Arctic Foraminifera from soundings obtained on the Austro-Hungarian North-Polar Expedition of 1872–1874. <i>Annals and Magazine of Natural History</i> . ser 5, 8(48): 393-418.
<i>Islandiella helenae</i>	Feyling-Hanssen, R. W.; Buzas, M. A. (1976). Emendation of <i>Cassidulina</i> and <i>Islandiella helenae</i> new species. <i>The Journal of Foraminiferal Research</i> . 6(2): 154-158.
<i>Islandiella norcrossi</i>	Cushman, J. A. (1933). New Arctic Foraminifera collected by Capt R. A. Bartlett from Fox Basin and off the northeast coast of Greenland. <i>Smithsonian Miscellaneous Collections</i> . 89 (9): 1-8.
<i>Lobatula lobatula</i>	Walker & Jacob, 1798. Not documented.
<i>Nonionellina labradorica</i>	Dawson, J. W. (1860). Notice of Tertiary fossils from Labrador, Maine, etc., and remarks on the climate of Canada in the newer Pliocene or Pleistocene period. <i>Canadian Naturalist and Geologist, Montreal</i> . 5: 188-200.
<i>Pseudopolymorphina</i> spp.	Cushman, J. A.; Ozawa, Y. (1928). An outline of a revision of the Polymorphinidae. <i>Contributions from the Cushman laboratory for foraminiferal research</i> . 4(1): 13-21.
<i>Quinqueloculina seminulum</i>	Linnaeus, C. (1758). <i>Systema Naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis. Editio decima, reformata [10th revised edition], vol. 1: 824 pp. Laurentius Salvius: Holmiae.</i>
<i>Robertinoides</i> spp	Höglund, H. (1947). Foraminifera in the Gullmar Fjord and the Skagerak. <i>Zoologiska bidrag från Uppsala</i> . 26: 1-328.
<i>Rosalina</i> spp.	Orbigny, A. D. d'. (1826). Tableau méthodique de la classe des Céphalopodes. <i>Annales des Sciences Naturelles</i> . vol. 7: 96-169, 245-314., available online at http://biodiversitylibrary.org/page/5753959 page(s): p. 271
<i>Stainforthia loeblichii</i>	Feyling-Hanssen, R. W. (1954). The stratigraphic position of the quick clay at Bekkelaget, Oslo. <i>Norsk Geol. Tidsskr.</i> 33: 185-196.
<i>Trilochulina</i> spp.	Orbigny, A. D. d'. (1826). Tableau méthodique de la classe des Céphalopodes. <i>Annales des Sciences Naturelles</i> . vol. 7: 96-169, 245-314.

Appendix 2 – foraminifera data tables

Begebekken	BB01	BB02	BB03	BB04	BB05	BB06	BB07	BB08	BB09	BB10	BB11	BB12
Sample name	BB01	BB02	BB03	BB04	BB05	BB06	BB07	BB08	BB09	BB10	BB11	BB12
Sample height (m.a.s.l.)	0,95	1,55	2,15	2,65	3,35	3,65	4,20	4,55	5,10	6,10	6,75	7,25
Wet weight (g)	43,6430	40,0200	44,0100	44,6635	41,6400	41,8050	45,2068	44,6000	46,4873	46,9422	44,8312	47,6133
Volume (cc)	23	20	22	20	20	20	21	20	20	21	20	20
Dry weight >100 µm (g)	22,33	16,058	13,47	31,1	27,75	25,98	29,24	33,58	35,38	33,36	30,44	42,07
Total benthics counted	377	357	202	138	332	138	502	347	387	0	0	0
Total agglutinates counted	0	0	0	0	0	0	0	0	0	0	0	0
Amount of sample counted	1	1	5/8	1	1	1	1	1	1	1	1	1
Benthics concentration (per dry g)	16,8831	22,2319	23,9941	4,4373	11,9640	5,3118	17,1683	10,3335	10,9384	0,0000	0,0000	0,0000
volume (cc) counted	23	20	13,75	20	20	20	21	20	20	21	20	20
Planktics concentration (per dry g)	0	0	0	0	0	0	0	0	0	0	0	0
Benthics concentration (per 10 cc)	163,9130	178,5000	146,9091	69,0000	166,0000	69,0000	239,0476	173,5000	193,5000	0,0000	0,0000	0,0000

Relative abundance (%) - Calcareous	BB01	BB02	BB03	BB04	BB05	BB06	BB07	BB08	BB09	BB10	BB11	BB12
<i>Astronomion hamadaense</i>	2,67	0,00	0,00	0,00	0,30	0,72	1,39	0,00	0,00	0,00	0,00	0,00
<i>Globocassidulina</i>	0,00	0,00	0,00	0,00	0,00	0,00	0,60	0,00	0,00	0,00	0,00	0,00
<i>Rosalina</i> spp.	0,53	0,84	0,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Juvenile <i>Lobatula lobatula</i>	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,29	0,00	0,00	0,00	0,00
<i>Cassidulina reniforme</i>	1,07	1,12	0,99	0,72	1,20	0,72	0,80	1,15	1,03	0,00	0,00	0,00
<i>Lobatula lobatula</i>	51,34	85,15	79,21	82,61	77,71	77,54	81,27	89,05	89,66	0,00	0,00	0,00
<i>Nonionellina labradorica</i>	4,28	0,28	1,98	0,00	0,00	0,72	1,79	1,15	0,00	0,00	0,00	0,00
<i>Cribrorophidium excavatum</i>	31,02	7,00	14,85	4,35	9,94	2,90	5,78	3,75	5,17	0,00	0,00	0,00
<i>Elphidium bartletti</i>	2,14	1,40	0,00	0,72	2,11	1,45	0,60	1,44	0,78	0,00	0,00	0,00
<i>Elphidium asklundi</i>	0,27	0,28	0,00	0,00	0,00	0,00	0,00	0,00	0,26	0,00	0,00	0,00
<i>Cribrorophidium magellanicum</i>	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Cribrorophidium williamsoni</i>	2,41	0,00	0,00	0,00	0,00	0,00	0,60	0,00	0,00	0,00	0,00	0,00
Unidentified	1,34	3,08	0,00	6,52	5,12	13,77	6,18	2,59	1,29	0,00	0,00	0,00
<i>Buccella frigida</i>	0,00	0,00	0,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Bolivimellina pseudopunctata</i>	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Cribrorophidium subarcticum</i>	0,00	0,00	0,00	0,00	0,00	0,72	0,00	0,00	0,00	0,00	0,00	0,00
<i>Stainforthia loeblichii</i>	0,00	0,28	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Trilochulina</i> spp.	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Haynesina orbicularis</i>	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Quinceloculina seminulum</i>	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Islandiella belenae</i>	2,94	0,56	0,50	3,62	3,31	1,45	1,00	0,58	1,29	0,00	0,00	0,00
<i>Islandiella norrossi</i>	0,00	0,00	0,50		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Pseudopolyornopina</i> spp.	0,00	0,00	0,00		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Elphidium</i> spp.	0,80	0,00	0,00		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
<i>Robertinoides</i> spp.	0,53	0,00	0,00		0,00	0,72	0,00	0,00	0,00	0,00	0,00	0,00
<i>Cribrorophidium albibullicatum</i>	0,27	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Numbers of foraminifera counted per sample	BB01	BB02	BB03	BB04	BB05	BB06	BB07	BB08	BB09	BB10	BB11	BB12
<i>Astronion hamadaense</i>	10	0	0	0	1	1	7	0	0	0	0	0
<i>Globocassidulina</i>	0	0	0	0	0	0	3	0	0	0	0	0
<i>Rosalina</i> spp.	2	3	1	0	0	0	0	0	0	0	0	0
Juvenile <i>Lobatula lobatula</i>	0	0	0	0	0	0	0	1	0	0	0	0
<i>Cassidulina reniforme</i>	4	4	2	1	4	1	4	4	4	0	0	0
<i>Lobatula lobatula</i>	192	304	160	114	258	107	408	309	347	0	0	0
<i>Nonionellina labradorica</i>	16	1	4	0	0	1	9	4	0	0	0	0
<i>Criboelphidium excavatum</i>	116	25	30	6	33	4	29	13	20	0	0	0
<i>Elphidium bartletti</i>	8	5	0	1	7	2	3	5	3	0	0	0
<i>Elphidium asklundi</i>	1	1	0	0	0	0	0	0	1	0	0	0
<i>Criboelphidium magellanicum</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Criboelphidium williamsoni</i>	9	0	2	2	1	0	3	0	2	0	0	0
Unidentified	5	11	0	9	17	19	31	9	5	0	0	0
<i>Buccella frigida</i>	0	0	1	0	0	0	0	0	0	0	0	0
<i>Bolivinelina pseudopunctata</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Criboelphidium subarcticum</i>	0	0	0	0	0	1	0	0	0	0	0	0
<i>Stamfortia loeblichii</i>	0	1	0	0	0	0	0	0	0	0	0	0
<i>Trilochulina</i> spp.	0	0	0	0	0	0	0	0	0	0	0	0
<i>Haynesina orbicularis</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Quinceloculina seminulum</i>	0	0	0	0	0	0	0	0	0	0	0	0
<i>Islandiella helena</i>	11	2	1	5	11	2	5	2	5	0	0	0
<i>Islandiella norrossi</i>	0	0	1	0	0	0	0	0	0	0	0	0
<i>Pseudopolymorphina</i> spp.	0	0	0	0	0	0	0	0	0	0	0	0
<i>Elphidium</i> spp.	3	0	0	0	0	0	0	0	0	0	0	0
<i>Robertinoides</i> spp.	2	0	0	0	0	1	0	0	0	0	0	0
<i>Criboelphidium albiumblicatum</i>	1	0	0	0	0	0	0	0	0	0	0	0
Sum calcareous benthic foraminifera	374	357	202	138	332	138	502	347	387	0	0	0

Sample name	EmfF01	EmfF02	EmfF03	EmfF04	EmfF05
Sample height (m.a.s.l.)	2.5	2.5	2.5	2.5	2.5
Wet weight (g)	40,8600	41,2000	41,5000	42,3023	41,7200
Volume (cc)	20	20	22	21	20
Dry weight >100 µm (g)	11.3	14,721	14,29	16,42	17,77
Total benthics counted	317	293	341	332	427
Total agglutinates counted	0	0	0	0	0
Amount of sample counted	1/64	1/64	1/32	5/256	1/32
Benthics concentration (# per dry g)	1795,3982	1273,8265	763,6109	1035,2253	768,9364
Volume (cc) counted	5/16	5/16	11/16	105/256	5/8
Planktics concentration (# per dry g)					
Ostracods concentration (# per dry g)	N/A	N/A	N/A	N/A	N/A
Benthics concentration (# per 10 cc)	10144,00	9376,00	4960,00	8094,48	6832,00
Agglutinates concentration (# per 10 cc)					
Planktics concentration (# per 10 cc)					
Ostracods concentration (# per 10 cc)	N/A	N/A	N/A	N/A	N/A

Relative abundance (%) - Calcareous	EmF01	EmF02	EmF03	EmF04	EmF05
<i>Astrononion hamadaense</i>	4,42	6,83	4,69	7,23	4,45
<i>Globocassidulina</i>	0,00	0,00	0,29	0,30	0,00
<i>Rosalina</i> spp.	6,62	3,75	7,62	5,12	5,85
Juvenile <i>Lobatula lobatula</i>	0,00	0,00	0,88	0,30	0,00
<i>Cassidulina reniforme</i>	11,67	11,60	12,32	9,64	12,41
<i>Lobatula lobatula</i>	51,74	56,66	52,49	52,11	60,89
<i>Nonionellina labradorica</i>	0,95	0,68	2,05	2,11	0,23
<i>Criboelphidium excavatum</i>	12,93	9,56	10,26	9,64	5,39
<i>Elphidium bartletti</i>	4,10	2,73	3,52	1,20	4,68
<i>Elphidium asklundi</i>	0,32	0,00	1,47	0,00	0,23
<i>Criboelphidium magellanicum</i>	0,00	0,00	0,00	0,30	0,00
<i>Criboelphidium williamsoni</i>	0,00	0,00	0,00	1,81	0,00
Unidentified	5,05	6,14	4,40	8,13	3,04
<i>Buccella frigida</i>	0,32	0,68	0,00	0,30	0,00
<i>Bolivinellina pseudopunctata</i>	0,00	0,00	0,00	0,30	0,00
<i>Criboelphidium subarcticum</i>	0,00	0,00	0,00	0,00	0,00
<i>Stainforthia loeblichii</i>	0,00	0,00	0,00	0,30	0,00
<i>Trilochulina</i> spp.	0,00	0,00	0,00	0,30	0,00
<i>Haynesina orbicularis</i>	0,00	0,00	0,00	0,60	0,00
<i>Quinceloculina seminulum</i>	0,00	0,00	0,00	0,30	0,00
<i>Islandiella helenae</i>	0,00	0,00	0,00	0,00	0,23
<i>Islandiella norcrossi</i>	0,00	0,00	0,00	0,00	0,00
<i>Pseudopolymorphina</i> spp.	0,00	0,34	0,00	0,00	0,00
<i>Elphidium</i> spp.	0,00	0,00	0,00	0,00	0,00
<i>Robertinoides</i> spp.	0,00	0,00	0,00	0,00	0,00
<i>Criboelphidium albiumbilicatum</i>	0,00	0,00	0,00	0,00	0,00

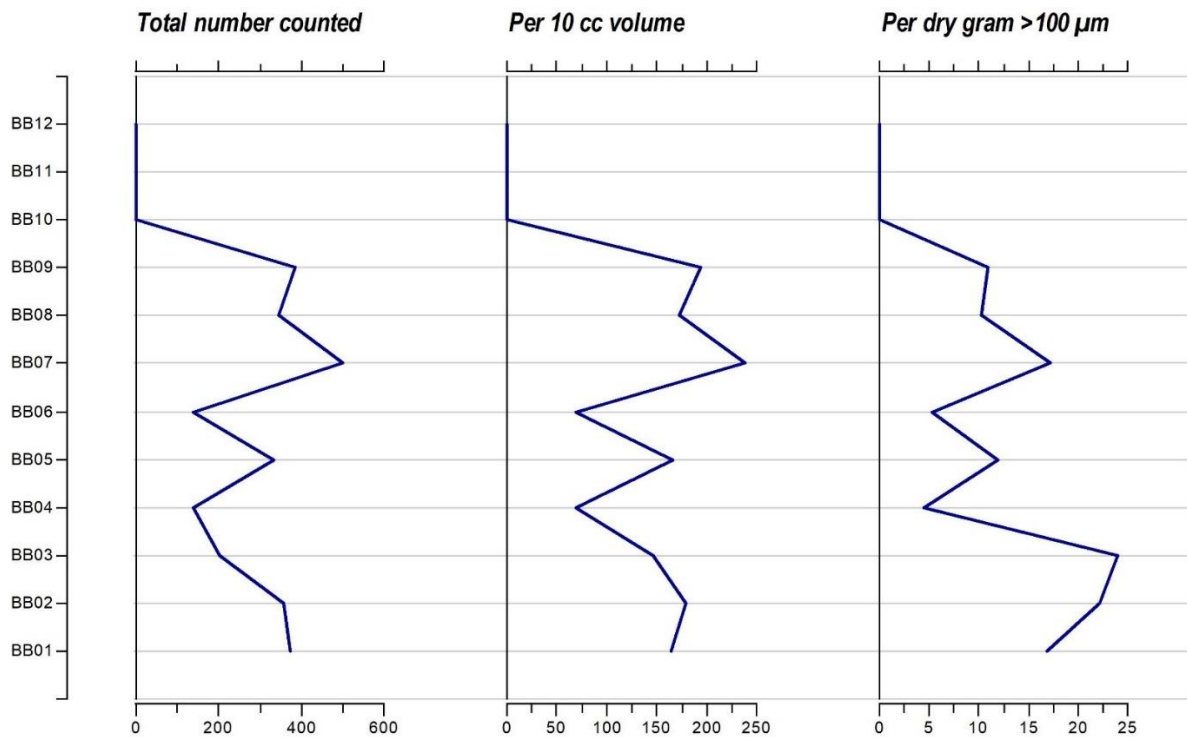
	EmF01	EmF02	EmF03	EmF04	EmF05
<i>Astrononion hamadaense</i>	14	20	16	24	19
<i>Globocassidulina</i>	0	0	1	1	0
<i>Rosalina</i> spp.	21	11	26	17	25
Juvenile <i>Lobatula lobatula</i>	0	0	3	1	0
<i>Cassidulina reniforme</i>	37	34	42	32	53
<i>Lobatula lobatula</i>	164	166	179	173	260
<i>Nonionellina labradorica</i>	3	2	7	7	1
<i>Criboelphidium excavatum</i>	41	28	35	32	23
<i>Elphidium bartletti</i>	13	8	12	4	20
<i>Elphidium asklundi</i>	1	0	5	0	1
<i>Criboelphidium magellanicum</i>	0	0	0	1	0
<i>Criboelphidium williamsoni</i>	4	2		6	10
Unidentified	16	18	15	27	13
<i>Buccella frigida</i>	1	2	0	1	0
<i>Bolivinellina pseudopunctata</i>	0	0	0	1	0
<i>Criboelphidium subarcticum</i>	0	0	0	0	0
<i>Stainforthia loeblichii</i>	0	1	0	1	1
<i>Trilochulina</i> spp.	2	0	0	1	0
<i>Haynesina orbicularis</i>	0	0	0	2	0
<i>Quinceloculina seminulum</i>	0	0	0	1	0
<i>Islandiella helenae</i>	0	0	0	0	1
<i>Islandiella norcrossi</i>	0	0	0	0	0
<i>Pseudopolymorphina</i> spp.	0	1	0	0	0
<i>Elphidium</i> spp.	0	0	0	0	0
<i>Robertinoides</i> spp.	0	0	0	0	0
<i>Criboelphidium albumbilicatum</i>	0	0	0	0	0
Sum calcareous benthic foraminifera	317	293	341	332	427

	Hiorthhamn		(HH) 08/09						
Sample ID		HH01F	HH02F	HH03F	HH04F	HH05F			
Volume (cc)		20	20	20	20	20			20
Wet weight (g)		37,3293	39,9901	38,47	34,56	38,2024			
Dry weight >100 µm (g)		-	-	-	-	-			-
Dry weight 63-100 µm (g)		-	-	-	-	-			-

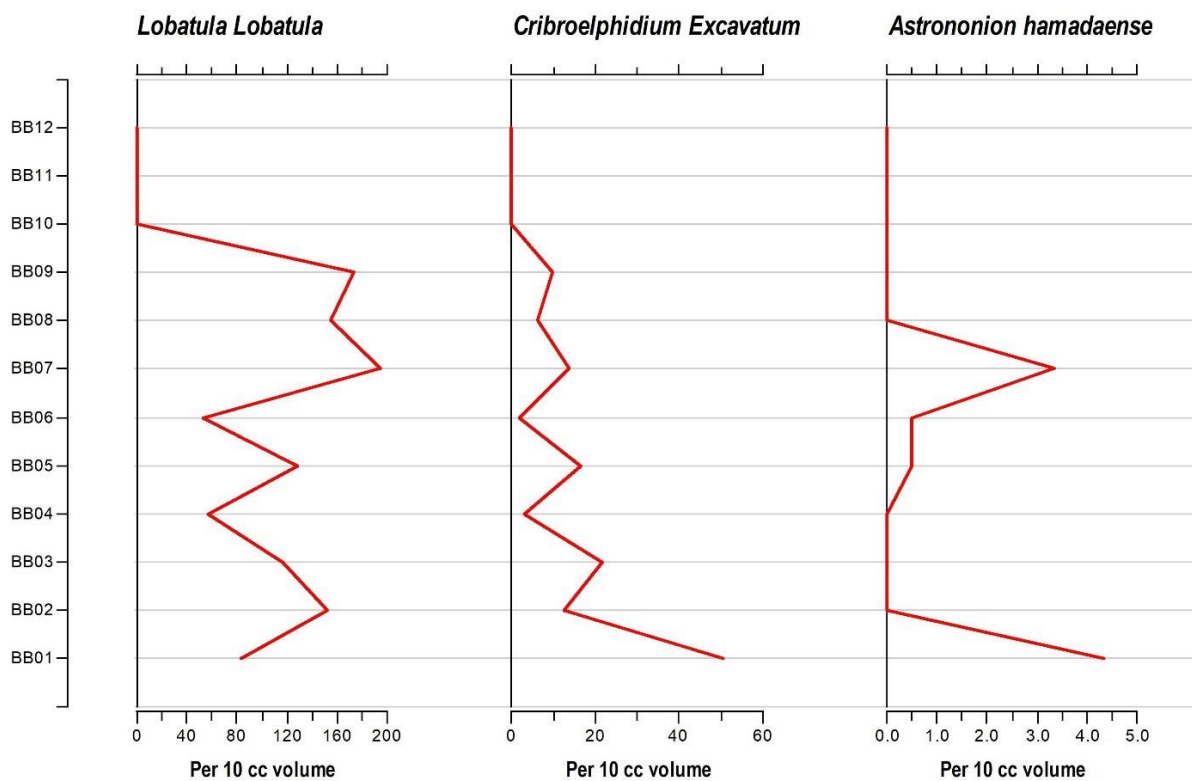
	Bolterdalen (BD) 30/10, Section 1									
Sample ID	BD-1-01	BD-1-02	BD-1-03	BD-1-04	BD-1-05	BD-1-06	BD-1-07	BD-1-08	BD-1-09	BD-1-10
Volume (cc)	20	20	20	21	20	20	20	20	20	20
Wet weight (g)	42,7040	39,0872	40,3484	39,7950	38,9131	46,2106	40,0511	43,1249	40,9980	47,4189
Dry weight >100 µm (g)	-	-	-	-	-	-	-	-	-	-
Dry weight 63-100 µm (g)	-	-	-	-	-	-	-	-	-	-

	Boldertalen (BD) 30/10, Section 2									
Sample ID	BD-2-01	BD-2-02	BD-2-03	BD-2-04	BD-2-05	BD-2-06	BD-2-07	BD-2-08	BD-2-09	BD-2-10
Volume (cc)	21	20	20	20	21	20	20	21	20	20
Wet weight (g)	39,8735	39,6001	39,5111	41,1181	39,9385	41,1050	44,7211	41,9526	40,5989	43,4962
Dry weight >100 µm (g)	-	-	-	-	-	-	-	-	-	-
Dry weight 63-100 µm (g)	-	-	-	-	-	-	-	-	-	-

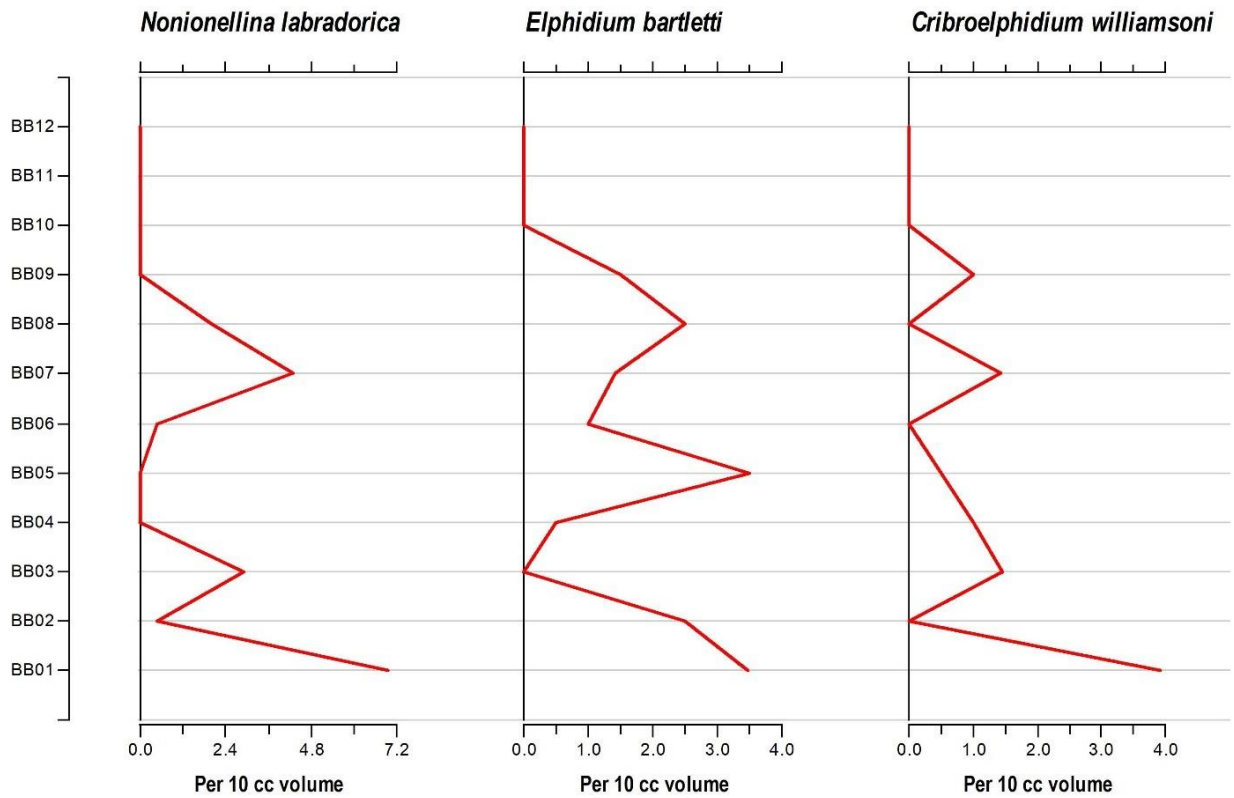
Appendix 3a: Foraminifera statistics from Bogebekken



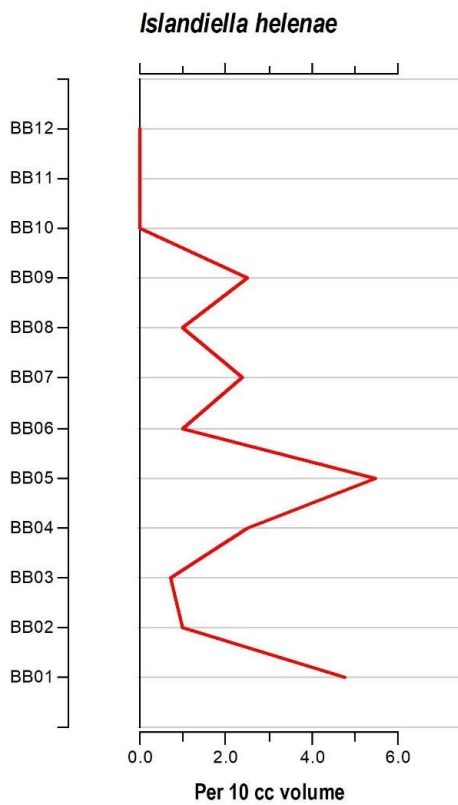
Left: numbers of foraminifera counted per sample. Middle: Estimated numbers of foraminifera per 10 cc sediments based on specimens counted per volume. Right: Estimated number of foraminifera per dry gram sieved sediments



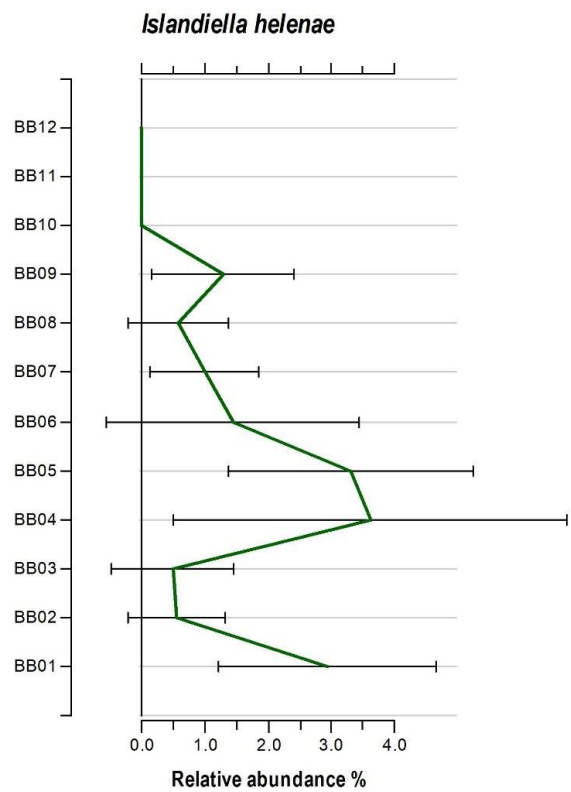
Estimated number of the mentioned species per 10cc sediments, estimated from the investigated volume.



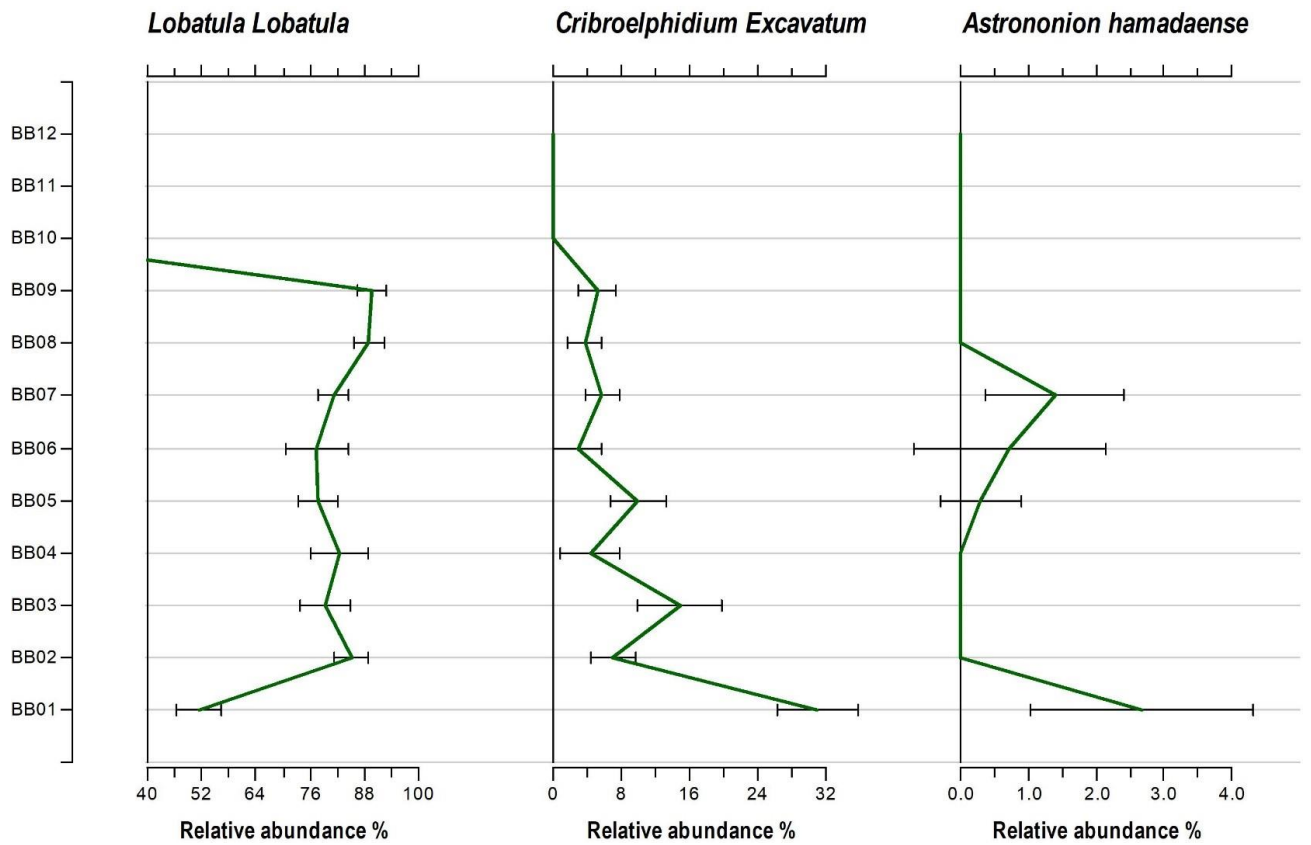
Estimated number of the mentioned specie per 10cc sediments, estimated from the investigated volume.



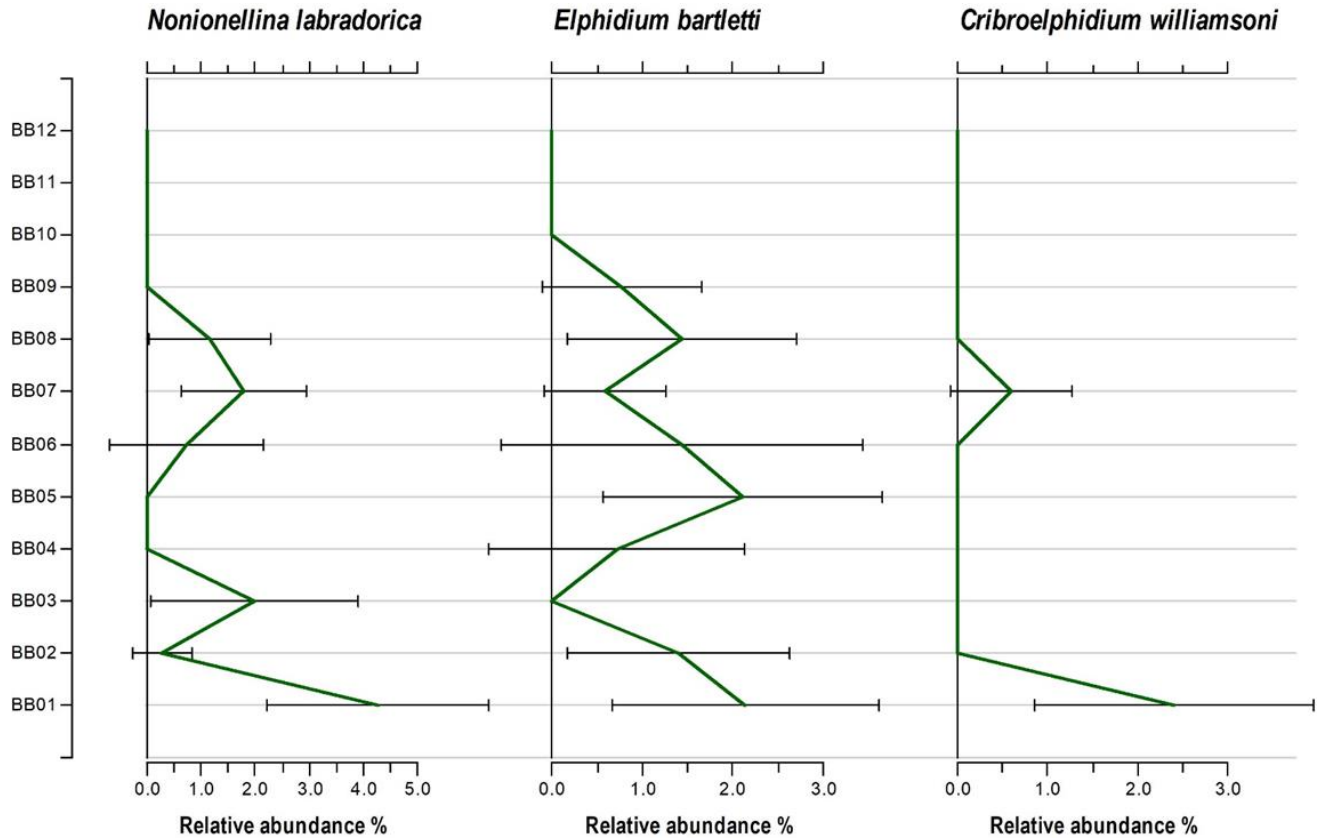
Estimated number of the mentioned specie per 10cc sediments, estimated from the investigated volume.



Abundance in percent of total foraminiferal abundance, with 95 % confidence interval

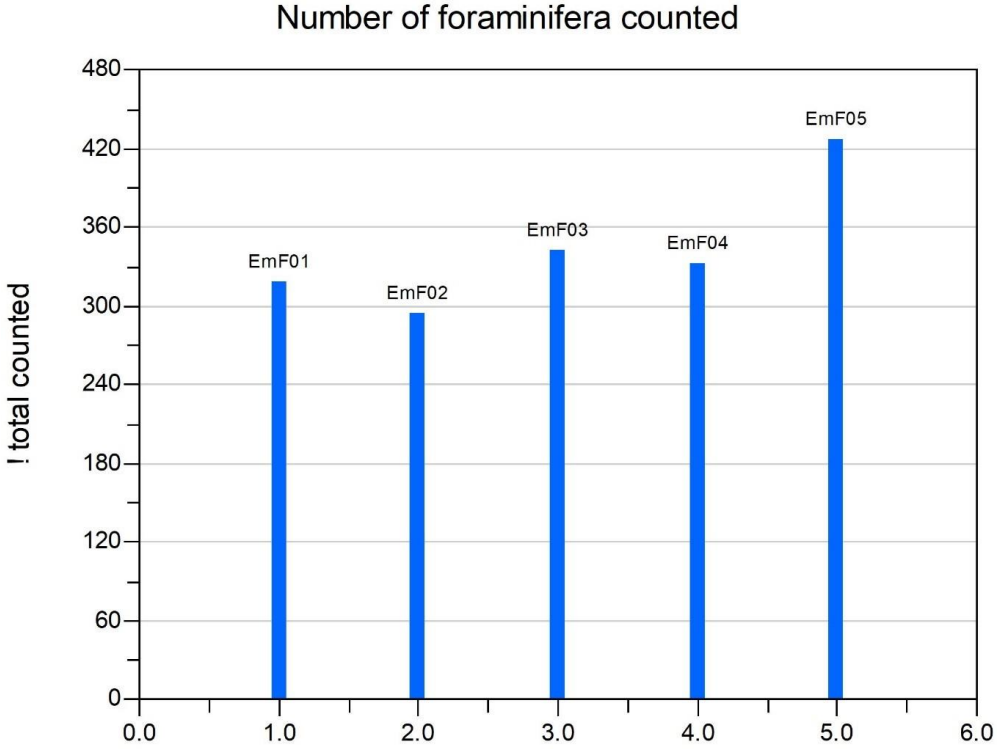


Abundance in percent of total foraminiferal abundance, with 95 % confidence interval

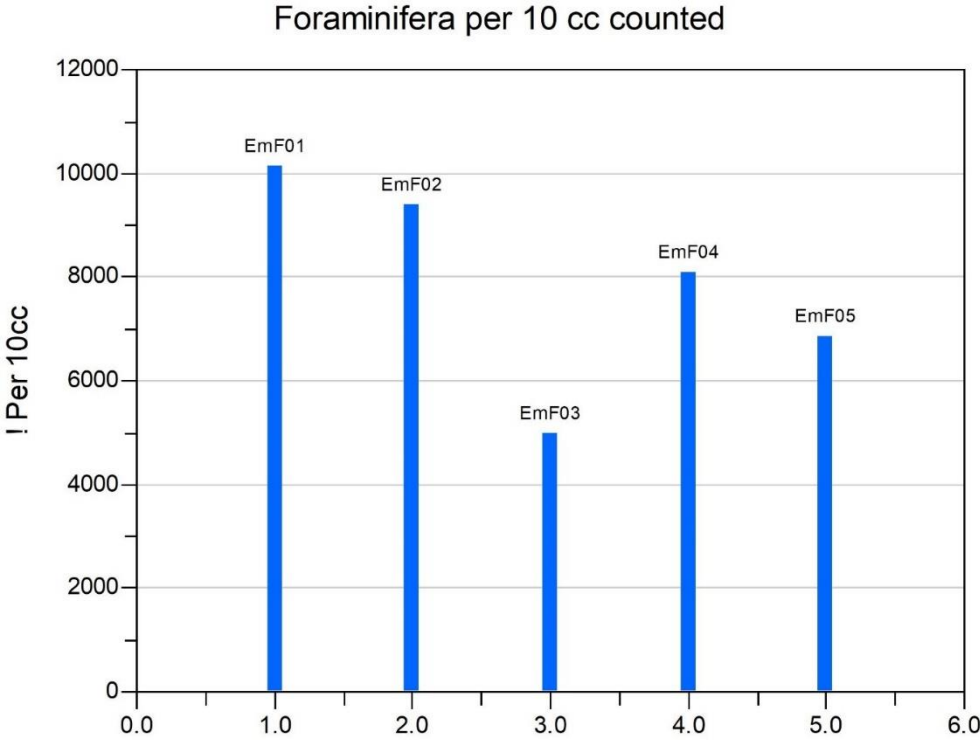


Abundance in percent of total foraminiferal abundance, with 95 % confidence interval

Appendix 3b: Foraminifera statistics from Erdmannflya

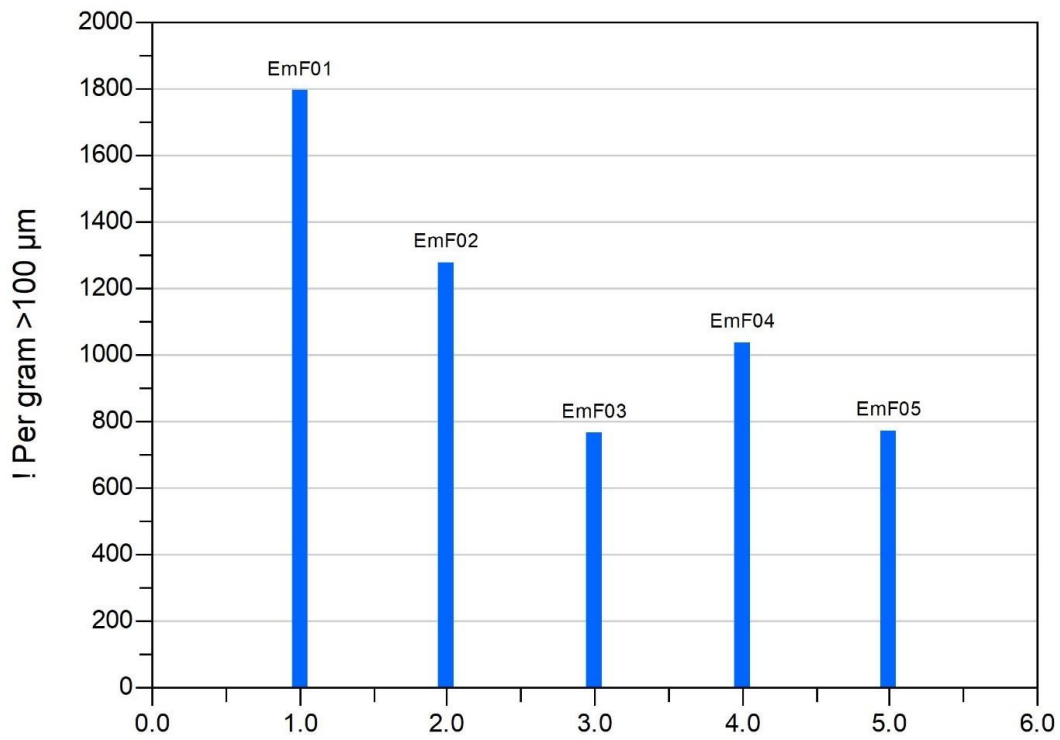


Number of foraminifera counted per sample

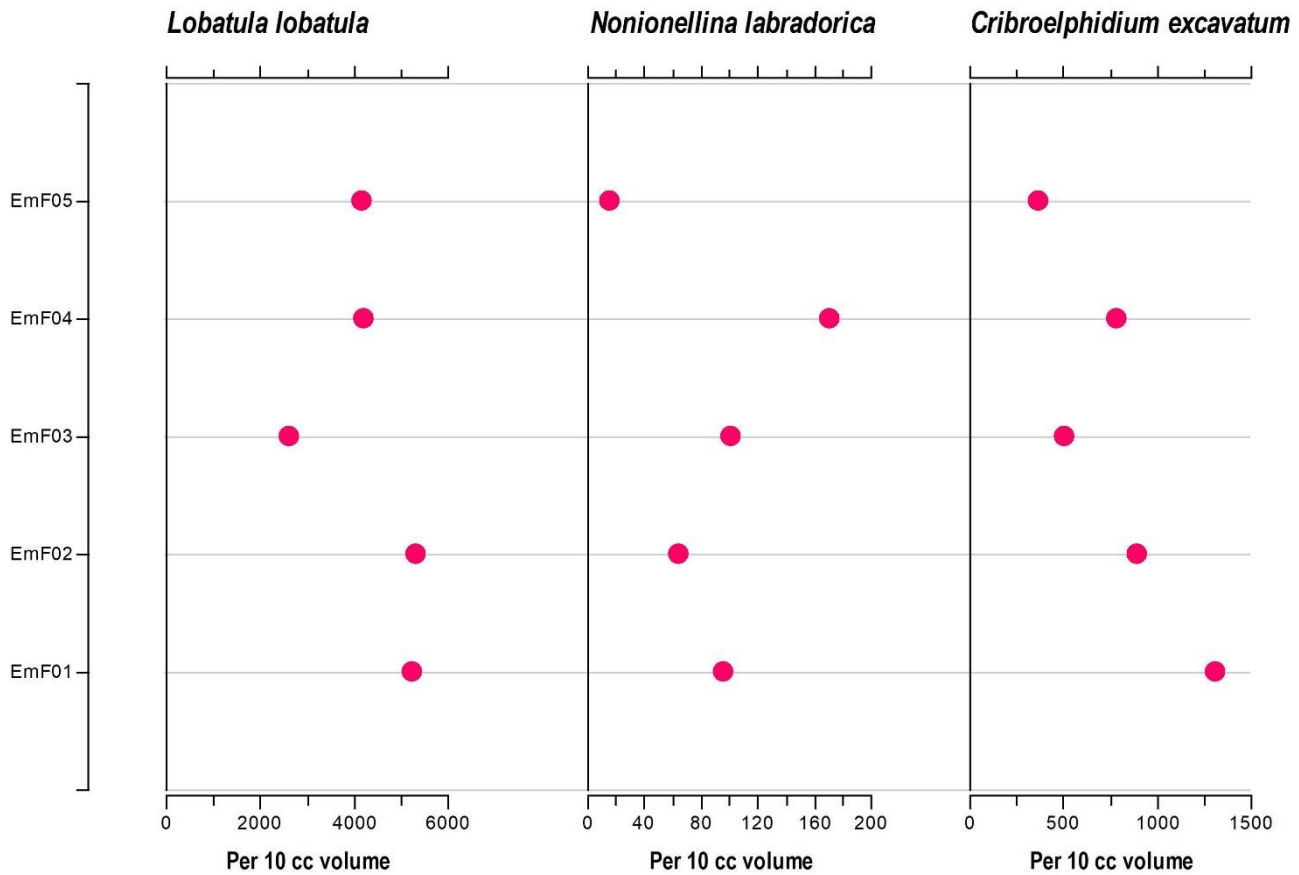


Estimated number of foraminifera per 10cc sediments

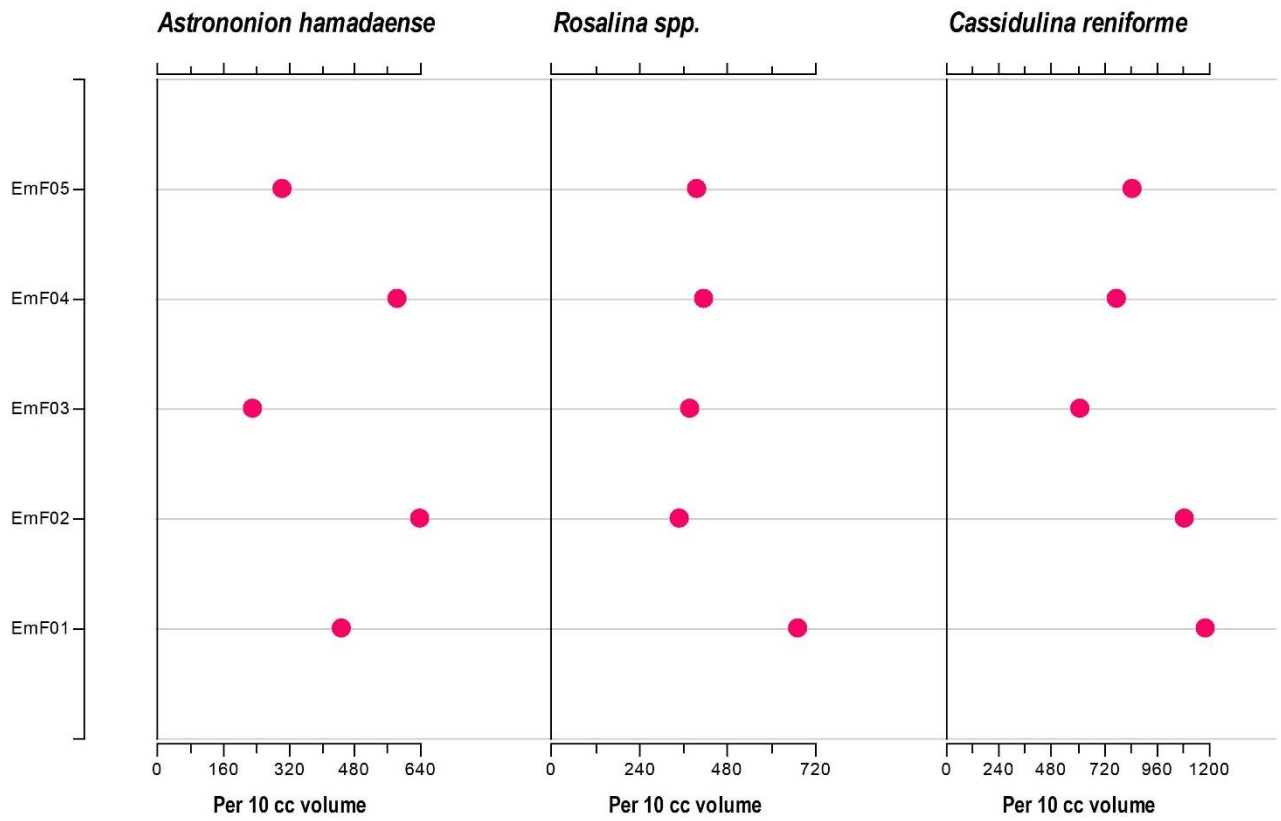
Foraminifera per gram dry sediment >100 micrometer



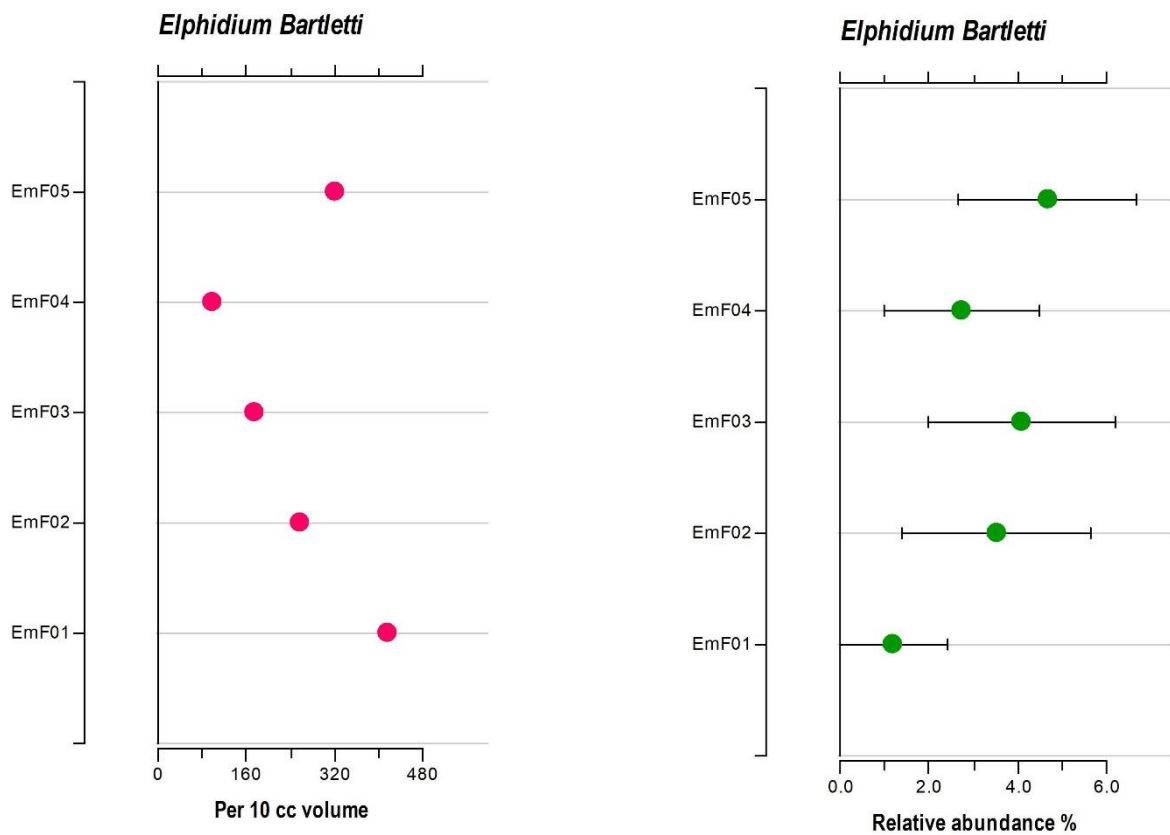
Estimated number of foraminifera per gram sieved sediment



Estimated number of the mentioned specie per 10cc sediments, estimated from the investigated volume.

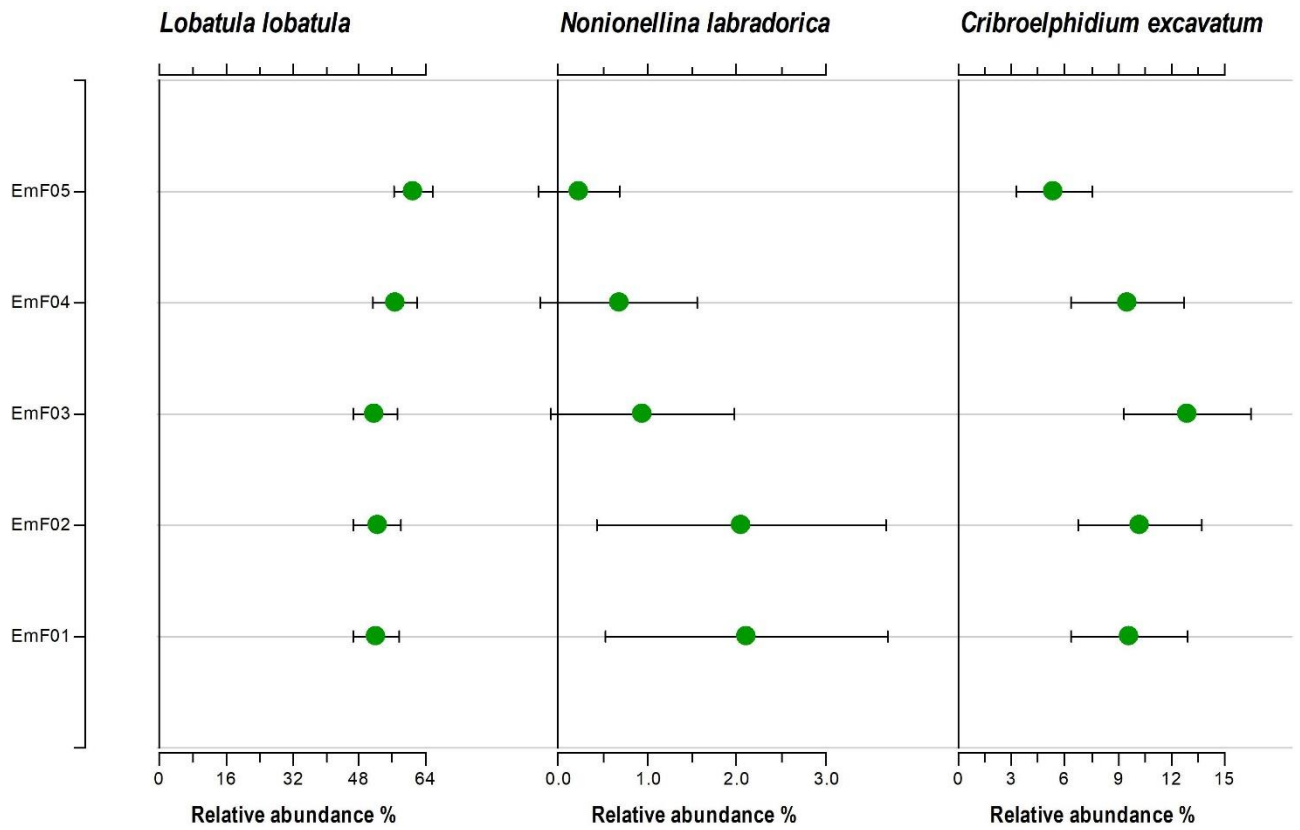


Estimated number of the mentioned specie per 10cc sediments, estimated from the investigated volume.

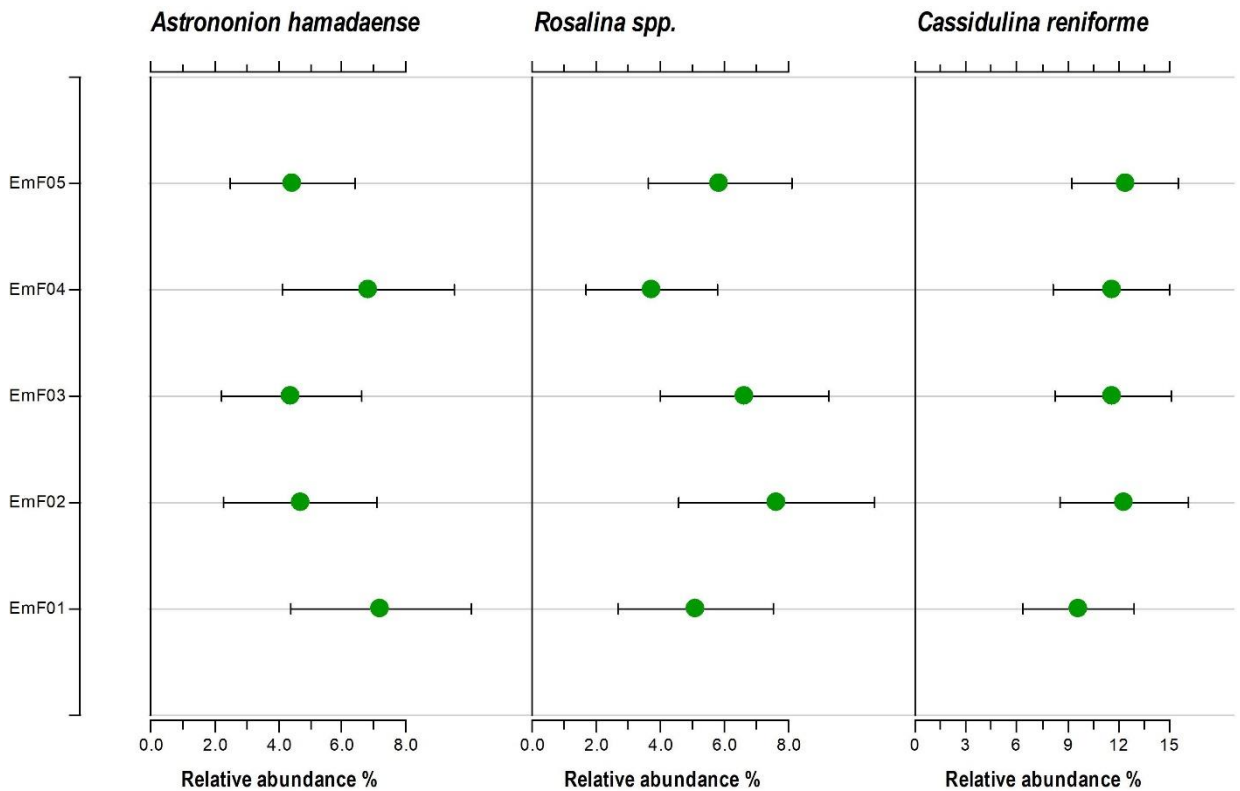


Estimated number of the mentioned specie per 10cc sediments, estimated from the investigated volume.

Abundance in percent of total foraminiferal abundance, with 95 % confidence interval

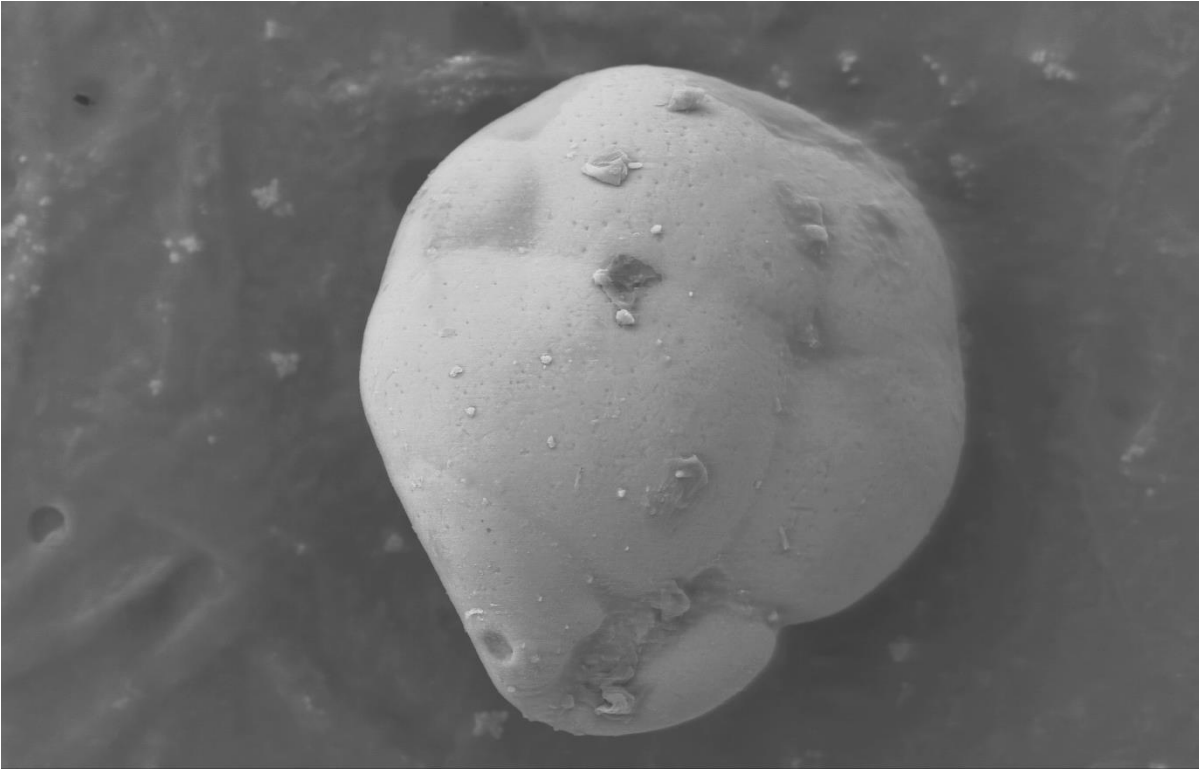


Abundance in percent of total foraminiferal abundance, with 95 % confidence interval



Abundance in percent of total foraminiferal abundance, with 95 % confidence interval

Appendix 4: SEM-photos of foraminifera species



20.0kV 9.2mm x300 BSE3D 15Pa 100um

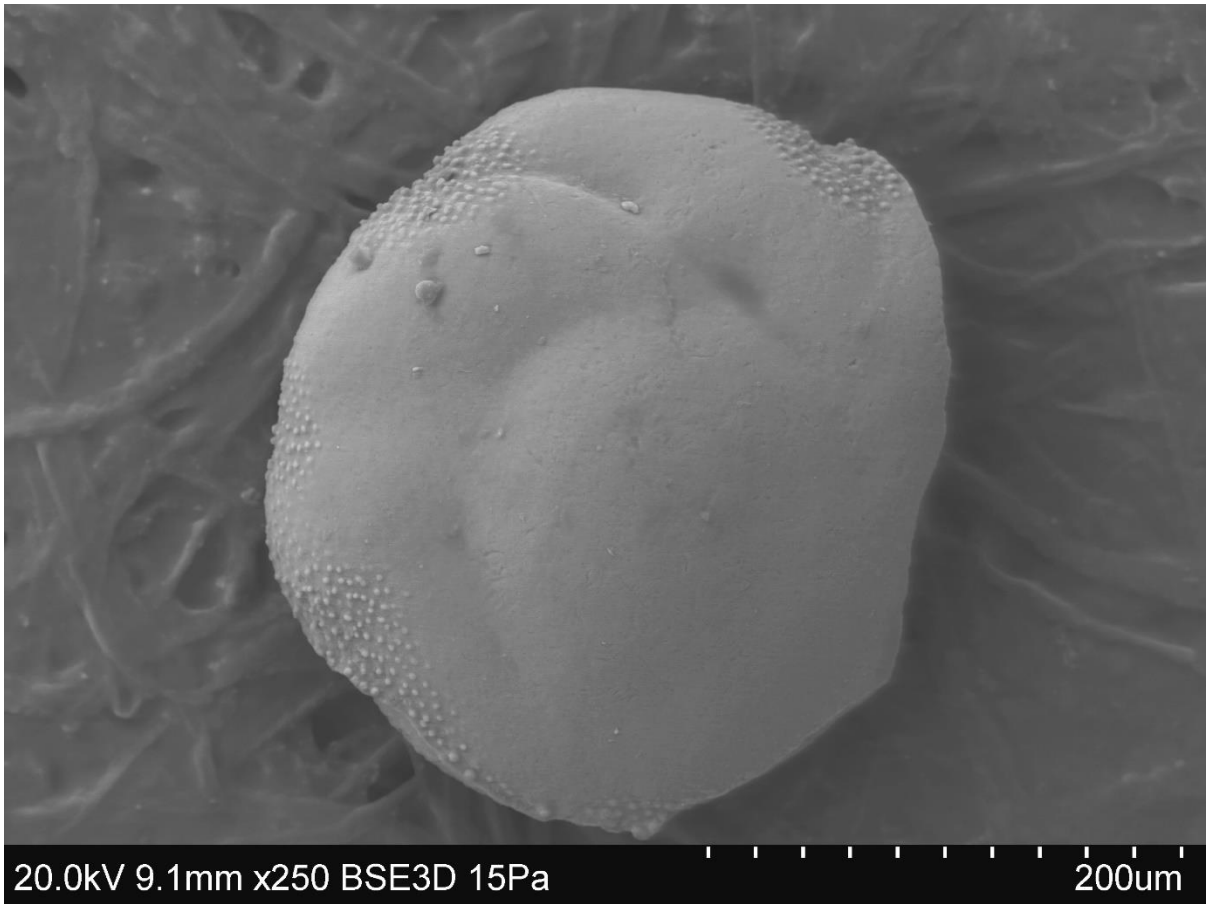


20.0kV 9.3mm x400 BSE3D 15Pa 100um

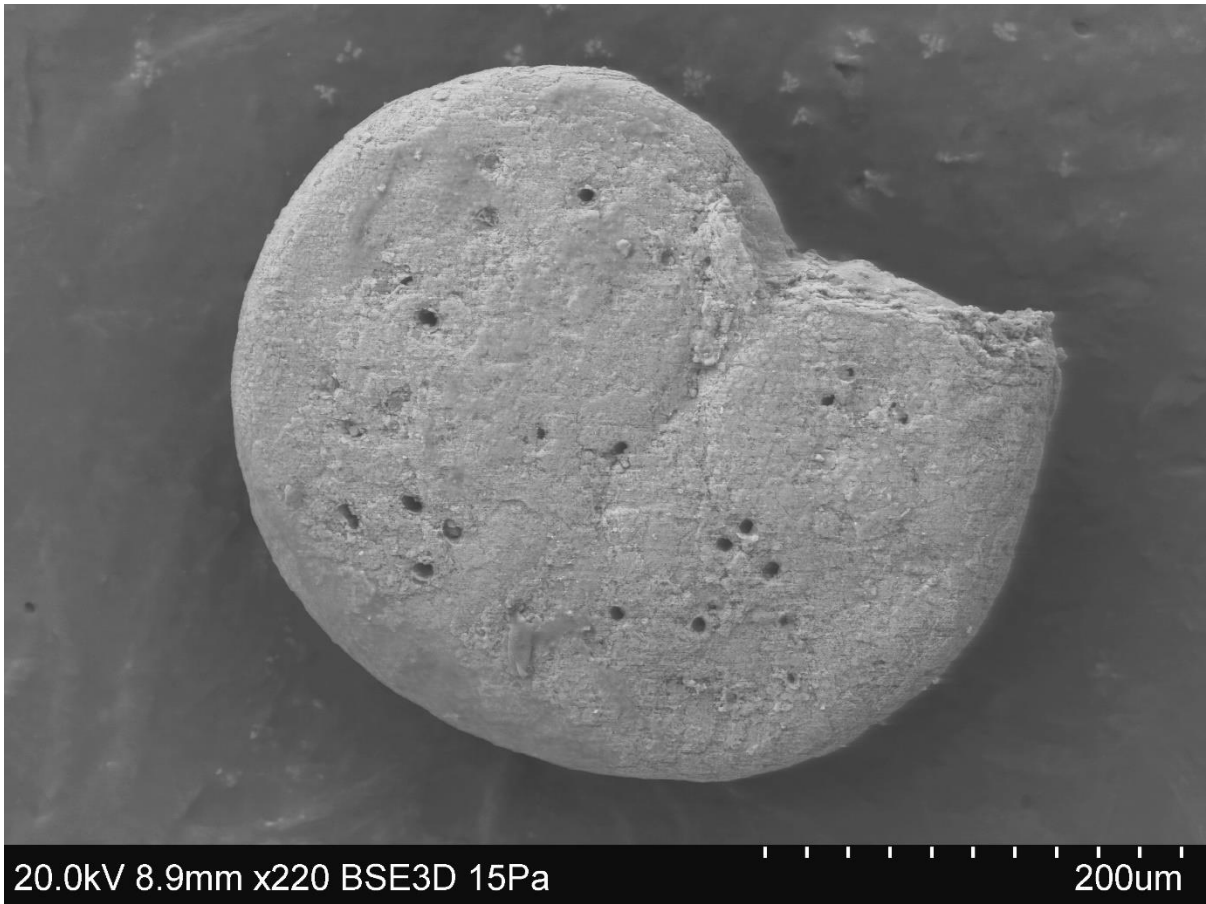
Upper and lower picture: Cassidulina reniforme



Upper and lower picture: *Astrononion hamadaense*



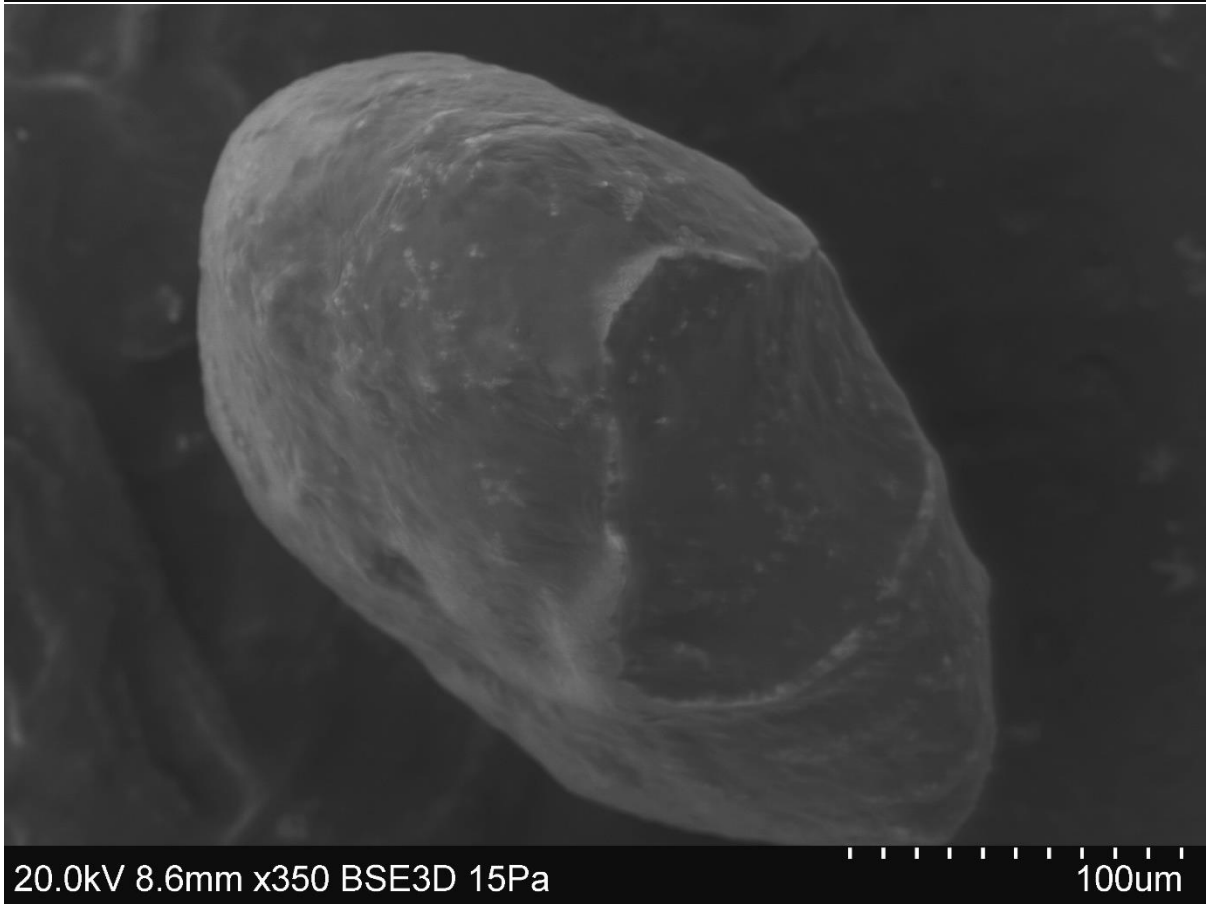
Upper and lower picture: *Rosalina* spp.



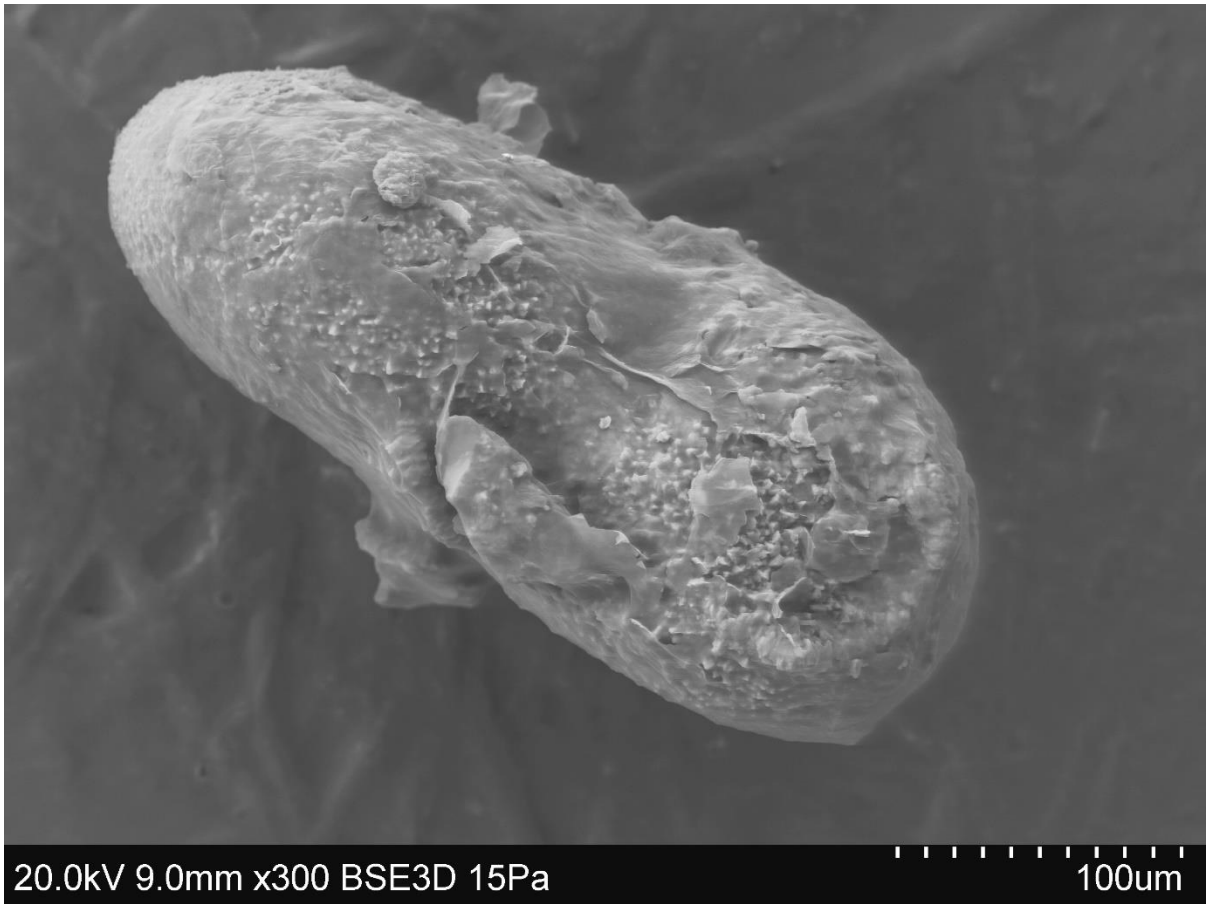
Upper and lower picture: *Lobatula lobatula*



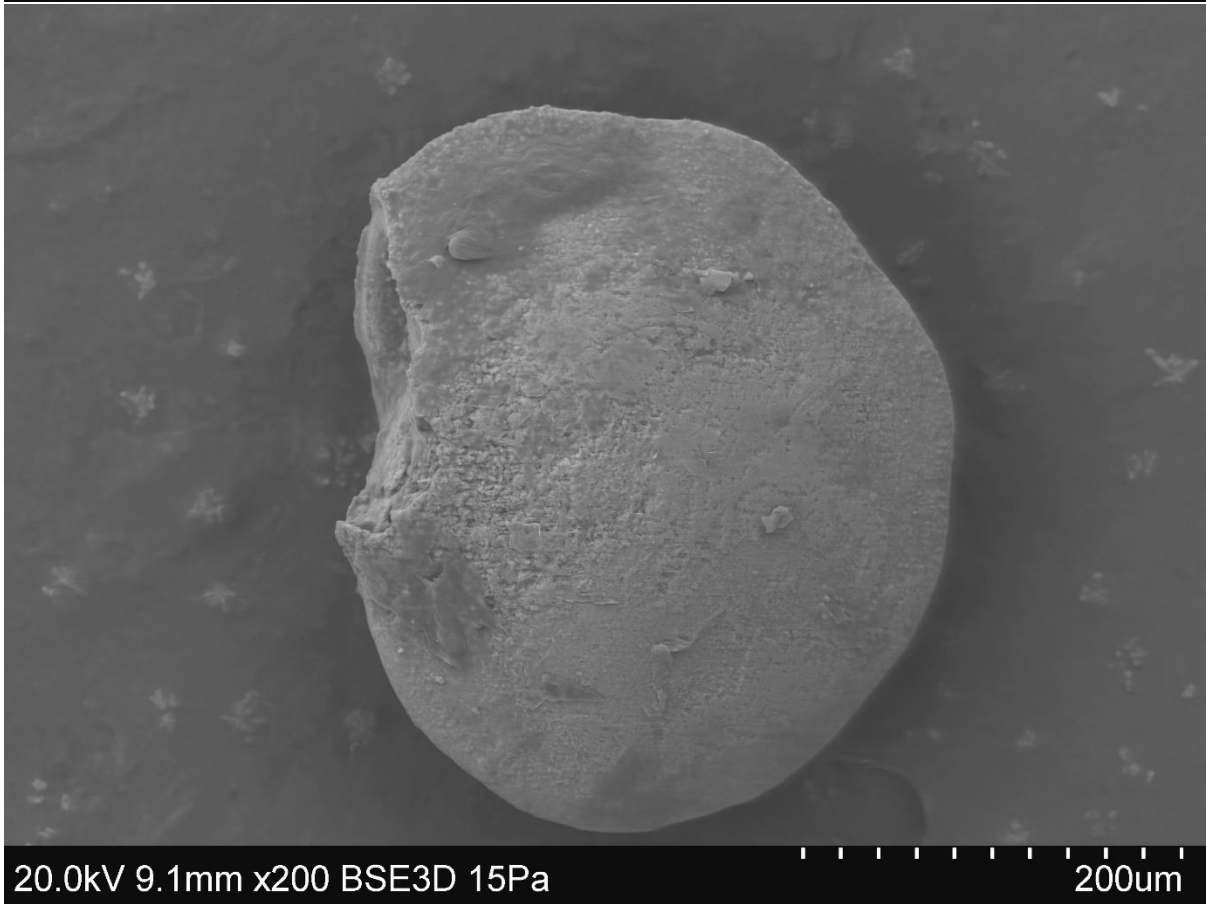
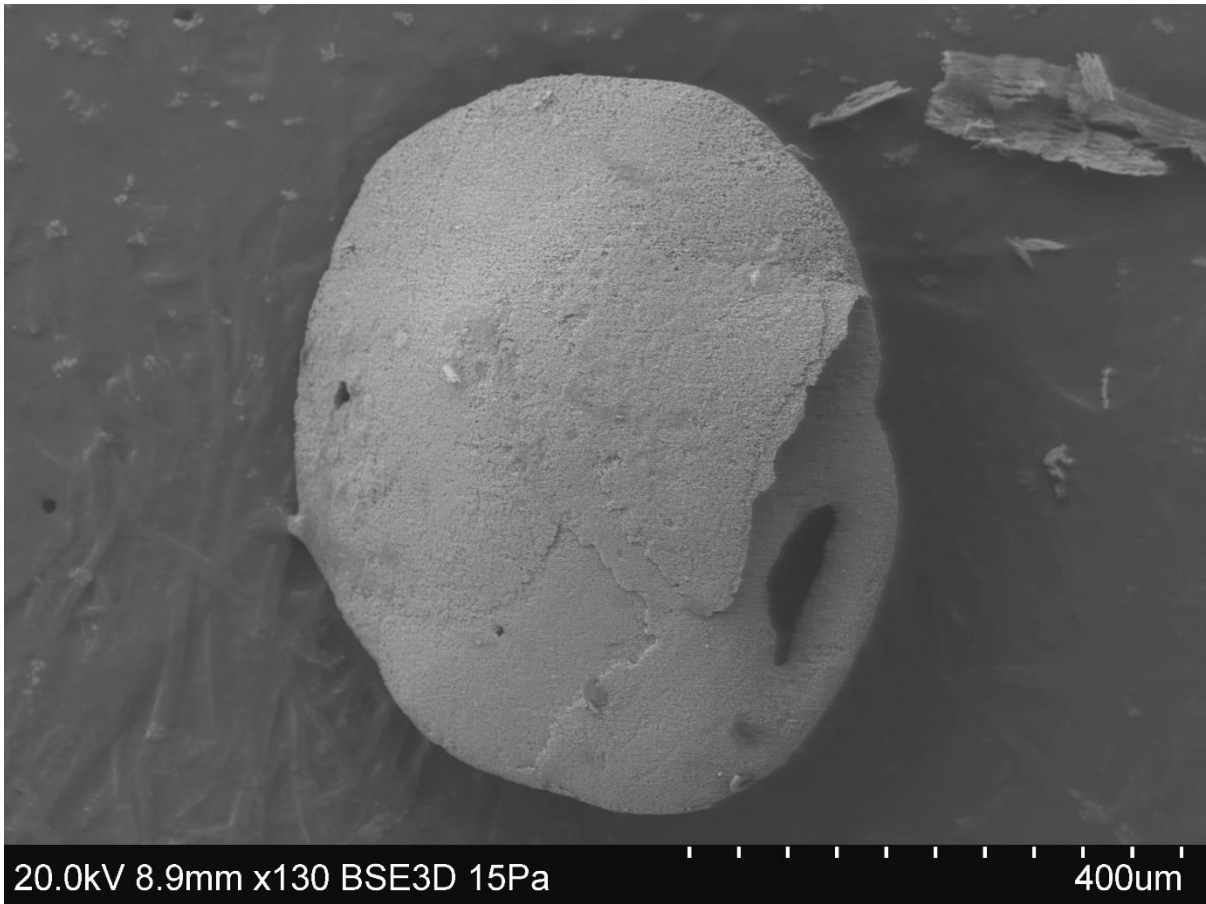
Upper and lower picture: *Nonionellina labradorica*



Upper and lower picture: *Cribroelphidium excavatum*



Upper and lower picture: *Elphidium bartlettii*



Upper and lower picture: *Islandiella helenae*

