UNIVERSITY OF TROMSØ UIT

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DEPARTMENT OF GEOLOGY

Palaeoenvironment of the Barents Sea during the last deglaciation and Holocene

Processes and timing

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Preface

This thesis was produced over a four year period as PhD student under the project "Palaeoenvironment of the Barents Sea during the last deglaciation and Holocene". This PhD position was financed by the Trainee School in Arctic Marine Geology and Geophysics (AMGG) which is hosted by the University of Tromsø and joins forces with the Geological Survey of Norway (NGU), Norwegian Polar Institute (NP) and the University Centre of Svalbard (UNIS). The aim behind this PhD project was to establish a closer collaboration between the geophysical research group led by Prof. Karin Andreassen and the palaeoceanographic group headed by Prof. Morten Hald and Dr. Katrine Husum.

During employment as a PhD student 25 % of working time was assigned to work for the Department of geology at the University of Tromsø, including teaching, outreach and secretary duties. Teaching activity encompassed the laboratory courses of GEO-2005 Sedimentology and GEO-8123 Marine geophysics.

In the course of this PhD period 61 days - spread over 5 marine geological cruises - were spent onboard R/V Jan Mayen which was renamed to R/V Helmer Hanssen in 2010. Beyond the obligatory study points, 20 credit points were gathered in the field of glacial geology and glaciology. Moreover, five certificates were obtained in various geophysical and geoscientific methods. During the PhD study acquired results were presented in two posters and ten talks at national and international workshops and conferences.

Acknowledgements

First and foremost I would like to thank my main supervisor Prof. Karin Andreassen for giving me the opportunity to join a very dynamic and enjoyable little research group working with geophysical methods in order to reconstruct past ice extend as well as patterns and processes of deglaciation. Karin gives all of us the freedom to develop our own ideas while she ensures that none of us lack financial, professional or moral support when needed. Secondly, I would like to acknowledge the enjoyable little research group itself, in particular Monica Winsborrow, Lilja Rún Bjarnadóttir and Rune Mattingsdal for sharing a common fascination for Quaternary marine geology, inspiring discussions and scientific exchange.

Moreover, I was affiliated to the palaeoceanographic research group which is now headed by Dr. Katrine Husum who has also taken over the role as official co-supervisor after Prof. Morten Hald and Prof. Dorthe Klitgaard-Kristensen. Katrine made sure that I was equally welcome in the ever-growing palaeoceanographic group and had possibilities for scientific exchange with respect to the sedimentological part of this thesis. Matthias Forwick, Juho Junttila, Katrine Husum, Tine L. Rasmussen, Jan Sverre Laberg, Simon P. Jessen, Steffen Aagaard-Sørensen and Anders Romundset are amongst the Tromsø colleagues that have discussed and/ or assisted in the work related to lithology and chronology in this thesis. Renata G. Lucchi from OGS in Trieste kindly supported part of this study with her expertise on lithology and sedimentary processes.

The crews of R/V Helmer Hanssen (formerly R/V Jan Mayen) as well as the laboratory, IT and administrative staff at the Department of geology are acknowledged for professional support and pleasant working atmosphere. A special thanks to the engineer Steinar Iverson who provided much appreciated technical help during and after scientific cruises. Stefan Bünz is acknowledged for technical assistance in seismic processing and other geophysical methods.

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The group of PhD students and young scientists at the Department of geology is acknowledged for being such a likeable and sociable lot. My apologies go to friends spread out in all parts of the planet for choosing to live in such a remote place and resulting sporadic contact. For sharing numerous fantastic ski trips, bike rides, mountain tours and social get-togethers that successfully distracted me from my PhD thesis I would like to thank my local friends and tour companions.

Thanks to my family for always making it such a pleasure to come back home and for their visits to this cold and dark place! I appreciate the great interest our families took in the writing of this PhD thesis. To my favourite tour companions, Ulva and Sigurd Daniel, thank you for sharing daily life, for priceless moral support and lots of happy hours!

1. Introduction

As indicated by the title of this PhD thesis “Palaeoenvironment of the Barens Sea during the last deglaciation and Holocene - Processes and timing” the scope of the corresponding studies are twofold. Firstly, processes, patterns and timing of the last deglaciation in the Barents Sea are reconstructed. Secondly and subordinately, depositional conditions on the Barents shelf during Holocene are elucidated.

The wish to advance the understanding of timing and processes of the decaying Barents Sea Ice Sheet (BSIS) is motivated by it being a powerful analogue to the marine-based West Antarctic Ice Sheet (WAIS; Siegert et al., 2002; Andreassen and Winsborrow, 2009). The striking geographical similarity of ice-free western Antarctica and the Barents Sea shelf (Mercer, 1970) implies that the palaeo BSIS and its decay can be used as an analogue to study retreat mechanisms and evaluate the likeliness for a pending collapse of the WAIS (Oppenheimer, 1998). But the BSIS as an analogue can be stretched to encompass also Greenland and East Antarctic ice streams that are grounded below present day’s sea level (cf. Lythe et al., 2001). Recent observations show that several outlet glaciers of the Greenland and Antarctic ice sheets grounded beneath sea level show a common pattern of acceleration, thinning and retreat (Shepherd et al., 2001; Krabill et al., 2004; Rignot, 2006). In contrast, the Ross ice streams in West Antarctica, equally grounded below sea level, reveal a more complex dynamic as the Holocene thinning trend has been reversed due to the stagnation of Kamb Ice Stream within the last two centuries (Conway et al., 2002; Catania et al., 2006). Large uncertainties exist with respect to the long term significance of these short term velocity trends. Studies of palaeo ice stream beds can provide such an urgently required longer term perspective.

The Barents Sea experienced repeated glaciations during the late Cenozoic (Elverhøi and Solheim, 1983; Vorren et al., 1988). Grounded ice is inferred to have reached the shelf break twice during the most recent Late Weichselian glaciation (Laberg and Vorren, 1996). It is well established that ice streams operated on the Barents continental shelf and in confluent fjords (Sættem et al., 1992; Andreassen et al., 2008; Ottesen et al., 2008a). It is further known that deglaciation of the Barents shelf took place stepwise (Polyak et al., 1995; Landvik et al., 1998; Winsborrow et al., 2010). This PhD thesis focuses on two main areas in the Barents Sea (Fig. 1). The cross-shelf trough Bjørnøyrenna (The Bear Island Trough) on the one hand, is the largest palaeo glacial system of the BSIS and important for overall mass balance of the ice sheet. The small glacial trough Kveithola on the other hand, drained a more confined part of the ice sheet on Spitsbergenbanken in the central Barents Sea.

The Holocene history of the Barents Sea is difficult to determine due to general scarcity of Holocene sediments on the Barents shelf. On the shallow banks and exposed areas in the southern Barents Sea winnowing and lag development due to strong bottom currents are an ongoing process (Vorren et al., 1978; Vorren et al., 1984). On the deeper banks the winnowing activity has ceased possibly due to eustatic rise of sea level reducing the erosional effect of the Norwegian Atlantic current on the seafloor (Vorren et al., 1978; Vorren et al., 1984). In this PhD thesis it is speculated whether an erosional boundary observed in Barents shelf sediments may have been caused by the Storegga slide and tsunami at 8.2 cal ka (7.7 ^{14}C ka; Haflidason et al., 2005).

2. Study area

This thesis depicts and discusses the development of selected areas in the western part of the epicontinental Barents Sea during last deglaciation and Holocene. Covering one of the widest continental shelves in the world, the Barents Sea is confined by continental slopes to the north and west, by Novaja Zemlja to the east, and by the Fennoscandian coast to the south (Fig. 1). The most prominent geomorphological feature of the western Barents Sea is the 850 km long, 150-200 km wide and 300-500 m deep Bjørnøyrenna cross-shelf trough. Bjørnøyrenna is flanked by shallow bank areas (<300 m): Spitsbergenbanken and Sentralbanken to the north and east, as well as Tromsøflaket and Nordkappbanken to the south (Fig. 1). Two north-east to north-west trending troughs just off the coast of Norway (Ingøydjupet and Djuprenna) reach water depths of 450 m. Over most of the Barents continental shelf an erosional boundary, referred to as Upper Regional Unconformity (URU), can be identified. It separates seaward-dipping stratified sedimentary rocks from overlying subparallel Quaternary sediments (Solheim and Kristoffersen, 1984; Vorren and Kristoffersen, 1986). Sediment cover above URU is generally thin (<100 m), but local areas of high accumulation with thicknesses of up to 200-300 m occur, particularly off the Finnmark coast (Elverhøi and Solheim, 1983; Vorren et al., 1989; Sættem et al., 1992). Trough mouth fans (TMF; Vorren and Laberg, 1997) have formed off the western and northern Barents Sea margins. TMFs are inferred to consist of stacked debris flow lobes deposited at the mouth of transverse troughs on glaciated continental shelves during subsequent glacial maxima. With an area of about 215,000 km^2 the Bjørnøya TMF is the largest on the north-west European glaciated continental margin (Fig. 1) and indicative of the importance of Bjørnøyrenna for ice and sediment drainage and therefore mass balance of the BSIS. Paper I treats a grounding line system in outer Bjørnøyrenna originating from the onset of deglaciation in detail, while Paper IV introduces a surge landsystem deposited in upper Bjørnøyrenna during a late stage of deglaciation. Paper V synthesises observations described in papers I and IV as well as showing unprecedented bathymetric data from the palaeo bed of Bjørnøyrenna Ice Stream.

Papers II and III are studies from Kveithola, an east-west trending trough located north-west of the island Bjørnøya (Fig. 1). This comparatively small trough is approximately 100 km long, 15-20 km wide and spans water depths of 400 to 200 m. It is flanked by Spitsbergenbanken to the north, east and south (<100 m). Its u-shaped cross-profile and mega-scale glacial lineations (MSGL; Rebesco et al., 2011) suggest that Kveithola was repeatedly occupied by an ice stream sourced locally by ice from shallow Spitsbergenbanken. However, only a small TMF is developed in front of Kveithola (Rebesco et al., 2011), implying that Kveithola was less important for the overall mass balance of the BSIS. The local character of the Late Weichselian glaciation on Spitsbergenbanken is supported by a study on Bjørnøya where striae orientation, erratic provenance and lack of raised beaches indicate a glaciation of local nature without post-glacial isostatic emergence (Salvigsen and Slettemark, 1995). Kveithola showed to be of key importance in understanding some of the ice dynamics and the timing of deglaciation of the north-western Barents Sea. This is because Kveithola has proven to be a sedimentary depocentre during the last deglaciation. While sediment thicknesses above URU reach 180 m locally in Kveithola (Elverhøi and Solheim, 1983; Solheim and Kristoffersen, 1984), modern accumulation rates are low and range from 5 cm/ka in the outer and mid trough to erosional conditions in the innermost trough (Elverhøi et al., 1989). This thesis demonstrates that 10 to 25 m of soft, deglacial sediments have been deposited in Kveithola. This sedimentary archive has been studied in order to reconstruct the regional deglaciation history (Paper II). Moreover abundant subglacial to ice-marginal deposits in Kveithola enable a detailed study of grounding line retreat in this small trough (Paper III).

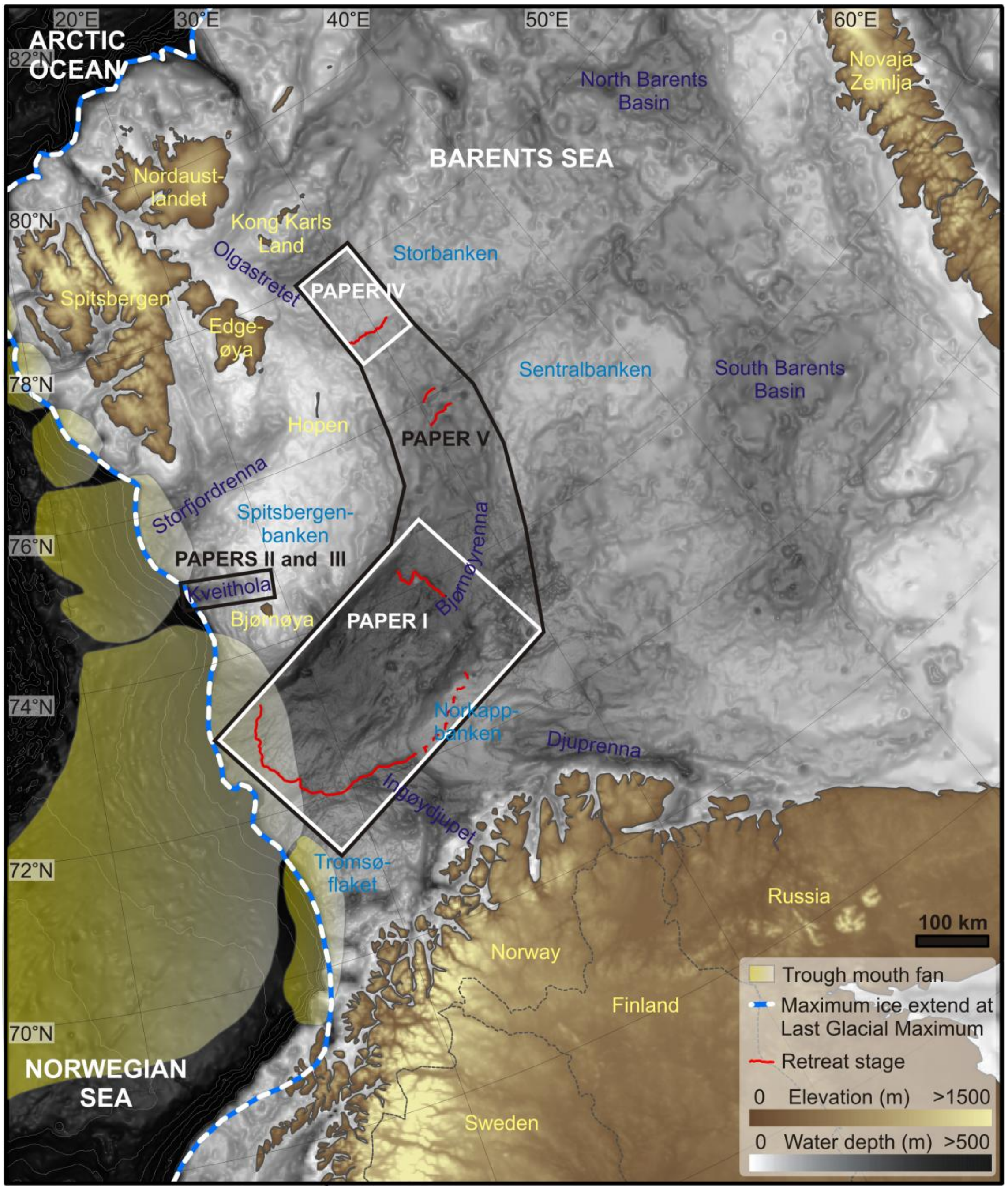

Fig. 1: Bathymetric and topographic overview of the Barents Sea area where studied areas of papers I to V are highlighted.

3. Summary of papers and contributions by single authors

3.1 Paper I

Rüther, D. C., Mattingsdal, R., Andreassen, K., Forwick, M., Husum, K., 2011. Seismic architecture and sedimentology of a major grounding zone system deposited by the Bjørnøyrenna Ice Stream during Late Weichselian deglaciation, *Quaternary Science Reviews,* 30 (19-20), 2776-2792.

Sediment deposits at ice stream grounding lines are commonly employed in the reconstruction of past ice sheet extent, but have also great potential in deciphering ice stream dynamics and processes as shown in this study. In outer Bjørnøyrenna a 280 km wide, arcuate sediment deposit has been investigated using regional swath and large-scale bathymetric data, 2D and 3D seismic data as well as sediment gravity cores. Based on its geomorphology the wedge-shaped deposit is divided into an up to 35 m high frontal part with large-scale depressions and an upstream part distinguished by the occurrence of mega-scale glacial lineations (MSGL). A seismic profile discloses increasing erosion for the upstream part of the wedge, coinciding with the location of MSGL. Whether the latter are erosional features or deposited following extensive erosion cannot be inferred from our data. Wedge configuration and internal structures lead us to suggest that the system was deposited during a rapid readvance as predominantly soft, diluted sediments were bulldozed by the ice front. The existence of imbricated thrust sheets of a harder material then surrounding till in front of the eastern part of the wedge is inferred from 3D seismic data. These are interpreted to be megablocks and rafts implying that the ice stream likely stagnated and froze to its bed prior to readvance. Observed large-scale depressions challenge existing concepts of marine glacial landsystems and are suggested to be dead-ice features. We speculate that these can form despite the buoyancy of ice as intense englacial thrusting develops into a decollement whereby the cold glacier snout gets overrun by ice masses from the interior. As a consequence slabs of ice are included in the push moraine mass. Radiocarbon dates indicate that the ice stream front was located in outer Bjørnøyrenna between approximately 17.1 cal ka (14.5 ^{14}C ka) and 16.6 cal ka (13.8 ^{14}C ka) before retreating further.

Rune Mattingdal’s contribution to this paper encompasses the creation of Figure 5, related analyses of the buried part of the wedge and the writing of short sections in the text which describe these results. Rune Mattingdal and Denise Rüther also discussed possible forming mechanisms. All other figures were created by Denise Rüther. Matthias Forwick assisted through practical supervision in the laboratory on the sediment gravity cores. Katrine Husum contributed by writing the part on qualitative foraminifera analyses. All other text was originally written by Denise Rüther. The manuscript was repeatedly reviewed by all co-authors. A final language check was conducted by Monica Winsborrow.

3.2 Paper II

Rüther, D. C., Bjarnadóttir, L. R. Junttila, J., Husum, K., Rasmussen, T., Lucchi, R. G., Andreassen, K., 2011. Pattern and timing of the north-western Barents Sea Ice Sheet deglaciation and indications of episodic Holocene deposition. Accepted in Boreas (21 Dec 2011).

Deglaciation of the Barents Sea commenced in the deeper troughs between 19 to 17 cal ka, while the dynamics and timing of glacial retreat from shallow bank areas is not well confined. Here we present a multi-proxy sedimentological study from a small trough west of Spitsbergenbanken on the western Barents Sea margin. The provenance of two acoustic sediment units has been investigated based on lithological facies, chronology, benthic stable isotope values as well as foraminifera and clay mineral assemblages. Four time slices with characteristic sedimentary environments could be identified. Prior to ~14.2 cal ka (12.8 ^{14}C ka) extensive sea ice cover accompanied persisting grounded ice on Spitsbergenbanken resulting in the deposition of rhythmically laminated muds. From ~13.9-14.2 cal ka (12.5-12.8 ^{14}C ka) muds rich in ice-rafted debris reflect the disintegration of grounded ice over Spitsbergenbanken. From ~10.3-13.1 cal ka (9.5-11.7 ^{14}C ka) shifting influence of suspension settling and iceberg rafting derived from a decaying BSIS in the north can be inferred from sediments with heterogeneous lithologies. Holocene deposition is episodic and consists of calcareous sands and shell debris indicative of strong bottom currents. We speculate that a marked erosional boundary at ~8.2 cal ka (7.8 ^{14}C ka) may be caused by the Storegga tsunami.

Lilja Bjarnadóttir and Renata Lucchi participated in the logging and sampling of opened cores, while Denise Rüther had the main responsibility for lithological and chronological results. Lilja Bjarnadóttir conducted all analyses of the geophysical data and contributed to figures 1B-H. Juho Junttila was responsible for the clay mineral analysis, wrote the corresponding parts in the method and result sections and contributed with clay mineral specific conclusions to the discussion. Likewise Tine Rasmussen and Katrine Husum were responsible for the benthic stable isotope ratios and foraminifera analyses, wrote corresponding parts in the method and result sections and contributed with isotope and foraminifera specific conclusions to the discussion. The main responsibility for the entire text and figures was held by Denise Rüther. All co-authors were participating in the review process.

3.3 Paper III

Bjarnadóttir, L. R., Rüther, D. C., Winsborrow, M. C. M., Andreassen, K., 2011. Grounding line dynamics during the last deglaciation of Kveithola, W Barents Sea, as revealed by seabed geomorphology and shallow seismic stratigraphy. Submitted to Boreas (24 Dec 2011).

Kveithola, a trough on the western Barents Sea margin, was repeatedly occupied by ice streams fed by ice on the shallow bank area Spitsbergenbanken. In this marine geophysical study we identify ten deglacial stages revealing a complex deglaciation history in Kveithola. Following full glacial conditions at the last glacial maximum, five stacked seismic units with chaotic seismic character and erosional boundaries are interpreted to be of subglacial origin and associated with five glacial readvances. Three acoustically transparent seismic units coincide with transverse ridges visible from the seafloor and are thought to have been deposited time-transgressively forming several generations of grounding-line fans. After final retreat of grounded ice from the trough a uniform glacimarine blanket was deposited sourced by ice sitting on Spitsbergenbanken. Two generations of mounded drifts in the inner part of the trough are interpreted to be of distal glacimarine origin derived through channels to the north. The inferred style of grounding zone deposition in Kveithola is suggested to be an intermediate case as compared to the established continuum between morainal banks and grounding line wedges.

Denise Rüther contributed by making Figure 1 and discussing the origin of the two youngest seismic packages. Lilja Bjarnadóttir was responsible for all other figures and text as well as related analyses of geophysical data. All co-authors were active in discussing and reviewing the text and figures.

3.4 Paper IV

Andreassen, K., Winsborrow, M. C. M., Bjarnadóttir, L. R., Rüther, D. C., 2012. Landform assemblage from the collapse of a marine-based ice stream. Submitted to Geology (2 Jan 2012).

Ice stream surges are shown to have occurred following the collapse of the Larsen Ice Shelf on former tributary glaciers raising concerns about the stability of the West Antarctic Ice Sheet. Here we present palaeo data from an event interpreted to reflect an ice stream surge leading to widespread break-up of a marine-based ice sheet. From a combination of large-scale Olex bathymetric data, regional swath bathymetry and chirp sub-bottom sounder data a surge landform assemblage is identified in upper Bjørnøyrenna, Barents Sea. This landsystem is marked by an acoustically transparent mud apron and lacks a moraine ridge indicating abundant meltwater and highly diluted soft sediments. Upstream from the smooth mud apron mega-scale glacial lineations are overprinted by rhombohedral crevasse-squeeze ridges suggesting accelerated flow of a quasi-floating ice stream which is heavily crevassed towards the margin. Downstream, the mud apron laps onto a seafloor heavily ploughed by multi-keeled mega-icebergs witnessing a rapid ice loss by large-scale iceberg calving prior to surge termination. The presented landform assemblage bears resemblance with surge landforms of tidewater glaciers, but the occurrence of mega-iceberg ploughmarks and lack of a morainal ridge are specific to rapid ice stream retreat and reflect the availability of abundant meltwater.

The bathymetry data was gridded by Monica Winsborrow and Lilja Bjarnadóttir. Monica Winsborrow further created Figure 1. Karin Andreassen has the main responsibility for text and remaining figures. All co-authors were actively discussing and reviewing the text.

3.5 Paper V

Rüther, D. C., Andreassen, K., Winsborrow, M. C. M., 2012. Changing ice stream flow regimes during the last deglaciation of Bjørnøyrenna, western Barents Sea. Unpublished manuscript (To be submitted to Geology).

Recently observed dynamics of Greenland and Antarctic outlet glaciers include acceleration and thinning as well as stagnation and thickening, raising the concern how these relate to the longer term perspective of ice stream life cycles. In this paper an extensive geophysical palaeo record from a single marine ice stream bed suggests the existence of two contrasting flow regimes from glacial maximum conditions towards its final retreat. From maximum glaciation to initial deglaciation glacial oscillations are driven by freeze-on and melt cycles as suggested by glaciotectonic landforms like chained megablocks and rafts. For the later stage of the last deglaciation accelerated flow of a quasi-floating ice stream can be inferred from observed crevasse-squeeze ridges. Along the path of ice stream retreat the morphologies of grounding line systems develop from a positive moraine profile to flat, acoustically transparent wedges, proving symptomatic for increasing availability of meltwater. We identify a transitional stage during early retreat of the Bjørnøyrenna Ice Stream where freeze-on and melt occur on shorter timescales and note that modern ice stream behaviour bears resemblance with the described transitional stage.

The bathymetry data was gridded by Monica Winsborrow and Denise Rüther. Denise Rüther made all figures and wrote the first draft accompanied by repeated feedback and reviews from Monica Winsborrow and Karin Andreassen.

4. Synthesis

Here the main findings of all five papers contained in this PhD thesis are put in a common context and discussed. The structure of this synthesis relates directly to the title and key content of this PhD thesis (Fig. 2).

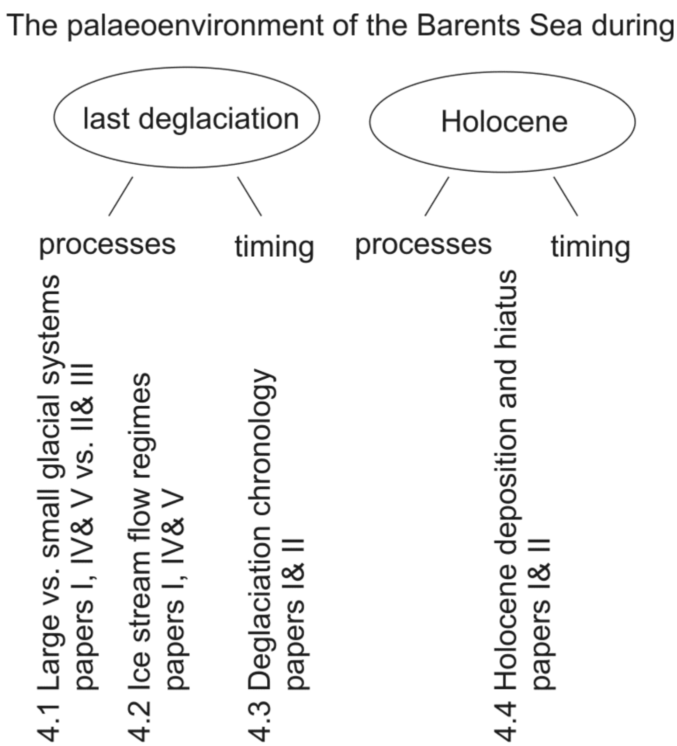

Fig. 2: Schematic overview on sections of the synthesis

4.1 Large vs. small glacial systems

Papers I, IV and V present and discuss data from the palaeo ice stream bed in Bjørnøyrenna, the largest cross-shelf trough in the Barents Sea (Fig. 1). Trough dimensions as well as enormous volume of sediment contained in the Bjørnøyrenna TMF (Vorren and Laberg, 1997) suggest that the Bjørnøyrenna Ice Stream has been a large glacial system with great importance for overall mass balance of the BSIS. Papers II and III are centred on Kveithola, a small trough at the western margin surrounded by Spitsbergenbanken (Fig. 1). The relatively small TMF on the continental slope off Kveithola (Rebesco et al., 2011) and a well confined ice catchment area on Spitsbergenbanken (Elverhøi and Solheim, 1983; Salvigsen and Slettemark, 1995) support the notion that this small glacial system had less importance for overall mass balance of the BSIS. At the same time, the smaller dimensions in Kveithola and its confined catchment area probably make the Kveithola Ice Stream more susceptible to external forcing factors (Rebesco et al., 2011). During early deglaciation atmospheric temperature rise was not significant (NGRIPmembers, 2004; Rasmussen et al., 2007) and glacial retreat was most likely driven by sea level rise (Yokoyama et al., 2000; Larsen et al., 2011). In addition, the warming of subsurface waters is probably of importance for glacial dynamics in entire Kveithola during deglaciation as the northern arm of the Norwegian Atlantic current (NwAC) travels northwards along the continental slope. Warm saline Atlantic water may have entered Kveithola (Rumohr et al., 2001) at times of particularly strong subsurface influence of the NwAC, i.e. during Bølling/Allerød, Early Holocene and at present (Ślubowska-Woldengen et al., 2008). In outer Bjørnøyrenna the ice margin was supposedly equally influenced by oceanic forcing while this impact may have become less intense as the ice stream retreated into mid to upper Bjørnøyrenna.

Analysis in Kveithola revealed a complex deglaciation pattern with at least six ice marginal retreat stages along the 100 km long trough (Fig. 9 in Paper III). The onset of deglaciation remains speculative, but outermost Storfjordrenna was ice free by 19.4 cal ka (16.8 ^{14}C ka; Rasmussen et al., 2007) giving a reasonable estimate. The upper part of a glacimarine blanket was dated to 14.2 cal ka (12.8 ^{14}C ka) in Paper II marking a minimum estimate for the completion of deglaciation in Kveithola. The seismic stratigraphy established in Paper III illustrates that an interpretation of the seafloor morphology alone might be misleading. Five transverse ridges are visible on the seafloor, while the seismic architecture suggests a more complex story of several episodes of retreat and readvance. Seven stacked seismic units with chaotic internal reflections and erosional boundaries (summarized as seismic package D in Paper III) are interpreted to be of subglacial origin. The western extents of these seismic units coincide with the location of transverse ridges. In addition three acoustically transparent units suggest time-transgressive deposition of fine sediments from subglacial meltwater at the former ice margins (seismic package C in Paper III). These units overly the stacked subglacial units, correspond to the locations of transverse ridges and are interpreted to be grounding-line fans where abundant sediment and meltwater is released (Powell and Alley, 1997). The data allow the identification of repeated switches from a distributed to a more effective drainage system and back again.

While the available dataset for Bjørnøyrenna is essentially less dense than the one in Kveithola, at least five acoustically transparent bodies can be identified from a longitudinal profile of chirp sub-bottom sounder data in 850 km long Bjørnøyrenna (Figs. 1B-D in Paper V). Best estimate for the initiation of Bjørnøyrenna deglaciation comes from slope records which suggest a strong meltwater pulse at 17.6 cal ka (14.5 corrected ^{14}C ka; Bischof, 1994). The first retreat stage in outer Bjørnøyrenna has been dated to 17.1 cal ka (14.5 ^{14}C ka; Paper I; Rüther et al., 2011). Datable material in the northern Barents Sea is scarce, but dates from raised beaches on Kong Karls Land and Edgeøya suggest that these areas were deglaciated by 11.2 cal ka (9.8 ^{14}C ka ;Salvigsen, 1981; Bondevik et al., 1995). Despite large uncertainties connected to the age estimates ice stream retreat through Bjørnøyrenna probably took longer time than in Kveithola. Available seismic data for outer and upper Bjørnøyrenna do not show any stacked subglacial units underlying the acoustically transparent bodies. In mid und upper Bjørnøyrenna bedrock is known to be frequently exposed or overlain by a very thin sediment layer (Elverhøi and Solheim, 1983; Solheim and Kristoffersen, 1984). It seems the small glacial system in Kveithola accreted relatively more subglacial sediment in a shorter time period than the large glacial system in Bjørnøyrenna. Whether these observations can be seen in the context of a greater influence of external forcing factors on glacial dynamics of a small confined glacial system is debatable. More importantly, the case study from Kveithola (Paper III) demonstrates that the availability of a wide spectrum of geophysical data may indicate a far more complex reality than suggested by swath bathymetric data alone.

4.2 Ice stream flow regimes

This PhD thesis is a contribution to a comprehensive set of palaeo data from the bed of the Bjørnøyrenna Ice Stream (papers I, IV and V). As argued in Paper V, we identify a change in flow regimes from glacial maximum conditions to the final stages of deglaciation from observed glacial landforms. Megablocks and rafts are exogenic, glaciotectonically emplaced, flat-topped buttes and have been shown to occur repeatedly throughout the glacial history of the Barents Sea in general and Bjørnøyrenna in particular (Sættem, 1994; Andreassen et al., 2007). From 3D seismic data megablocks and rafts have been shown to be frequently configured in chains aligned with palaeo ice flow (Andreassen and Winsborrow, 2009). Such a configuration implies that a period of net freeze-on and stagnating ice enables the freezing of slabs of the subsurface to the glacier bed and is followed by a period of ice streaming when slabs are ripped apart and aligned in chains. Glacial rafts have for the first time been observed directly on the seafloor (Fig. 2A in Paper V) in mid Bjørnøyrenna. Two generations of ice streaming can be identified in mid Bjørnøyrenna and the observed rafts are thought to be emplaced by the older generation when ice was draining the trough between Sentralbanken and Storbanken (Fig. 1), possibly during glacial maximum. Glaciotectonic deformation observed elsewhere in the Barents Sea is generally restricted to the early phase of the last glacial cycle (Sættem, 1994; Gataullin et al., 2001; Epshtein et al., 2011). From theoretical concepts it can be concluded that freeze-on in response to climate changes is expected to be slow under thick ice (Alley et al., 1997). It is therefore deemed possible that net basal freezing occurred on timescales of 100s to 1000s of years during the build-up of the BSIS. However thrusted megablocks and rafts also occurred during the initial deglaciation in outer Bjørnøyrenna (Fig. 5D in Paper I; Rüther et al., 2011) suggesting that freeze-on and re-activation of ice streaming can occur on shorter timescales of 10s to 100s of years. This conjecture is backed up by theoretical considerations which suggest that freeze-on in response to climate change can be rapid under thin and surging glaciers (Alley et al., 1997). In summary cycles of freeze-on and ice streaming characterize glacial dynamics during maximum glacial conditions to initial deglaciation.

As deglaciation in Bjørnøyrenna progressed increasing availability of meltwater is suggested by a large meltwater channel (Fig. 3D in Paper V) and the deposition of acoustically transparent sediment wedges lacking an associated moraine ridge (Figs. 1B-C in Paper V). Sediment bodies with a similar acoustic character in the south-eastern Barents Sea are shown to consist of clast-poor diamicts of low shear strength and interpreted to represent thick layers of water-saturated tills (Epshtein et al., 2011). A comprehensive landform assemblage from the final stage of deglaciation in Bjørnøyrenna is presented in papers IV and V. Observed landforms in the upstream part of the landsystem include mega-scale glacial lineations overprinted by rhombohedral ridges (Figs. 2A-C in Paper IV and Figs. 3A-B in Paper V). Small-scale rhombohedral ridges are commonly associated with surging tidewater glaciers (Ottesen and Dowdeswell, 2006; Ottesen et al., 2008b) and are inferred to form subglacially as till is squeezed into basal crevasses (Sharp, 1985). From physical concepts it can be concluded that basal crevasses under grounded glaciers are restricted to the case where high tensile stresses are combined with high basal water pressure equalling the ice overburden pressure (van der Veen, 1998). The occurrence of crevasse-squeeze ridges is therefore indicative of an accelerated, quasi-floating ice stream. As a whole, these observations stress the increasing importance of subglacial meltwater transport and suggest accelerated flow without indications of intermittent freeze-on during the disintegration of the BSIS.

As put forward in Paper V, the internal cyclicity of long-term ice stream velocity changes has successfully been captured by the undrained plastic bed model (Tulaczyk et al., 2000). Under the assumption of a plastic bed rheology and a negligible effect of meltwater transport, the model predicts two stable modes at the ice stream bed: ice streaming or stagnation, while variations in ice thickness are able to trigger a switch between modes (Bougamont et al., 2003). Including a regional hydrological system to a 3D higher order ice sheet model results in the prediction of higher velocities and a greater tendency towards ice streaming rather than stagnation in the long run (Bougamont et al., 2011). It would be interesting whether a case could be produced where upon a certain amount of subglacial water input, ice streaming becomes the only possible mode. Modelling experiments support the great sensitivity of ice stream dynamics towards meltwater input (Bougamont et al., 2011) and stress the need for palaeo data in order to better constrain the regional hydrological system. This PhD thesis hopefully provides such constraints.

4.3 Deglaciation chronology

Papers I and II contribute to the deglaciation chronology of the Barents shelf. In outer Bjørnøyrenna close to the western shelf break, three radiocarbon ages from the base of a glacimarine unit underlain by till give the first direct minimum estimates for the onset of deglaciation in the central Barents Sea (Paper I). The timing of ice sheet retreat in this area has previously merely been based on indirect evidence from continental slope records. A strong meltwater pulse derived from the southern part of the BSIS could be identified at about 17.6 and 17.0 cal ka (14.5-14 corrected ^{14}C ka) based on IRD analyses (Bischof, 1994). Particularly during early Holocene high bottom currents on the Barents shelf resulted in winnowing of sediments and low preservation potential of deglacial sediments (Vorren et al., 1983; Vorren et al., 1984) hampering earlier dating attempts. Our approach in this study was to aim for sediment gravity cores located downstream of a large arcuate grounding line system in the hope that deglacial sediment was more abundant and therefore better preserved. From eight downstream cores six had glacimarine intervals with thicknesses varying from 20-160 cm. From the bottom of three of these glacimarine intervals sufficient bulk benthic foraminifera were picked for AMS dating, yielding ages of 17.1 cal ka (14.5 ^{14}C ka), 16.9 cal ka (14.3 ^{14}C ka) and 16.6 cal ka (13.8 ^{14}C ka). How do these ages compare with the established deglaciation chronology along the western margin? For the western Svalbard margin there is wide agreement for a distinct meltwater peak at 17.9 cal ka (14.8 corrected ^{14}C ka; Jones and Keigwin, 1988; Elverhøi et al., 1995). On the other hand, some authors point out the significance of a smaller, short-termed IRD pulse as distinct deglaciation signal around or shortly before 20 cal (Knies et al., 1999 for the northern margin; Jessen et al., 2010 for the western margin). Outermost Storfjordrenna was deglaciated by approximately the same time period as revealed by an IRD peak in the slope record from about 21.2 to 19.8 cal ka (Jessen et al., 2010) and by a series of radiocarbon dates in hemipelagic sediments indicating open water since at least 19.4 cal ka (16.8 ^{14}C ka; Rasmussen et al., 2007). To our knowledge, there are no indications of an earlier meltwater peak on the southern margin, off Bjørnøyrenna. A possible explanation is that available continental slope records may not have sufficient resolution to detect a small, short-lived peak. A commonly shared premise is that a rising sea level together with atmospheric and oceanic warming played a major role for the initiation of deglaciation of the BSIS (e.g. Polyak et al., 1995; Landvik et al., 1998). Under this premise it is unlikely that the onset of deglaciation on the south-western margin took place significantly later than on the north-western and northern margins since the ice margin was situated at comparable water depths.

In Kveithola (Paper II) chirp sub-bottom sounder data suggest that 15-35 m of soft sediments overly subglacial landforms. Therefore, the transitions from till to glacimarine units could not be reached by sediment gravity coring. The majority of soft sediments mapped with the help of geophysical methods (Paper III) have proven to be of deglacial character (Paper II). Asymmetric drift sediments mounding to 20 m thickness in the inner trough, are dated to ages between 13.1-10.3 cal ka (11.7-9.5 ^{14}C ka) and interpreted to represent distal glacimarine sediments derived from a northern source. Furthermore, it is suggested that grounded ice covering Spitsbergenbanken disintegrated between 14.2 cal ka (12.8 ^{14}C ka) and 13.9 cal ka (12.5 ^{14}C ka) depositing the uppermost 1-2 m of a 15 m thick glacimarine blanket. This is the first indirect age estimate of a deglaciation age for Spitsbergenbanken. Immediately below the uppermost glacimarine blanket up to 3 m of rhythmically laminated muds is recovered indicating extensive sea ice cover in the area. This interval is inferred to be older than 14.2 cal ka (12.8 ^{14}C ka) and can be correlated with laminated muds dated to 14.7-14.4 cal ka (13.1-12.9 ^{14}C ka; Rasmussen et al., 2007) along the Svalbard continental slope and outer shelf. These intervals are suggested to reflect high sedimentation rates from turbid meltwater plumes during Bølling interstadial (Peersen, 2006; Rasmussen et al., 2007; Jessen et al., 2010). Comparable laminated muds in the southern Barents Sea are interpreted to be deposited in an environment covered by sea ice (Vorren et al., 1983; Vorren et al., 1984) between 14.7-14.2 cal ka (13.0-12.8 ^{14}C ka; Junttila et al., 2010). While correlating well with previously established chronologies (e.g. Rasmussen et al., 2007; Jessen et al., 2010) the presented Kveithola chronology also offers new insights in the regional pattern and timing of deglaciation. The method of correlating dated lithological units with acoustic sediment units has proven to be a powerful tool allowing for sediment architecture to be an integral part of the interpretations.

4.4 Holocene deposition and hiatus

Holocene sediment has proven to be scarce in the studied area ranging in thickness from 10-84 cm in six sediment gravity cores from Kveithola and 0-54 cm in eleven cores from outer Bjørnøyrenna. A study of over 200 sediment gravity cores in the southern Barents Sea concludes that the early Holocene is characterized by erosional activity and winnowing on the banks and other exposed areas (Vorren et al., 1984). A presumable less pronounced erosional regime from 8.6 cal ka (7.8 corrected ^{14}C ka) results in the deposition of a mixture of reworked sediments and recent predominantly biogenic sands, referred to as palimpsest sediments (Vorren et al., 1978; Vorren et al., 1984). Paper I presents Holocene dates from two sediment gravity cores in outer Bjørnøyrenna, one downstream and one upstream from a large arcuate grounding line system. In the downstream core a glaci-proximal sediment plume deposit is directly overlain by Holocene palimpsest sediment dated to 3.1 cal ka (3.3 ^{14}C ka) at its base. Holocene palimpsest sediments are preceded by subglacial till in the upstream core and the Holocene base is dated to 6.9 cal ka (6.5 ^{14}C ka) and 2.0 cal ka (2.5 ^{14}C ka) 14 cm higher up. In summary, these ages indicate a hiatus throughout early Holocene until approximately 7 cal ka or longer, in accordance with early results (e.g. Vorren et al., 1984).

The Holocene sediment unit identified in Kveithola (Paper II) consists of calcareous sands and shell debris and has a well-developed erosional base in all of the six studied cores. Six of eleven radiocarbon ages are centred around the erosional base giving an approximate age of 8.2 cal ka (7.8 ^{14}C ka). The lack of early Holocene sediments on the banks and other exposed areas in the southern Barents Sea has been explained with the existence of strong bottom currents which weakened due to eustatic sea level rise at about 8.6 cal ka (Vorren et al., 1984). Observed mixing of sediment across the erosional boundary can probably not be explained by a change in the strength of bottom currents alone. It is speculated here that the large submarine Storegga slide and subsequent tsunami with a well-established age of 8.2 cal ka (7.7 ^{14}C ka; Haflidason et al., 2005) is the cause of the observed erosional contacts. Marine evidence for impact and erosion of the Storegga slide has previously been found in western and northern Norway and in the Faroe-Shetland Channel (Sejrup et al., 2001; Hald et al., 2003; Rasmussen and Thomsen, 2010). Ages from the longest Holocene record in a core from the outer trough further suggest that deposition during late Holocene was episodic with very low sedimentation rate between 8.0 to 1.5 cal ka (7.6-2.0 ^{14}C ka). The observed ages of potential hiatuses prior to 8.2, 5.6 and 1.5 cal ka all coincide with North Atlantic cooling episodes (Klitgaard-Kristensen et al., 1998; Moros et al., 2004) indicating that changes in sedimentation rate may be climatically induced. However, it is notable that the occurrence of three tsunamis at 8.2, 5.5 and 1.5 cal ka was inferred for the North Sea from lake records on the Shetland Islands (Bondevik et al., 2005). While the timing of the Storegga slide is well-constrained (Haflidason et al., 2005), only rough Holocene time estimates exist for the Trænadjupet and Andøya slides (Laberg and Vorren, 2000; Laberg et al., 2002). Chronology presented in this thesis is not conclusive and improved age constraint is needed in order to advance the understanding of Holocene deposition and erosion on the Barents shelf.

5. Future work

As indicated in the section on “Large vs. small glacial systems” the available dataset from the large glacial system in Bjørnøyrenna and a small glacial system in Kveithola is exceptional. In order to be able to compare the ice stream retreat through Kveithola and Bjørnøyrenna in more depth further age control is desirable. Moreover, the acoustically transparent retreat stages identified in Bjørnøyrenna are worth to be studied in greater detail since they might help to understand processes which were active during late deglaciation. Such a study should make vital use of seismic data in order to establish whether the acoustically transparent bodies are underlain by any ice-marginal subglacial units as the case for Kveithola. In seems that Kveithola has functioned as a sediment trap both during glaciations and deglaciation, including subglacial till as well as soft deglacial sediments. Future studies in Kveithola should ideally include shallow drillings in order to decipher the entire deglaciation history and recover stratigraphic units out of reach with sediment gravity coring.

During the initial work on sediment gravity cores from outer Bjørnøyrenna the author was puzzled by the presence of black, attenuated mud clasts in the subglacial till units. The idea whether such pellets can form subglacially during freeze-on was considered (Slawek Tulaczyk, personal conversation). Thin sections were produced based on twelve samples from three cores downstream of, on and upstream of a large arcuate grounding line system in outer Bjørnøyrenna by Adrian Palmer in London. During further sedimentological studies a fresh-looking version of black mud clasts was found to be abundant in glacimarine sediments. These appear to be typical along the southern Svalbard continental margin and are suggested to be shale flakes derived from Late Jurassic hot shales (Björlykke and Elverhøi, 1975; Elverhøi et al., 1995; Andersen et al., 1996). It is therefore considered most likely that attenuated clasts in the subglacial till are shale flakes that have not been homogenized completely, suggesting subglacial till deformation to be non-pervasive. Despite of this twist the thin sections that were produced represent valuable material that a future study may be based on. Exceptionally strong plasmic fabric (van der Meer et al., 2003) has for example been observed and would be well worth quantifying and studying in greater detail.

The usefulness of the calibration of marine radiocarbon ages prior to the Holocene can be questioned due to the large variability of marine reservoir corrections in deglaciated regions of the world (Reimer et al., 2009). Until today, no real alternatives to radiocarbon dating exist on the Barents shelf since tephra chronology, magnetic susceptibility and paleomagnetism are not applicable. A preference for calibrated ages has developed recently. However, as long as the authors of the Marine09 calibration curve themselves doubt the meaningfulness of the calibrated ^{14}C timescale during deglaciation (Reimer et al., 2009) uncalibrated ^{14}C ages should remain to be the point of reference. As argued above this PhD thesis contributes to the improvement of the deglaciation chronology in the Barents Sea, yet there are still numerous open chronological questions. Establishing deglaciation ages in Kveithola will only be possible through a drilling campaign. In Bjørnøyrenna however, several retreat steps remain undated and largely unstudied. A similar approach as in outer Bjørnøyrenna is recommended in order to pinpoint deglaciation ages to single grounding line positions. In this PhD thesis the combination of geophysical and sedimentological methods has proven to be a fruitful instrument in order to investigate processes and timing of specific glacial and Holocene events. As a concluding remark, the work with a wide marine geological method spectrum is highly recommended for future work at the Department of geology in Tromsø, meaning that the cooperation between research groups should be further encouraged.

6. References

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