UNIVERSITY OF TROMSØ UIT

FACULTY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF GEOLOGY

Processes and dynamics during deglaciation of a polar continental shelf

Examples from the marine-based Barents Sea Ice Sheet

Lilja Rún Bjarnadóttir

A dissertation for the degree of
Philosophiae Doctor

October 2012

Table of contents

Acknowledgements

I am forever grateful to Professor Karin Andreassen for granting me the opportunity to work on this project, which has been so rewarding in many different ways. Karin made sure I had everything I needed in order to pursue the scientific questions I found most interesting and actively included me in the planning and execution of several research cruises. She also made sure I could attend relevant courses and participate in numerous international workshops and conferences. Most importantly, she gave me the freedom to try and fail, to figure things out on my own, while always showing me a lot of trust and faith in my ability. I also want to thank my other co-supervisors, Monica Winsborrow at the University of Tromsø, Professor Doug Benn at the University Centre in Svalbard (UNIS), Dag Ottesen and later Margaret Dolan at the Geological Survey of Norway (NGU). Monica, thank you so much for all your time, advice and reassurance throughout the years. You have managed to balance your work as co-supervisor and the role of a friend beautifully, doing a great job at both! Doug, thank you for a wonderful half a year at UNIS, for inspiring discussions and limericks. Thank you Dag and Margaret for always answering any queries of mine promptly, and being so positive and helpful all the way.

I also feel extremely privileged to have worked with so many brilliant and nice people. Karin put together a research group of people with different backgrounds, proving very rewarding both professionally and on the personal level. I feel very lucky to have had the opportunity to work with these terrific people. I would especially like to thank Monica Winsborrow, Denise Rüther and Rune Mattingsdal who were there from the start, for all the inspiring discussions and laughs, on work and off during the last few years. It has been a true pleasure and I hope to have many opportunities in the future to work and play with all of you! A lot of other people hold a big share in this work. Big thanks go out to all the Ph.D. students and young scientists at the department, who are a bunch of terrific people. Special thanks go to the captain and crew of R/V Helmer Hanssen (formerly R/V Jan Mayen), Steinar Iversen, Stefan Bünz and technical and administrative staff of the Department of Geology. I would also like to thank everyone I have had the opportunity to get to know and work with outside the department during cruises, conferences and workshops. Warm thanks go to the prominent club “Haugtussur” for their moral support, sisterhood and good humour throughout my years in Tromsø. I also wish to thank Lindsay Wilson especially for helping out as “tante” when needed, for being a good friend and a great knitting/ginic partner. All of you have made this journey shorter and more enjoyable. To all my other friends out there in the real world I offer my love and recognition. I have missed you on my lonely planet and hope to see more of you in coming years.

Last but not least, never ending thanks and love go to my family! Mamma, pabbi, Beta and the rest of my family, thank you for never ending support and encouragement and for always being there for me as a safe harbour in stormy weather, I deeply appreciate it. Anders, thank you for being my partner in life, always standing strongly by my side. You make me feel very privileged and grateful. Finally, Stormur Tor and Snædís Tindra, thank you for being so incredibly patient with your mother. From now on there will be plenty of time for reading, playing… for å gå på tur og kose seg…fyrir fíflagang, fjör og knús. Ég elska ykkur!

Preface

The work presented in this thesis was funded through a 4-year grant from the Ph.D. Research School in Arctic Marine Geology and Geophysics (AMGG), University of Tromsø. All Ph.D. candidates funded by AMGG must meet the requirements given by the University of Tromsø and AMGG, including participation in AMGG-organised courses which included a research cruise, a scientific workshop and a course in science philosophy and ethics. In addition to the obligatory courses, several courses in marine geophysics (theory, interpretation, processing) and glaciology were completed, along with safety training (for cruises and fieldwork in the Arctic), and a number of software courses for example GMT, IVS Fledermaus, ArcGis and Schlumberger Petrel.

The main supervisor was Professor Karin Andreassen. Co-supervisors were Professor Doug Benn, University Centre in Svalbard, Monica C. M. Winsborrow, University of Tromsø and Geological Survey of Norway and Dag Ottesen/Margaret Dolan, Geological Survey of Norway. The work was carried out in the years 2007-2012, including a 1 year maternity leave and half year exchange period at the University Centre in Svalbard (UNIS). AMGG funding requires that 25% of the four-year period is used for “duty-work” assigned by the administration of the Department of geology and supervisors. This work included being a teaching assistant in two courses (*GEO-1001 Introduction to geology* and *GEO-3123 Marine geophysics*) in addition to participating in outreach work, database compilation, cruise planning and data processing.

The data used in this thesis was acquired during six marine geological/geophysical cruises in the years of 2008-2012 on R/V Helmer Hanssen (formerly R/V Jan Mayen), out of which the candidate participated in three and was active in the planning of four, and one cruise in the autumn of 2011 on R/V Akademik Strakhov. The results of this Ph.D.-work have been presented in two posters and ten talks at a number of international conferences and workshops, as well as at several meetings and workshops with collaborating colleagues from all over Europe. The thesis contains five original research papers of which Lilja Rún Bjarnadóttir is first author of three papers, second author of one and third author of one.

1. Introduction

Already in 1978 Mercer postulated that warming climate might lead to widespread drawdown and thinning of ice sheets caused by ice stream speed-up. Recent observations of ice shelf break-up and speed-up of glaciers in Antarctica and the Arctic have called for increased public awareness about the influence of climate warming on glaciers worldwide (Antoniades et al., 2011; De Angelis & Skvarca, 2003; Howat et al., 2005; Joughin et al., 2010; Rignot et al., 2004). This has led to an increase in research of glacier dynamics, where much of the attention has been focused on ice streams and the grounding line of marine-terminating glaciers. However, the inaccessibility of glacier beds and grounding lines makes direct research of modern glaciers costly and difficult. Furthermore, longer temporal records are needed in order to understand the long term influence of e.g. warming climate. For these reasons many researchers have found the study of geomorphic imprints of formerly glaciated areas suitable for gaining an overview of glacial processes and a timescale of their operation (Ó Cofaigh & Stokes, 2008). By studying how palaeo ice sheets responded to previous events of considerable warming (e.g. the Bølling-Allerød interstadial; Johnsen et al., 1992), we may be able to foresee how the glaciers and ice shelves of the Arctic and Antarctica will respond to continued warm conditions.

1.1 Ice streams

Ice streams are defined as narrow arteries of ice within an ice sheet (Bennett, 2003) capable of rapid advection of ice to ice sheet margins, that account for the majority of ice and sediment discharge from ice sheets (e.g. Bamber et al., 2000; Bennett, 2003). They are highly dynamic features and experience ice flow velocities of at least one magnitude higher than surrounding ice (Bamber et al., 2000; Paterson, 1994) and may experience large spatial and temporal variations (Bindschadler et al., 2003b; Catania et al., 2006; Conway et al., 2002; Hulbe & Fahnestock, 2007; Winsborrow et al., 2012). Ice streams are characterised by a heavily crevassed trunk with well-defined lateral shear margins (Echelmayer et al., 1994; Joughin et al., 1999). The large scale surface signature of ice streams is repeated on the ice stream bed as shown by studies of palaeo ice stream bedforms in both terrestrial and marine settings. This is well illustrated by the distribution of streamlined bedforms (Canals et al., 2000; Ó Cofaigh et al., 2002; Stokes & Clark, 1999; Wellner et al., 2006). Like ice surface features, bedforms are considered to be indicative of ice stream flow direction and tend to be arranged in a converging/diverging fan-shaped pattern at ice stream onsets/termini respectively, whilst being highly parallel in the main ice stream trunk (e.g. Stokes & Clark, 1999). Bedforms such as megascale glacial lineations (MSGLs) and drumlins become increasingly elongated in the ice flow direction as a result of accelerated ice flow velocities downstream (Stokes & Clark, 2002). Lateral margins are identified by lateral moraines or an absence of streamlined bedforms (Stokes & Clark, 1999, 2001) and palaeo terminus positions by the location of terminal moraines or grounding zone systems (Anderson et al., 2001; Mosola & Anderson, 2006). The distribution and type of bedforms reflect the processes that acted at the ice-bed interface (Stokes & Clark, 2002), sometimes allowing reconstruction of palaeo ice sheet dynamics (Ó Cofaigh & Stokes, 2008).

1.2 Factors influencing ice flow velocity and grounding line retreat

Early theoretical work concluded that ice acceleration and consequent thinning could be achieved by loss of buttressing ice shelves (Weertman, 1974). This view was later disputed (Alley & Whillans, 1991; Hindmarsh, 1993; Mayer & Huybrechts, 1999; Vaughan, 1993), but after the breakup of Larsen B Ice Shelf in 2002, the effect of loss of buttressing ice shelves on ice flow velocities was dramatically demonstrated. Here some of the adjacent glaciers experienced an up to eightfold acceleration and significant thinning followed by retreat, while other glaciers in the same area which were still buttressed by the ice shelf experienced no ice acceleration (De Angelis and Skvarca, 2003; Rignot et al., 2004; Scambos et al., 2004). However, the loss of buttressing ice shelves is not the only reason ice streams and outlet glaciers are speeding up. A general trend of glacier acceleration (without the loss of buttressing ice shelves) followed by thinning and retreat has been registered for a majority of the major outlet glaciers in Greenland (Howat et al., 2005; Joughin et al., 2010).

Ice stream velocity also depends on the response of glaciers to external forcing factors such as changes in climate and sea level. Climatic warming can lead to thinning and/or acceleration of glaciers and ice shelves through increased surface melting with warmer air temperatures (Scambos et al., 2003; Zwally et al., 2002), increased basal melting due to warming oceans (Bindschadler, 2006; Payne et al., 2004; Shepherd et al., 2004). Furthermore, sea level rise can destabilise the grounding line, causing the glacier to float off the seabed as a result of buoyancy. This leads to immediate retreat of the grounding line to a point where the water is shallower or the ice sheet is thicker (Alley et al., 2007; Anderson, 2007). If sea level rise and sedimentary stabilisation work on the same timescale, retreat may be paced by grounding zone systems, allowing ice streams to withstand a sea level rise of up to several meters (Alley et al., 2007; Anandakrishnan et al., 2007). However, when very rapid sea level rise occurs (such as at the end of the last glaciation) it will be a primary control on grounding line positions, if other factors affecting ice sheets more rapidly (such as sub-shelf water temperatures) are stable (Alley et al., 2007). The spatial/temporal variability in tidal range has also been pointed out as potential destabilising factors influencing the grounding line (Bindschadler et al., 2003a, 2003b; Ó Cofaigh, 2011).

In contrast, Conway et al. (1999) consider the current retreat of the WAIS to be non-dependent on sea level or climate forcing and point out that the WAIS has been continually retreating since the Early Holocene and that it may well continue and end with total disintegration of the WAIS. Furthermore, Hulbe & Fahnestock (2004, 2007) argue that the type of thinning and consequent retreat observed for WAIS ice streams can be explained by the dynamic nature of ice streams. They suggest ice streams experience kinematic cycles of slowdown, stagnation and reactivation and relate those to the availability of basal meltwater. Further they suggest these changes may lead to ice stream reorganisation through flow switching and do not necessarily lead to full ice sheet disintegration.

1.3 Influence of meltwater on ice flow velocity and sediment distribution

The distribution and supply of subglacial meltwater may also play a key role in modulating ice flow velocities (Bell, 2008). Ice flow velocity changes (e.g. at the onsets of ice streams) have been observed to coincide with subglacial geological boundaries and explained by shifts in subglacial drainage system types (Anderson et al., 2001; Raymond et al., 2001; Tulaczyk et al., 2000). Early work suggested that the streaming of ice is primarily achieved by subglacial sediment deformation or direct sliding on a thin subglacial water film (Alley et al., 1986; Blankenship et al., 1986; Kamb, 2001). Today, both deformation and sliding are considered to occur in areas of reduced basal stress, as a result of inefficient draining of subglacial meltwater through distributed drainage systems bed (Bell, 2008). On the other hand, where effective drainage systems prevail meltwater drains out of the glacier system without influencing flow velocities (Bell, 2008). Such systems may occur as R-channels incised up into the base of the ice (Röthlisberger, 1972), or as N-channels cut down into the substrate (Nye, 1976). R-channels are usually large, while N-channels vary greatly in size from a few metres to several kilometres where the largest are referred to as tunnel valleys (Röthlisberger, 1972; Piotrowski 1994, 1999). Tunnel valleys are considered to be eroded by pressurised subglacial meltwater as response to the abundance of basal meltwater greatly exceeding the drainage capacity of the subglacial drainage systems and aquifer (e.g. Kehew et al., 2012).

The subglacial hydrological system also plays an important role in the distribution, transportation and deposition of sediment by ice streams. Sediment can be transported and deposited at the grounding line in several different ways by ice streams. Firstly, supraglacial and englacial sediment may be dumped due to calving and melt-out at the grounding line (Powell & Domack, 2002). Secondly, the ice may push sediment mechanically such as at an ice margin (Powell & Domack, 2002). Thirdly, the concept of a layer of deforming sediment at the ice-bed interface providing both a manner of transporting sediments and supporting fast ice flow has become an accepted phenomena of ice streams supported by several examples (Alley et al., 1987; Blankenship et al., 1986; Engelhardt et al., 1990; Powell and Domack, 2002). Fourthly, subglacial meltwater is able to carry and deposit large amounts of sediment at the grounding line (Powell & Domack, 2002). Sediment transportation and delivery may thus be viewed as a range of states from fairly rigid sediment being pushed directly by the ice, to a sediment slurry or even sediment in meltwater suspension being ejected at the grounding line. The key factors governing which process is dominant appear to be the amount of meltwater in proportion to the amount of sediment, along with the type of hydrological system (channelised or distributed). It appears that this balance governs the way grounding zone systems look and behave, and that much can be learned about the ice dynamics of a palaeo ice streams from the study of palaeo grounding zone systems.

2. Study area and objectives

The Barents Sea is an epicontinental sea, located north of Scandinavia and northwest Russia(fig. 1). The large scale bathymetry is characterised by shallow bank areas (<300 m bsl), separated by deeper troughs (<500 m bsl). The Barents Sea was repeatedly glaciated through the Quaternary, with ice sheets reaching the continental shelf margins in the west and north (fig. 1; Elverhøi & Solheim, 1983; Vorren et al., 1988; Svendsen et al., 2004a). During glaciations ice streams occupied the main troughs, transporting debris and depositing trough mouth fans, out of which the Bjørnøyrenna trough mouth fan is the largest (Andreassen & Winsborrow, 2009; Vorren & Laberg, 1997). The Upper Regional Unconformity (URU) separates sediments deposited during these glacial events from underlying sedimentary rocks (Elverhøi and Solheim, 1983; Sigmond, 2002). The sediments are generally <100 m thick in the central and eastern Barents Sea but may much thicker in the western part (Elverhøi &Solheim, 1983; Vorren et al., 1989).

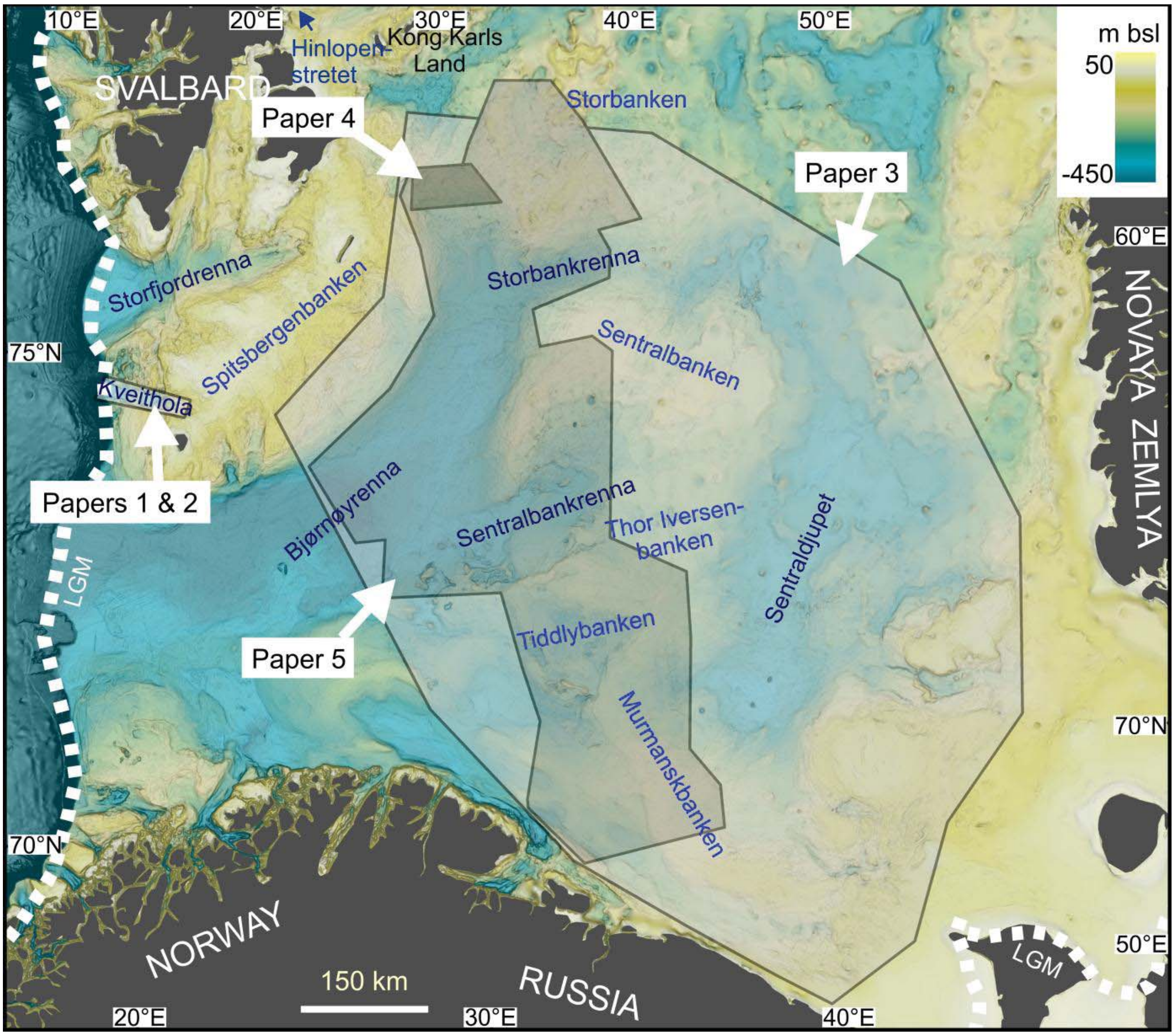

Figure 1. Map of the Barents Sea. The study areas covered in papers 1-5 are indicated by the shaded polygons. Also shown are major bank areas and seafloor troughs. White dashed line indicates ice sheet extent during the LGM (Svendsen et al., 2004a . The bathymetry is IBCAO v.3 (Jakobsson et al., 2012).

Two main areas of the Barents Sea are covered in this thesis. The Kveithola trough on the western margin of Spitsbergenbanken (fig.1), is the case study of papers 1 and 2. Paper 3 focuses on the central and south Barents Sea (fig.1), paper 4 covers the uppermost part of Bjørnøyrenna, west of Storbanken (fig.1) and paper 5 focuses on the central Barents Sea, namely Bjørnøyrenna, Storbanken, Storbankrenna, Sentralbanken, Sentralbankrenna, Thor Iversen-banken, Tiddlybanken and Murmanskbanken (fig.1).

This thesis is entitled “Processes and dynamics during deglaciation of a polar continental shelf, examples from the marine-based Barents Sea Ice Sheet” and its main aim is to explore what can be learned about the pattern of retreat of the Barents Sea Ice Sheet and subglacial/ice-marginal processes, from seafloor geomorphology and subsurface characteristics of sediment deposits. Special attention has been paid to ice stream grounding line processes and dynamics. A suite of marine geophysical methods were used during data acquisition and datasets included multibeam swath bathymetry, chirp sub-bottom sediment profiler, and multi-channel sparker/single-channel airgun seismic. In Kveithola, a number of seabed sediment cores were acquired, their lithology and physical properties described, and samples dated for chronological control. In addition, the Olex fisheries database of echo-soundings (www.olex.no) and the IBCAO v.3 dataset (Jakobsson et al., 2010) were used for mapping of large seafloor features.

3. Summary of papers

3.1 Paper 1

Rüther, D.C., Bjarnadóttir, L.R., Junttila, J., Husum, K., Rasmussen, T.L., Lucchi, R.G., Andreassen, K., 2012: Pattern and timing of the north-western Barents Sea Ice Sheet deglaciation and indications of episodic Holocene deposition, *Boreas* 41, 494-512. Doi: 10.1111/j.1502-3885.2011.00244.x

This paper describes the provenance of acoustic (chirp) units identified in Kveithola, a trough on the western margin of the Barents Sea, based on their correlation with sediment units identified in sediment (gravity) cores from the area. Identification of source-area and depositional environment is based on the combined results of lithological facies analysis, clay mineral content, oxygen isotope analysis and chronology based on radiocarbon dates of paired bivalve shells. Interpretation of depositional environments was based on the results from the different core analyses combined with chirp stratigraphy of the uppermost ~30 m of the trough sediments. The main results indicate that the trough was deglaciated by 14.2 cal ka, while ice was still lingering on the shallower Spitsbergenbanken and proximal glacimarine conditions prevailed. In the following period (14.2–13.9 cal ka), the trough was characterised by more distal glacimarine conditions as disintegration of the ice sheet on the bank led to deposition of IRD rich muds. At a later time (13.1-10.3 cal ka), the depositional geometry suggests sediments arrived through a channel north of the innermost part of the trough. A reoccurring shift in dominance between calving and meltwater drainage at the margin of the receding Barents Sea Ice Sheet further north, is recorded by heterogenous lithologies in the sediment. Furthermore, we speculate that an erosional boundary identified in the cores was formed as the Storegga tsunami (~8.1 cal ka) passed through Kveithola.

Contribution of authors: DR, LRB and KA planned and executed the acquisition of the data. DR, LRB and RGL did the sedimentary core description and logging and discussed results and interpretation of these, LRB assisted DR with identification and sampling of macro-fossils for radiocarbon dating, while DR was responsible for further chronological work and all final interpretations of sediment properties. JJ was responsible for all parts of the study and text concerning clay mineral analysis and interpretation. KH and TLR were responsible for all parts of the study and text which had to do with sampling, analysis and interpretation of oxygen isotope analysis. LRB was responsible for analyses and interpretation of geophysical data, made fig. 1B-H and contributed to writing about this part of the study. DR was responsible for the text, but all authors contributed to discussions and writing of the paper.

3.2 Paper 2

Bjarnadóttir, L.R., Rüther, D.C., Winsborrow, M.C.M., Andreassen, K., 2012: Grounding line dynamics of the Kveithola ice stream, W Barents Sea, as identified from seabed geomorphology and shallow seismic stratigraphy, *Boreas* (Early view). Doi: 10.1111/j.1502-3885.2012.00273.x.

This paper describes the retreat dynamics of a palaeo-ice stream in the well constrained trough Kveithola at the western margin of the Barents Sea shelf. The relatively small size of the ice stream system (compared to its larger neighbours) allowed for complete data coverage of the palaeo-ice stream bed. The results of this study reveal a complex picture of the deglaciation of this ice stream, which appears to have been very dynamic, as summarised in a conceptual model. The model includes ten deglacial stages which were identified based on seismic and acoustic data. The first eight are based on the distribution of subglacial and ice-marginal sediment units and describe a punctuated retreat of the ice stream, including one large readvance. The thickest accumulations of ice-marginal sediments are interpreted to be grounding line fans formed by deposition from meltwater evacuated at the ice margin, at a time of ice stream still-stand. Thinner accumulations, referred to as retreat sheets, are interpreted to be formed through the same process during retreats. We suggest that the different appearance of grounding line fans within the trough are directly related to the configuration and maturity of the subglacial meltwater system. The last two stages in the model describe the post-retreat environment in the trough and are characterised by deposition of draping units of glacimarine sediments.

Contribution of authors: All authors participated in planning and acquiring the data. LRB was responsible for processing and all interpretation (e.g. horizon mapping) of the data, as well as making all figures apart from figure 1 which was made by DR. All authors took part in discussions about the results. LRB was responsible for writing the manuscript, while all co-authors contributed actively throughout the writing and review of the paper.

3.3 Paper 3

Bjarnadóttir, L.R., Winsborrow, M.C.M., Andreassen, K.: Tunnel valleys in the Barents Sea *In review*.

In this paper we present a study of hitherto unknown valleys on the seafloor of the central Barents Sea. The valleys were mapped and their main attributes described. Based on their geometry, distribution and association with other geomorphic features they are interpreted to be tunnel valleys. Tunnel valleys are eroded by pressurised subglacial meltwater and we favour a polygenetic formation through some combination of meltwater outburst floods, steady-state drainage and ice erosion. The occurrence of tunnel valleys indicates that large portions of the Barents Sea Ice Sheet were warm-based during retreat across the central Barents Sea and that the amount of available subglacial meltwater frequently exceeded the drainage capacity of the existing subglacial drainage network and substrate. Further it indicates that the formation of channelised systems into the substrate was required in order to effectively drain the excess water from the ice sheet bed. We suggest this reflects an increased input of meltwater to the ice sheet bed, possibly as a result of climate warming towards the end of the last deglaciation.

Contribution of authors: LRB identified and mapped all described features, made all figures and was responsible for writing the paper. MCMW and KA participated in discussions and structuring and writing of the paper.

3.4 Paper 4

Andreassen, K., Winsborrow, M.C.M., Bjarnadóttir, L.R., Rüther, D.C. Landform assemblage from the collapse of the Bjørnøyrenna palaeo-ice stream, northern Barents Sea. *In review*.

Bjørnøyrenna is the largest cross-shelf trough in the Barents Sea, and it was occupied by a large ice stream during the last glaciation. Here we present a landform assemblage on the seafloor in upper Bjørnøyrenna. The presented landforms include a large acoustically transparent sediment wedge with mega-scale glacial lineations on the surface, which are overlain by a network of rhombohedral crevasse squeeze ridges. The sediment wedge is superimposed on striking parallel grooves interpreted to have been ploughed by mega-icebergs. The orientation of the grooves becomes gradually more chaotic, which is inferred to be due to break-up of the mega-icebergs into smaller icebergs. The sediment wedge is interpreted to consist largely of sediments deposited subglacially in a meltwater-rich environment and proglacially by subglacial meltwater evacuated along the whole margin of the Bjørnøyrenna Ice Stream. The described geomorphic pattern is consistent with stagnation and consequent float-off and break-up of the Bjørnøyrenna Ice Stream. The described landform assemblage bears many similarities to those of smaller surge-type glaciers, indicating that the similarities between small and large glacier systems may be greater than previously thought. Current models of Antarctic ice stream retreat do not capture such a meltwater-dominated retreat. However, with increasing climate warming and meltwater production the model presented in this paper may become increasingly applicable.

Contribution of authors: LRB discovered the described system. All authors planned data acquisition, KA, MCMW and DR acquired the data. LRB and MCMW processed the data. KA was responsible for writing the paper and making the figures, except for fig. 1, which was made by MCMW. All authors contributed in discussions and to the writing of this paper.

3.5 Paper 5

Bjarnadóttir, L.R., Winsborrow, M.C., Andreassen, K. Deglaciation of the central Barents Sea. *In prep*.

This paper describes the pattern of deglaciation in the central Barents Sea based on the study of marine geophysical datasets from five research cruises. The datasets include multibeam swath bathymetry, chirp data and seismic data. The main geomorphic features are mapped, described and interpreted. Based on the geomorphic mapping, major palaeo-ice margin positions, palaeo-ice flow directions and areas characterised by different ice flow dynamics have been identified. Based on the distribution of geomorphic features and glacidynamic context identified in this study and other published accounts, a new reconstruction of the withdrawal of the Barents Sea Ice Sheet across the central part of the Barents Sea has been made. The reconstruction reveals a change in ice dispersal patterns as deglaciation progressed. Furthermore, the conclusions indicate that in some areas ice streams draining the ice sheet went through reoccurring phases of fast and slow ice flow, sometimes including readvances or ice stream stagnation and ice shelf formation. In these areas retreat was characterised by episodic retreat. Retreat in other areas was slow but indications of a switch to more dynamic ice flow is observed for some of them during a late stage of deglaciation. We suggest this variability of dynamics is strongly linked to the availability of subglacial meltwater and efficiency of the subglacial drainage system an thereby also influenced by a warming climate during late deglaciation.

Contribution of authors: All authors were involved in planning cruises and acquiring data on board R/V Helmer Hanssen. LRB compiled the datasets, mapped geomorphic features, made all figures and was responsible for writing the manuscript. MCMW and KA contributed during the writing phase through structuring, discussions and review of the manuscript.

4. Synthesis

In this Ph.D. study the seafloor geomorphology of chosen areas of the Barents Sea has been mapped and analysed. Based on the geomorphic mapping, in combination with analysis of seismic stratigraphy and chirp stratigraphy, the retreat of the Barents Sea Ice Sheet in the Kveithola trough on the western margin of the Barents Sea Shelf and in the central part of the Barents Sea has been reconstructed. Below the main conclusions of this thesis are summarised.

4.1 The Kveithola trough

Papers 1 and 2 constitute a case study of the deglaciation of the Kveithola trough (fig. 1). An ice stream is inferred to have flowed from Spitsbergenbanken to the west, through the trough, reaching the shelf break at the LGM. This is based on the apparent seafloor geomorphology which is inherited from a deeper lying relief, representing the combined surface of subglacial and ice marginal deposits. The Kveithola Ice Stream is interpreted to have been very dynamic and have retreated in an episodic manner, with a total of six prolonged ice margin positions, whereof one represents a considerable readvance. The ice margin positions are represented by subglacial and ice marginal deposits. It is suggested that the geometry and characteristics of grounding line deposits in Kveithola are related to the availability of subglacial meltwater and reflect the configuration of the drainage system. The deglaciation of the Kveithola trough was followed by glacimarine conditions with deposition of an up to 20 m thick blanket of ice-proximal sediments. The sediment blanket is too thick to be penetrated with a gravity corer and thus it was not possible to acquire material for dating the onset of deglaciation. However, it is inferred to have been roughly synchronous with Storfjordrenna (fig. 1), which was ice free by ~19.4 cal ka (Rasmussen et al., 2007). Gravity cores from the upper part of the glacimarine sediment blanket, contain rhythmically laminated muds older than 14.2 cal ka interpreted to represent extensive sea ice cover combined with a large input of sediment from glacial meltwater plumes. The upper part of the glacimarine sediment blanket was dated to 14.2-13.9 cal ka, interpreted to represent an estimate for when Spitsbergenbanken was deglaciated. The last glacimarine influence in Kveithola is represented by up to 20 m thick sediment drifts brought to the inner part of Kveithola from a distal northern source. These sediments were dated to 13.1–10.3 cal ka, after which slow hemipelagic sedimentation commenced. A hiatus with an erosional base is identified in all six studied cores, characterised by mixing of sediment across the boundary, and abrupt changes from glacial to interglacial $\delta^{18}O$ values which started sometime between 8.6-7.8 cal ka ago. We suggest that the erosional boundary may represent the passing of the Storegga tsunami ~8.1 cal ka ago (Bondevik et al., 2012), which has been documented for a similar propagation distance on the adjacent Norwegian coastline (Romundset & Bondevik, 2011).

4.2 The central Barents Sea

Papers 3-5 describe the palaeo ice flow directions, retreat pattern and dynamics during deglaciation of the Barents Sea Ice Sheet in the central part of the Barents Sea. During the early phase of deglaciation, ice flowed into Bjørnøyrenna from a crest-shaped ice divide inferred to have been centred on Storbanken and extended to the west across Kong Karls Land and to the south towards Sentralbanken (fig. 1). Meanwhile the area from Sentralbankrenna (informal name; fig. 1) in the north to Tiddlybanken in the south (fig. 1) were fed by ice flowing from the northeast. Ice retreat in Bjørnøyrenna and Sentralbankrenna is inferred to have been episodic, while slower retreat is suggested for the remaining areas. It is suggested that the ice stream in Bjørnøyrenna went through several cycles of ice streaming and slowdown during this phase, including stagnation and possibly ice shelf formation. It is not known for how long this early phase persisted.

During a later phase of deglaciation a shift in palaeo ice flow directions (inferred from streamlined bedforms) indicate a gradual shift of source area for the ice in Bjørnøyrenna (fig. 1), where the ice divide migrated towards northwest, assuming a new position over the southern part of Hinlopenstretet (fig. 1). A later phase of ice retreat onto Storbanken (fig. 1) sourced from the east is also suggested, but it is unclear if these occurred during the same time. An advance of streaming ice in the inner part of Storbankrenna (informal name; fig. 1) may have occurred during this time but the exact timing is unknown. Retreat in Bjørnøyrenna during this phase continued to be episodic, while ice retreat on the bank areas is believed to have been slow. Changes in ice flow directions are also observed for later phases of ice flow in Sentralbankrenna and on Thor Iversen-banken, indicating that ice flow became more topographically controlled as ice retreated from deeper areas towards shallower and a switch to slow retreat occurred. The timing of these events is unknown. Ice continued to flow towards Tiddlybanken from the northeast and retreat is inferred to have been slow. However, a later phase of more topographically controlled ice advance from east onto Murmanskbanken is observed, which is inferred to have involved streaming ice. The timing of this event is unknown.

Chronological control in the central Barents Sea is generally lacking. However the ice sheet retreat can be constrained by dates of 16.9-17.5 cal ka (2σ) marking the onset of glacimarine sedimentation in outer Bjørnøyrenna (Rüther et al., 2011) and 14-2-15.6 cal ka (2σ) in the Central Deep (Polyak et al., 1995) and 11.-11.6 cal ka (2σ) age of driftwood on raised beaches in Kong Karls Land (Salvigsen, 1981).

4.3 Meltwater influence on grounding line deposits and cyclical ice stream behaviour

In all the papers, meltwater is identified as an important contributor to the observed patterns. This is because the amount of meltwater and type of drainage system can influence both the style of deposition and glacial dynamics. In paper 1, identified variations in lithological and acoustic units are amongst other attributed to varying input of glacial meltwater plumes. In paper 2, the geometry of the subglacial meltwater drainage system is inferred to control the geometry of grounding line accumulation. Paper 3 describes features interpreted to have been eroded by subglacial meltwater. In paper 4, meltwater is suggested to have both promoted fast ice flow and been important for grounding line deposition. In paper 5, cyclical ice stream behaviour is attributed to a balance between meltwater availability and maturity of the subglacial drainage system.

Glacial meltwater appears to have had a “Goldilocks effect” on the Barents Sea Ice Sheet throughout its retreat, where the fine-tuned balance between the availability of subglacial meltwater and ice dynamics, led to reoccurring cycles of fast ice flow followed by slowdown (and sometimes stagnation before fast flow was re-established) in the main troughs. With too little meltwater the ice moves very slowly, with too much it may experience extreme acceleration (which can in the end lead to overextension and stagnation), but with just the right amount of meltwater the ice can adopt a range of flow forms between these two end members.

Three types of grounding line deposits were identified in Kveithola and the central Barents Sea. The first type are acoustically transparent sediment accumulations referred to as ATBs. The ATBs are attributed to deposition from glacial meltwater emerging at the grounding line of streaming ice (based on upstream occurrence of MSGLs), implying that subglacial meltwater pressure was high and sediment strength low enough to support accelerated ice flow by sliding and/or deformation. The second type are large semi-transparent ridges interpreted to be moraines formed by ice push at prolonged stillstand positions of the ice margin, which indicate high yield strengths of subglacial sediments inferred to be the result of being well drained. The third type are small sediment ridges interpreted to be annual recessional moraines. In the central Barents Sea, the lateral geometry of the acoustically transparent deposits are not as well known as in Kveithola, where the features were divided into small or large isolated or merged grounding line fans attributed to different types of subglacial drainage systems. Increased data coverage might reveal similar patterns in the central Barents Sea. No examples of a widespread pattern of large or small retreat ridges have been confidently identified in Kveithola, although the occurrence of small push moraines was inferred in a few locations. In the central Barents Sea those types of grounding line deposits are mainly limited to the shallower bank areas. Moraines have previously been described on western Spitsbergenbanken (Solheim & Kristoffersen, 1984), based on which a similar pattern is suggested to apply for Kveithola.

The networks of stagnation ridges identified upstream of some of the ATBs in Bjørnøyrenna (papers 4 and 5) have not been observed in other parts of the study areas and to our knowledge this is the first account of such features in the Barents Sea directly related to the deglaciation of the Barents Sea Ice Sheet. It is a significant find in more than one way. First of all this suggests that stagnation and reactivation of the Bjørnøyrenna Ice Stream occurred more than once during the last deglaciation. Second, the apparent lack of disturbance of the features strongly suggests the stagnant ice floated free of its bed and formed an ice shelf. This seems to be supported by the occurrence of corrugated furrows directly upstream of the proximal end of inferred ice shelves. Similar features indicating the formation of ice shelves have not been described in relation to the last deglaciation of the Barents Sea before.

We suggest that stagnation may have occurred through three main processes. First, extension associated with acceleration caused ice stream thinning which may have led to basal freezing and stagnation, as previously suggested for the Bjørnøyrenna Ice Stream (Andreassen & Winsborrow, 2009; Rüther, 2012). We consider this process to have been especially important during early times of deglaciation when there was little input of supraglacial meltwater. Second, with warming climate during later phases of deglaciation supraglacial meltwater input to the ice sheet bed probably increased. This would have resulted in ice stream acceleration as a result of enhanced basal lubrication, which could have led to increased ice sheet drawdown to a point where the ice stream decelerated and perhaps stagnated. Third, highly increased melt rates would have led to very high subglacial meltwater pressures. We suggest that tunnel valleys were formed as a consequence of the amount of subglacial meltwater exceeding the drainage capacity of the subglacial drainage system and the substrate, in order to effectively drain the excess of water. Large drainage events may, in some cases, have led to the termination of fast ice-flow, and/or induced ice retreat. Several other factors may also have influenced these dynamic changes but better chronological control is needed to explore those relationships. However, it is clear that environmental forcing factors such as climate and sea level are inherently important.

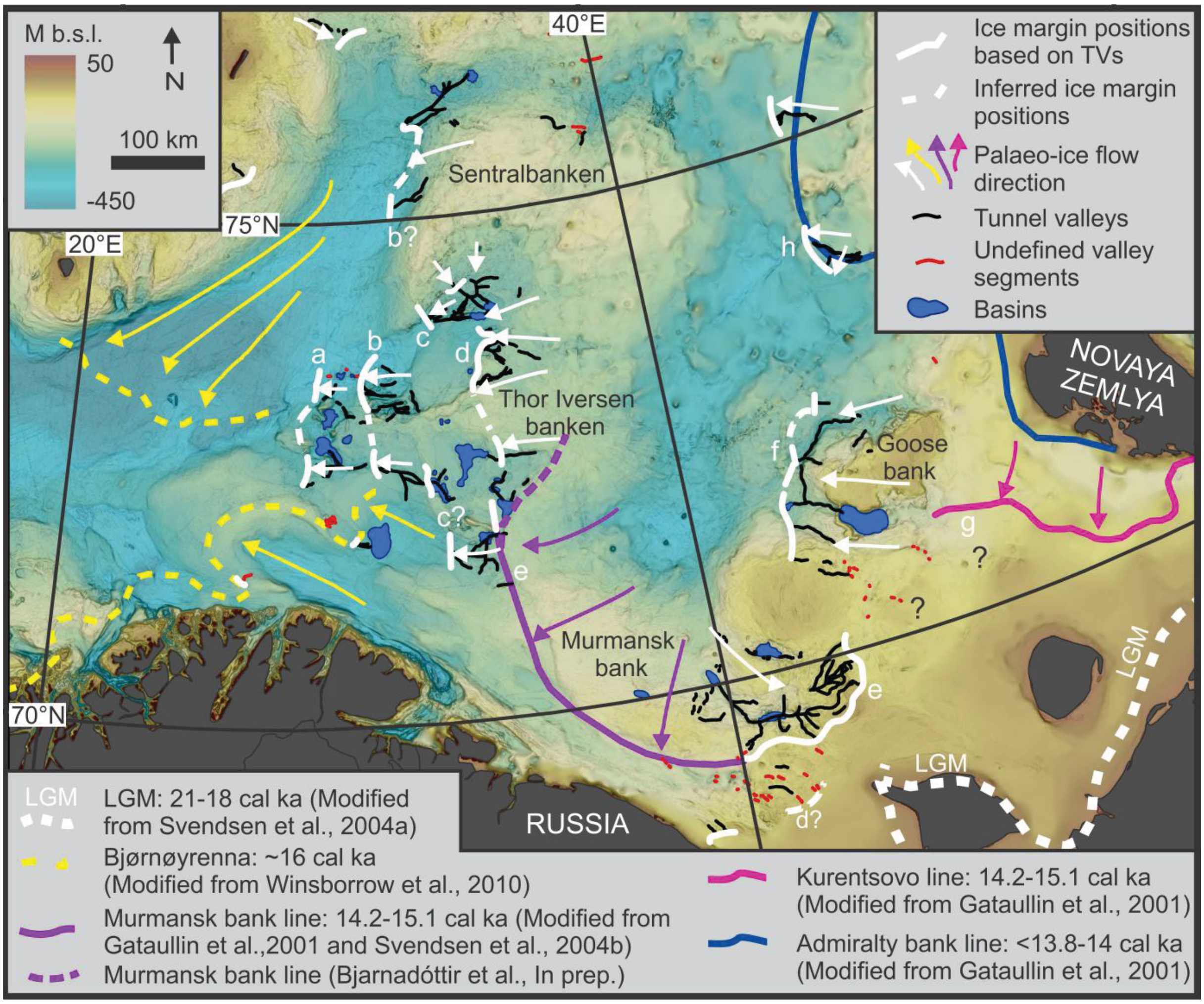

Figure 2. A map of the Barents Sea showing the location of tunnel valleys (TVs) and potential sites of subglacial meltwater ponding (basins). Also indicated are previously published ice margin positions and suggested palaeo-ice flow directions. The letters a-h indicate potential ice margin positions based on tunnel valley terminations. The bathymetry is the IBCAO v.3 dataset (Jakobsson et al., 2012).

A large portion of the tunnel valleys identified in paper 3 appear to terminate at ice margin positions identified in paper 5. In light of the cyclical ice flow behaviour described in paper 5, we suggest that tunnel valleys may have formed in every location where the ice sheet experienced highly elevated subglacial meltwater pressures without being able to respond to them dynamically enough. An attempt to reconstruct ice margins based on this idea (fig. 2) fits well with several of the ice retreat stages which were reconstructed in paper 5, but unverified stages also appear. It would be interesting to see if further investigation can confirm these ice margin positions, or provide evidence that some of the tunnels valleys have been reused through several glaciations.

5. Future work

The results from Kveithola highlight the advantages of combining a range of marine geophysical methods which has proven successful for deciphering complex patterns of past glacial activity. Conversely, the results from the central Barents Sea clearly demonstrate the limitations of only acquiring high frequency acoustic data. More high-resolution seismic data is needed from the central Barents Sea in order to verify whether the mapped trough-transverse ridges represent bedrock protrusions or moraines representing ice margin positions.

Radiocarbon dating of micro- and macro-fossils from sediment cores would make a vital contribution to any multi-discipline approach to study past glacial activity in the Barents Sea. A particular problem in the Barents Sea, however, is the lack of dateable material. Without time constraint on suggested retreat stages it is impossible to confidently put them into a temporal framework with respect to sea-level and climate variations.

Furthermore, close collaboration with research groups working on reconstructing palaeo-oceanographic environments using a multi-proxy approach is recommended. This may aid in recognising environmental conditions such as sea ice cover, ocean temperatures and ocean current systems, as well as establish a detailed chronology of deglaciation. Improved understanding of these factors could enable estimates of grounding line retreat rates and duration of different ice flow phases. It might also shed light on whether ice shelves commonly formed during the retreat of the Barents Sea Ice Sheet and how long they persisted.

Further investigation of the distribution and thickness of sediments and the depth to the Upper Regional Unconformity (URU) in the whole Barents Sea, would also be interesting. Having successfully built a model for both the URU and surface sediments, this might help to understand the effect of the substratum on for example the distribution of subglacial water and zones of fast ice-flow, and would also work as a basis for targeting especially interesting areas in that respect. Furthermore, in order to explore the relationship between substrate and glacial dynamics properly, more geophysical data is required and a number of geotechnical wells would ideally be needed from both sediments and bedrock to assess sediment properties such as permeability and porosity.

Finally, it would be worthwhile to revisit old studies/data from both the Norwegian and Russian parts of the Barents Sea with the aim to combine what is known about the glacial history (e.g. about the seismic stratigraphy, sediment thickness and properties, deglaciation ages, palaeo-ice flow patterns and dynamics), into a common framework. This might result in some reinterpretations and perhaps better constraints on the pattern and extent of the Barents Sea Ice Sheet during the last deglaciation.

6. References

Alley, R. B., Blankenship, D. D., Bentley, C. R. & Rooney, S. T. 1986: Deformation of till beneath ice stream B, West Antarctica. *Nature 322*, no.6074, p. 57-59.

Alley, R. B., Blankenship, D. D., Bentley, C. R. & Rooney, S. T. 1987: Till beneath ice stream B 3. Till deformation: evidence and implications. *Journal of Geophysical Research 92 (B9)*, p. 8921-8929.

Alley, R. A. & Whillans, I. M. 1991: Changes in the west Antarctic ice sheet. *Science 299*, 959-963.

Alley, R. A., Anandakrishnan, S., Dupont, T. K., Parizek, B. R. & Pollard, D. 2007: Effect of Sedimentation in Ice-Sheet Grounding-Line Stabilty. *Science 315*, 1838-1841.

Anandakrishnan, S., Catania, G., Alley, R. A. & Horgan, H. 2007: Discovery of Till Deposition at the Grounding Line of Whillans Ice Stream. *Science 315 (30)*, 1835- 1838.

Anderson, J. B. 2007: Ice Sheet Stability and Sea-Level Rise. *Science 315 (30)*,1803- 1804.

Anderson, J. B., Wellner, J. S., Lowe, A. L., Mosola, A. B. & Shipp, S. 2001: Footprint of the expanded West Antarctic Ice Sheet: ice stream history and behaviour. *Geological Society of America Today 11*, 4-9.

Andreassen, K. & Winsborrow, M. C. M. 2009: Signature of ice streaming in Bjørnøyrenna, Polar North Atlantic, through the Pleistocene and implications for ice-stream dynamics. *Annals of Glaciology 50 (52)*, 17-26.

Antoniades, D., Francus, P., Pienitz, R., St-Onge, G. & Vincent, W. F. 2011: Holocene dynamics of the Arctic´s largest ice shelf. *Proceedings of the National Academy of Sciences of the United States of America 108*, 18899-18904.

Bamber, J. L., Vaughan, D. G. & Joughin, I. 2000: Widespread complex flow in the interior of the Antarctic Ice Sheet. *Science 287*, no. 5456, 1248-1250.

Bell, R. E. 2008: The role of subglacial water in ice-sheet mass balance. *Nature v. 1*, 297-304.

Bennett, M. R. 2003: Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. *Earth-Science Reviews 61 (3-4)*, 309-339.

Bindschadler, R. A., King, M. A., Alley, R. B., Anandakrishnan, S. & Padman, L. 2003a: Tidally controlled stick-slip discharge of a West Antarctic ice stream. *Science 301*, no. 5636, 1087-1089.

Bindschadler, R. A., Vornberger, P. L., King, M. A. & Padman, L. 2003b: Tidally driven stick-slip motion in the mouth of Whillans Ice Stream, Antarctica. *Annals of Glaciology 36*, 263-272.

Bindschadler, R. 2006: Hitting the Ice Sheets Where It Hurts. *Science 311*, 1720-1721.

Blankenship, D. D., Bentley, C. R., Rooney, S. T. & Alley, R. B. 1986: Seismic Measurements Reveal a Saturated Porous Layer beneath an Active Antarctic Ice Stream. *Nature 322*, no. 6074, 54-57.

Bondevik et al., Storvik, S. K. & Skjerdal, G. 2012: Green mosses date the Storegga tsunami to the chilliest decades of the 8.2 ka cold event. *Quaternary Science Reviews 45*, 1-6.

Canals, M., Urgeles, R. & Calafat, A. M. 2000: Deep sea-floor evidence of past ice streams off the Antarctic Peninsula. *Geology 28 (1)*, 31-34.

Catania, G. A., Scambos, T. A., Conway, H. & Raymond, C. F. 2006: Sequential stagnation of Kamb Ice Stream, West AntarcticaL: *Geophysical Research Letters, v. 33 (14)*, L14502.

Conway, H., Hall, B. L., Denton, G. H., Gades, A. M. & Waddington, E. D. 1999: Past and future grounding-line retreat of the West Antarctic Ice Sheet. *Science 286*, no. 5438, 280-283.

Conway, H., Catania, G., Raymond, C. F., Gades, A. M., Scambos, T. A. & Engelhardt, H. 2002: Switch of flow direction in an Antarctic ice stream. *Nature 419*, no. 6906, 465-467.

De Angelis, H. & Skvarca, P., 2003: Glacier surge after ice shelf collapse. *Science 299*, no. 5612, 1560-1562.

Echelmayer, K. A., Harrison, W. D., Larsen, C. Mitchell, J. E. 1994: The role of the margins in the dynamics of an active ice stream. *Journal of glaciology 40*, p. 11.

Elverhøi, A. & Solheim, A. 1983: The Barents Sea ice sheet - a sedimentological discussion. *Polar Research 1*, 23-42.

Engelhardt, H., Humphrey, N., Kamb, B. & Fahnestock, M. 1990: Physical Conditions at the Base of a Fast Moving Antarctic Ice Stream. *Science 248*, no. 4951, 57-59.

Gataullin, V., Mangerud, J. & Svendsen, J.I. 2001: The extent of the Late Weichselian ice sheet in the southeastern Barents Sea. Global and Planetary Change 31 (1-4), 453-474.

Hindmarsh, R. C. A. 1993: Modeling the dynamics of ice sheets. *Progress in Physical Geography 17*, 391-412.

Howat, I. M., Joughin, I., Tulaczyk, S. & Gogineni, S. 2005: Rapid retreat and acceleration of Helheim Glacier, east Greenland. *Geophysical Research Letters 32*, no. L2205.

Hulbe, C. & Fahnestock, M. 2004: West Antarctic ice-stream discharge variability: mechanism, controls and pattern of grounding-line retreat. *Journal of Glaciology 50*, no. 171, 471-484.

Hulbe, C. & Fahnestock, M. 2007: Century-scale discharge stagnation and reactivation of the Ross ice streams, West Antarctica. *Journal of Geophysical Research 112*, no. F03S27, 11.

http://www.olex.no, 2012: A fisheries database of echosoundings.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H. W., Zaraskaya, Y., Accettella, D., Armstrong, A., Anderson, R. M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J. V., Hall, J. K., Hell, B., Hestvik, O. B., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S. V., Pedrosa, M. T., Travaglini, P. G.

& Weatherall, P. 2012: The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0. Geophysical Research Letters 39, LI2609.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C. U., Iversen, P., Jouzel, J., Stauffer, B. & Steffensen, J. P. 1992: Irregular glacial interstadials recorded in a new Greenland ice core. *Nature 359*, no. 24, 311- 313.

Joughin, L., Gray, L., Bindschadler, R., Price, S., Morse, D., Hulbe, C., Mattar, K. & Werner, C. 1999: Tributaries of West Antarctic Ice streams revealed by RADARSAT interferometry: *Science 286*, no. 5438, 283-286.

Joughin, I., R., Smith, B. E., Howat, I. M., Scambos, T. & Moon, T. 2010: Greenland flow variability from ice-sheet-wide velocity mapping. *Journal of Glaciology 56*, 415-430.

Kamb, B. W. 2001: Basal zone of the West Antarctic ice streams and its role in the lubrication of their rapid motion, *In Alley, R. B., and Bindschadler, R., eds., The West Antarctic Ice Sheet: Behaviour and Environment, Antarctic Research Series 77*, 157-199.

Kehew, A. E., Piotrowski, J. A. & Jørgensen, F. 2012: Tunnel valleys: Concepts and controversies – A review. *Earth Science Reviews*, doi: 10.1016/j.earscirev.2012.02.002.

Mayer, C. & Huybrechts, P. 1999: Ice-dynamic conditions across the grounding zone, Ekstromisen, East Antarctica. *Journal of Glaciology 45*, 384-393.

Mercer, J. 1978: West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster. *Nature 271*, 321-325.

Mosola, A. B. & Anderson, J. B. 2006: Expansion and rapid retreat of the West Antarctica Ice Sheet in eastern Ross Sea: possible consequences of over-extended ice streams? *Quaternary Science Reviews 25*, no. 17-18, 2177-2196.

Nye, J.F. 1976: Water flow in glaciers; jökulhlaups, tunnels, and veins. Journal of Glaciology 17, 181–207.

Ó Cofaigh, C., Pudsey, C. J., Dowdeswell, J. A. & Morris, P. 2002: Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf. *Geophysical Research Letters 29*, no. 8, p. art. no.-1199.

Ó Cofaigh, C. & Stokes, C. R. 2008: Reconstructing ice-sheet dynamics from subglacial sediments and landforms: introduction and overview. *Earth Surface Processes and Landforms 33*, 495-502.

Ó Cofaigh, C. 2011: Past ice-shelf collapse in West Antarctica. *Nature 476*, 290-291.

Paterson, W. S. B. 1994: *The Physics of Glaciers*, Oxford, Pergamon Press, 250 p.

Payne, A. J., Vieli, A., Shepherd, A. P., Wingham, D. J. & Rignot, E. 2004: Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. *Geophysical Research Letters 31*, no. 23, p. art. no.-L23401.

Piotrowski, J.A. 1994: Tunnel-valley formation in northwest Germany—geology, mechanisms of formation and subglacial bed conditions for the Bornhöved tunnel valley. Sedimentary Geology 89, 107–141.

Piotrowski, J.A. 1999: Channelized subglacial drainage under soft-bedded ice sheets.: evidence from small N-channels in Central European Lowland. Geological Quarterly 43, 153–162.

Polyak, L., Lehman, S., Gataullin, V. & Timothy Jull, A. J. 1995: Two-step deglaciation of the southeastern Barents Sea. *Geology 23*, no. 6, 567-571.

Powell, R. D. & Domack, E. 2002: Modern glaciomarine environments, *In Menzies, J., ed., Modern and Past Glacial Environments*, Oxford, Butterworth-Heinemann, p. 445-486.

Rasmussen, T. L., Thomsen, E., Slubowska, M. A., Jessen, S., Solheim, A. & Koc, N. 2007: Paleoceanographic evolution of the SW Svalbard margin (76 degrees North) since 20, 000 radiocarbon years before present. *Quaternary Research 67*, 100- 114.

Raymond, C. E., Echelmeyer, K., Whillans, I. M. & Doake, C. S. M. 2001: Ice stream shear margins, *In Alley, R. A., and Bindschadler, R., eds., The West Antarctic Ice Sheet: Behaviour and Environment 77*, Washington, American Geophysical Union 137-155.

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A. & Thomas, R. 2004: Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters 31*, no. 18, p. art. no.-L18401.

Romundset, A. & Bondevik, S. 2011: Propagation of the Storegga tsunami into ice-free lakes along the southern shores of the Barents Sea. *Journal of Quaternary Science 26 (5)*, 457-462.

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*, 2776-2792.

Rüther, D. C., 2012, *Palaeoenvironment of the Barents Sea during the last deglaciation and Holocene. Processes and timing*. Unpublished Ph.D.thesis, University of Tromsø, 116 p.

Röthlisberger, H., 1972: Water pressure in intra- and subglacial channels. Journal of Glaciology 177–203.

Salvigsen, O. 1981: Radiocarbon dated raised beaches in Kong Karls Land, Svalbard, and their consequences for the glacial history of the Barents Sea. *Geografiska Annaler 63A*, no. 3-4, 283-291.

Scambos, T., Hulbe, C. & Fahnestock, M. 2003: Climate-induced ice shelf disintegration in the Antarctic peninsula. *Antarctic research series 76*, 335-347.

Scambos, T. A., Bohlander, J. A., Shuman, C. A. & Skvarca, P. 2004: Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophysical Research Letters 31*, no. 18, p. art. no.-L18402.

Shepherd, A., Wingham, D. & Rignot, E. 2004: Warm ocean is eroding West Antarctic Ice Sheet. *Geophysical Research Letters 31*, no. 23, p. art. no.-L23402.

Sigmond, E. M. O., 2002: Geological Map, Land and Sea Areas of Northern Europe, Scale 1:4 million: Geological Survey of Norway.

Solheim, A. & Kristoffersen, Y. 1984: Physical environment Western Barents Sea, 1:1,500,000; Sediments above the upper regional unconformity: thickness, seismic stratigraphy and outline of the glacial history. *Norsk Polarinstitutt Skrifter 179B*, 3-26.

Svendsen, J. I., Alexanderson, H., Astakhov, V. I., Demidov, I., Dowdeswell, J. A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H. W., Ingólfsson, Ó., Jakobsson, M., Kjær, K. H., Larsen, E., Lokrantz, H., Lunkka, J. P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M. J., Spielhagen, R. F. & Stein, R. 2004a: Later Quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23 (11-13), 1229-1271.

Svendsen, J. I. Gataullin, V., Mangerud, J. & Polyak, L. 2004b: The glacial history of the Barents and Kara Sea region. *In Ehlers, J. & Gibbard, P. L. (eds), Quaternary Glaciations – Extent and Chronology. Part 1: Europe*, Amsterdam, Elsevier.

Stokes, C. R. & Clark, C. D. 1999: Geomorphological criteria for identifying Pleistocene ice streams. *Annals of Glaciology 28*, 67-74.

Stokes, C. R. & Clark, C. D. 2001: Palaeo-ice streams. *Quaternary Science Reviews 20*, no. 13, 1437-1457.

Stokes, C. R. & Clark, C. D. 2002: Are long subglacial bedforms indicative of fast ice flow? *Boreas, 31 (3)*, 239-249.

Tulaczyk, S., Kamb, W. B. & Engelhardt, H. F. 2000: Basal mechanics of Ice Stream B, West Antarctica 1. Till mechanics. *Journal of Geophysical Research-Solid Earth 105*, no. B1, 463-481.

Vaughan, D. G. 1993: Implications for the break-up of Wordie Ice Shelf, Antarctica for sea level. *Antarctic Science 5*, 403-408.

Vorren, T., Hald, M. & Lebesbye, E. 1988: Late Cenozoic environments in the Barents Sea. *Paleoceanography 3* (5), 601-612.

Vorren, T., Lebesbye, E., Andreassen, K. & Larsen, K.-B. 1989: Glacigenic sediments on a passive continental margin as exemplified by the Barents Sea. *Marine Geology 85*, 251- 272.

Vorren, T. O. & Laberg, J. S. 1997: Trough mouth fans - Palaeoclimate and ice-sheet monitors. *Quaternary Science Reviews 16*, no. 8, 865-881.

Weertman, J. 1974: Stability of the junction of an ice sheet and an ice shelf. *Journal of Glaciology 13*, 3-11.

Wellner, J. S., Heroy, D. C. & Anderson, J. B. 2006: The death mask of the antarctic ice sheet: Comparison of glacial geomorphic features across the continental shelf. *Geomorphology 75 (1-2)*, 157-171.

Winsborrow, M. C. M., Stokes, C. R. & Andreassen, K. 2012: Ice-stream flow switching during deglaciation of the southwestern Barents Sea. *Geological Society of America Bulletin 124*, 275-290.

Zwally, H. R., Abdalati, W., Herring, T., Larson, K., Saba, J. & Steffen, K. 2002: Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow. *Science 297*, no. 5579, 218-222.

Paper 1

Paper 2

Paper 3

Paper 4

Paper 5

ISBN xxx-xx-xxxx-xxx-x