UiT
THE ARCTIC
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The Faculty of Science and Technology
Department of Geosciences

Collapse of a marine-based ice sheet

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Mariana da Silveira Ramos Esteves
A dissertation for the degree of Philosophiae Doctor – August 2018

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Tromsø, August 2018

Centre for
Arctic Gas Hydrate,
Environment and Climate

Supervisors:

Dr. Monica C. M. Winsborrow

CAGE - Centre for Arctic Gas Hydrate,

Environment and Climate,

Department of Geosciences,

UiT – The Arctic University of Norway, Tromsø, Norway.

Professor Karin Andreassen

CAGE - Centre for Arctic Gas Hydrate,

Environment and Climate,

Department of Geosciences,

UiT – The Arctic University of Norway, Tromsø, Norway.

Associate Professor Denise C. Rüther

Western Norway University of

Applied Science (HVL), Sogndal, Norway.

Dr. Lilja R. Bjarnadóttir

Geological Survey of Norway (NGU),

Trondheim, Norway.

Photos and illustration by Mariana Esteves

Cover page – Glaciology course field trip to Paulabreen, Svalbard 2015

Page i – Calving front of Hornbreen, Svalbard 2013

Page iii – 'Adventure awaits' - Linocut 2018

Page v – Helmer Hanssen sails home through the fjords in northern Norway after research cruise 2013

"When one tugs at a single thing in nature, one

finds it attached to the rest of the world."

— *John Muir*

This doctoral thesis wouldn't have been possible without the support, encouragement and guidance of many people who have been with me throughout this journey and it is to those whom I would like to acknowledge and dedicate this thesis.

Acknowledgements

First and foremost, I would like to thank my four supervisors. It has been my pleasure to be supervised and guided by four inspiring women. I feel very privileged to have worked with them.

Karin, I am forever grateful to you for giving me the incredible opportunity to undertake this PhD and for always ensuring that I had all of the support that I needed to pursue my research interests and to develop professionally through numerous research cruises, conferences, and courses. You have always supported me throughout these years (particularly during a bit of a rough start), providing crucial advice and guidance along the way, whilst also having confidence and trust in my ability to give me the freedom to figure things out on my own, help plan cruises, and learn from occasional 'trial and error' experiences.

Monica, I am deeply grateful to you for your endless encouragement, support and guidance these last few years, both as a supervisor and a friend – it has been invaluable! Your enthusiasm for science and life is inspiring, and I am really thankful to you for always being there for me with a positive outlook and helpful advice and insights on life, adventures and science.

Denise and Lilja, thank you both for your enthusiasm, support, guidance and numerous scientific discussions – your attention to detail greatly improved the PhD and research papers. Lilja, I would also like to say thank you for always being such a positive influence and for all of your words of wisdom and advice, particularly during those times when I felt that the end was nowhere in sight.

I am very grateful to my co-authors and collaborators for their scientific discussions and contributions to the papers. In particular, I am really grateful to Stephen Livingstone for his support, enthusiasm, and scientific insights.

Thank you to the 'lab girls' (Trine, Karina, and Ingvild) – you are a fantastic team, always willing to help everyone out no matter how big or small the task and for always being happy to answer our countless questions. Matthias, Inger, Margrethe, and Kai, I really appreciate all of your help with numerous issues that we had during the PhD and for always being open and willing to offer a helping hand. Thank you to the IT guys, especially Rolf and Helge, here at the department and the crews of R/V Helmer Hanssen for your support.

I would also like to thank WP2 and my colleagues here at CAGE and the department of geosciences for all of the interesting conversations and times together, and thank my old and new officemates for all of the interesting discussions, coffee/tea-breaks, numerous BBQs/cakes/sweets/ice-creams (perhaps too many…), ski trips, and nice company to work with.

Special thanks go to my friends here in Tromsø for all of their support and encouragement. These past five years have been incredibly fun thanks to you guys and I have loved every moment of our time together filled with ski trips, hikes, breakfasts-lunches-dinners, scientific discussions, road trips and just generally having a good time – Yulia, Carly, Henry, Alex, Dasha, Pasha, Malin, Anna, Alexey, Emmelie, David, Giacomo, Hanne, Andrea B, Eythor, Sunil, Kate, Friede, Noortje, Sarah, Nicole, and others. I would also like to thank Emil for his support in helping me integrate into the Norwegian way of life, for sharing his enthusiasm for the outdoors and reminding me to always be happy and keep my shoulders down… and that one pair of skis is never enough!

To our friends in NYC, thank you for all of the Wednesday beers/trips/dinners/science discussions/fun times together during those months. In particular, I would like to say a huge thank you to Jonny and Jen for making our time in NYC as incredible as it was, filled lots of amazing city and outdoor adventures. Thank you both for your patience when I couldn't join in due to work, for endless encouragement and support, and for always being there for us.

To my friends at home and in particular Julz, Amy, and Amanda, thank you for always being there for me no matter what, for all of the visits these past years, and for making it a pleasure to come back home.

Andrea, Robert, Brad, and Rob, thank you for all of your invaluable support, encouragement and enthusiasm for life, adventures and cakes these years – it has been an absolute pleasure to share so many nice memories and adventures with you.

Mãe, Howard, Francisco e família, sem vocês este doutoramento não teria mesmo sido possível. Desde o início que sempre me apoiaram com toda a vossa confiança e alinharam com todas as minhas decisões, embora ás vezes pudessem parecer um pouco malucas. Adorei todas as nossas aventuras pelo mundo! Agradeço todo o vosso carinho, ajuda e incentivo, assim como a vossa compreensão para o tempo que não pude passar com vocês durante todo o processo do doutoramento. 'Grão a grão enche a galinha o papo' – e após cinco anos a trabalhar neste projecto, finalmente o papo ficou cheio... Até ao próximo capítulo...

Calvin, to you I owe my biggest acknowledgement. I am deeply thankful that you are my partner in life, adventures and work – your love, support and enthusiasm for life and adventure continues to inspire me every day. Thank you for always believing in me, making me laugh and smile through the good and difficult times, and for providing me with immeasurable amounts of happiness, support, and encouragement to do bigger and better things in life. Your patience this past year has been admirable and I am really grateful to you for always being there for me and for your ability to make light of any situation. I look forward to joining you for many more adventures!

Tusen takk,

Mariana

Summary

The Barents Sea Ice Sheet (BSIS) is a good palaeo-analogue to the West Antarctic Ice Sheet (WAIS), and understanding the key processes occurring during the deglaciation of the BSIS can yield important insights into the drivers and response of marine-based ice sheets to climatic changes. This is important since marine-based ice sheets, such as the BSIS and WAIS, are particularly vulnerable to oceanic and climatic changes, as their bed lie largely below sea level. The Barents Sea is therefore an ideal study site for investigations of the processes and mechanisms occurring at the beds of marine-based ice sheets, and can provide insights into the spatial and temporal fluctuations in glaciodynamics and subglacial hydrology occurring at the bed during the last deglaciation.

Prior to this doctoral thesis, few palaeo-glaciological studies had been undertaken in the central Barents Sea, and so little was known of the palaeo-ice streams and subglacial drainage networks in this region. This project used a multi-proxy approach combining both glacial geomorphological and sedimentological analyses to extend our knowledge of the glacidynamics, retreat patterns and subglacial hydrology of the Sentralbankrenna glacial system in the central Barents Sea.

The key findings of this doctoral thesis and its associated papers are as follows:

1) The first comprehensive reconstruction of the retreat patterns and dynamics of the Sentralbankrenna glacial system, highlighting that Sentralbankrenna Ice Stream underwent a six-stage episodic retreat, which was characterised by rapid ice break-up punctuated by margin stillstands or short readvances (paper 1);

2) The first combined geomorphological and sedimentological evidence for palaeo-subglacial lakes in the Barents Sea, as well as indications for the presence of a hydrologically active subglacial lake system undergoing fill-drain cycles on Thor Iversenbanken (paper 2);

3) Demonstrated the strong control of ice dynamical setting on the nature and organisation of subglacial hydrological systems, through detailed characterisation of three distinct palaeo meltwater networks, located within close proximity of each other in the Sentralbankrenna glacial system (paper 3).

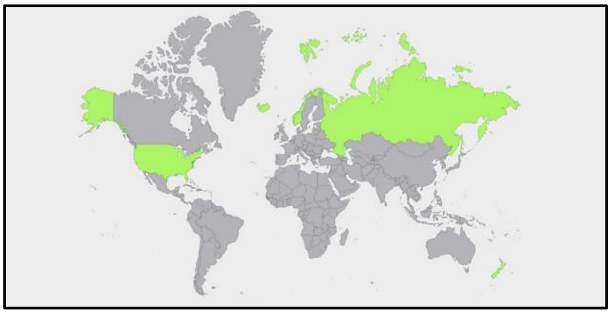
This doctoral thesis provides comprehensive insights into the ice retreat patterns in the central Barents Sea, the character of subglacial hydrological systems in this area and glaciodynamic influences on the hydrological networks observed, as well as providing the first sedimentological study of palaeo-subglacial lakes in the Barents Sea.

Preface

This doctoral thesis was undertaken at the Centre for Arctic Gas Hydrate, Environment and Climate (CAGE), Department of Geosciences, UiT the Arctic University of Norway (UiT) between the period of March 2013 and August 2018. The project was funded through a four-year grant from UiT, with additional support from the Research School in Arctic Marine Geology and Geophysics (AMGG) and CAGE (research grant 223259). The main supervisor was Dr. Monica Winsborrow (CAGE, UiT). Co-supervisors were Professor Karin Andreassen (CAGE, UiT), Dr. Lilja Bjarnadóttir (Geological Survey of Norway), and Associate Professor Denise Rüther (Western Norway University of Applied Science).

The four-year PhD program at UiT requires that one year of the project (25%) be dedicated to duty work. To meet this requirement a 60-ECT master equivalence project, consisting of several courses and two dissertations was undertaken. Furthermore, the doctoral program requires that 30-ECT worth of courses be undertaken and for this, the following courses were completed: *Philosophy of Science and Ethics; AMGG workshop; Glaciology; Reconstruction of glacial marine sedimentary processes and environments.*

Throughout this PhD, I have had the opportunity and privilege to present my work and attend several courses, workshops, summer schools, conferences and meetings around the world, as well as the opportunity to take part in many research cruises around Svalbard and in the Barents Sea. The sediment cores and chirp subsurface datasets used in articles 2 and 3 were collected during the CAGE research cruise in summer 2015. I was responsible for planning the acquisition of these datasets, and participated in the cruise. The MAREANO Programme (www.mareano.no) provided the multibeam bathymetric dataset used in all three articles of this PhD project, as well as a TOPAS profile used in paper 3.



Countries visited during PhD related travels (highlighted).

Conferences, workshops and meetings

2017

AGU Fall Meeting, New Orleans, USA. Poster presentation.

2016

CAGE Winter Meeting, Tromsø, Norway. Poster presentation.

AMGG Annual Meeting, Tromsø, Norway. Oral presentation.

2015

CAGE Winter Meeting, Tromsø, Norway. Contribution to poster presentation.

MAREANO 10 year celebration conference. Oslo, Norway. Oral presentation.

IGS International Symposium on Hydrology of Glaciers and Ice Sheets, Höfn, Iceland. Poster presentation.

AMGG Annual Meeting, Tromsø, Norway. Oral presentation.

2014

CAGE Winter Meeting, Tromsø, Norway. Poster presentation.

SCAR Biennial Meetings & Open Science Conference, Auckland, New Zealand. Attended only.

AMGG Annual Meeting, Tromsø, Norway. Oral presentation.

2013

ACDC summer school ResClim, Norway.

PAST Gateways International Conference and Meeting, St. Petersburg Russia. Attended only.

ResClim All Staff Meeting, Sommarøya Norway. Poster presentation.

AMGG Annual Meeting, Tromsø Norway. Oral presentation.

Cruises

2015	2014	2013
AG-839 Teaching cruise, 4 days field trip, Isfjorden - Svalbard CAGE Research Cruise, 2.5 weeks, Central Barents Sea	CAGE Research Cruise, 2 weeks, Southern Svalbard and Central Barents Sea	GLACIBAR Research Cruise, 1 week, Southern Svalbard and Central Barents Sea AMGG Teaching Cruise, 1 week, Southern Svalbard

Articles

This thesis consists of an introduction and three papers (1 published, 1 in review and 1 manuscript):

Paper I

Mariana Esteves, Lilja R. Bjarnadóttir, Monica C.M. Winsborrow, Calvin S. Shackleton, Karin Andreassen, 2017. **Retreat patterns and dynamics of the Sentralbankrenna glacial system, Central Barents Sea.** *Quaternary Science Reviews* 169, 131-147.

Paper 2

Mariana Esteves, Denise C. Rüther, Monica C.M. Winsborrow, Stephen J. Livingstone, Karin Andreassen, (in review). **An interconnected palaeo-subglacial lake system in the central Barents Sea.** *Boreas*

Paper 3

Mariana Esteves, Monica C.M. Winsborrow, Calvin S. Shackleton, Lilja R. Bjarnadóttir, Karin Andreassen, (In Prep). **The influence of ice dynamics on subglacial meltwater systems: an example from the central Barents Sea.**

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1. Introduction

1.1. Scientific challenge

As the global climate continues to change, the Greenland and Antarctic Ice Sheets are increasingly vulnerable and already experiencing significant mass loss attributed to increasing ocean and atmospheric temperatures (Mercer, 1978; Bindschadler, 2006; Rignot et al., 2014). As a marine-based ice sheet where the majority of its bed is grounded below sea level, the West Antarctic Ice Sheet (WAIS) is particularly vulnerable to these changes. If the WAIS underwent total collapse and disintegration, it could potentially raise global sea level by 6 m, posing a significant threat to coastal communities around the globe. The response of ice sheets to ocean and atmospheric warming is complex, but the nature of the subglacial environment, and in particular the amount and distribution of meltwater at the base of an ice sheet, plays an important role in regulating the dynamics of overlying ice. Accessing the subglacial environment of contemporary ice sheets is challenging, and as such studying the geomorphological and sedimentological imprints left by the former ice sheets offers a very fruitful means of increasing our understanding of the processes that occur at the bed of an ice sheet.

The former Barents Sea Ice Sheet (BSIS) is a good palaeo-analogue for the WAIS (Andreassen and Winsborrow, 2009), as they were both largely marine-based, had similar sizes and extents during the Last Glacial Maximum (LGM; 18-21 cal ka BP), and overlay sedimentary bedrock. Understanding the key processes occurring during the deglaciation of this ice sheet can yield important insights into the drivers and response of marine-based ice sheets to climatic changes.

While considerable research has been undertaken on the southwestern margins of the BSIS and around Svalbard over the last few decades (for a recent review see Patton et al., 2015), the glacial history of the central Barents Sea is comparatively poorly studied. This is despite it being an important area comprised of multiple ice domes, ice divides, ice streams and tributaries which likely exerted a fundamental control on the dynamics and configuration of the BSIS as a whole (fig. 1 A). Until recently, few datasets were available to study the central Barents Sea due to political border disputes between Norway and Russia. Following the delineation of the marine border between the two countries in 2011 (fig. 1 A), acquisition of marine geophysical and sedimentological datasets from this central section of the Barents Sea was permitted. This has included high-resolution multibeam bathymetric mapping (through the MAREANO Programme), as well as several research cruises from CAGE and UiT acquiring sedimentological and geophysical datasets. These datasets form the basis for this thesis, providing a unique opportunity to investigate the processes occurring at the ice-bed interface of the central regions of the BSIS during deglaciation.

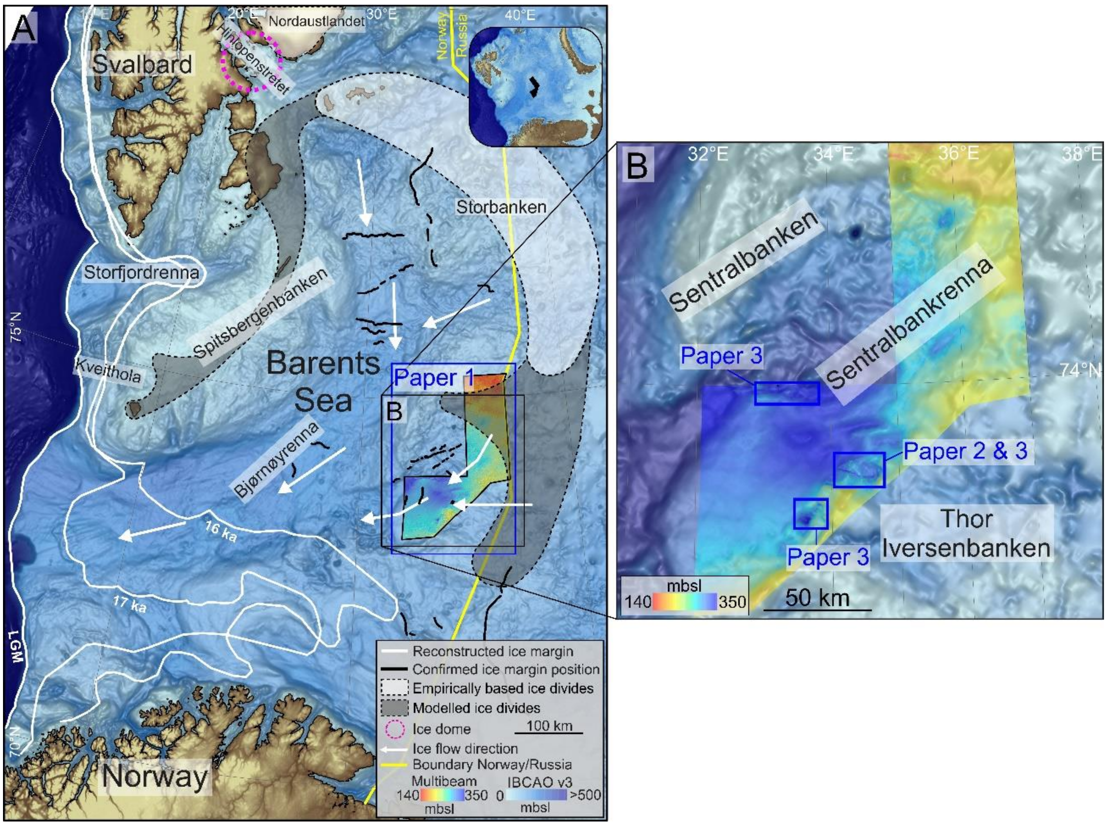

Figure 1. Map of the Barents Sea with the study areas for each of the papers included in this doctoral thesis. **A)** Location of paper 1 (c.f. *section 3.1.*) in the central Barents Sea and also several hypothesised ice margin extents (Svendsen et al., 2004; Winsborrow et al., 2010; Hughes et al., 2015), confirmed ice margin positions (Rüther et al., 2012; Andreassen et al., 2014; Bjarnadóttir et al., 2014), and ice dome and ice divide positions (Bondevik et al., 1995; Ottesen et al., 2005, Patton et al., 2015; Dowdeswell et al., 2010). **B)** Location of the study areas for paper 2 (c.f. *section 3.2.)* and paper 3 (c.f. *section 3.3.*). Background bathymetry is from the International Bathymetric Chart of the Arctic Ocean (IBAO) version 3.0 (Jakobsson et al., 2012). Multibeam bathymetry: © Kartverket.

1.2.Background

1.2.1. Geological/oceanographic setting

The Barents Sea is a large epi-continental sea characterised by relatively shallow banks (100-200 mbsl) and large, deeper troughs (300-500 mbsl). The geology subcropping the unlithified sediments within and surrounding the study areas (fig. 1 B; c.f. *section 1.3.)* in Sentralbankrenna and northwestern Thor Iversenbanken are predominantly early Cretaceous sedimentary bedrocks with some smaller sections of late Jurassic-early Cretaceous bedrock (Sigmond, 1992). The Quaternary sediments in the Barents Sea, overlying the Mesozoic and early Cenozoic bedrock are generally quite thin (<10-15 m) due to extensive erosion over multiple glaciations (c.f. *section 1.2.2.*). Furthermore, the preservation of Holocene sediments is also limited in the Barents Sea, due to high bottom water current velocities (Loeng, 1983) and low accumulation rates of 2-5 cm/ka (Elverhøi et al., 1989; Vorren et al., 1989).

The Arctic Polar Front crosses the Barents Sea between 74°-75° N and it is the intersection between warmer, saline North Atlantic waters and the cooler, low-salinity Arctic waters (Loeng, 1991; Pfirman et al., 2013). In the central Barents Sea the Arctic Polar Front follows the 200 m water depth contour and experiences high bottom water current velocities, which can reach up to 25-30 cm/s at water depths of 270 m (Loeng, 1983). This, in combination with tidal and storm activity, promotes the erosion and winnowing of sediments on shallow banks such as Spitsbergenbanken (Elverhøi et al., 1989) and most likely Sentralbanken and Thor Iversenbanken.

1.2.2. Glaciological setting

The Barents Sea experienced multiple glaciations throughout the Cenozoic (Elverhøi and Solheim, 1983; Vorren et al., 1988; Vorren and Laberg, 1997), with the most recent glaciation taking place in the Late Weichselian when the BSIS extended to the continental shelf break (Landvik et al., 1998; Svendsen et al., 1999, 2004). The BSIS was a dynamic multi-domed ice sheet with several active ice streams draining it during the LGM, the largest of which was the Bjørnøyrenna Ice Stream, which had a catchment area in excess of 350,000 km^2 (Winsborrow et al., 2010; Andreassen et al., 2014; Bjarnadóttir et al., 2014), and numerous tributaries including the Sentralbankrenna Ice Stream (c.f. *section 3.1.*). The ice streams occupying the Barents Sea cross-shelf troughs transported large quantities of ice and sediment from the interior of the ice sheet to the ice margins, depositing extensive trough mouth fans on the continental slope composed of glacigenic debris flow deposits (Laberg and Vorren, 1995; Dowdeswell et al., 1996; Kleiber et al., 2000; Andreassen et al., 2004).

Numerous empirical and modelling studies have focused on reconstructing the BSIS glaciodynamics and ice margin extents, particularly along its western margin. These reveal a general pattern of intermittent periods of rapid ice break up and margin stability during overall retreat from its maximum shelf-edge extent (e.g. Bondevik et al., 1995; Svendsen et al., 2004; Ottesen et al., 2005; Andreassen et al., 2008; Dowdeswell et al., 2010; Winsborrow et al., 2010; Rüther et al., 2012; Andreassen et al., 2014; Bjarnadóttir et al., 2014; Patton et al., 2015). However, chronological constraints on deglaciation remain poor due a scarcity of dateable material. Available dates indicate that the Bjørnøyrenna Ice Stream retreated from the southwestern Barents Sea shelf edge by 17.1 cal. ka BP (Rüther et al., 2011) and that deglaciation occurred in the central Barents Sea between 16-14 cal. ka BP (Salvigsen, 1981; Winsborrow et al., 2010; Hughes et al., 2015), with the mouth of Sentralbankrenna experiencing ice-free conditions by 13.9 cal. ka BP (Rise et al., 2016).

1.3. Study areas

All of the study areas in this thesis are located in the central Barents Sea within the Sentralbankrenna glacial system, which encompasses Sentralbankrenna and adjacent banks – Sentralbanken and Thor Iversenbanken (140-350 mbsl; fig. 1). Paper 1 (fig. 1 A; c.f. *section 3.1*.) focuses on the overall large-scale glacial geomorphology within the Sentralbankrenna glacial system. Paper 2 (fig. 1 B; c.f. *section 3.2*.) focuses on the northwestern flanks of Thor Iversenbanken and combines both glacial geomorphology and sedimentological analyses. Paper 3 (fig. 1B; c.f. *section 3.3*.) zooms out to focus on three areas at the mouth of Sentralbankrenna and northwestern flank of Thor Iversenbanken, compiling previously published data with new glacial geomorphological mapping.

1.4. Aims of the study

Prior to the initiation of this PhD, few studies had been undertaken in the central Barents Sea, leaving a gap in our knowledge of the retreat patterns and dynamics of the BSIS in this area. This doctoral thesis used a multi-proxy approach (c.f. *section 2*) to extend our understanding of the Sentralbankrenna glacial system, one of the major tributaries to the Bjørnøyrenna Ice Stream during the LGM, and later a major independent ice stream significantly influencing the BSIS ice mass balance.

This doctoral thesis aimed to:

1) Better understand the processes of importance for destabilization and subsequent collapse of a marine-based ice sheet;

2) Provide an extensive reconstruction of the retreat patterns and glaciodynamics of the Sentralbankrenna glacial system;
3) Investigate the sedimentary record of palaeo-subglacial lakes on Thor Iversenbanken and develop our understanding of the subglacial hydrology and depositional environments in this area;
4) Determine the influence of glaciodynamics on the development of specific subglacial channel and lake systems.

This doctoral thesis provides comprehensive insights into the ice retreat patterns in the central Barents Sea, the character of subglacial hydrological systems in this area and glaciodynamic influences on the hydrological networks observed, as well as providing the first sedimentological study of palaeo-subglacial lakes in the Barents Sea.

2. Material and methods

2.1. Multibeam bathymetric data

The high-resolution (5 m) multibeam bathymetric data presented in this PhD thesis was provided by the MAREANO Programme (www.mareano.no), which comprises the Institute of Marine Research, the Geological Survey of Norway (NGU) and the Norwegian Mapping Authority. It covers 17,000 km^2 of the Sentralbankrenna glacial system in the central Barents Sea. The landforms were interpreted and visualized using both QPS Fledermaus and Esri ArcMap v10.1. During the mapping stage of the glacial landforms in paper 1, the horizontal resolution of the grid size was resampled to 25 m, to enable a greater focus on the mapping of larger glacial landforms. The 5 m resolution dataset was utilized in paper 3. The International Bathymetric Chart of the Arctic Ocean (IBCAO; v. 3.0.) with 500 m grid size resolution (Jakobsson et al., 2012), was used in the overview figures in the papers presented in this thesis, to give a broader overview of the bathymetric features in the surrounding areas of the Barents Sea.

2.2.Subsurface acoustic data

Several chirp lines were collected over the basins on the northwestern flanks of Thor Iversenbanken (data is presented in paper 2), during a CAGE research cruise in 2015. The aim was to collect long- and cross-profiles of the basins and channels observed in this area, and to use this data for identifying potential coring sites. The subsurface survey was undertaken on the research vessel R/V Helmer Hanssen, which used the X-STAR Full Spectrum Sonar chirp subbottom profiler, a hull mounted chirp system, operating at 4 kW with a shot rate of 1 second. The chirp data was analysed and visualized using the Kingdom software 8.8. A TOPAS profile in Sentralbankrenna was provided by the Geological Survey of Norway (NGU) and used in paper 3. This was visualized using Schlumberger Petrel E&P Software Platform 2015.

2.3. Sedimentological data

Nine sediment cores were extracted from a suite of basins on the northwestern flanks of Thor Iversenbanken during the 2015 CAGE research cruise on the R/V Helmer Hanssen. Significant planning was undertaken prior to the cruise to identify good core locations based on the glacial geomorphological mapping presented in paper 1. The final core locations were based on chirp data collected during the same cruise. There are three main basins in the study area with differing sizes, all interlinked by channels leading into and out of them. In order to get a complete overview of the depositional environments within these basins, cores were collected along a transect; from the bank, across the basin margin into the deepest part of the basins. At each location, two cores were taken (with the exception of the bank site due to a technical fault with the corer). Out of the nine cores collected, four sediment cores were stored at the Department of Geosciences, UiT, cold-storage facility Fløyahallen for future sampling and the remaining five of the sediment cores were analysed further for this thesis (table 1).

Table 1. Overview of the gravity cores used in this doctoral thesis.

Core ID	Latitude (N)	Longitude (E)	Water Depth (m)
CAGE15-5-1221-GC	73°36.590’	34°41.446’	253
CAGE15-5-1222-GC	73°37.042’	34°36.065’	310
CAGE15-5-1225-GC	73°38.048’	34°40.612’	305
CAGE15-5-1228-GC	73°38.107’	34°42.156’	291
CAGE15-5-1230-GC	73°38.918’	34°43.722’	300

2.3.1. Core collection and sampling

Five of the cores (table 1) were opened immediately onboard, in order to collect sediment samples for several analyses including measurements for biomarkers, sulphur, and chloride concentrations. These samples were frozen at -20°c and due to time constrains were not used in this thesis, however suggestions for their potential use are discussed in the future work section of this thesis (c.f. *section 5.2.2.)*. Lithostratigraphic logging and core descriptions, as well as measurements for the undrained shear strength with the fall cone test (following method proposed by Hansbo, 1957), were also undertaken shortly after core splitting.

Further sediment sampling was undertaken at the sediment laboratory at the Department of Geosciences, University of Tromsø. A total of 204 samples were taken, with two sediment samples taken at each 10 cm interval and at additional intervals of interest. The first lot of samples were wet sieved at 63, 100, and 250 µm size fractions and then scanned for foraminifera prior to having the bulk foraminifera (benthic and planktonic) picked for radiocarbon dating (c.f. *section 2.3.3*.) due to the scarcity of foraminifera present in the samples. The second lot of samples taken were used for the grain size analysis (c.f. *section 2.3.2.*).

2.3.2. Lithological analyses

The physical and geochemical properties of the five cores were measured at the Department of Geosciences, University of Tromsø. The core halves were x-rayed and the magnetic susceptibility was measured using the Geotek Multi-Sensor Core Logger (Weber et al., 1997). High-resolution photographs were taken and the cores were scanned with the Avaatech X-ray fluorescence (XRF) core scanner to measure the element ratios within the sediments. No major changes were observed in XRF or magnetic susceptibility results, therefore this data was not used in the papers presented in this thesis. These results are however included as supplementary material. Ice-rafted debris (IRD) clasts larger than 1 mm were counted from x-radiographs at 2 cm intervals (following the method proposed by Grobe, 1987).

The second lot of sediment samples taken weighed approximately 2g and were used for grain size analysis. In order to achieve a better measurement of the grain sizes, we used a chemical treatment to remove the organic matter and calcium carbonate. The procedure for this chemical treatment was the following: adding 20% HCL to the sample and leaving it for 24 hours, centrifuging it for 4 minutes at 4000 rpm and removing excess fluid, adding distilled water to the test tube and mixing it with the sediment, then repeating this process three times. Following this, 20% H_2O_2 was added and the samples were placed in a water bath at 85 °C for 2 hours, and if needed more 20% H_2O_2 was added until the organic material had been dissolved. The samples were centrifuged for a further four minutes at 4000 rpm and mixed with distilled water prior to being freeze-dried. Bulk measurements of the grain sizes fractions were then analysed using the Beckman Coulter LS 13 320 Particle Size Analyzer.

2.3.3. Radiocarbon dating

After the wet sieving of the samples into the 63, 100, and 250 µm size fractions, all of the samples from the 100 µm fraction were scanned and the bulk foraminifera picked. The majority of the samples were scarce in foraminifera, but two core depths had sufficient material for dating, in core 1221 (30-31 cm) and 1230 (10-11 cm). The results from these samples should be treated with caution as they contained very low quantities of carbon (0.13 mgC for the samples in core 1221, and 0.2 mgC for the sample in core 1230). The samples were sent to Poznań Radiocarbon laboratory, Poland, to be ^{14}C dated using accelerator mass spectrometry (AMS; table 2). The radiocarbon dates were then processed using the Calib 7.1. software (Stuiver & Reimer, 2017). The age calibration was based on the Marine13 calibration curve (Reimer et al., 2013) and a global mean marine reservoir age of ΔR=71±21 (Mangerud et al., 2006).

Table 2. Uncorrected and calibrated radiocarbon dates (mean probability; 1σ range; 2σ range)

Core name and sample depth	Material	Radiocarbon age (14C BP)	Calibrated age (cal BP)	1σ range	2σ range	Lab ID
1221 30-31 cm	Bulk foraminifera	35700±1200	39679	38559-41088	36853-41933	Poz-90724
1230 10-11 cm	Bulk foraminifera	1670±35	1165	1116-1226	1057-1256	Poz-90445

3. Summary of papers

3.1. Paper I

Mariana Esteves, Lilja R. Bjarnadóttir, Monica C.M. Winsborrow, Calvin S. Shackleton, Karin Andreassen. (2017). **Retreat patterns and dynamics of the Sentralbankrenna glacial system, central Barents Sea.** *Quaternary Science Reviews* 169, 131-147.

Using high-resolution (5 m) bathymetry data provided by the MAREANO Programme, this paper identified and investigated the glacial landforms present in the Sentralbankrenna glacial system, which includes Sentralbankrenna and parts of the adjacent banks, Sentralbanken and Thor Iversenbanken (fig. 1 A). A number of glacial landforms were observed, including grounding zone wedges, retreat ridges, mega-scale glacial lineations, iceberg ploughmarks, tunnel valleys, meltwater channels and basin-like depressions. By analyzing the observed landform assemblages, we provided new insights into the spatial and temporal variations of the ice margin, as well as the distribution of fast and slow flowing ice within the Sentralbankrenna glacial system, which included: 1) fast flowing and dynamic Sentralbankrenna Ice Stream; and 2) slower, inter-ice stream areas over the banks of Sentralbanken and Thor Iversenbanken. The observations provide the basis for a six-stage reconstruction of the ice stream retreat through deglaciation since the LGM, highlighting a rapid but spatially variable pattern of retreat, which may have been significantly influenced by the presence of abundant meltwater. This study provides detailed insights into the behavior and dynamics of the BSIS in the central Barents Sea throughout the last deglaciation.

Author contributions:

LRB provided access to the bathymetric dataset. ME identified, mapped, described and interpreted all landforms this study, with assistance from CSS on the mapping and interpretation over Thor Iversenbanken. All co-authors were involved in discussions regarding the landform interpretation and structure of the manuscript. ME was responsible for the writing and making all figures in the manuscript, while all co-authors contributed actively throughout the writing and editing of the paper.

3.2. Paper II

Mariana Esteves, Denise C. Rüther, Monica C. M. Winsborrow, Stephen J. Livingstone, Karin Andreassen (in review). **An interconnected palaeo-subglacial lake system in the central Barents Sea.** *Boreas*

Five sediment gravity cores were examined to investigate an extensive subglacial hydrological system, comprising of three palaeo-subglacial lake basins interconnected by meltwater channels, on the northwestern flank of Thor Iversenbanken (fig. 1 B). The sediment cores underwent several sedimentological analyses, with the aim to identify a subglacial hydrological signal in the sediment record, representing the first sedimentological study of palaeo-subglacial lakes in the Barents Sea. The sediment records, in combination with glacial geomorphological observations, show clear indications for the presence of meltwater and differing levels of hydrological activity within these former palaeo-subglacial lakes. The hydrologically active subglacial lakes are characterized by winnowed till associated with increased meltwater during drainage events. Whereas the less hydrologically active subglacial lakes are characterized by the preservation and deposition of relatively homogeneous, massive diamict associated to the rain-out of sediment from basal ice. Two successions of Bouma units were also observed in all of the basin sediment records, consistent with irregular flushing of meltwater. These palaeo-subglacial lakes were likely to have been relatively shallow (<20 m), transient and hydrologically dynamic features within the subglacial hydrological system on Thor Iversenbanken, significantly influencing the ice flow velocities of the Sentralbankrenna Ice Stream.

Author contributions:

KA was the scientific leader of the CAGE research cruise to the study area. ME was in charge of selecting core extraction sites, undertaking core collection and all of the sedimentological data analyses. The interpretation of the results was undertaken by ME with several discussions with all other coauthors and in particular DR. ME was responsible for the writing and making all figures in the manuscript, while all co-authors contributed actively throughout the writing and editing of the paper.

3.3. Paper III

Mariana Esteves, Monica C. M. Winsborrow, Calvin S. Shackleton, Lilja R. Bjarnadóttir, Karin Andreassen (In Prep). **The influence of ice dynamics on subglacial meltwater systems: an example from the central Barents Sea.**

This paper focuses on three subglacial hydrological systems in the central Barents Sea (fig. 1 B). We combine results from previous studies (including some from papers 1 and 2) with new glacial geomorphological mapping that used the high-resolution MAREANO bathymetric dataset and a TOPAS subsurface profile. The three hydrological systems are located within close proximity of each other yet display highly distinct hydrological configurations, highlighting the importance of local ice dynamics on the production, routing and storage of subglacial drainage. Area 1 was located beneath the central trunk of the Sentralbankrenna palaeo-Ice Stream, and is characterized by anastomosing networks of tunnel valleys interlinking basins. Area 2, also located beneath the palaeo-ice stream but on top of the grounding zone wedge and near the ice stream lateral shear margin, is characterized by an apparently poor developed meltwater network of unconnected channels and a deep basin. Area 3, was located beneath the bank ice over Thor Iversenbanken near the ice stream shear margin, and is characterized by a dendritic tunnel valley system with three interconnected basins. The description of these three contrasting hydrological networks contributes to the known record of palaeo-ice sheet hydrological configurations and their associated glaciodynamic settings. It further demonstrates that a high-diversity of subglacial hydrological systems can be present within relatively small spatial scales, highlighting that caution should be taken with simplifying the local meltwater dynamics in areas with large glaciodynamic variations.

Author contributions:

ME identified, mapped, described and interpreted all landforms this study, with assistance from CSS with the mapping and interpretation. All co-authors were involved in several discussions regarding the landform interpretations and structure of the manuscript. ME was responsible for the writing and making the figures in the manuscript, while all co-authors contributed actively throughout the writing and editing of the paper.

4. Synthesis

4.1. Reconstructing ice stream retreat patterns and dynamics

Paper 1 focuses on reconstructing the retreat patterns of the Sentralbankrenna glacial system through the mapping and interpretation of glacial landform assemblages. The geomorphic imprints within the trough and on the adjacent banks differ, indicating that there were different glaciodynamic processes occurring in the overlying ice. In this section, we will discuss the importance of ice streams, the mechanisms of ice stream retreat, and their associated landforms and discuss what we observed in the Sentralbankrenna glacial system.

Ice streams are highly dynamic, fast flowing corridors of ice that transport large amounts of ice and sediment from the interior of an ice sheet to the margins (Bamber et al., 2000), significantly influencing the ice sheets stability and mass balance (Bennett, 2003; Bell, 2008). Observations have shown that ice streams can experience considerable spatial and temporal variability at short (sub-decadal) time scales, through lateral migration, acceleration and thinning, deceleration and stagnation, and the switching on and off of fast flow (e.g. Anandakrishnan and Alley, 1997; Conway et al., 2002; Joughin et al., 2004; Bindschadler, 2006; Rignot, 2008; Rignot et al., 2011). Ice streams are vulnerable to climatic and oceanic changes, and increases in ocean temperatures promotes enhanced ice mass loss, through increased calving and melting at the grounding zone (where grounded ice loses contact with the bed). This can lead to the acceleration of ice streams and the potential destabilisation of an ice sheet (Oppenheimer, 1998; Rignot et al., 2004; Bindschadler, 2006).

It is therefore important to understand the driving forces that influence spatial and temporal variability in these systems. However, investigating the beds of contemporary ice streams is difficult and often relies on indirect geophysical and remote sensing approaches. It has long been recognised that ice streams leave a series of diagnostic geomorphic and sedimentological signatures as they retreat (e.g. Stokes and Clark, 1999; Dowdeswell et al., 2008; Ó Cofaigh et al., 2008) and so, an alternative method to the study of these intriguing and complex systems is through the study of their remnants and imprints on palaeo-ice stream beds.

By investigating the glacial landform assemblages on palaeo-ice stream beds, the style and dynamics of ice retreat from an area can be determined (fig. 2; Dowdeswell et al., 2008). Mega-scale glacial lineations (MSGL) have been observed to form at the base of active ice streams (King et al., 2009) and their geomorphic imprint has been widely observed in the geological record (e.g. Stokes and Clark, 1999; Andreassen et al., 2004; Wellner et al., 2006; Graham et al., 2009; Andreassen et al., 2014). They are elongated parallel sets of ridge-grove features, with elongation ratios >10:1 formed in soft, deformation till beneath streaming ice. If MSGLs are observed in the geological record without any modification or imprinting of other ice marginal deposits then we can infer that the ice stream retreated rapidly (Dowdeswell et al., 2008). However, MSGLs superimposed by ice marginal features can indicate two types of retreat dynamics: episodic or slow (fig. 2).

Dowdeswell et al. (2008) propose that the presence of grounding zone wedges (GZW) overprinting MSGLs are indicative of episodic retreat, characterised by rapid ice stream breakup between longer marginal stillstands (fig. 2). This is the type of retreat that we observed in Sentralbankrenna, and in paper 1 we describe a six stage retreat pattern through the trough, highlighting the episodic retreat of the margin characterised by periods of rapid ice breakup punctuated by margin stillstands or short readvances. We based this interpretation on the presence of six large GZW, both over-printing and overprinted by MSGLs. GZW have been observed widely on high-latitude palaeo-ice stream beds (e.g. Mosola and Anderson, 2006; Ó Cofaigh et al., 2008; Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015) and are characterised by their clear, wedge-like asymmetric morphology. They are typically formed at the grounding zone of fast-flowing ice streams through the rapid deposition and deformation of subglacial sediment at the ice margin, as well as through the redistribution of marginal sediments by gravity flow processes (Powell and Alley, 1997; Dowdeswell and Fugelli, 2012).

In paper 1 we observed differences between the morphologies of the GZW: some had clear downstream extents, while others were comprised of several radially shaped fans, indicating that the ice streams experienced differing ice dynamics at their margin. In addition to this, we also proposed the possibility that subglacial meltwater played a significant role during the deposition of the GZW, influencing the stability of the ice margin. This interpretation was based on the presence of several channels breaching the GZW and the radially shaped fans of differing spatial scales indicating deposition through ice margin meltwater plumes formed as meltwater exits subglacial drainage outlets, and sub-aqueous debris flows.

We also observed narrower, symmetrical ridges on the bank areas, interpreted to be recessional moraines and retreat ridges. Dowdeswell et al. (2008) proposed that the presence of these landforms at the beds of former ice streams indicate slower margin retreat (fig. 2). These landforms have been widely observed at the bed of ice streams and inter-ice stream areas and are suggested to typically form at the margin of tidewater ice cliffs through a combination of processes, including squeeze-push from the ice margin and deformation of the sediment (Powell, 1981; Powell and Domack, 1995; Kirkbride and Warren, 1997; Powell and Alley, 1997; Dowdeswell et al., 2008). We differentiated the recessional moraines and retreat ridges based on their size, however both are indicative of an ice margin stabilization and short stillstand during overall retreat.

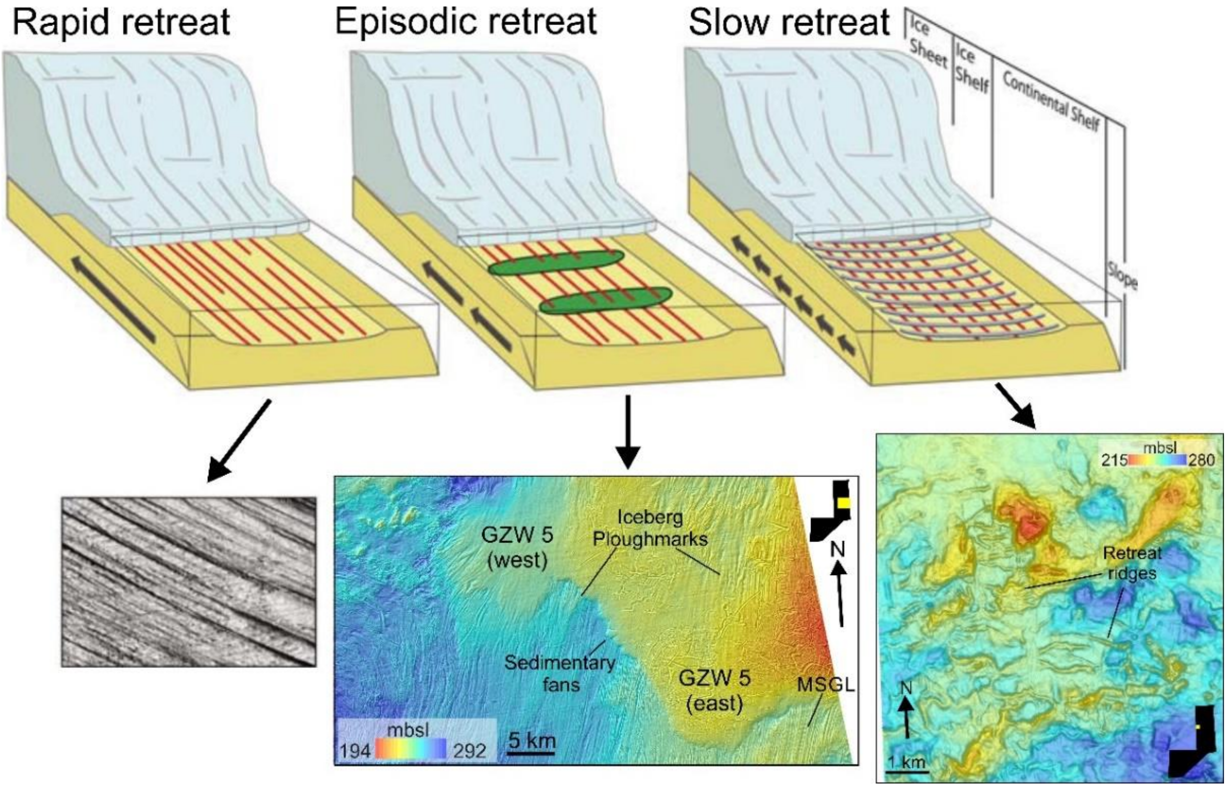

Figure 2. Schematic modified from Dowdeswell et al. (2008) showing the submarine landform assemblages for the different styles of ice stream retreat across high-latitude continental shelves. Examples for each style of retreat are presented. Example for rapid retreat is from Dowdeswell et al. (2008). Examples for episodic retreat (Sentralbankrenna) and slow retreat (Sentralbanken) have been modified from Esteves et al. (2017; paper 1). GZW – Grounding Zone Wedge; MSGL – Mega-scale glacial lineation.

4.2. Ice sheet subglacial hydrology

Subglacial hydrology has been observed to directly influence the overlying ice dynamics and behavior of an ice sheet (Bell, 2008; Stearns et al., 2008), primarily through its influence on basal frictional resistance and subglacial sediment strength (Alley et al., 1986; Engelhardt and

Kamb, 1997; Tulaczyk et al., 2002). Variations in the production and routing of melt at the bed influences flow velocities of overlying ice, promoting acceleration of the ice due to increased water pressures, sediment deformation and therefore basal traction (Kamb, 1987; Zwally et al., 2002; Pattyn, 2008; Vaughan et al., 2013), and whilst triggering deceleration of ice due to water piracy, refreezing and stiffening of the bed, and channelization of drainage configurations leading to increased effective pressure (e.g. Röthlisberger, 1972; Alley et al., 1994; Bougamont et al., 2003; Bartholomew et al., 2010; Andrews et al., 2014). The principal modes of subglacial drainage are hypothesized to include: 1) thin films of water at the ice bed (Weertman, 1972; Alley et al., 1989); 2) water saturated porous till layers (Alley et al., 1986; Blankenship et al., 1986); 3) distributed cavity systems (Lliboutry, 1968; Kamb, 1987); 4) R-channels incised upward into basal ice (Röthlisberger, 1972; Boulton et al., 2009); and 5) N-channels incised into the ice bed (Nye, 1976; Walder and Fowler, 1994; Ng, 2000; Carlson et al., 2007).

The distribution and drainage routing of meltwater at the bed can undergo rapid changes, triggering significant variations in basal traction, and impacting on ice sheet dynamics and mass balance. It is therefore crucial to understand the behaviour and mechanisms occurring within subglacial hydrological systems. The beds of contemporary ice sheets/streams are often inaccessible or difficult to reach, and investigations into the subglacial hydrology of an ice sheet make use of indirect methods such as radio-echo sounding, satellite altimetry and numerical modelling to analyse the controls on and impacts of subglacial hydrology (e.g. Robin et al., 1970; Pattyn, 2008; Smith et al., 2009; Thoma et al., 2010; Wright and Siegert, 2012; Palmer et al., 2013; Vaughan et al., 2013; Flowers, 2015). Changes in ice velocities and surface elevations have been observed in connection with the activity of extensive subglacial drainage networks comprised of channels and subglacial lakes beneath the present-day ice sheets (Kapitsa et al., 1996; Siegert, 2005; Wingham et al., 2006; Fricker et al., 2007; Stearns et al., 2008; Smith, 2009; Wright and Siegert, 2012).

An alternative method to investigate these systems is by investigating evidence of palaeo-subglacial hydrology in the geological record. Such approaches offer the potential to study drainage systems in fine resolution and across broad spatial areas, and have revealed extensive networks of channels and palaeo-subglacial lakes incised into the former beds of palaeo-ice sheets (e.g. Munro-Stasiuk, 2003; Christoffersen et al., 2008; Kehew et al., 2012; Nitsche et al., 2013; Livingstone and Clark, 2016; Livingstone et al., 2016; Bjarnadóttir et al., 2017; Kuhn et al., 2017; Simkins et al., 2017). In the Barents Sea, empirically based studies, have revealed extensive evidence for hydrological systems comprised of channels and basins beneath the former BSIS (e.g. Bjarnadóttir et al., 2012, 2017; paper 1, 2 and 3) and the potential for subglacial lakes and water routing has been investigated through modelling (Gudlaugsson et al., 2017; Patton et al., 2017).

This doctoral thesis contributes to our understanding of subglacial hydrology of the BSIS, yielding new insights into meltwater production, routing and storage and the overall organisation of hydraulic systems. During investigations for paper 1, networks of tunnel valleys interconnecting basins interpreted to have hosted palaeo-subglacial lakes were observed in Sentralbankrenna and on the northwestern flank of Thor Iversenbanken. Paper 2 used this mapping in combination with sediment records from the basins on Thor Iversenbanken to identify the first palaeo-subglacial lake system in the Barents Sea. The networks observed in paper 1 displayed distinct drainage system organisations and so, paper 3 used higher resolution investigations of three main channel and basin networks to identify the potential influence of overlying ice dynamics on the formation of the distinct meltwater systems.

The tunnel valleys that we observed in Sentralbankrenna and Thor Iversenbanken are deep, pronounced features incised onto the seafloor to varying widths and depths. Tunnel valleys have undulating long profiles and are suggested to form erosionally by subglacial meltwater at the base of the ice sheet (e.g. Ó Cofaigh, 1996; Kehew et al., 2012; Greenwood et al., 2016). In this area, we suggest that the observed tunnel valleys formed through a combination of steady drainage and outburst floods from the upstream subglacial lakes (Bjarnadóttir et al., 2012, 2017; paper 1). The tunnel valleys have different spatial distributions and drainage organisations, with anastomosing, dendritic and unconnected networks depending on their location within the glacial system (paper 3). These tunnel valleys connect several basins, interpreted to have hosted palaeo-subglacial lakes and are discussed in the following section.

4.3. Investigating subglacial lakes

Subglacial lakes are important components of the subglacial hydrological system of an ice sheet, with the potential to store large volumes of meltwater, which can drain over periods of months to years (Gray et al., 2005; Wingham et al., 2006; Siegfried and Fricker, 2018). These drainage events promote transient downstream ice velocity accelerations (Stearns et al., 2008) and thus, influencing ice sheet stability and mass balance (Bell, 2008). Subglacial lakes were first identified in Antarctica using airborne radio-echo sounding (Robin et al., 1970; Oswald and Robin, 1973) and now over 380 subglacial lakes have been observed in Antarctica (e.g.

Wright and Siegert, 2012) and several more beneath the Greenland Ice Sheet (e.g. Palmer et al., 2013). Subglacial lakes have been commonly observed to be located both close to ice divides, at the heads of ice streams and close to the grounding line, and they can range from deep, stable features, to shallow, highly transient features (Wright and Siegert, 2012). Limited access to present day subglacial lakes due to technical and logistical challenges means that, with the exception of access to the accreted ice layers in Lake Vostok (Karl et al., 1999) and the ice marginal subglacial Lake Whillans (Christner et al., 2014; Tulaczyk et al., 2014; Hodson et al., 2016), investigations into these systems has largely relied on geophysical approaches.

An alternative method for studying these complex and intriguing systems is to investigate the geological record for palaeo-subglacial lakes and their associated channel systems at the bed of former ice sheets (e.g. Munro-Stasiuk, 2003; Christoffersen et al., 2008; Livingstone et al., 2016; Bjarnadóttir et al., 2017; Esteves et al., 2017; in review; Kuhn et al., 2017; Simkins et al., 2017). These study sites are often much more logistically accessible and offer a comprehensive view of the surrounding geology and topography, as well as a greater spatial and temporal perspective on the overall subglacial hydrological characteristics. For this reason, the palaeo-subglacial lakes observed in central Barents Sea offer a unique opportunity to study these complex and intriguing systems at the bed of a former marine-based ice sheet. Paper 2 investigated three basins interconnected by meltwater channels that form part of a larger dendritic tunnel valley network on the northwestern flank of Thor Iversenbanken (c.f. *section 3.2.*), using a combination of geomorphological and sedimentological approaches. The results from this study highlighted the hydrologically dynamic and transient nature of these relatively shallow palaeo-subglacial lakes.

Identifying palaeo-subglacial lakes in the geological record does however present some challenges, due to uncertainties relating their geomorphological and sedimentological expressions, particularly since our understanding of these environments is largely theoretical or from indirect geophysical data. Diagnostic criteria have been proposed by Bentley et al. (2011) and Livingstone et al. (2012), highlighting the dominant sedimentological processes likely to occur in a subglacial lake, such as the reorganisation and deposition of sediments from the melt-out from basal ice, turbidity flows, and suspension settling. Several studies combining geophysical, geomorphological and sedimentological data, have observed distinctive characteristics of palaeo-subglacial lakes in the geological record. These includes the presence of flat spots or basins connected by meltwater channels incised into the bed (Livingstone et al., 2016; Simkins et al., 2017; Kuhn et al., 2017), just as we observed in the Sentralbankrenna glacial system (c.f. *section 3.2.*), as well as the presence of low-chloride pore water concentrations in a structureless silty clay sediment unit interpreted to have been deposited in an enclosed, lacustrine, low-energy environment (Kuhn et al., 2017).

5. Concluding remarks and recommendations for future work

5.1. Concluding remarks

The Barents Sea is an ideal study site for palaeo-glaciological investigations of the processes and mechanisms occurring at the beds of marine-based ice sheet. Data from this region provides valuable insights into the spatial and temporal fluctuations in glaciodynamics occurring during the last deglaciation. Prior to the work presented in this thesis relatively few palaeo-glaciological studies had been undertaken in the central Barents Sea, and so little was known of the palaeo-ice streams and subglacial drainage networks in this region. This PhD thesis provides a comprehensive analysis of the glacidynamics, retreat patterns and subglacial hydrology in the Sentralbankrenna glacial system in the central Barents Sea.

The key findings of this project are as follows:

1) First comprehensive reconstruction of the retreat patterns and dynamics of the Sentralbankrenna glacial system using glacial geomorphology and landform assemblages (paper 1);
2) The Sentralbankrenna Ice Stream underwent episodic retreat, with periods of rapid ice break-up punctuated by margin stillstands (paper 1);
3) The first combined geomorphological and sedimentological evidence for palaeo-subglacial lakes in the Barents Sea (paper 2);
4) Identification of a sedimentological signature for hydrologically active palaeo-subglacial lakes (paper 2);
5) Local variations in glaciodynamics caused significant differences in subglacial hydrological systems and their channel/basin organisations in the central Barents Sea, despite being located within close proximity of each other (paper 3).

5.2. Future work

While the papers in this doctoral thesis provide a better understanding of the retreat patterns and dynamics of the Sentralbankrenna glacial system, as well as the subglacial hydrology of the BSIS, further work investigating these complex and intriguing systems through geophysical and sedimentological would be extremely fruitful. In this section, recommendations for both geophysical and sedimentological investigations are made, which would advance our knowledge of the BSIS deglaciation history and understanding of the subglacial hydrological systems within.

5.2.1. Geophysical investigations

When mapping the glacial landforms in the Sentralbankrenna glacial system there was a limited availability of subsurface profiles over the area, which meant that we could not map the full subsurface extents of the landforms nor the depths of sediment infill in the basins observed.

Undertaking seismic and chirp profiles would be beneficial here, particularly over key glacial landforms such as the grounding zone wedges in upper Sentralbankrenna and over the basins hypothesized to have hosted palaeo-subglacial lakes. This would greatly improve our understanding of the depositional environments and the size, extent and internal structures of the landforms. In addition, this would delimit basin and channel sediment infills, helping in the estimation of water capacities for subglacial lakes and tunnel valley water volume calculations.

The acquisition of a 3D seismic cube over the mega-scale glacial lineations within Sentralbankrenna would offer the potential to identify multiple generations of ice streaming as well as revealing information on the internal structure of sub-ice stream sediments.

Lastly, more extensive bathymetric mapping over key features in Sentralbankrenna glacial system. In particular, it would be beneficial to map the full downstream and upstream extents of the meltwater networks and grounding zone wedges, which have been observed to extend beyond the margins of the currently available datasets. This would significantly improve our interpretations of these systems.

5.2.2. Sedimentological investigations

The Sentralbankrenna glacial system provides a unique study site to investigate a variety of processes, including ice marginal landforms, subglacial hydrological systems and ice dynamics (ice streams and inter-ice stream areas). However, there are few chronological constraints available in this area due to limited availability of dateable material and so, it would be greatly beneficial to undertake strategic sediment coring with the aim to collect samples for radiocarbon dating to better constrain the retreat patterns of the BSIS in the central Barents Sea.

In addition to this, sediment coring of the observed basins in Sentralbankrenna suggested to have hosted palaeo-subglacial lakes would be extremely beneficial to further our understanding of the sedimentary record diagnostic for subglacial lakes. A particularly appealing target would be the large basin, with relatively thick sediment infill (~30 m) in area 2 of paper 3. This offers the potential to sample multiple generations of subglacial lake infilling. During the sediment sampling of potential palaeo-subglacial lake sediments, analyses of biomarkers, sulphur and chloride concentrations would be advantageous as it would highlight the presence of life, environmental conditions, and the ‘freshness’ of these palaeo-subglacial lakes. The use of chloride concentrations has proved useful in the discovery of new palaeo-subglacial lake in Antarctica (Kuhn et al., 2017) and can provide important clues on whether the subglacial lakes were influenced by a mix of fresh and seawater (if the subglacial lake was near an ice margin) or just by fresh meltwater, yielding insights on the possible processes occurring at the ice-bed interface during the ice sheet retreat and eventual collapse.

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Paper I

Retreat patterns and dynamics of the Sentralbankrenna glacial system, central Barents Sea.

Mariana Esteves, Lilja R. Bjarnadóttir, Monica C.M. Winsborrow,

Calvin S. Shackleton, Karin Andreassen, (2017).

Quaternary Science Reviews 169, 131-147.

Quaternary Science Reviews 169 (2017) 131–147

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Retreat patterns and dynamics of the Sentralbankrenna glacial system, central Barents Sea

Mariana Esteves [a,*], Lilja R. Bjarnadóttir [b], Monica C.M. Winsborrow [a], Calvin S. Shackleton [a], Karin Andreassen [a]

[a] CAGE - Centre for Arctic Gas Hydrate, Environment and Climate, Department of Geosciences, UiT the Arctic University of Norway, 9037 Tromsø, Norway
[b] Geological Survey of Norway (NGU), Postboks 6315 Sluppen, 7491, Trondheim, Norway

ARTICLE INFO

Article history:
Received 17 January 2017
Received in revised form
30 May 2017
Accepted 1 June 2017

Keywords:
Late quaternary
Deglaciation
Barents Sea Ice Sheet
Glacial geomorphology
Sentralbankrenna palaeo-ice stream
GZW
MSGL
Marine-based ice sheet
Ice stream reconstruction
Glacial dynamics

ABSTRACT

The Barents Sea Ice Sheet (BSIS) is a good palaeo-analogue for the present day West Antarctic Ice Sheet. Both were marine-based ice sheets, particularly vulnerable to ocean warming and sea-level rise. Understanding the BSIS ice dynamics and patterns of retreat since the Last Glacial Maximum (LGM) is useful in developing our knowledge of spatial and temporal variations during marine-based ice sheet retreat. While the western margins of the Barents Sea have been extensively studied, few studies have focused on the central regions, which hosted key ice stream tributaries and major ice domes and divides. Presenting a new high-resolution (5 m) bathymetric dataset, this glacial geomorphological study focuses on the Sentralbankrenna palaeo-glacial system in the central Barents Sea. A large number of grounding zone wedges, mega-scale glacial lineations and areas with tunnel valleys and palaeo-subglacial basins were identified. These form the basis for a six-stage reconstruction of ice stream retreat through deglaciation since the LGM. In reconstructing the retreat of the Sentralbankrenna Ice Stream, we document the rapid but highly spatially variable pattern of retreat of a marine-based ice sheet margin. The presence of several tunnel valleys and interconnected palaeo-subglacial basin systems indicates an abundance of meltwater, likely to have been stored and released through several discharge events, significantly influencing the ice stream margin dynamics. This study provides insight into the behaviour and dynamics of ice during the late stages of the BSIS deglaciation within the central Barents Sea, increasing our understanding of grounding line processes.

1. Introduction

Ice streams are important and highly dynamic components of contemporary- and palaeo-ice sheets, transporting large amounts of ice and sediment from the ice sheet interior to the margins (Bamber et al., 2000); thereby significantly influencing the stability of the ice sheet (Bennett, 2003). Insight into the processes that occur at ice margins is of vital importance for understanding ice-ocean interactions and the consequences of ocean warming (Alley et al., 2005; Bindschadler, 2006; Pritchard et al., 2009). In particular, processes occurring at the grounding zones (where grounded ice loses contact with the bed), where a large amount of mass is lost by calving and melting (Jenkins and Doake, 1991; Rignot and Jacobs, 2002). This, in conjunction with other climatic changes, can lead to acceleration of ice streams, promoting destabilisation in the interior of the ice sheet (Oppenheimer, 1998; Rignot et al., 2004; Shepherd et al., 2004; Bindschadler, 2006). Present day Antarctic and Greenland Ice Sheets are vulnerable to oceanographic and climatic changes, such as increasing surface water temperatures and atmospheric warming, particularly at their ocean margins, thus it is essential to develop our understanding of the processes and mechanisms that influence the spatial and temporal retreat of ice streams.

During the Last Glacial Maximum (LGM; 18–21 cal ka BP) a large marine-based ice sheet covered the Barents Sea, extending to the western continental shelf break (Fig. 1; Svendsen et al., 2004). The Barents Sea Ice Sheet (BSIS) is considered a good palaeo-analogue for marine-based ice sheets (Siegert et al., 2002) such as the present-day West Antarctic Ice Sheet (WAIS). They have many similarities, both are marine-based with their beds mostly below sea-level, both are overlying sedimentary bedrock, and had similar

* Corresponding author.
E-mail address: mariana.esteves@uit.no (M. Esteves).

http://dx.doi.org/10.1016/j.quascirev.2017.06.004
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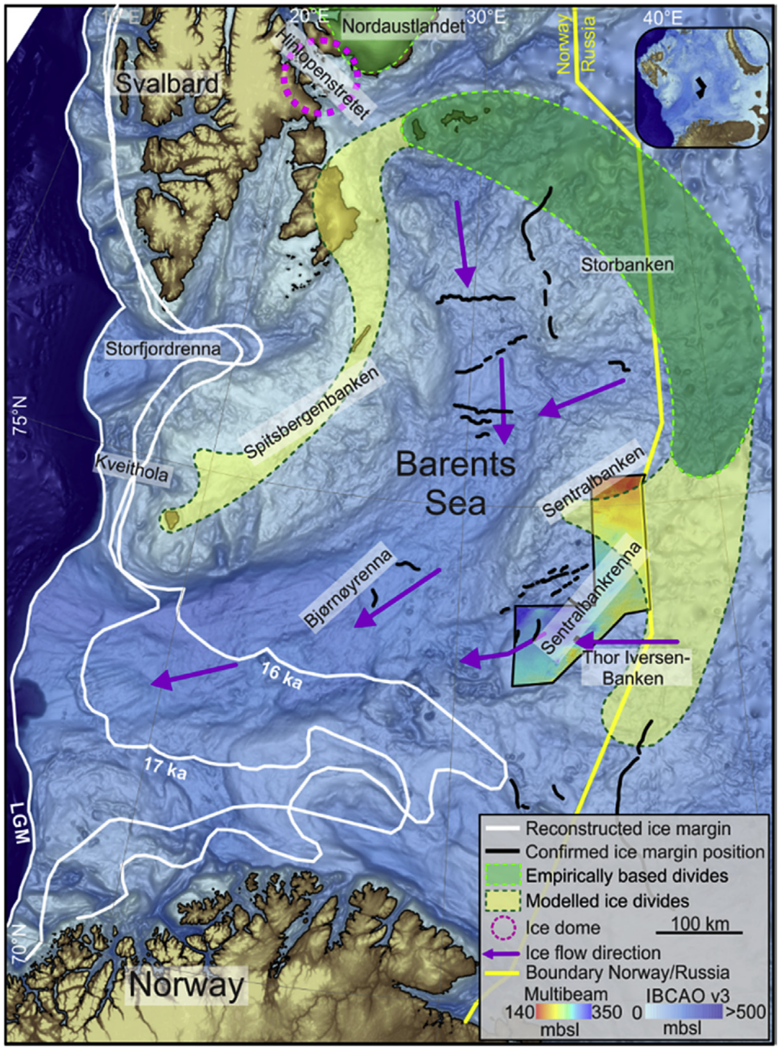

Fig. 1. Map of the Barents Sea, showing the location of the study area (multibeam bathymetry: © Kartverket), the marine border between Norway and Russia, the Last Glacial Maximum (LGM; Svendsen et al., 2004) and 17- and 16-cal ka BP ice margin extents (Winsborrow et al., 2010; extents north of Kveithola from Hughes et al., 2015), as well as the confirmed ice margin positions based on geophysical investigations (Rüther et al., 2012; Andreassen et al., 2014; Bjarnadóttir et al., 2014). The general ice flow directions are indicated by the purple arrows. The locations for the Storbanken ice divide (Bondevik et al., 1995; Ottesen et al., 2005), its speculated extent over Sentralbanken/Thor Iversenbanken/Spitsbergenbanken (Patton et al., 2015) and the Hinlopenstretet ice dome (Dowdeswell et al., 2010) are also presented. Background bathymetry is from the International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0 (Jakobsson et al., 2012a). Inset map shows the location of the study area in relation to the whole Barents Sea. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sizes and extents during the LGM (Andreassen and Winsborrow, 2009). However, unlike the WAIS, the BSIS completely deglaciated following the LGM.

Details of its deglaciation history are preserved in the glacial sediments and landforms imprinted onto the seafloor of the Barents Sea and have been extensively studied in southwest Barents Sea and parts of the Svalbard margin (Fig. 1; i.e. Vorren and Kristoffersen, 1986; Elverhøi et al., 1993; Solheim et al., 1996; Landvik et al., 1998; Dowdeswell et al., 2010; Winsborrow et al., 2010; Rüther et al., 2012; Ingólfsson and Landvik, 2013; Andreassen et al., 2014; Bjarnadóttir et al., 2014; Piasecka et al., 2016). In contrast, the central Barents Sea remains poorly studied, despite it being the site of a major ice dome and ice divides for the BSIS, as well as hosting several ice streams and their tributaries.

Ice streams leave a series of characteristic geomorphic imprints on the seafloor, which document the spatial and temporal patterns of retreat. By studying these we can gain valuable insights into the processes and mechanisms controlling ice stream behaviour (Stokes and Clark, 2001; Livingstone et al., 2012a).

Until recently, there has been a particular scarcity of bathymetric data available from the central Barents Sea due to a political Norwegian-Russian border dispute. This is in contrast to that available from the southwestern Barents Sea where several surveys have been undertaken. We present a high-resolution dataset from the central Barents Sea, immediately west of the border between Norway and Russia (Fig. 1). Focusing on the Sentralbankrenna Ice Stream and its glacial system, which encompasses the adjacent bank areas Sentralbanken and Thor Iversenbanken. The Sentralbankrenna Ice Stream was a tributary to Bjørnøyrenna during the LGM and an important area during the final stages of the central BSIS deglaciation. In this paper, we present glacial geomorphological mapping from the bed of the Sentralbankrenna palaeo-Ice Stream, which is then interpreted to determine ice flow patterns and ice dynamics during deglaciation. We document rapid, episodic ice stream retreat associated with periods of increased ice margin break up punctuated by margin stillstands or short readvances. Subglacial meltwater was abundant in this area and is suggested to have significantly influenced the overlying ice by facilitating fast flow both for the Sentralbankrenna and Bjørnøyrenna Ice Stream.

2. Glacial and regional setting/Study area

The Barents Sea is the largest epi-continental sea in the world and is characterised by relatively shallow banks (100–200 mbsl) and large, deep troughs (300–500 mbsl; Fig. 1). Investigations into the large trough mouth fans at the shelf break suggest that the Barents Sea has undergone multiple glaciations during the Cenozoic (Vorren et al., 1988; Vorren and Laberg, 1997), with the most recent having taken place in the Late Weichselian (Landvik et al., 1998; Svendsen et al., 2004). During this final glaciation, the BSIS reached the continental shelf break (Fig. 1; Svendsen et al., 1999), depositing sediments along the northern and western continental slopes forming large trough mouth fans composed of glacigenic debris flow deposits (Laberg and Vorren, 1995; Dowdeswell et al., 1996; Kleiber et al., 2000; Andreassen et al., 2004).

The BSIS was a multi-domed ice sheet, and the ice divides for the LGM and early phase of deglaciation have been extensively studied and derived based on empirical data-sets (e.g. Bondevik et al., 1995; Forman, 2004; Ottesen et al., 2005) and glacial-isostatic adjustment modelling (e.g. Lambeck, 1995, 1996; Auriac et al., 2016). These studies indicate that one of the ice domes was located over Storbanken, in the northern Barents Sea, and may have extended over Sentralbanken (Fig. 1; Bjarnadóttir et al., 2014; Patton et al., 2015; Piasecka et al., 2016). During the late phase of glaciation, the ice divide over Storbanken migrated northwest, into separate ice domes over e.g. Hinlopenstretet (Dowdeswell et al., 2010) and Nordaustlandet (Hormes et al., 2013).

During the LGM several ice streams occupied the cross shelf troughs; although not necessarily active synchronously these transported ice and sediments from the inner sectors of the BSIS to its margins (Ottesen et al., 2002; Andreassen et al., 2008; Bjarnadóttir et al., 2014; Patton et al., 2015; Vorren and Laberg, 1997). Empirical and modelling evidence suggest that during maximum glacial extent these ice streams were not topographically constrained, with the Bjørnøyrenna Ice Stream flowing straight from eastern Barents Sea where there was an ice divide located over the south east Barents Sea (Bjarnadóttir et al., 2014; Piasecka et al., 2016; Patton et al., 2016). However, throughout deglaciation the BSIS underwent several changes in flow regime, ice dynamics, and reorganisation of ice dome/divide and ice stream locations, as well as, ice stream flow switching (Polyak et al., 1995; Andreassen et al., 2008; Winsborrow et al., 2010, 2012; Bjarnadóttir et al., 2014; Patton et al., 2015). Towards the end of the deglaciation, as the ice sheet thinned, flow became more topographically controlled (Andreassen et al., 2008; Winsborrow et al., 2010, 2012; Bjarnadóttir et al., 2014; Patton et al., 2015).

The largest Barents Sea palaeo-ice stream was the Bjørnøyrenna Ice Stream, a major outlet of the BSIS with a catchment area in excess of 350,000 km^2, which occupied Bjørnøyrenna (Fig. 1; Winsborrow et al., 2010; Andreassen et al., 2014; Bjarnadóttir et al., 2014). It is likely that this ice stream had several tributaries, including the fast flowing ice coming from Sentralbankrenna, within our study area (Fig. 1; Bjarnadóttir et al., 2014). Given the area of Sentralbankrenna (>30,000 km^2), the behaviour and flow patterns of this tributary likely played a significant role in controlling ice dynamics and the flow regime of the Bjørnøyrenna Ice Stream.

The glacial imprints left by the Bjørnøyrenna Ice Stream have been extensively studied (e.g. Vorren and Laberg, 1997; Andreassen et al., 2008; Andreassen and Winsborrow, 2009; Rüther et al., 2011; Andreassen et al., 2014; Bjarnadóttir et al., 2014; Piasecka et al., 2016), and suggest dynamic ice margins and rapid, but episodic retreat patterns throughout the trough during deglaciation since the LGM. Bjarnadóttir et al. (2014) and Newton and Huuse (2017) suggest a number of former ice margin positions throughout the central Barents Sea (Fig. 1) based on ice marginal features such as grounding zone wedges and retreat ridges. Several meltwater features are also described in the central Barents Sea, including in Sentralbankrenna and Thor Iversenbanken (Bjarnadóttir et al., 2017; Newton and Huuse, 2017).

Deglaciation in the western part of the Barents Sea initiated by 17.5 cal ka BP (Rüther et al., 2011). Due to lack of data in the central Barents Sea, there are large uncertainties about the timing of full deglacial conditions over this region. Hughes et al. (2015) provide estimates (min, med, max) of ice margin extents, suggesting that the central Barents Sea became ice free sometime between 16 and 12 cal ka BP. We suggest that our study area would have been undergoing deglaciation after 16 cal ka BP, based on ice margin extents of Hughes et al. (2015) and Winsborrow et al. (2010; Fig. 1).

3. Datasets and method

The bathymetric data presented herein was provided by the MAREANO Programme (www.mareano.no). The original dataset has a horizontal resolution of 5 m, with the multibeam covering an area of approximately ~17,000 km^2 over Sentralbankrenna and the northwestern flanks of Thor Iversenbanken (Fig. 1). The horizontal grid size was decreased during the mapping stage to a resolution of 25 m to focus on the larger-scale glacial features. The bathymetric dataset was used to carry out detailed mapping of the distribution and morphology of glacial sediments and landforms on the seafloor (Fig. 2A). The landforms were mapped and visualised using Esri ArcMap v10.1 and QPS Fledermaus. The International Bathymetric Chart of the Arctic Ocean (IBCAO; version 3.0), with a grid size of 500 m, consisting of several bathymetric datasets of varying resolution (Jakobsson et al., 2012a), was used to give a broader overview of the seafloor bathymetry.

4. Results and interpretation

The key glacial landforms identified in the study area are described and interpreted below (Fig. 2A). The results are then synthesised (Fig. 2B and E), providing new insights into the spatial and temporal variations of the ice margin and the distribution of fast and slow flowing ice within the Sentralbankrenna glacial system during the final stages of BSIS deglaciation, as well as the influence of this glacial system on the wider BSIS.

4.1. Sedimentary deposits: large grounding zone features

4.1.1. Description

The most prominent, large-scale features identified in Sentralbankrenna are nine, trough-transverse sediment ridges or wedges (Fig. 2A–G; Table 1). The southernmost (farthest downstream) sedimentary deposit 1 (labelled GZW 1 in Fig. 2B) is a large and prominent wedge-shaped feature at a minimum 295 m water depth and extending across the mouth of Sentralbankrenna (Fig. 2B and C). It is visible on both the high resolution multibeam and the IBCAO data (Fig. 2A) and has a height of ~35 m relative to the seafloor downstream of the feature. Sedimentary deposit 1 has a dome-like shape and a slightly steeper ice-distal, downstream slope compared its ice-proximal, upstream slope (Fig. 2B and C; Table 1). This sedimentary deposit extends across 100 km of the trough in a NE-SW direction. It has a width of ~35 km, at the widest point visible in the multibeam dataset; however, measurements taken using IBCAO suggest that it extends beyond this high resolution dataset, having a width of ~60 km. Bjarnadóttir et al. (2014) discuss multibeam and subsurface data from this area and conclude

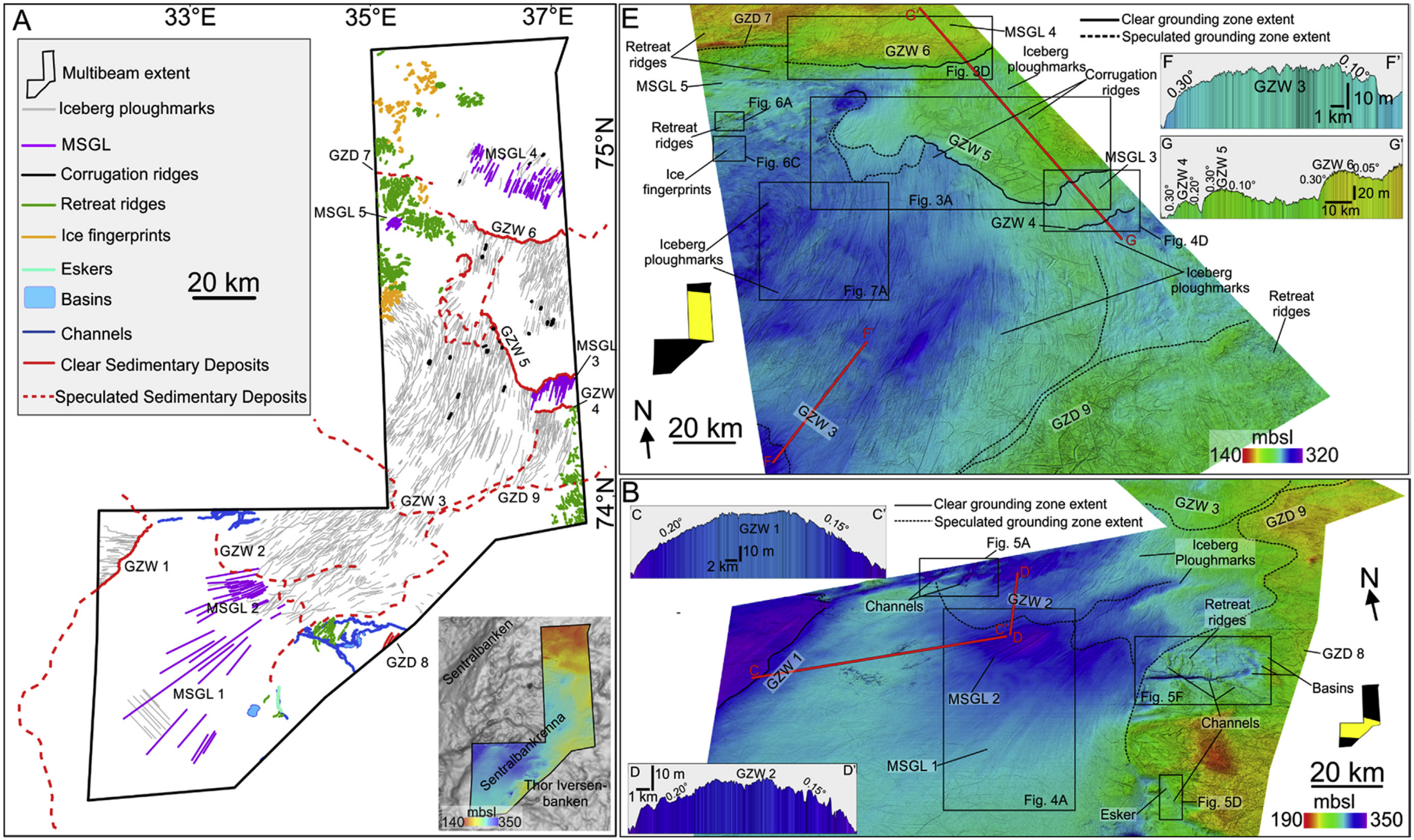

Fig. 2. Geomorphology of the Sentralbankrenna glacial system. A – Mapped glacial landforms within the study area. B – Overview of the glacial landforms in the southern part of Sentralbankrenna within the multibeam data set (GZW – Grounding Zone Wedge; GZD – Grounding Zone Deposit; MSGL – Mega-Scale Glacial Lineation). C – Cross profile of GZW 1. D – Cross profile of GZW 2. E – Overview of the glacial landforms in the northern part of Sentralbankrenna. F – Cross profile of GZW 3. G – Cross profile over GZW 4, 5 and 6. Multibeam bathymetry: © Kartverket.

Table 1
Overview and comparison of grounding zone deposits. C.f. section 4.1 and 4.2 for further details and interpretations. Height is in relation to seafloor downstream of feature. Length relates to that visible in the high-resolution bathymetry dataset as well as IBCAO bathymetry.

Descriptive name (c.f. section 4.1)	Location and orientation	Water depth (mbsl)	Height (m)	Width (km)	Length (km)	Distal/ Proximal slope (°)	Key characteristics	Interpretation	Described in:	Present in figures:
Grounding Zone Deposit 1 (GZW 1)	Sentralbankrenna NE-SW	295	~35	~35–60	~100	0.20/0.15	• Dome-like shape (slightly asymmetric) • Four generations of GZW (Bjarnadóttir et al., 2014) • Overprinted by MSGL 1 and 2 in proximal slope • Breached by tunnel valley in its northern extent (Bjarnadóttir et al., 2017)	Grounding Zone Wedge	Bjarnadóttir et al. (2014) Newton and Huuse, 2017 This study	Fig. 2A - C
Grounding Zone Deposit 2 (GZW 2)	Sentralbankrenna NW-SE	305	~10	~15	~45	0.20–0.79/ 0.15	• Dome-like shape (slightly asymmetric) • Subdued feature due to heavily scoured surface • Breached by tunnel valley in its northern extent Bjarnadóttir et al. (2017)	Grounding Zone Wedge	Bjarnadóttir et al. (2014) This study	Fig. 2 A, B and D
Grounding Zone Deposit 3 (GZW 3)	Sentralbankrenna NE-SW	265	~26	~15	~80	0.30/0.10	• Asymmetrical shape; steeper ice distal slope • Heavily scoured surface; overprinting and overprinted by iceberg ploughmarks • Uncertain extent (too dense scouring)	Grounding Zone Wedge	Bjarnadóttir et al. (2014) This study	Fig. 2 A, B, E and F
Grounding Zone Deposit 4 (GZW 4)	Sentralbankrenna W-E	235	~30	~10	~14	0.30/0.20	• Asymmetric shape • Overprinting many iceberg ploughmarks • Overprinted by MSGL 3	Grounding Zone Wedge	This study	Figs. 2 A, E, G and 4 D
Grounding Zone Deposit 5 (GZW 5)	Sentralbankrenna NW-SE	215 (East) 250 (West)	~31 (East) ~10 (West)	~30 (East) ~20 (West)	~35	0.30/0.10 (East) 0.20/ 0.10(West)	• Not a fully developed GZW, composed of several ice-proximal fans, particularly in the mid-sections and in the western side Eastern side: • Asymmetrical wedge-like shape • Overprinting MSGL 3 • Several high and prominent sedimentary fans where the feature extends west Western side: • Located in deeper part of trough • Radial fan-like deposit • Break in slope indicates a composite feature of two large fan-deposits • Steep ice distal side • Heavily overprinting and overprinted by iceberg ploughmarks	Intermediate Grounding Zone Wedge	Eastern part of GZW 5 described in Newton and Huuse, 2017 This study	Figs. 2 A, E, G and 3 A - C
Grounding Zone Deposit 6 (GZW 6)	Sentralbankrenna ESE-WNW	190	~60	~15	~37		• Well preserved • Prominent asymmetrical wedge-shaped feature • Overprinted by MSGL 4 • Overprinting several large iceberg ploughmarks downstream of the GZW • Several lobate features along its margin • Western extent subdued due to overprinting by other features	Grounding Zone Wedge	Newton and Huuse, 2017 This study	Figs. 2 A, E, G, and 3 D - E
Grounding Zone Deposit 7 (GZD 7)	Sentralbankrenna W-E	160	~50	~4	~20	1.50/0.75	• Less prominent asymmetrical shape • Narrow feature in comparison to GZW 1-6 • Several retreat ridges up and downstream of this moraine	Recessional Moraine	This study	Fig. 2 A and E
Grounding Zone Deposit 8 (GZD 8)	Located on Thor Iversenbanken NE-SW	240	~3-11	~200 –340 m	~2–5	1.90/1.20	• Similar morphology to GZD 7 • Composed of three closely spaced symmetrical sedimentary deposits	Recessional Moraine	Bjarnadóttir et al. (2014) This study	Fig. 2 A and B
Grounding Zone Deposit 9 (GZD 9)	Located on Thor Iversenbanken NE-SW	220	~25	~8	~45	0.30/0.15	• Subdued feature due to being heavily scoured by iceberg ploughmarks • Morphology is clearer in the northern-most part of Thor Iversenbanken • Uncertain extent and unclear shape	Grounding Zone Deposit	Bjarnadóttir et al. (2014) This study	Fig. 2 A, B and E

that this deposit is a composite landform, consisting of at least four generations of grounding zone wedges, which have an acoustically transparent internal structure. Overprinting the ice proximal side of sedimentary deposit 1, are several large elongated linear features (previously described and interpreted in Bjarnadóttir et al., 2014; cf. section 4.2.; Fig. 2A and B). At its northern extent there is a deep erosional channel that cuts through the sedimentary wedge (cf. section 4.3; Fig. 2A and B).

Sedimentary deposit 2 (Fig. 2B; GZW 2) joins the first sedimentary deposit on its west but is orientated in a more NW-SE direction and is not as large as sedimentary deposit 1. Deposit 2 is less prominent in the bathymetric dataset, mainly due to a heavily scoured surface. With its crest at a slightly deeper water depth (~305 m) than GZW 1, it extends for ~45 km. It has a slightly asymmetric wedge-like shape, with an ice distal slope of ~0.20° that is ~10 m high from the level of the seafloor, downstream of the wedge. At its widest part, sedimentary deposit 2 is at least ~15 km (Fig. 2D). It lies directly upstream from the deep elongated linear features overprinting the eastern side of grounding zone deposit 1 (previously described and interpreted in Bjarnadóttir et al., 2014; cf. section 4.2.; Fig. 2A; GZW 1). In its western part several deep channel-like features appear to have cut through the upstream part of the deposit (cf. section 4.3), giving this part of the deposit a steeper ice proximal slope, in contrast to the rest of sedimentary deposit 2 (Table 1).

Sedimentary deposit 3 (Fig. 2B and E; GZW 3) is located in mid-Sentralbankrenna at a minimum water depth of ~265 m and, similar to sedimentary deposit 2, has a slightly asymmetrical wedge-like profile, with a steeper downstream, ice distal slope (Table 1). The surface of the deposit is heavily grooved, having both been overprinted by and overprinting many curvilinear furrows. The extent of the full deposit is unclear due to this heavy scouring, however, it seems that it extends for at least ~80 km, with a NW-SE orientation in its western, more prominent part, and more NE-SW orientation in its eastern part, which extends towards sedimentary deposit 4. It is ~26 m high and up to ~15 km wide.

Adjacent to the eastern-most part of sedimentary deposit 3, is the much smaller yet pronounced sedimentary deposit 4, which is located at a water depth of ~235 m (Fig. 2E; GZW 4). It is ~14 km long with a height of ~30 m in relation to the seafloor downstream (Fig. 2G; Table 1). This deposit has a W-E orientation and a large quantity of furrows overprint and possibly have reworked its western side and thus, maybe concealing its full extent (Fig. 2E). Moreover, it has been heavily overprinted by large elongated parallel linear features on the ice proximal side (Fig. 2E; cf. section 4.2).

Sedimentary deposit 5 is located on the eastern part of Sentralbankrenna and has a distinct asymmetrical wedge-like shape (Fig. 2E,G and 3A; GZW 5). Based on its morphology and seafloor expression the wedge can be divided into eastern and western sections (Fig. 3A). It extends in a NW-SE direction for ~35 km, and is located in water depths of ~215 m at its eastern side and ~250 m at its western side. The eastern side of the deposit has a clear asymmetric shape, with a width of ~30 km at its widest point, a height of ~31 m and a steeper ice distal slope (Figs. 2G and 3A and B; Table 1). The eastern side of this deposit extends slightly north in the middle of the feature (between the western and eastern side), forming a wedge-shaped ridge dividing it from its western counterpart (Fig. 2A).

The western side of sedimentary deposit 5 is less pronounced than its eastern side and has a radial, fan-like geometry, with a height of ~10 m, width of ~20 km and a less steep overall profile (Fig. 3A and C; Table 1). A clear break in slope can be traced along the whole of the ice distal side of this western section of the wedge (indicated by the red arrow in Fig. 3A and C), perhaps indicating a second wedge-like feature. The extent of the lower wedge is unclear, although it has a similar overall profile to that which overlies it, with a steep ice distal slope and a height and width of ~10 m and ~8 km, respectively (Figs. 2E and 3A and C; Table 1). This western side of sedimentary deposit 5 is located in a deeper part of trough, and the fan-shaped deposits are heavily overprinted by, and themselves overprint, many semi-parallel curvilinear furrows (cf. section 4.6). In the middle section of sedimentary deposit 5, between the western and eastern sides of the deposit, are several smaller fan-shaped deposits. These are greater in height but smaller than the fan-shaped western margin of deposit 5 (heights ~20 m, widths ~1.5 km; Fig. 3A).

North of deposit 5 is a large and prominent sedimentary deposit 6 (Figs. 2E and 3D; GZW 6). It is located at a much shallower depth than sedimentary deposits 1–5, with the crest of the sedimentary deposit at ~190 m water depth. This deposit appears to be well preserved with little indications of overprinting from other features, except for a small number of elongated linear features imprinted into its ice proximal slope (cf. section 4.3) and some randomly orientated furrows on the crest (cf. section 4.6). The wedge extends in an ESE-WNW direction for ~37 km, is ~15 km at its widest point and has a clear asymmetrical shape (Fig. 2G; Table 1) with many lobate features making up its margin (Fig. 3D and E). The extent of the western-most part of the wedge is a little unclear as it fades into an area dominated by smaller sedimentary ridges (cf. section 4.4).

Sedimentary deposit 7 (Fig. 2E; GZD 7) is to the west of the sedimentary deposit 6, located in the northwestern part of

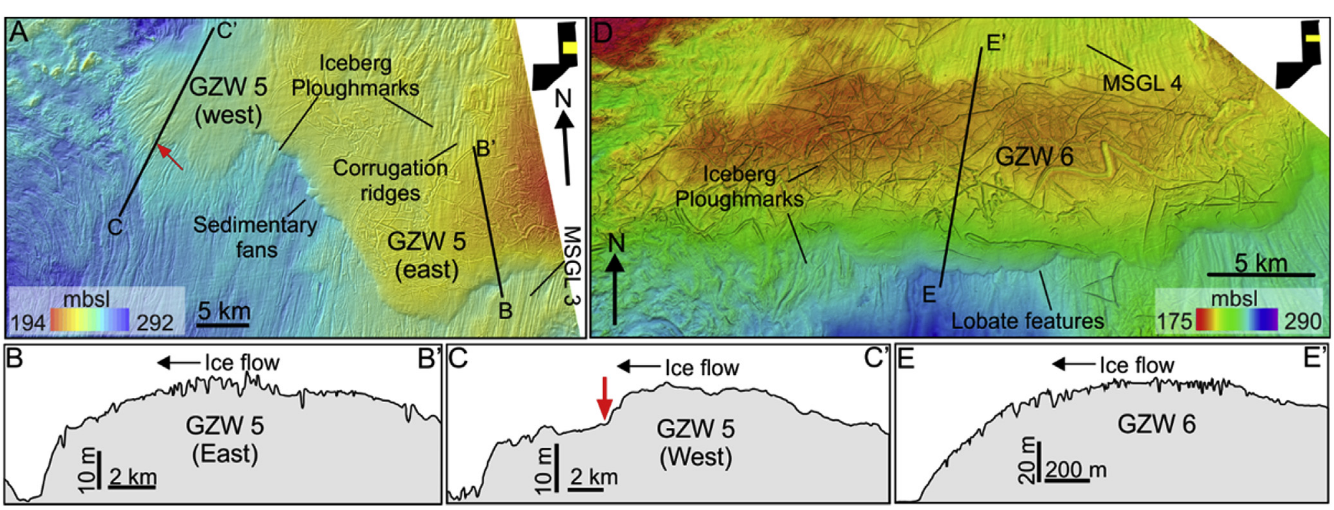

Fig. 3. Grounding zone wedges in upper Sentralbankrenna. A – High resolution multibeam of GZW 5 showing several sedimentary fans, iceberg ploughmarks and corrugation ridges. B – Cross profile of the eastern side of GZW 5. C – Cross profile of the western side of GZW 5, with the red arrow pointing at the slope break and possible overlap with a second phase of wedge formation. D – High resolution multibeam of GZW 6, showing its lobate features on the ice distal side of the wedge, MSGL 4 and iceberg ploughmarks. E – Cross profile of GZW 6. Multibeam bathymetry: © Kartverket. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Sentralbankrenna at a water depth of ~160 m. Unlike the sedimentary deposits previously described, it is more symmetrical, considerably higher and narrower (Table 1), and height of ~50 m in relation to the seafloor downstream. It extends for ~20 km in a W-E direction and is ~4 km at its widest section. In the areas up and downstream of this large sedimentary deposit there are many small, pronounced sedimentary ridges (cf. section 4.4).

Sedimentary deposit 8 (GZD 8; Fig. 2B), on the north-western flanks of Thor Iversenbanken at a water depth of ~240 m, has similar morphological characteristics to sedimentary deposit 7 (Table 1). This deposit is composed of three closely spaced, symmetrical sedimentary deposits, orientated in a NE-SW direction, which have widths and heights ranging from 200 to 340 m and 3–11 m, respectively. These have been previously described and interpreted by Bjarnadóttir et al. (2014).

On the northern flanks of Thor Iversenbanken, connecting with the mid-section of Sentralbankrenna, is sedimentary deposit 9 (GZD 9; Fig. 2B and E), which is ~45 km long and its surface has been heavily scoured by both curvilinear and randomly orientated furrows (Fig. 2B and E). At its widest point (in the northern most part of Thor Iversenbanken), it has a width of ~8 km and height of ~25 m (Table 1), however as it extends into the north-western part of Thor Iversenbanken, its shape and seafloor expression becomes less pronounced.

4.1.2. Interpretation

We identified nine large sedimentary deposits (Fig. 2A–G; Table 1) and interpret these to indicate former grounding line positions. Based on their morphology and seafloor expression, two main types of deposits are identified within the Sentralbankrenna glacial system. The first have clear wedge-like forms and are interpreted to be grounding zone wedges (GZWs). In contrast, the second type of deposits are smaller, narrower and lacking a pronounced wedge-like form and so, while they are interpreted to also represent ice marginal deposits these will be referred to as grounding zone deposits (GZDs). Of the mapped landforms sedimentary deposits 1–6 are interpreted to be GZWs and will henceforth be referred to as GZW 1–6 (Fig. 2B and E, Table 1). This interpretation is consistent with that of Bjarnadóttir et al. (2014) who previously interpreted GZW 1–3 in our study. Sedimentary deposits 7–9 are interpreted to be GZD and will henceforth be referred to as GZD 7–9 (Fig. 2B and E, Table 1). We propose that the steep, narrow GZDs 7, 8 and 9 (Fig. 2E) are large recessional moraines (GZD 8 previously described and interpreted in Bjarnadóttir et al., 2014). Such landforms typically form at tidewater ice cliffs through a combination of processes, such as squeeze-push from under the ice mass and the deformation of the sediment beneath (Powell, 1981, 1991; Powell and Domack, 1995; Powell and Alley, 1997) and are typical for inter-ice stream areas (Kirkbride and Warren, 1997; Ottesen and Dowdeswell, 2009). There is a noticeable lack of scouring both downstream and upstream of these features, and it is therefore likely that the ice here was slower moving, with little calving occurring at the margin.

GZWs have been observed and extensively studied in many locations on high-latitude palaeo-ice stream beds (e.g. Mosola and Anderson, 2006; Ó Cofaigh et al., 2008; Bjarnadóttir et al., 2013, 2014; Rydningen et al., 2013). These are ice-marginal landforms, formed at the grounding zone of fast-flowing ice streams (Powell and Domack, 1995; Dowdeswell et al., 2008) and are suggested to temporarily stabilise the ice stream grounding line to the effects of sea-level rise (Alley et al., 2007; Anandakrishnan et al., 2007).

GZW 1–6 all have similar morphological and acoustic characteristics: slight-to-prominent asymmetric profiles (steeper ice-distal slopes), a relatively high length-to-height ratio and are acoustically transparent, which are typical of GZWs (Powell and Domack, 2002; Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015). These wedge-like deposits are formed through rapid deposition and deformation of subglacial sediment at the ice margin, and its subsequent redistribution through gravity flow processes (Powell and Alley, 1997; Dowdeswell and Fugelli, 2012). Their acoustic transparency reflects the unsorted nature of the diamictic debris being deposited at the grounding zone (Batchelor and Dowdeswell, 2015). The presence of GZWs in the palaeo-record enables identification of ice margin positions during stillstands or re-advances (from decades to centuries), and their morphology and relation to other geomorphological features can provide clues to the overlying ice dynamics and retreat patterns (e.g. Mosola and Anderson, 2006; Alley et al., 2007; Anandakrishnan et al., 2007; Dowdeswell et al., 2008; Ó Cofaigh et al., 2008; Dowdeswell and Fugelli, 2012; Livingstone et al., 2012a, 2016a). Thus, the six GZWs in Sentralbankrenna (GZW 1–6) indicate that ice streaming within this trough experienced periods of ice break up and rapid retreat, punctuated by stabilisation during stillstands or readvances.

GZW 1 is the largest within this dataset and is composed of four generations of deposition (Bjarnadóttir et al., 2014). From its position in relation to the rest of the features, we suggest this to be the oldest ice marginal landform within the dataset, deposited by ice flowing in a north-west to south-east direction. GZW 2 is not as prominent as the other GZW1-4, perhaps indicating that the ice margin was stable in this position for a relatively short period, when the ice stream was undergoing fast retreat and the grounding line only just grounded. Alternatively, it may represent changes in the flux of sediment to the grounding line. The northern sections of GZW 1 and 2 have been breached by several channels (c.f. section 4.3), indicating that meltwater was likely to have been present during the formation of these GZW.

GZW 3 is heavily scoured and overprinted by curvilinear furrows (Fig. 2B and E, c.f. section 4.6.). To the east, GZW 4 is overprinted by elongated linear features on its ice-proximal side (Fig. 2E, c.f. section 4.2.), suggesting that this was formed under fast flowing ice (Ó Cofaigh et al., 2005; Graham et al., 2010), and that the ice was still streaming during or after the final stages of its formation.

The eastern side of GZW 5 (Fig. 5A) represents a classic GZW, with an asymmetrical profile and high length-to-height ratio. We suggest that the grounding line of the Sentralbankrenna Ice Stream was stable in this area for some time allowing a large and clear GZW to develop. In contrast, the western part of GZW 5 resembles a large radially shaped fan, with a clear slope break at its downstream margin. The western side of GZW 5 may represent a large grounding line fan (Fig. 3A), indicating that this part of the deposit was highly influenced by meltwater, with sediment deposition either due to subglacial meltwater derived sediment plumes, subaqueous debris flows, or a combination of the two. This is likely to be a composite feature, formed and reshaped during two stillstand/readvance events, with the sediment fans having been deposited by a relatively ice proximal meltwater plume from a subglacial meltwater conduit ending at the ice margin. In between the western and eastern side of GZW 5 there are many smaller grounding line fans along its ice distal slope (Fig. 5A). Similar features have been described as part of GZWs in Kveithola, western Barents Sea (Bjarnadóttir et al., 2013) and in Storfjordrenna, NW Barents Sea (Shackleton et al., Submitted), and interpreted as intermediate GZWs, heavily influenced by meltwater activity at the former ice margin. We propose that GZW 5 also represents such an intermediate GZW. Whilst the eastern and western part of this sedimentary wedge have been described as part of the same deposit, it is clear that the ice margin experienced different ice dynamics along its front. It is possible that a large embayment in the ice margin formed over the western part of GZW 5 due to its position within the deeper section of the trough, enabling the formation of the GZW radial fan-shaped geometry.

Further north, GZW 6 is a large and very prominent feature on the seafloor, with a very clear terminus on its ice distal side (Fig. 3D). Based on its location, we suggest that this GZW was formed during the late stages of deglaciation in this trough. This is consistent with interpretation from Newton and Huuse (2017).

4.2. Linear elongated features: mega-scale glacial lineations

4.2.1. Description

Within Sentralbankrenna we identify five areas with differing orientations where assemblages of broadly parallel linear elongated ridge-groove features can be seen on the seafloor (Fig. 2A, B and E; MSGL 1–5). The first area (MSGL 1; Figs. 2B and 4A) is located on the ice proximal side of GZW 1 and is characterised by the largest amplitude ridge-groove features mapped in Sentralbankrenna. Here the features have a predominant NE-SW orientation, with ridges ~880–2680 m wide, ~25–42 km long, heights between ~2 and 3 m, and with elongation ratios (width:length) ranging from 1:15 to 1:28 (Fig. 4B). The second area (MSGL 2) of pronounced parallel elongate ridge-groove features is located between GZW 1 and GZW 2, slightly north of area 1 (Figs. 2B and 4A), and has been previously described and interpreted by Bjarnadóttir et al. (2014). These pronounced parallel elongate ridge-groove features extend in an ENE-WSW direction with an individual length of ~11–14 km, ~350–1200 m wide, 2–8 m high, and elongation ratios ranging from 1:12 to 1:32 (Fig. 4C). Both the first and second area of elongated features are located in the deepest part of the study area (area 1 water depth is ~295 m; area 2 water depth is ~320 m).

The third area (MSGL 3; Figs. 2E and 4D) is located in the eastern part of mid-Sentralbankrenna, where very clear parallel linear ridge-groove features can be observed overlying and terminating on top of GZW 5 (Fig. 4D). These landforms are orientated in a NNE-SSW direction and are smaller than those in areas 1 and 2, ~5–10 km long, ~180–530 m wide, heights ~2–7 m (Fig. 4E), with elongation ratios between 1:12 and 1:53. The fourth area (MSGL 4; Fig. 2E) is located on the ice proximal slope of GZW 6, in the north-easternmost part of Sentralbankrenna. Here, large ridge-groove linear features are imprinted onto the seafloor, with lengths of ~4–8 km, widths of ~240–640 m, heights of ~1–6 m, and elongation ratios between 1:12 and 1:32. These features are oriented in a NE-SW direction. The fifth area (MSGL 5; Fig. 2E), is west of the fourth, just south of sedimentary deposit 7, in the northwestern part of Sentralbankrenna. In this area, the ridge-groove features are oriented in an ENE-WSW direction, extend ~2.7–3.1 km in length, are ~85–100 m wide, have heights between ~0.4–0.8 m, and elongation ratios ranging from 1:28 to 1:33. The linear features in the fifth area are relatively short and cover only a small area, unlike similar features found in other areas. This area is also surrounded by many small sedimentary ridges (cf. section 4.4).

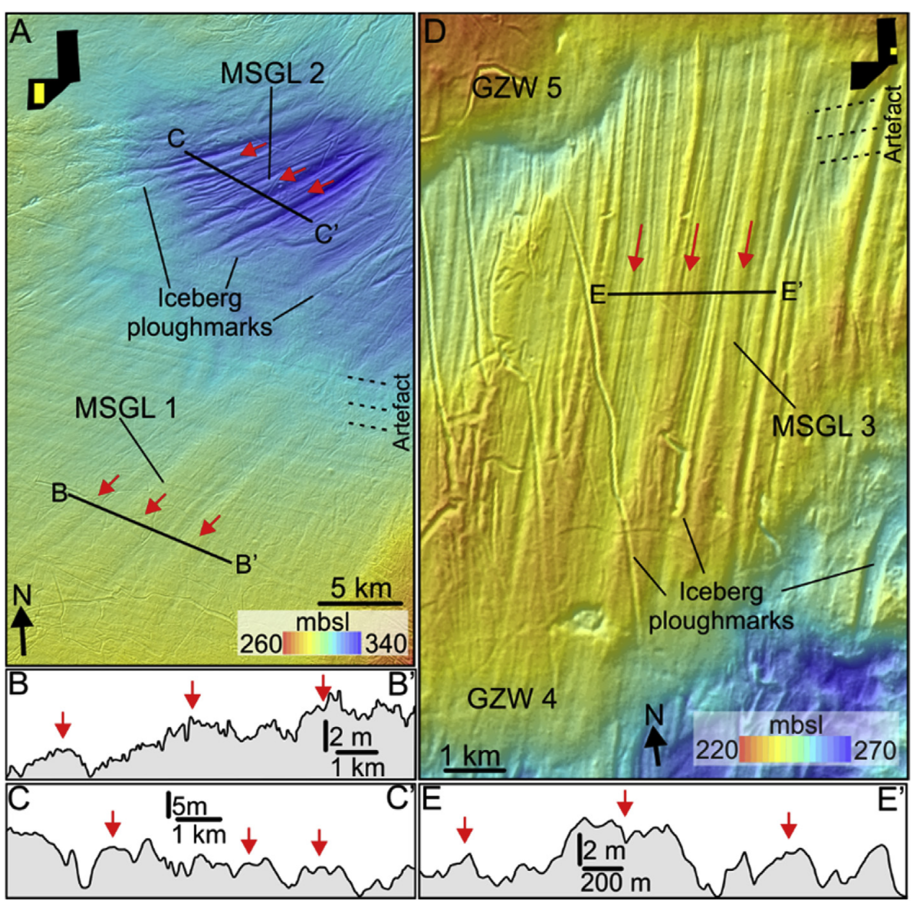

Fig. 4. Mega-scale glacial lineations. A. Multibeam showing MSGL 1 and 2. B – Cross profile of MSGL 1. C – Cross profile of MSGL 2. D - Multibeam of MSGL 3 overprinting the ice proximal side of GZW 4. E – Cross profile of MSGL 3. The red arrows pointing to the positive feature of the MSGL. Multibeam bathymetry: © Kartverket. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

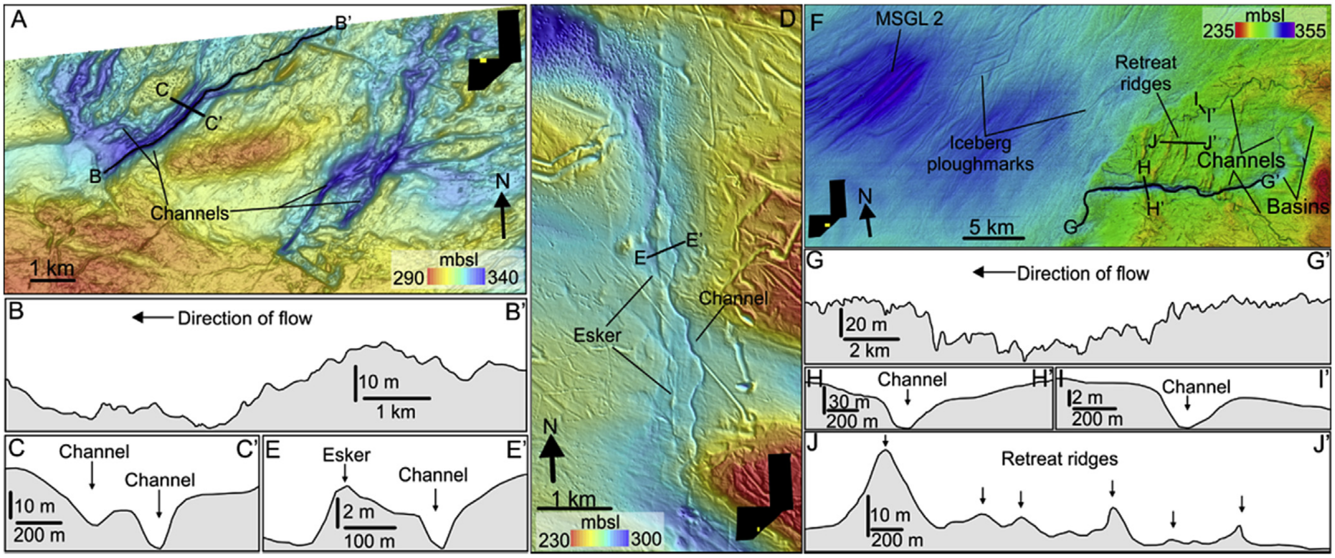

Fig. 5. Meltwater channels and subglacial basins. A – Channel area to the north of GZW 2 showing linked tunnel valley system (highlighted channels in the location map). B – Long profile of a tunnel valley. C – Cross section of the tunnel valley. D - Channel area in the western part of Thor Iversenbanken, showing a long sinuous channel with an esker running adjacent to it (highlighted channels in the location map). E Cross section of the channel and esker. F - Channel and basin area to the east of MSGL 2, showing a large tunnel valley (Bjarnadóttir et al., 2017) with several basins upstream from the main channel (highlighted channels in the location map). G – Long profile through the main central channel leading from the basins. H and I – Cross profiles of channels in the channel and basin area. J – Cross profile through the retreat ridges cross cutting the channels. Multibeam bathymetry: © Kartverket.

4.2.2. Interpretation

The linear elongated ridge-groove features in areas 1–5 are interpreted to be mega-scale glacial lineations (MSGLs; henceforth areas 1–5 are now referred to as MSGL 1–5). MSGLs are formed beneath fast flowing ice (Clark, 1993), and have been widely used to identify the location of palaeo-ice streams in formerly glaciated areas (e.g. Stokes and Clark, 1999, 2001; Graham et al., 2009).

The MSGLs within Sentralbankrenna show different scales and different positions in relation to other glacial geomorphological features. MSGLs 1 to 4 are all located on the ice-proximal slope of GZWs, thus indicating that the ice overlying these areas was fast flowing during or after the deposition of the wedges (Ó Cofaigh et al., 2005; Dowdeswell et al., 2008; Graham et al., 2010). MSGL 5, located downstream of GZD 7, is considerably smaller than the other MSGLs, and has a differing orientation in comparison to the ridge features around it (cf. section 4.4). It is possible that MSGL 5 are older features that have been partially buried by younger sedimentary ridge features.

MSGLs 1 are considerably larger than the other MSGLs, both in terms of the area that they cover and also the amplitude of the features, and are likely related to a period when the Sentralbankrenna Ice Stream was fast flowing and depositing GZW 1. MSGLs 2 immediately upstream, have a slightly different orientation, suggesting a switching in ice stream flow direction within the trough during ice stream retreat from GZW 1 to GZW 2. Subglacial meltwater, in conjunction with easily deformable sediment (Fowler, 2010), may have played a significant role in enabling the formation of the MSGLs in area 1 and 2. In support of this, several meltwater channels have been previously identified in the areas adjacent to the MSGLs (Bjarnadóttir et al., 2012, 2014; 2017; this study, c.f. section 4.3.), indicating that there was abundant meltwater discharging into this area.

The formation of MSGLs 3 and 4 was likely to have occurred simultaneously to the formation of GZW's 4 and 6, respectively. Meanwhile, the timing of the formation of MSGL 5 and its relationship with the surrounding landforms remains more uncertain. No further MSGLs within Sentralbankrenna, or on the ice proximal sides of GZW 2 and 3, were observed during this study. Rather than reflecting a lack of fast flowing ice in this area, we suggest that MSGLs may have been present but have been subsequently obscured by heavy scouring of the seafloor (Fig. 2A,B and E).

4.3. Seafloor channels and basins: meltwater features

4.3.1. Description

Located between GZW 1 and GZW 3 are three areas with channel-like furrows and depressions on the seafloor (Fig. 2A and B). The first area is located in the northern part of GZW 2, upstream of GZW 1 (Fig. 5A). Here, several channels were identified, extending on the seafloor for ~7–20 km in length, with an undulating long profile (Fig. 5B). The channels have varying widths and depths, 80–155 m and 3–10 m, respectively (Fig. 5B and C). All the mapped channels in this area are orientated NE-SW and are interlinked in a large anastomosing system (Fig. 5A), cutting through the northern part of GZW 2 and GZW 1 (Fig. 2B). These have been described and interpreted by Bjarnadóttir et al. (2012, 2017).

In the western part of Thor Iversenbanken, adjacent and to the east of MSGLs 1, is a long single channel (Fig. 5D), oriented SE-NW. This channel extends ~4 km on the seafloor, is ~60 m wide and 3 m deep (Fig. 5E). There is also an elongated, relatively straight, ridge running parallel to this channel (Fig. 5D and E), with the same length but with a width and height of ~92 m and ~2 m, respectively. To the west of this area is a large depression on the seafloor (Fig. 2A), ~3.5 km long, ~1.8 km wide, with a depth of ~40 m.

East of MSGLs 2, in the north-western flanks of Thor Iversenbanken, is a third channel and basin area (Figs. 2B and 5F). Here, several channels merge in a dendritic manner downstream of three depressions, and cut through a number of small sedimentary ridges (c.f. section 4.4), previously identified by Bjarnadóttir et al. (2012, 2014, 2017). These channels are orientated SE-NW towards the trough, where they end abruptly, close to the slope break. The main channel in this area is ~310 m wide, ~32 m deep and ~50 km long (Fig. 5G and H). The northern-most channel in the basin area splits into two, with one channel connecting to the depressions from the northeast, subsequently feeding into the main channel and the other, a single meandering channel, extending ~40 km, ~150 m wide, and ~7 m deep (Fig. 5I) towards the trough. The depressions on the seafloor are situated upstream of the main channel and are relatively shallow, < 20 m deep, with basin-like shapes and lengths/widths ranging from, 2.3–4 km and 1–1.5 km, respectively.

4.3.2. Interpretation

The meltwater channel network north of GZW 2 (Fig. 5A) is interpreted to be an extensive system of tunnel valleys, which have been previously described by Bjarnadóttir et al. (2012, 2017). These features are erosionally formed by subglacial meltwater at the base of the ice sheet (Ó Cofaigh, 1996; Kehew et al., 2012; Greenwood et al., 2016). The channels have breached GZWs 1 and 2 (Fig. 2B), indicating that they may have been formed gradually over time and have been active during the build-up of both GZWs 1 and 2.

The smaller channel on the western flanks of Thor Iversenbanken (Fig. 5D) is interpreted to have formed subglacially under a channelised meltwater regime and the elongated ridge running parallel to it is interpreted as an esker. It is possible that this esker may have formed during a period when the ice was slower moving in this area or possibly even close to the ice margin, during which the meltwater conduits remained stable for sufficient time for esker to form. Similar formation processes have been suggested for the formation of eskers observed in Canada (Storrar et al., 2014). We suggest that the large depression west of this channel and esker (Fig. 2A) may have served as a subglacial basin once hosting a subglacial lake, however, further subsurface and empirical data is required to verify this.

East of MSGL 2 a series of arborescent channels form a dendritic hydraulic network downstream of three basins. These channels have been previously described and interpreted by Bjarnadóttir et al. (2012; 2017) and Newton and Huuse (2017) to be tunnel valleys formed gradually over time and to have been active close to the ice margin. The main channel has an undulating long profile (Fig. 5G), with a shallowing at the mouth of the channel, indicating that there must have been significant pressure from overlying ice to cause subglacial water to be driven uphill. The channel ends abruptly when it enters the trough, either indicating the channel ending at the margin, or suggesting a possible boundary, or shear margin, between the slower inter-ice stream ice on Thor Iversenbanken and the streaming ice of the Sentralbankrenna Ice Stream (c.f. section 5.1.2.).

The basins upstream of the dendritic channel network are inferred to have hosted palaeo-subglacial lakes, based on their geomorphic properties (e.g. as described in Livingstone et al., 2012b) and the presence of channels leading into and out of the basins, as well as evidence of channels cutting through some of the basins. We suggest that these lakes would have discharged a large amount of meltwater into the channels and may have undergone several periods of drainage and infilling, similar to those identified in Antarctica (Wingham et al., 2006; Fricker and Scambos, 2009) and Greenland (Palmer et al., 2013). Similar palaeo-subglacial lakes have been described elsewhere, for example in Canada, by Christoffersen et al. (2008) and Livingstone et al. (2016b). While these channels and basins are not located at the onset zone of the ice stream, we propose that the presence of these channel areas at the sides of the trough may have played a significant role for the development of MSGLs and/or in the facilitation of ice streaming in the trough (e.g. King et al., 2009; Fowler, 2010), providing a mechanism for rapid discharge of meltwater into the trough. Running perpendicular to the channels in this area are several sedimentary ridges (cf. section 4.4; Bjarnadóttir et al., 2014), which have been breached at several points, suggesting that the channels in this area were active during a period of ice retreat in this area. Furthermore, Bjarnadóttir et al. (2012, 2017) suggested that the tunnel valleys in this basin and channel area (Fig. 5F) may have undergone several outburst floods, which we suggest may have been promoted by the presence of the palaeo-subglacial basins further upstream.

Meltwater plays an important role in ice sheet and ice stream dynamics, facilitating fast ice flow for overlying ice (Hulbe and Fahnestock, 2004; Bell, 2008; Greenwood et al., 2016). The channels observed in Sentralbankrenna and on Thor Iversenbanken must have formed subglacially since the ice stream had a marine margin.

4.4. Sedimentary ridges: retreat ridges

4.4.1. Description

Within the bathymetric dataset there are four distinct areas with small sedimentary ridges; linear, parallel features, with a symmetrical shape. The first area is located in the channel and basin area, east of GZW 2, where four large ridges are clearly visible running perpendicular to the channels (Fig. 5F; Bjarnadóttir et al., 2014), with widths ranging from 400 to 600 m and heights between 8 and 17 m, they have a regular spacing between 1 and 3 km (Bjarnadóttir et al., 2014, 2017). Between these larger ridges, there are many slightly smaller ridges, with widths and heights ranging from 110 to 240 m and 3–14 m, respectively, as well as a regular spacing of 150–350 m (Fig. 5J). The sedimentary ridges in this area occur 1–3 km upstream from a visible slope break between Thor Iversenbanken and Sentralbankrenna, and at a water depth ranging between 260 and 300 m.

The second area with several small sedimentary ridges is located in the northern-most flanks of Thor Iversenbanken, to the east of grounding zone deposit 9 (Fig. 2A and E) in water depths ranging from 220 to 235 m. Short and narrow ridges were also identified with a more north-south orientation, with widths and heights ranging from 84 to 405 m and 4–12 m, respectively.

To the west of GZW 5, downstream of GZD 7, is sedimentary ridge area three, where there are several ridges with an approximately W-E orientation, widths ranging from 95 to 155 m and heights of 3.5–6 m, in water depths ranging from 245 to 270 m (Fig. 6A and B). North of this area, both up- and down-stream of the GZD 7 is sedimentary ridges area four, which, in comparison to the other areas, is located at a much shallower water depth between 180 and 230 m (Fig. 2E). Here, many sedimentary ridges are observed with an approximate NE-SW direction, widths of 100–185 m and heights of 3.5–8 m.

4.4.2. Interpretation

The small, linear, semi-parallel sedimentary ridges identified in the study area have a semi-regular spacing, and are interpreted to be retreat ridges. These features are indicative of stabilisation of the ice margin during overall retreat (Ottesen and Dowdeswell, 2006). The retreat ridges on Thor Iversenbanken are likely to have been formed by slow ice flowing from the east, over Thor Iversenbanken. Those in the upper parts of Sentralbankrenna are more likely to have been formed by ice flowing from Sentralbanken. The four larger retreat ridges in the channel and basin area on Thor Iversenbanken, have previously been interpreted as recessional moraines, indicative of a longer margin stillstand (Bjarnadóttir et al., 2014). Based on their geomorphic characteristics and setting we find it likely that the smaller ridges in this area also represent recessional moraines or smaller push moraines, although without subsurface data, their origin cannot been confirmed.

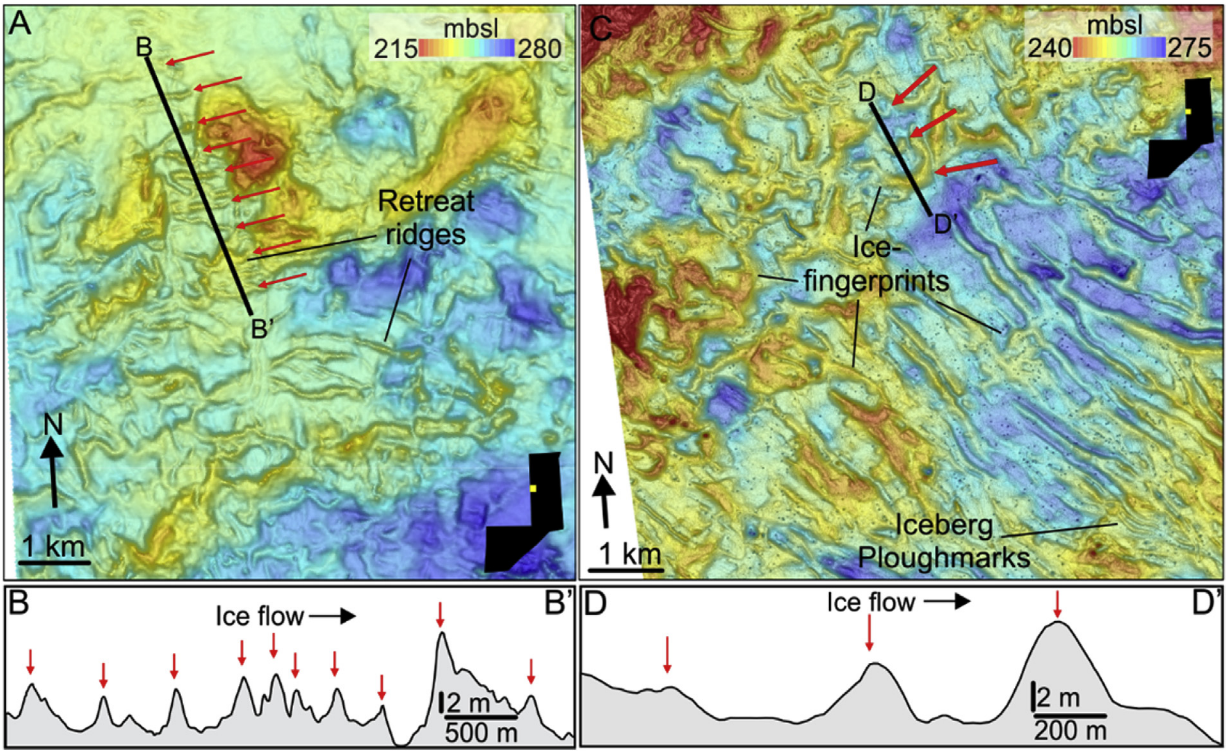

Fig. 6. Ice-marginal features indicating slow retreat. A – Retreat ridges located to the west of GZW 5 (highlighted ridges in the location map). B – Cross profile of the ridges. C – Ice fingerprints downstream of the retreat ridges (highlighted features in the location map). D – Cross profile of the ice fingerprints. Multibeam bathymetry: © Kartverket.

4.5. Short, flat imprints with sedimentary berms: ice-fingerprints

4.5.1. Description

Along the north-western margin of Sentralbankrenna two areas have been mapped, to the west of GZW 5 (Fig. 6C) and upstream of GZD 7 (Fig. 2A and E), where the seafloor is characterised by elongate, semi-parallel, flat bottomed features that have lengths and widths ranging from 150 to 2500 m and 180–700 m, respectively. Many of these features terminate in long crescentic, asymmetric shaped berms, with heights between 1 and 6 m and widths of 100–450 m (Fig. 6C and D). These features appear downstream of the mapped retreat ridges (cf. section 4.4) as short and wide imprints, which overprint longer and narrower imprints that in some locations merge or turn into with curvilinear furrows without berms (cf. section 4.6; Fig. 6C).

4.5.2. Interpretation

These semi-parallel, flat-bottomed features with sedimentary berms on their downstream end are interpreted to be ice fingerprints, glacial features formed beneath an ice margin experiencing transverse extensional flow (Bjarnadóttir et al., 2014). The geomorphological sequence we observe in this area is as follows, 1) retreat ridges, 2) ice fingerprints, 3) furrows (in a distal to proximal order). This is similar to that observed in other locations within the Barents Sea (Bjarnadóttir et al., 2014) and in Iceland (Geirsdóttir et al., 2008). We suggest that these ice fingerprints may have been formed by an advancing ice cliff margin or icebergs characterised by fingers or sliver of ice, possibly during a period of extensive pervasive sea ice, which provided the buttressing needed for the ice margin to not break up directly into icebergs. Such a mechanism has been proposed for the formation of ice fingers in Iceland (Geirsdóttir et al., 2008).

4.6. Linear and curvilinear furrows: iceberg ploughmarks

4.6.1. Description

The seafloor throughout much of Sentralbankrenna and the shallower bank areas is heavily scoured with many furrows of varying shapes and sizes (Fig. 2A, B, E and 7A). On the shallower parts of Thor Iversenbanken and Sentralbanken, as well as on top of most of the large sedimentary deposits, there are several relatively narrow, randomly orientated curvilinear furrows, with a V-shaped cross-profile (Fig. 7B). Their widths range from ~65 to 210 m and their depths from ~0.5–10 m. Downstream of GZW 1 are several uniform, relatively narrow U-shaped furrows, with widths extending 70–125 m, depths between 0.75 and 6 m, and orientated ESE-WNW. Between GZW 1 and GZW 2 the furrows are less common, with fewer features mapped.

In mid-to upper-Sentralbankrenna, between GZW 2 and GZW 5 there are many semi-parallel curvilinear furrows orientated parallel to the troughs long-axis (Fig. 2A, B and E), many of the furrows between GZW 3 and GZW 5 display one of two distinct orientations (Fig. 7A). The dominant orientation for the furrows in this area is NE-SW parallel to the trough long-axis, however, coming from Sentralbanken downstream of the retreat ridges and ice fingerprints to the west of GZW 5, there are several furrows orientated in a NW-SE direction. Both these sets converge in the mid-section of Sentralbankrenna at a water depth of 260–290 m (Fig. 7A), before following the dominant NE-SW orientation in a more uniform manner. Widths and heights of these furrows vary from 100 to 1500 m and 1–8 m, respectively (Fig. 7B). A clear downstream termination of furrows is, in most cases, not observed in the study area. Within some of the furrows in upper Sentralbankrenna, in particular those downstream of and overprinting GZW 5 (Fig. 2E), are several relatively regularly spaced (140–170 m), small sedimentary ridges that appear roughly perpendicular to the furrow

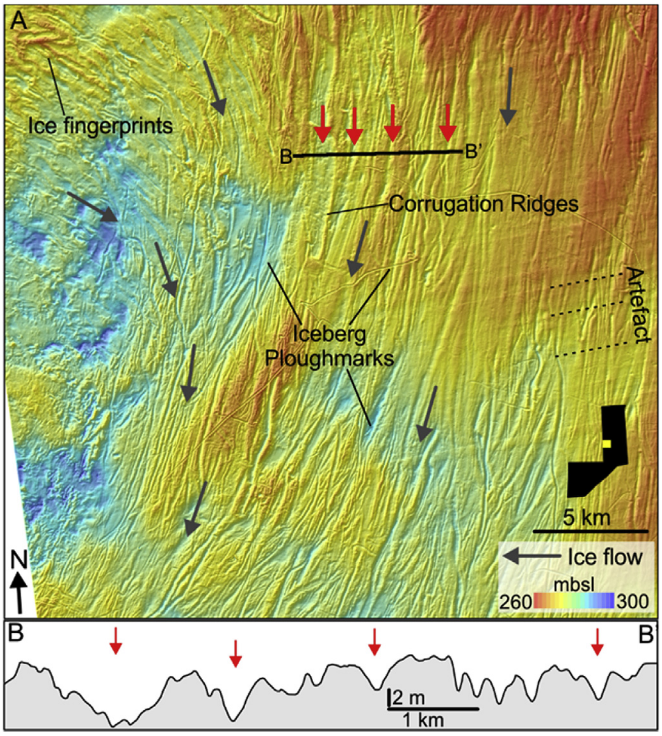

Fig. 7. Iceberg ploughmarks and corrugation ridges. A – Iceberg ploughmarks between GZW 3 and GZW 5 (highlighted ploughmarks in the location map), showing the convergence between two different ploughmarks orientations (Grey arrow). Multibeam acquisition artefacts are highlighted by the dashed line. B - Cross profile of the ploughmarks. Multibeam bathymetry: © Kartverket.

length orientation, and have heights ranging from 0.5 to 2 m and widths from 150 to 300 m.

4.6.2. Interpretation

We interpret the furrows observed within the dataset to be iceberg ploughmarks, formed by the scouring of seafloor sediments by grounded iceberg keels. Such features have been documented extensively across formerly glaciated continental margins (e.g. Barnes and Lien, 1988; Kuijpers et al., 2007; Dowdeswell et al., 2010; Andreassen et al., 2014; Bjarnadóttir et al., 2014; Dowdeswell and Hogan, 2016), and can be used to infer the proximity to the ice margin, with the assumption that more uniform scours suggest ice proximal icebergs and those randomly orientated indicative of ice distal icebergs whose path is dictated by the wind or ocean currents (Smith and Banke, 1983). Alternatively, it is possible that larger icebergs may be less sensitive to wind or ocean currents than smaller icebergs.

There are fewer iceberg scours between GZW 1 and GZW 2, than within the rest of upper Sentralbankrenna, possibly due to a deepening of the trough meaning that the calved icebergs keels did not reach the seafloor, or otherwise due to surface sediment cover in this area burying all but the deepest ploughmarks. The uniform ploughmarks visible on the seafloor between GZW 3 and GZW 5 (Fig. 7A) show two main source directions. Less dominant ploughmarks come from Sentralbanken in a NW-SE orientation and more dominant ploughmarks orientated N-S following the axis of Sentralbankrenna. It is possible that the ploughmarks between GZW 3 and GZW 5 may be obscuring older features, although this cannot be confirmed with the data currently available. We propose that the ice margin at GZW 5 may have been highly dynamic with a high calving rate based on the large quantity of ploughmarks downstream of the GZW; or alternatively that there was a rapid break-up of the ice margin when it was at GZW 3, and subsequent retreat from GZW 3 to GZW 5.

Within several of the furrows, in particular those present downstream and on top of GZW 5, are many short and linear ridges that run perpendicular to the scour marks (Fig. 7A). We interpret these to be corrugation ridges. Corrugation ridges have been identified in both palaeo- and contemporary environments (Solheim and Pfirman, 1985; Jakobsson et al., 2011; Graham et al., 2013; Andreassen et al., 2014). We infer that these features were formed by icebergs trapped in a dense ice matrix, where their keels squeezed the seafloor sediment into small ridges under a tidal regime (Jakobsson et al., 2011).

5. Discussion

5.1. The Sentralbankrenna glacial system

A complex assemblage of glacial landforms was mapped in the study area, composing of multiple grounding zone deposits, MSGLs, meltwater features and retreat ridges. Based on this geomorphological record we propose that the Sentralbankrenna glacial system experienced several retreats and/or readvances, each marked by a GZW or GZD, during the period of overall deglaciation since the LGM. The glacial system comprised of the fast flowing Sentralbankrenna Ice Stream and slower moving inter-ice stream ice masses located over northern Sentralbanken and northern Thor Iversenbanken (Fig. 8A). In the southern part of Sentralbankrenna there are a number of meltwater features, suggesting that subglacial meltwater was abundant in this area and that basal hydrology may have played a key role in determining the location of ice streaming by facilitating lubrication of the ice stream bed.

In the following sections, we present a 6-stage reconstruction of the deglaciation of the Sentralbankrenna glacial system. Due to the poorly constrained chronology from the central Barents Sea, we are only able to provide a relative chronology for stages 2–6, however it seems plausible that the trough was deglaciated sometime after 16 cal ka BP (Fig. 1; Winsborrow et al., 2010; Hughes et al., 2015).

5.1.1. Stage 1 – LGM and early deglaciation

Stage 1 relates to the LGM and early deglaciation, during which the BSIS was at its maximum extent, reaching the shelf break. Several ice streams were active during this period (Fig. 8A); the largest of these was the Bjørnøyrenna Ice Stream, which had tributaries of fast flowing ice coming from Storbankrenna and Sentralbankrenna (Fig. 8A; Bjarnadóttir et al., 2014). During maximum glacial conditions the Bjørnøyrenna Ice Stream was not topographically controlled, as evidenced by the identification of east-west oriented MSGLs in central Bjørnøyrenna (Piasecka et al., 2016) and supported by numerical modelling (Patton et al., 2016). The BSIS was a multi-domed ice sheet, with a potential source for Sentralbankrenna being the ice dome likely located over Storbanken, in the northern Barents Sea, and extending over Sentralbanken towards the south-eastern Barents Sea (Fig. 8A; Patton et al., 2015; Piasecka et al., 2016).

5.1.2. Stage 2 – post LGM

Stage 2 relates to an ice margin position associated with the deposition of GZW 1 (Fig. 8B). During, or prior to, this stage Sentralbankrenna Ice Stream and Bjørnøyrenna Ice Stream became separated by an inter-ice stream area overlying Sentralbanken, thus significantly reducing the catchment area for Bjørnøyrenna Ice Stream. This separation was likely associated with a northwesterly shift in source area for the Bjørnøyrenna Ice Stream (Andreassen et al., 2014), potentially coinciding with an ice dome that has

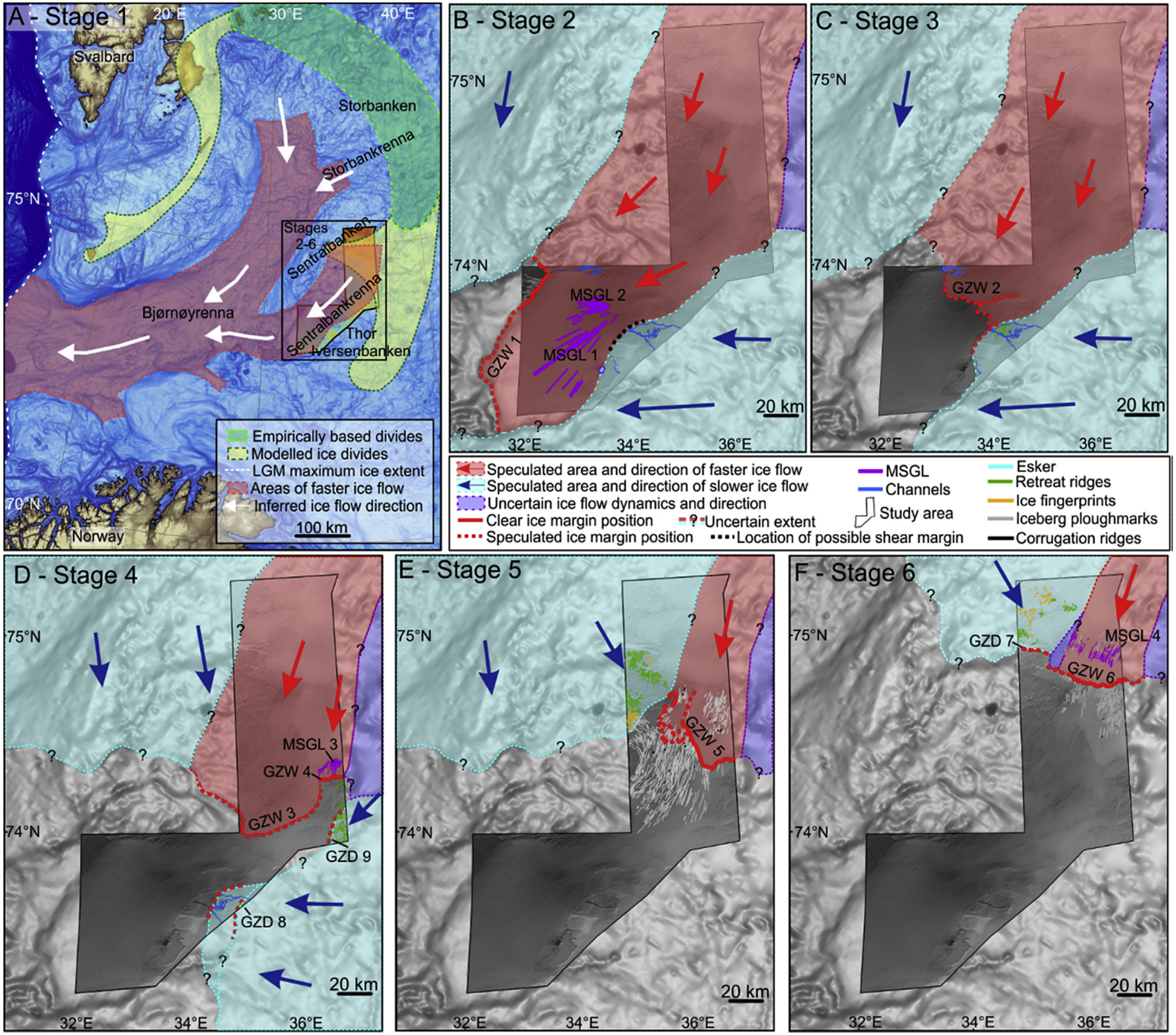

Fig. 8. 6-Stage reconstruction of the ice dynamics in the Sentralbankrenna glacial system based on the glacial landforms mapped in the multibeam dataset. A – Stage 1, the BSIS LGM ice extent and ice dynamics showing: the areas of suggested fast flow and its flow direction (modified from Patton et al., 2015), LGM maximum ice extent (Svendsen et al., 2004), modelled ice divide (Patton et al., 2015), and the empirically based ice divides (Bondevik et al., 1995; Ottesen et al., 2005; Andreassen et al., 2014; Bjarnadóttir et al., 2014); B-F – Stage 2–6 of the Sentralbankrenna glacial system reconstruction and the mapped glacial features associated to each stage. Multibeam bathymetry: © Kartverket.

been suggested over Hinlopenstretet (Dowdeswell et al., 2010, Fig. 1), with the Sentralbankrenna Ice Stream likely still fed by an ice divide located over Storbanken.

During this stage, the Sentralbankrenna Ice Stream flowed in an ENE-WSW direction, with its ice margin marked by GZW 1 (Figs. 1 and 8B). Based on subsurface data, GZW 1 from this study is a composite feature formed by four generations of GZW, indicating that this margin may have been relatively stable during its initial retreat stage (Bjarnadóttir et al., 2014). Fast flowing ice occupied the whole trough and continued even during the last phases of GZW development, as evidenced by large MSGLs 1 and 2 (Fig. 4A) on the ice proximal side of the wedge. On the adjacent shallower area of Thor Iversenbanken the geomorphology indicates the presence of slower flowing, less active ice, coming from the southeast Barents Sea. A large shear margin likely existed at the boundary between these two ice masses and this is marked by a clear slope break and abrupt end to the channels east of MSGLs 2 (Fig. 8A).

Meltwater coming from the channels and subglacial basins in southern Sentralbankrenna may have contributed to the location and dynamics of the Sentralbankrenna Ice Stream (Fig. 8B). The subglacial basins east of MSGL 2 are likely to have been active, connected and undergoing periods of rapid discharge and infilling, possibly on a seasonal timescale, similar to subglacial lakes in Greenland (Palmer et al., 2013) and in Antarctica (Fricker and Scambos, 2009; Smith et al., 2009). MSGL 1 are significantly larger than MSGL 2 (Fig. 4A) indicating that they may have been formed during the peak period of GZW 1 deposition, whereas MSGL 2 may have been formed as a product of ice stream flow switching. This could occur due to changes in water supply to the trough, or during the final stage of GZW 1 deposition prior to rapid margin breakdown and retreat back to GZW 2. Alternatively, MSGL 1 and 2 may represent a single ice stream event, where the ice stream has a more arcuate shape and MSGL 1 was positioned closer to the centre of the ice stream, where ice flow would have been faster.

5.1.3. Stage 3

The retreat from GZW 1 to GZW 2 was likely to have been relatively fast, prior to the ice margin stabilising and coming to another stillstand and marking the initiation of stage 3 (Fig. 8C). Tunnel valleys near the northern extent of GZW 2 have eroded through the deposit, indicating that these channels must have been active during the formation of the sedimentary deposit and that meltwater continued to play a significant role in the facilitation of ice streaming, contributing to the lubrication of the ice bed in the trough upstream of this margin.

During this stage, the channel areas on Thor Iversenbanken are unlikely to have contributed to the facilitation of fast flow of the Sentralbankrenna Ice Stream, however, they will have still played a role in the ice dynamics of the overlying Thor Iversenbanken inter-ice stream ice. It is unclear where the ice margin on Thor Iversenbanken was during this stage. However, based on the retreat ridges and recessional moraines identified in the channel and basin area we suggest periodic stillstands during the retreat across Thor Iversenbanken, and that the ice margin here may have been more of an ice cliff, in contrast to the ice margins forming GZW 2. Furthermore, we suggest that the subglacial basins would have continued to be active during this time, undergoing periods of infilling and rapid discharge, however, probably at a much slower discharge rate than during stage 2.

5.1.4. Stage 4

Sentralbankrenna Ice Stream may not have been stable at GZW 2 for a significant amount of time before it retreated back to GZW 3, based on its less prominent morphology. The location of GZW 3 marks the start of stage 4 (Fig. 8D). GZW 3 extends across the trough and is not particularly prominent due to being heavily scoured and overprinted. Based on the eastern extent of GZW 3, which extends almost to GZW 4, it is likely that it was formed during the time when the Sentralbankrenna Ice Stream began to split away from the slower moving inter-ice stream ice over Thor Iversenbanken and deposited GZD 9 (Fig. 2E). Due to the large amount of scourmarks on the seafloor it is difficult to determine the ice flow direction for the deposition of GZW 3. This makes it unclear whether: 1) ice came from the Sentralbankrenna ice stream orientated ENE-WSW; or 2) the ice dynamics in the northeastern Sentralbanken, an area previously inferred to be occupied by slower moving ice (Bjarnadóttir et al., 2014), underwent a change in regime, from a slow-to-more active ice mass, thus causing it to rapidly readvance in a NW-SE direction and almost reach the ice on Thor Iversenbanken (Fig. 8D). However, based on the sequence of 1) retreat ridges, 2) ice fingerprints and 3) ploughmarks, as well as the general positioning of GZW 3, we infer that this GZW was likely formed by ice flowing from Sentralbanken, which may have buried and eroded older features (i.e. the possible continuation of ice margin towards GZW 4). The sudden change in ice dynamics within the inter-ice stream ice over Sentralbanken may be due to loss of buttressing from the Sentralbankrenna Ice Stream, which by this stage could have retreated back to GZW 4 or even GZW 5. Should this be the case, then we speculate that the ice from Sentralbanken had a relatively fast readvance into the trough prior to retreating back to shallower ground, where the ice margin stabilised and formed several retreat ridges at its front. Prior to its stabilisation, the ice front may have experienced high calving rates and during periods of pervasive sea-ice, sections of the ice front were able to extend forming ice-fingerprints before calving.

5.1.5. Stage 5

Stage 5 (Fig. 8E) relates to the deposition of GZW 5 by the Sentralbankrenna Ice Stream and to the retreat ridges seen in upper Sentralbankrenna downstream of GZD 7 deposited by inter-ice stream ice coming from northern Sentralbanken. There are clear uncertainties in regards to the overall ice margin position and extent in the trough during this stage. We suggest that ice coming from the northern part of Sentralbanken, in the inferred inter-ice stream bank area, may have had an ice cliff margin, been relatively stable and experiencing a slow retreat, based on the deposition of the small retreat ridges and then the larger recessional moraine (GZD 7; Figs. 2E and 8E).

GZW 5 is suggested to be an intermediate GZW as defined by Bjarnadóttir et al. (2013) and Shackleton et al. (submitted). With a highly dynamic ice margin, this GZW will have been deposited under different levels of margin stability across the ice front, with a distinct difference between the west and eastern section. Differing water depths and the presence/lack of subglacial meltwater may have led to the distinct character of deposits within these two areas.

GZW 5 clearly displays different morphologies from the east to the west, with the shallower eastern extent having a more characteristic symmetric wedge like shape most likely formed through a line source deposition and based on its size and morphology may have been stable for a long period or had considerable and/or rapid sediment deposition. Whereas the western extent of GZW 5, displays a radial fan-like shape located in the deeper part of the trough, formed by point source deposition, such as from a subglacial meltwater conduit. This western extent may have experienced periods of stability enabling the formation of such large ice proximal fans.

While it is clear that subglacial meltwater played a significant role in the formation of these fans, little indication for meltwater was observed in this area. However, since the western extent of

GZW 5 was located in a deeper section of the trough, it is possible that this section of the ice margin had higher calving rates due to increased marginal buoyancy (e.g. processes suggested by Pelto and Warren, 1991; Benn et al., 2007), as supported by the dense area of iceberg ploughmarks downstream of this area (Fig. 7A). This area of the ice margin, in contrast to the shallower areas adjacent, will therefore have had ice funnelled into it, providing a low-pressure pathway for meltwater. Thus, the ice margin over the western part of GZW 5 is likely to have been extremely sensitive to oceanographic changes (i.e. sea temperature and sea-level), since it was located in the deeper section of the trough and thus, may have been the first area to have responded to environmental changes during this stage, forming a large embayment.

Overprinting the eastern side of GZW 5 are several large semilinear iceberg ploughmarks containing corrugation ridges. It is unclear whether the formation of these relates to an ice margin break-up due to floatation caused by the infiltration and undercutting of warmer ocean waters and/or to sea level rise into a subglacial margin cavity, or whether these ploughmarks relate to a highly dynamic calving margin when the ice front was located at GZW 6 (c.f. section 5.1.6). In the case of the latter, large deep-keeled icebergs may have become stuck on the shallower GZW 5 crest, possibly in conditions of pervasive sea ice, and been influenced by tidal motion, forming the corrugation ridges through similar processes to that which are suggested for similar observations in Greenland fjords (Amundson et al., 2010), on the northern Svalbard shelf (Dowdeswell and Hogan, 2016) and in West Antarctica (Jakobsson et al., 2012b; Graham et al., 2013).

It is uncertain whether the ice margin over GZW 5 and the ice margin over the retreat ridges downstream of GZD 7 were coeval. Although, we have inferred based on the direction and density of iceberg ploughmarks downstream of GZW 5 that the ice margin may have extended across the trough, with the ice front over the western part of GZW 5, having formed an active calving bay (Fig. 8E).

5.1.6. Stage 6 — final retreat phase

Stage 6 is the final retreat phase in this reconstruction and relates to the northern-most mapped GZW 6 and GZD 7 (Fig. 8F), which may have been active at the same time. During this stage, the inter-ice stream ice was likely to have had a longer stillstand, enabling it to deposit a large recessional moraine (GZD 7; Fig. 2E). The narrow and high symmetric morphology of this deposit indicates the possibility of an ice cliff as the ice margin, which underwent very little calving, hence the clear preservation of the features downstream of this deposit. During a later phase of deglaciation, this margin may have continued to retreat and migrate towards the shallower bank areas, where it once again stabilised and began to exhibit slow retreat and deposit retreat ridges.

GZW 6 is a very good example of a classic GZW (e.g. Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015), with a dense area of MSGLs overprinting the ice proximal side of the GZW, indicating that ice was very active and streaming until the final stages of the GZW formation. Based on the asymmetric shape and large size of GZW 6, as well as the positioning of MSGL 4, we infer that this was formed by rapid deposition of sediment when the Sentralbankrenna Ice Stream was undergoing a final advance/retreat cycle. It is likely that the Sentralbankrenna Ice Stream continued to be fed by the ice divide over Storbanken.

5.2. Influence of the Sentralbankrenna glacial system on the BSIS

The glacial fluctuations occurring within Sentralbankrenna would have significantly contributed to the overall dynamics of the BSIS, based on the large size (>30,000 km^2) and critical location within the central part of the former ice sheet. During the initial phase of deglaciation following the LGM, Sentralbankrenna Ice Stream acted as a tributary to the adjacent Bjørnøyrenna Ice Stream, and therefore likely had a strong influence on its behaviour (Fig. 8A). However, this influence lessened as deglaciation continued into its later phases and we suggest that the two ice streams were separated by non-streaming ice located over Sentralbanken (Fig. 8B), thus significantly reducing the catchment area for the Bjørnøyrenna Ice Stream.

Following the identification of several large grounding zone deposits, studies have suggested that the Bjørnøyrenna Ice Stream experienced episodic retreat (Andreassen et al., 2008; Winsborrow et al., 2010; Bjarnadóttir et al., 2014). Similarly, during the later phases of deglaciation in the central Barents Sea, when the ice was more topographically controlled, Sentralbankrenna Ice Stream underwent a step-wise, episodic retreat as inferred from the landform assemblages of large GZW in combination with MSGLs (Fig. 8B-F). This pattern of rapid ice break-up punctuated by short stillstands or readvances is consistent with a general model for marine ice stream retreat proposed by Ó Cofaigh et al. (2008) and Dowdeswell et al. (2008).

In the adjacent bank areas, Sentralbanken and Thor Iversenbanken, the landform assemblage observed is that of slower, non-streaming, inter-ice stream ice. The features observed in these areas are similar to those identified in other high latitude palaeo-inter-ice stream areas, such as in the northwestern Svalbard (Ottesen and Dowdeswell, 2009) and eastern Amundsen Sea Embayment (Klages et al., 2013). Bjarnadóttir et al. (2014) proposed the presence of a smaller, local ice dome located over north Sentralbanken and based on the geomorphology in our study area, we suggest that the ice flow direction is consistent with a persistent mass of ice over Sentralbanken.

The presence of meltwater features, such as tunnel valleys and subglacial basins, indicates that there must have been an extensive and active subglacial hydrological system, which strongly influenced the dynamics of the overlying ice by: 1) facilitating ice streaming through lubrication of the bed; and 2) promoting dynamic ice margin conditions (i.e. formation of western part of GZW 5). The presence of several large subglacial meltwater systems associated with high levels of meltwater discharge, such as the tunnel valleys, in combination with highly dynamic calving margins in the upper Sentralbankrenna, suggest that the ice was still dynamically active and warm based.

6. Conclusions

Unlike the western Barents Sea which has been extensively investigated, the central Barents Sea remains scarcely studied. Observations and insights gained in this study have contributed to the overall knowledge of the BSIS deglaciation, particularly during the later stages. Analysis of a new high resolution bathymetric dataset, presented in this study, revealed glacial landform assemblages related to both the former Sentralbankrenna Ice Stream and the inter-ice stream areas in the adjacent banks, Sentralbanken and Thor Iversenbanken, in the central Barents Sea. Several large GZWs and MSGLs, as well as many smaller grounding zone deposits and meltwater associated features were observed, forming the basis for a 6-stage reconstruction of the deglaciation since the LGM (Fig. 8A—F).

While Sentralbankrenna Ice Stream underwent episodic retreat, with periods of rapid ice break up punctuated by margin stillstands or short readvances, the bank areas underwent much slower retreat rates, allowing numerous retreat ridges and recessional moraines to be formed. Further, the observed glacial meltwater features (tunnel valleys and subglacial basins) suggest that subglacial meltwater was abundant in this central part of the former ice sheet. The activity of subglacial water is likely to have greatly influenced the dynamics of overlying ice, and we suggest that periodical fill/release of water from subglacial lakes might have facilitated fast flow both for the Sentralbankrenna and Bjørnøyrenna Ice Stream.

Acknowledgements

We would like to acknowledge Kartverket (the Norwegian Hydrographic Service), the Geological Survey of Norway and the MAREANO programme for the provision of this dataset, used here under a CC by 4.0 license (https://creativecommons.org/licenses/by/4.0/legalcode). This is a contribution to CAGE (Centre for Arctic Gas Hydrate, Environment and Climate) that is funded by the Research Council of Norway through the Centre of Excellence funding scheme grant no. 223259. Furthermore, we would like to acknowledge the editor and reviewer, Neil Glasser, and our second reviewer, Stephen Livingstone, for their insightful and constructive comments, which have greatly helped to improve this manuscript.

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Paper II

An interconnected palaeo-subglacial lake system in the central Barents Sea.

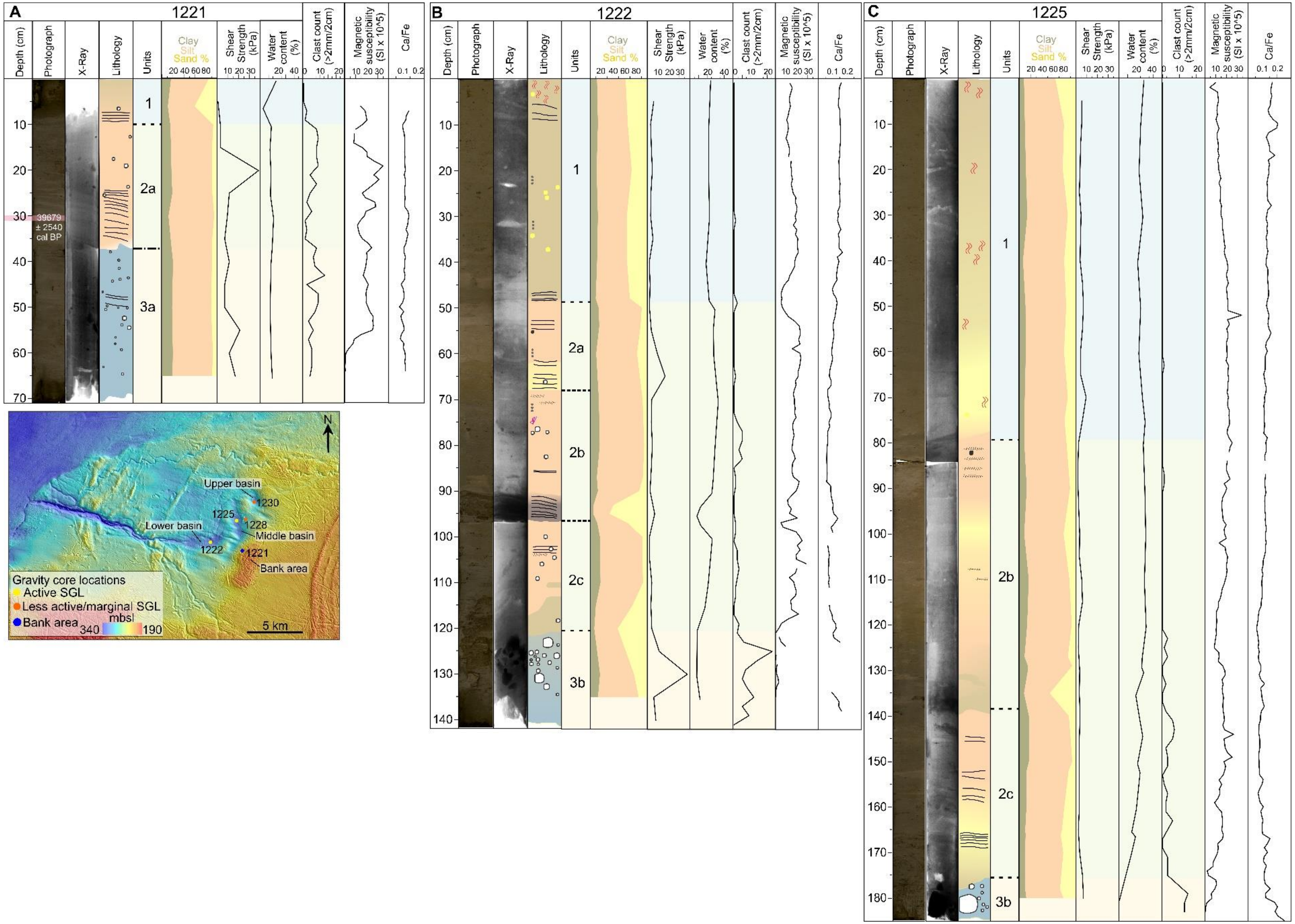
Mariana Esteves, Denise C. Rüther, Monica C. M. Winsborrow, Stephen J. Livingstone, Karin Andreassen, (in review).

Paper III

The influence of ice dynamics on subglacial meltwater systems: an example from the central Barents Sea.

Mariana Esteves, Monica C. M. Winsborrow, Calvin S. Shackleton, Lilja R. Bjarnadóttir, Karin Andreassen, (In Prep).

Supplementary material



A
1221
B
1222
C
1225
Depth (cm)
Photograph
X-Ray
Lithology
Units
Clay
Silt
Sand %
Shear Strength (kPa)
Water content (%)
Clast count (>2mm/2cm)
Magnetic susceptibility (SI x 10^5)
Ca/Fe
39679 ± 2540 cal BP
1
2a
2b
2c
3a
3b
Upper basin
Lower basin
Middle basin
Bank area
1221
1222
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1230
Gravity core locations
Active SGL
Less active/marginal SGL
Bank area
mbsl
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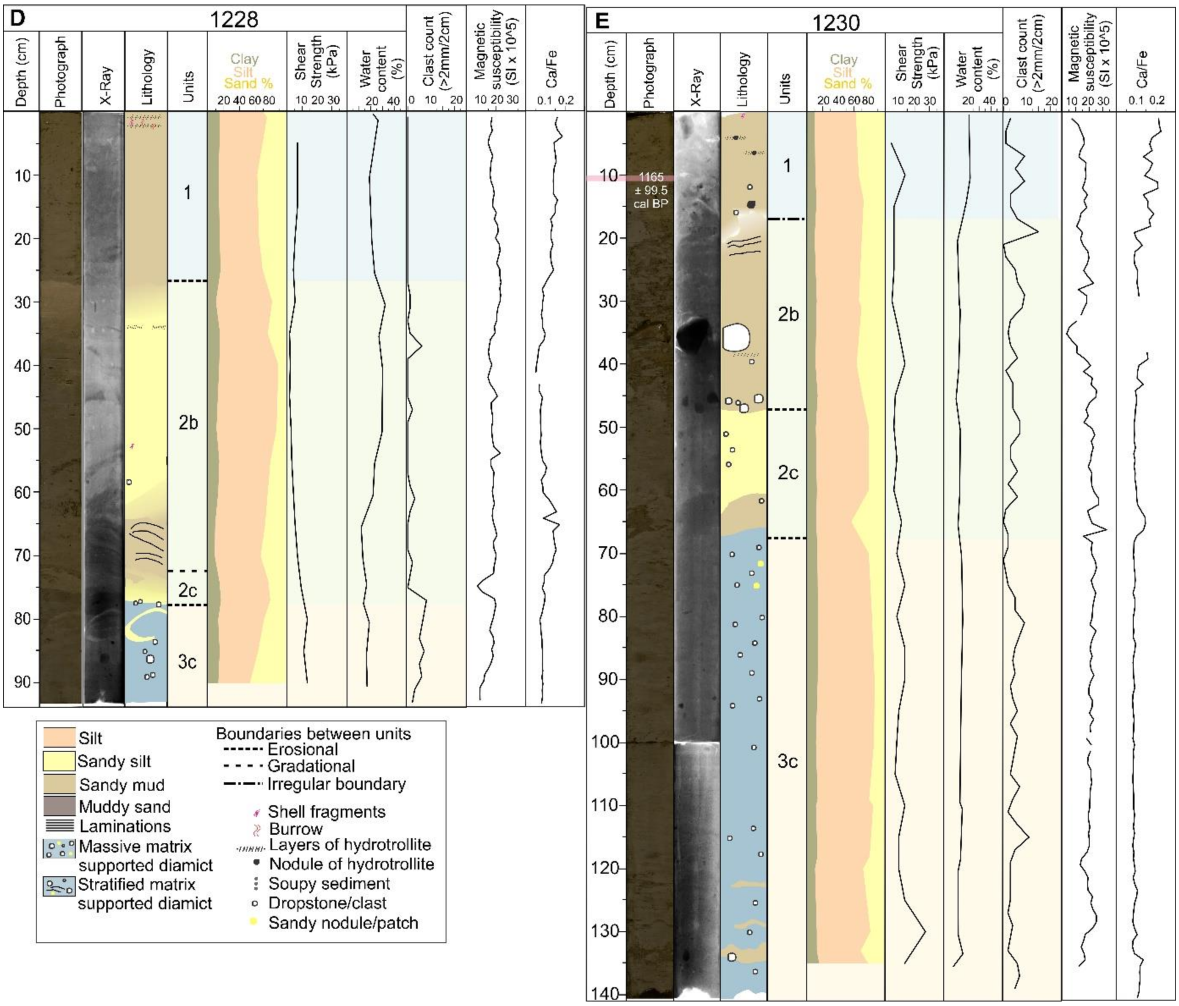
190
5 km
N



Supplementary figure 1. A-E) Overview of all the cores and their lithology, granulometry, and physical properties as in paper 2. However, in these figures we have included the unused magnetic susceptibility and XRF Ca/Fe results. These results were unused in paper 2, but we suggest that they might be important for future investigations into palaeo-subglacial lake depositional environments.