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Late Weichselian ice-sheet dynamics and deglaciation history of the northern Svalbard margin

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Oscar Fransner

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Abstract

This thesis presents new results from marine geological and geophysical studies based on sediment gravity cores, airgun, subbottom acoustic and high-resolution swath bathymetric data from fjords, the continental shelf and slope north of Nordaustlandet, Svalbard. From these records, the glacial landform assemblages as well as the glacial and postglacial sedimentary environments were interpreted. Where possible, ^{14}C dating was performed to reconstruct the timing of deglaciation. Research presented in this thesis contributes to a better understanding of the extent, timing and rates of decay of the Svalbard-Barents Sea Ice Sheet (SBIS) during the Late Weichselian, as well as to the understanding of the glacial and interglacial processes that have shaped the northern Svalbard margin.

Kvitøya and Albertini Troughs hosted streaming ice during the Quaternary. While Kvitøya Trough has a well-developed Trough Mouth Fan (TMF) at its mouth, Albertini Trough mouth is withdrawn and lacks a TMF. The extra accommodation space for sediments created by downfaulted bedrock below Albertini Trough mouth is likely the main reason for the lack of a TMF off Albertini Trough, which shows the influence of local structural geology on TMF build-up.

Depth contours of the International Bathymetric Chart of the Arctic Ocean (IBCAO) indicate the presence of cross-shelf troughs off Duvefjorden and Albertinibukta, suggesting the source areas for the repeated ice flows feeding Albertini Trough during the Quaternary. Subglacial landforms in Rijpfjorden and Duvefjorden suggest northerly flowing ice streams in both fjords during the Last Glacial Maximum (LGM). The higher elongation ratio of the subglacial landforms in Duvefjorden and the deeper fjord basin there, suggest a larger and/or more focused ice flow in Duvefjorden compared to in Rijpfjorden.

Listric fault scarps in the Quaternary sediments of Albertini Trough mouth formed during early deglaciation due to a locally unstable sediment stratigraphy there. Overridden terminal moraines with De Geer and push moraines on top, as well as a grounding zone wedge superimposed by glacial lineations indicate multiple readvances of the grounded ice sheet during a generally slow deglaciation of the central Albertini Trough. The deglacial dynamics in Albertini Trough are partly attributed to the shallowing and narrowing of the trough itself, which facilitated ice sheet grounding there. A southwards orientation change from S-N to SSW-NNE of the glacial lineations in Albertini Trough indicates that the ice flow from Duvefjorden became increasingly dominant during deglaciation. Radiocarbon dates from the continental shelf west of Albertini Trough suggest that the retreat of the SBIS front significantly increased with time during deglaciation.

The absence of retreat-related landforms in Rijpfjorden's deeper areas (>-210 m) as well as in Duvefjorden, suggests the presence of floating glacier fronts influenced by calving during deglaciation. Radiocarbon dates from inner Rijpfjorden and central Duvefjorden indicate that these areas were deglaciated before c. 10.6 ka and 11.0 ka, respectively. The thickness of the deglacial-postglacial sediments in Rijpfjorden and Duvefjorden reaches up to 26 m, which gives linear accumulation rates of c. 66 cm/kyr. The high sedimentation rates and steep slopes

in the fjords were important for triggering mass flows, common in both fjords during the Holocene.

Preface

This dissertation is submitted in partial fulfillment of the requirements for the Degree of Philosophiae Doctor (PhD) in Science. This 3-year PhD work was supervised by Prof. Riko Noormets from the University Centre in Svalbard (UNIS) and Prof. Karin Andreassen from UiT The Arctic University of Norway. This research received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n° 317217. The research forms part of the GLANAM (GLAciated North Atlantic Margins) Initial Training Network.

The thesis work was mainly conducted at UNIS. Secondment took place at the Geological Survey of Denmark and Greenland (GEUS), Copenhagen, according to the agreements of GLANAM. The majority of the sedimentological work was conducted at the Department of Geological Sciences at Stockholm University. The candidate attended the transferrable skills courses and workshops organized by GLANAM. The transferrable skills courses covered topics of communication, entrepreneurship, scientific writing and communication with media. To obtain PhD education equivalent to 30 credit points, the candidate attended both mandatory courses at UiT and optional courses at UNIS. These courses covered both regional and more specified topics of the Arctic together with a course in research ethics. For data collection and PhD education, the candidate participated and assisted in four research cruises with R/V Helmer Hanssen and two cruises including both R/V Viking Explorer and M/V Stålbas. Two excursions were carried out on sea ice around Svalbard using snow mobiles.

The results and progress of the PhD work were presented at the GLANAM workshops which took place in the following locations: Jæren, Norway; Durham, England; Copenhagen, Denmark; Longyearbyen, Svalbard; and Coleraine, Northern Ireland. Furthermore, the candidate attended three PAST gateways conferences that took place in Trieste, Italy; Potsdam, Germany; and Trondheim, Norway. For the PAST gateways conferences, the results were presented on posters. The candidate was also an associated researcher in the FROZEN project, and held three oral presentations during the FROZEN workshops, which took place in Stockholm/Uppsala, Sweden and in Longyearbyen, Svalbard.

This three years PhD work has resulted in three research papers as well as in a short contribution to "Atlas of submarine glacial landforms: Modern, Quaternary and Ancient". The candidate has also contributed as coauthor to the papers "Icesheet 1.0: A program to produce paleo-ice sheet reconstructions with minimal assumptions (Gowan et al., 2016)" and "Past ice flow in Wahlenbergfjorden and its implications for late Quaternary ice sheet dynamics in northeastern Svalbard (Flink et al., 2017)".

This doctoral thesis is a synopsis of the three research papers focusing on the Late Weichselian extent, timing and rates of decay of the SBIS north of Nordaustlandet, as well as on glacial and interglacial processes that have shaped the region. The research papers are:

Paper I

O. Fransner, R. Noormets, A. Flink, K. Hogan, M. O'Regan, M. Jakobsson, 2017. Glacial landforms and their implications for glacier dynamics in Rijpfjorden and Duvefjorden, northern Nordaustlandet, Svalbard. Journal of Quaternary Science 32:437-455.

Paper II

O. Fransner, R. Noormets, A. Flink, K. Hogan, J.A. Dowdeswell, 2017. Sedimentary processes on the continental slope off Kvitøya and Albertini Troughs north of Nordaustlandet, Svalbard – the importance of structural-geological setting in trough-mouth fan development. Marine Geology doi:10.1016/j.margeo.2017.10.008.

Paper III

O. Fransner, R. Noormets, T. Chauhan, M. O'Regan, M. Jakobsson, 2018. Late Weichselian ice stream configuration and dynamics in Albertini Trough, northern Svalbard margin. Arktos doi 10.1007/s41063-017-0035-6.

Acknowledgements

There are many people who have been important during this journey of completing my PhD thesis. Everyone from supervisors and colleagues to family and friends has been valuable. First out is my main supervisor Prof. Riko Noormets. Thank you for making this PhD position and thesis possible to me. Joining your Arctic adventures has given me a lot of knowledge and experience I could not even dream of before. Whether in big or small ships, in calm or wavy seas, with or without icebergs – it was always great fun, and I learned a lot during the journey. I am also grateful for yours, Kelly's and Julian's time, patience and advice, which have improved all the work behind this thesis.

I thank UNIS for hosting me during the last three years. It is a great university centre with a unique atmosphere. I know it will be hard to top that working environment in my future career. I also thank the Department of Geological Sciences at Stockholm University for letting me using their great sediment core facilities and for all the help and support I got there. Special thanks here go to Malin Kylander, Eve Arnold, Carina Johansson, Matt O'Regan and Martin Jakobsson.

As proud as I am for having been a part of UNIS, I am equally proud for having being a part of GLANAM, which funded this work and therefore made it possible together with Riko. GLANAM also gave me the opportunity to get to know many high-ranked scientists all over Europe within my research field. All the workshops and secondments I have joined through GLANAM have both greatly improved this work and also developed me on a personal level. The GLANAM network has also given me friends for life from the other fellows that I have worked with. I am sure that these connections will be of greatest importance also for our future careers. Having such a strong network already during the time as a PhD student is worth a lot. Although the whole GLANAM team was a great group of people, I would like to give the two fellows Benjamin Bellwald and Dimitrios Ktenas some extra attention. I always had great fun with you at the GLANAM locations wherever we met.

I thank the crews of R/V Helmer Hanssen, M/S Stålbas, and Kenneth at Viking Explorer for making it possible for me and the rest of my research group to acquire our data. No matter if we went to fjords, troughs or continental slopes the operations were professional and the moods were always good.

There are many people that have been important behind the scenes as well. Living in Longyearbyen gives the opportunity to see many new faces from all over the world due to the high turn-over rate of people. This is very rewarding, but sometimes also exhausting. I am therefore happy that I had such a great company of friends who have stayed here throughout most of the seasons when I was here. Special thanks go to Anne, Teena, Dani, Zoe, Hanna, Lena, Aleksandra, Mark, Martin, Pete, Sri, Anatoly, Sebastian, Petter, Xiangcai, Graham, Chris, Christian and Marius who have been colleagues and good friends.

Isolde, that you moved up here and stayed through both polar night and polar day gave me extra support to finish this work. Thank you for the understanding and advice that you gave me during busy times and for all the good moments that made the end of my stay here even better than what I could imagine.

I also want to thank Martin Wikmar and Robin Dymlind at Clinton Marine Survey for their patience with me graduating, but also because they kindly let me use their facilities to improve this work.

Last but not least, my family and friends back home in Sweden. Our continuous contact and visits that both you and me have been doing during these three years have given me important guidance and energy boosts that made it possible for me to finish this work.

This research has received funding from the People Programme (Marie Curie Actions) of the European Union’s Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n° 317217. The research forms part of the GLANAM (GLAciated North Atlantic Margins) Initial Training Network.

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1 Introduction

1.1 General background

The global climate is highly influenced by the alternation between cold glacials and warmer interglacials (e.g. Faleide et al., 1996; Svendsen et al., 1999). The glacial-interglacial alternations are significantly affected by solar insolation, which largely depends on the Milankovitch cycles (Imbrie and Imbrie, 1979). The Milancovitch cycles consist out of precession of equinoxes, oscillation of the earth's axial tilt and eccentricity of the earth's orbit (Imbrie and Imbrie, 1979) (Fig. 1). These cycles have dominant frequencies of 23 k.y, 41 k.y and 100 k.y respectively (Imbrie and Imbrie, 1979). Each glacial and interglacial period has been assigned to a "marine isotope stage" (MIS), with even and uneven numbers respectively (Svendsen et al., 1999). An exception to this is the last glacial cycle (MIS 2-4), which includes an interstadial interval MIS3, that is not considered a full interglacial period.

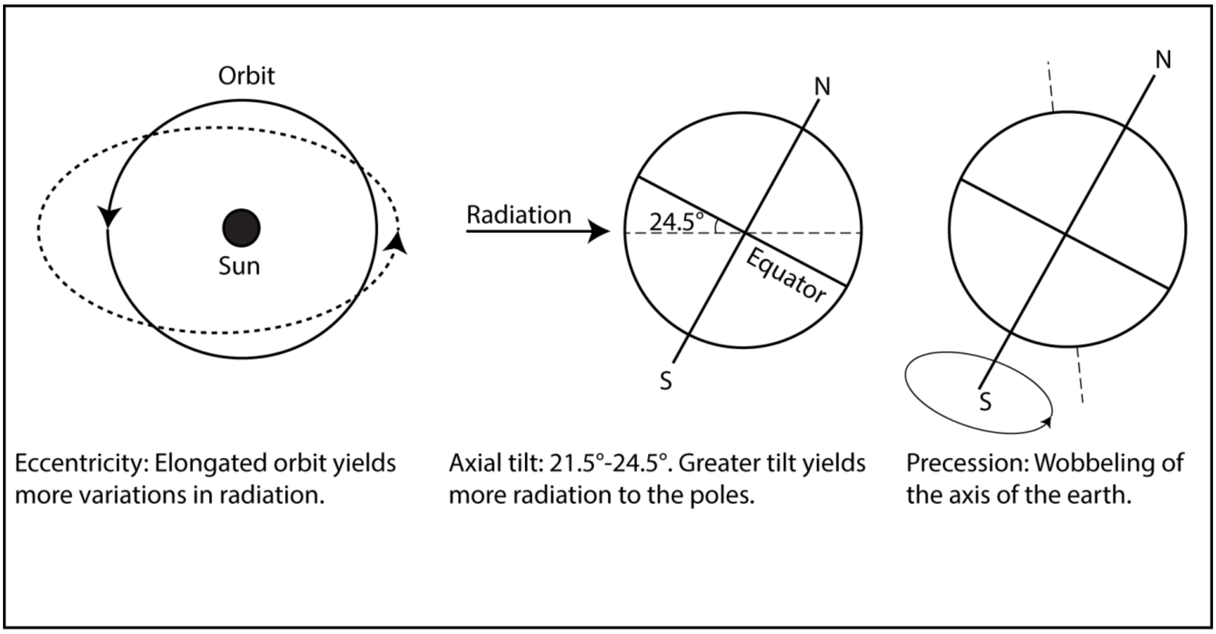

Figure 1. The Milankovitch cycles describes the frequent movements that affect the earth when orbiting the sun (Modified from Lowe and Walker, 1997).

The glacial-interglacial cycles of the Pleistocene significantly shaped the geology of both hemispheres, including the region of Svalbard and Barents Sea (e.g. Svendsen et al., 1999). The Quaternary period and the Pleistocene epoch started ca 2.58 million years ago (Cohen et al., 2013). During the Quaternary glaciations, Svalbard and Barents Sea was under constant influence of the repeated advance and decay of the marine terminating Svalbard-Barents Sea Ice Sheet (SBIS) (e.g. Siegert et al., 2001). The build up towards peak glacial conditions during the last glacial cycle occurred during MIS 2, named in Europe as the Late Weichselian. It started about 28000 years ago, and lasted until the beginning of Holocene epoch, ca 11700 years ago (Cohen et al., 2013).

Ice sheets consist of slow flowing inter-ice stream regions that separate corridors of faster flowing ice streams which drain the ice sheets (e.g. Bentley, 1987; Ó Cofaigh et al., 2003). Thick ice in topographic depressions generally leads to higher internal deformation and basal sliding, which facilitates faster ice flow there (Clarke et al., 1977). The capability of ice streams to affect the ice sheet mass-balance make them important to understand. In particular, marine terminating ice streams are of interest since they have the potential to rapidly transfer ice from the interior to the margin of ice sheets, where mass-loss commonly occurs due to calving of the terminus (e.g. Anandakrishnan and Alley, 1997). Rapid transfer of marine terminating ice into the sea therefore has the potential to influence the global sea level (e.g. Clark, 1994; Stokes et al., 2005). The oceanic as well as climatic conditions at the margins of ice sheets are therefore closely related to the future state of these ice sheets. To predict how marine based ice sheets interact with climate is hard, however it is clear that rapid transfer of marine terminating ice into the sea has potential to influence global sea level (IPCC 2014). Therefore, in order to better understand the interaction between climate, sea-level change and presence of glaciers, it is important to study the dynamics of marine-based ice sheets.

It is difficult to observe and monitor glacial dynamics and processes of contemporary glacier beds due to limited access to such environments. However, paleo-ice sheets are often regarded as analogues to modern ice sheets (Jakobsson et al. 2011; O'Cofaigh 2012). Ice flows often leave landform records that vary with the configuration and dynamics of the ice flow as well as with the type of substrate that the ice flows are eroding (Clarke et al., 1977). By studying the types and distribution of glacial landforms it is possible to reconstruct configuration and dynamics of paleo ice sheets, which also is valuable data for ice sheet modellers and their prediction of contemporary ice sheet behaviour. Interpretations of paleo landform records can be supported by the deglacial and postglacial sediment stratigraphy from where organic matter can be retrieved for radiocarbon dating. These dates are valuable results in order to time deglaciation and to connect it to other climate-induced processes such as sea-level change. However, due to the erosive powers of the advancing ice, the landform record on the sea bed is generally limited to Late Weichselian ice sheet dynamics. Glacially influenced sediments and morphology reaching further back in time are often better preserved on continental slopes which are protected from ice sheet erosion (e.g. Geissler and Jokat, 2004). It is therefore important to include marine geological studies of the continental slope when studying ice sheet configuration and dynamics.

1.2 Previous studies

The Late Weichselian glacial history is well-studied along the western continental margin of Svalbard (e.g. Andreassen et al., 2004; Ottesen et al., 2005; Landvik et al., 2005; Rebesco et al., 2011; Rebesco et al., 2014). The SBIS was drained by several ice streams flowing across the western continental margin of Svalbard during the LGM (e.g. Siegert et al., 2001). The SBIS reached the shelf edge around 22 ka BP (c.f. Ingolfsson and Landvik, 2013). The many fjords connected to cross-shelf troughs along the western continental margin of Svalbard show the pathway of these ice streams (e.g. Ottesen et al., 2005). Trough mouth fans (TMFs) are found off several trough mouths along the western continental margin of Svalbard, including Kongsfjorden, Isfjorden and Storfjorden (Laberg and Vorren, 1996; Elverhøi et al., 1997; Sarkar et al., 2011). The TMFs indicate that significant volumes of eroded sediments were transported by the ice streams and deposited over the continental shelf edge (e.g. Laberg and Vorren, 1996; Elverhøi et al., 1997). Deglaciation of the western Svalbard margin started ca. 15 ka BP (c.f. Ingolfsson and Landvik, 2013). The ice retreated into the fjords of Svalbard, which were deglaciated around 10 ka BP (Landvik et al., 1998).

Knowledge of the Late Weichselian glacial history of the northern Svalbard margin is relatively scarce compared to the western Svalbard margin. The main reasons for this are the remoteness of the northern margin together with the generally harsh sea ice conditions in the region. In recent years decreasing sea ice cover has allowed surface vessels to reach the western Svalbard margin, which has opened new research opportunities in the region (e.g. Hogan et al., 2010a; b; Batchelor et al., 2011; Chauhan et al., 2015; 2016a,b).

Just like along the western continental margin of Svalbard, the SBIS was drained by fast-flowing ice streams that formed major cross-shelf troughs also along the northern margin. These cross-shelf troughs are Hinlopen, Albertini and Kvitøya Troughs (Batchelor et al., 2011; Hogan et al., 2010a; Noormets et al., 2012). The Hinlopen Trough mouth and adjacent slope have been covered in several papers due to the deposits of the megaslide that was triggered there (e.g. Vanneste et al., 2006; Winkelmann et al., 2008; Hogan et al., 2013).

Although radiocarbon ages are relatively rare from the northern Svalbard margin, it is established that the SBIS reached the continental shelf edge north of Svalbard ca 23-22 ka BP (Chauhan et al., 2016b). Furthermore, deglaciation of this region began ca 18.5 ka BP with calving as a major process for mass-loss of the ice front (Knies et al., 2001; Chauhan et al., 2016b).

1.3 Regional setting of the study area

The Barents Sea region, including the northern continental margin of Svalbard, was located on 20˚N in the Carboniferous, but drifted to 55˚N in the Triassic before it reached its present position (Worsley and Aga 1986; Heafford, 1988; Doré, 1995). The northward drift of the Barents Sea region therefore affected its sedimentary environments, which changed from carbonate to clastic dominated deposits (e.g. Gee et al., 2008). The rifting and breakup of the Norwegian-Greenland Sea reshaped the Barents Sea region. The northwestern continental margin was significantly affected by tectonic uplift which formed Spitsbergen after the breakup of the Norwegian-Greenland Sea (Faleide et al., 1996).

The northern continental margin of Svalbard is today confined by the Nansen Basin to the north, the Yermak Plateau to the west and the Svalbard archipelago to the south (Fig. 2a). The geology of the northern continental margin of Svalbard is dominated by Late Precambrian crystalline rocks of the Hecla Hoek formation (Elverhøi and Lauritzen, 1984; Hogan et al., 2010a). Due to the tectonic forces leading to uplift, the bedrock of the Svalbard margin is relatively faulted (Geissler and Jokat, 2004). The degree of faulting tends to vary locally. While the bedrock below Kvitøya Trough mouth occurs 2.0-2.5 sec TWT below the seafloor, the bedrock off the neighboring Albertini Trough mouth is more downfaulted and present between 2.5 and 4 sec TWT below the seafloor (Geissler and Jokat, 2004).

The archipelago of Svalbard is today situated between 74˚-81˚ N in the Norwegian Arctic (Fig. 2a). Spitsbergen is the largest island of the archipelago, followed by Nordaustlandet. Nordaustlandet is situated in the northeastern part of Svalbard, and is confined by Hinlopen and Kvitøya Troughs to the west and east respectively (Fig. 2b). While the northwards drift of the Barents Sea region is mainly recorded in the sedimentary rocks of Spitsbergen, Caledonian Rijpfjorden granite and migmatite dominate the geology of ice-free areas of northern Nordaustlandet (Flood et al., 1969; Dallmann et al., 2002; Johansson et al., 2005) (Fig. 2b).

Glacial-interglacial processes of the Pleistocene significantly reshaped Svalbard and its continental margin (e.g. Mangerud et al., 1998). The many fjords of the northern Svalbard margin, such as Duvefjorden, Rijpfjorden, Wahlenbergfjorden and Wijdefjorden indicate drainage pathways that were eroded by fast-flowing parts of the SBIS (Ottesen et al., 2005, 2007; Hogan et al., 2010a; Batchelor et al., 2011; Flink et al., 2017; Fransner et al., 2017b). The fast-flowing ice reached out onto the continental shelf and formed larger ice streams that reached the continental shelf edge during glacial maxima (e.g. Hogan et al., 2010a; Batchelor et al., 2011). The ice streams eroded troughs such as Kvitøya and Hinlopen Troughs, which channelized the ice flow and its glacigenic sediment to the shelf edge north of Svalbard (e.g. Hogan et al., 2010a; Batchelor et al., 2011). Progradational sequences in seismic data suggest that both Albertini and Kvitøya Troughs were important drainage conduits during multiple glacial periods of the Quaternary before the Late Weichselian (Geissler and Jokat, 2004).

The SBIS reached the continental shelf edge off northern Svalbard for the last time during the LGM, ca 23-22 ka BP (Chauhan et al., 2016b). The start of deglaciation of the shelf edge is dated to ca 18.5 ka BP (Chauhan et al., 2016b). In general, there are three expected lithofacies of unconsolidated deglacial and postglacial sediments draped on top of the bedrock in the Barents Sea region. They are; (1) diamicton, (2) pebbly mud and (3) massive Holocene mud (Elverhøi et al., 1989). The upper continental slope of the northern Svalbard margin hosts older unconsolidated sediments (Chauhan et al., 2015; 2016b). These sediments are influenced by contouritic currents, mass-flow processes as well as IRD from icebergs (Chauhan et al., 2016b).

The waxing and waning of the SBIS over the northern continental margin of Svalbard has consequently led to recurrent deposition of glacial and interglacial sediments (e.g. Vanneste et al., 2006). The different physical properties of these sediments likely led to a locally unstable sediment stratigraphy (Vanneste et al., 2006). The unstable sediment stratigraphy probably facilitated the Hinlopen megaslide triggered by glacio-isostatic movements during deglaciation (Vanneste et al., 2006). The major reminders of the formerly glaciated northern margin of Svalbard are the two ice caps, Vestfonna and Austfonna, which are covering most of the Nordaustlandet (Hagen et al., 1993) (Fig. 2b). Austfonna is the largest ice cap in Eurasia, which covers an approximate area of 8120 km^2 (Hagen et al., 1993). Overall, the Svalbard archipelago is covered to 57 % by glaciers, which means that glacial processes still are highly active and shape the landscape of Svalbard (Nuth et al., 2013).

The West Spitsbergen Current is strongly influencing the modern oceanography of the northern continental margin of Svalbard, where it is subdivided into the Yermak and the Svalbard branches (e.g. Slubowska et al., 2005) (Fig. 2a). The two branches supply the Arctic Ocean with warm, Atlantic water (Slubowska et al., 2005). The movement of the Svalbard branch along the northern margin of Svalbard is also significant for the distribution and reworking of unconsolidated sediments (Slubowska et al., 2005; Vanneste et al., 2006).

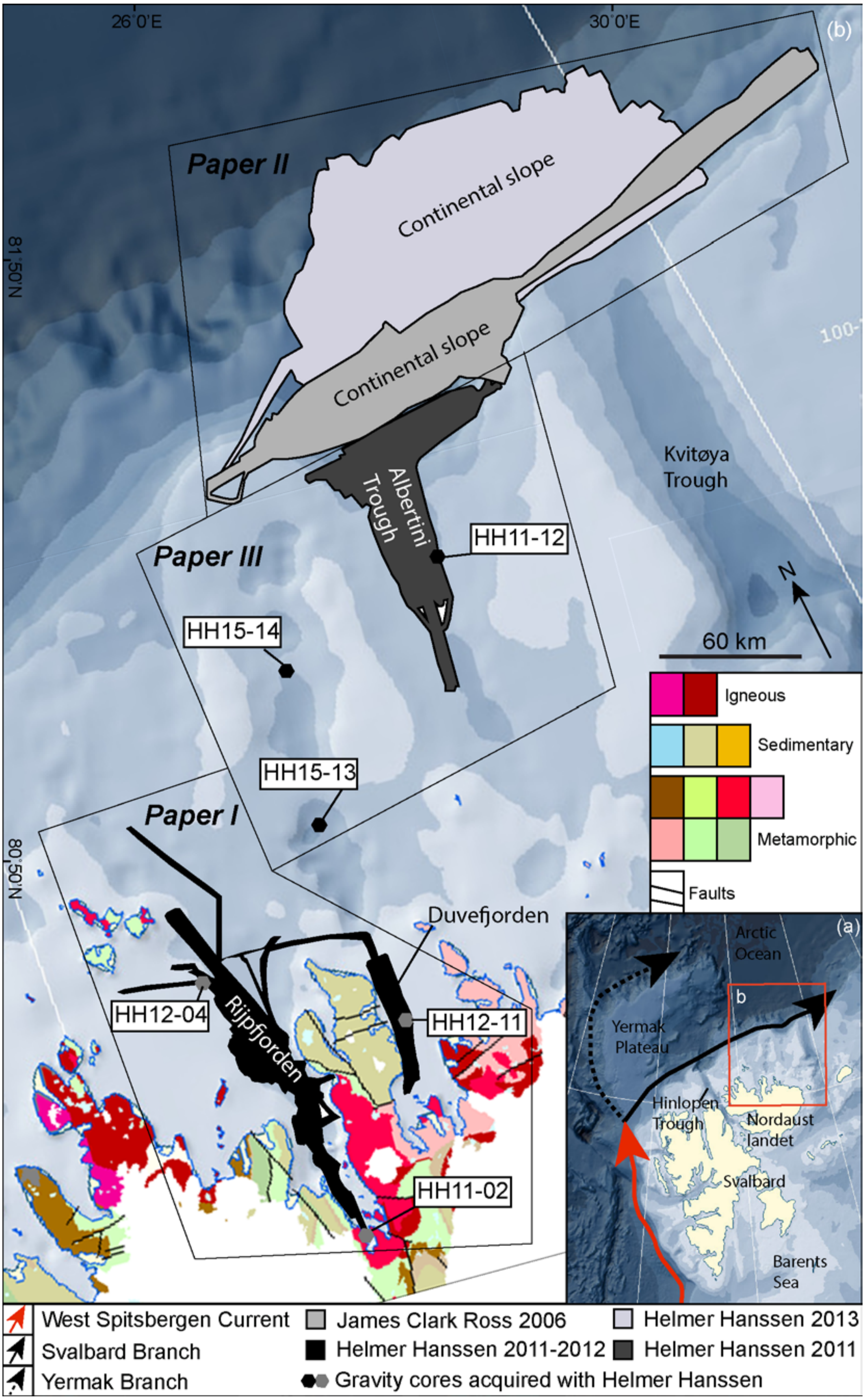

Figure 2. (a) IBCAO map of the Svalbard region. The arrows indicate the West Spitsbergen current and its subdivisions which are the Svalbard and Yermak branches (After Slubowska et al., 2005). (b) The shaded infills of the datasets indicate when the data were collected. The black lines surrounding the datasets show in which

paper the data are included. Most of Nordaustlandet is covered by the Vestfonna and Austfonna ice caps, which are separated by an ice-free area. The terrestrial map is modified from online Svalbardkartet by Norsk Polarinstitutt. The bathymetric background maps are from IBCAO version 3.0 (Jakobsson et al., 2012).

1.4 Objectives of the thesis

This thesis constitutes a part of "Work package 1" in the GLANAM network, titled "Ice sheet history on circum-North Atlantic shelves". Focus in this Thesis is on the northern Svalbard margin, with two main objectives: (1) to contribute to the understanding of the extent, timing and rates of decay of the SBIS on the northern continental margin of Svalbard during the Late Weichselian, and (2) to determine the role of different glacial/interglacial sedimentary processes in shaping the northern Svalbard margin.

In order to fulfill the first objective, multibeam bathymetric data together with ^{14}C ages of sediments are of greatest importance for this study. The bathymetric datasets are used to study the submarine glacial geomorphology, which provides insights into the extent and the rates of decay of the northern SBIS during the Late Weichselian. The ^{14}C ages retrieved from benthic foraminifera in sediment cores are needed to determine the timing of deglaciation, which provide minimum ages for when the area of interest became ice-free.

Sediment cores together with acoustic subbottom and airgun data are used to address the second main objective of this thesis. Correlations of these data have made it possible to interpret the structure and distribution of the quaternary sediment stratigraphy. ^{14}C dating provides the age and linear sedimentation rates of the acoustic stratigraphy. Multibeam bathymetric data provide an additional tool for studying interglacial sedimentary processes on the continental shelf edge and slope.

1.5 Thesis outline

This thesis is divided into two sections. Section 1 is titled "Overview" and contains five separate chapters. The first chapter is the introduction. The introduction gives a general background to this work, presents previous studies from the region and goes through the regional setting of the study area. Finally, the objectives of this thesis are presented in the end of the introduction. The second chapter presents the materials and methods that have been used in order to complete the thesis. The third chapter briefly summarizes each paper in the thesis. It further delineates the contribution of each author to the respective papers. The synthesis of the PhD work is presented in chapter four. The fifth chapter covers future perspectives of this study.

2 Materials and methods

2.1 Materials

Geophysical data from five different scientific cruises are included in this thesis. These data consist of high-resolution swath bathymetric, chirp and airgun data. These data cover most of Rijpfjorden, Duvefjorden, Albertini Trough and a significant area of the adjacent continental slope north of Nordaustlandet (Fig. 2b). Six sediment gravity cores were investigated in these studies; two from Rijpfjorden, one from Duvefjorden, one from Albertini Trough and two from the continental shelf west of Albertini Trough (Fig. 2b). The majority of the data were collected on UNIS marine geological/geophysical cruises on R/V Helmer Hanssen during 2011-2015. The acquisition of the airgun seismic data took place using a Delph GI dual airgun system with a 30 m long streamer. The chirp data were acquired using an Edge Tech 3300-HM (2 kHz-16 kHz) hull-mounted, subbottom profiler. The Edge Tech 3000-HM has a vertical resolution between 6 and 10 m, and a penetration depth of maximum 80 m in soft clays. The multibeam bathymetric data were acquired with a Kongsberg EM300, 30 kHz multibeam echo-sounder system. Parts of the swath-bathymetric data from the continental shelf edge were acquired and provided by the Scott Polar Research Institute, UK using a Kongsberg EM12, 12 kHz multibeam system on board of the RRS James Clark Ross. The specifications for when the datasets were collected and in which paper they are included are presented in Figure 2b.

2.2 Methods

2.2.1 GeoTek Multi-sensor core logger (MSCL)

The MSCL at the Department of Geological Sciences, Stockholm University, Sweden was used for measuring p-wave velocity, bulk density and magnetic susceptibility in 1 cm intervals of the freshly scraped working halves of the cores (Fig. 3).

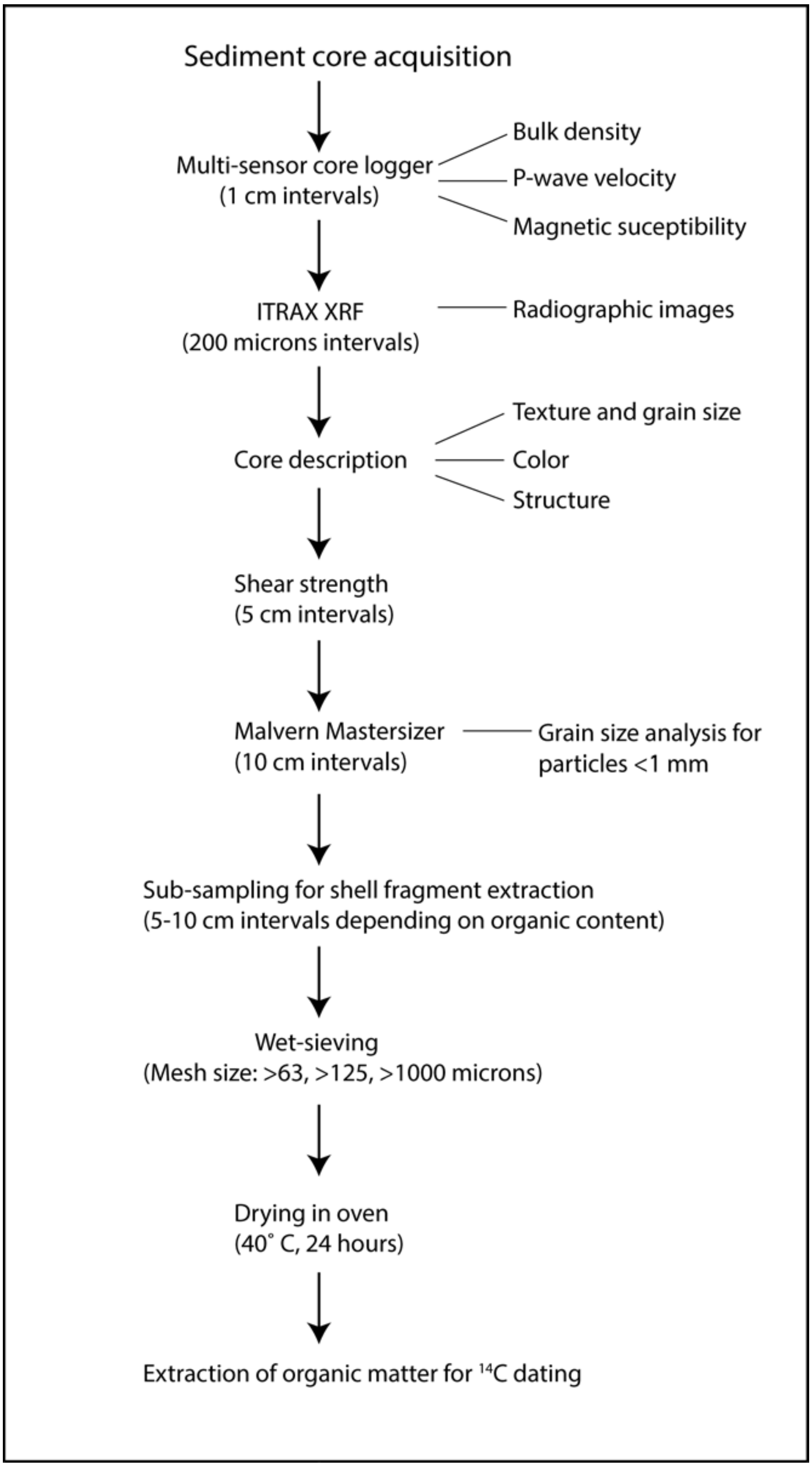

Figure 3. Flow-chart of the sedimentological methods used to complete this thesis.

2.2.2 ITRAX XRF

The ITRAX core scanner at the Department of Geological Sciences, Stockholm University was used for acquiring radiographic images of the working halves of each core presented in this thesis. The radiographic images were acquired with a resolution of 200 microns (Fig. 3).

2.2.3 Lithological-logging and subsampling

The lithological logging consisted of identification of grain size, texture, sedimentary structures and color variations (Fig. 3). The color description was done using the Munsell soil color chart. The destructive part started with shear strength, which was measured in 5 cm intervals using a Controls group liquid limit penetrometer. For grain sizes smaller than 1 mm, a Malvern Master Sizer 3000 laser particle analyser was used at 10 cm intervals (Fig. 3).

Sub samples with dimensions of 5×1 cm (length-width) were taken from all cores for extracting shell fragments and tests of benthic foraminifera for ^{14}C dating (Fig. 3). The samples were wet-sieved and dried in an oven at 40˚ C for 24 hours. Organic matter for ^{14}C dating were primarily extracted from the 125 > µm fraction, but also from the > 63 µm fraction if necessary.

2.2.4 ^{14}C dating

In total, 12 samples of benthic foraminifera and shell fragments were dated for ^{14}C in three different laboratories. Seven of the samples were dated using single stage accelerator mass spectrometry (SSAMS) at the radiocarbon dating laboratory at Lund University, Sweden. Three of the samples were dated using accelerator mass spectrometry (AMS) at the AMS laboratory, ETH Zurich, Switzerland. Two of the samples were dated using AMS at Queen's University, Belfast, Northern Ireland. The seven ^{14}C ages used in paper I were calibrated using Calib 7.1 with the Marine13 calibration curve. Marine13 has a default marine reservoir correction of 405 years (Reimer et al., 2013) which was applied for direct comparison with Chauhan et al., 2016b. Calib 7.1 with the Marine13 calibration curve were also used for the calibration of the five ^{14}C ages in paper III. However, here the regional North Atlantic-Norwegian Sea marine reservoir effect was corrected for (360 ± 30 years) plus a local correction of 105 ± 24 years (giving a reservoir age for Svalbard of 465 ± 24 years). These calibration settings were used for easier comparison with Hogan et al., 2017. The calibrated age ranges in papers I and III as well as in this synthesis are presented as mean of 1sigma standard deviation (68.3%), and are hereafter referred to as "cal. ka BP".

2.2.5 Processing, gridding and mapping of glacial landforms in swath-bathymetric data

The multibeam bathymetric data were processed, gridded and visualized using the QPS Fledermaus software (Fig. 4). The isometric grid cell size varies between 5 and 50 m depending on the depth range covered by the different data sets. The gridded data were exported to Arc Map (version 10.1) where the glacial landforms were mapped as shape files. The final bathymetric maps were made using both Arc Map and Adobe Illustrator (Fig. 4).

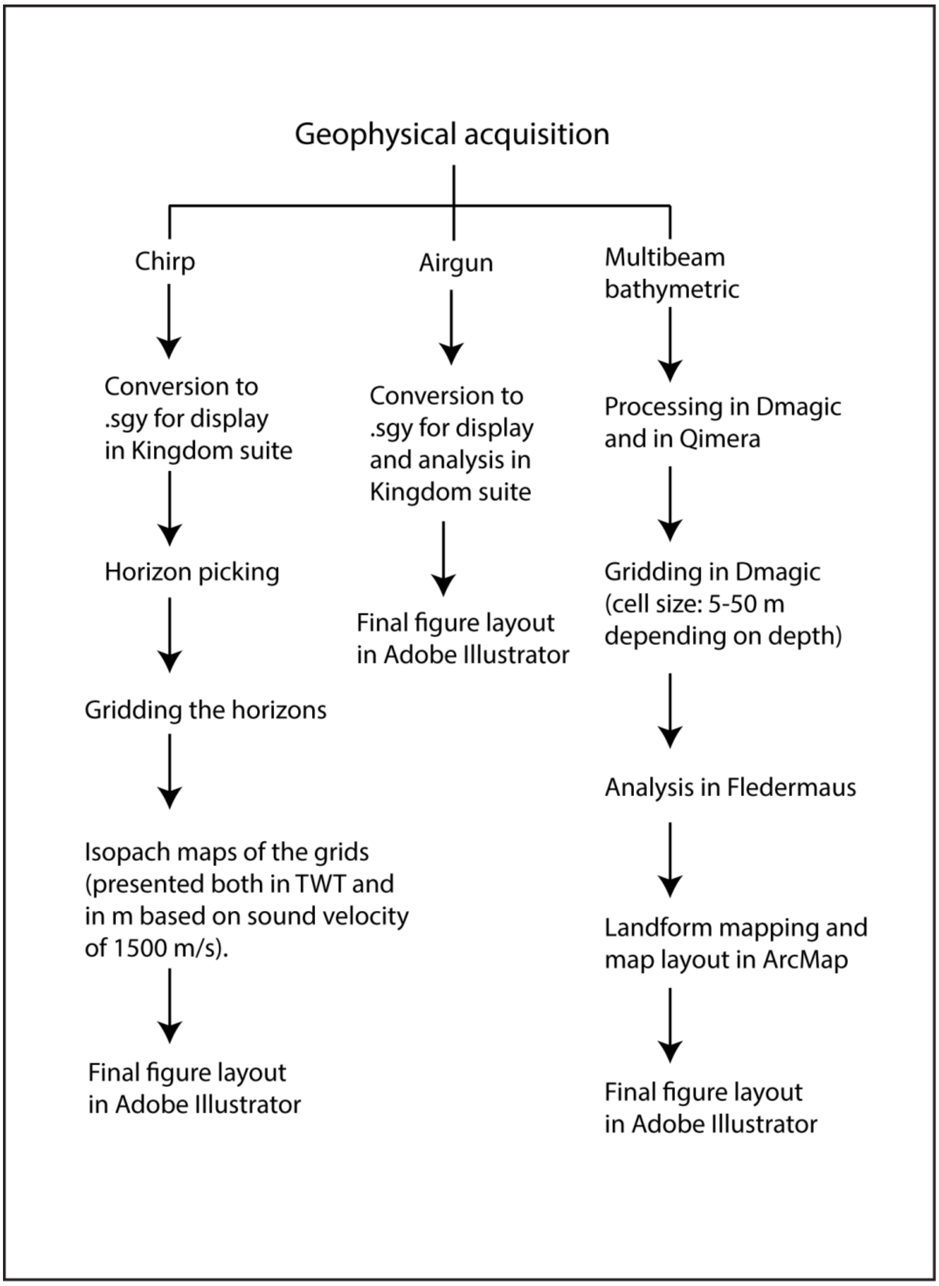

Figure 4. Flow-chart of the geophysical methods used to complete this thesis.

2.2.6 Horizon picking and gridding of acoustic stratigraphy

The chirp subbottom profiles were converted from .jsf to .sgy format using the Discover software by Edge Tech (Fig. 4). The converted .sgy files were imported to SMT Kingdom 8.8 where the data were analyzed. Prominent acoustic reflectors were digitized in order to distinguish different acoustic facies (Fig. 4). The acoustic facies were correlated to the sediment gravity cores when possible. Thickness and distribution maps of the acoustic facies in Rijpfjorden and Duvefjorden were created using "Flex gridding", which is the default gridding algorithm in SMT Kingdom. The thickness maps are presented in both two-way-travel-time (TWT) and in meters, where a sound velocity of 1500 m/s was used for the conversion (Fig. 4). The airgun data was converted to .sgy in order to display it in SMT Kingdom (Fig. 4).

3 Summaries of papers and authors' contribution

3.1 Paper I

O. Fransner, R. Noormets, A. Flink, K. Hogan, M. O'Regan, M. Jakobsson, 2017. Glacial landforms and their implications for glacier dynamics in Rijpfjorden and Duvefjorden, northern Nordaustlandet, Svalbard. Journal of Quaternary Science 32:437-455.

The goal of this study was to reconstruct ice stream configuration and dynamics of Rijpfjorden and Duvefjorden, northern Nordaustlandet, Svalbard. The study was performed using sediment gravity cores together with subbottom acoustic and swath-bathymetric data.

The major findings show that both Rijpfjorden and Duvefjorden were occupied by topographically controlled, northwards flowing ice-streams. The erosional patterns by the ice-streams show significant differences between the fjords, which is suggested to partly be due to the variation in bedrock types. The erosion was probably considerably higher in areas of relatively low-resistant sedimentary bedrock compared to areas of harder, crystalline rock types. Larger elongation ratios of crag-and-tails in Duvefjorden and the comparatively well-developed trough north of the fjord suggest that the ice stream in Duvefjorden was more focused and/or larger compared to the one in Rijpfjorden. Deglaciation was partly controlled by topographical differences, where the ice retreated slower over shallower areas (<210 m water depth) indicated by the presence of De Geer moraines. Assuming annual formation, the spacing of the De Geer moraines gives a retreat rate of 100-250 m/yr from the shallow areas. ^{14}C ages from the sediments indicate that inner Rijpfjorden and central Duvefjorden were deglaciated before c. 10.6 cal. ka BP and 11.0 cal. ka BP, respectively. This gives sediment accumulation rates of up to 66 cm/kyr. Total thickness of deglacial-postglacial sediments in the two fjords reaches up to 26 m. The thickest sediment depositions are correlated to the deeper areas of the fjords where the ice streams eroded deeper into bedrock. Mass-flow deposits were identified in sediment core and chirp data from both fjords. The mass-flows forming these deposits are suggested to have been triggered due to steep slopes in combination with relatively high sedimentation rates during the Holocene.

Contribution of authors

Oscar Fransner did all the laboratory work on the sediment cores as well as the sample preparation for ^{14}C radiocarbon dating. He also prepared the chirp sonar files for the Kingdom suite and created the isopach maps. He was also responsible for drafting the manuscript drafting and figure making. Riko Noormets was responsible for the acquisition of the sediment cores and geophysical data where Oscar Fransner assisted. Riko Noormets also supervised the geophysical processing for this paper. Anne Flink assisted in the sediment laboratory work. Kelly Hogan assisted during the acquisition of the data and corrected language. Both Matt O'Regan and Martin Jakobsson facilitated and supervised the sediment laboratory work. Matt O'Regan also corrected language. All the co-authors have discussed the presented ideas and reviewed the manuscript.

3.2 Paper II

O. Fransner, R. Noormets, A. Flink, K. Hogan, J.A. Dowdeswell, 2017. Sedimentary processes on the continental slope off Kvitøya and Albertini Troughs north of Nordaustlandet, Svalbard – the importance of structural-geological setting in trough-mouth fan development. Marine Geology doi:10.1016/j.margeo.2017.10.008.

The goal of this study was to reconstruct the glacial and interglacial sedimentary processes that shaped the continental slope north of Nordaustlandet, Svalbard. The study was performed using airgun, subbottom acoustic and swath-bathymetric data.

Major findings show that Kvitøya Trough mouth has an adjacent TMF while Albertini Trough is cut back into the shelf edge and lacks a TMF. The continental slope off Albertini Trough is instead dominated by acoustically stratified sediments that are eroded by large canyon networks. The larger catchment area of Kvitøya Trough may partly explain these clear sedimentologial and geomorphological differences, since it supplied the adjacent TMF with more sediment relative to the catchment of Albertini Trough. However, the heavily downfaulted shelf edge of Albertini Trough acted as an accumulation trap for the glacigenic sediments, which limited the volume of glacigenic sediments on the adjacent slope and therefore prevented TMF formation. The little glacigenic input on the continental slope off Albertini Trough therefore facilitated the formation and development of the large canyon systems there. The effect of the downfaulted bedrock on the glacigenic sediments in Albertini Trough clearly highlights the importance of structural-geological setting in TMF development.

The volume of the Kvitøya TMF is small compared to TMFs of the western Svalbard margin. This may be due to the harder, more erosion-resistant bedrock of the northern Svalbard margin and/or because of the larger drainage areas of the troughs connecting to the TMFs along the western margin.

Contribution of authors

Oscar Fransner assisted during the scientific cruise where the majority of the geophysical data were acquired. He also processed and gridded the geophysical data. Oscar Fransner was responsible for drafting the manuscript and figure making. Riko Noormets was responsible for the acquisition of the geophysical data and supervised the geophysical work of this paper. Anne Flink, Kelly Hogan and Julian Dowdeswell assisted in the acquisition of the majority of the geophysical data. Kelly Hogan and Julian Dowdeswell corrected language. The ideas presented were discussed by all the co-authors who also reviewed the manuscript.

3.3 Paper III

O. Fransner, R. Noormets, T. Chauhan, M. O'Regan, M. Jakobsson, 2018. Late Weichselian ice stream configuration and dynamics in Albertini Trough, northern Svalbard margin. Arktos doi 10.1007/s41063-017-0035-6.

The goal of this study was to reconstruct the configuration and dynamics of ice flow in Albertini Trough. Focus was also put on the timing of deglaciation of the continental shelf west of Albertini Trough. Major findings show that Albertini Trough accommodated geologically controlled ice flows during the Quaternary period. These ice flows sourced from Duvefjorden and Albertinibukta, northern Nordaustlandet. The lack of retreat-related landforms in Albertini Trough mouth indicates that the ice margin was floating there during deglaciation. However, a complex landform record in the outer trough consisting of De Geer and push moraines superimposed on a series of terminal moraines with a grounding zone wedge with glacial lineations on top indicate a slow, stepwise retreat with at least three readvances during deglaciation. The southwards narrowing and shallowing of Albertini Trough contributed to the grounding line stabilizations in the trough. However, the several sets of glacial lineations in the trough show a general southward change in orientation, from S-N to SSW-NNE. This orientation change indicates that the ice flow sourcing from Duvefjorden became increasingly dominant during deglaciation. Furthermore, a southward increase in distance between the De Geer moraines in Albertini Trough suggests that the retreat rate increased with time during deglaciation. Two sediment cores from the continental shelf west of Albertini Trough consist of subglacial diamicton with sharp transition to marine mud on top. These transitions were ^{14}C-dated to 15.3 and 14.0 cal. ka BP, supporting the increased retreat rate over the continental shelf during deglaciation. Fresh listric fault scarps in the Albertini Trough mouth indicates recent soft sediment faulting. The faulting indicates relatively unstable sediments, which likely arise due to the heavily downfaulted bedrock as well as different physical properties of the glacial-interglacial sediments.

Contribution of authors

Oscar Fransner assisted during the scientific cruises where the airgun data from Albertini Trough and the sediment cores from the west of Albertini Trough were collected. He also processed and gridded the geophysical data and did the laboratory work on the sediment cores. Oscar Fransner was also responsible for sample preparation of the resulting ^{14}C ages from HH15-13 at 180-181 cm as well as from HH15-14 at 129-130 cm. Oscar Fransner was responsible for drafting the manuscript drafting and figure making. Riko Noormets was responsible for the acquisition of the sediment cores and the geophysical data. He also supervised the geophysical work. Teena Chauhan was responsible for sample preparation of the resulting ^{14}C ages from HH15-13 at 190-191 and 200-201 cm as well as from HH15-14 at 150-151 cm. Sedimentary lab work was supervised by Matt O'Regan and Martin Jakobsson whom also corrected language. The ideas presented in the paper were discussed by all the co-authors who also reviewed the manuscript.

4 Synthesis

The focus of the dissertation lies on the geological evolution of the northern continental margin of Svalbard since the Late Weichselian, in particular the configuration and dynamics of the SBIS, but also how the margin was shaped by glacial and interglacial sedimentary processes since the late Quaternary. Three research papers form the thesis. The first paper presents the configuration and dynamics of Late Weichselian ice flows in Rijpfjorden and Duvefjorden, northern Nordaustlandet. The emphasis is on clarifying the contribution of the ice flows of northern Nordaustlandet to the drainage of the SBIS as well as the timing and behavior of the SBIS during deglaciation of the area. Post glacial sedimentation types and their distribution in the fjords are described using the lithology and physical properties of gravity cores and integrating this with subbottom acoustic data. ^{14}C dates are also used to establish sedimentation rates in the fjords.

The second paper presents both the glacial and interglacial sedimentary processes that have shaped the continental slope north of Nordaustlandet, Svalbard. The area covered by the continental slope adjacent to the Albertini and Kvitøya Trough mouths is considered. The emphasis is on clarifying the significant geometrical and morphological differences that are present below the respective trough mouths and how these relate to glacial and interglacial sedimentary processes.

The third paper presents ice stream configuration and dynamics in Albertini Trough as well as timing of deglaciation of the continental shelf north of Nordaustlandet. The focus lies on explaining the drainage route for the ice flow in Albertini Trough. Also the type of retreat during deglaciation of Albertini Trough is addressed. The ^{14}C ages west of Albertini improve the understanding of the timing of deglaciation from the shelf edge to Rijpfjorden and Duvefjorden.

To summarize, the main objectives with this thesis are to (1) contribute to understanding the extent, timing and rates of decay of the SBIS on the northern continental margin of Svalbard during the Late Weichselian, and (2) to determine the role of different glacial/interglacial sedimentary processes in shaping the northern Svalbard margin. A synthesis of how this thesis addresses these 2 objectives is presented below.

4.1.1 Glacial and interglacial sedimentary processes on the continental slope north of Nordaustlandet during the Quaternary period.

Kvitøya, Albertini and Hinlopen Troughs were important drainage pathways for the SBIS during the Quaternary glaciations (Hogan et al., 2010a; Batchelor et al., 2011; Fransner et al., 2018). While the ice streams occupying Kvitøya and Hinlopen Troughs had comparatively large catchment areas offshore Nordaustlandet, depth-contours of the IBCAO indicate that ice flowing in Albertini Trough mainly sourced in Duvefjorden and Albertinibukta, northern Nordaustlandet (Hogan et al., 2010a; Batchelor et al., 2011; Fransner et al., 2018) (Fig. 5a). The respective ice flows were separated by crystalline bedrock of high erosion resistance until they merged north of Karl XII-Øya (Fig. 5a). The ice flows that fed Albertini Trough during the Quaternary period were therefore geologically controlled (Fransner et al., 2018).

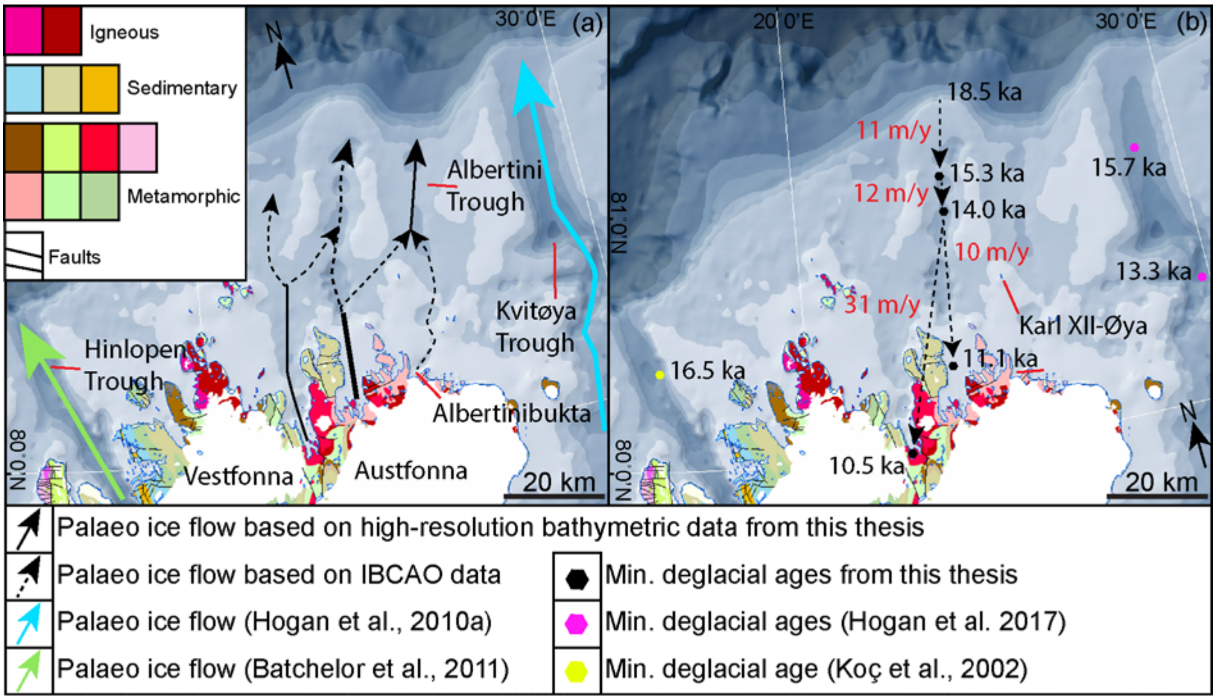

Figure 5. Suggested LGM ice stream drainage routes on the continental shelf north of Nordaustlandet, Svalbard (arrowed). The different thicknesses of the arrows suggest relative differences in ice volume in the troughs, where thicker arrows equals larger ice volumes. Bathymetric background map is from IBCAO v.3.0 (Jakobsson et al., 2012). The bedrock geology is from Svalbardkartet (Norsk Polarinstitutt). (b) Deglaciation speed (numbers in red) is based on minimum deglacial ages from this thesis (black dots) together with the shelf edge deglaciation of 18.5 cal. ka BP from Chauhan et al., 2016b. Minimum deglacial ages from Hogan et al., 2017 and Koc et al., (2002) are presented as purple and light-green dots respectively.

The repeated ice stream activity in Kvitøya, Albertini and Hinlopen Troughs during subsequent glacials eroded glacigenic sediments that were transported northwards (Hogan et al., 2010a; Batchelor et al., 2011; Fransner et al., 2017a). In the Kvitøya and Hinlopen Troughs, the northwards moving ice streams delivered glacigenic sediments to the shelf edge which eventually led to major sediment accumulation on the continental slope and formation of TMFs (Fig. 6a) (Geissler and Jokat, 2004; Hogan et al., 2010a; Batchelor et al., 2011; Fransner et al., 2017a). The debris-flow and/or levee-deposits on the lower continental slope and rise suggest that a significant amount of the glacigenic sediments from Kvitøya Trough mouth bypassed the upper slope. The bypassing of sediments is attributed to the relatively steep upper slope gradients (< 9°) off Kvitøya Trough, yielding unstable sediment deposition areas for glacial sediments there (Fransner et al., 2017a). O'Cofaigh et al., (2003), whom suggested that TMF build-up is favored by slope gradients < 1°, support this interpretation. The estimated volume of Kvitøya TMF is 1000 km^3 (Fransner et al., 2017a). A comparison of Kvitøya and Hinlopen Troughs becomes relevant since these are the major troughs of the northern Svalbard margin which in addition are eroded into similar, crystalline bedrock (Hogan et al., 2010; Batchelor et al., 2011) (Fig. 5a). The catchment areas of these two troughs, together with the dimensions of the troughs as well as the estimated volumes of their associated glacigenic sediments on the slope are similar. This may suggest that the Quaternary ice streams that occupied these troughs were of similar significance for the drainage of the SBIS (Fransner et al., 2017a).

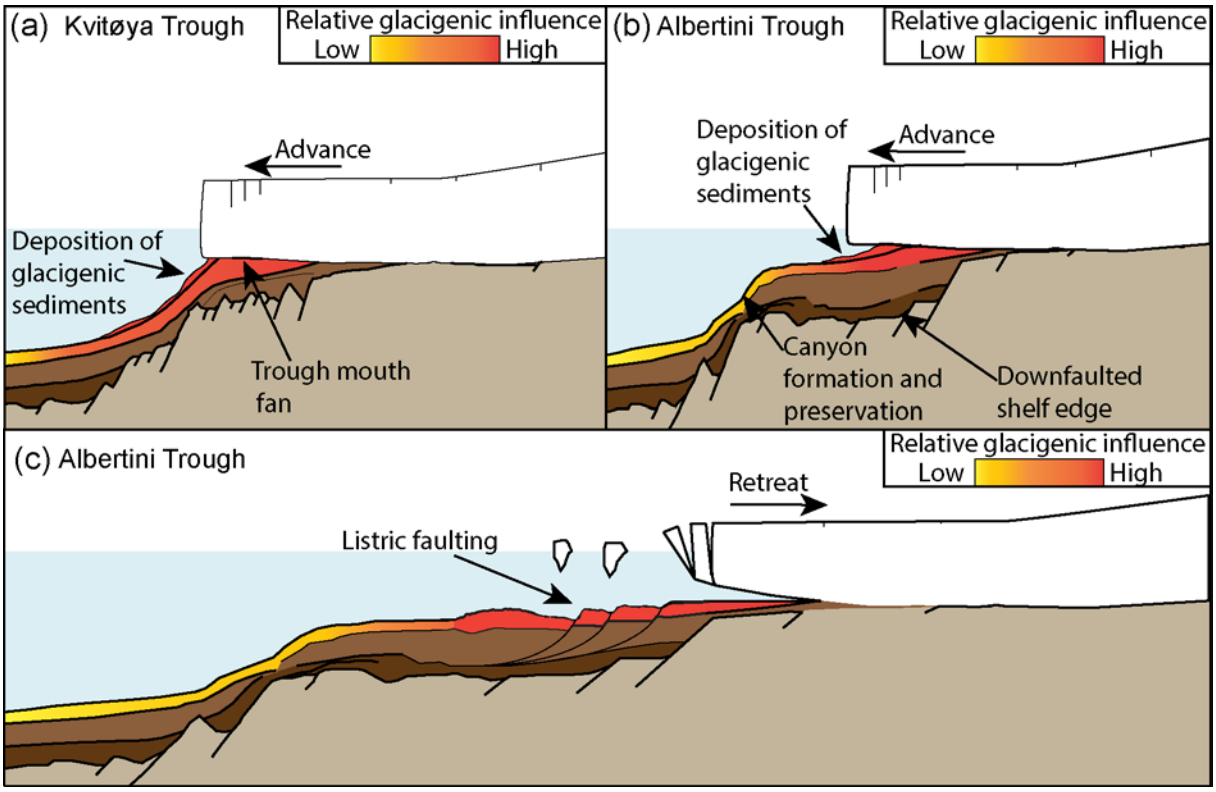

Figure 6. (a) Repeated Quaternary ice stream activity in Kvitøya Trough pushes glacigenic sediments over the shelf edge, which builds the Kvitøya TMF. The relatively steep slope angle beyond the shelf edge facilitates for the glacigenic sediments to reach down to the continental rise. (b) Repeated Quaternary ice stream activity in Albertini Trough pushes glacigenic sediments down into the downfaulted shelf edge, which prevents TMF build-up beyond Albertini Trough. Instead, the continental slope off Albertini Trough is dominated by complex networks of canyons, which develop in absence of glacigenic deposition. (c) The heavy load of glacigenic sediments in the downfaulted shelf edge of Albertini Trough likely contributed to listric faulting that was triggered after deglaciation of the area. The seismic models are based on data from Geissler and Jokat, 2004.

A majority of the glacigenic sediments transported to Albertini Trough mouth were accumulated at the close proximity of the trough mouth due to the locally downfaulted bedrock that formed an ample accommodation space there (Geissler and Jokat, 2004; Fransner et al., 2017a) (Fig. 6b). The trapping of the glacigenic sediments in Albertini Trough mouth therefore led to a concave morphology of the shelf edge, and prevented the build-up of a TMF at an adjacent continental slope (Fig. 6b) (Fransner et al., 2017a). The volume of the trapped glacigenic sediments in Albertini Trough mouth is estimated to 770 km^3, which is comparable to the estimated volume of Kvitøya TMF (Fransner et al., 2017a).

The continental slope off Albertini Trough is dominated by thick, stratified acoustic units (Geissler and Jokat, 2004; Fransner et al., 2017a). These acoustic units are interpreted to have formed due to deposition and reworking of sediments from contour currents and/or down-slope turbidity currents since the late Pliocene (Fransner et al., 2017a). The thick successions of these acoustic units indicate that the contour currents and/or down-slope turbidity currents also dominated the sedimentary environment below Albertini Trough during the Quaternary period as a consequence of the trapping of glacigenic sediments in Albertini Trough mouth (Fransner et al., 2017a). A 0.3 s TWT long slide scar in the acoustically stratified units below the sea floor indicates a mass-wasting event from the middle continental slope off Albertini Trough during early Quaternary period (Fransner et al., 2017a). Although the 23.6 km long slide scar indicates that the sediment evacuation was dramatic, it contributed to the cut-back shelf-edge morphology of Albertini trough mouth (Fransner et al., 2017a).

At the upper slope off Albertini Trough, the semi-parallel internal reflectors of the Quaternary acoustic units indicate that the sedimentary environment was influenced by both, gravity driven processes as well as by suspension settling (Fransner et al., 2017a). The correlation between the chirp stratigraphy and a sediment core study by Chauhan et al., (2016b) suggests that glacigenic gravity driven processes were common during the maximum extent of the SBIS (Fransner et al., 2017a). However, unlike at the middle to lower continental slope, the absence of contourites on the upper continental slope off Albertini Trough indicates the absence of contouritic currents there during the Quaternary period (Fransner et al., 2017).

The lower influence of glacigenic sediments on the continental slope on both the western and eastern flanks of Kvitøya TMF (including the continental slope off Albertini Trough) during the Quaternary period led to development and preservation of complex tributary canyon systems there (Fransner et al., 2017a) (Fig. 6b). The strong multibeam-backscatter within the tributary canyons suggests relatively coarse-grained deposits most likely deposited by sediment-laden meltwater, which also eroded the canyons into the continental slope during deglaciation (Fransner et al., 2017a). A submarine fan is located on the continental rise adjacent to the end of the tributary canyons, which suggests the depocentre for a substantial amount of coarse grained sediments that bypassed the canyons (Fransner et al., 2017a).

The tributary canyon system on the western flank of Kvitøya TMF (below Albertini Trough mouth) is better developed and with greater dimensions compared to its counterpart on the eastern side (Fransner et al., 2017a). These dimension differences suggest that the western flank has been exposed to significantly more erosion by sediment-laden melt water compared to the tributary canyon system on the eastern side of Kvitøya TMF (Fransner et al., 2017a) (Fig. 6b). A channel on the upper continental slope off Albertini Trough which is connected to the tributary canyon system downslope is suggested to have led a focused flow of sediment-laden meltwater to the tributary canyon system, which significantly contributed to the erosion of those canyons (Fransner et al., 2017a).

4.1.2 The Late Weichselian ice flow configuration and dynamics in Rijpfjorden, Duvefjorden and on the continental shelf

The elongated glacial landforms in Rijpfjorden and Duvefjorden, such as glacial lineations, crag-and-tails and glacially polished bedrock show that both fjords hosted ice streams with northerly to northeasterly flow directions during LGM (Fransner et al., 2017b). The considerably higher elongation ratios of the glacial lineations in Duvefjorden as well as the deeper basin there indicate a more focused and/or larger ice flow there compared to that in Rijpfjorden (Fransner et al., 2017b).

The Rijpfjorden has a varied depth, which correlates with the costal geology (Fransner et al., 2017b). The inner and central fjord basins likely consist of sedimentary bedrock while the streamlined bedrock in the shallow central to outer Rijpfjorden as well as the inner continental shelf are probably of the crystaline bedrock types (Fransner et al., 2017). The lower resistance to glacial erosion of the sedimentary bedrock caused the ice to flow into these areas eroding the deeper basins there (Fransner et al., 2017b). The relatively shallow water dephs of the continental shelf north of Rijpfjorden indicate that ice flow likely slowed down when it met the more resistant crystalline bedrock there (Fransner et al., 2017b). The more resistant bedrock north of Rijpfjorden is therefore suggested to have hampered trough development there (Fransner et al., 2017b).

Based on the geological map, the geology of the basin of Duvefjorden is probably similar to the sedimentary bedrock of the adjacent Prins Oscars Land (Fransner et al., 2017b) (Fig. 5a). The bedrock in Duvefjorden is therefore dominated by sedimentary rocks unlike in Rijpfjorden, where the sedimentary bedrock only is present locally (Fransner et al., 2017b). When the LGM ice streamed through Duvefjorden, it therefore eroded a significantly deeper and narrower basin in the sedimentary bedrock compared to in Rijpfjorden. Therefore, the easily eroded bedrock in Duvefjorden likely contributed to a build-up of a larger and/or more focused ice stream there compared to in Rijpfjorden during the LGM (Fransner et al., 2017b). Although the LGM ice flow in Rijpfjorden was probably smaller compared to the one in Duvefjorden, IBCAO depth contours support that the ice flow from Rijpfjorden continued out onto the continental shelf (Fig. 5a). Both Rijpfjorden and Duvefjorden were therefore drainage outlets for the SBIS (Fransner et al., 2017b) (Fig. 5a).

The depth contours of the IBCAO indicate that LGM ice flow from Duvefjorden followed and/or eroded a trough north of Duvefjorden (Fig 5a). The ice flow from Duvefjorden was divided into two branches north of Karl XII-Øya, where one branch continued northwards while the other branch deflected towards Albertini Trough (Fig. 5a). Although there are no high resolution bathymetric data from Albertinibukta, northern Nordaustlandet, depth contours of the IBCAO also suggest that another ice stream flowed from there into Albertini Trough during the LGM (Fig. 5a). The glacial lineations in Albertini Trough indicate that the LGM ice flow continued through Albertini Trough and reached the trough mouth (Fransner et al., 2018). The majority of the glacigenic sediments transported through Albertini Trough during LGM were deposited in its downfaulted trough mouth, just like during the earlier Quaternary glaciations (Fransner et al., 2017a). However, the chirp acoustic stratigraphy of the upper continental slope suggests the presence of glacigenic sands on the upper continental slope that are characteristic to glacial proximal marine sedimentary environment during the LGM, around 24-23 cal. ka BP (Chauhan et al., 2016b).

4.1.3 Deglaciation of the continental shelf

The beginning of deglaciation of the northern Svalbard shelf is dated to c. 18.5 cal. ka BP (Chauhan et al., 2016b) (Fig. 5b). A radiocarbon age from the sediment gravity core HH15-14 indicates that the central continental shelf became ice free around 15.3 cal. ka BP (Fransner et al., 2018) (Fig. 5b). This means that deglaciation of the outermost 35 km of the continental shelf took approximately 3.2 ka, which gives an average retreat rate of 11 m/y (Fransner et al., 2018) (Fig. 5b).

Gullies incising the Kvitøya TMF as well as the absence of sediment infill in some of the larger tributary canyons on the flanks of the Kvitøya TMF suggest that large volumes of sediment-laden meltwater likely were released from the SBIS during early deglaciation (Fransner et al., 2017a). Albertini Trough mouth is heavily scoured by icebergs, while other landforms generally are absent there (Fransner et al., 2018). This landform assemblage suggests that the ice stream terminus was floating in Albertini Trough mouth and disintegrated mainly through calving (Fransner et al., 2018). The floating ice stream margin in Albertini Trough has been attributed to the relatively deep trough there together with the high relative sea level during early deglaciation (Forman et al., 1987; Fransner et al., 2018). The many iceberg ploughmarks in Albertini Trough mouth may also indicate that other glacial landforms were eroded by iceberg scouring. However, a floating margin in Albertini Trough mouth is considered as likely since floating margins during early deglaciation also have also been reported from the neighbouring ice streams in Hinlopen and Kvitøya Troughs (e.g Landvik et al., 1998; Kleiber et al., 2000; Koc et al., 2002).

Listric fault scarps with fresh appearance in Albertini Trough mouth suggests that the listric faulting was triggered after deglaciation of the area (Fig. 6c). The listric faulting took place in the Quaternary deposits of Albertini Trough (Fransner et al., 2018). The instability of these sediments filling the space on top of the downfaulted basement is suggested as the most important factor behind the faulting (Fransner et al., 2018) (Fig. 6c). The glacial landforms assemblage in the central parts of Albertini Trough is complex and includes overridden terminal moraines superimposed by De Geer moraines, followed southwards by a grounding zone wedge with glacial lineations on top (Fransner et al., 2018). This landform assemblage indicates where the retreating Albertini ice stream became grounded and made several shorter readvances during an overall slow and steady retreat from central Albertini Trough (Fransner et al., 2018). The glacial lineations indicating readvances of the ice margin throughout Albertini Trough display a gradual orientation change from S-N towards SSW-NNE towards south. This orientation change was attributed to changes in ice stream flow, where the ice sourced in Duvefjorden gradually became more dominant compared to the one from Albertinibukta (Fransner et al., 2018). With increasing distance to the ice margin, the sedimentation environment changed across the northern Svalbard margin. Fining upwards diamicton at the base, followed by mud with decreasing IRD contents are often found in the cores, indicating that the deglaciation of the northern Svalbard shelf led to gradual transitions in the sedimentary environments from subglacial to glacimarine environments (Fransner et al., 2017b; Fransner et al., 2018).

A radiocarbon age from the gravity core HH15-13 indicates that the area of the core location, 15 km south of HH15-14, became free from glacier ice around 14.0 cal. ka BP (Fransner et al., 2018) (Fig. 5b). The average retreat rate between these two core locations is therefore 12 m/y (Fransner et al., 2018). At the time of 14.0 cal. ka BP, large parts of Hinlopen Trough were already free from glacier ice, indicating that the deglaciation of the continental shelf north of Nordaustlandet was slower compared to in Hinlopen Trough. (Hogan et al., 2017 and references therein) (Fig. 5b). Minimum deglaciation ages from Kvitøya Trough are somewhat similar to the deglaciation ages form the continental shelf presented in this thesis (Fig. 5b). However, a somewhat faster deglaciation rate for Kvitøya Trough compared to the continental shelf north of Nordaustlandet have earlier been suggested (Hogan et al., 2017). The faster deglaciation of Kvitøya and Hinlopen Troughs has been attributed to more intense calving there as a consequence of the deeper waters in those troughs (Hogan et al., 2017 and references therein).

The distance from the core location of HH15-13 to inner Rijpfjorden is ca 110 km. Deglaciation of this distance took ca 3.5 ka if taking into account that Rijpfjorden was free from glacier ice by 10.5 cal. ka BP (Fransner et al., 2017a; Fransner et al., 2018) (Fig. 5b). The timing of deglaciation between these points indicates an average retreat rate of ca 31 m/y from the central continental shelf to inner Rijpfjorden (Fransner et al., 2018). The significant increase in average retreat rate of the inner half of the continental shelf edge compared to the outer one matches relatively well with the rapidly rising sea-level which peaked between 10 and 11 cal. ka BP (Forman et al., 1987; Bondevik et al., 1995; Forman et al., 2004). Furthermore, the numerous iceberg ploughmarks in central Albertini Trough as well as on the inner continental shelf north of Rijpfjorden indicate that calving was an important process for mass-loss for the SBIS during the deglaciation (Fransner et al., 2017b; in press). The absence of other retreat-related glacial landforms in in the deeper basin of Duvefjorden supports a floating glacier margin mainly decaying through calving during the deglaciation (Fransner et al., 2017b). Deglaciation of central Duvefjorden was complete by 11 cal. ka BP (Fransner et al., 2017b).

The record of retreat-related glacial landforms in Rijpfjorden is dominated by De-Geer moraines in water depths shallower than 210 m, which indicate a relatively slow and grounded retreat in those areas (Fransner et al., 2017b). A radiocarbon age from inner Rijpfjorden indicates that the deglaciation of Rijpfjorden was complete around 10.6 cal. ka BP, which is somewhat later than when central Duvefjorden free from glacier ice (Fransner et al., 2017b). The timing of the complete deglaciation of the northern Svalbard shelf was therefore approximately 8000 years, where the retreat rate of deglaciation appears to have significantly increased for the inner half of the continental shelf (Fransner et al., 2018).

4.1.4 The Holocene

Relatively homogenous muds from the continental shelf as well as in Duvefjorden indicate that the sedimentary environments during the Holocene were marine-dominted (Fransner et al., 2017b; Fransner et al., 2018). The upcore decreasing IRD content in these muds suggest that iceberg calving and transport still took place, but became of less importance (Fransner et al., 2017b; Fransner et al., 2018).

The thickest deglacial-postglacial sediments (<26 m) accumulated in Rijpfjorden and Duvefjorden, particularly in their deep basins eroded by earlier ice flows (Fransner et al., 2017b). Sediment mass flows were triggered in the deep basins of Duvefjorden as well as the inner Rijpfjorden during the Holocene (Fransner et al., 2017b). The mass flows were triggered by high sedimentation rates on steep slopes that led to inherently unstable sediment cover (Fransner et al., 2017b). HH12-11 from central Duvefjorden shows significant changes in magnetic susceptibility values during middle Holocene, which could indicate changes in sediment source, and potentially changed meltwater drainage pattern of the Austfonna ice cap. The changes in magnetic susceptibility could therefore indicate a somewhat more dynamic drainage pattern for Austfonna compared to Vestfonna if they already were separated during mid-late Holocene (Fransner et al., 2017b). Alternatively, the changes in magnetic susceptibility could reflect the reorganization of meltwater drainage patterns linked to the separation of Vestfonna and Austfonna.

5 Future perspectives

This thesis was written based on sediment cores and geophysical data from the northern Svalbard margin. The thesis presents new knowledge regarding the extent, timing and rates of decay of the SBIS during the Late Weichselian as well as glacial/interglacial processes that have shaped the area.

The timing of deglaciation of the northern Svalbard margin is still of relatively low resolution. This is due to the sparse abundance of dateable organic matter in the acquired sediment cores. However, previous studies (e.g. Knies et al., 2001; Chauhan et al., 2016b) together with the results of this Thesis give a good base for the timing of deglaciation. Naturally, new radiocarbon dates from new sediment cores from the shelf would increase the resolution of the deglaciation history and dynamics between the shelf edge and the inner fjords of Nordaustlandet.

There are clear indications from the radiocarbon dates presented in this Thesis that deglaciation rate of the northern Svalbard shelf significantly increased with time. These radiocarbon dates does not however reveal the dynamics of deglaciation of the inner continental shelf norh of Nordaustlandet. In order to increase the understanding of the inner shelf deglaciation, new multibeam bathymetric data from the inner continental shelf north of Rijpfjorden and Duvefjorden, including the area of the inner Albertini Trough is needed.

However, it is important to highlight that the majority of the glacial landforms and sediments in fjords and on the continental shelf, including the data presented in this Thesis most likely reach back to the LGM, but not further. When trying to understand the Quaternary glaciations, this is a relatively short time span of about 20 thousand years. This means that in order to go further back in time, other methods are needed. Well-preserved glacigenic sediments making up TMFs on the continental slopes constitutes an important archive for glacigenic activity for reaching further back than the Late Weichselian (e.g. Pope et al., 2016). Further acquisition of high-resolution seismic data from the continental slopes can therefore increase our understanding of long-term ice sheet activity.

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7 Research papers