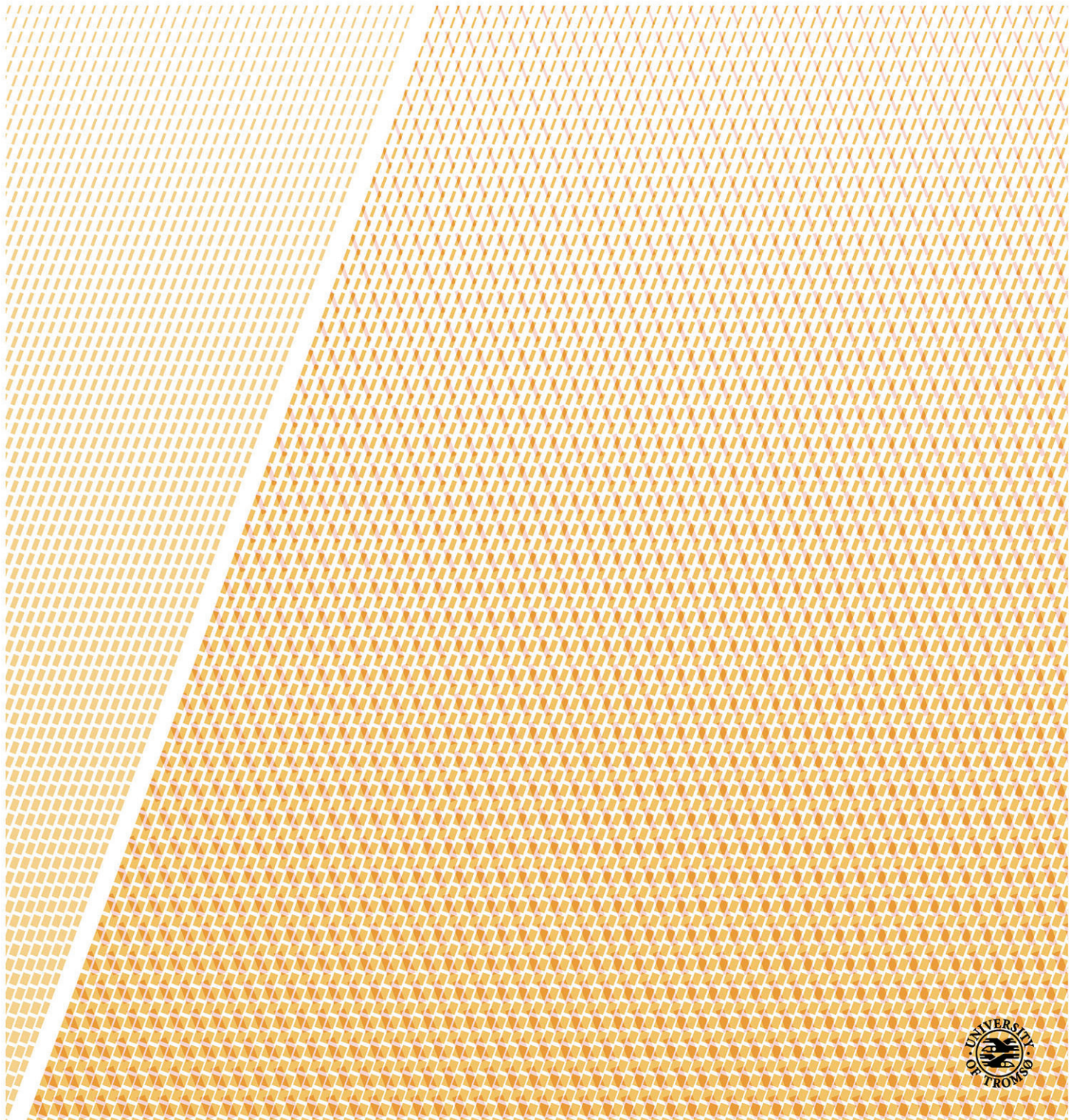


Sedimentary processes, late Cenozoic evolution and sediment yield on the continental margin offshore Troms, northern Norway

Tom Arne Rydningen

A dissertation for the degree of Philosophiae Doctor – March 2014



Preface

The work forming the basis for this Ph.D. thesis was carried out at the Department of Geology, Faculty of Science and Technology, University of Tromsø – the Arctic University of Norway, from September 2010 until March 2014.

This study is an Industrial Ph.D. project originally funded by Front Exploration and the Research Council of Norway. DONG E&P Norge AS purchased Front Exploration in August 2012 and co-funded the last part of the project. The work was supervised by Tore O. Vorren and Jan Sverre Laberg from the University of Tromsø, and Vidar Kolstad from DONG E&P Norge AS/Front Exploration. Tore sadly passed away in June, 2013 – after which Jan Sverre acted as my main supervisor. Most of the work was carried out at the University of Tromsø and at DONG E&P Norge AS/Front Exploration. I also spent four months during the autumn of 2012 analyzing data for the thesis at the Geological Survey of Canada at the Bedford Institute of Oceanography (BIO) in Dartmouth, Nova Scotia, Canada. David Mosher and Ned King kindly hosted the stay, and provided technical assistance as well as valuable comments.

During the Ph.D., I gave talks and presented posters at national and international conferences (e.g. the Norwegian Winter Meeting 2011, European Geological Union 2012, and 3P Arctic 2013). I also participated in three annual Industrial Ph.D. meetings hosted by the Research Council of Norway, as well as one All Staff Meeting at the ResClim research school (2011). Several obligatory courses and one software course (SMT Kingdom Suite) were completed. Two days were spent during the fall of 2011 presenting part of my work in Senjahopen and Tromsø at the ‘Norwegian Science Week’ organized by the Research Council of Norway and the University of Tromsø.

The data used in this study was kindly provided by the Norwegian Defense Research Establishment (2D-seismic data) and the Norway Digital Program (bathymetric data). Also, the Norwegian Petroleum Directorate kindly allowed for the upper sections of recently acquired 2D- and 3D-seismic profiles to be published.

This thesis consists of an introduction and three scientific papers, providing new information about sedimentary processes, late Cenozoic evolution and sediment yield on the continental margin off Troms, northern Norway. These three papers are:

Paper 1

Rydningen, T.A., Vorren, T.O., Laberg, J.S., Kolstad, V., 2013. The marine-based NW Fennoscandian ice sheet: glacial and deglacial dynamics as reconstructed from submarine landforms. *Quaternary Science Reviews* 68, 126-141.

Paper 2

Rydningen, T.A., Laberg, J.S., Kolstad, V., in prep. Seabed morphology and sedimentary processes on high-gradient Trough Mouth Fans offshore Troms, northern Norway. To be submitted to *Geomorphology*.

Paper 3

Rydningen, T.A., Laberg, J.S., Kolstad, V., in prep. Late Cenozoic evolution of high-gradient Trough Mouth Fans and canyons on the glaciated continental margin offshore Troms, northern Norway – palaeoclimatic implications and sediment yield. Manuscript.

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I am very grateful to my colleagues at DONG for always being interested in my work and for encouraging me. Thank you for providing a productive and inspiring working environment.

I am very grateful to my colleagues and good friends at the University of Tromsø for discussions, trips, social activities and coffee breaks. My special thanks go to Kjetil Indrevær, thank you for all the good help when I tried to sort out how to be an Industry Ph.D.

I would also like to thank everyone at BIO for stimulating discussions during my stay there, especially David Mosher, David Piper and Calvin Campbell for their valuable feedback and critical questions. I would also like to thank Francky Saint-Ange and John Evangelatos for fruitful discussions and social input.

I would like to thank Jan P. Holm for technical assistance, Edward (Ned) King for helpful advice and feedback on Paper 1, Mariana da Silveira Ramos Esteves for correcting the English of Paper 2, Torbjørn Dahlgren, Geoffrey D. Corner and Nigel Marsh for valuable feedback on Paper 3, and Rikke Bruhn for her comments on the introduction.

I would like to express my gratitude to the King's for making me feel like a part of the family during my stay in Halifax. I felt at home in your welcoming and warming house.

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1. Introduction

Previous studies of high-latitude continental margins have shown that Trough Mouth Fans (TMF) and prograding wedges, i.e. sediment accumulations at the mouth of transverse shelf troughs, are important palaeoclimatic archives which receive large sediment volumes during peak glaciations (Vorren et al., 1988a; 1989; 1998; Aksu and Hiscott, 1992; Hiscott and Aksu, 1994; 1996; Laberg and Vorren, 1995; 1996a; b; King et al., 1996; Vorren and Laberg, 1997; Clausen, 1998; Dahlgren et al., 2005; Sejrup et al., 2005; Rebesco et al., 2006). Also, the seabed in the catchment areas, and buried palaeo-continental shelf surfaces, represent snapshots of subglacial conditions, and therefore contain information about ice sheet dynamics and properties during the shelf-wide, peak glaciations (Andreassen et al., 2004; 2007; 2008; Ottesen et al., 2005a; b; 2008; Ottesen and Dowdeswell, 2009).

In general, the largest TMFs and prograding wedges, characterized by low slope angle, as well as the seabed imprint of palaeo-ice sheets which fed these, are best studied. The smaller and high-gradient TMF systems have received less attention, although they are widespread on formerly glaciated continental margins; off northern Norway (this study), Greenland (Clausen, 1998; Garcia et al., 2012), Canada (Batchelor and Dowdeswell, in press) and in Antarctica (Amblas et al., 2006). High-gradient TMFs are of interest because they appear to be dominated by other erosional and depositional processes than their low-angle counterparts (Ó Cofaigh et al., 2003), and because they comprise information about the margin evolution including the Neogene ice sheet history (Clausen, 1998). Furthermore, the TMFs, and the hinter-lying shelves are situated on continental margins which are of great interest for the petroleum industry, e.g. the continental margin off Troms (Figure 1) and the Greenland margin. For the industry, it is important to identify glacial erosion and sedimentation in order to understand uplift and subsequent leakage of hydrocarbon reservoirs, as well as the subsidence and maturation history of source rocks, respectively (e.g. Henriksen et al., 2011). This necessitates the need for improved understanding of the evolution of glaciated shelves, including sedimentary processes and quantification of rates of sedimentation and erosion.

1.1 The Norwegian continental margin

1.1.1 The morphology of the Norwegian continental shelf

The large-scale morphology of the Norwegian continental shelf, extending from the North Sea to the Svalbard shelf, is characterized by deep shelf-crossing troughs (250-500 m) separated by shallower banks (>20-200 m) (Figure 1). The width of the shelf varies greatly; narrow parts occur offshore Møre and Lofoten-Vesterålen – with shelf widths of 65 and 10 km,

respectively (Figure 1). The mid-Norwegian margin is up to 260 km wide, while the epicontinental Barents Sea shelf reaches up to 1500 km in width (Vorren et al., 1998).

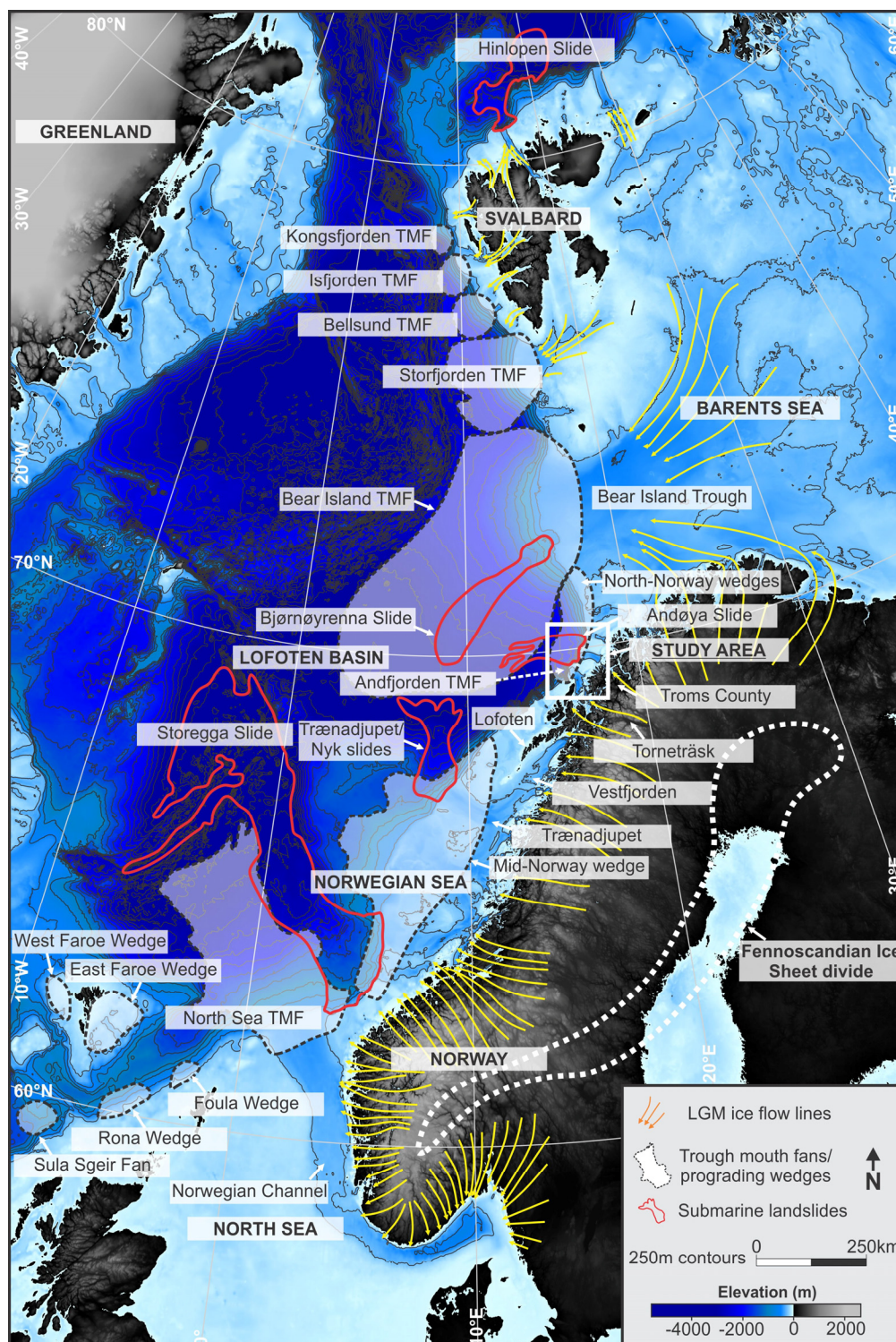


Figure 1: Overview of the Norwegian-Barents Sea-Svalbard margin showing the location of TMFs and prograding wedges (Dahlgren et al., 2005); submarine landslides (Vorren et al., 1998; Vanneste et al., 2006); and LGM ice divide and flow lines of the Fennoscandian and Barents Sea/Svalbard Ice Sheets (Ottesen et al., 2005a). The white frame shows the location of the study area. TMF=Trough Mouth Fan. The map is generated from the IBCAO (Jakobsson et al., 2012) and ETOPO (Amante and Eakins, 2009) data bases.

The present morphology of the troughs and banks on the high-latitude shelves is largely a result of glacial processes during the Last Glacial Maximum (LGM) and the following deglaciation (Figure 2) (Vorren, 2003). Troughs were eroded during this period by fast-flowing ice streams, i.e. arteries of rapidly flowing ice masses within the ice sheet. The positions of the ice streams and the lateral extent of these are marked by seabed imprints of mega-scale glacial lineations (MSGSL) and lateral moraines/lateral shear zone moraines (Stokes and Clark, 1999; 2002a; b). Grounding zone systems, i.e. moraines and grounding zone wedges (GZW) are common in the troughs, where they mark the position of halts or re-advances of the ice-streams during the deglaciation (Vorren et al., 1983; 1988b; Vorren and Plassen, 2002; Ottesen et al., 2005a; b; 2008; Laberg et al., 2007a). The banks are commonly characterized by moraine ridges, oriented transverse to ice flow and indicating a sluggish-flowing ice here during LGM, and a slowly retreating ice-sheet margin during the deglaciation (Ottesen and Dowdeswell, 2009).

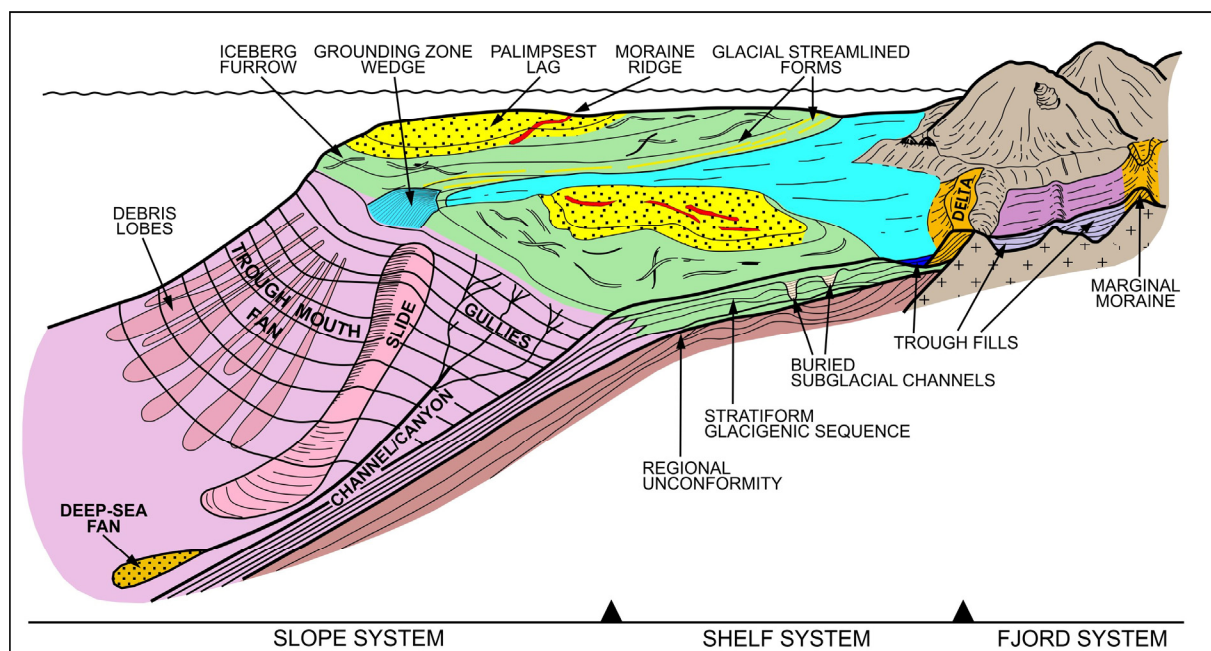


Figure 2: Model showing the main glacigenic morphological elements and lithofacies of a passive glaciated continental margin, exemplified by the margin off northern Norway. The figure is slightly modified from Vorren (2003).

1.1.2 Palaeo-ice streams on the Norwegian continental shelf during the LGM

More than 20 fast-flowing palaeo-ice streams traversed the Norwegian continental shelf during the LGM (Ottesen et al., 2005a). These were fed from ice flowing through converging fjords and valleys inshore (Vorren and Plassen, 2002; Ottesen et al., 2008). The palaeo-ice streams, the largest ones located in the Norwegian Channel and the Bear Island Trough, drained major parts of the Fennoscandian and Barents Sea ice sheets (Figure 1) (Ottesen et al.,

2005a). The Vestfjorden-Trænadjupet palaeo-ice stream (Ottesen et al., 2005b), and the palaeo-ice streams offshore Troms, northern Norway (Vorren and Plassen, 2002; Ottesen et al., 2005a; b; 2008) shielded the Lofoten-Vesterålen area. Thus, this part of the Norwegian shelf was fed by local glaciers, and smaller palaeo-ice streams prevailed here (Vorren et al., in prep).

Calculations of palaeo-ice stream velocities have shown that the Vestfjorden-Trænadjupet palaeo-ice stream flowed at a rate of 750 m/yr (Ottesen et al., 2005a), while the Bear Island palaeo-ice stream is estimated to have flowed at 2500 m/yr (Vorren and Laberg, 1996). These values are comparable to modern analogues in Antarctica, which flow at velocities of a couple of hundred meters to a few km/yr (Rignot et al., 2011).

1.1.3 The deglaciation of the Andøya/Troms – SW Barents Sea area

The earliest detailed mapping of the continental shelf off Troms is the soundings of the Sveinsgrunnen and Malanggrunnen banks done by Holtedahl (1940) (Figure 3). The impressive level of detail from hand-contoured maps of these banks allowed for identification of ‘ridge-lateral elevations’ and ‘rounded, sometimes elongate hollows and elevations’ which were interpreted as lateral moraines and ground-, terminal moraine patterns, respectively. Both morphologies were interpreted to be formed by grounded ice in these areas (Holtedahl, 1940). Later studies of the shelf seabed and subsurface sediments indicated the presence of several grounding zone systems related to still-stands or re-advances during the overall retreat of the ice sheet from the shelf (Holtedahl, 1953; Andersen, 1965; 1968; Rokoengen et al., 1979; Vorren et al., 1983; 1988b; Vorren and Plassen, 2002; Ottesen et al., 2005a; 2008).

The island of Andøya in Vesterålen is considered to be a key area for understanding the deglaciation of the continental shelf due to its proximity to the shelf break and the occurrence of the oldest postglacial sediments in onshore Scandinavia here (Vorren and Elvsborg, 1979; Vorren et al., 1983; 1988b; 2013; in prep.). The Endleten moraine on northern Andøya is dated to 18.7 cal ka (15.5 ¹⁴C ka) and correlated to the Egga-II moraine at the shelf break in Andfjorden; these deposits have been interpreted to mark the onset of deglaciation in this area (Vorren et al., 1988b). The Flesen event, named after the Flesen moraine in Andfjorden, is dated to 17.5 cal ka (14.6 ¹⁴C ka) and correlated onshore by Vorren and Plassen (2002) (Figure 4). The Flesen moraine has a time correlative GZW in the outer Bear Island Trough dated to around 17.09 cal ka (14.53 ¹⁴C ka) (Rüther et al., 2011). At this time, the glacier still covered much of the Vestfjorden area (Figure 1) (Laberg et al., 2007a). Most of Andøya and

the adjacent shelf areas, as well as the major troughs in the SW Barents Sea were deglaciated during the D-event at ~16.6-15.9 cal ka (13.8-13.2 ¹⁴C ka) (Figure 4) (Vorren and Plassen, 2002; Winsborrow et al., 2010).

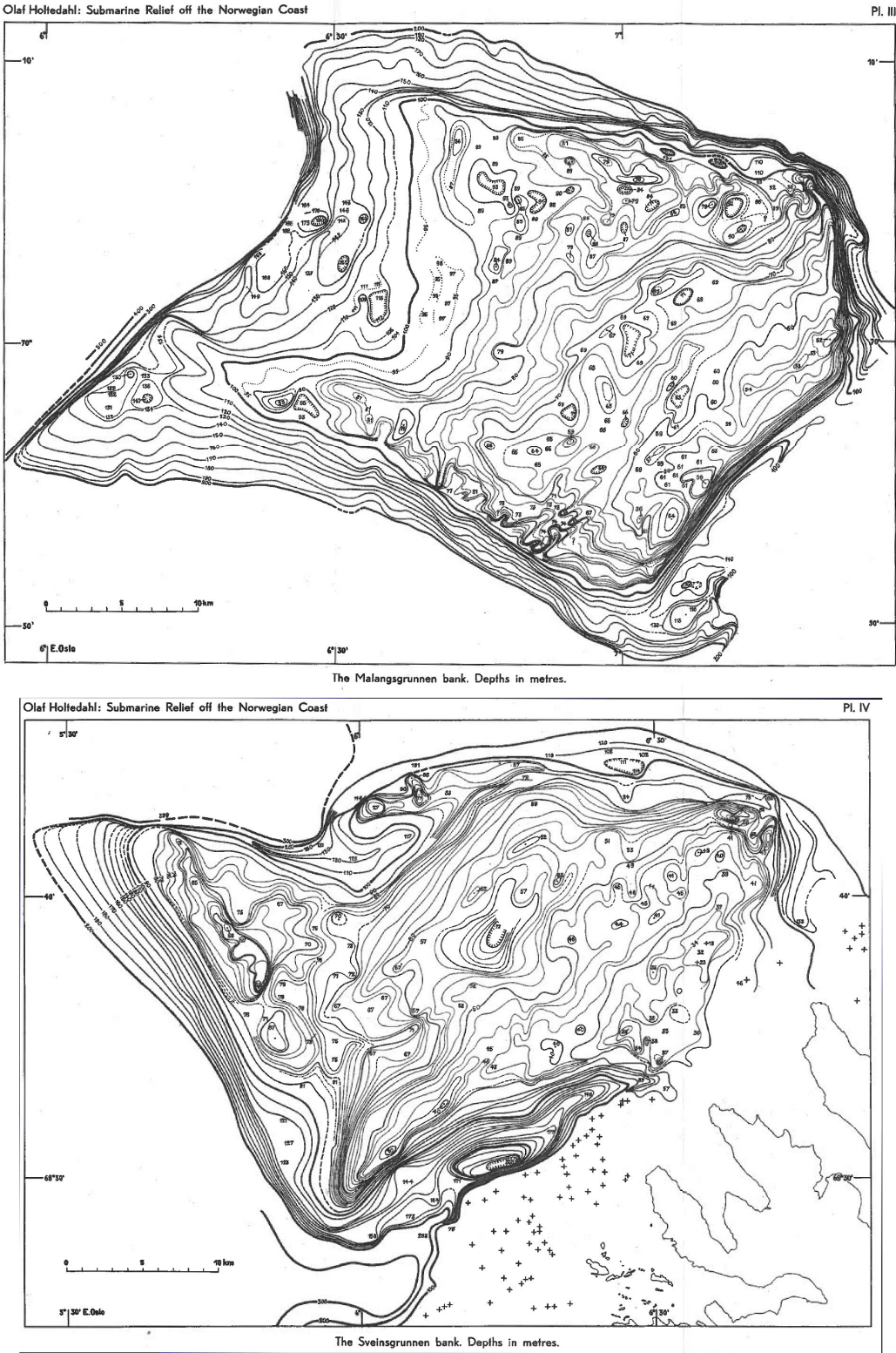


Figure 3: Hand-contoured bathymetric maps of the Malangsrunden (above) and Sveinsgrunden banks on the continental shelf off Troms (Holtedahl, 1940).

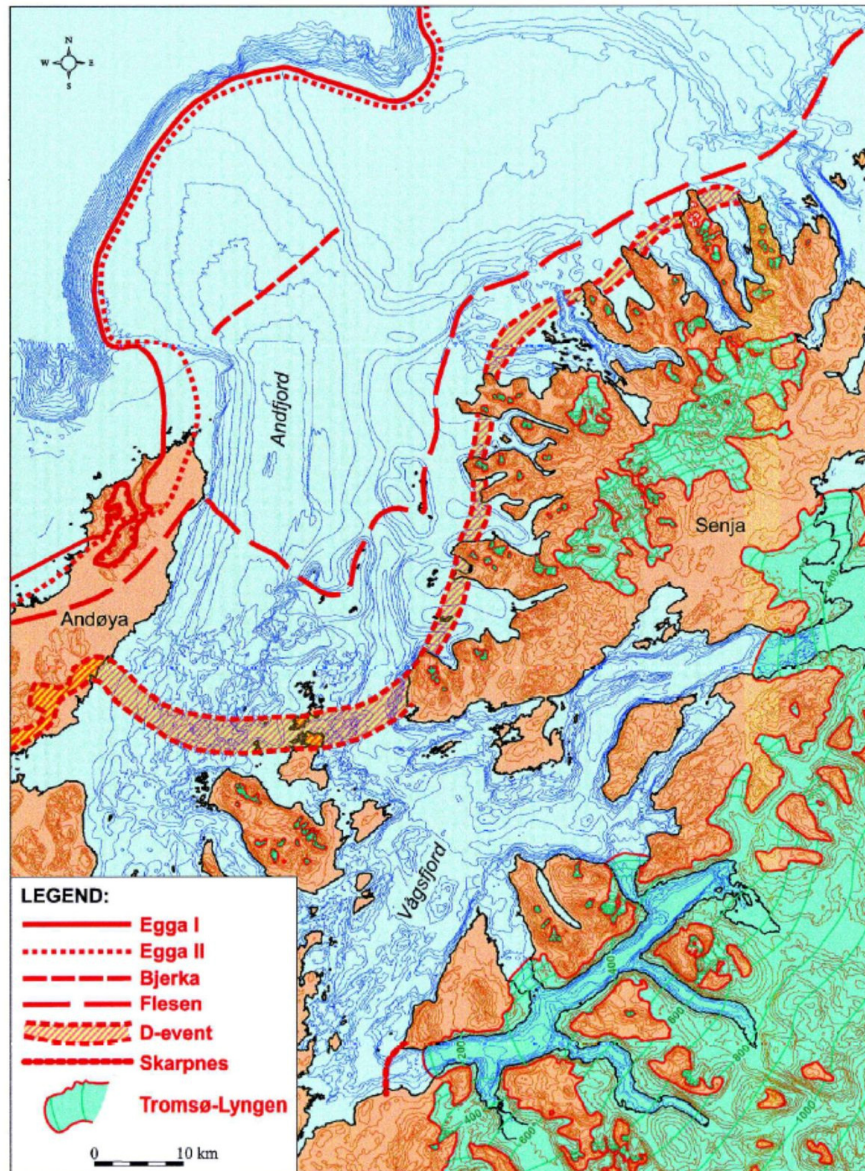


Figure 4: Reconstruction of the Fennoscandian Ice Sheet extent during the LGM and deglaciation in the Andøya-Andfjorden area. From Vorren and Plassen (2002).

1.1.4 The morphology of the Norwegian continental slope

The Norwegian continental slope contains pronounced sediment accumulations, i.e. TMFs, prograding wedges and sediment drifts (Vorren et al., 1989; 1998; Laberg and Vorren, 1995; 1996a; b; King et al., 1996; 1998; Dahlgren et al., 2005; Laberg et al., 2005a; Sejrup et al., 2005). The wedges and fans comprise sediments accumulated by density-driven flows such as glacial debris flows (GDF) and turbidity currents, that were active mainly during the glacial maxima (e.g. Laberg and Vorren, 1995; Vorren et al., 1998; Dahlgren et al., 2005), and by along-slope contour currents, which dominated during interglacials (Laberg et al., 2005a). The glacial sediments were brought to the continental margin by subglacial sediment transport, predominantly at the base of fast-flowing palaeo-ice streams (e.g. Ottesen et al.,

2005a). TMFs developed in areas where ice stream locations remained stable through several glaciations, e.g. the North Sea, the Bear Island and the Storfjorden TMFs (Laberg and Vorren, 1995; 1996a; b; King et al., 1996; Dahlgren et al., 2005). Prograding wedges, which do not display a characteristic fan-shape, i.e. offshore mid-Norway, were formed by laterally shifting ice-streams between peak glaciations (Dowdeswell et al., 2006).

The continental slope off Lofoten-Vesterålen is characterized by submarine canyons and sediment drifts, accumulated from northward-flowing contour currents (Bugge, 1983; Kenyon et al., 1987; Taylor et al., 2000; Laberg et al., 2005b; 2007b; Rise et al., 2013; Baeten et al., submitted). In the south, the drift sediments completely or partly fill in the canyons (Baeten et al., 2013), while fresh canyon morphologies occur in the north – indicative of recent active downslope flow (Laberg et al., 2007b; Rise et al., 2013).

Submarine landslides are common on the Norwegian continental slope, with key examples being the Storegga Slide (Bugge et al., 1987), the Trænadjupet Slide (Laberg and Vorren, 2000), the Andøya Slide (Laberg et al., 2000), the Bjørnøyrenna Slide (Laberg and Vorren, 1993), and the Hinlopen Slide (Vanneste et al., 2006) (Figure 1). Common for these are that they cut back all the way to the shelf break, i.e. they terminate upslope in over-consolidated subglacial deformation till.

1.1.5 Glacigenic debris flows and turbidity currents

The main building blocks of TMFs and prograding wedges are sediments deposited from GDFs; the most important sediment distribution process on the upper and middle fan (Vogt et al., 1993; Laberg and Vorren, 1995; King et al., 1996; Vorren and Laberg, 1997). GDFs rework sediment that is brought to the shelf break mainly by subglacial transport processes (Figure 5) (Vorren et al., 1989; Aksu and Hiscott, 1992; Laberg and Vorren, 1995; King et al., 1996, 1998). Sediments are mobilized on the upper slope by small-scale failures and evolve into debris flows, which transport the sediments downslope. The debris flows can extend for several hundred kilometers into the deep sea, with individual debris flow lobes being up to 40 km wide. Depending on lithology, debris flows may transform into turbidity currents by incorporation of ambient water (Hampton, 1972) or by downslope acceleration (Fisher, 1983).

Turbidity currents may be erosional on the continental slope, and they are able to transport debris into the deep sea and deposit it here as distal lobes (e.g. Mulder, 2011). The formation and evolution of submarine canyons and gullies on the upper slope of both Arctic and Antarctic margins are often associated with turbidity current erosion (Vorren et al., 1998;

Laberg et al., 2007b; Gales et al., 2013a; b; Rise et al., 2013). Gully-forming turbidity currents are suggested to have initiated from discharges of sediment-laden subglacial meltwater on the north-Norwegian continental slope (Gales et al., 2013a).

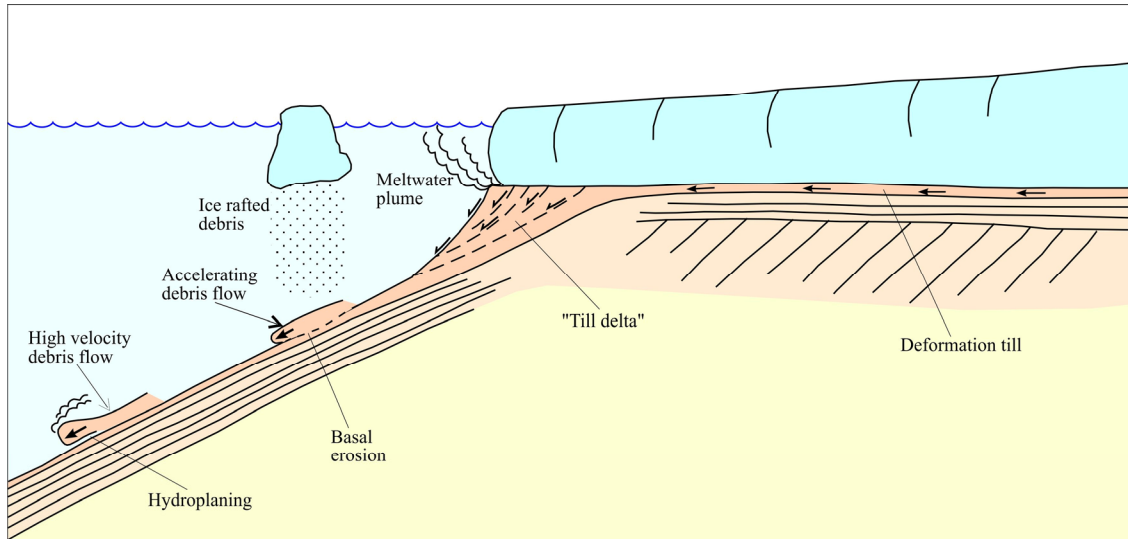


Figure 5: Schematic model showing the main sedimentary processes on the shelf break-upper slope during full-glacial conditions. Modified from Laberg and Vorren (1995).

1.2 Trough Mouth Fans and glacialic prograding wedges

1.2.1 Palaeoclimatic archives

TMFs and prograding wedge complexes in high-latitude shelves have accumulated during numerous glaciations from the late Cenozoic (e.g. Vorren et al., 1998; Dahlgren et al., 2005; Rebesco et al., 2006). As such, these systems are palaeoclimatic archives and ice-sheet monitors (Vorren and Laberg, 1997). It is inferred that the number of ice sheet advances to the shelf break are documented by the number of debris flow sets in the continental slope record, which are separated by hemipelagic interglacial/interstadial sediments (Vorren et al., 1989; Laberg and Vorren, 1995; King et al., 1996; Vorren and Laberg, 1997).

The glacial sedimentary environment can be elucidated from palaeo-surfaces within the fans and wedges, extracted from 3D-seismic mapping techniques. Subtle landforms such as iceberg ploughmarks and MSGL, as well as GDF lobes can be identified on palaeo-surfaces (e.g. Andreassen et al., 2004; 2007; Ottesen et al., 2009; Laberg et al., 2010). Fast-flowing ice streams on the mid-Norwegian margin and in the SW Barents Sea are indicated by the presence of MSGL on buried palaeo-surfaces, dated to 1.5 Ma (Andreassen et al., 2007;

Ottesen et al., 2009). Also, the deposition of GDF lobes on the Bear Island TMF testifies to contemporary shelf-wide glaciations (Laberg et al., 2010).

1.2.2 Glacigenic sediment yield through the Quaternary

Glaciers are very effective agents in long-term landscape denudation (Vorren et al., 1991; Dowdeswell et al., 2010). The total volume of glacigenic sediments deposited on the mid-Norwegian margin throughout the Quaternary is 104,700 km³, giving an average sedimentation rate of 0.24 m/ka (Table 1) (Dowdeswell et al., 2010). Between 395,000 km³ (Fiedler and Faleide, 1996) and 464,000 km³ (Vorren et al., 1991) of glacigenic sediments accumulated along the SW Barents Sea margin, giving an average sedimentation rate of 0.38/0.40 m/ka (Table 1) (Laberg et al., 2012). In comparison, fluvial sedimentation rates on non-glaciated continental margins by the Amazon and Mississippi rivers are an order of magnitude lower, between 0.01 and 0.025 m/ka (Elverhøi et al., 1998).

TABLE 2. COMPILATION OF GLACIAL EROSION AND SEDIMENTATION RATE ESTIMATES FROM GLACIATED AREAS OF THE NORTHERN AND SOUTHERN HEMISPHERE

Area	Average erosion rate (mm/yr)	Average sedimentation rate (cm/k.y.)	Period (Ma)	Reference
Southwestern Barents Sea	0.4	38	0–2.7	This study
Western Fennoscandia	0.19	24	0–2.7	Dowdeswell et al. (2010)
Southwestern Fennoscandia	0.12		0–1.1	Hjelstuen, 2011, personal comm.
Eastern Canada	0.13		0–0.8	Hiscott and Aksu (1996)
East Greenland		2.8/4.8	0–0.8	Berger and Jokat (2008)
East Antarctica	0.001–0.002		0–34	Jamieson et al. (2005)

Note: Table shows rates of glacial erosion and sedimentation in areas affected by the Barents Sea ice sheet (southwestern Barents Sea), the Fennoscandian ice sheet (western and southwestern parts), the Laurentide ice sheet (eastern Canada), the Greenland ice sheet (east Greenland), and the East Antarctic Ice Sheet (east Antarctica) averaged over the duration of the ice sheets.

Table 1: Rates of glacial erosion and sedimentation on the northern and southern hemisphere averaged over the duration of the respective ice sheets. From Laberg et al. (2012).

The average rate of erosion in the catchment area for the Norwegian margin has been calculated to 0.15 m/ka for the Southern Fennoscandia (Hjelstuen et al., 2012), 0.19 m/ka for the Western Fennoscandia (Dowdeswell et al., 2010), and 0.40 m/ka for the SW Barents Sea (Laberg et al., 2012) (Table 1).

In Fennoscandia, glacial erosion was selective (Table 1) and included low-relief surfaces which were less affected by Pleistocene erosion (Hall et al., 2013). An example of this is the Torneträsk area; one of the largest drainage outlets for the Vestfjorden ice stream (see Figure 1 for location), where as much as 30 % of the surface is essentially unaffected by glacial erosion (Kleman and Stroeven, 1997). The presence of a thick drift cover zone in central and northern Sweden, in the catchment area for the Fennoscandian Ice Sheet, results from fluctuating ice sheets during the early and middle Quaternary, i.e. later east-centered ice sheets had a low flow velocity with possible frozen bed areas which was inefficient in eroding the bedrock (Kleman and Stroeven, 1997; Kleman and Hättestrand, 1999; Kleman et al., 2008).

1.2.3 High-gradient Trough Mouth Fans

The majority of the studied TMFs on the northern hemisphere have low slope gradients ($<4^\circ$) and cover vast areas (Figure 6) (Vorren et al., 1998; Dahlgren et al., 2005; Batchelor and Dowdeswell, in press). High-gradient TMFs ($>4^\circ$) occur less commonly at trough mouths across the high Arctic (Figure 6) (Batchelor and Dowdeswell, in press), and on the West Antarctic Peninsula Margin (Amblas et al., 2006). They have generally received less attention, and on the Norwegian margin they are only described from Andfjorden (Vorren et al., 1984; 1998; Dahlgren et al., 2005).

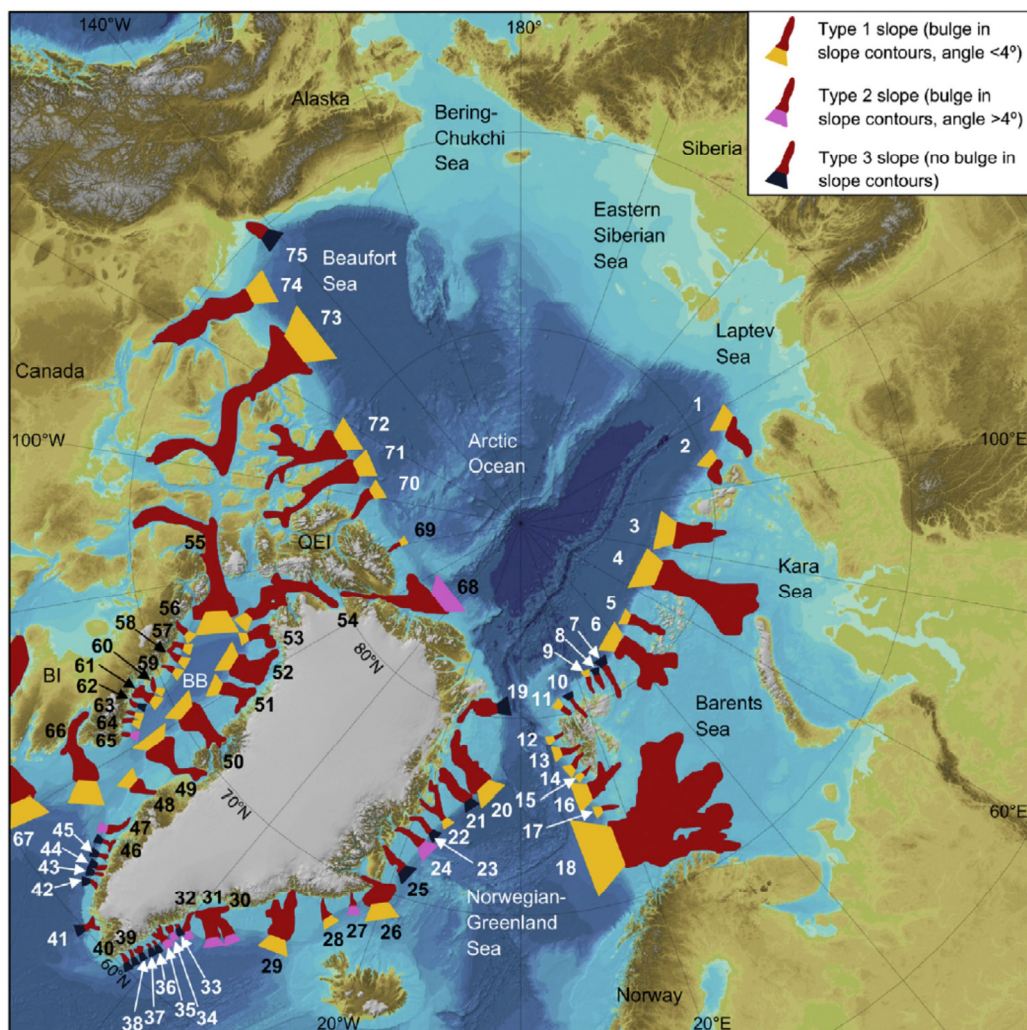


Figure 6: Locations of cross-shelf troughs (red) with low- and high-gradient sloping depocentres in yellow and pink, respectively. Cross-shelf troughs without pronounced depocentres are indicated in black. From Batchelor and Dowdeswell (in press).

Based on swath-bathymetric data from a steep trough slope at the West Antarctic Peninsula margin, Amblas et al. (2006) describe canyon-channel systems formed by turbidity currents. Similarly, from the eastern Greenland margin debris flow deposits and channels/gullies formed by turbidity currents have been described on high-gradient TMFs from seismic

profiles (Clausen, 1998) and swath-bathymetric data (Garcia et al., 2012). Thus, subglacial debris delivered to high-gradient TMFs is prone to downslope transportation by confined turbidity currents, and a higher level of erosion and sediment delivery to the deep sea is therefore observed in high-gradient TMFs compared to low-gradient TMFs (Figure 7) (Ó Cofaigh et al., 2003).

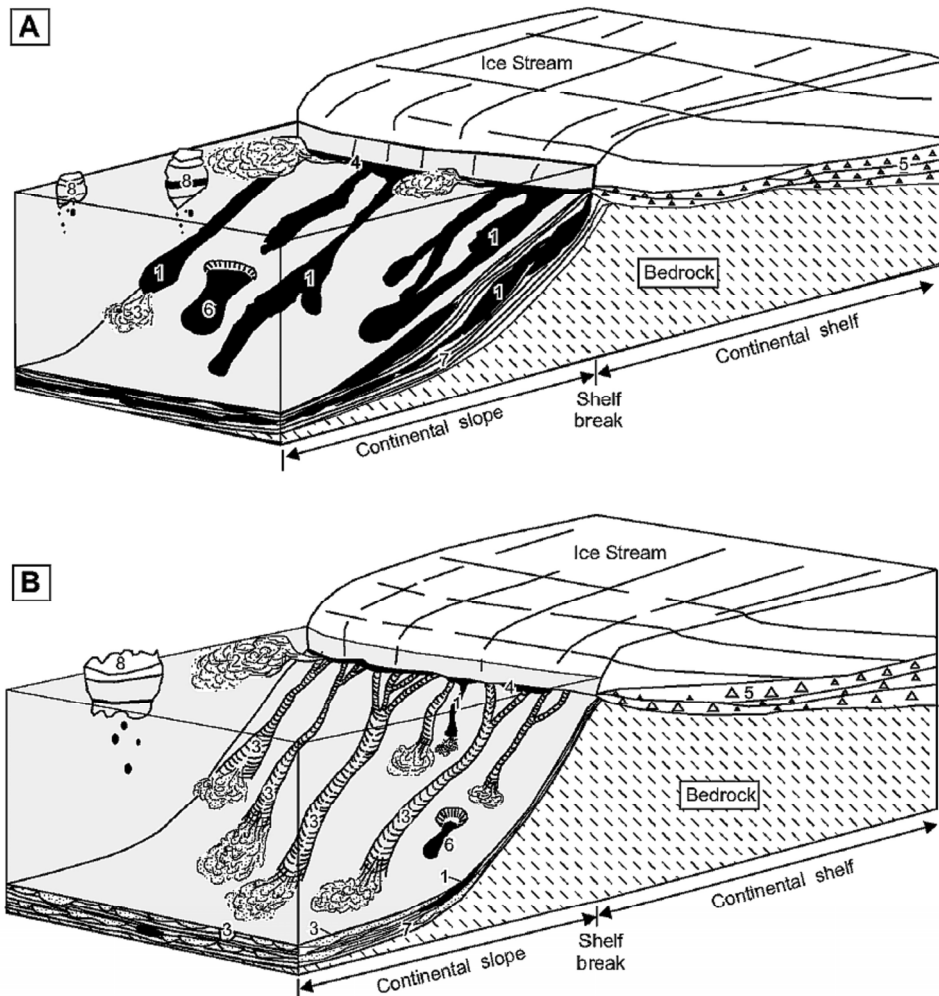


Figure 7: Conceptual model of continental slope sedimentation in front of an ice stream at the shelf break. A: Classic Trough Mouth Fan with low slope gradient ($< 1^\circ$) where debris flow activity and suspension settling from turbid meltwater plumes dominate sedimentation. B: Steep slope ($>10^\circ$). Large volumes of subglacial sediment are transported to the ice-stream margin and upper continental slope. Turbidity currents quickly develop due to the steep slope, and erode channels and gullies due to rapid downslope flow. The figure is modified from Ó Cofaigh et al. (2003).

2 Study area and aims

2.1 Study area

The study area for this Ph.D. project is located on the continental margin offshore Troms County, northern Norway (Figure 1 and 8). It covers an area of about 10,000 km² and has water depths ranging from 30 to 2400 m (Figure 8). The shelf is between 30 and 60 km wide west of the islands of Senja and Kvaløya, measured from the crystalline-sedimentary bedrock contact to the shelf break (Figure 8). The continental slope generally dips westwards at 10° (Dahlgren et al., 2005), which is steep compared to the rest of the Norwegian continental margin (Vorren et al., 1998). Three overdeepened cross-shelf troughs are separated by shallow and relatively flat bank areas, and coast-parallel troughs are situated east of the banks. The shelf break is situated at between 100 to 300 m water depth. Three TMFs and two canyons, as well as one inter-fan slope area has been identified west of the shelf break (Figure 8 and 9).

2.2 Aims of the study

This study aims to elucidate the ice sheet dynamics on the continental shelf off Troms during the LGM and the deglaciation, characterize sedimentary processes of high-gradient TMFs, evaluate the late Cenozoic evolution of the continental margin, and estimate the sediment yield.

The study results are presented in three papers. Paper 1 focuses on the continental shelf. Glacial landforms are here mapped and described from swath bathymetric data (Figures 8 and 9) and high-resolution seismic profiles. The ice flow during the LGM, and the deglaciation dynamics, is reconstructed based on the mapped landforms. Paper 2 focuses on the present-day morphology of the high-gradient TMFs and submarine canyons situated at the mouths of cross-shelf troughs and seawards of the banks, respectively (Figures 8 and 9). Integration of swath-bathymetric data and multichannel seismic profiles allowed for an ample understanding of the sedimentary processes involved. The results in this study are compared to other previously described high-gradient TMFs, as well as low-gradient TMFs, in order to further shed light upon and contrast the dominating sedimentary processes. Paper 3 focuses on the late Cenozoic evolution of the continental margin, reconstructed from 2D and 3D-seismic data (Figure 10). The sediment yield, including sedimentation rates on the fans and erosion rates in the catchment area, as well the potential of high-gradient TMFs as palaeoclimatic archives are discussed here.

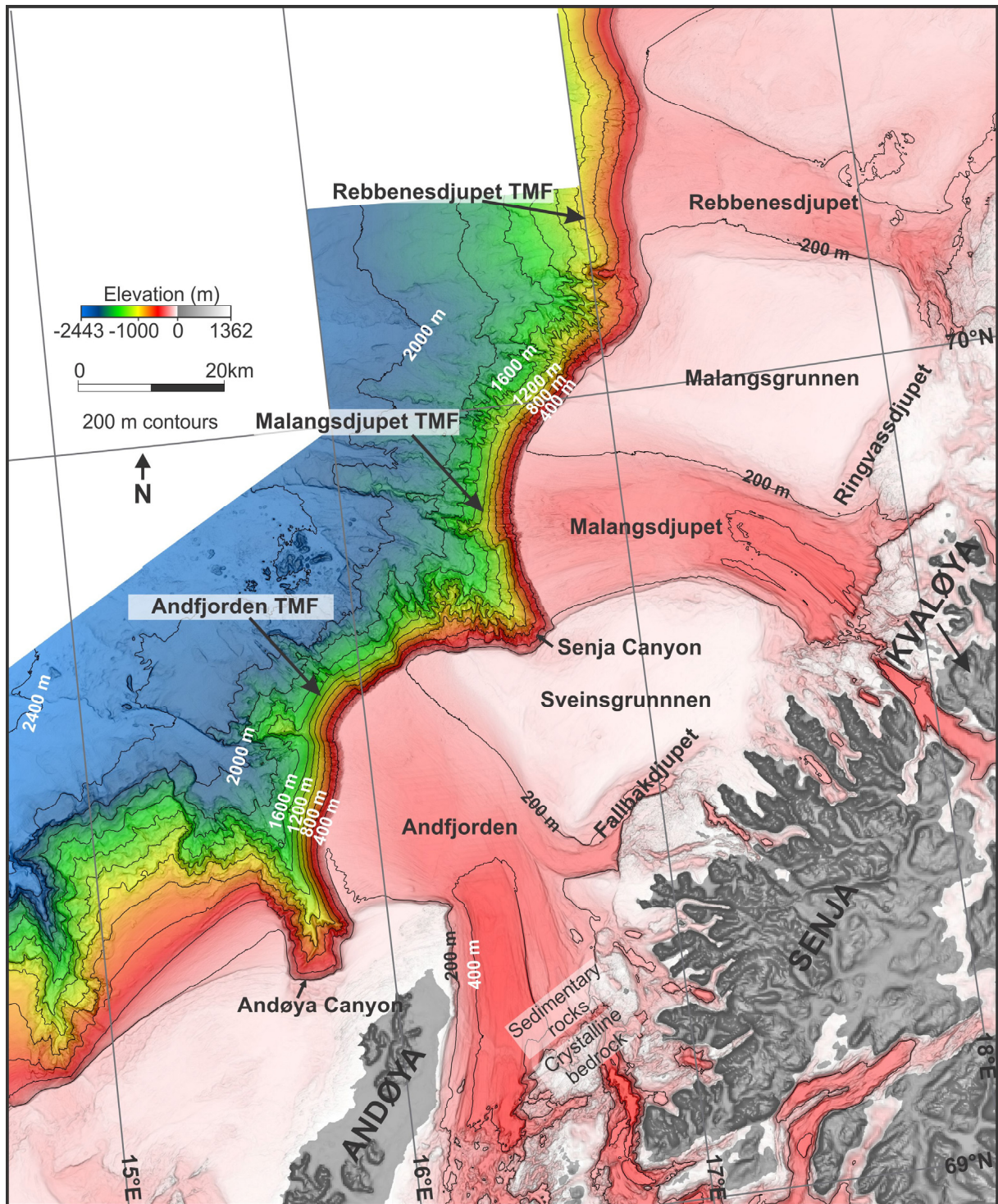


Figure 8: Bathymetric map of the study area offshore Troms County, northern Norway. The main landforms on the continental shelf and slope are indicated. Contour intervals are 200 m. See Figure 1 for location and Figure 9 for interpretation of landforms.

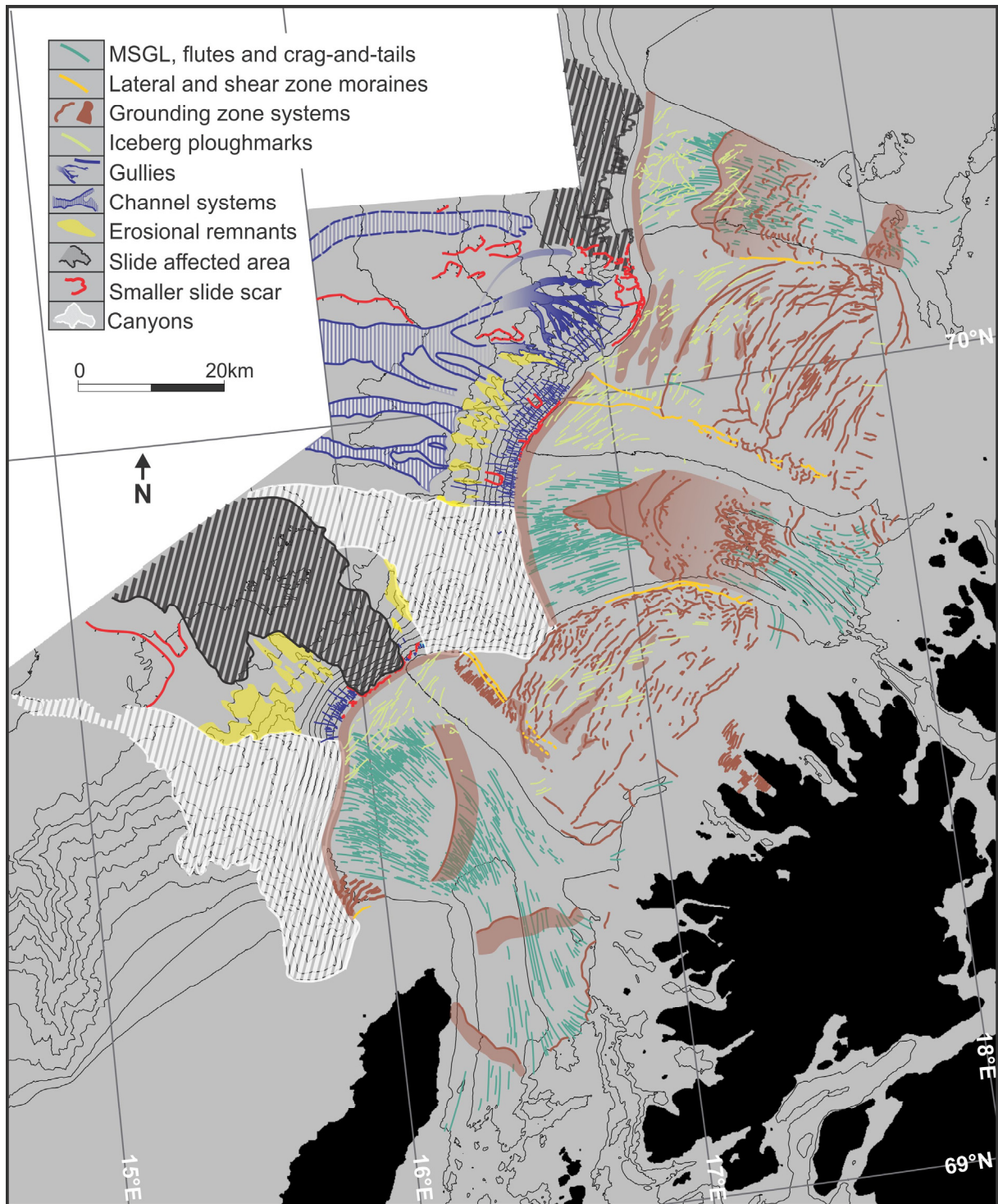


Figure 9: Summary of mapped landforms on the continental shelf (Paper 1) and slope (Paper 2). Contour intervals are 200 m.

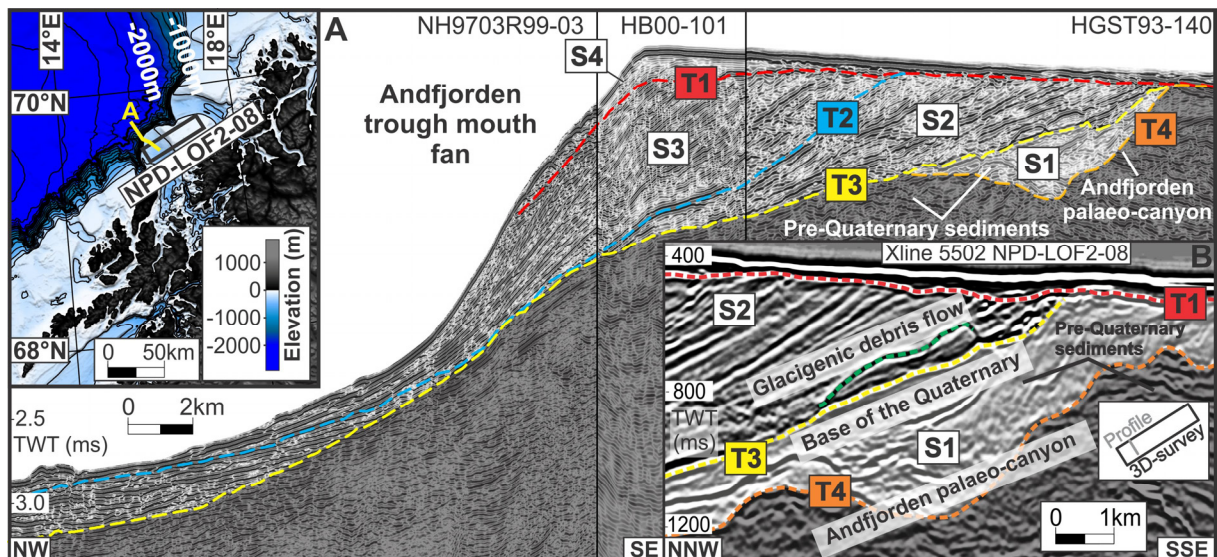


Figure 10: Composite 2D-seismic line (A) and cross-line from the 3D-seismic survey NPD-LOF2-08 (B) showing the late Cenozoic seismic stratigraphy on the Troms margin as exemplified from the Andfjorden TMF (Paper 3). Contour interval on inset figure is 200 m.

3 Data and methods

The main data sets for this study are bathymetric data and seismic records. Swath-bathymetric data collected by the Norwegian Hydrographic Service between 1990 and 2004 using Simrad EM100 and EM1002 was provided to the University of Tromsø through the Norway Digital program. The data is available as UTM-points with 50x50 m horizontal spacing within 12 nautical miles from the shoreline. Outside this boundary the data is available as 25x25 m and 5x5 m data points. The gridding and visualization of horizons were done in ED50 UTM zone 32N. Different displays, artificial illumination sources and vertical exaggeration have been applied in order to obtain the optimal imaging of the horizons morphology.

The seismic data in this study consist of 10 2D-seismic surveys collected by the petroleum industry during the last decades and one high-resolution seismic survey collected by the Norwegian Defense Research Establishment in 2001. In addition, the Norwegian Petroleum Directorate acquired new 2D multichannel seismic lines and 3D-seismic surveys in the study area between 2007 and 2009 (Oljedirektoratet, 2010). These data are not released, but the upper sections were made available for this study.

Radiocarbon dates from earlier studies were calibrated according to Reimer et al. (2009). More detailed descriptions of the data and methods used are given in the three papers.

4 Summary of papers

4.1 Paper 1

Rydningen, T.A., Vorren, T.O., Laberg, J.S., Kolstad, V., 2013. The marine-based NW Fennoscandian ice sheet: glacial and deglacial dynamics as reconstructed from submarine landforms. *Quaternary Science Reviews* 68, 126-141.

In Paper 1, the marine-based NW Fennoscandian Ice Sheet is reconstructed for the LGM and the deglaciation using swath-bathymetric data and high-resolution seismic profiles from the continental shelf off Troms. The extent and dynamics of the ice sheet are reconstructed from MSGL, lateral shear zone moraines and grounding zone systems. MSGL extending to the shelf break testifies to the presence of fast-flowing ice streams in the cross-shelf troughs during the LGM, while the morphology of the banks indicates presence of coeval sluggish-flowing ice. The marine-based part of the Fennoscandian Ice Sheet was sourced via fjords and valley systems inshore. Based on a balance flux approach the palaeo-ice stream velocities during the LGM is estimated to be ~350 m/yr. The deglaciation of the shelf occurred in three events: i) During the Torsken-1 event the ice sheet retreated from the shelf break in the troughs and halted or readvanced to form GZWs and the Torsken moraine, ii) During the Torsken-2 event the glacier initiated the retreat from the banks, punctuated by several still-stands or readvances, iii) The Flesen event is characterized by deposition of prominent end moraines in the inner parts of the troughs and banks. Despite the reverse bed slope in the troughs, the presence of grounding zone systems here testifies to an episodic retreat of the glacier across the shelf following the LGM. This is probably due to the variations in widths of the cross-shelf troughs, i.e. the retreating glacier slowed down in narrow parts of the troughs as the ice flux increased here.

4.2 Paper 2

Rydningen, T.A., Laberg, J.S., Kolstad, V., in prep. Seabed morphology and sedimentary processes on high-gradient Trough Mouth Fans offshore Troms, northern Norway. To be submitted to *Geomorphology*.

In Paper 2, swath-bathymetric data and multichannel seismic profiles is analyzed in order to describe downslope sedimentary processes on high-gradient TMFs and inter-fan areas on the continental slope off Troms. The highest gradient (10-15°) TMFs: the Andfjorden and Malangsdjupet TMFs, are dominated by gullies on the upper slope merging into channels downslope, i.e. forming gully-channel complexes. A large slide, the Andøya Slide, has

probably removed much of such a complex on the Andfjorden TMF. The somewhat gentler Rebbenesdjupet TMF, which slopes up to 8°, is dominated by a number of small and relatively shallow slide scars, inferred to be related to small-scale sediment failures of glaciomarine and/or contouritic sediments. The Andøya and Senja canyons cut into the TMFs, and frequent turbidity current activity widened and deepened the canyons. The inter-fan slopes of Malangsrunden acted as a funnel for turbidity currents forming a dendritic pattern of gullies downslope. A conceptual model for high-gradient TMFs was compiled based on the processes identified in the study area. In the model, gully-forming turbidity currents originating from sediment-laden bottom waters or small-scale sediment failures on the upper slope, are routed through a zone of high-relief ridges into channels on the lower slope. The turbidity currents continue into the deep sea, thus promoting efficient sediment by-pass across the TMFs. Processes on high- and low-gradient TMFs are compared. Gully-channel complexes occur on high-gradient TMFs, while they are rare on low-gradient TMFs, where GDFs are found to be typical ‘building blocks’. Large submarine landslides are found to occur at both TMF types.

4.3 Paper 3

Rydningen, T.A., Laberg, J.S., Kolstad, V., in prep. Late Cenozoic evolution of high-gradient Trough Mouth Fans and canyons on the glaciated continental margin offshore Troms, northern Norway – palaeoclimatic implications and sediment yield. Manuscript.

In Paper 3, 2D- and 3D-seismic data from the Troms margin is analyzed in order to describe the late Cenozoic evolution, and quantify the rates of sedimentation and erosion throughout the Quaternary here. The Andfjorden and Malangsdjupet palaeo-canyons were active on this margin prior to the onset of northern hemisphere glaciation, and canyon infill prevailed before ~2.7 Ma. Glaciomarine and glaciofluvial sedimentation dominated between ~2.7 and ~1.5 Ma, and during this period the ice sheet possibly reached the shelf break at least once. The minimum average sedimentation rate for this period was 0.20 m/ka. The glaciers expanded at ~1.5 Ma, and the ice covered the shelf several times up until ~0.7 Ma. Fast-flowing palaeo-ice streams established in the cross-shelf troughs and delivered subglacial deformation till to the outer shelf. These deposits were later reworked by debris flows and turbidity currents. The Troms margin was possibly established as an inter-ice flow sector during this period, i.e. the bulk of the Fennoscandian Ice Sheet drained north into the SW Barents Sea and south to the mid-Norwegian margin. The minimum average sedimentation rate for this period was 0.15 m/ka. From ~0.7 Ma ice streams continued to traverse the troughs, while sluggish-flowing ice

was located at the banks. The Andfjorden and Malangsdjupet TMFs were dominated by sediment by-pass during this period. The minimum average sedimentation rate was 0.14 m/ka. The minimum total average erosion and erosion rate during the Quaternary for the Troms margin catchment area is 50-140 m and 0.02-0.05 m/ka, respectively. These rates are low compared with the SW Barents Sea and the mid-Norwegian margin. This is probably due to several factors, including bedrock composition of the catchment areas as well as ice sheet build-up, timing and dynamics.

5 Synthesis: Late Cenozoic evolution of the mid-Norwegian – SW Barents Sea continental margin – implications for the evolution of the Fennoscandian and Barents Sea ice sheets

This study focuses on the late Cenozoic evolution of the continental margin offshore Troms, situated between the major glacial depocentres on the mid-Norwegian margin and in the SW Barents Sea (Vorren et al., 1991; 1998; Laberg and Vorren, 1995; 1996a; b; Fiedler and Faleide, 1996; Henriksen and Vorren, 1996; Dahlgren et al., 2005; Rise et al., 2005; Sejrup et al., 2005; Ottesen et al., 2009; Dowdeswell et al., 2010; Laberg et al., 2012). This part of the Norwegian margin is previously little explored, and thus the new studies presented here have the potential to improve on the understanding of sedimentary processes and sediment yield across a glaciated continental margin. Also, a better basis for understanding the relation between the late Cenozoic evolution of the mid-Norwegian margin and the SW Barents Sea, and from this, the evolution of the Fennoscandian – Barents Sea Ice Sheets is provided by this study.

An improved understanding of the Fennoscandian Ice Sheet behavior on the Troms margin during peak glacial conditions is provided through identification of glacial landforms and their origin (Figure 9) (Paper 1). The seabed imprint from both fast-flowing ice streams which overlay the troughs (Vorren and Plassen, 2002; Ottesen et al., 2005a; 2008), and sluggish flowing ice which covered the banks, provide important analogs for buried palaeo-surfaces on the shelf. Also, the reconstructed glacier dynamics on the shelf provides a good background for understanding the downslope processes on the continental slope. Furthermore, a new reconstruction of the deglaciation of the shelf is presented. This includes both the ice retreat from the troughs, building on earlier studies (Vorren et al., 1983; 1988b; Vorren and Plassen, 2002; Ottesen et al., 2008), and the identification of new grounding zone systems in the troughs and marginal moraines on the banks. Thus, an improved understanding of the deglaciation of the area highlights that the retreat of the ice sheet was more dynamic, including more halts/readvances than previously thought.

The seabed morphology of the continental slope off Troms, the only part of the Norwegian slope where high-gradient TMFs occur (Vorren et al., 1984; Dahlgren et al., 2005) was mapped in detail for the first time from extensive swath-bathymetric data and multichannel seismic profiles (Paper 2). This has allowed for a more comprehensive understanding of sedimentary processes on such fans, including the identification of gully-channel complexes (Figure 9). Accordingly, extensive erosion on high-gradient TMFs is found, contrasting the

low-gradient prograding wedges and TMFs, which are dominated by deposition from GDFs during peak glaciations. Also, the mapped seabed morphology of high-gradient TMFs and submarine canyons provide valuable analogs for buried palaeo-slopes in the area.

The late Cenozoic sediments on the Troms margin, previously only discussed as part of more regional studies by Dahlgren et al. (2005) and Oljedirektoratet (2010) were here studied in detail and forming the basis for the reconstruction of the late Cenozoic evolution of the mid-Norwegian – SW Barents Sea margin (Paper 3). Glaciofluvial/glaciomarine conditions prevailed on the Troms margin between ~2.7 and ~1.5 Ma, similar to coeval palaeoenvironments in the SW Barents Sea (Laberg et al., 2010) and on the mid-Norwegian margin (Rise et al., 2005; Ottesen et al., 2009). The calculated sedimentation rate (0.20 m/ka; Paper 3) is comparable to the SW Barents Sea (0.16/0.22 m/ka; Laberg et al., 2012) and the mid-Norwegian margin (0.18 m/ka; Dowdeswell et al., 2010).

Repeated events of glaciers reaching the shelf break and fast-flowing ice streams traversing the shelf are inferred from ~1.5 Ma on the mid-Norwegian margin, the continental margin off Troms and in the SW Barents Sea, with sedimentation rates of 0.17 m/ka (Dowdeswell et al., 2010), 0.15 m/ka (Paper 3) and 0.50/0.64 m/ka (Laberg et al., 2012), respectively. The relatively low sedimentation rates off mid-Norway and Troms are attributed to an earlier build-up of large ice masses in the north (Knies et al., 2009) and the establishment of the Troms margin as an inter-ice flow sector during this period. Ice streams repeatedly traversed the Norwegian margin during the last ~0.7 Ma, with low sedimentation rates off Troms (0.14 m/ka; Paper 3) due to deflection of ice streams to the north and south. Highest sedimentation rates are found on the mid-Norwegian margin (between 0.38 and 0.52 m/ka; Dowdeswell et al., 2010), while more trough-focused sedimentation resulted in overall lower sedimentation rates in the SW Barents Sea (0.18/0.22 m/ka; Laberg et al., 2012).

The average glacial erosion (50-140 m) and erosion rate (0.02-0.05 m/ka) for the Troms margin catchment area are found to be low (Paper 3) compared to the mid-Norwegian margin (~500 m and 0.19 m/ka; Dowdeswell et al., 2010) and the SW Barents Sea (~1000 m and 0.40 m/ka; Laberg et al., 2012). This is most likely due to the earlier ice sheet build-up in the north and the development of the Troms margin as an inter-ice flow sector from ~1.5 Ma. In addition, more easily erodible sedimentary rocks is inferred for the SW Barents Sea, giving overall higher erosion rates here compared to the mid-Norwegian margin and the Troms margin.

In sum, this study shows that the continental margin off Troms can be described as an inter-ice flow sector situated between major glacigenic depocentres to the north and south. Also, large variations in sedimentation and erosion are found to occur along the glaciated continental margin (Paper 3). Even though the studied area was traversed by fast-flowing ice streams during the last ~1.5 Ma (Paper 1 and 3), sedimentation rates have been low since this time. As a result, high-gradient TMFs dominated by turbidity current activity developed here (Paper 2) – in contrast to areas of higher rates where larger sediment accumulations formed, i.e. low-angle TMFs and prograding wedges dominated by debris flows.

6 Future research

Future research should aim at testing the hypotheses and results presented in Papers 1-3; this include the deglaciation dynamics on the continental shelf presented in Paper 1, the nature and origin of the downslope sedimentary processes on the continental slope described in Paper 2, and the rates of sedimentation and erosion given in Paper 3. Also, the glacial sequence on the continental margin off Troms should be further studied in terms of understanding both processes which formed the present-day morphology of the high-gradient TMFs, and processes which formed buried palaeo-slopes.

Paper 1 reconstructed the deglaciation of the continental shelf based on glacial landforms. Absolute dating of offshore moraines in this area is limited to the Flesen Moraine in the Andfjorden trough (Vorren et al., 1983; Vorren and Plassen, 2002). Thus, the reconstruction of the deglaciation of this shelf can be improved, and from core sampling and dating of grounding zone systems the reconstruction in Paper 1 could be tested. For instance, dating of the Stormekta Moraine in the Rebbenesdjupet trough would indicate as to whether the ice retreat in this trough was synchronous with the Andfjorden trough, i.e. of same age as the Flesen Moraine.

In Paper 2, the high-gradient TMFs are described from swath-bathymetric data and seismic profiles. Sediment cores from these fans should be applied in further describing and characterizing these slope systems in terms of sedimentary processes involved. Also, the explanation for the difference between the gully-channel complex morphology of the Andfjorden/Malangsdjupet TMFs and the shallow slide-dominated Rebbenesdjupet TMF could be further investigated based on sediment core samples.

The model showing processes on high-gradient TMFs in Paper 2 is compared to high-gradient TMFs on other glaciated margins. However, these descriptions are based on poor data coverage, i.e. 2D-seismic data from the SE Greenland margin (Clausen, 1998) or restricted multi-beam coverage from the east Greenland margin (Garcia et al., 2012) and the West Antarctic Peninsula margin (Amblas et al., 2006). Thus, studies based on a more complete swath-bathymetric data coverage on other systems would provide a better basis for comparing processes on different high-gradient TMFs.

As a consequence of the Troms margin not being opened for petroleum exploration, no exploration wells have penetrated the glacial sediments here. Thus, the chronology of the glacial units described in Paper 3 is based on a comparison with the established and dated

SW Barents Sea stratigraphy (Knies et al., 2009) and the Naust sediments on the mid-Norwegian margin (Rise et al., 2005; Ottesen et al., 2009). The oldest glacial prograding unit on the Troms margin is outcropping on the lower slope as erosional remnant ridges (Figure 9), and could be relatively easily sampled from shallow drilling. Therefore, sediments from the early glacial phases could be recovered and possibly dated here. Sediment samples from unit S2 and S3 would also provide a better understanding of the sediments physical properties and their influence on the slope stability through S2 and S3 time. Furthermore, detailed mapping of sedimentary processes on buried palaeo-slopes on the Troms margin from 3D-seismic data would provide an improved understanding of the margin construction including styles of progradation through the Quaternary.

The total erosion and erosion rates presented in Paper 3 are minimum estimates. By also quantifying the amount of sediments in the Lofoten Basin (Figure 1), the most distal sediments originating from the study area, these values could be better constrained. Furthermore, the total erosion and erosion rates could be tested based on cosmogenic radionuclide data from the catchment area. By measuring of remnant nuclide concentrations from samples taken both from relict areas and sites influenced by glacial erosion, the level of erosion resulting from the last glaciation can be constrained; similar to what has been done by Stroeven et al. (2002).

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Paper 1

Paper 2

Paper 3

