Ice-sheet dynamics and glacial development of the Norwegian continental margin during the last 3 million years

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Norway
2006

Dissertation for the degree dr. philos

Abstract

This thesis is mainly about the dynamics of the palaeo-ice sheets that covered Scandinavia, Barents Sea and Svalbard during the last glaciation. Morphological interpretation of regional and detailed bathymetric data sets on the Norwegian shelf from the North Sea (57˚N) to Svalbard (80˚N) has elucidated the ice-flow patterns along the western margin of the Scandinavian and Barents/Svalbard ice sheets. About 20 cross-shelf troughs with glacial lineations are interpreted as former pathways for fast-flowing ice streams. The two largest palaeo-ice streams were the Norwegian Channel Ice Stream and Bear Island Ice Stream, each 150-200 km wide at their mouths. Studies of large-scale margin morphology and seismic-reflection profiles have identified large submarine fans at the mouths of several major cross-shelf troughs.

Improved knowledge of the regional development of the margin, and detailed morphological maps of the buried palaeo-surfaces, show that similar large-scale glacial processes have been active in a substantial part of the Late Pliocene/Pleistocene (c. last 3 million years).

Interpretation of a large seismic data base has made it possible to map the whole Naust Formation, which comprises sediments deposited on the mid-Norwegian margin during the last 3 million years. During this period, large quantities of glacially derived material were transported westward from the Norwegian mainland and the inner parts of the shelf, and deposited mainly as prograding sediment wedges into a basin of intermediate depth offshore of Mid Norway. The deposits are more than 1000 m thick over an extensive area, and the shelf edge migrated up to 150 km westwards.

Very-high-resolution bathymetric data has made it possible to study sedimentary processes related to recently surging glaciers on Svalbard (the last few hundred years). The data sets also show that mega-scale glacial lineations not only can form beneath large ice streams, but are also produced over a few years beneath surging tidewater glaciers lying on deforming sedimentary beds.

Table of Contents

List of papers included in the thesis

1: Ottesen, D., Rise, L., Rokoengen, K. and Sættem, J., 2001: Glacial processes and large-scale morphology on the mid-Norwegian continental shelf. *In* Martinsen, O.J. and Dreyer, T., (Eds.), *Sedimentary Environments Offshore Norway – Palaeozoic to Recent:* Norwegian Petroleum Society Special Publication, 10, 441-449. Elsevier Science B.V., Amsterdam.

2: Ottesen, D., Dowdeswell, J.A., Rise, L., Rokoengen, K. and Henriksen, S., 2002: Large-scale morphological evidence for past ice-stream flow on the mid-Norwegian continental margin. *In* Dowdeswell, J.A. and Ó Cofaigh, C. (eds.), *Glacier-Influenced Sedimentation on High-Latitude Continental Margins*, 245-258. Geological Society of London, Special Publication 203.

3: Ottesen, D., Dowdeswell, J.A. and Rise, L., 2005a: Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2500-km-long Norwegian-Svalbard margin (57° - 80°N). *Geological Society of America Bulletin, 117*, 1033-1050.

4: Ottesen, D., Rise, L., Knies, J., Olsen, L. and Henriksen, S., 2005b: The Vestfjorden-Trænadjupet palaeo-ice stream drainage system, mid-Norwegian continental shelf. *Marine Geology, 218*, 175-189.

5: Rise, L., Ottesen, D., Berg, K. and Lundin, E., 2005: Large-scale development of the mid-Norwegian margin during the last 3 million years. *Marine and Petroleum Geology, 22*, 33-44.

6: Dowdeswell, J.A., Ottesen, D. and Rise, L., 2006: Flow switching and large-scale deposition by ice streams draining former ice sheets. *Geology*, 34, 313-316. doi: 10.1130/G22253.1.

7: Ottesen, D. and Dowdeswell, J.A., 2006: Assemblages of submarine landforms produced by tidewater glaciers in Svalbard. *Journal of Geophysical Research, 111*, 1-16. F01016, doi:10.1029/2005JF000330.

8: Ottesen, D., Dowdeswell, J.A., Landvik, J.Y. and Mienert, J., 2006: Dynamics of the Late Weichselian ice sheet on Svalbard inferred from high-resolution sea-floor morphology. *Boreas*, In press.

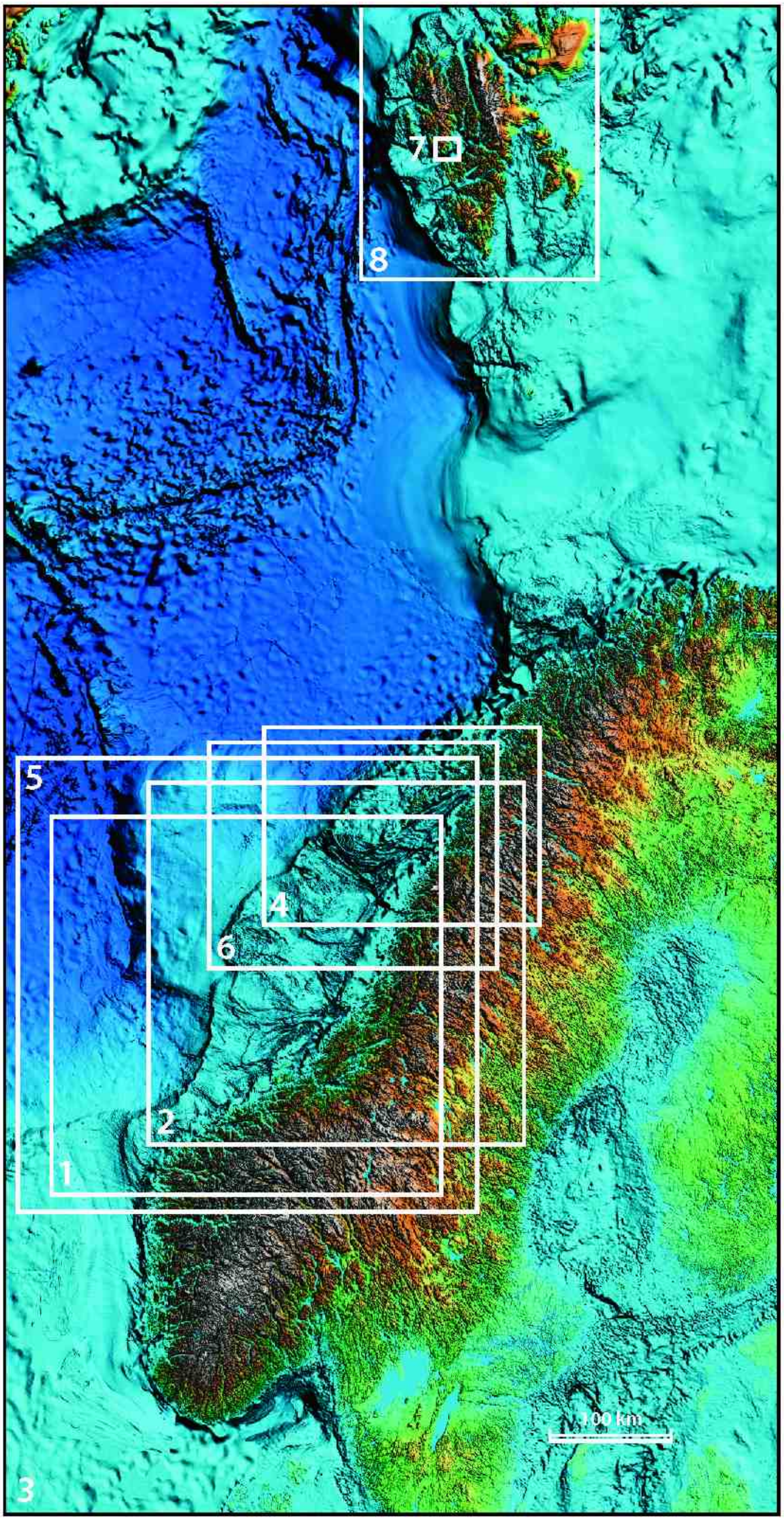

Fig. 1. Overview map of Scandinavia and Svalbard with surrounding sea areas. The locations of the study areas for the individual papers in the thesis are shown. Numbers refer to paper number listed on the previous page. Paper 3 covers most of the area shown on the figure.

Preface and acknowledgements

This dissertation has been prepared for the degree of doctor philosophiae at the University of Bergen. The thesis comprises eight papers, of which seven are published and one manuscript is in press. The papers were written at the Geological Survey of Norway in the period 2000 to 2006 and during a 4-month research stay in 2005 at the Scott Polar Research Institute, University of Cambridge, England.

The papers are based on data from various sources: bathymetric data are provided mainly by the Norwegian Hydrographic Service, and seismic and well/core data are from Norsk Hydro ASA, Statoil ASA, Sintef Petroleum Research, Geological Survey of Norway (NGU), Norwegian Petroleum Directorate (NPD), Petroleum Geo-Services, TGS-Nopec and Fugro-Geoteam. To all these institutions I am very grateful.

Our participation in the Ormen Lange Project (Norsk Hydro ASA, headed by Kjell Berg/Petter Bryn) and the Seabed Project (Norsk Hydro ASA, headed by Espen Sletten Andersen/Tom Bugge) has given us access to a large seismic data base (2D/3D) and well/core information which has proved to be invaluable for our understanding of the development of the Norwegian continental margin over the last 3 million years.

The compilation of this work was made possible by the generous support of the Geological Survey of Norway and by the Seabed Project of the Norwegian Deepwater Programme.

I would like to thank all my colleagues in the marine geology group at the Geological Survey of Norway. A special thanks goes to Leif Rise (NGU), mentor and supervisor, who has provided strong support throughout the entire period of research. I am also particularly grateful to Professor Julian Dowdeswell, Scott Polar Research Institute, University of Cambridge. His support and participation during the preparation of several of the papers are very much appreciated. He also made it possible for me to make a 4-month research visit to Cambridge in 2005. I should also like to extend my thanks to Kåre Rokoengen as a good colleague and inspirator, and to several other persons who have been involved in various parts of this research, including all the co-authors and everybody who is acknowledged in the individual papers.

Finally, warm thanks to my family for their patience during many long evenings in the office.

Objectives of the thesis

The objective of this thesis has been to understand the processes that have shaped the Norwegian continental margin during the last glaciation with emphasis on the importance of ice-stream drainage across the shelf to the shelf edge. Improved knowledge of the regional development of the margin, and detailed morphological maps of the buried palaeo-surfaces, show that similar large-scale glacial processes have been active in a substantial part of the Late Pliocene/Pleistocene (c. last 3 million years). Process studies related to recently surging glaciers on Svalbard (the last few hundred years) have also been undertaken on the basis of very-high-resolution bathymetric data.

Introduction

This thesis is mainly about the dynamics of the palaeo-ice sheets that covered Scandinavia, the Barents Sea and Svalbard during the last glaciation (Fig. 2). Determining the location of palaeo-ice streams is crucial in order to produce accurate reconstructions of palaeo-ice sheets. The best investigated modern ice streams are those of the Siple Coast in Western Antarctica (Bentley, 1987; Clarke, 1987). During recent years, an understanding has evolved that ice streams play a key role in determining the overall ice-sheet mass balance. An ice stream is defined as part of an ice sheet where ice flows faster and not necessarily in the same direction as the surrounding ice (Swithinbank, 1954). These curved features in the ice have velocities from 100 m to several kilometres per year, are from 10 to 100 km wide and can reach a length of several hundred kilometres. They are present in most large ice masses and drain most of their mass. For example, over 90 % of all ice discharged by the Antarctic Ice Sheet occurs as ice streams (Bamber et al., 2000). Due to the marine-based nature of the West Antarctic Ice Sheet, scientists have feared for the stability of the ice sheet, and thus extensive research has been carried out during the last 20 years. However, our understanding of ice streams is often reliant on short-term observations over the last few decades (Bindschadler and Vornberger, 1998). Investigations of palaeo-ice streams allow us to obtain information about their behaviour throughout whole cycles of operation, and thus advance our understanding of ice-stream behaviour and their impact on ice-sheet configuration. Palaeo-ice streams have been located in the former Laurentide Ice Sheet (Dyke and Morris, 1988; Clark and Stokes, 2001; Stokes and Clark, 2003; Stokes et al., 2006), the Fennoscandian Ice Sheet (Boulton et al., 2001; Punkari, 1997; Ottesen et al., 2005a,b; Rise et al., 2004; Sejrup et al., 2003), in the Barents Sea (Andreassen et al., 2004) and in the West Antarctic Ice Sheet (Shipp et al., 1999; Canals et al., 2000; Dowdeswell et al., 2004; O'Cofaigh et al., 2002; Evans et al., 2004). Recently, palaeo-ice streams have also been identified in the Upper Ordovician rocks of northern Africa (Moreau et al., 2005).

The morphological interpretation of regional and detailed bathymetric data sets on the Norwegian continental shelf from the North Sea (57˚N) to Svalbard (80˚N) has revealed a dynamic ice-flow pattern along the western margin of the Scandinavian and Barents/Svalbard ice sheets (Ottesen et al., 2001, 2005a). About 20 cross-shelf troughs with mega-scale glacial lineations (MSGL; elongate ridges and grooves oriented parallel to trough long axes) are interpreted as former pathways for fast-flowing ice streams (Fig. 2). The two largest palaeo-ice streams were the Norwegian Channel Ice Stream and Bear Island Trough Ice Stream, each 150-200 km wide at their mouths. The Norwegian Channel Ice Stream was 800 km long and originated in the Skagerrak area between Norway and Denmark. It followed the coast of Norway to the shelf break outside western Norway at 62°N. Studies of the large-scale margin morphology and seismic profiles have identified large submarine fans at the mouths of several major cross-shelf troughs (King et al., 1996; Nygård et al., 2004; Sejrup et al., 2003; Vorren and Laberg, 1997; Dowdeswell et al., 2006).
Five of the eight papers in the thesis are about the ice-flow patterns in the Fennoscandian Ice Sheet during the last glaciation (Papers 1, 2, 3, 4 and 8), whereas paper 6 is about ice-sheet dynamics during the last few glaciations, where we have shown how an ice stream several hundred kilometres in length has undergone major switching in flow direction from one glaciation to the next. This is based on bathymetric data from the present sea floor in combination with studies of 2D seismic lines and 3D seismic data sets. Here, mapping of buried surfaces with glacial lineations has been carried out, and this has shown that the general ice flow over the area has undergone major changes from the third and second last to the last glaciation.

Paper 8 is about the ice-sheet dynamics in the Svalbard Ice Sheet based on bathymetry from the fjords and shelf areas around Svalbard.

During several studies of the regional seismic stratigraphy of the mid-Norwegian shelf, we have outlined the development of the area during the last c. 3 million years. This period comprises all the 30-40 glacial-interglacial cycles that occurred in the Plio/Pleistocene, and shows a very extensive outbuilding of the shelf, with width progradations of up to 150 km and extensive areas with sediments exceeding 1000 m in thickness. This is the focus of Paper 5.

Sedimentary processes taking place beneath modern glaciers are difficult to observe directly, but are important for the understanding of the nature and rate of glacier motion. Sea-floor sediments that are unaffected by mass-wasting processes, currents or iceberg ploughmarks are an important archive for landforms formed beneath glaciers. In two small tributary fjords to Isfjorden, Svalbard (Borebukta and Yoldiabukta), we have had access to two very detailed data sets of multibeam bathymetry. The sea-floor morphology of these fjords comprises a series of landforms which are related either to a surge that took place c. 100 years ago, or to the period of stagnation and ice retreat afterwards. The landforms are well dated, based on aerial photographs showing the former positions of the ice front of Borebreen and Wahlenbergbreen. In paper 7 we describe these forms and discuss their formation.

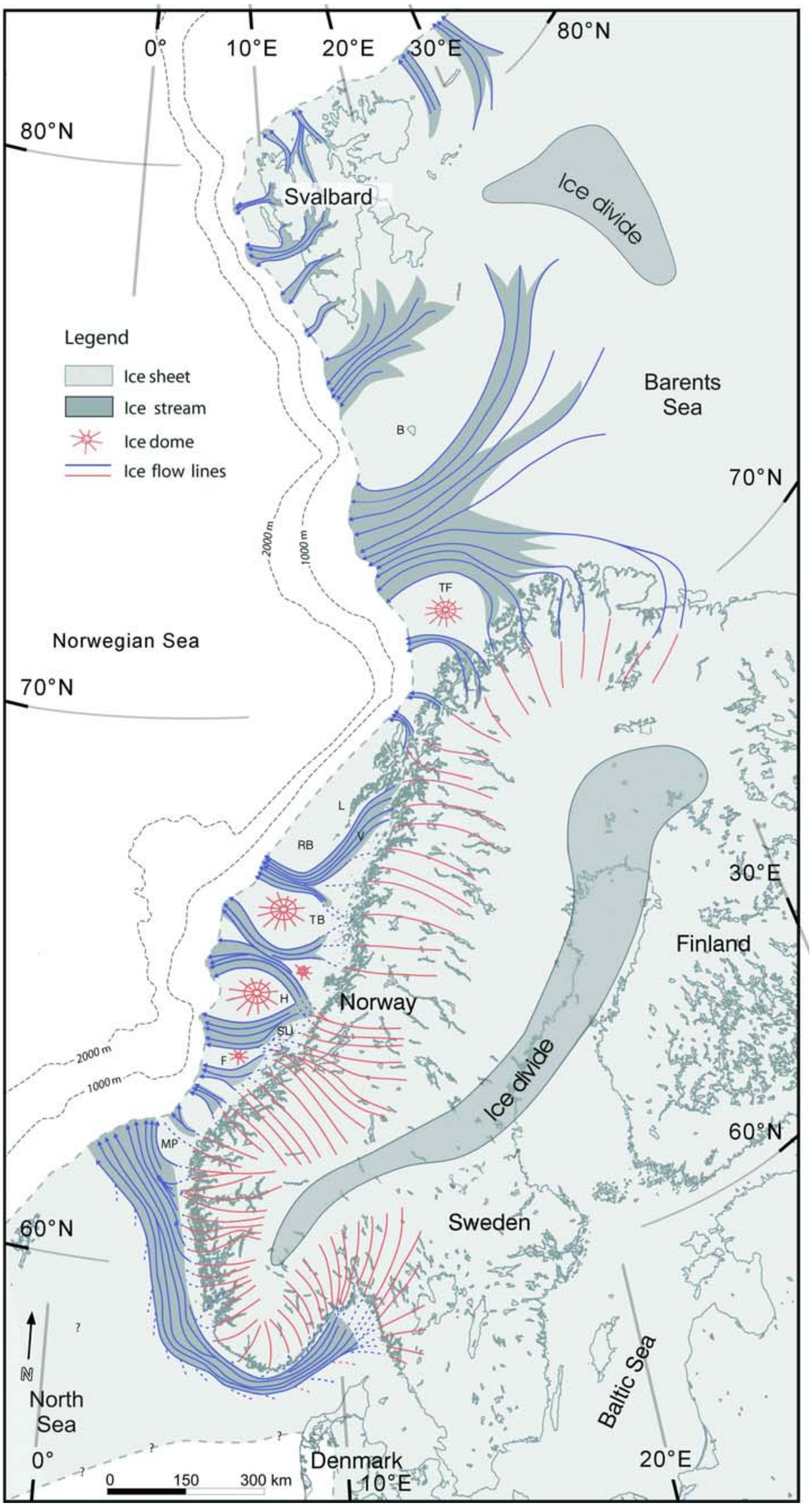

Fig. 2. Ice-sheet model for the last glacial maximum. From Ottesen et al. (2005a).

Historical background

The Norwegian continental shelf has long been investigated by biologists, hydrographers and geologists (Holtedahl, 1993). However, cruises only for geological purposes very seldom took place. Nansen was a pioneer regarding work about the geology of the continental shelves. In 1904 he published a paper entitled 'The bathymetrical features of the North Polar Seas. A discussion of the continental shelves and previous oscillations of the shore-line'. This work was published partly as a result of the Fram Expedition of 1893-96. Nansen compiled the first 'realistic' map of the whole of the Arctic Ocean with the morphology of the surrounding continental shelves, which at that time was a really impressive work. A complete bathymetric map of the Norwegian continental shelf was also included, based on a map published by Norges Geografiske Opmåling (now the Norwegian Mapping Authority). This map covered the areas between the North Sea Plateau (56°N) and the Barents Sea (73°N). Nansen discussed the development of the continental shelf and concluded that, in preglacial time, these areas were situated more than 500 m higher than today relative to the present sea level. The evidence for this was the valley-like depressions found on the slope outside the shelf edge, which he thought were caused by river erosion. He assumed that the seafloor morphology was later modified by glacial erosion and sea level oscillations.

The Norwegian Hydrographic Service carried out extensive sea-floor mapping in the years just before the Second World War. In 1940, Olaf Holtedahl published a bathymetrical map series of the Norwegian coastal waters and shelf areas mainly based on these data at scales between 1: 400 000 and 1: 600 000. These maps formed a very good basis for geological evaluations; he considered that the shelf had been levelled by subaerial processes, but emphasised also the glacial influence based on the large-scale seafloor morphology.

In the early 1950s, Hans Holtedahl made several geological cruises on the outer shelf outside Møre. He discussed different hypotheses for the formation of the shelf, but on the basis of the knowledge that existed at that time, he was open to several possibilities. However, on the outer shelf he found some steps in the slope, and interpreted them as fault scarps. He inferred that the shelf probably consisted of in-situ rocks, and from dredged samples that the upper layers were composed of glacial sediments. The dredged material from the continental slope showed a high percentage of angular rocks, mainly red and grey granites and gneisses, and he concluded that the area was underlain by the same rocks as in the adjacent land areas (Holtedahl, 1950, 1953). Our knowledge of the evolution of the Norwegian shelf was very limited for a long period of time (Holtedahl, 1993), but Sellevold et al. (1967) and Eldholm and Nysæther (1969) demonstrated for the first time the existence of thick deposits of sedimentary rocks and Quaternary sediments on the continental shelf north of 62°N by the use of continuous seismic profiling.

With the first hydrocarbon finds around 1970, an extensive exploration of the shelf started, and still goes on. Many hundred-thousand profile kilometres of seismics have been collected, large areas have been covered with 3D seismics, and many hundred exploration wells have been drilled. Our knowledge of the 'shallow geology' has also improved enormously, with high-resolution seismics, geotechnical borings and detailed site-survey studies. Due to all these investigations, we can say that the Norwegian continental shelf is probably the best investigated glaciated margin in the world today.

The formation of the Norwegian Channel has been widely debated. Helland (1885) suggested that an ice stream flowed in the Norwegian Channel from the inner Skagerrak area along the Norwegian coast around Skagerrak to its outlet outside Stadt (62°N). This was based on the form of the channel, but also on the rocks from the areas around Oslo that were found in tills in the Jæren area. Nansen (1904) attributed the form of the Norwegian Channel to fluvial erosion, later modified by glacial erosion. O. Holtedahl (1964) concluded, on the basis of new echosounder data, that the Norwegian Channel was primarily a tectonic depression, later affected by glacial erosion. Andersen (1964) also rejected the possibility that the tills deposited on Jæren were deposited by a 'Skagerrak glacier' flowing in the Norwegian Channel, but instead were deposited by glaciers from the east. Interpretation of seismic data collected in the 1970s revealed buried erosional features indicating ice movement along the axis of the channel (Rokoengen and Rønningsland, 1983). Also, the present bathymetry and sediment ridges indicated that ice streams flowing out from the coast were bent towards north-northwest along the channel (Rise and Rokoengen, 1984). However, it was not until after 1995 that the presence of a Norwegian Channel Ice Stream was accepted (Sejrup et al., 1996; Longva and Thorsnes, 1997). Mega-scale glacial lineations (MSGL) in a confluent pattern were mapped in the inner Skagerrak (Longva and Thorsnes, 1997; Sejrup et al., 2003), and extensive studies of the seismic stratigraphy of the North Sea Fan (King et al., 1996) showed several hundred metres of sediment dumped on the continental slope outside the shelf edge as glacigenic debris flows.

Study area

The Norwegian Shelf comprises an area of c. 1 000 000 km^2 from the North Sea in the south (55°N) to Svalbard in the north (81°N). The North Sea is a shallow epicontinental sea with depths between 50 m and 200 m, and is separated from the Norwegian mainland by a coast-parallel trough up to 700 m deep, the Norwegian Channel. The mid-Norwegian shelf from Møre (62°N) to Lofoten (68°N) has water depths between 100 m and 500 m. It is rather narrow outside Møre (60 km wide), but widens to 250 km at 65°N. The major morphological features on the mid-Norwegian shelf comprise several shallow bank areas (100 m to 300 m deep) separated by east-west oriented cross-shelf troughs (200 m to 500 m deep). The shelf off Lofoten and Vesterålen is narrow, but widens towards the north into the Barents Sea, which generally is between 200 m and 400 m deep and reaches 500 m in the Bear Island Trough.

Bathymetric data

Motivation for this thesis germinated in 1997 when the Geological Survey of Norway (NGU) obtained access to a regional bathymetric data set from the Norwegian Hydrographic Service (NHS). The data had partly been published (Bugge, 1975) in the form of about 60 bathymetric charts (1: 100 000, 25 m depth contours), covering most of the Norwegian shelf between 58°N and 71°N. The bathymetry was collected during many cruises with a single-beam echosounder as late as 1990, and was presented as a series of maps with original soundings at scales between 1: 30 000 and 1: 100 000. The depths were plotted along the ship track lines, and later all these depth values were digitised, and one xyz-file was produced for each map sheet. At

NGU, these files were merged into one single data file, and gridded with a cell size of 500 m. This resulted in a uniform bathymetric data set between Stavanger (58°N) and Lofoten (67°N) covering a large part of the Norwegian shelf (more than 200 000 km^2), with an appropriate resolution for displaying the large-scale seafloor morphology. The possibility to merge all the 60 map sheets into one single digital data set, and to visualise them in many different ways, gave a new dimension for using the data. Different colour scales, depth contour intervals or illumination angles showed a wealth of 'new morphological features' on the seabed. Most of these features are related to Late Weichselian glacial processes, and the interpretation of the morphology revealed a complex and dynamic ice-flow pattern. Ice streams had flowed towards the shelf break during the last glacial maximum in a series of troughs, most of them crossing the shelf, while more passive/stagnant ice occupied the shallower banks between the troughs (Ottesen et al., 2001, 2005a) (Fig. 2). A similar pattern was described in the Ross Sea in West Antarctica (Shipp et al. 1999; Mosola and Anderson, 2006). At the same time, we obtained access to the entire analogue seismic data base of Sintef Petroleum Research (formerly Continental Shelf Institute; IKU). This regularly spaced seismic grid (generally N-S, E-W, 10-20 km spacing) of high-resolution seismic lines (sparker, Penetration Echosounder and Deep Towed Boomer) covers the shelf areas between 60°30'N and 71°30'N. These data have been used in the study of glacial and slope stability processes, for example by Bugge et al. (1978), Bugge (1980, 1983); Lien (1983); Rokoengen (1980); King et al. (1991). The combination of regional bathymetry and the seismic profiles strengthened the interpretations, and improved our regional understanding of the glacial processes on the mid-Norwegian shelf.

In the 1980s, the multibeam echosounder technique was developed, and this gave new possibilities for mapping the shape of the sea floor, and especially for studying morphological features related to subglacial processes. The possibility of covering large areas with detailed measurements in a relative short time brought marine geology a large step forward (Loncarevic et al., 1994). The NHS started to use this technology around 1985, and in a cooperative project the NHS collected a large bathymetric data set between 1992 and 1995 covering 8 000 km^2 of the Skagerrak. NGU collected a dense grid of high-resolution seismic lines in the same area (Longva and Thorsnes, 1997). The swath bathymetry showed a large number of glacial features, for example mega-scale glacial lineations (MSGL), drumlins, crag-and-tails and glaciotectonic features (hill-hole topography). This was the first large area mapped by multibeam bathymetry on the Norwegian shelf, and in combination with the high-resolution seismic lines revealed for the first time the onset zone of the Norwegian Channel Ice Stream (Fig. 2). Here, the strong erosional capability of the ice stream was documented, with the removal of several hundred metres of sediments during the last glacial maximum (Longva and Thorsnes, 1997; Sejrup et al., 2003; Ottesen et al., 2005a).

After the Skagerrak Project, large bathymetric data sets from many areas along the Norwegian coast and shelf provided us with a lot of information about glacial processes. For example, Ottesen et al. (2005b) mapped the path of a 400 km-long palaeo-ice stream that flowed in Vestfjorden and Trænadjupet during the last glacial maximum. Swath bathymetry made it possible to observe relict and recent morphological features, revealing small and large-scale geological processes. Complete coverage of sea-floor areas also makes it possible to target specific areas of interest, for example coring sites. In addition, computer technology has improved much over the last years, with increased storage capacity, calculation capability and much improved visualisations, making quantitative data of sea-floor morphology increasingly useful.

Ice streams, palaeo-ice streams and ice-sheet reconstructions

After 1980, extensive research on the dynamics of the West Antarctic Ice Sheet (WAIS) has been carried out (Clarke, 1987; Bindschadler et al., 1996; Bamber et al., 2000). The ice streams of the Siple Coast were mapped (Bentley, 1987; Shabtaie and Bentley, 1987), and the importance of the ice streams as regulators of the mass balance of the ice sheet was recognised (Joughin and Tulaczyk, 2002). However, due to the thick ice, very little is known about the conditions of the ice-bed interface. Only a few of the collected cores penetrate to the bottom of the ice (Kamb, 2001; Tulaczyk et al., 2001), and the poor resolution and the limited availability of the geophysical methods gives only limited information of the surface below the ice sheet (Smith, 1997). By studying areas that were glaciated earlier, for example the Norwegian

Shelf, important information about the behaviour of the former ice sheets can be achieved.

Swithinbank (1954) defined an ice stream as part of an ice sheet where ice flows faster and not necessarily in the same direction as the surrounding ice. Pure ice streams are bounded by ice on both sides, whereas topographic ice streams are controlled by bedrock channels. All kinds of transitional forms between these two types exist. On the Norwegian shelf, most palaeo-ice streams followed topographic depressions. In the fjord zone, the ice flow was directed through deep bedrock troughs a few kilometres wide and 500 m to 2000 m height amplitude. When these ice streams or outlet glaciers crossed the border between the crystalline and sedimentary rocks seaward from the coastline on the inner shelf, they seem to reorganise, forming much wider corridors of fast ice flow (20-150 km wide).

In reconstructing former ice sheets, the locations of the palaeo-ice streams need to be known. This is important glaciologically, because these features regulate ice-sheet mass balance and the stability of an ice sheet. Stokes and Clark (1999) have outlined several diagnostic criteria for this, such as characteristic ice-stream shape and dimensions, highly convergent flow patterns, highly attenuated bedforms, abrupt lateral margins and lateral shear-margin moraines. From both the regional and the detailed bathymetric data sets, a dynamic ice-flow pattern has been revealed on the mid-Norwegian shelf (Papers 1, 2, 3, 4 and 6). The rapidly flowing sectors of the ice sheet (ice streams) were identified, and several of the criteria outlined by Stokes and Clark (1999) have been found on the Norwegian shelf. The ice sheet covering Svalbard was also drained by fast-flowing ice streams (Paper 8). Major fjords and their adjacent cross-shelf troughs are identified as the main drainage routes for ice streams draining the ice sheet. Extensive areas with trough-parallel glacial lineations in the cross-shelf troughs suggested fast ice flow by palaeo-ice streams. On the west coast of Svalbard, major pathways existed along Bellsund, Isfjorden and Kongsfjorden. Along the northern Svalbard margin, most of the ice drained through Woodfjorden and the Woodfjorden cross-shelf trough, and the Wijdefjorden-Hinlopen Strait.

The stability of ice streams

Study of ice flow in modern ice sheets has revealed a pattern of on/off switching of ice streams (Anandakrishnan and Alley, 1997) and lateral changes of ice-stream margins through time (Jacobel et al., 2000; Conway et al., 2002; Hulbe and Fahnestock, 2004). Investigating palaeo-ice streams, including flow patterns, and the form and size of trough-mouth fans, can tell us something about the stability of an ice-sheet system through time. For instance, on the Norwegian shelf, the size and form of the two largest flow paths for palaeo-ice streams indicate rather stable ice-stream paths through many glacial periods. The Norwegian Channel drained the Norwegian Channel Ice Stream, and the Bear Island Trough drained the Bear Island Trough Ice Stream. The suggested age for the formation of the Norwegian Channel is 1.1 million years according to Sejrup et al. (1995), and the Norwegian Channel Ice Stream largely followed this path from that time. Many glacial erosion surfaces are developed in the outer parts of the Norwegian Channel (Sejrup et al., 2003), and a total of nearly 2 km of sediments, mainly glacigenic debris flows (Nygård et al., 2005), have been deposited on the North Sea Fan (Rise et al., 2005). Based on 3D-seismic studies, Sejrup et al. (2003) and Rise et al. (2004) show an initial flow pattern on the bottom of the NCIS with a strong northerly ice flow across the Måløy Plateau close to the Norwegian mainland outside Stadt (62°N).

The Bear Island Fan, located in front of the Bear Island Trough, comprises up to 3.5 km of glacigenic sediments, and is by far the largest trough-mouth fan on the Norwegian Shelf. A series of glacial erosional surfaces shows a pattern of erosion and deposition by the ice stream through a large number of ice advances across the Barents Sea (Andreassen et al., 2004). The main flow path seems to have been stable through many glacial periods.

Mapping of the depocentres of the outer mid-Norwegian shelf over the last three glaciations (Rise et al., 2005) has shown that the ice streams generally followed the depressions across the shelf, but the sediment contribution of the individual ice streams seems to have varied through time. In the Storegga Slide area, a large fan from the second last glaciation has been mapped (Rise et al., 2005). This fan indicates a very active ice flow in the depression between Frøyabanken and Buagrunnen at that time. Farther north, outside the southern part of Haltenbanken, a major depocentre

exists dating from the last glaciation. Most of the sediments of this fan have probably been channelled along the depression south of Haltenbanken.
The seismic stratigraphy of the Skjoldryggen area shows a major depocentre containing sediments deposited over several glaciations. However, the study has also revealed that Trænadjupet is a very young morphological feature, carved out recently by an ice stream during the last glaciation (Dowdeswell et al., 2006). The location of past ice streams can be inferred from the presence of large-scale streamlined bedforms (mega-scale glacial lineations, Clark, 1993). The lineations are formed at the base of fast-flowing ice streams by deformation processes affecting the upper few metres of sediment. The study of buried surfaces in 3D-seismic data sets has shown that an ice stream flowing out Vestfjorden towards the Skjoldryggen area in the second and third last glaciations, switched in direction by about 90 degrees and carved out the whole of Trænadjupet, up to 90 wide and 150 m deep, mainly during the last glaciation. Thus, these observations generally show that although ice streams tend to follow the same path from glaciation to glaciation, they may from time to time make large changes in flow path.

Seismic stratigraphy of the glacial sediments of the Norwegian shelf

The analogue seismic recordings from the mid-Norwegian shelf gave important information about glacial processes during the last few glacial cycles. A very complex glacial history was revealed, with numerous cycles of glacial erosion and deposition. However, the analogue recordings made it impossible to look below the seabed multiple. Our database on the mid-Norwegian shelf was considerably increased through the Ormen Lange Project and the Seabed Project (Rise et al., 2002, 2005; Ayers et al., 2004). Within these joint industrial projects, we mapped the upper stratigraphy of the shelf as a basis for slope stability evaluations. Several large slides have occurred on the outer shelf and upper slope during the last 2 million years, with the Holocene Trænadjupet Slide as the last (Berg et al., 2005). Access to a large data base of digital seismic lines enabled us to look into the layers below the Upper Regional Unconformity (URU). The URU is commonly a pronounced seismic reflector on the mid-Norwegian shelf, and during the 1970s and 80s was interpreted as the boundary between a complex stack of rather flat-lying glacigenic sediment packages (mainly till and glaciomarine sediments) and underlying sedimentary bedrock. It later appeared that what had earlier been called underlying 'sedimentary bedrock' on the mid-outer shelf was actually composed of thick sequences of generally prograding clinoform layers of glacial origin deposited during the last 3 million years (Rokoengen et al., 1995; Ottesen et al., 2001; Henriksen and Vorren, 1996; Dahlgren et al., 2005; Rise et al., 2005). Further studies of digital, multichannel seismic lines have shown that the URU is not always one single surface as, in some areas, several unconformities may be developed.

In the Ormen Lange Project and the Seabed Project (Rise et al., 2002, 2005; Ayers et al., 2004), the whole of the Naust Formation between 62°N and 68°N has been mapped (Figs. 3 and 4). One of the objectives of these studies was to compile a unified stratigraphy across the whole area from Sognefjorden in the south to the Lofoten shelf in north. The diagram in Fig. 3 shows the simplified stratigraphic subdivisions of the Naust Formation. It has been subdivided into five sequences (Figs. 3 and 4), each with one of the Naust letters, N, A, U, S and T, from bottom to top (Ayers et al., 2004; Rise et al., 2006). The total thickness map of the Naust Formation (Fig. 4d) shows a major depocentre at the outlet of the Norwegian Channel and a major depocentre along the present shelf edge farther north, both with large areas of sediments exceeding 1000 m in thickness. During the Naust N time (Fig. 4a), large amounts of sediment were transported into the basin, with the main depocentre (up to 1400 ms twt – two-way travel time thickness) in the northernmost part of the mid-Norwegian shelf. The shelf prograded to a position close to the present shelf break during this period. The Naust S and T sequences, which comprise deposits from the last three glaciations, form the largest depocentre (up to 1000 ms twt) in front of the outlet of the Norwegian Channel. Sediments deposited on the North Sea Fan have been transported by the Norwegian Channel Ice Stream, and this implies that the Norwegian Channel Ice Stream was very active during a late stage of Naust time (King et al., 1996; Sejrup et al., 2003; Nygård et al., 2005, 2007). Loading of the shelf with glacier-derived sediments has generally resulted in subsidence of the outer shelf areas, with an increasing probability for preservation of palaeo-surfaces. On the mid-Norwegian shelf, the areas around the coast-parallel, deltaic, Molo Formation have been a hinge area. Generally, the areas outside have subsided, whereas the areas inside have been uplifted.

The architecture of the mid-Norwegian margin is related to large-scale features such as depth of the basin, character of the sediment source area, width of catchment area, elevation, etc. On the mid-Norwegian shelf, the depth of the basin has played a major role in the build-out of the Naust Formation on the shelf. Both to the south (the Møre Basin) and to the north (Lofoten Basin), deep basins exist, and a rather limited progradation has taken place (30-60 km), in contrast to the central areas east of the Vøring Plateau. Here, the basin is much shallower, making it easier for the glaciers to fill in the basin and build out the shelf. The progradation has been up to 150 km towards the northwest in this area. The North Sea Fan represents a major depocentre in front of the mouth of the Norwegian Channel. In spite of thicknesses of almost 2 km into the deep Møre Basin, the progradation has been very limited. Instead, the fan has an aggradational form.

Fig. 4 illustrates the build-out pattern of the shelf through Naust time. It appears that the construction has occurred from ESE towards WNW extensively along the whole shelf. This pattern favours a build-out caused by an ice sheet, on a line source along the whole western margin of the ice sheet. The earliest progradation occurred in the north, southwest of Lofoten, where the shelf edge was built out almost to its present position during Naust N time, between c. 2.7 and 1.5 million years ago. Prograding wedges are characteristic of many glaciated margins in several places around the world (Nielsen et al., 2005), and prominent examples are found on both sides of Greenland, in the shelf areas outside the Faroe Islands and in the Ross Sea.

To understand the depositional environment of the mid-Norwegian shelf, we have looked at old, buried surfaces of the Naust Formation to search for glacial features, such as MSGL or iceberg ploughmarks. In the outer part of Haltenbanken, a surface with glacial lineations and iceberg ploughmarks is found deep in the Naust Formation (Fig. 5). This surface is located in the transition zone between the sequences Naust A and N with a suggested age of c. 1.5 million years. This implies that at least 800 ms (c. 800 m) of sediments have been deposited by glacial processes in this area during the last 1.5 million years.

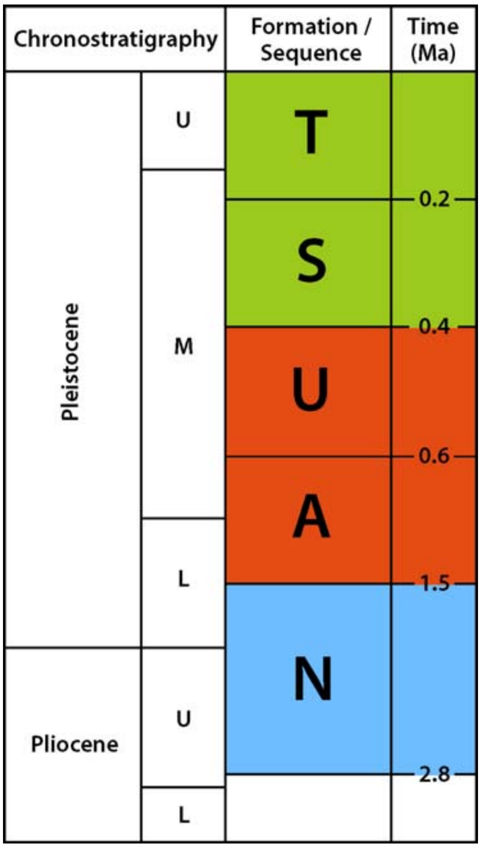

Fig. 3. Diagram showing the Naust stratigraphic scheme (Rise et al. 2006).

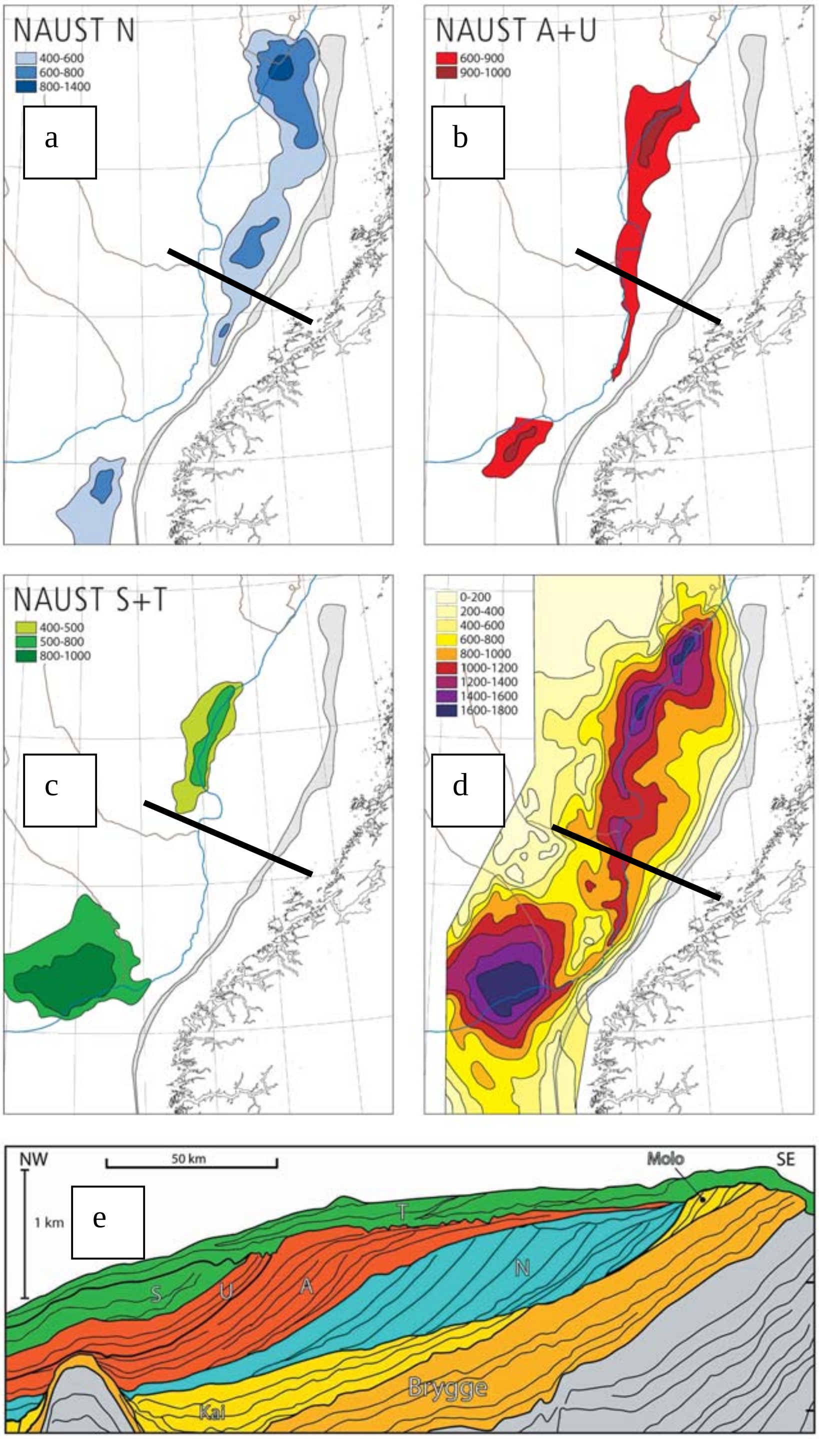

Fig. 4. Time thickness maps in milliseconds (two-way travel time) of the Naust Formation and the Naust sequences. A) Main depocentre for the Naust N sequence, B) Main depocentre for the Naust A+U sequences, C) Main depocentre for the Naust S+T sequences, D) Total Naust Formation. Hachure shows the subcrop of the Molo and Kai Formations on the shelf. E) Geoprofile of seismic line GMNR-94-310 across Haltenbanken.

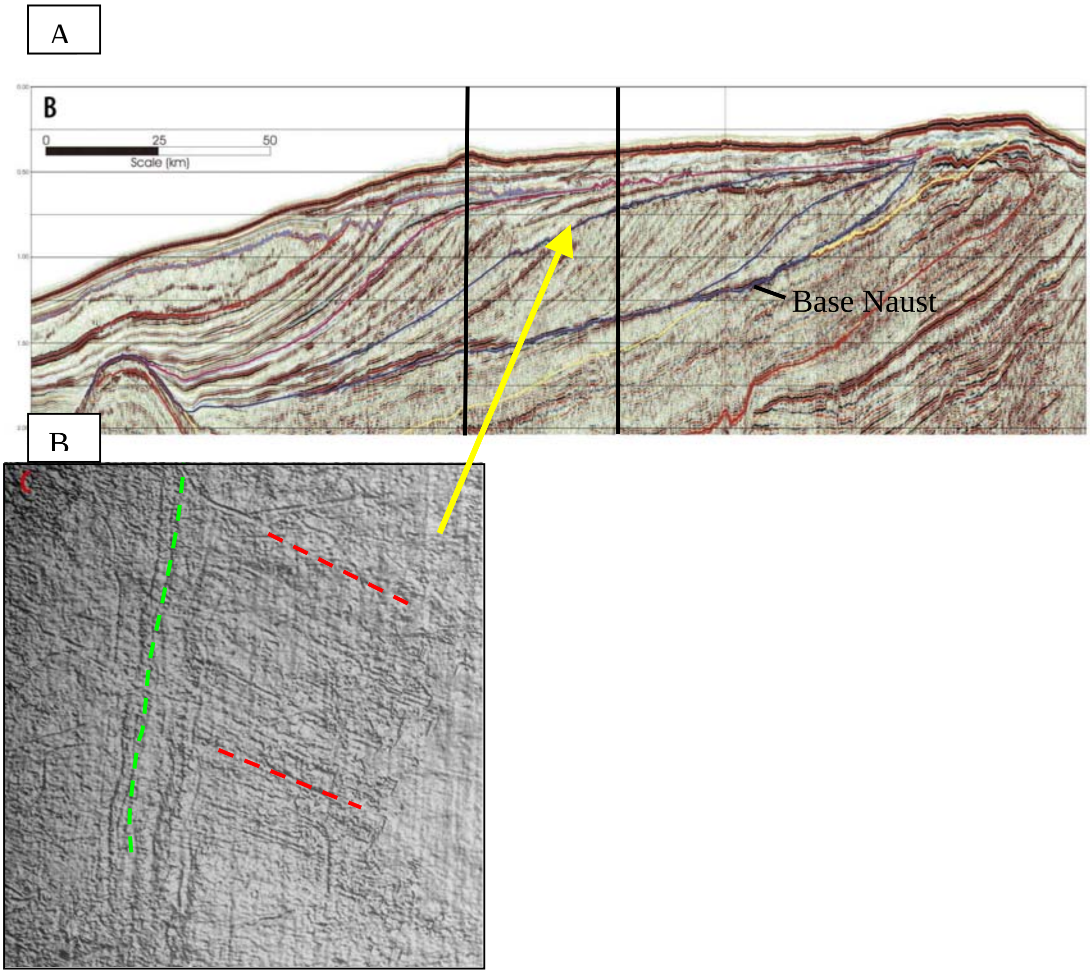

Fig. 5. A) Seismic line GMNR-94-310 across Haltenbanken. B) Buried linear bedforms (MSGL) (red stippled line) and iceberg ploughmarks (green stippled line) from Haltenbanken about 300 m below the modern sea floor (see figure 5a for location). The surface represents the top of sequence Naust N, approximately 1.5 million years.

Future work

In this thesis, several themes have been discussed and some new conclusions have been drawn on the basis of the published papers. However, many unsolved questions still remain, and further work is suggested below:

Determining the sedimentary environment of the oldest Naust sequences

The large volume of the Naust Formation has raised the question as to how these sediments were deposited on the shelf during such a short period of time (less than 3 million years). Our knowledge is limited about the inferred depositional environment during the deposition of the lower parts of the Naust Formation. We have used a few 3D seismic lines to look at these sedimentary sequences and some old surfaces have provided indications of glacial activity. For example, Fig. 5B depicts a surface with glacial lineations from the lower parts of the Naust Formation (suggested age - c. 1.5 million years) on the outer part of Haltenbanken. Careful inspection of the lower parts of the Naust Formation in 3D seismic cubes from appropriate areas may help us to understand better the depositional processes that took place.

Side-wall cores and cutting materials in exploration wells can also give important information about the sedimentary environment during deposition. Eidvin and Rundberg (2001) analysed several core samples from the Tampen area, west of the Norwegian Channel. In well 34/7, a high content of ice-rafted debris was found in a side-wall core at 1120.5 m depth. The sample is taken from a sequence of prograding clinoforms located in the transition zone between the Naust N and Naust A sequences (inferred age of c. 1.5 million years). Most of the clasts are eroded from crystalline rocks, showing that they originate from the Norwegian mainland. These features point to a glacial environment during the deposition of the oldest part of the Naust Formation. However, further work needs to be done to acquire a better understanding of the depositional processes of the lower Naust Formation. A search for glacial landforms on palaeo-surfaces is part of this planned work.

Dating of the Naust sequences

Accurate dating of Cenozoic sediments is important for understanding the processes that have led to the uplift of Fennoscandia, which is the original source of most of the sediment. The ages given in the diagram in Fig. 3 for the individual Naust sequences are very tentative, especially for the oldest sequences N and A. The poorly developed ages of the different Naust sequences are partly due to the generally poor quality of the samples (cuttings), and also because much of the material has been extensively reworked during many cycles of erosion and deposition.

Studies of the subglacial environment

Many uncertainties still exist about ice-flow mechanisms related to ice streams, but it is known that some ice streams transport sediments either carried within the ice or dragged along as a sediment layer beneath the ice (deformation till). The many bathymetric data sets presented here make a good basis for further studies of such processes. The different scales of the glacial lineations, from small ridges less than a metre high to mega-ridges in the bottom of the Norwegian Channel (up to several 100 km long and several tens of metres high), indicate that different processes must have taken place during ice flow. The large volumes of sediment deposited in some of the trough-mouth fans during very short time intervals (Nygård et al., 2007) also stress the importance of this point.

Plio-Pleistocene erosion of Mid Norway

Based on seismic mapping, the total volume of the Naust Formation on the Norwegian Shelf between Sognefjorden and Lofoten (180 000 km^3) has been mapped. Redistribution and restoration of the sediments, back to the land/sea areas from where they were eroded, is important for modelling the Late Cenozoic uplift history of the inner shelf and adjacent land areas of Norway. In this way, we can obtain a complete sediment budget for a glaciated margin.

Presentation of the papers

In **Paper 1**, Ottesen, D., Rise, L., Rokoengen, K. and Sættem, J., 2001: **Glacial processes and large-scale morphology on the mid-Norwegian continental shelf**, a dynamic ice-sheet model with the palaeo-ice streams and intermediate ice domes for the western margin of the Scandinavian Ice Sheet is presented for the first time. The regional bathymetric data sets are explained and presented as the basis for the reconstruction.

In **Paper 2**, Ottesen, D., Dowdeswell, J.A., Rise, L., Rokoengen, K. and Henriksen, S., 2002: **Large-scale morphological evidence for past ice-stream flow on the mid-Norwegian continental margin**, several new detailed bathymetric data sets are presented. These data sets come from various sources, both multibeam bathymetry and 3D seismic data, and illustrate streamlined, sedimentary bedforms located in the cross-shelf troughs. A regional 2D-seismic line is presented and interpreted, showing the general depositional pattern of the mid-Norwegian shelf. A reconstruction of parts of the ice sheet during the last glacial maximum is made by a numerical ice-sheet model, where the ice-flow velocities and the sediment thicknesses are computed.

In **Paper 3**, Ottesen, D., Dowdeswell, J.A. and Rise, L., 2005a: **Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2500-km-long Norwegian-Svalbard margin (57° - 80°N)**, an extensive bathymetric data set covering the whole of the shelf from the North Sea to Svalbard is presented together with several detailed data sets. Morphological interpretation of the data sets has revealed a dynamic ice-flow pattern along the western margin of the Scandinavian and Barents/Svalbard ice sheets. About 20 cross-shelf troughs with mega-scale glacial lineations (MSGL; elongate ridges and grooves oriented parallel to trough long axes) are interpreted as former pathways for fast-flowing ice streams. The two largest palaeo-ice streams were the Norwegian Channel Ice Stream and Bear Island Trough Ice Stream, each 150-200 km wide at their mouths. The Norwegian Channel Ice Stream was 800 km long, originated in the Skagerrak area between Norway and Denmark, and followed the coast of Norway to the shelf break outside western Norway at 62°N.

In **Paper 4**, Ottesen, D., Rise, L., Knies, J., Olsen, L. and Henriksen, S., 2005b: **The Vestfjorden-Trænadjupet palaeo-ice stream drainage system, mid-Norwegian continental shelf**, the ice-sheet dynamics of Vestfjorden and Trænadjupet have been reconstructed during the last glacial maximum on the basis of a regional and several detailed bathymetric data sets. An ice stream in the Vestfjorden-Trænadjupet depressions off northern Norway transported glacial debris to the shelf edge and into the deep sea during the last glaciation. This palaeo-ice stream was approximately 400 km long and covered an area of ~20,000 km^2. Including a complex system of tributary fjords and valleys in Nordland county, the drainage basin had an area of c. 150,000 km^2 within the Fennoscandian Ice Sheet (FIS) during the Last Glacial Maximum (LGM). A pattern of well-developed, subglacial, sedimentary bedforms was produced (e.g., mega-scale lineations, drumlins). Ice-stream shear margin moraines are located on both sides of Trænadjupet, defining the width of the palaeo-ice stream (~90 km at the shelf edge). A large recessional moraine (the Tennholmen Ridge) has been mapped in Vestfjorden. It is 80 m high, 20 km wide and 60 km long. We have interpreted this ridge as a grounding zone moraine, formed during a halt or a readvance of the ice stream during the last deglaciation.

In **Paper 5**, Rise, L., Ottesen, D., Berg, K. and Lundin, E., 2005: **Large-scale development of the mid-Norwegian margin during the last 3 million years,** work in a joint industrial project (the Ormen Lange Project) carried out by the authors is presented. The development of the shelf is outlined, with more than 1000 m of glacial sediments being deposited over large areas of the outer shelf, and with a shelf edge migration towards the west during the Late Pliocene/Pleistocene of up to 150 km. The depositional pattern of the sediments during the last three glaciations on the outer shelf is also shown.

In **Paper 6**, Dowdeswell, J.A., Ottesen, D. and Rise, L., 2006: **Flow switching and large-scale deposition by ice streams draining former ice sheets**, the complex glacial history of the Trænabanken, Vestfjorden, Trænadjupet and Skjoldryggen areas of the mid-Norwegian shelf during the last few glaciations is outlined. Here, the use of 3D seismic data made it possible to reconstruct different ice-drainage directions during the Saalian/Elsterian compared to the last glaciation. This evidence demonstrates large-scale switching of ice-stream flow within a major ice sheet from one glaciation to the next. A new trough was excavated through sediments during the Weichselian to produce the 150 m-deep depression now known as Trænadjupet.

In **Paper 7**, Ottesen, D. and Dowdeswell, J.A., 2006: **Assemblages of submarine landforms produced by tidewater glaciers in Svalbard**, two very detailed bathymetric data sets from the sea floor of Borebukta and Yoldiabukta, tributary fjords to Isfjorden, Svalbard, show assemblages of submarine landforms linked to glacier surging. These landforms are essentially unmodified since their initial deposition over the past hundred years because they have not been subjected to subaerial erosion or periglacial activity. The data sets also show that mega-scale glacial lineations can form not only beneath large ice streams, but also rapidly over a few years beneath surging tidewater glaciers lying on deforming sedimentary beds.

In **Paper 8**, Ottesen, D., Dowdeswell, J.A., Landvik, J. and Mienert, J., 2006: **Dynamics and retreat of the Late Weichselian Svalbard Ice Sheet inferred from high-resolution sea-floor morphology,** the ice-sheet dynamics of the shelf areas around Svalbard were reconstructed and discussed based on a large number of bathymetric data sets from the Norwegian Hydrographic Service and from the University of Tromsø.

References:

Anandakrishnan, S. and Alley, R.B., 1997: Stagnation of Ice Stream C, West Antarctica by water piracy. *Geophysical Research Letters, 24,* 265-268.

Andersen, B. G., 1964: Har Jæren vært dekket av en Skagerrakbre? Er Skagerrakmorenen marin leire? *Norges Geologiske Undersøkelse*, *228,* 5-11.

Andreassen, K., Nilssen, L.C. and Rafaelsen, B., 2004: Three-dimentional seismic data from the Barents Sea margin reveal evidence of past ice streams and their dynamics. *Geology, 32,* 729-732, doi: 10.1130/G20497.1

Ayers, S., Evans, D., Rise, L. and Ottesen, D., 2004: Mid- to Late Cenozoic Geomodel of the Mid-Norwegian Continental Margin. Model Volume. Norwegian Deepwater Programme. Seabed Project Phase II. Report no. SP2-02-FS-01R-00001-04 compiled by Fugro Survey Limited. 108 pp.

Bamber, J.L., Vaughan, D.G. and Joughin, I., 2000: Widespread complex flow in the interior of the Antarctic Ice Sheet. *Science, 287*, 1248-1250.

Bentley, C.R., 1987: Antarctic ice streams: a review. *Journal of Geophysical Research, 92,* 8843-8858.

Berg, K., Solheim, A. and Bryn, P., 2005: The Pleistocene to recent geological development of the Ormen Lange area. *Marine and Petroleum Geology, 22*, 45-56.

Bindschadler, R., Vornberger, P., Blankenship, D., Scambos, T. and Jacobel, R., 1996: Surface velocity and mass balance of Ice Streams D and E, West Antarctica. *Journal of Glaciology, 42,* 461-475.

Bindschadler, R.A. and Vornberger, P., 1998: Changes in the West Antarctic ice sheet since 1963 from declassified satellite photography. *Science*, *279*, 689-692.

Boulton, G.S., Dongelmans, P., Punkari, M. and Broadgate, M., 2001: Palaeoglaciology of an ice sheet through a glacial cycle: the European ice sheet through the Weichselian. *Quaternary Science Reviews, 20*, 591-625.

Bugge, T., 1975: Kart med kystkontur og dybdekoter for den norske kontinentalsokkel. *Continental Shelf Institute (IKU), Publ. 55*, 21pp.

Bugge, T., 1980: Øvre lags geologi på kontinentalsokkelen utenfor Møre og Trøndelag. (Shallow geology on the continental shelf off Møre and Trøndelag, Norway). *Continental Shelf Institute (IKU), Publ. 104*, 44pp.

Bugge, T., 1983: Submarine slides on the Norwegian continental margin, with special emphasis on the Storegga area. *Continental Shelf Institute (IKU), Publ. 110*, 152 pp.

Bugge, T., Lien, R. and Rokoengen, K., 1978: Kartlegging av løsmassene på kontinentalsokkelen utenfor Møre og Trøndelag: seismisk profilering. *Continental Shelf Institute (IKU), Publ. 99*, 55 pp.

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

Clark, C.D., 1993: Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surface Processes and Landforms, 18*, 1-29.

Clark and Stokes, 2001: Extent and basal characteristics of the M'Clintock Channel Ice Stream. *Quaternary International, 86*, 81-101.

Clarke, G.K.C., 1987: Fast glacier flow: Ice streams, surging, and tidewater glaciers. *Journal of Geophysical Research, 92*, 8835-8841.

Conway, H., Catania, G., Raymond, C., Scambos, T., Engelhardt, H., and Gades, A., 2002: Switch of flow direction in an Antarctic ice stream. *Nature, 419*, 465-467.

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygård, A. and Sejrup, H.P., 2005: Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology, 22*, doi: 10.1016/j.marpetgeo.2004.12.008.

Dowdeswell, J.A., Ó Cofaigh, C. and Pudsey, C.J., 2004: Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream. *Geology, 32*, 13-16.

Dowdeswell, J.A., Ottesen, D. and Rise, L., 2006: Flow switching and large-scale deposition by ice streams draining former ice sheets. *Geology, 34*, 313-316.

Dyke, A.S. and Morris, T.F., 1988: Drumlin fields, dispersal trains and ice streams in Arctic Canada. *Canadian Geographer, 32*, 86-90.

Eidvin, T. and Rundberg, Y., 2001: Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. *Norsk Geologisk Tidsskrift, 81*, 119-160.

Eldholm, O. and Nysæther, E., 1969: Seismiske undersøkelser på den norske kontinentalsokkel 1968. Tekn. Rap. 2, del C, Seismic Obs. Univ. Bergen. 29 pp.

Evans, J., Dowdeswell, J.A. and Ó Cofaigh, 2004: Submarine bedforms and former ice sheet flow in the Gerlache Strait and on the inner continental shelf, Antarctic Peninsula. *Journal of Quaternary Science, 19*, 397-407.

Helland, A., 1885: Om Jæderens løse afleiringer. *Meddelelser fra Den Naturhistoriske Forening i Kristiania 1885*, 27-42.

Henriksen, S. and Vorren, T. O., 1996: Late Cenozoic sedimentation and uplift history on the mid-Norwegian continental shelf. *Global and Planetary Change, 12*, 171-199.

Holtedahl, H., 1950: A study of the topography and the sediments west of Møre, W.Norway. *Univ. Bergen, Årb., Naturv. R. 5*, 1-58.

Holtedahl, H., 1953: Noen sub-marin-geologiske undersøkelser utenfor Norges vestkyst. *Norsk Geologisk Tidsskrift, 32*, 235-237.

Holtedahl, H., 1993: Marine Geology of the Norwegian Continental Margin. *Geological Survey of Norway, Special Publication, 6*, 150 pp.

Holtedahl, O., 1940: The submarine relief off the Norwegian coast, with bathymetrical map in seven sheets of the Norwegian coastal waters and adjoining seas. *Norske Vid. Akad. Oslo. Mat. Naturv. Klasse*, 43 pp.

Holtedahl, O., 1964: Echo-soundings in the Skagerrak. With remarks on the geomorphology. *Norges Geologiske Undersøkelse, 223*, 139-160.

Hulbe, C. and Fahnestock, M.A., 2004: West Antarctic ice-stream discharge variability: mechanism, controls and pattern of grounding-line retreat. *Journal of Glaciology, 50*, 471-484.

Jacobel, R.W., Scambos, T.A., Nereson, N.A. and Raymond, C.F., 2000: Changes in the margin of Ice Stream C, Antarctica. *Journal of Glaciology, 46 (152)*, 102-110.

Joughin, I.R. and Tulaczyk, 2002: Positive mass balance of Ross ice streams , West Antarctica. *Science, 295*, 476-480.

Kamb, B., 2001: Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion. *In* R.B. Alley and R.A. Bindschadler, (Eds.), The West Antarctic Ice Sheet: Behavior and Environment: *American Geophysical Union, Antarctic Research Series, 77*, 157-199.

King, L. H., Rokoengen, K., Fader, G. B. J. and Gunleiksrud, T., 1991: Till-tongue stratigraphy, *Geological Society of America Bulletin, 103*, 637-659.

King, E.L., Haflidason, H., Sejrup, H.P., Elverhøi, A. and Aarseth, I., 1996: Quaternary seismic stratigraphy of the North Sea Fan: glacially fed gravity flow aprons, hemipelagic sediments, and large submarine slides. *Marine Geology, 130*, 293-315.

Lien, R., 1983: Pløyemerker etter isfjell på norsk kontinentalsokkel. *Continental Shelf Institute (IKU), Publ. 109*, 147 pp.

Loncarevic, B.D., Courtney, R.C., Fader, G.B.J., Giles, P.S., Piper, D.J.W., Costello, G., Hughes Clarke, J.E. and Stea, R.R., 1994: Sonography of a glaciated continental shelf. *Geology, 22*, 747-750.

Longva, O. and Thorsnes, T., (eds.), 1997: Skagerrak in the past and at the present – An integrated study of geology, chemistry, hydrography and microfossil ecology. *Geological Survey of Norway*, *Special Publication*, *8*, 100 pp.

Moreau, J., Ghienne, J.-F., le Heron, D.P., Rubino, J-l. and Deynoux, M., 2005: 440 Ma ice stream in North Africa. *Geology*, *33*, 753-756.

Mosola, A.B. and Anderson, J.B., 2006: Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: possible consequence of over-extended ice streams? *Quaternary Science Reviews*, *25*, 2177-2196.

Nansen, F., 1904: The bathymetrical features of the north-polar seas. *Scient. Res. Norwegian North Polar Expedition 1893-1896.4*, 13, 1-232.

Nielsen, T., De Santis, L., Dahlgren, K.I.T., Kuijpers, A., Laberg, J.S., Nygård, A., Praeg, D. and Stoker, M.S., 2005: A comparision of the NW European glaciated margin with other glaciated margins. *Marine and Petroleum Geology, 22*, 1149-1183.

Nygård, A., Sejrup, H.P., Haflidason, H., Cecci, M. and Ottesen, D., 2004: The deglaciation history of the southwestern Fennoscandian Ice Sheet between 15 and 13 ^{14}C ka. *Boreas, 33*, 1-17.

Nygård, A., Sejrup, H.P., Haflidason, H. and Bryn, P., 2005: The glacial North Sea Fan, southern Norwegian Margin: Architecture and evolution from the upper continental slope to the deep-sea basin. *Marine and Petroleum Geology, 22*, 71-84.

Nygård, A., Sejrup, H.P., Haflidason, H., Lekens, W.A.H., Clark, C.D. and Bigg, G.R., 2007: Extreme sediment and ice discharge from marine based ice streams; new evidence from the North Sea. *Geology,* in press.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A. and Morris, P., 2002: Evolution of subglacial bedforms along a palaeo-ice stream, Antarctic Peninsula continental shelf: *Geophysical Research Letters, 29 (8)*, 10.1029/2001GL014488.

Ottesen, D., Rise, L., Rokoengen, K. and Sættem, J., 2001: Glacial processes and large-scale morphology on the mid-Norwegian continental shelf. *In* Martinsen, O.J. and Dreyer, T., (Eds.), *Sedimentary Environments Offshore Norway – Palaeozoic to Recent:* Norwegian Petroleum Society Special Publication, 10, 439-447. Elsevier, Amsterdam.

Ottesen, D., Dowdeswell, J.A., Rise, L., Rokoengen, K. and Henriksen, S., 2002: Large-scale morphological evidence for past ice-stream flow on the Norwegian continental margin. *In* Dowdeswell, J.A. and Ó Cofaigh, C. (eds.), *Glacier-Influenced Sedimentation on High-Latitude Continental Margins*, 245-258. Geological Society of London, Special Publication, 203.

Ottesen, D., Dowdeswell, J.A. and Rise, L., 2005a: Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2500-km-long Norwegian-Svalbard margin (57° - 80°N). *Geological Society of America Bulletin, 117,* 1033-1050.

Ottesen, D., Rise, L., Knies, J., Olsen, L. and Henriksen, S., 2005b: The Vestfjorden-Trænadjupet palaeo-ice stream drainage system, mid-Norwegian continental shelf. *Marine Geology*, *218*, 175-189.

Ottesen, D. and Dowdeswell, J.A., 2006: Assemblages of submarine landforms produced by tidewater glaciers in Svalbard. *Journal of Geophysical Research 111*, 1-16. F01016, doi:10.1029/2005JF000330.

Ottesen, D., Dowdeswell, J.A., Landvik, J. and Mienert, J., 2006: Dynamics of the Late Weichselian ice sheet on Svalbard inferred from high-resolution sea-floor morphology. *Boreas*, In press.

Punkari, M., 1997: Glacial and glaciofluvial deposits in the interlobate areas of the Scandinavian Ice Sheet. *Quaternary Science Reviews, 16,* 741-753.

Rise, L. and Rokoengen, K., 1984: Surficial sediments in the Norwegian sector of the North Sea between 60°30' N and 62°N. *Marine Geology, 58*, 287-317.

Rise, L., Ottesen, D., Larsen, E., Lundin, E, Olsen, L. and Thorsnes, T., 2002: Large scale development of the mid-Norwegian shelf and margin with emphasis on the last 3 million years. NGU report no. 2002.015. Rev. 1. 200 pp.

Rise, L., Olesen, O., Rokoengen, K., Ottesen, D. and Riis, F., 2004: Mid-Pleistocene ice drainage pattern in the Norwegian Channel imaged by 3D seismics. *Quaternary Science Reviews, 23,* 2323-2335.

Rise, L., Ottesen, D., Berg, K. and Lundin, E., 2005: Large-scale development of the mid-Norwegian margin during the last 3 million years. *Marine and Petroleum Geology, 22*, 33-44.

Rise, L., Ottesen, D., Longva, O., Solheim, A., Andersen, E.S. and Ayers, S., 2006: The Sklinnadjupet Slide and its relation to the elsterian glaciation on the mid-Norwegian margin. *Marine and Petroleum Geology, 23,* 569-583.

Rokoengen, K., 1980: De øvre lags geologi på kontinentalsokkelen utenfor Møre og Romsdal. (Shallow geology on the continental shelf off Møre and Romsdal). *Continental Shelf Institute (IKU), publ. 105,* 49 pp.

Rokoengen, K. and Rønningsland, T.M., 1983: Shallow bedrock geology and Quaternary thickness in the Norwegian sector of the North Sea between 60°30'N and 62°N. *Norsk Geologisk Tidsskrift*, *63*, 83-102.

Rokoengen, K., Rise, L., Bryn, P., Frengstad, B., Gustavsen, B. Nygaard, E. and Sættem, J., 1995: Upper Cenozoic stratigraphy on the mid-Norwegian continental shelf. *Norsk Geologisk Tidsskrift, 75,* 88-104.

Sejrup, H.P., Aarseth, I., Haflidason, H., Løvlie, R., Bratten, Å., Tjøstheim, G., Forsberg, C.F. and Ellingsen, K.I., 1995: Quaternary of the Norwegian Channel: glaciation history and palaeoceanography. *Norsk Geologisk Tidsskrift*, *75*, 65-87.

Sejrup, H.P., King, E., Aarseth, I., Haflidason, H. and Elverhøi, A., 1996: Quaternary erosion and depositional processes: western Norwegian fjords, Norwegian Channel and North Sea Fan. *Geological Society of London*, *117*, 187-202.

Sejrup, H.P., Larsen, E., Haflidason, H., Berstad, I.M., Hjelstuen, B.O., Jonsdottir, H., King, E.L., Landvik, J.Y., Longva. O., Nygard, A., Ottesen, D., Raunholm, S., Rise, L. and Stalsberg, K., 2003: Configuration, history and impact of the Norwegian Channel Ice Stream: *Boreas, 32*, 18-36.

Sellevoll, M.A., Eldholm, O. and Gammelsæter, H., 1967: Refraksjons-seismiske undersøkelser av den norske kontinentalsokkel mellom 62°N og 65°N. Teknisk Rap. 1, Seismic Obs., Univ i Bergen.

Shabtaie, S. and Bentley, C.R., 1987: West Antarctic ice streams draining into the Ross ice shelf: configuration and mass balance. *J. Geophys. Res.*, *92(B2)*: 1311-1336.

Shipp, S.S., Anderson, J.B., and Domack, E.W., 1999: Late Pleistocene-Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: Part 1 – Geophysical results: *Geological Society of America Bulletin, 111*, 1486-1516.

Smith, A.M., 1997: Basal conditions on Rutford Ice Stream, West Antarctica from seismic observations. *Journal of Geophysical Research, 102 (B1)*, 543-552.

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

Stokes, C.R. and Clark, C.D., 2001: Palaeo-ice streams. *Quaternary Science Reviews, 20*, 1437-1457.

Stokes, C.R. and Clark, C.D., 2003: The Dubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet behaviour on the Canadian Shield and insights regarding the controls on ice-stream location and vigour. *Boreas, 32*, 263-279.

Stokes, C.R., Clark, C.D. and Winsborrow, M.C.M., 2006: Subglacial bedform evidence for a major palaeo-ice stream and its retreat phases in Amundsen Gulf, Canadian Arctic Archipelago. *Journal of Quaternary Science*, *21*, 399-412.

Swithinbank, C.W.M., 1954: Ice streams. *Polar Record*, *7*, 185-186.

Tulaczyk, S.M., Scherer, R.P. and Clark, C.D., 2001: A ploughing model for the origin of weak tills beneath ice streams: a qualitative treatment: *Quaternary International, 86*, 59-70.

Vorren, T.O. and Laberg, J.S., 1997: Trough mouth fans – palaeoclimate and ice sheet monitors. *Quaternary Science Reviews, 16,* 865-881.

Authorship statement

This thesis comprises eight papers, all of which have been written and prepared at the Geological Survey of Norway during the period 2000-2006. Most of the interpretations, upon which the papers are based, were conceived at NGU in the same period. I am the first author of six of these papers. This implies that the initial planning of the papers, writing of a first draft of the text, and preparing the figures and tables have been done by me. These six papers have between one and four co-authors, and the preparation of the individual papers has certainly been a team effort with many discussions and revisions throughout the project. In all these cases, I had the 'leading role' in finalising the manuscripts for submission, and in the process of revision after the reviewers had sent their comments to the journal editors.

In **paper 1**, the dynamic ice-sheet model with the palaeo-ice streams and intermediate ice domes for the western margin of the Scandinavian Ice Sheet is presented for the first time. The basis for this work was through the processing of the regional bathymetric data sets and combining these data with the knowledge from the present ice streams of the Siple coast of Western Antarctica. This work was intitated by Dag Ottesen, and the data processing, interpretation and a first draft of the text and figures were made by me. Leif Rise and Kåre Rokoengen provided support and suggestions during discussions and writing, whereas Joar Sættem contributed with his knowledge of the geotechnical properties of the glacial sediments on the shelf.

Paper 2 developed after a meeting at Bristol Glaciological Centre, University of Bristol, in 2001. The initiatives to this paper came jointly from Dag Ottesen and Julian Dowdeswell. Here, several new detailed bathymetric data sets were presented, all of which were processed, visualised and interpreted by Dag Ottesen. Julian Dowdeswell performed the modelling of the reconstruction of parts of the ice sheet during the last glacial maximum. Leif Rise and Kåre Rokoengen played supportive roles with their general knowledge of the glacial stratigraphy of the shelf, and Sverre Henriksen, Statoil, contributed with the 3D seismic data set from Trænadjupet.

In **paper 3,** many data sets are presented outlining regional and detailed ice-sheet dynamics of most of the Norwegian shelf. The results are based on many different bathymetric data sets, and these were all assembled, visualised and interpreted by Dag Ottesen. The initative for this paper and a first draft, including all figures and tables, were made by me. Julian Dowdeswell contributed much during the actual writing process, whereas Leif Rise contributed with his general and detailed knowledge of most of the Norwegian shelf.

In **paper 4**, which is about the ice-sheet dynamics of Vestfjorden and Trænadjupet, the first author has assembled and visualised the bathymetric data sets. Most of the interpretations of the data sets were done jointly by Dag Ottesen and Leif Rise. A first draft of the text and figures was made by Dag Ottesen, whereas Leif Rise, Jochen Knies, Lars Olsen and Sverre Henriksen contributed to varying degrees during the writing process.

Paper 5, where Leif Rise is the first author, is the result of almost two years work/research by Rise and Ottesen for the Ormen Lange Project (Norsk Hydro ASA) with Kjell Berg (Norsk Hydro ASA) as the contact person. All interpretations were made by us together in this project, Leif Rise wrote most of the text, while Dag Ottesen prepared most of the figures.

Paper 6, where Julian Dowdeswell is the first author, is the result of a long period of research over several years at NGU to understand the complex glacial history of the Trænabanken, Vestfjorden, Trænadjupet and Skjoldryggen areas of the mid-Norwegian shelf. The first ideas, leading to a partly different ice-drainage model during Saalian/Elsterian compared to the last glaciation, were hatched during the interpretation of 2D seismic lines in the Ormen Lange Project. Subsequent interpretation of 3D seismic, done by me in the Seabed Project strongly supported this model. The interpretations and figures were made jointly by Rise and Ottesen, Julian Dowdeswell took the 'leading role' in preparing the paper and wrote most of the first draft of the text.

Paper 7 is about a very detailed bathymetric data set from the sea floor of Borebukta, a tributary fjord to Isfjorden, Svalbard. The compilation of the data and production of the figures were done by the first author, whereas the intepretations and the writing were carried out by me together with Julian Dowdeswell.

Paper 8 is about the ice-sheet dynamics of the shelf areas around Svalbard based on many bathymetric data sets from the Norwegian Hydrographic Service and from the University of Tromsø. These data sets were compiled, visualised and interpreted by Dag Ottesen, and a first draft of the manuscript was written by me. All co-authors contributed with comments and partial rewriting in the production of the final manuscript.