Glacial processes and large-scale morphology on the mid-Norwegian continental shelf

Dag Ottesen, Leif Rise, Kåre Rokoengen and Joar Sættem

A regional digital bathymetric data set covering most of the mid-Norwegian continental shelf is presented and gives a unique regional view into glacial processes and ice-sheet dynamics on this part of the continental shelf during the Weichselian, indicating that forms and deposits were created by a highly dynamic ice sheet. At times, ice flow was mainly channelised through ice streams located in bathymetric depressions on the shelf areas. Glacial sedimentary processes are discussed with a focus on the marine-based part of the Scandinavian ice sheet during the last glaciation (the Weichselian).

Ice sheets that grounded on the shelf edge are thought to have been responsible for depositing complex prograding sequences on the mid-Norwegian shelf during several glaciations from Late Pliocene time, reaching a maximum thickness of 1500 m on the shelf edge. During interglacials, the shelf areas were sediment-starved with little or no clastic sedimentation. On top of these prograding units, several packages of Quaternary sediments (mainly till of Weichselian age) show a more aggradational pattern.

Improved knowledge about the deposition and age of the upper Cenozoic sediment wedge has proved vital for revealing the ice-sheet dynamics and may also be important in understanding the maturation and migration of hydrocarbons on the mid-Norwegian shelf.

Introduction

A number of studies during the last 30 years have confirmed that the present morphology of the mid-Norwegian continental shelf (Fig. 1) is mainly a result of glacial processes (Holtedahl and Sellevold, 1972; Bugge, 1980; Rokoengen, 1980; Gunleiksrud and Rokoengen, 1980; Lien, 1983; Rise and Rokoengen, 1984; Rise et al., 1984; King et al., 1987; Holtedahl, 1993). The stratigraphy and age of the offshore deposits have also shown that glacial processes on the mid-Norwegian continental shelf involved sediment redistribution to a far greater extent and much faster than previously thought (Haflidason et al., 1991; Rokoengen et al., 1995; Henriksen and Vorren, 1996; Sættem et al., 1996; Vorren and Laberg, 1997; Eidvin et al., 1998; Rokoengen and Frengstad, 1999).

Improved models of ice-sheet dynamics within areas where the substratum shows changes on a regional scale are very important in order to understand the sediment transport from land to shelf areas, within shelf areas and onto the upper continental slope. The combination of sedimentological, geotechnical and acoustic data from the shelf areas off mid-Norway offer a unique data set to constrain such models both qualitatively and quantitatively. The purpose of the present contribution is to discuss the glacial sedimentary processes and the dynamics of the large ice sheets on the mid-Norwegian continental shelf in the light of regional bathymetric, seismic and sedimentological data. We will focus on the marine-based part of the Scandinavian ice sheet during the last glaciation (the Weichselian), and especially the behaviour of the ice streams, which are fast moving parts of an ice sheet.

Previous investigations/geological setting

In IKU's regional mapping off mid-Norway during the 1970s and early 1980s, the bedrock surface was divided into eleven units informally named I to XI and with ages of the sampled units ranging from Triassic to Pliocene. Due to basinward subsidence and glacial erosion in the inner part of the shelf, the units subcrop more or less parallel to the coast with decreasing ages westwards (Bugge et al., 1984; Rokoengen et al., 1988, 1995; Sigmond, 1992).

Bedrock unit IX (Fig. 2) is found about 50 km west of the crystalline basement as a prominent ridge dominated by sand and with greater resistance to later glacial erosion than the presumably more clay-rich sediments below and above. From unit IX and landwards, the Quaternary is fairly thin. The bathymetry, especially between Frøyabanken and Haltenbanken, reveals varying resistance to erosion of the Mesozoic and Tertiary bedrock units.

An interpreted profile on the mid-Norwegian shelf (Fig. 2) illustrates the upper Cenozoic stratigraphy.

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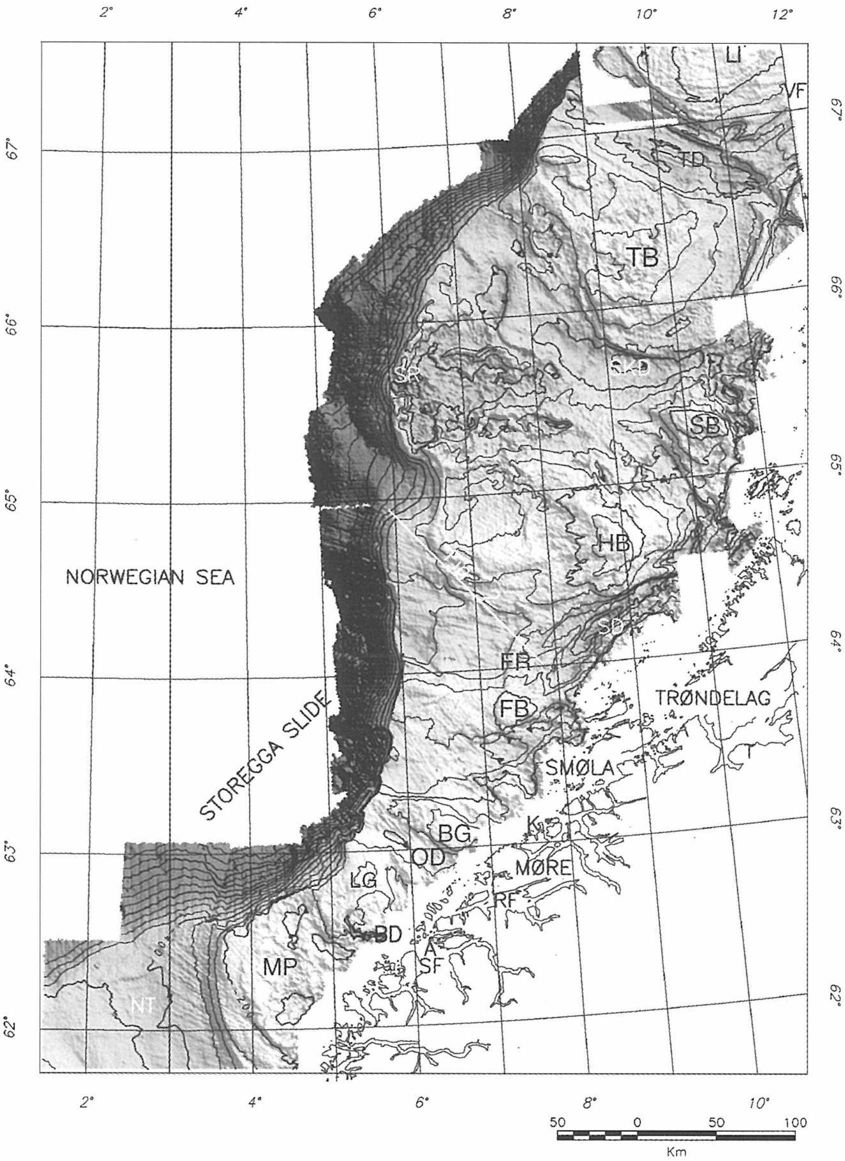

Fig. 1. Shaded relief map covering the mid-Norwegian shelf with 50 m depth contours. The data have been collected by the Norwegian Hydrographic Service with single-beam echosounder. *LI* = Lofoten Islands; *VF* = Vestfjorden; *HB* = Haltenbanken; *SKD* = Sklinnadjupet; *TD* = Trænadjupet; *SD* = Suladjupet; *FB* = Frøyabanken; *FR* = Frøyryggen; *RF* = Romsdalsfjorden; *SF* = Storfjorden; *LG* = Langgrunna; *MP* = Måløyplatået; *BG* = Buagrunnen; *BD* = Breisunddjupet; *OD* = Onadjupet; *NT* = Norwegian Trench; *TB* = Trænabanken; *SR* = Skjoldryggen.

At the present shelf edge, the extensive and complex wedge reaches a maximum thickness of about 1500 m (Rokoengen et al., 1995). A marked change in depositional pattern is observed at the regional unconformity below unit D: (1) the lower units show complex and strongly prograding sequences; (2) the upper units are subhorizontal, exhibiting both progradation and aggradation.

There has been a long debate whether the different units are of glacial or non-glacial origin, especially with age estimates varying from Oligocene to Quaternary (Rokoengen et al., 1995). Eidvin et al. (1998) analysed six exploration wells on the mid-Norwegian shelf and dated the oldest parts of the sedimentary wedge on the outer continental shelf to Late Pliocene. They correlated this with a pronounced expansion of the north European glaciers dated at about 2.6 Ma by Jansen and Sjøholm (1991). Unit IX was assigned an Early Oligocene age (Eidvin et al., 1998), but a younger age can still not be excluded.

The succession below the irregular base of unit D (units L–E, Fig. 2) exhibits large-scale clinoforms prograding towards the northwest and gradually building out the shelf edge. In general, the units are sheet-like with erosional boundaries in the inner part. Most of the sediments below the irregular base of unit D (units K–E) seem to have been deposited by glacial processes, e.g. deposition by grounded glaciers as various types of tills, as proximal glaciomarine sediments, or by redeposition by

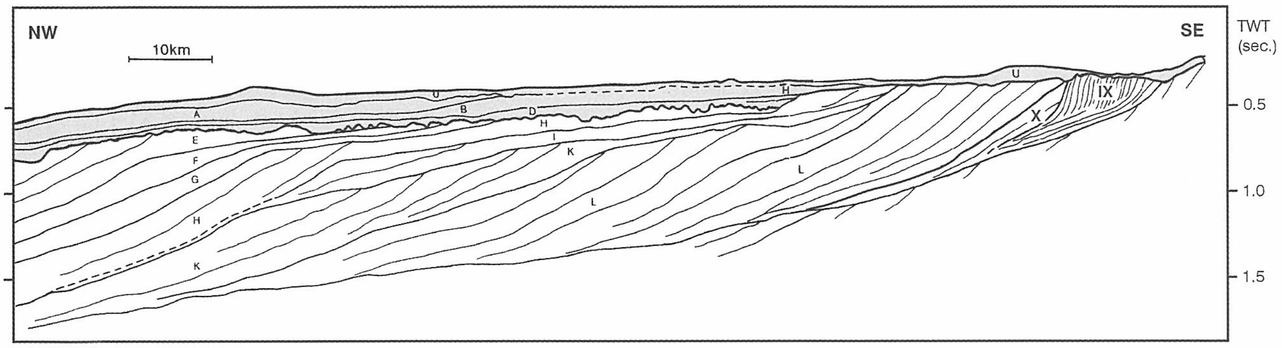

Fig. 2. Composite geoseismic profile showing the upper Cenozoic stratigraphy across the mid-Norwegian shelf. Modified after Rokoengen et al. (1995). The units K–E represent Upper Pliocene/Pleistocene sediments, while the units D, B, A and U above the angular unconformity probably represent the last interglacial/glacial cycle. See Fig. 1 for location.

slumping or debris flows down the continental slope during the Late Pliocene/Pleistocene (Rokoengen et al., 1995; Henriksen and Vorren, 1996; Eidvin et al., 1998), but a younger age can still not be excluded.

The sediments above the angular unconformity (units D, B, A and U) represent mainly the last interglacial/glacial cycle (Rokoengen et al., 1995; Sættem et al., 1996). The typically irregular base of unit D is interpreted to be the result of strong glacial sculpturing, probably both constructional and erosional, in late Saalian time. The acoustically layered unit D consists of marine (Eemian) and glaciomarine sediments (Sættem et al., 1996). The three topmost units (B, A and U) are dominated by unsorted material representing Weichselian tills, possibly from three major glacial advances on the continental shelf. Unit B may represent deposits from the first (early) Weichselian glaciation on the shelf, and unit A deposits from the maximum glaciation. Unit U consists of till from the last glacial advances reaching the shelf edge and glaciomarine clays from the last deglaciation (Rokoengen et al., 1995). Units B, A and U have been subdivided into a number of subunits using the till-tongue model (King et al., 1987).

Knowledge about climatic changes and Scandinavian ice-sheet variations during the last glacial period (the Weichselian) have increased significantly during the last 20 years as a result of studies in the deep sea (Veum et al., 1992; Fronval et al., 1995), of Greenland ice cores (Grootes et al., 1993; Taylor et al., 1993), and from investigations of the Quaternary stratigraphy on land (Larsen and Sejrup, 1990; Olsen, 1997). Based on more than 100 ^{14}C AMS-datings, Olsen (1997) reported the glacial variations during the last 45,000 years, suggesting the existence of extensive ice-free areas in several intervals alternating with rapid ice-growth periods. The last glacial maximum comprises two major glacial expansion phases, dated at 22,000 years BP and 16,000 years BP. Both advances probably reached the outer parts of the shelf and are correlated with the uppermost unit A and unit U, respectively.

The two youngest till units near the shelf edge (till tongues 23 and 24 in unit U) were deposited at about 15,000 and 13,500 years BP according to ^{14}C AMS-dating of shells (Rokoengen and Frengstad, 1999). Along the mid-Norwegian coast, several ^{14}C-dates give ages older than 12,000 years BP, indicating a very rapid deglaciation of the entire shelf area. How these rapid changes in ice-sheet extent and configuration are expressed on the shelf is so far poorly known, but through the regional bathymetric data set we can better imagine the nature of these processes (Figs. 2 and 4).

Sea-bottom morphology related to ice-sheet dynamics

Bathymetric data base

The Norwegian Hydrographic Service collected single-beam echosounder data during the years 1965–1985. The regional bathymetric data set covers a large part of the Norwegian continental shelf south of 68°N with an average line spacing of 500 m. Previous bathymetric charts have also been produced (Bugge, 1975; Bugge et al., 1987).

The data were gridded with a cell size of 500 m and plotted as coloured contour maps with a 5 m contour interval, and as shaded relief maps. The data set covers the areas from the outer coastal zone with crystalline bedrock to the shelf edge and parts of the continental slope, in certain areas down to 1000 m water depth. The data were collected by an Atlas Penguin echosounder (100 kHz). The positioning system used was Decca Main Chain with an absolute accuracy commonly better than 100 m, but within some areas not better than 500 m. The relative accuracy (repeatability) is, however, much better and the morphology on maps in scales of 1 : 500,000 or less will not be significantly influenced by the inaccuracy.

The major morphological features on the mid-Norwegian shelf between the outlet of the Norwegian Trench at about 62°N and the Lofoten Islands at about 67°30′N are shown in Figs. 1, 3 and 4. Between the outlet of the Norwegian Trench and northwards to 64°N, the shelf is rather narrow (60–100 km wide), in contrast to areas further north. In the Skjoldryggen area (Fig. 1), the shelf reaches its greatest width, about 250 km.

The shelf includes bank areas with water depths of 100–300 m north of 63°30′N (Trænabanken, Sklinnabanken, Haltenbanken and Frøyabanken). South of 63°30′N there are several large bank areas with water depths less than 100 m (Buagrunnen and Langgrunna, Fig. 1), in addition to Griptarane west of Kristiansund where crystalline rocks crop out at the surface. In the north, Trænabanken and Haltenbanken represent the largest bank areas (Fig. 1).

The banks are separated by east–west-oriented depressions 350–500 m deep north of 64°N and 150–300 m deep south of 64°N. North of 64°N they are up to 60 km wide, while on the southern half of the shelf, between 62°N and 64°N, they are narrower, and reach 10–20 km in width.

The Trænadjupet area

Trænadjupet is the best expressed ice-stream drainage depression in the northern part of the study area (Fig. 1). It is between 40 km and 60 km wide and generally widens towards the shelf edge. The bathymetry shows linear elements parallel to the trough axis, reflecting the flow direction of ice streams. In the eastern part of Trænadjupet, at least two different glacial drainage systems coalesced. Ice flow from the northeast (Vestfjorden) and southeast joined to become one major ice stream along Trænadjupet (Fig. 3). The bathymetry indicates that the ice stream from the southeast cuts linear features formed by an ice stream from the northeast, and thus reflects the latest erosive phase. The glacial deposits in the Trænabanken area are eroded in the Trænadjupet depression (King et al., 1987).

The Sklinnadjupet–Skjoldryggen system

The Sklinnadjupet is a symmetric, U-shaped trough approximately 30 km wide, up to 470 m deep and 100 km long, presumably mainly eroded by ice streams flowing south of Trænabanken during the last glaciation (Fig. 3). The eastern part of Sklinnadjupet has acted as a confluence basin for drainage of ice from the onshore areas. The trough is oriented approximately east–west. The form and trend of the western part of Sklinnadjupet indicate that during the latest phase, the Sklinnadjupet ice stream was deflected towards the north, and flowed in a northwesterly direction out to the shelf edge. This is probably because the ice sheet east of Skjoldryggen was frozen to the ground or pinned by a large, supposedly mainly ice-pushed ridge, Skjoldryggen (Sættem et al., 1996).

In the eastern part of the Sklinnadjupet, the bathymetry indicates that former confluencing glaciers drained into the depressions (Fig. 3). Evidently, Sklinnadjupet received glacial ice from large inland areas. It appears that the shallow bank areas acted as barriers that partly controlled the dynamics of the ice flowing from inland areas to the continental shelves. In the Tromsøflaket bank area off northern Norway, a similar observation and outline of a possible glacial mechanism was discussed by Sættem (1990).

Sklinnadjupet partly parallels another major ice-stream drainage route east of the Haltenbanken area and southwest of Sklinnabanken (Fig. 3). This depression is oriented NW–SE between Haltenbanken and Skinnabanken and continues westwards towards the Skjoldryggen area.

Skjoldryggen (Fig. 3) has for a long time been interpreted as an end-moraine ridge at the outermost shelf edge (for further reference, see Holtedahl, 1993). It is almost 200 km long, up to 200 m high and 10 km wide and is by far the largest end-moraine on the Norwegian continental shelf. The morphology east of the Skjoldryggen is complex, comprising several depressions and ridges (Fig. 3). Sættem et al. (1996) reported glaciotectonic deformation in this area, and the bathymetric data set discussed herein supports this interpretation. It seems that the displaced blocks were either transported to and incorporated into the Skjoldryggen moraine ridge, or existed as individual or complex ridges. Sættem et al. (1996) suggested that, following the advance of the ice margin to Skjoldryggen, the ice lobe which deposited the ridge froze to the ground beneath. This pinned the ice, and led to a build up of stress at the ice lobe base which gave rise to glaciotectonic displacement of blocks of frozen sediments.

The glacial stratigraphy in both Haltenbanken and Trænabanken outlines thick units of Weichselian sediments (units A, B and U, Fig. 2). King et al. (1987) described three till units, each comprising stacked till tongues with intervening glaciomarine sediments deposited during successive advances and retreats of the ice-sheet grounding line. The units generally occupy the outer and central portions of the shelf, with a thickness of up to 400 m in the Skjoldryggen area, whereas an erosional morphology dominates the central to inner shelf.

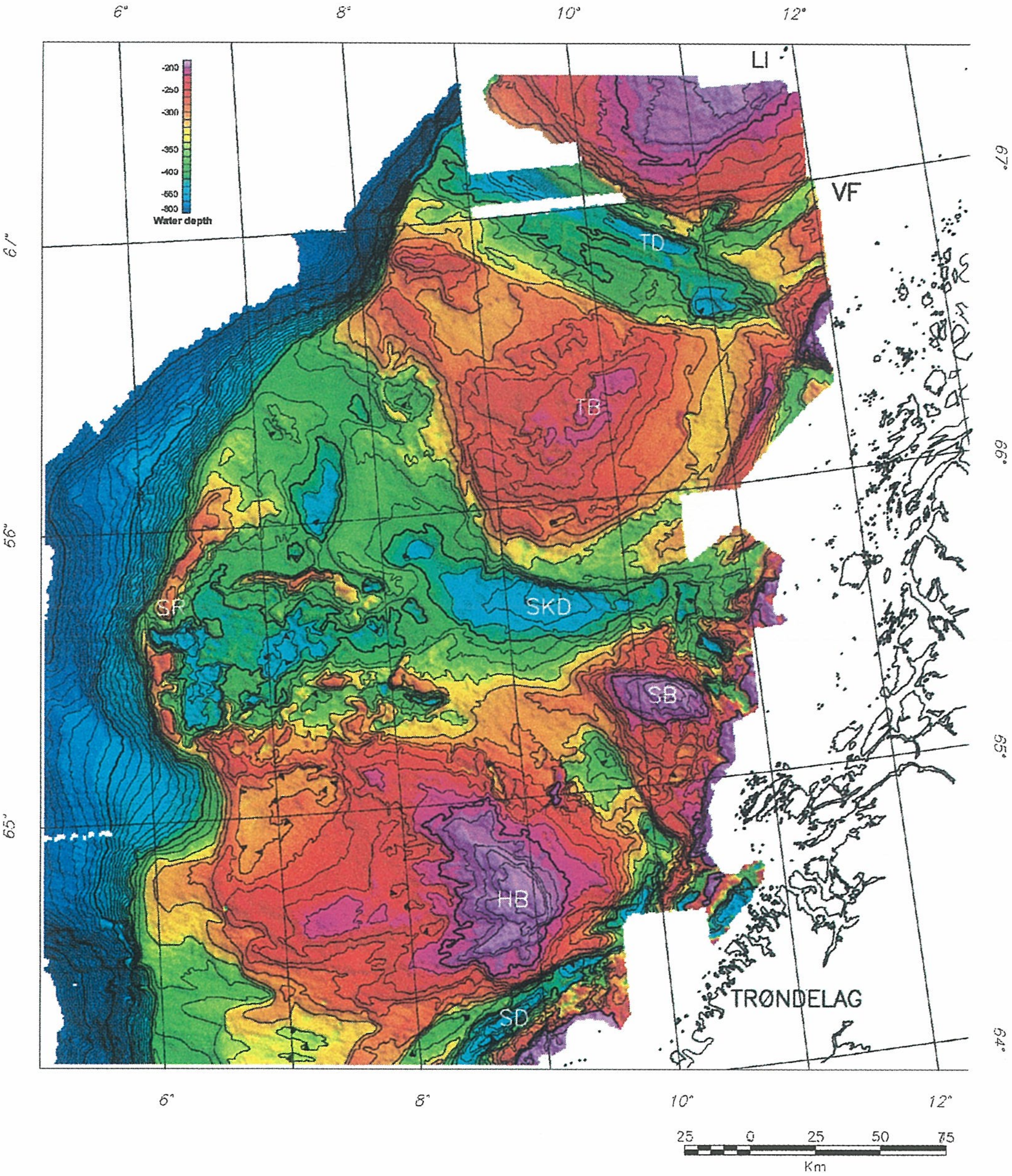

Fig. 3. Colour-shaded relief map with 20 m depth contours based on a 500 m grid cell size. *LI* = Lofoten Islands; VF = Vestfjorden; *HB* = Haltenbanken; *SKD* = Sklinnadjupet; *TD* = Trænadjupet; *SD* = Suladjupet; *FB* = Frøyabanken; *FR* = Frøyryggen; *TB* = Trænabanken; *SR* = Skjoldryggen.

Ice drainage offshore Trøndelag

The shallow parts of Haltenbanken have in certain periods probably prevented an active westward flow of the ice sheet. Several SW–NE-trending depressions (including Suladjupet, Fig. 3) indicate that ice mainly drained southwestwards, east of Haltenbanken, turning westwards across Frøyryggen north of Frøyabanken.

The Suladjupet depression is more than 500 m deep and eroded 200–300 m below the surrounding sea bottom (Figs. 3 and 4). The depression was formed by glacial erosion, mainly of the dark, Upper Jurassic/Lower Cretaceous claystone of the Spekk Formation. IKU bedrock unit IX subcrops below a thin Quaternary cover at Frøyryggen, and it is evident that this sandy unit has been resistant to glacial erosion. Prograding glacial sequences and a wide erosional depression are seen west of Frøyryggen (Bugge, 1980; Bugge et al., 1987; Rokoengen et al., 1995).

Ice drainage offshore Møre

The continental shelf offshore Møre is very narrow compared to the areas further north (Fig. 4). Several WNW–ESE-trending depressions are separated by shallow bank areas. We believe that these troughs have also been drainage routes for ice streams. Out-

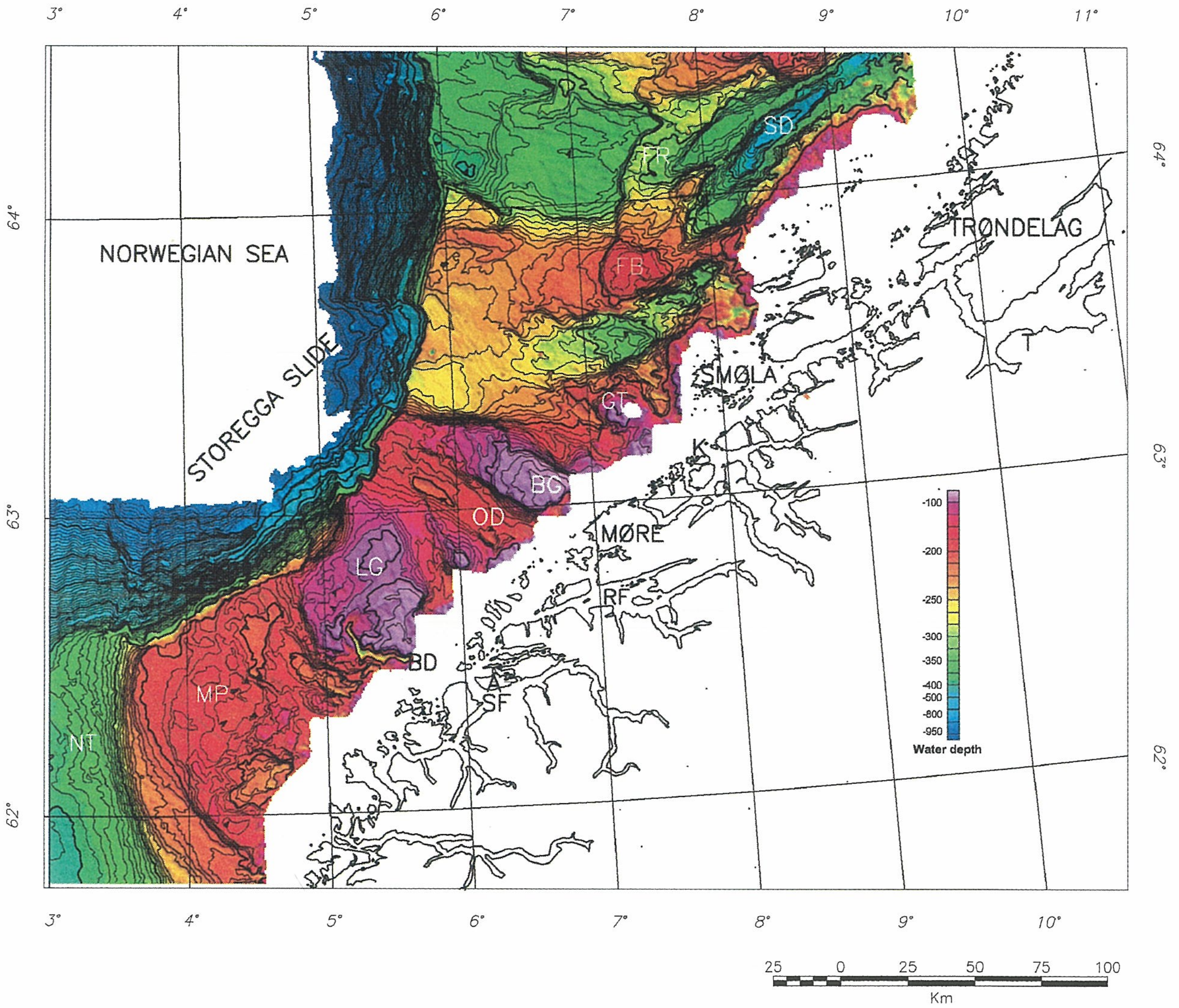

Fig. 4. Colour-shaded relief map of the shelf area off Møre with 20 m depth contours. On Måløyplatået large curved ridges dominate, while further north, depressions which extend from land to the shelf break separate shallower bank areas. The depressions are interpreted to have been drainage routes for ice streams during maximum expansion of the late Weichselian ice sheet. *SD* = Suladjupet; *FB* = Frøyabanken; *FR* = Frøyryggen; *RF* = Romsdalsfjorden; *SF* = Storfjorden; *LG* = Langgrunna; *MP* = Måløyplatået; *BG* = Buagrunnen; *BD* = Breisunddjupet; *OD* = Onadjupet; *NT* = Norwegian Trench; *K* = Kristiansund; *Å* = Ålesund.

side Smøla (Fig. 4), the ice drainage is directed in a southwesterly direction, towards the northern part of the Storegga slide. Another ice stream has passed south of the Griptarane highs towards the northwest, and coalesced with the ice stream off Smøla (Fig. 4). Northwest of Romsdalsfjord, a NW–SE-trending depression (Onadjupet) ends in the Storegga slide area at the shelf break. Northwest of Ålesund, another depression extends almost to the shelf break where it coalesces with the aforementioned ice-stream eroded channel (Fig. 4).

Langgrunna is a large bank area that guided ice-stream flow both south and north of the bank (Fig. 4). Breisunddjupet forms a narrow, elongated depression, representing the continuation of the deep Storfjord drainage system onto the open shelf, and ends in the eastern part of Langgrunna (Fig. 4). This extended fjord feature is very uncommon on the shelf and indicates special glacial conditions during its formation; for instance, erosion by very channelised ice flow in an area where the surroundings were covered by frozen based ice could produce such a feature. A possible tectonic origin has also been discussed (Rokoengen, 1980).

South of Breisunddjupet, an ice-stream drainage route from the east onto the northern part of Måløyplatået can be inferred (Fig. 4). Måløyplatået is the southernmost bank area of the mid-Norwegian shelf, located close to the outlet of the Norwegian Trench. Thus, this area probably was influenced by the large Norwegian Trench Ice Stream from time to time (King et al., 1996), as the ice drainage from the mainland either was deflected in a northerly direction and/or partly assimilated by the Norwegian Trench Ice Stream. On Måløyplatået (Fig. 4), arcuate ridges indicate major halts during deglaciation (Rokoengen, 1980; Rise and Rokoengen, 1984; Rise et al., 1984).

Ice-flow model

From the present bathymetric data set (Figs. 1, 3 and 4) and earlier investigations on the Norwegian continental shelf (Rise and Rokoengen, 1984; King et al., 1987; Rokoengen et al., 1995; Sættem et al., 1996; Vorren and Laberg, 1997), we have reconstructed a probable flow pattern of the western part of the Scandinavian ice sheet during the late Weichselian (Fig. 5). In addition we have used investigations from Antarctica as a basis for the model.

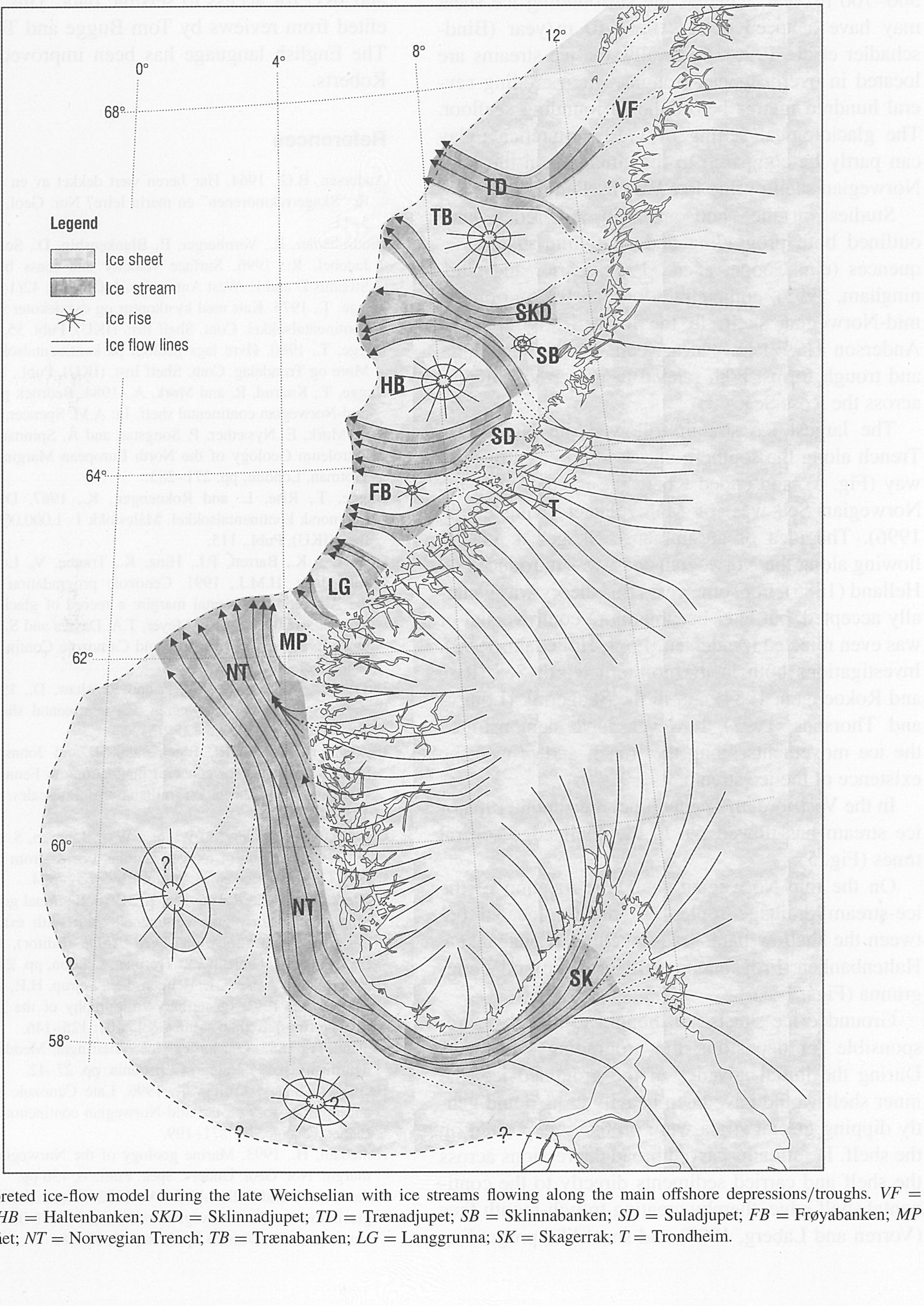

Fig. 5. Interpreted ice-flow model during the late Weichselian with ice streams flowing along the main offshore depressions/troughs. *VF* = Vestfjorden; *HB* = Haltenbanken; *SKD* = Sklinnadjupet; *TD* = Trænadjupet; *SB* = Sklinnabanken; *SD* = Suladjupet; *FB* = Frøyabanken; *MP* = Måløyplatået; *NT* = Norwegian Trench; *TB* = Trænabanken; *LG* = Langgrunna; *SK* = Skagerrak; *T* = Trondheim.

Extensive research has been carried out in West Antarctica during recent years in order to understand the ice-sheet dynamics of large, marine-based ice sheets (e.g. Shabtaie and Bentley, 1987). The emphasis has been on the large ice streams which drain about 90% of the West Antarctic ice sheet. These ice streams are fast moving parts of ice sheets, normally 300–500 km long, 50–80 km wide and with speeds of 300–700 m/year, whereas the surrounding ice sheet may have a speed of less than 10 m/year (Bindschadler et al., 1996). Generally, the ice streams are located in overdeepened troughs, often eroding several hundred metres below the surrounding seafloor. The glaciological setting of West Antarctica today can partly be compared to the situation on the mid-Norwegian shelf during late Weichselian time.

Studies on the shelf areas in Antarctica have outlined both prograding and aggrading glacial sequences (e.g. Cooper et al., 1991; Larter and Cunningham, 1993), comparable to what we find on the mid-Norwegian shelf. In the Ross Sea, Shipp and Anderson (1997) have described glacial megaflutes and trough forms, both related to palaeo-ice streams across the Ross Sea.

The largest ice stream followed the Norwegian Trench along the southern and western coast of Norway (Fig. 4), and ended where the ice calved in the Norwegian Sea west of Måløyplatået (King et al., 1996). The idea of an immense Skagerrak glacier flowing along the Norwegian coast was introduced by Helland (1885). For some years this theory was generally accepted, but later became more controversial or was even rejected (Andersen, 1964; Holtedahl, 1993). Investigations both in the northern North Sea (Rise and Rokoengen, 1984) and in the Skagerrak (Longva and Thorsnes, 1997), however, have demonstrated the ice movements along the trench and proven the existence of the ice stream.

In the Vestfjorden/Trænadjupet area another major ice stream has flowed out to the shelf edge several times (Fig. 5).

On the mid-Norwegian shelf, the location of the ice-stream drainage routes are mainly located between the shallow bank areas, such as Trænabanken, Haltenbanken, Frøyabanken, Buagrunnen and Langgrunna (Figs. 3–5).

Grounded ice sheets are thought to have been responsible for depositing the prograding sequences. During the initial advance of the grounded ice, the inner shelf would have been heavily eroded and gently dipping glacial strata were probably deposited on the shelf. Ice streams carved broad depressions across the shelf and carried sediments directly to the continental shelf edge, thereby creating trough-mouth fans (Vorren and Laberg, 1997) and sheet-like prograding sequences (King et al., 1987). During interglacial periods, the shelf areas were starved of sediment and thus received little or no clastic sedimentation.

Acknowledgements

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D. OTTESEN *Geological Survey of Norway, N-7491 Trondheim, Norway*
L. RISE *Geological Survey of Norway, N-7491 Trondheim, Norway*
K. ROKOENGEN *Norwegian University of Science and Technology, N-7034 Trondheim, Norway*
J. SÆTTEM *SINTEF Petroleum Research, N-7465 Trondheim, Norway*
Present address: Sauherad Kommune, N-3812 Akkerhaugen, Norway