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The Vestfjorden-Trænadjupet palaeo-ice stream drainage system, mid-Norwegian continental shelf

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Abstract

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. Our interpretation is based mainly on regional and detailed bathymetry, and 2D and 3D seismic data. 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 ca. 150,000 km^2 within the Fennoscandian Ice Sheet (FIS) during the Last Glacial Maximum (LGM). The location of the palaeo-ice stream prevented large ice masses from reaching the montainous areas of Lofoten and Vesterålen. A local ice dome was established in these areas. The palaeo-ice stream eroded extensively into both Mesozoic and Cenozoic sedimentary rocks, and Quaternary sediments. 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). These moraines are commonly 10–20 m high, a few kilometres wide, and reach several tens of kilometres in length. 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-line moraine, formed during a halt or a readvance of the ice stream during the last deglaciation. The large transport of glacial debris towards the grounding line occurred during this stage. Northeast of the Tennholmen Ridge, several smaller moraine ridges were developed at still-stands during deglaciation.

Keywords: palaeo-ice stream; marine geology; bathymetry; ice flow; Fennoscandian Ice Sheet; glacial lineations; ice-sheet stability

1. Introduction

Studies of the marine-based West Antarctic Ice Sheet (WAIS) have revealed a dynamic ice sheet with drainage of most of the ice through fast-flowing ice streams (Bindschadler et al., 1996; Bamber et al.,

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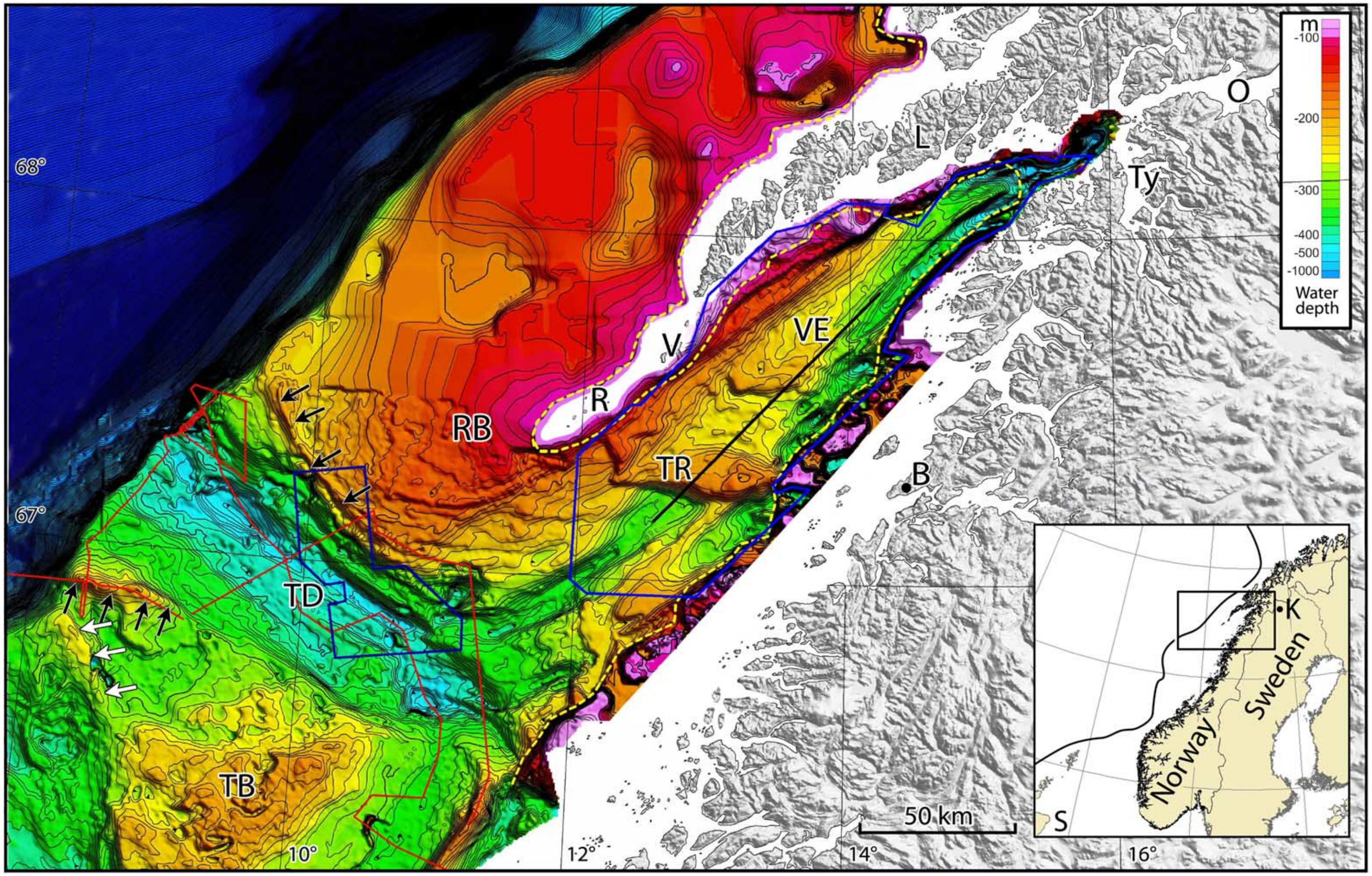

Fig. 1. Location map and regional bathymetry of the study area on the Norwegian margin (inset). The border between crystalline basement rocks and sedimentary rocks is marked by the yellow dashed line. Blue lines mark the limits of the swath mapped area in Vestfjorden (Fig. 2) and the two 3D seismic surveys in Trænadjupet (Fig. 3). The red lines correspond to the cruise 9902 ship track. The black line shows the position of a reflection seismic profile in Vestfjorden (Fig. 5). Black arrows mark ice-stream shear margin moraines on both sides of Trænadjupet. White arrows mark ice-stream shear margin moraine on the outer Trænabanken formed by a palaeo-ice stream flowing towards NNW. TB—Trænabanken, TD—Trænadjupet, RB—Røstbanken, VE—Vestfjorden, R—Røst, V—Værøy, L—Lofoten, B—Bodø, O—Ofotfjorden, Ty—Tysfjorden, TR—Tennholmen Ridge, K—Kebnekaise.

2000). During the Last Glacial Maximum (LGM), a large part of the WAIS reached the shelf break or the outer parts of the Ross Sea shelf (Domack et al., 1999). Investigations of the topography of the Ross Sea shelf revealed deep troughs with intermediate bank areas. Mega-scale glacial lineations are found in the bottoms and along the sides of the troughs (Shipp et al., 1999; Wellner et al., 2001), and these are interpreted to be the imprints of fast-flowing palaeo-ice streams from the time when the WAIS covered most of the Ross Sea. Similar elongate bedforms are also mapped on the shelf off the Antarctic Peninsula (Canals et al., 2000; Ó Cofaigh et al., 2002).

Studies of the sea-floor morphology on the southern and middle Norwegian shelf have revealed a similar pattern to that found in West Antarctica, with evidence of ice-sheet drainage through palaeo-ice streams (Ottesen et al., 2001, 2002, 2005; Dahlgren et al., 2002; Sejrup et al., 2003; Nygård et al., 2004). The largest of these palaeo-ice streams was the Norwegian Channel Ice Stream that drained a substantial part of the Fennoscandian Ice Sheet during the LGM (Longva and Thorsnes, 1997; Sejrup et al., 2003). This ice stream was 800 km long, originated in the Skagerrak area between Norway and Denmark, and had a width of 150 km at the shelf break outside western Norway at 62°N. Farther north, Ottesen et al. (2001, 2005) mapped several palaeo-ice streams on the mid-Norwegian shelf between Stadt and the Lofoten Islands (62°N–68°N).

The study area covers Vestfjorden and Trænadjupet on the shelf outside the county of Nordland in northern Norway, extending from 66°N to 68°N, and is located adjacent to the Lofoten archipelago (Fig. 1). Vestfjorden is an open NE–SW-trending embayment, whereas Trænadjupet is an elongated trough representing the continuation of Vestfjorden to the shelf edge. In this study, the regional bathymetry strongly indicates that Vestfjorden (67–68°N, 11–16°E, southeast of the Lofoten Islands) and Trænadjupet formed an important pathway for ice-sheet drainage during the Late Weichselian (Fig. 1).

Very few papers on the glacial geology of the study area have been published (Dekko, 1975; Rokoengen and Sættem, 1983). Andersen (1975, 1979) reconstructed two morainal zones on the shelf west of Lofoten, called Egga I and II, and argued that the Egga I moraine at the shelf edge could represent the Weichselian glacial maximum. Rokoengen and Sættem (1983) constructed a sediment thickness map of Vestfjorden based on an open grid of single-channel seismic lines. The glacial geology of the Lofoten archipelago, with alpine mountains up to 1000 m in height, is also poorly understood (e.g. Bargel, 2003). Lack of Quaternary sediments and dateable material has made it difficult to establish a detailed glacial history for the area. However, deep weathering in certain locations suggests that large areas of the mountainous islands (mountain peaks frequently higher than 1000 m) were not covered by glaciers, or possibly existed as nunataks during successive glacial periods. This study supports this view, indicating the former existence of an efficient ice drainage from the central parts of the Fennoscandian Ice Sheet into Vestfjorden, south and east of Lofoten, and into Andfjorden north and east of the archipelago. We present regional and detailed bathymetric maps as well as interpreted 2D and 3D seismics from the Vestfjorden-Trænadjupet area. Both the bathymetric and the seismic reflection data have been used to describe the large-scale morphology of the sea-floor and various detailed submarine landforms related to glacial processes. Maximum ice configuration models for the LGM are proposed, and the deglaciation history of the area is briefly discussed.

The significance of the very long subglacial bedforms for glaciology is examined and the implications with respect to subglacial processes are discussed. A 60 km long, 20 km wide and up to 80 m thick ice-stream grounding line moraine is described, demonstrating the large transport capacity of marine ice streams.

2. Methods

To describe the sea-floor morphology of the area, five datasets have been used (Fig. 1):

(1) Single- and multibeam (EM100), echosounder bathymetric data from several cruises collected by the Norwegian Hydrographic Service, from which a 500 m grid cell size covering the whole study area has been derived. The Vestfjorden, Trænadjupet and Trænabanken areas are cov-

ered by data of good quality, in contrast to poor data from the shelf areas outside the Lofoten Islands (Fig. 1).

(2) Simrad EM100 multibeam bathymetry collected by the Norwegian Hydrographic Service in 1985, covering most of Vestfjorden (8000

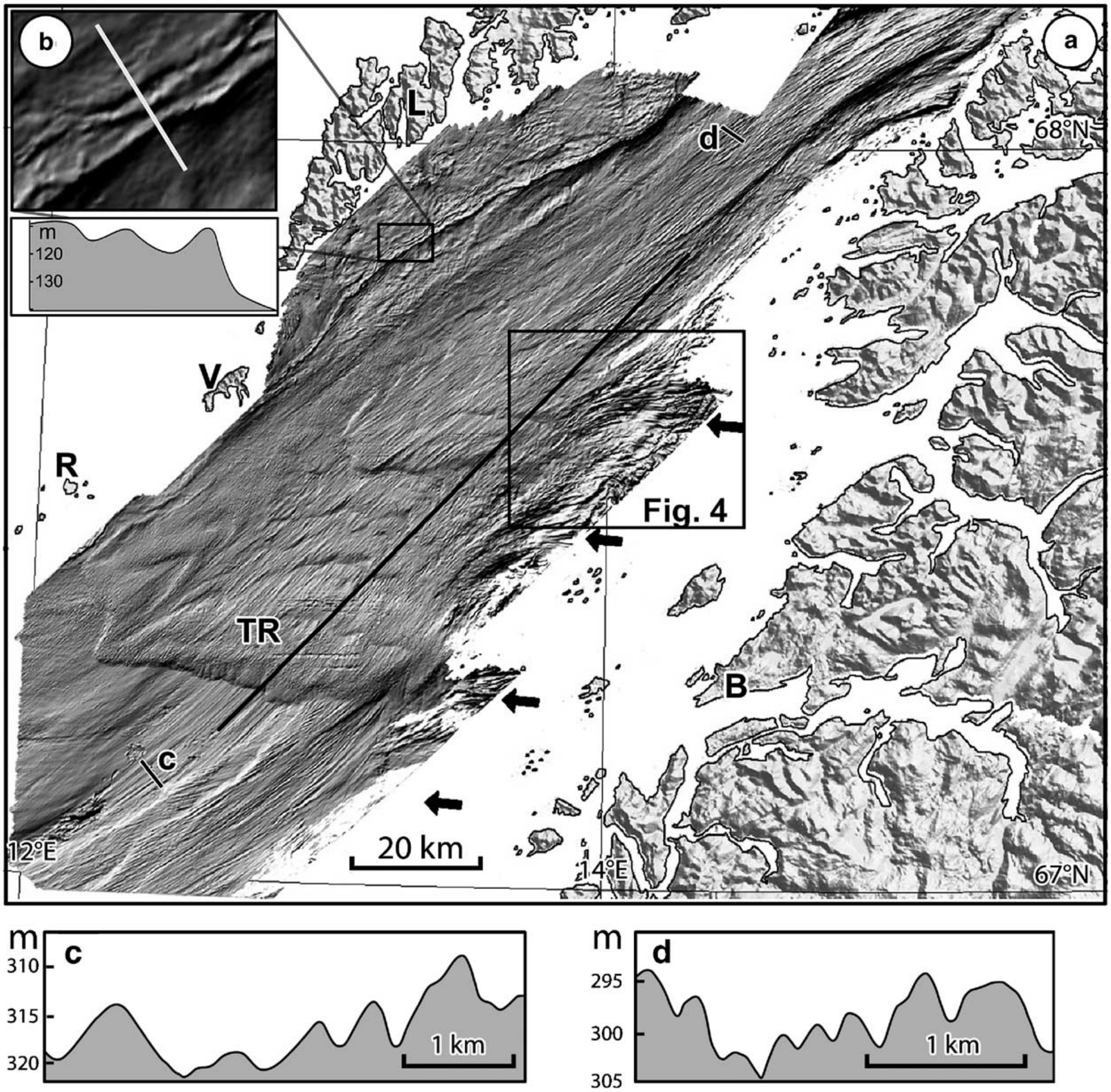

Fig. 2. (a) Shaded relief image of the sea-floor of Vestfjorden from multibeam bathymetry. See Fig. 1 for location. Grid cell size is 50 m. Note the extensive glacial lineaments parallel to the trough axis. Four tributary ice-flow systems (marked by arrows) derive from the fjords to the east of Vestfjorden. The flow was deflected as the ice was assimilated into the main trunk of the palaeo-ice stream in Vestfjorden. (b) Enlarged image and sea-floor relief of the zone of terminal moraines that possibly formed by a southeasterly ice flow from the Lofoten islands, after the Vestfjorden ice stream retreated. (c) Sea-floor relief perpendicular to the ice flow southwest of the Tennholmen Ridge. (d) Sea-floor relief from the inner Vestfjorden. TR—Tennholmen Ridge, R—Røst, V—Værøy, L—Lofoten, B—Bodø. The black line shows the position of a seismic line shown in Fig. 5.

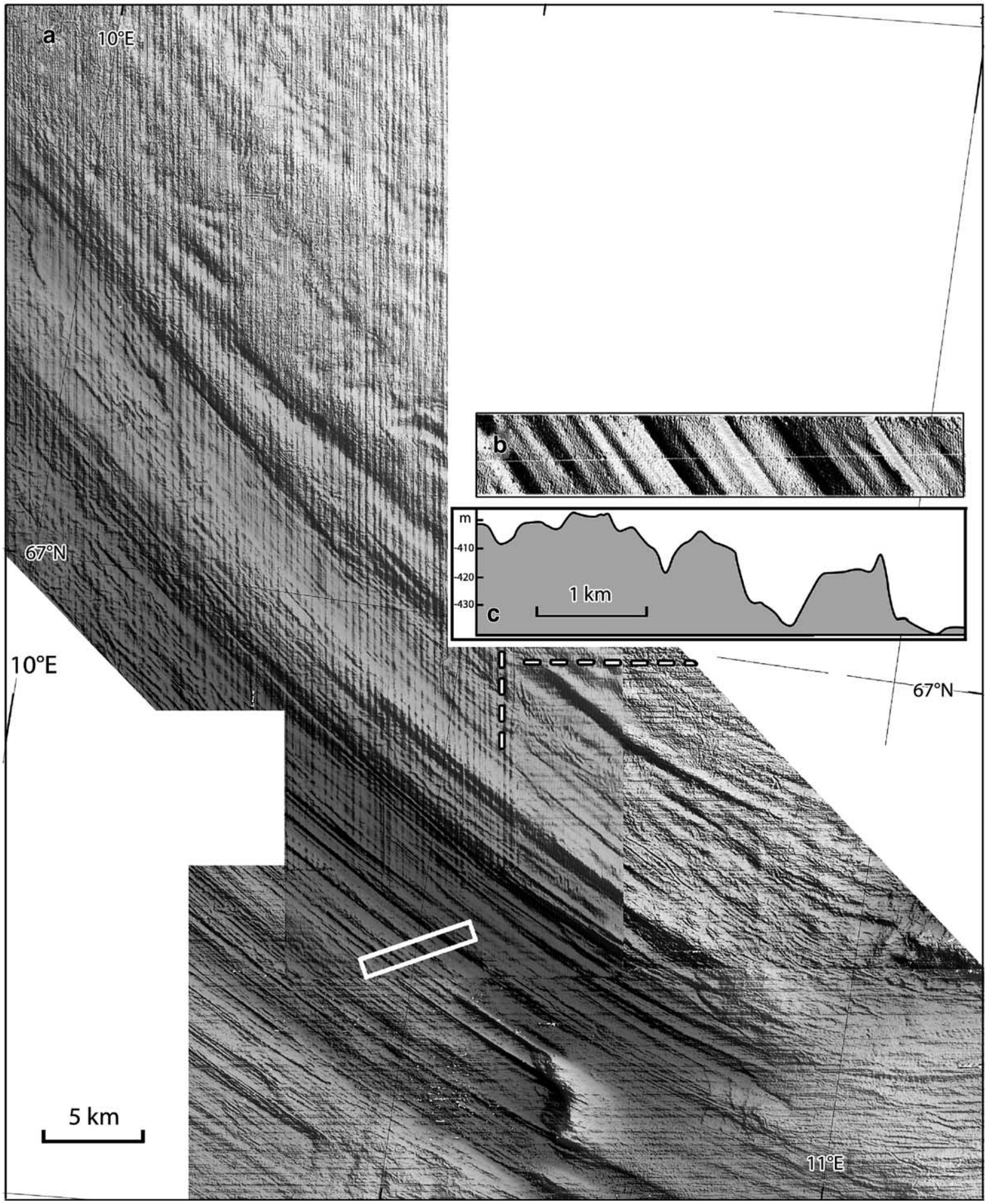

Fig. 3. a) Sea-floor morphology of the inner Trænadjupet, based on interpreted 3D-seismic datasets (ST9404 and ST9604). See Fig. 1 for location. Dashed lines show direction of seismic survey lines. b) Detailed sea-floor morphology from a multibeam bathymetric line (cruise 9902). For location see (a). Note small pockmarks on the sea-floor. (c) Sea-floor relief along the line shown in (b).

km^2) (Figs. 1 and 2). Water depths in the survey area varies between 20 and 650 m. The data were gridded with 50 m horizontal spacing and displayed as illuminated shaded relief images at scales from 1:250,000 to 1:50,000.

(3) Bathymetry from two 3D-seismic datasets (ST9404, ST9604) with a line spacing of 25 m, covering in total ca.~1700 km^2. These datasets cover parts of Trænadjupet and parts of the bank areas to the north (Figs. 1 and 3). Sea-floor bathymetry was extracted after converting milliseconds to metres by using a sound velocity of 1480 m/s.

(4) Multibeam bathymetry (Simrad EM 1002) from the cooperative test cruise 9902 between the Norwegian Hydrographic Service and the Geological Survey of Norway (NGU) (Fig. 1). The data cover parts of Trænadjupet and parts of the bank areas to the south and north. The data normally had a point density of 3–10 m and were gridded at 5 m cell size. The data cover mainly a corridor along the ship track up to ca. 1 km wide.

(5) Shallow seismic data. The Continental Shelf Institute (IKU) collected a regional grid of sparker data in the Trænabanken/Trænadjupet area in the years 1978, 1979 and 1982 (Rise, 1988). A single-channel streamer with analogue recording was utilized with filtering at 50–500 kHz. The line spacing was about 10 km on east–west profiles and 25 km on cross-profiles. In Vestfjorden, two lines parallel to the fjord axis were collected, in addition to several cross-lines in 1972 and 1982. NGU also acquired Geopulse boomer and 15 in.^{3} sleeve-gun seismic lines in 2000, 2001 and 2003 in Vestfjorden.

3. Large-scale geomorphology and geological setting

Vestfjorden is an open NE–SW-trending embayment between the Lofoten islands and the Norwegian mainland (Fig. 1). Although the term fjord is applied, it is very different compared to the fjords along the coastline of western Norway. It is approximately 250 km long and represents the seaward continuation of the E–W-trending Ofotfjorden, which is up to 550 m deep and ca. 70 km long (Fig. 1). Ofotfjorden is 5–10 km wide, narrowing in the transition zone towards Vestfjorden. Another large fjord system, the N–S-trending Tysfjorden, opens into the innermost Vestfjorden (Fig. 1). The mountains of the Lofoten islands reach a height of more than 1000 m, and had an important influence on regional ice flow in the area. Whereas the inner, narrow part of Vestfjorden is overdeepened (600 m water depth), the ‘fjord’ widens and shallows southwestwards. Off Værøy, 150 km out in the ‘fjord’, the water depth is 200–300 m and the width is 50–60 km. In outer Vestfjorden, the water depth increases to 350–400 m.

Vestfjorden comprises a sedimentary basin of Mesozoic and Cenozoic rocks (Rokoengen and Sættem, 1983; Løseth and Tveten, 1996). On the southeastern side, the boundary to the crystalline rocks is marked by an up to 300 m high step (Fig. 1). This is interpreted to be the result of enhanced glacial erosion of the downfaulted Vestfjorden Basin (Rokoengen and Sættem, 1983). On the northern side, near the Lofoten archipelago, the crystalline boundary is not so clear, except in the inner fjord (Fig. 1).

Vestfjorden apparently terminates where the basin coincides with the wide and slightly deeper, NW–SE-trending, Trænadjupet cross shelf trough. This depression is approximately 150 km long, 40 km wide in the inner part and ~90 km wide at its mouth at the shelf break (Fig. 1). The water depth varies from 200 to 300 m along the sides, whereas the central part of Trænadjupet reaches 400–500 m. On both sides of Trænadjupet, staircase-like slopes are observed with a total height of 200 m. The benches are parallel to the trough axis and extend to the shelf break. In the inner part of Trænadjupet, poorly consolidated Tertiary sandstones or siltstones forming the underlying sedimentary bedrock are exposed (Rokoengen and Sættem, 1983). Farther out, glacial erosion has carved into thick units of Late Pliocene and Quaternary sediments (Henriksen and Vorren, 1996).

The sea-floor of both Vestfjorden and Trænadjupet is generally covered by a thin layer of fine-grained sediments from the deglaciation and the Holocene. Except for the deepest areas in inner Trænadjupet, where up to 25 m of these sediments exist, the

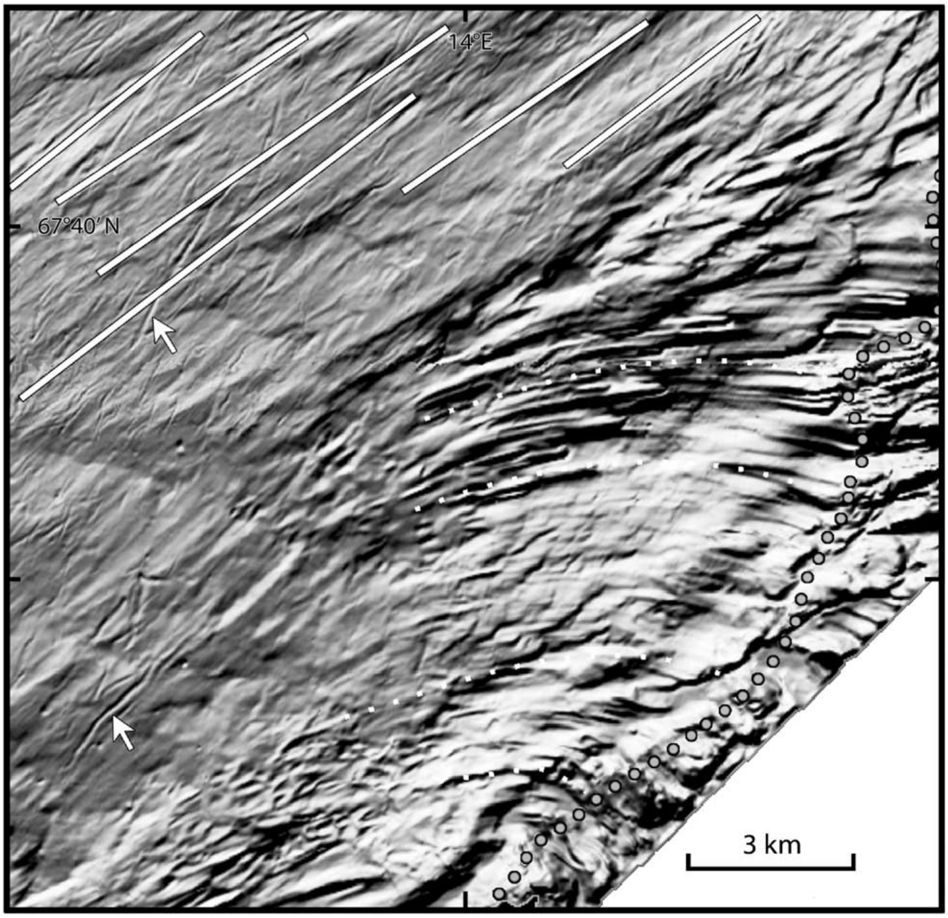

Fig. 4. Multibeam bathymetry from the eastern side of Vestfjorden showing drumlins and glacial lineations indicating confluent ice flow. Ice coming out from the fjords north of Bodø (white dotted lines) formed drumlins west of the crystalline rocks (grey dotted line). The tributary ice flow was deflected and assimilated into the main ice- stream trunk in Vestfjorden (white lines). Arrows show location of some of the iceberg ploughmarks of the area. See Fig. 2 for location.

subglacial forms found on the sea-floor have not been obliterated by these sediments.

3.1. Interpretation of the sea-floor morphology

The marine-geophysical datasets acquired from Vestfjorden and Trænadjupet have been examined systematically for the presence of sea-floor topographic features linked to the former presence of grounded ice sheets on this part of the mid-Norwegian shelf. The sea-floor of Vestfjorden and Trænadjupet comprises: (1) glacially-eroded troughs; (2) streamlined glacial lineations; (3) longitudinal ridges; and (4) transverse morainal ridges. All of these features will be interpreted in the context of past glacier flow. We describe, in the present paper, the morphology and the spatial pattern of these subglacial landforms that are regarded as diagnostic of the presence of grounded ice and, in several cases, of fast glacier flow. Examples of these features are presented in Figs. 1–5, and a map and interpretation of the set of subglacial landforms seen on the sea-floor is shown in Fig. 6.

3.1.1. Glacially-eroded troughs

In the innermost narrow part of Vestfjorden, there is a 600 m deep, elongated trough parallel to the axis of the fjord (Fig. 1). The trough has partly been eroded in

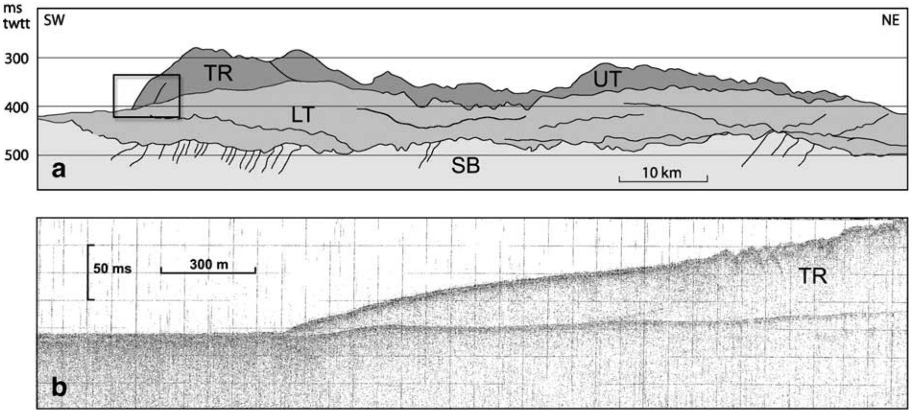

Fig. 5. (a) Line drawing of seismic profile IKU-V4-72. See Figs. 1 and 2 for location. (b) Seismic profile NGU0008006. See box in (a) for location. The Tennholmen Ridge (TR) is interpreted as a grounding-line moraine deposited by the palaeo-ice stream in Vestfjorden during a still-stand or readvance during the deglaciation. SB—sedimentary bedrock, LT—lower till unit(s), UT—upper till unit deposited during the last phase of the deglaciation in Vestfjorden.

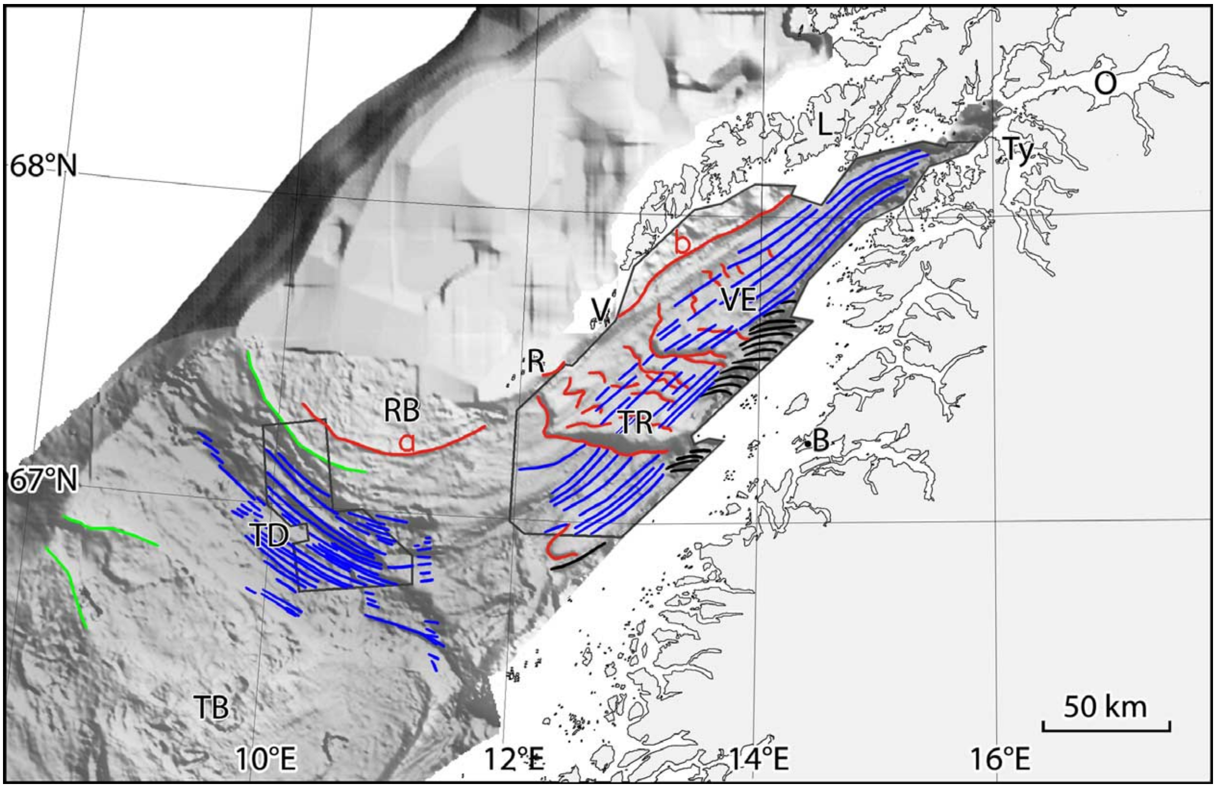

Fig. 6. Interpreted subglacial landforms in the Vestfjorden-Trænadjupet drainage system. Green lines—ice-stream shear margin moraines. Dark blue lines—mega-scale glacial lineations. Black lines—drumlins. Red line—transverse moraine ridge. Ridges marked a and b are marginal moraines discussed in the text. Abbreviations as in Fig. 1.

bedrock, and partly in Quaternary sediments. On the southern side of the inner part of Vestfjorden, several troughs are located close to the border with the crystalline rocks. The largest of the troughs is NE–SW-oriented, 75 km long and 10 km wide. These troughs, that continue towards the east, were probably formed by tributary ice infilling the fjords. On the northern side of Vestfjorden, a steep slope indicates large-scale glacial erosion in both sedimentary and crystalline rocks. In the inner part of the fjord, the height of this slope is more than 300 m, decreasing towards the southwest. In Trænadjupet, several elongated troughs are developed. The largest of these, 50 × 15 km and 480 m deep, is located just landward of the shelf break (Fig. 1).

3.1.2. Glacial lineations

The sea-floor of most of Vestfjorden is dominated by extensive sedimentary lineations parallel to the 'fjord' axis. These lineations comprise drumlins with blunt stoss faces, megaflutes and larger mega-scale glacial lineations named 'bundles' by Canals et al. (2000) (Figs. 2 and 4). Clark (1993) defined these streamlined, subglacially-formed features on the basis of their length, height and width. Whereas drumlins and megaflutes may reach a length between 100 and 1000 m, mega-scale glacial lineations may reach lengths of several tens of kilometres.

In inner Vestfjorden, the spacing between submarine ridges varies between 300 and 700 m, and the individual ridges are commonly 200–500 m wide and up to10 m high (Fig. 2). Southwest of the Tennholmen Ridge, in outer Vestfjorden, highly elongate glacial lineations are found (Fig. 2). These lineations disappear beneath the glacial sediments that made up the ridge itself.

In Trænadjupet, both multibeam bathymetric data and the interpreted sea-floor horizon from the 3D-seismic data show extensive glacial lineations parallel to the trough axis (Fig. 3). Most of the deeper parts of the Trænadjupet are covered with mega-scale glacial lineations. The spacing between the tops of the lineations is commonly 400–600 m, whereas the average width and height of the individual lineations are commonly 200–500 m and 5–10 m, respectively (Fig. 3b and c). The glacial lineations seen on Fig. 3 are overprinting the prominent staircase-like northern slope of Trænadjupet seen on Fig. 1. This indicates that the palaeo-ice stream has been very erosive in the area, eroding both in thick units of Quaternary sediments and in Tertiary bedrock.

The most prominent drumlins are found in the eastern part of Vestfjorden at ca. 67°30′N, 14°E (Fig. 4). The drumlins are localised just west of the border between the crystalline and sedimentary rocks. The drumlins, up to 7 km long and 25 m high, are oriented parallel to one another and show a westerly ice-flow direction, turning towards the southwest after a few kilometres.

3.1.3. Longitudinal ridges

On both sides of Trænadjupet, two ridges parallel with the trough axis have been mapped (marked with black arrows in Fig. 1). The ridge on the northern side reaches a length of 70 km, a height of 20 m and is 2–3 km in width. The ridge on the southern side is 35 km long, up to 50 m high and 6 km wide. Similar ridges have been described from the Canadian Arctic (Clark and Stokes, 2001; Stokes and Clark, 2002), where they have been interpreted as ice-stream, shear margin moraines formed at the transition zone between fast-flowing ice and adjacent passive ice which may have been frozen to its bed.

The two ridges, on either side of Trænadjupet, are also interpreted as ice-stream, shear margin moraines and we infer that these indicate the positions of the palaeo-ice stream margins. At the shelf break the width of the palaeo-ice stream is, therefore, estimated at ~90 km.

The ages of these moraine ridges are uncertain, but they probably formed during the LGM. A similar ridge is also present on outer Trænabanken (marked with white arrows in Fig. 1), and is interpreted as having been deposited by an ice stream flowing northwestwards in the depression south of Trænabanken towards the shelf edge (Figs. 1, 6 and 7).

3.1.4. Transverse moraine ridges

Two large and several smaller sea-floor moraine ridges, perpendicular to the inferred ice-flow direction, are present in the Vestfjorden area (Figs. 1 and 2). These ridges occur in the upper sediment unit that includes the Tennholmen Ridge and in the sediments 60 km to the northeast (Fig. 5). This upper unit reaches a maximum thickness of ~100 ms (ca. 80 m). It is deposited on top of a fluted surface that is visible

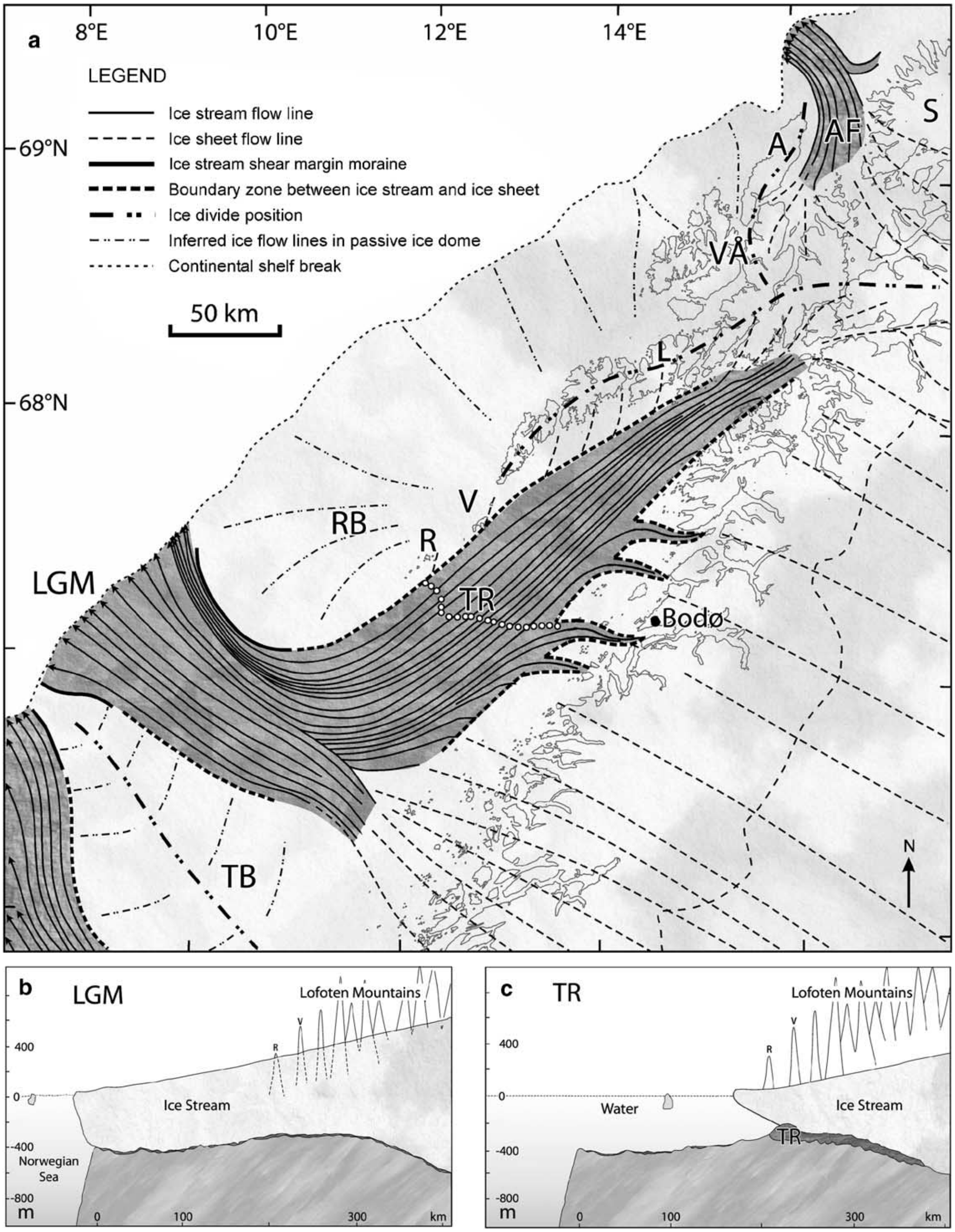

Fig. 7. (a) Ice-sheet reconstruction for the Last Glacial Maximum (LGM), with the main ice domes, ice divides and ice-stream flow lines. TB—Trænabanken, TR—Tennholmen Ridge, RB—Røstbanken, L—Lofoten, R—Røst, V—Værøy, VÅ—Vesterålen, A—Andøya, AF—Andfjorden, S—Senja. Length profile from the shelf edge to the inner Vestfjorden along the axis of Trænadjupet and Vestfjorden during (b) the LGM and (c) deglaciation with deposition of the Tennholmen Ridge.

in front of the Tennholmen Ridge (Fig. 2) and has itself a fluted surface.

The Tennholmen Ridge, located 200–300 m below sea level, crosses Vestfjorden between Bodø and Røst (Figs. 1 and 2). It is about 60 km long, up to 20 km wide and 80 m high. The ridge starts ~40 km west of Bodø, just west of the border of crystalline rocks, and ends 10 km off the island Røst. Both the bathymetry (Fig. 2) and the seismic profiles (Fig. 5) show that the ridge is composed of at least two till units. Except for the boundary between the two till sheets, no internal structures can be seen in the upper till on the seismic profiles (Fig. 5a and b). The second ridge is located 40–50 km farther northeast in Vestfjorden. This ridge, located 220–260 m below sea level, is about 30 km long and 5 km wide. Between the two ridges, there is a complex pattern of sediment lobes or tongues (Fig. 2). These forms are relatively small compared to the two main ridges, but the sediments of the tongues are part of the same unit (Fig. 5a). The two large transverse moraine ridges and the lobes are interpreted to have been deposited during the deglaciation, during a halt or advance in the general ice recession.

On Røstbanken, one distinctive ridge has been mapped (marked *a* in Fig. 6). The ridge is 60 km long, and its form is rather similar to the ice-stream, shear moraine farther out (Fig. 1). We are uncertain as to the mode of formation of this ridge, but have interpreted it to be a moraine ridge, representing the position of the ice front during deglaciation. This is based on 3D seismic data from Ottesen et al. (2005) which show that this ridge is the outermost of a series of recessional moraines on Røstbanken.

Another prominent ridge has been detected just southeast of the Lofoten islands in Vestfjorden, marked b in Fig. 6. This ridge is located parallel to and 10–15 km off the Lofoten islands (Fig. 2a). One or two other smaller ridges subparallel to the main ridge are also found in the area (Fig. 2b). We have interpreted the ridge in Vestfjorden as a terminal moraine, on the basis of its position and irregular form. The moraine ridges probably represent a minor advancing phase of the ice-front position, occurring after the ice stream disappeared from the Vestfjorden. Nygård et al. (2004) have shown that ice sourced from the adjacent land areas advanced towards the basin after the Norwegian Channel Ice Stream retreated. Raunholm et al. (2003) have also documented the same from the Jæren area in southwestern Norway.

4. Discussion

4.1. Ice-stream systems

The surrounding mountainous areas make the Vestfjorden sedimentary basin a natural drainage route for an ice stream. The Vestfjorden-Trænadjupet ice-drainage system was made up of one major ice stream flowing in Vestfjorden and continuing into the Trænadjupet trough, and fed by a complex system of tributaries. In the eastern part of Trænadjupet, ice masses from the northeast (Vestfjorden), east and southeast joined to form a major ice stream following along Trænadjupet to the shelf break (Figs. 1, 6 and 7). Fig. 4 shows glacial lineations and drumlins indicating ice flow along the fjords north of Bodø. The well-developed flow-parallel features (drumlins and mega-scale glacial lineations) indicate that this tributary had a substantial velocity when it coalesced with the ice stream in Vestfjorden. The flow lines illustrate how this tributary north of Bodø was deflected towards the southwest and assimilated into the major trunk of the Vestfjorden ice stream.

This scenario is comparable to the ice-flow pattern of the Antarctic Ice Sheet today, where each major drainage system of the ice sheet is fed by a complex system of tributaries penetrating up to hundreds of kilometres into the interior of the ice sheet (Bamber et al., 2000). For instance, a modern analogue to the full-glacial Vestfjorden-Trænadjupet ice-drainage system, although much larger, is the Lambert Glacier-Amery Ice Shelf system of East Antarctica (Hambrey, 1991; Hambrey and Dowdeswell, 1994). This system is one of the most important routes for the discharge of ice from the East Antarctic Ice Sheet, draining approximately 20% of the ice sheet. Hambrey (1991) mapped eight major flow units within the system making up the main trunk of the ice stream, and estimated the residence time of ice in the Lambert Glacier-Amery Ice Shelf system to be up to several thousand years.

Ottesen et al. (2001, 2005) reconstructed the locations of ice streams on the mid-Norwegian shelf during the LGM and pointed out that the initiation of the palaeo-ice streams was generally located just at the boundary zone between crystalline and sedimentary rocks (Fig. 1). The largest palaeo-ice stream on the North Sea margin, the >800 km long Norwegian Channel Ice Stream, was located parallel to the coast, also just outside the border zone between the crystalline and sedimentary rocks (Longva and Thorsnes, 1997; Sejrup et al., 2003).

Basal ice velocity and duration of flow are the primary parameters that control the initiation and development of ice-moulded landforms. Extremely long, mega-scale glacial lineations are therefore a product of either rapid flow for a short duration, or slower velocities over a much greater period of time (Clark, 1993). Clark argued that it is unlikely that mega-scale glacial lineations are formed by a slow process and suggested that they are formed under very rapid ice flow, either as in ice streams or by surges. The well-developed glacial lineations in Trænadjupet (Fig. 3) indicate substantial ice velocities in the palaeo-ice stream flowing out Trænadjupet. Stokes and Clark (1999) have developed criteria for identifying ice streams, and the Vestfjorden-Trænadjupet palaeo-ice stream appears to fulfil several of these, such as characteristic shape and dimensions, highly elongated bedforms and abrupt lateral margins with development of shear moraines.

4.2. Ice-sheet reconstruction during the Last Glacial Maximum

The ice-sheet configuration and flow along the Vestfjorden-Trænadjupet basin during the Last Glacial Maximum has been reconstructed (Fig. 7). The glacial lineations on the sea bed and striations over adjacent land areas, together with the large-scale topography of the sea-floor and land areas (Nordkalott Project, 1986), have been utilised in reconstructing ice-flow directions (Fig. 6). In the coastal areas along the southeastern margin of Vestfjorden, glacial striations indicate a strong regional ice flow towards the northwest. Along the eastern part of the Lofoten region, striations on outcrops of crystalline rocks indicate that ice drainage was towards the south and southwest into Vestfjorden (Andersen, 1975). The mega-scale lineations indicating fast ice flow are confined to the Vestfjorden-Trænadjupet drainage system. Ice-stream shear margin moraines indicate the positions of the border zones of the palaeo-ice streams of the area. Over Trænabanken, the presence of a passive and probably cold-based ice dome is proposed, with an ice divide trending NW–SE across the middle of Trænabanken (Fig. 7). In the depression south of the Trænabanken area, another ice stream flowed towards north–northwest (Ottesen et al., 2001; Dahlgren et al., 2002; Rise et al., 2005). Its lateral margin on Trænabanken is indicated by an ice-stream shear margin moraine near the shelf edge (Figs. 6 and 7). The Vestfjorden palaeo-ice stream border zone is located close to the eastern side of the Lofoten islands. Ice from the Lofoten islands is thought to have been effectively drained into the main ice stream in Vestfjorden. The ice divide over the Lofoten and Vesterålen islands has been reconstructed with a branch trending northwards into Vesterålen and Andøya (Fig. 7). The ice divide in the Lofoten area continued eastwards along the northern side of Ofotfjorden. It separates the Vestfjorden-Trænadjupet system from a major ice-drainage pathway from the central ice dome of northern Sweden into the Andfjorden areas (Fig. 7).

The ice configuration on the shelf outside Lofoten-Vesterålen is poorly known. Given the presence of these two major ice-drainage systems, it is inferred that the Lofoten-Vesterålen area and the surrounding shelf areas were covered by a cold-based (?) local ice cap with very slow ice flow. This implies that the ice cap was likely to have been built up mainly from local sources in the mountainous area of Lofoten and Vesterålen. The continental shelf west of Lofoten shows a very thin cover of Quaternary sediments, generally less than 20 m, and a number of areas comprise exposed bedrock (Rokoengen and Sættem, 1983). A more continuous cover of Quaternary sediments towards the shelf break suggests a more active ice-marginal zone, probably during the LGM. However, due to the poor quality of the regional bathymetry on the shelf west of Lofoten, the sea-floor morphology provides little information on past glacial processes and pathways.

During the LGM, the ice divide in central Sweden was located over a wide area with the centre as a large and complex, cold-based ice dome/divide zone east and south of the Kebnekaise mountain region (Fig. 1) and farther east across the northern part of the Baltic Sea (Ljungner, 1949; Hirvas et al., 1988; Kleman, 1990). Using this information, a total ice-sheet drainage area of nearly 150,000 km^2 in what is now Norway and Sweden can be calculated for the whole Vestfjorden-Trænadjupet ice drainage system. This drainage area is separated from the drainage system north of the Ofotfjorden, where the onset area of the Andfjorden ice-stream system is located (Vorren and Plassen, 2002) (Fig. 7). To the south, the former ice-stream catchment area reached south of 66°N. Inferred ice domes occurred on Trænabanken and Røstbanken (Ottesen et al., 2002), but these stagnant domes probably contributed very little to the total ice flux into Trænadjupet. In this period, the areal extent of the ice stream is estimated to have been about 20,000 km^2, comprising the whole area from the onset zone in Ofotfjorden/inner Vestfjorden to the shelf break.

We can use our estimate of the drainage basin area of the LGM Vestfjorden-Trænadjupet system to calculate the past velocity of the ice stream that we describe (Fig. 6). If we assume a full-glacial snow precipitation of 0.25 m $year^{-1}$ water equivalent, this gives a mass input of 37.5 km^3 $year^{-1}$ to the drainage basin. The width of fast-flowing ice at the trough mouth is about 90 km (Fig. 6). The former ice thickness at the ice-stream seaward margin was probably about 500 m, giving a cross-section for ice discharge of about 50 km^2. Using these values, a mean velocity of 0.75 km $year^{-1}$ is calculated for the former ice stream, assuming that the glacial system is in equilibrium with the imposed Quaternary climate. This value compares well with those of ice streams draining the Antarctic Ice Sheet today (Alley and Bindschadler, 2001).

4.3. Deglaciation of the shelf

The morphological indicators of past ice flow in Vestfjorden-Trænadjupet (e.g., mega-scale lineations, drumlins) suggest at least two phases of activity. The oldest–possibly from the LGM (Fig. 7b)–is indicated by glacial lineations in the outer Vestfjorden and Trænadjupet areas. The youngest phase (Fig. 7c) is related to the build-up of a large 'grounding-line' moraine (the Tennholmen Ridge) in the mid-outer Vestfjorden area.

King et al. (1987, 1991) developed a conceptual model for deposition of till and glacimarine sediments on the mid-Norwegian continental shelf (the 'till-tongue model'). Each till unit was divided into a number of sub-units, or till tongues. A till tongue consists of a wedge-shaped deposit characterised by seismically incoherent reflections ('glacial till'), commonly with thin 'stratified glacimarine sediments' deposited above.

The Tennholmen Ridge is very similar to the till tongues described by King et al. (1987, 1991) and Rokoengen and Frengstad (1999). Alley et al. (1989) described a depositional unit at the grounding line of Ice Stream B in West Antarctica, referring to it as a till delta. We suggest that the Tennholmen Ridge is an example of a depositional unit formed at the grounding line of a former ice stream, although it is not a deltaic unit in the sense described by Alley et al. (1989).

The deglaciation of the outer mid- and southern-Norwegian shelf took place approximately 15,000 ^{14}C years ago (Lehman et al., 1991; Hjelstuen et al., 2004). Based on several radiocarbon datings, Vorren and Plassen (2002) propose a deglaciation in Andfjorden at 14.7 ^{14}C ka and a subsequent glacial readvance in the same area from 13.8 to 13.2 ^{14}C ka. The deglaciation chronology of Trænadjupet and Vestfjorden is poorly constrained, but we infer that the deglaciation pattern of Vestfjorden/Trænadjupet was similar to that of Andfjorden. From our bathymetric and seismic data, there are no indications of a halt in the ice recession between the shelf edge and Vestfjorden. We suggest, therefore, that the ice withdrew rapidly to Vestfjorden, where the palaeo-ice stream deposited the Tennholmen Ridge moraine between 15,000 and 13,000 ^{14}C year BP during a still-stand or most likely a readvance. The outer coastal areas of Nordland were ice free by about 12.5 ^{14}C ka BP (Olsen, 2002), and we infer that also the inner parts of Vestfjorden were deglaciated at the same time.

5. Conclusions

1. On the basis of the sea-floor morphology derived from regional and detailed bathymetric data together with seismic profiles, the ice-drainage pathways of the shelf areas outside mid-Norway (66°–68°N) have been reconstructed, and a deglaciation history is proposed.

2. Extensive glacial lineations and related ice-flow features on the sea-floor of both Vestfjorden and Trænadjupet show that a large palaeo-ice stream fed by tributary ice from neighbouring fjords (Fig. 7) flowed towards the shelf edge in these depressions. Vestfjorden functioned as a major ice-drainage route for a large basin (about 150,000 km^2) within the Fennoscandian Ice Sheet during the Last Glacial Maximum. After the palaeo-ice stream passed the outermost Lofoten islands, it turned 90° towards NW along Trænadjupet on its way towards the shelf break. The ice stream eroded extensively into thick units of old glacial sediments and sedimentary bedrock in Trænadjupet.
3. Draining of ice through two palaeo-ice stream drainage systems, Vestfjorden-Trænadjupet and Andfjorden to the north (Fig. 7), effectively prevented ice from the central part of the Fennoscandian Ice Sheet from reaching the Lofoten-Vesterålen archipelago and the adjacent shelf. This led to a passive ice dome covering these areas during the Last Glacial Maximum. On Trænabanken, south of Trænadjupet, a passive ice dome probably existed.
4. Ice-stream shear margin moraines are found on both sides of Trænadjupet, up to 50 m high, a few kilometres wide and up to several tens of kilometres long (Fig. 6). The moraines were formed in the shear zone between the fast-flowing ice stream and the surrounding passive ice domes.
5. The inferred dimensions of the Vestfjorden-Trænadjupet palaeo-ice stream, together with estimates of the drainage basin area and accumulation rate, allow the average velocity of the ice flow to be calculated to about 750 m/year.
6. After the first break-up of the palaeo-ice stream in Vestfjorden-Trænadjupet (ca. 15,000 ^{14}C year BP), the palaeo-ice stream withdrew rapidly to Vestfjorden (Fig. 7c), where, during a halt or most likely a readvance, it deposited an up to 80 m thick unit of glacial sediments (the Tennholmen Ridge) (Fig. 5a).

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