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)

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ABSTRACT

Morphological interpretation of regional and detailed bathymetric data sets on the 2500-km-long Norwegian 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. About 20 cross-shelf troughs with megascale glacial lineations (MSGL; elongate ridges and grooves oriented parallel to trough long axes) are interpreted as former pathways for fast-flowing ice streams. Studies of large-scale margin morphology and seismic profiles have identified large submarine fans at the mouths of several major cross-shelf troughs. Less dynamic ice probably existed on shallower banks. The two largest paleo-ice streams were the Norwegian Channel Ice Stream and Bear Island Trough Ice Stream, each 150–200 km wide at the mouth. The lengths of individual MSGL vary from hundreds of meters to several tens of kilometers, and the distance between ridges varies from 0.1 to 3 km. MSGL amplitudes reach 15 m, but are commonly <10 m. The onset of MSGL and, hence, fast ice flow is generally close to the outer coast, at the border zone between crystalline rocks and softer sedimentary rocks. Transverse submarine ridges on various scales, commonly parallel to the shelf edge, reflect either the maximum ice-sheet position or the recessional pattern of the ice sheet. Lateral ice-stream moraines several tens of kilometers long have also been mapped along the sides of several cross-shelf troughs, identifying the border zone between fast ice flow and stagnant or slow-flowing ice on intervening banks.

Keywords: Barents Sea Ice Sheet, Scandinavian Ice Sheet, glacial lineations, ice flow, ice-sheet dynamics, paleo-ice stream, seafloor morphology.

INTRODUCTION

Fast-flowing ice streams and outlet glaciers are responsible for ~80%–90% of mass transfer to the margins of the huge ice-sheet drainage basins of Antarctica and Greenland (e.g., Bentley, 1987). These ice streams, commonly tens of kilometers in width and up to hundreds of kilometers in length, are typical features of modern ice-sheet dynamics (e.g., Fahnestock and Bamber, 2001; Whillans et al., 2001). The fast-flowing units are separated from slower-flowing ice by marked shear zones with high-velocity gradient (e.g., Bentley, 1987; Bindschadler et al., 1996). During the Quaternary, ice sheets also developed over western Eurasia during a number of cold, glacial stages (e.g., Svensen et al., 1999; Boulton et al., 2001; Dyke et al., 2002; Mangerud et al., 2002). There is increasing evidence that these ice sheets too were drained preferentially by fast-flowing ice streams set within slower-moving ice that was commonly frozen to its bed (e.g., Dowdeswell and Siegert, 1999). The presence of fast-flowing ice streams within Quaternary ice sheets has been inferred from observations of large-scale streamlined sedimentary features using satellite imagery of the land surface (e.g., Boulton and Clark, 1990; Stokes and Clark, 2001) and, more recently, marine-geophysical observations of the seafloor (e.g., Longva and Thorsnes, 1997; Shipp et al., 1999; Canals et al., 2000, 2002; Ó Cofaigh et al., 2002; Dowdeswell et al., 2004). The increasing spatial resolution of numerical models of ice sheets means that the models are now able to resolve ice streams a few tens of kilometers wide, but geological evidence is also required to pinpoint the past locations and dimensions of this fast-flowing ice.

In this paper, we present and interpret marine-geophysical data from the continental shelf and slope west of the 5.5 million km² late Weichselian Eurasian Ice Sheet (Siegert and Dowdeswell, 2002), which extended from the North Sea, northward over the Norwegian and Barents Sea continental shelves, to the western and northern margins of Svalbard (e.g., Landvik et al., 1998; Mangerud et al., 1998; Ó Cofaigh et al., 2002; Svendsen et al., 1999, 2004). Here we term this entire area, from 57° to 80°N, the Norwegian margin (Fig. 1). We have used observations of the detailed form of the seafloor covering ~75,000 km² on the 2500-km-long western margin of this former ice sheet. Submarine landforms diagnostic of fast-ice-stream flow and also relating to ice retreat during deglaciation are used to reconstruct the spatial pattern of past ice-sheet flow along this extensive former ice-sheet margin. First we describe and interpret the geomorphology of specific seafloor landforms and their bathymetric setting, which is derived mainly from high-resolution swath-bathymetric and three-dimensional seismic data sets. We then outline the distribution of these submarine landforms along the continental margin and discuss their implications for the ice-flow dynamics of the western side of the Late Quaternary Eurasian Ice Sheet.

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QUATERNARY BACKGROUND

Glacier-Influenced Submarine Fans on the Continental Margin

Ice sheets have been a major source of sediments to the Eurasian continental margins over the last 2 million years or so (Jansen and Sjøholm, 1991; Rokoengen et al., 1995; Butt et al., 2000; Rise et al., 2005). During a series of glacial-interglacial cycles, ice sheets built up over Svalbard, the Barents Sea, and Scandinavia. During full-glacial conditions, when these ice sheets reached the continental shelf break, sediment delivery to the upper continental slope increased rapidly (Elverhøi et al., 1998; Dowdeswell and Siegert, 1999; Sejrup et al., 2003). By contrast, deposition in interglacials, such as the Holocene, comprised mainly slow hemipelagic sedimentation (e.g., Andersen et al., 1996). The existence of large submarine fans, located at the mouths of major cross-shelf troughs and fjords, also implies that sediment delivery was not uniform along the ice-sheet margin (Dowdeswell et al., 1996; Vorren et al., 1998). These fans include the North Sea Fan (King et al., 1996), several depocenters off the Norwegian shelf (e.g., King et al., 1987; Dahlgren et al., 2002; Henriksen and Vorren, 1996; Rise et al., 2005), the Bear Island and Storfjorden fans offshore of the Barents Sea (Vorren et al., 1998; Hjelstuen et al., 1996), and a series of smaller fans west of Svalbard (Elverhøi et al., 1998; Dowdeswell and Elverhøi, 2002). The fans have been ascribed to the delivery of sediments to the continental margin by fast-flowing ice streams located predominantly in large cross-shelf troughs (Dowdeswell et al., 1996; Vorren et al., 1998; Dowdeswell and Siegert, 1999). However, until the acquisition of detailed bathymetric data from the continental shelves themselves, there was little direct evidence for...
rapid ice flow. The presence of large-scale seafloor sedimentary lineations, oriented parallel to the long axes of cross-shelf troughs, is now regarded as compelling evidence of the former presence of fast-flowing ice streams (e.g., Shipp et al., 1999; Stokes and Clark, 1999; Canals et al., 2000; O Cofaigh et al., 2002; Ottesen et al., 2002; Dowdeswell et al., 2004). Indeed, three-dimensional reflection-seismic data sets also show large-scale lineations at the surface of buried units in the Quaternary stratigraphic record (Rauflesen et al., 2002; Andreassen et al., 2004; Rise et al., 2004).

**Latest Quaternary History of the Scandinavian, Barents Sea, and Svalbard Margin**

The submarine landforms we investigate are inferred to be a product of the action of ice on the seafloor sedimentary. Dated cores from the Skagerrak at 58°N to the western and northern margins of Svalbard at 80°N demonstrate several points that are important for our study (e.g., Lehman et al., 1991; Svendsen et al., 1992; Knudsen et al., 1996; Rokoengen and Frengstad, 1999; Koc et al., 2002, Landvik et al., 2005). First, massive diamictic sediments, commonly containing stones with glacially striated and faceted surfaces, are found on the continental shelves and in the troughs and outer fjords of the area (Rokoengen and Frengstad, 1999; Nygård et al., 2004). This indicates that the ice sheet advanced through fjords, onto the continental shelf and to the shelf edge along the entire margin during the last (late Weichselian) glaciation, which reached a maximum possibly slightly before 18,000 yr B.P. Where radiocarbon dates have been obtained from below the diamictic sediments, they indicate ages older than ~30,000 yr B.P. The chronostratigraphy of the entire margin supports ice advance after 30,000 yr ago (e.g., Andersen et al., 1996; Landvik et al., 1998; Mangerud et al., 1998; Sejrup et al., 2000). Second, deglaciation along this margin took place from ~15,000 yr B.P. on the outer shelf, according to the dated onset of glacialmarine and then open-marine sedimentation. Fjords and troughs, such as Isfjorden and Kongsfjorden in Svalbard, Andfjorden, and Vestfjorden in northern Norway and the Skagerrak in the southernmost part of our study area were deglaciated by 13,000, 14,000–15,000, and 14,000–15,000 yr B.P., respectively (Svendsen et al., 1992; Knudsen et al., 1996; Vorren and Plassen, 2002; Landvik et al., 2005). From these briefly summarized chronostratigraphic data, we conclude that the seafloor sediments and landforms that we describe are related to the action of late Weichselian ice.

**DATA ACQUISITION AND METHODS**

Several data sets provide information on the morphology of the continental shelf, beginning in the south from the Skagerrak and Norwegian Channel, on the continental shelf west of Norway, the Barents Sea and Svalbard, and concluding with the area north of Svalbard (Fig. 1).

First, 100 kHz single-beam echo-sounder data collected by the Norwegian Hydrographic Service (NHS) between 1965 and 1985 have been used to produce a regional bathymetry of the area. The echo-sounder data have an average line spacing of 500 m and, accordingly, bathymetric values were gridded at a cell size of 500 m. These data are plotted as colored contour maps (10 m contour interval) or as shaded relief maps. Where regional single-beam echo-sounder data are lacking or of poor quality, bathymetric information has been augmented by digital two-dimensional seismic lines. This is mainly in the southern part of the Norwegian sector of the North Sea Plateau and in parts of the Barents Sea.

Several other types of geophysical data are available for parts of the continental margin. These include swath-bathymetric and three-dimensional (3D) seismic imagery with a much higher resolution (3–50 m grid-cell size) than the single-beam echo-sounder data (Table 1).

The navigational control on these data sets is a few meters or better, being derived from differential GPS. In total, an area of ~75,000 km² is covered with detailed bathymetric or other seafloor mapping data (Table 1).

With swath-bathymetric data were acquired using Kongsberg Simrad EM-100 and EM-1002 systems. 3D seismic-reflection data are available from five different areas covering ~15,000 km² (Table 1). They have line spacings of 12.5 m, 25 m, or 50 m. These data were gridded with a cell size of 25 m or 50 m. One data set (2460 km²) is made up of four 3D seismic surveys from the Norwegian Channel between 61°N and 62°N (BNP9401, NI9405, NI9202, and SG9603M). Further data sets were obtained from two parts of the Froybankhola and southern Haltenbanken (810 km²) and from Skjoldlydørgen (10,000 km²) and Trænadjupet (1000 km²). Results from two 3D seismic surveys from the southern Barents Sea were provided by Andreassen et al. (2004).

In addition, ~30,000 km² of side-scan sonar data have been collected by the NHS in the years 1982–1985 (Table 1). Of this, 25,000 km² covered parts of the Norwegian Channel and the northeastern North Sea Plateau outside southwestNorway in water depths between 65 m and 360 m (Ottesen et al., 2000). On Rostbanken, a further 4000 km² of side-scan sonar data from NHS has been interpreted. The data sets comprise north-south-oriented lines with a line spacing of 500 m. The side-scan sonar used was a Klein 531T, operated at 50 kHz and displaying 300 m of the seafloor on each side of the towed fish.

**SEAFLOOR MORPHOLOGY**

Detailed marine-geophysical observations of submarine morphology have been examined systematically for the presence of seafloor topographic features linked to the former presence of ice sheets on the continental shelves of the North and Norwegian Seas. We now describe

<p>| TABLE 1. MARINE-GEOPHYSICAL DATA SETS USED IN THIS STUDY |</p>
<table>
<thead>
<tr>
<th>AREA NO.</th>
<th>AREA NAME</th>
<th>AREA (KM²)</th>
<th>DATA SOURCE</th>
<th>CELL SIZE (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Skagerrak</td>
<td>8000</td>
<td>EM100/EM1002</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>Norwegian Channel/North Sea Plateau</td>
<td>25,000</td>
<td>Side-scan sonar</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>Norwegian Channel</td>
<td>1300</td>
<td>EM100</td>
<td>50</td>
</tr>
<tr>
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<td>Norwegian Channel west of Norway</td>
<td>2480</td>
<td>3D seismic</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>Buagrunnen</td>
<td>1000</td>
<td>3D seismic</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>Froybankhola</td>
<td>270</td>
<td>EM1002</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>Haltenbanken south</td>
<td>540</td>
<td>3D seismic</td>
<td>25</td>
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<td>8</td>
<td>Sula Ridge</td>
<td>210</td>
<td>EM1002</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Skjoldlydørgen</td>
<td>10,000</td>
<td>3D seismic</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>Outer Trænadjupet</td>
<td>300</td>
<td>EM1002</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>Trænadjupet</td>
<td>1000</td>
<td>EM1002</td>
<td>5</td>
</tr>
<tr>
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<td>Trænadjupet</td>
<td>1640</td>
<td>3D seismic</td>
<td>25</td>
</tr>
<tr>
<td>13</td>
<td>Røstbanken</td>
<td>4000</td>
<td>Side-scan sonar</td>
<td>–</td>
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<tr>
<td>14</td>
<td>Vestfjorden</td>
<td>8500</td>
<td>EM100</td>
<td>50</td>
</tr>
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<td>15</td>
<td>Andfjorden</td>
<td>800</td>
<td>EM1002</td>
<td>50</td>
</tr>
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<td>16</td>
<td>Svalbard West</td>
<td>5600</td>
<td>EM1002</td>
<td>50</td>
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<tr>
<td>17</td>
<td>Svalbard North</td>
<td>700</td>
<td>EM1002</td>
<td>50</td>
</tr>
<tr>
<td>18</td>
<td>Svalbard East</td>
<td>3000</td>
<td>EM1002</td>
<td>50</td>
</tr>
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</table>

Note: Swath bathymetric data are labelled EM, followed by a number representing the particular Kongsberg system used.
the morphology and spatial pattern of a series of submarine landforms that are regarded as diagnostic of the presence of grounded glacier ice in general and, in several cases, of fast glacier flow in particular.

Megascale Lineations

Description

Lineations in seafloor sediments are observed in a series of shelf troughs as well as in several outer fjords along the continental Norwegian and Svalbard coasts. The streamlined lineations are elongated in the direction of the long axis of the depressions. They range in length from hundreds of meters to several tens of kilometers (Table 2). Their wavelengths vary from 0.1 km to 3 km and amplitude up to 15 m. Several examples of seafloor lineations in troughs and fjords along the Norwegian margin are shown in Figure 2. The locations of these sets of lineations are drawn along the entire length of the margin, from the Skagerrak and Norwegian Channel (58°–59°N), Frøybankhola (64°N), Trenadjupet (67°N), and Wijdefjorden-Woodfjorden in northern Svalbard (80°N). The features occur in fjords, in cross-shelf troughs, and at trough margins close to the shelf break. In each case, there is evidence in the form of acoustic-stratigraphic records to demonstrate that the features are sedimentary bedforms rather than sculpted bedrock forms. One example of lineations from side-scan sonar data provides a comparison with sea bed. This transition from irregular crystalline rock to sedimentary seafloor and its association with the onset of seafloor lineation is also illustrated from swath bathymetry of the inner Skagerrak and Andfjorden (Figs. 2A and 3). In these locations, streamlined bedrock interspersed with smoothed or drumlinized sediments is replaced downstream by megascale lineations in a sedimentary sea bed. This transition from irregular crystalline bedrock to streamlined sedimentary bedforms can be found at several locations outside the Norwegian coast. Some large northwest-trending crag and tail ridges are evident southwest of Bergen (Fig. 1A). Similar observations on landform transition associated with changing bed substrate have also been reported from several parts of the Antarctic continental margin (e.g., Wellner et al., 2001; O’Coifaigh et al., 2002).

Interpretation

The streamlined lineations described above are similar morphologically to landforms described as megascopic glacial lineations (Clark, 1993; Stokes and Clark, 1999) or bundle structures (Canals et al., 2000, 2002). We use the former term here. The lineations appear to result from soft-sediment deformation at the base of fast-flowing ice streams that are draining large ice sheets (Tulaczyk et al., 2001; Dowdeswell et al., 2004). Such features have been observed from a number of cross-shelf troughs in Antarctica, including several off the Antarctic Peninsula and in the Ross Sea (Domack et al., 1999; Shipp et al., 1999, 2002; Canals et al., 2000, 2002; Wellner et al., 2001; O’Coifaigh et al., 2002; Dowdeswell et al., 2004). They have also been reported from the mid-Norwegian shelf (Ottesen et al., 2002) and have been observed on satellite imagery of parts of northern Canada (Clark, 1993). A hypothesis for their formation relates to the action of so-called keels, formed at the ice-stream base in the lee of bed obstructions (Tulaczyk et al., 2001).

The distribution of the sets of lineations we observe from the Norwegian margin is consistent with it having an origin beneath grounded glacier ice. The locations of lineation sets in troughs and fjords is linked to relatively thick ice, which would reach the pressure melting point before thinner ice on adjacent shallow banks (Paterson, 1994; Dowdeswell and Siegert, 1999). A regime of basal melting and, potentially, sediment deformation would thus be expected. The observed patterns of convergence and divergence take place, respectively, at the confluence of fjords (Figs. 2A and 3A) and where a fjord reaches a setting less constrained

<table>
<thead>
<tr>
<th>Area</th>
<th>Data source</th>
<th>Type of lineations</th>
<th>Length (km)</th>
<th>Average distance between ridge crests (m)</th>
<th>Average ridge width (m)</th>
<th>Ridge height max (m)</th>
<th>Ridge height average (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skagerrak</td>
<td>mbb</td>
<td>msgl</td>
<td>&gt;10</td>
<td>200–600</td>
<td>150–400</td>
<td>12</td>
<td>2–5</td>
</tr>
<tr>
<td>NE North Sea Plateau</td>
<td>sss</td>
<td>msgl</td>
<td>N.D.</td>
<td>100–500</td>
<td>?</td>
<td>&lt;10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Frøybankhola</td>
<td>mbb</td>
<td>msgl</td>
<td>&gt;5</td>
<td>300</td>
<td>150</td>
<td>8</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Haltenbanken south</td>
<td>3D seis.</td>
<td>msgl</td>
<td>max 9</td>
<td>220</td>
<td>120</td>
<td>5–10</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Sula Ridge</td>
<td>mbb</td>
<td>msgl</td>
<td>max 5</td>
<td>300</td>
<td>150</td>
<td>15</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Northeast of Skjoldryggen</td>
<td>3D seis.</td>
<td>msgl</td>
<td>&gt;15</td>
<td>260</td>
<td>170</td>
<td>10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Trenadjupet</td>
<td>3D seis.</td>
<td>msgl</td>
<td>&gt;10</td>
<td>400–500</td>
<td>250</td>
<td>10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Wijdefjorden</td>
<td>mbb</td>
<td>drumlins</td>
<td>max 7</td>
<td>500</td>
<td>200–400</td>
<td>25</td>
<td>5–15</td>
</tr>
<tr>
<td>Andfjorden</td>
<td>mbb</td>
<td>msgl</td>
<td>max 13</td>
<td>370</td>
<td>210</td>
<td>5</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Andfjorden</td>
<td>mbb</td>
<td>drumlins</td>
<td>max 5</td>
<td>850</td>
<td>310</td>
<td>15</td>
<td>&lt;7</td>
</tr>
<tr>
<td>Barents Sea</td>
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<td>msgl</td>
<td>max 35</td>
<td>3700</td>
<td>3000</td>
<td>10</td>
<td>N.D.</td>
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<td>Isfjorden, Svalbard</td>
<td>mbb</td>
<td>msgl</td>
<td>&gt;5</td>
<td>500–700</td>
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<td>8</td>
<td>&lt;5</td>
</tr>
<tr>
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<td>mbb</td>
<td>msgl</td>
<td>&gt;4</td>
<td>450–800</td>
<td>410–470</td>
<td>10</td>
<td>2–5</td>
</tr>
<tr>
<td>Wijdefjorden, northern Svalbard</td>
<td>mbb</td>
<td>msgl</td>
<td>max 5</td>
<td>480</td>
<td>260</td>
<td>10</td>
<td>2–4</td>
</tr>
</tbody>
</table>

Note: mbb—multibeam bathymetry; sbb—single beam bathymetry; msgl—megascale lineations; sss—side-scan sonar.
Figure 2. Megascale glacial lineations (MSGL) on the Norwegian margin (see Fig. 1 for locations). (A) EM100 shaded-relief image of the seafloor of the inner part of Skagerrak. MSGL (white lines) appear in a convergent pattern after crossing the border zone between the crystalline and sedimentary rocks (stippled line). This area represents the onset zone for the Norwegian Channel Ice Stream. Water depths between 300 m and 700 m.

(B) EM1002 shaded-relief image of an area on the outer mid-Norwegian shelf. The shelf edge marks the headwall of the Storegga Slide. MSGL oriented toward the WNW are found in the trough where the seafloor has been protected against iceberg scouring. The glacial lineations have a maximum height of 8 m and the distance between the ridges is on average 300 m. (C) Shaded-relief image of the seafloor of Trænadjupet from 3D seismics. Extensive megascale glacial lineations are parallel to the axis of the Trænadjupet. Maximum height of the ridges is 10 m and the average spacing is 400–500 m. (D) EM1002 shaded-relief image of the seafloor of outer Wijdefjorden (Wi) and Woodfjorden on the northern side of Svalbard. MSGL (arrows) follow the long axis of Wijdefjorden, whereas the lineations in Woodfjorden diverge around the island of Moffen. Maximum water depth is 200 m. (E) 50 kHz side-scan sonar image of the seafloor of the North Sea Plateau adjacent to the Norwegian Channel. MSGL are oriented toward the WNW. Such features are found in a large area along the southern flank of the Norwegian Channel (Fig. 12A).
PALEO-ICE STREAMS ALONG THE NORWEGIAN-SVALBARD MARGIN

by valley-side topography (Figs. 2D and 5). Such convergence and divergence of flow is observed in many modern ice masses in similar topographic settings.

Ridges Parallel to Inferred Ice-Flow Direction

Description

Individual linear ridges of tens of kilometers in length and up to 50 m in relative elevation have been observed running along the lateral margins of cross-shelf troughs. The ridges occur on either one side of a trough or sometimes as pairs on both sides. There is little acoustic penetration of these lateral ridges by subbottom profilers, suggesting they may be made up of coarse diamictic sediments. Examples of these lateral ridges are given from the mouths of Isfjorden and Kongsfjorden troughs, as they approach the shelf break west of Svalbard (Fig. 6) and from along both sides of Trennadjupet (Ottesen et al., 2002) (Fig. 7). The ridges are major topographic features, extending up to 50 m above the surrounding topography. Beyond the trough mouths at the edge of prograding continental shelves, low-gradient submarine fans are found on the continental slope (Fig. 6A) (e.g., Boulton, 1990; Dowdeswell et al., 1996; King et al., 1996; Vorren and Laberg, 1997; Elverhøi et al., 1998; Dowdeswell and Elverhøi, 2002).

In addition to these lateral ridges, some very long and wide ridges are observed in the bottom of the outer part of the Norwegian Channel, subparallel to the channel axis. The ridges are up to 200 km long, sometimes over 50 m high, and spaced ~20–30 km apart; one is ~400 km in length (Fig. 1A). Seismic data show that these features are formed in late Weichselian till.

Interpretation

The extensive lateral ridges are interpreted to be glacier-derived moraine systems that delimit the lateral margins of fast-flowing former ice streams. They are found in association with the trough-floor megascale glacial lineations described above. Similar features have also been described from terrestrial settings in the Canadian Arctic that are also regarded as former ice streams draining parts of the late Wisconsinan North American Ice Sheet (Dyke and Morris, 1988; Boulton and Clark, 1990; Stokes and Clark, 2001). In both the examples we describe from the Norwegian margin and those from North America, megascale lineations are not found beyond the lateral moraine ridges, which thus appear to mark the boundaries of fast-ice-stream flow.

The formation of these ridges is presumably linked to the shear zone and high stress gradient between fast- and slow-flowing ice at ice-stream lateral margins (e.g., Bentley, 1987). Stokes and Clark (2001), in discussing the geomorphic criteria diagnostic of paleo-ice streams, note that these ridges are not always present in the geological record, and it is their spatial association with megascale lineations that is of particular significance for paleoenvironmental interpretation. It should be noted that swath-bathymetric imagery of a number of paleo-ice streams on the continental shelves of Antarctica has not revealed the presence of clearly defined lateral ridges (e.g., Shipp et al., 1999, 2002; Canals et al., 2000; Ó Cofaigh et al., 2002).

The very large longitudinal ridges in the Norwegian Channel are oriented along the channel axis and are also inferred to represent the direction of past ice flow. The fact that a number of the medium long ridges begin at the mouths

Figure 3. Geomorphic evidence of convergent ice flow (locations in Fig. 1A). (A) EM100 shaded-relief swath bathymetry of two sets of streamlined subglacial bedforms in Vestfjorden. The first bedform set is oriented in a NE-SW direction (upper left part of image), representing the main flow of the paleo-ice stream in Vestfjorden. A second set represents ice flow from the fjords around Bodo into Vestfjorden from the east (dotted lines). This ice was then deflected and assimilated into the main trunk of the paleo-ice stream in Vestfjorden. Stippled line marks the border between crystalline rocks (east) and sedimentary rocks (west). (B) Single-beam echo-sounder data (line spacing 500 m) from Sklinnadjupet, mid-Norwegian shelf. Large streamlined subglacial bedforms representing convergent ice flow from the northeast, east, and southeast into Sklinnadjupet (white lines). The height of the ridges is up to 40 m and the width up to 4 km. Stippled line marks the border between the crystalline rocks (east) and sedimentary rocks (west). SK—Sklinnadjupet; SB—Sklinnabanken. Water depths between 130 m and 450 m.
of fjord systems entering the channel and are deflected to the north with distance from the fjord mouth suggests that they may be associated with processes at the ice base where ice flowing from individual fjords joins the main Norwegian Channel Ice Stream.

**Transverse Ridges**

**Description**

Seafloor ridges oriented transverse to the direction of former ice flow and, therefore, generally parallel to the continental shelf edge are located in two principal settings on the Norwegian margin. The first is either at or close to the shelf break. These ridges, commonly tens of meters in relative height and up to more than 100 km in length, are exemplified by the Skjoldryggen ridge at the edge of the mid-Norwegian shelf (Fig. 8A) and ridges on the outer shelf west of Prins Karls Forland, Svalbard (Fig. 8C).

A second setting for transverse ridges is inshore of the shelf break, where series of ridges are formed inshore of shelf-edge features. The complex of transverse ridges, organized in a subparallel pattern southeast of Skjoldryggen, is probably the best-developed example on the Norwegian margin (Fig. 9A). Similar sets of transverse ridges are illustrated by those on the northern side of Trenadjupet (Fig. 9B). Approximately 50 ridges are mapped from the data set, the largest reaching a maximum height of 20 m. The average spacing between the ridges is 800 m, and the width of each ridge is 400–800 m. In Vestfjorden, several transverse ridges have a more lobate form (Fig. 9C). These lobate moraine features are developed in a till sheet deposited during deglaciation (~13,000–14,000 yr B.P.) and comprise up to 100 m of sediments (Fig. 9C). The largest ridge has a width of up to 20 km and a length of ~60 km.

A variant of transverse-ridge features is found within a few kilometers of many tidewater glaciers in Svalbard. Here, the ridges commonly take an arcuate form, in some cases conforming broadly to the shape of the modern ice front. We use the seafloor morphology in front of Hinlopen Glacier, an 8-km-wide, 25-km-long, ice-cap glacier in northeastern Spitsbergen, to illustrate such features (Fig. 10), although a number of other examples from around Svalbard have similar characteristics.

**Interpretation**

Ridges at or near the shelf break are interpreted to be terminal moraines recording the furthest advance of full-glacial ice across the continental shelf. These terminal moraines are commonly observed in the areas of the margin between large submarine fans, where full-glacial sedimentation rates are relatively low (Elverhøi et al., 1998). They have been used to infer the presence of an ice margin that is not fast flowing (Dowdeswell and Elverhøi, 2002; Landvik et al., 2005). Alternatively, they may form on prograding margin sediments, but at times when fast ice flow and rapid sediment delivery may have ceased. An example of this type of setting is the Skjoldryggen area on the mid-Norwegian shelf (Dahlgren et al., 2002; Rise et al., 2005). Ridges inshore of such terminal moraines are inferred to be moraines or series of moraines that record stillstands or ice-front oscillations during retreat of the ice margin during deglaciation (Nygård et al., 2004). The moraines southeast of Skjoldryggen, including at least 50 clearly defined ridges up to 20 m high, 35 km long, and covering an area of ~500 km², are an excellent example of such a retreat sequence (Fig. 9A).

Arcuate ridges, formed within a few kilometers of the present margins of tidewater glaciers in Svalbard, are interpreted as submarine terminal moraines (Fig. 10). These moraines mark the maximum extent of a previous ice advance. In the Svalbard case, these features record the ice-front positions at the height of the cold period known as the Little Ice Age ~100 yr ago (e.g., Liestol, 1976; Sexton et al., 1992). Indeed, high-resolution side-scan sonar investigations of seafloor morphology between such terminal moraines and the present glacier front have imaged series of much smaller moraine ridges (<1 m high), which are interpreted as annual moraines marking small winter readvances punctuating retreat during each summer (Sharp, 1984; Boulton, 1986; Whittington et al., 1997).
Larger sets of retreat ridges have been reported by Shipp et al. (2002) from a trough in the Ross Sea, Antarctica, which record sequential retreat over several thousands years.

Glaciotectonic Submarine Landforms

Description

Sets of so-called hill-hole pairs are found on the seafloor in a number of areas of the Norwegian margin (Fig. 11). They exhibit topographic depressions (holes) about the same size as the positive relief (hill). The so-called hill is commonly arcuate and concave in the direction of former ice flow and lies downflow of the depression (Sættem, 1990). The features we observe cover areas of up to 800 km² in the Skagerrak, and the hills have amplitudes of up to 30 m but are normally less than 15 m. The depressions may be up to 30 m deep but are normally less than 20 m deep. Our observations suggest that hill-hole pairs tend not to be associated with landform suites interpreted to be indicative of fast glacier flow. Examples from the north side of the Skagerrak and east of Skjoldryggen on the mid-Norwegian shelf are shown (Fig. 11). These landforms characteristically form in sets where the hill-hole axis is subparallel to the inferred direction of ice flow. The overall appearance of the seafloor east of the Skjoldryggen Moraine Ridge, with large depressions and ridges (Fig. 8A), indicates that most of the area (~3000 km²) has been influenced by glaciotectonic processes.

Interpretation

The sedimentology and structural geology of hill-hole pairs have been examined in detail in terrestrial locations at, for example, the margin of the former North American ice sheet in the Canadian Prairies (Moran et al., 1980). The submarine landforms we report here are almost identical in form to these terrestrial features. On land, the hills are made up of thrust-block moraines apparently formed at former ice margins and the holes are the source region, which can be up to a few kilometers upflow. Compresive subglacial stresses, leading to tectonism, are thought to be induced by basal freezing close to thin ice-sheet margins (Moran et al., 1980). If overridden by subsequent ice readvance, the features may be streamlined. Sættem (1990) has also argued that freezing of water on to the base of the ice may drain excess pore water from subglacial fine-grained sediments and lead to overconsolidation and tectonism. This is demonstrated in samples from geotechnical borings in the Skjoldryggen area (Sættem et al., 1996). Christoffersen and Tulaczyk (2003) have proposed a similar theory of basal freeze-on to induce water-pressure changes that curtail fast ice-stream flow in modern ice sheets.
Figure 6. (A) Regional bathymetry (single-beam echo sounder) of the major fjords and shelf off western Svalbard. The three major ice-drainage systems are shown: Kongsfjorden and Kongsfjordrenna, Isfjorden and Isfjordrenna, and the Van Mijenfjorden (vM)–Van Keulenfjorden (vK)–Bellsund system. Each topographic trough continues from the fjords across the shelf to the shelf edge. PKF—Prins Karls Forland. (B) Lateral ice-stream ridge along the southern side of Kongsfjorden trough from EM1002 swath bathymetry. The ridge is ~5 km wide and rises up to 50 m above the surrounding area. Several smaller transverse moraine ridges are seen on the shelf south of the ridge. Water depths between 50 and 250 m (2 m depth contours).

Figure 7. Color shaded-relief bathymetry of the Vestfjorden (V)–Trænadjupet (T) paleo-ice stream drainage system. Due to the high mountains of the Lofoten Islands (L), the paleo-ice stream followed Vestfjorden toward the SW and turned 90° toward the NW after passing the outermost islands of Lofoten. MSGL are present on the seafloor (Fig. 2C, 3A, and 9C). Lateral ice-stream moraines on both sides of Trænadjupet are indicated with arrows. TB—Trænabanken; RB—Røstbanken.
Figure 8. Submarine ridges oriented transverse to ice flow. (A) Single-beam echo sounder data (500 m cell size) showing Skjoldroyggen (SR) (located in Fig. 1A), the largest moraine ridge on the Norwegian shelf. The ridge is 150 km long, 10 km wide, and up to 200 m high. (B) Seismic profile crossing Skjoldroyggen and down the slope onto the Voring Plateau. Skjoldroyggen comprises Weichselian sediments deposited above up to 200-m-thick Saalian sediments (second last glaciation). The Elsterian (third-last glaciation) eroded many of the westward-dipping Naust units in this area, and deposited the glacial debris mainly west of the present shelf edge (Skjoldroyggen). The three last glaciations deposited up to 500 m of sediments in this area. The Base Naust horizon represents the onset of major Late Plio-Pleistocene progradation of the shelf, probably mainly controlled by glaciations. (C) Moraine ridge complex (the Forlandet moraine complex, Landvik et al., 2005) (marked with arrows) on the shelf west of Prins Karls Forland, Svalbard (for location see Fig. 6A). East of the ridge complex, large depressions exist, possibly formed by glaciotectonic processes below the ice near the ice front. This north-south-trending ridge complex exists on most of the shelf between Kongsfjorden and Isfjorden and was probably formed during the Last Glacial Maximum (LGM). Maximum height of the ridge is 30 m. East of the large depressions, several minor moraine ridges are present. Water depths between 70 and 220 m.
Figure 9. Transverse submarine ridges located in shelf and fjord settings. (A) 3D seismic data from south and east of the Skjoldryggen moraine ridge (see Fig. 1A for location). A suite of recessional moraine ridges illustrates the general pattern of ice-sheet retreat from west to east. The average spacing between the ridges is 650 m and the ridge-width varies between 300 and 600 m. Maximum ridge height is 20 m. Water depth is between 290 and 320 m. (B) 3D seismic data from Røstbanken, north of Trænadjupet (for location see Fig. 7). A suite of recessional moraines illustrates the general retreat pattern of the ice sheet on the shelf southwest of the Lofoten Islands. This retreat probably started just after the Vestfjorden-Trænadjupet Ice Stream disappeared from Trænadjupet (13,000–15,000 yr B.P.). The average spacing between the ridges is 800 m, and each ridge has a width between 400 and 800 m. Maximum ridge height is 15 m. (C) Swath bathymetry of the outer part of Vestfjorden (for location see Fig. 7) showing several moraine ridges or lobes. The largest, informally named the Tennholmen Ridge (TR), is up to 100 m high, 20 km wide, and 60 km long. On top of the lobes, extensive MSGL are found with directions parallel to the axis of Vestfjorden. This till unit was deposited during deglaciation period 15,000–13,000 yr B.P. Below and in front of TR a till surface with extensive MSGL is found. This surface was probably formed during the LGM, when the paleo-ice stream extended to the shelf edge. Three systems of drumlins/megascale lineations coming from the east and turning toward the SW (marked with arrows) provide evidence of ice flow from different fjords into the main paleo-ice stream in Vestfjorden. (D) The inset seismic profile shows the outer part of the acoustically incoherent Tennholmen Ridge.
clear. Megascale lineations are also well developed in the Vestfjorden–Trænadjupet system in northern Norway and in a number of Svalbard fjords for which we have high-resolution seafloor data. Elsewhere on the mid-Norwegian shelf where high-resolution seafloor mapping has been undertaken, streamlined linear features are also found in the troughs of Suladjupet and Sklimnadjupet (Fig. 12). Locally, wide ridges up to 100 km long are also observed at the lateral margins of cross-shelf troughs (Figs. 6, 7, and 12), although paired ridges on both sides of a trough or outer fjord are rare.

Large transverse ridges are also present at a number of locations on the shelves and outer fjords of the Norwegian margin (Figs. 8 and 12). In several areas, such as the mid-Norwegian and western Svalbard shelves, they are present on the outer shelf, locally close to the shelf break. Where they are colocated with megascale lineations, for example in Vestfjorden (Figs. 9C and 12), they tend to overlie the latter stratigraphically. In addition, sets of hill-hole pairs are usually, but not exclusively, located beyond the boundaries of several well-developed areas of megascale lineations.

**INTERPRETATION OF PAST ICE-SHEET FLOW**

The distribution of submarine landforms shown in Figures 1 and 12 is used to infer the pattern of late Weichselian ice flow on the Norwegian margin (Fig. 13). Megascale glacial lineations are interpreted as indicators of the fast flow of former ice streams. These streamlined sedimentary bedforms are found in most of the major troughs crossing the Norwegian continental shelf and in many of the larger fjord systems (e.g., Vestfjorden and Andfjorden in northern Norway).

Ottesen et al. (2001) have predicted the distribution of fast-flowing ice along southern and western Norway, and this pattern has been extended along the 2500-km-long Norwegian margin as shown in Figure 13. We cannot be sure that all these ice streams were active under late Weichselian full-glacial conditions, but the chronological control that is available along the margin suggests that this is probably the case. Changing sedimentation rates along the Svalbard margin between ~30,000 yr ago and the Holocene also support this view, indicating that fast ice-stream flow in the cross-shelf trough beyond Isfjorden began during ice advance at ~22,000 yr B.P. and continued throughout the late Weichselian full-glacial period (Dowdeswell and Elverhøi, 2002).

The convergence of ice-flow indicators where fjords join together demonstrates that ice derived from large basins draining west from the interior of the Eurasian Ice Sheet provides the discharge necessary for fast ice flow (Fig. 13). Simple glaciological calculations involving balance flux and basin geometry illustrate this (e.g., Clarke, 1987). The interior basin draining into Trænadjupet from Vestfjorden and neighboring areas (Fig. 13), for example, is ~150,000 km². If we assume a full-glacial snow precipitation of 0.25 m yr⁻¹ water equivalent, this gives a mass input of 37.5 km³ yr⁻¹ to the drainage basin. The width of fast-flowing ice at the trough mouth is ~90 km (Figs. 12 and 13). If we assume an ice thickness of ~600 m (present water depth plus 100 m for sea-level lowering), this gives a cross section for ice discharge of ~50 km². Using these values, a balance velocity of 750 m yr⁻¹ is calculated for the former ice stream, assuming that the glacial system is in equilibrium with the imposed Late Quaternary climate.

Ice velocities of this magnitude are comparable to the rate of ice flow observed in modern ice streams draining the Greenland and Antarctic ice sheets, which typically flow at velocities of hundreds to a few thousands of meters per year (e.g., Bentley, 1987; Bindschadler et al., 1996; Whillans et al., 2001). Ice motion through internal deformation alone would be only a few meters per year (Paterson, 1994), implying that the flow of former ice streams, such as those draining through Trænadjupet and other Norwegian-margin troughs, must be accounted for mainly by a reduction in basal friction. In principle, this could be related to either the presence of water at the glacier bed or by deformation of unconsolidated and probably saturated basal sediments (e.g., Tulaczyk et al., 1998; Kamb, 2001). The known presence of such deformable material with a streamlined surface, together with the absence of geomorphic evidence for channelized water flow, implies that the deformation of basal sediments is likely to be a major contributor to the fast flow of the paleo-ice streams identified on the Norwegian margin.

Independent three-dimensional numerical-model experiments by Payne and Baldwin (1999) and Boulton et al. (2003) have produced a similar pattern of ice flow to that shown in Figure 13. Topographically controlled ice streams are shown to drain the bulk of the interior of the Scandinavian Ice Sheet. The modeling work demonstrates that fast ice-stream flow is likely
to take place preferentially in deep troughs and fjords because of basal melting, and thus some form of rapid basal motion takes place first beneath such thick ice. The ice streams then stabilize within deep troughs, separated by intervening ridges of slower-flowing ice frozen to the bed. Model predictions of the locations of ice streams match well not only with our evidence on former ice flow, inferred from the distribution of submarine landforms on the western Norwegian margin (Fig. 12), but also with mapping of streamlined geomorphic features on the Scandinavian landmass, particularly east of the main mountain chain (Boulton et al., 2001).

Where transverse moraine systems are mapped together with megascale lineations paralleling the long axes of troughs, the former are usually superimposed upon the latter, indicating that the ridges have often formed at stillstands or slowdowns during deglacial ice retreat. Transverse moraine ridges close to the continental shelf break are interpreted as terminal moraines. They are inferred to be linked to areas of slower-flowing ice fed from rather small local drainage basins located between ice streams. Skjoldryggen, the largest moraine ridge on the Norwegian shelf, is an exception to this. The Skjoldryggen region has been a very active area of sedimentation, where up to 500 m of debris has been deposited during the last three glaciations (Rise et al., 2005) (Fig. 8B). The push-shaped form of the Skjoldryggen moraine ridge is thought to have taken place in a late stage of the Last Glacial Maximum.

Two further types of features that we map are linked to former ice-stream margins and the area beyond such shear zones. Lateral moraines, which we observe only locally in proximity to megascale lineations, are interpreted as marking the edges of fast ice flow. They presumably relate to basal processes at the shear zones between fast- and slow-flowing ice (Stokes and Clark, 2001, 2003). Hill-hole pairs are usually but not invariably distributed outside the inferred boundaries to ice-stream flow. In such locations they are linked to slower-moving ice and may form in deglacial situations where thinning marginal ice leads to basal freezing and a stress regime that is compressive longitudinally (Moran et al., 1980). Their orientation should, nonetheless, be a useful indicator of the direction of past ice flow, with the erosional hole formed upstream of the depositional hill.

Finally, the large-scale view of the beds beneath former ice sheets provided by the marine-geophysical record can be used as an important point of reference for our understanding of basal

Figure 11. Seafloor geomorphic features interpreted to be of glaciotectonic origin. (A) The seafloor east of Skjoldryggen from a 3D seismic data set (Fig. 8A). The image shows a glaciotectonically formed hill-hole pair. The ridge rises 70 m above the surrounding surface, and the depression has a maximum depth of 15 m. Ice-flow direction indicated by arrow. Water depth is between 350 m and 420 m. (B) Seafloor of the Arendal Terrace (AT) located north of the deep Skagerrak Trough (Fig. 1A). The surface of AT is very irregular, comprising ridges and depressions trending in a convergent pattern (white arrows) indicating ice flow toward the southwest. The ridges reach 30 m in height and up to 15 km in length, whereas the elongated depressions may reach a length of 5 km and a width of 1 km. The ridges and depressions are interpreted to have been subglacially formed by glaciotectonics, where the glacier incorporated sediments and either removed them from the area or dumped them in front as a ridge. This pattern probably formed just outside the ice-stream shear zone (marked with white dots). (C) Seismic profile across AT, which comprises up to 200 m of laminated sediments (blue) capped by an LGM till unit (light green). The acoustically laminated sediments probably filled the deepest parts of the Skagerrak and were later partly eroded by the Norwegian Channel Ice Stream (hachures).
Figure 12. Geomorphic maps of the submarine landforms on the Norwegian-Svalbard margin derived from seafloor imagery. (A) Norwegian margin to 69°N. (B) Barents Sea and Svalbard margin. S—Skagerrak; NC—Norwegian Channel; SU—Suladjuvet; SK—Sklinnadjuvet; V—Vestfjorden.
processes in modern ice sheets. Reflection-seismic investigations of the nature of modern ice-sheet beds are logistically difficult, and only a limited number of studies have taken place (e.g., Blankenship et al., 1987; Smith, 1997; Kamb, 2001). Similarly, airborne and ice-surface radar investigations of ice-sheet bed geometry are limited by the relatively large radar footprint at frequencies suitable for penetration through ice up to several kilometers thick (Dowdeswell and Evans, 2004). Marine-geophysical investigations of former ice-sheet beds have few of these physical restrictions, and very large areas can therefore be examined at a relatively high spatial resolution (e.g., Dowdeswell et al., 2004).

CONCLUSIONS

The large-scale view of the beds beneath former ice sheets given by marine-geophysical records provides important data for the reconstruction of past ice-sheet flow directions and dynamics. We have identified several distinctive styles of seafloor geomorphic features from the continental shelf and slope west of the 5.5 million km$^2$ late Weichselian Eurasian Ice Sheet, extending ~2500 km from 57°–80° N (Fig. 1) and have discussed their implications for ice-sheet flow.

Streamlined lineations in seafloor sediments are observed in a number of cross-shelf troughs and outer fjords along the Norwegian margin (Fig. 12). They range in length from hundreds of meters to several tens of kilometers. These streamlined sedimentary features are morphologically similar to landforms previously described as megascalar glacial lineations (Clark, 1993; Stokes and Clark, 1999) or bundle structures (Canals et al., 2000, 2002).

The distribution of the sets of seafloor lineations on the Norwegian margin is consistent with having an origin beneath fast-flowing, grounded glacier ice. The locations of lineation sets in relatively deep troughs and fjords are linked to the former presence of relatively thick ice, which would reach the pressure melting point before thinner ice on adjacent shallow banks (Paterson, 1994; Dowdeswell and Siegert, 1999). The observed patterns of convergence and divergence of form are similar to the flow characteristics of many modern ice masses in similar topographic settings.

Individual linear ridges, tens of kilometers long and up to ~50 m high, were also observed in a number of locations on the Norwegian margin, running along the lateral margins of cross-shelf troughs (Fig. 12). They are not found at the lateral margins of all troughs and invariably not as pairs within a single trough. These extensive ridges are interpreted to be glacier-derived...
moraine systems that delimit the lateral margins of fast-flowing former ice streams. The formation of these ridges was presumably linked to the shear zone and high-stress gradient between fast- and slow-flowing ice.

Seafloor ridges oriented transverse to the direction of former ice flow and therefore generally parallel to the continental shelf edge are located in two settings on the Norwegian margin. The first is either at or close to the shelf break. The second is inshore of the shelf break, where series of ridges are formed inshore of shelf-edge features. Transverse ridges at or near the shelf break are interpreted to be terminal moraines recording the latest advance of full-glacial ice. Ridges inshore of such terminal moraines are inferred to be moraines or series of moraines that record stillstands or minor readvances during deglacial retreat of the ice margin.

The distribution of submarine landforms on the Norwegian margin (Figs. 1 and 12) is used to infer the pattern of fast-flowing ice during the last glacial period (Fig. 13). Megascale glacial lineations are interpreted as indicators of former ice streams. The known presence of deforming seafloor sediments with a streamlined surface, together with the absence of geomorphic evidence for channelized water flow, implies that the deformation of basal sediments is likely to have been a major contributor to the fast flow of the paleo-ice streams identified on the Norwegian margin. Independent three-dimensional numerical-model experiments (Payne and Balsley, 1999; Boulton et al., 2003) have produced a similar pattern of ice flow to that shown in Figure 13, with topographically controlled ice drainage starting from the bulk of the interior of the Scandinavian Ice Sheet.

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