# Dynamics of the Late Weichselian ice sheet on Svalbard inferred from high-resolution sea-floor morphology

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High-resolution bathymetric mapping of the fjords and continental shelf around the Svalbard archipelago shows an extensive pattern of large- and medium-scale submarine landforms formed by differences in ice-flow regimes. Mega-scale glacial lineations, lateral moraines, transverse ridges and glaciotectonic features are superimposed on the large-scale fjord, shelf and cross-shelf trough morphology of the margin. From these landforms we infer the ice flow and dynamics of the last ice sheet on Svalbard. Major fjords and their adjacent cross-shelf troughs are identified as the main routes for ice streams draining the ice sheet. On the west coast of Svalbard major pathways existed along Bellsund, Isfjorden, and Kongsfjorden. Along the northern Svalbard margin most of the ice drained through Woodfjorden cross-shelf trough, and Wijdefjorden-Hinlopen Strait. Extensive areas with trough-parallel glacial lineations in the cross-shelf troughs suggest fast ice flow by palaeo-ice streams. Lateral ice-stream moraines, several tens of kilometres in length, have been mapped along the margins of some of the cross-shelf troughs, identifying the border zone between fast ice flow and stagnant or slow-flowing ice on intervening banks. Several general implications can be drawn from the interpretation of the glacier-derived submarine landforms around Svalbard. First, the Late Weichselian ice sheet was partitioned into fast-flowing ice streams separated by slower-moving ice. Secondly, our submarine morphological evidence supports earlier sedimentological, stratigraphical and chronological studies in implying that a large ice sheet reached the shelf edge around almost all of western and northern Svalbard in the Late Weichselian. The idea of a relatively restricted ice sheet over Svalbard, with ice-free conditions in some areas of the west coast at the last glacial maximum, is therefore unlikely to be correct. Thirdly, the ice sheet appears to have retreated more rapidly from the cross-shelf troughs and outer fjords, although sometimes this occurred in a punctuated pattern indicated by grounding-zone wedges, and more slowly from the intervening shallower banks. In addition, a grounding zone for the ice sheet has been mapped at the shelf edge 10-20 km off the northwest coast of Svalbard, suggesting that ice did not reach the adjacent Yermak Plateau during the Late Weichselian.

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There is now a consensus that the Late Weichselian ice sheet reached the continental shelf edge west and north of Svalbard (Svendsen *et al*. 1992, 1996; Andersen *et al*. 1996; Landvik *et al*. 1998; Mangerud *et al*. 2002; Svendsen *et al*. 2004). However, the detailed geometry and dynamics of the ice sheet are still being unravelled. Due to the fragmentary geological record on land, and the limited information available from which to infer ice-sheet elevations, relative sea-level histories and glaciological modelling have been used to reconstruct the geometry of the former ice sheet (Lambeck 1995, 1996; Landvik *et al*. 1998; Siegert *et al*. 2001; Siegert & Dowdeswell 2001).

In a recent study combining new marine evidence and land records, Landvik *et al*. (2005) suggested that ice streams drained the major fjords and cross-shelf troughs of north-western Svalbard. Their work indicated that a configuration of fast-flowing ice streams and dynamically less active ice in intervening areas was compatible with the terrestrial geological record for the Late Weichselian. Ottesen *et al*. (2005a) studied the sea-floor morphology of the entire western margin of the Scandinavian, Barents Sea and Svalbard ice sheets and showed that about 20 fast-flowing ice-streams were channelled by fjords and cross-shelf troughs. Detailed marine geological studies have confirmed the existence of large ice stream systems in, for example, the Norwegian Channel (Longva & Thorsnes 1997; King *et al*. 1996; Sejrup *et al*. 1998, 2003) and on the Barents Sea margin (Andreassen *et al*. 2004). The significance of fast-flowing ice during the Late Weichselian is also consistent with observations of the dynamics of modern ice caps and ice sheets where ice streams, flowing rapidly as well-defined curvilinear features set within slower-moving ice, drain very large interior basins and provide a major mechanism of mass loss to the oceans (Rignot & Thomas 2002). This dynamic configuration characterises not only the huge modern ice sheets of Antarctica and Greenland ($10^6$ to $10^7$ km$^2$) (e.g. Bentley 1987; Bamber *et al*. 2000; Rignot & Kanagaratnam 2006), but is also typical of many smaller ice caps ($10^3$ to $10^4$ km$^2$) present in the Arctic today (e.g. Dowdeswell *et al*. 1999, 2002, 2004a; Burgess *et al*. 2005).

In the present study, we use new bathymetric data sets from the fjords and continental shelf areas around Svalbard (Fig. 1) to reconstruct in detail the flow direction and dynamics of the last Svalbard Ice Sheet. We present examples of the submarine landforms that we use to infer ice-flow directions and dynamics and produce an updated reconstruction of the form and flow of the ice sheet that covered Svalbard and the surrounding shelf seas during the Late Weichselian.

## Methods

*Regional single beam echo sounder data*

The Norwegian Hydrographic Service (NHS) collected single beam echo sounder (Atlas Penguin echo sounder 100 kHz) data during the years 1965-1994. The data cover the fjords, shelves and the continental slope around Svalbard, in several areas down to more than 2000 m water depth. The data quality differs from area to area, mainly due to varying density of survey lines and navigational accuracy. Data from the whole area are gridded with a 1 km cell size.

*Detailed multibeam echo sounder bathymetry*

In the period between 1999 and 2004 the NHS collected multibeam bathymetric data (EM1002, depth range 20-1000 m) in the fjords and on the adjacent shelf areas around Svalbard. We have access to about 14000 km$^2$ of these data (Table 1). The data sets have been gridded with either a 10 or 50 m cell size, dependent on the sampling density. The University of Tromsø has also collected multibeam bathymetry (EM300) in several areas. In the outer Kongsfjordrenna and adjacent continental slope, the RV *Jan Mayen* collected about 1500 $km^2$, and in October 2004, one line was collected north of Svalbard. Bathymetric data from this line were gridded with a cell size of 10 m. For visualisation, the data are presented as colour-coded or black-and-white shaded relief images.

## Sea-floor landforms

Detailed marine-geophysical observations of sea-floor morphology on the continental shelves and in several of the major fjords of Svalbard have been examined systematically for the presence of submarine landforms linked to ice flow during the Late Weichselian glaciation. On the shelf and in most outer-fjord locations the postglacial sedimentation is limited, often to only a few tens of centimetres (e.g. Elverhøi & Solheim 1983; Elverhøi 1984) and the glacial morphology is easily mapped. In some inner-fjord settings the amount of Holocene sedimentation can be several metres and sometimes more than 10 m, and here sea-floor features are sometimes partially obscured (e.g. Elverhøi *et al.* 1983, 1998). We now describe the morphology and distribution of several submarine landform types that are regarded as diagnostic of the presence of grounded glacier ice in general and, in several cases, of fast glacier flow in particular.

*Mega-scale lineations*

*Description*. - Streamlined linear or curvilinear submarine features are observed in several major fjords and cross-shelf troughs on the Svalbard margin. The sea-floor features are elongated in the direction of the long-axis of the depressions. They vary from hundreds of metres to more than ten kilometres in length. Their wavelengths range between 0.1 km to 2 km and amplitudes are up to 15 m. Examples of sea-floor lineations on the Svalbard margin are shown in Figs 2, 3, 4, 5. In each case, acoustic-stratigraphic records show that the features are sedimentary bedforms rather than sculpted bedrock. In addition, some sets of lineations show signs of convergence, especially when fjords or troughs join. Less frequently, the divergence of lineation sets has also been observed. An example comes from the mouths of Wijdefjorden and Woodfjorden in northern Svalbard, where a single set of lineations in the 15 km-wide fjord-proper diverges into two sets around the island of Moffen on the shelf beyond the fjord mouth (Ottesen *et al*. 2005a).

*Interpretation*. - The streamlined sedimentary lineations described above are similar in form to features described as ‘mega-scale glacial lineations’ (Clark 1993; Stokes & Clark 1999). Such features have been reported from the continental shelves of, for example, Norway and Antarctica (e.g. Shipp *et al*. 1999, 2002; Canals *et al*. 2000, 2002; Ottesen *et al*. 2002, 2005a; Wellner *et al*. 2001; Ó Cofaigh *et al*. 2002; Dowdeswell *et al*. 2004b) and have also been observed on satellite imagery of parts of northern Canada (Clark 1993). The sets of lineations appear to result from soft-sediment deformation at the base of fast-flowing ice streams draining large ice masses (Tulaczyk *et al*. 2001; Dowdeswell *et al.* 2004b; Ó Cofaigh *et al*. 2005).

The spatial pattern of the lineation sets is compatible with formation beneath grounded glacier ice. The fact that lineation sets are found in the cross-shelf troughs and fjords links them to the former presence of relatively thick ice, presumably at the pressure melting point (Paterson 1994; Dowdeswell & Siegert 1999). Basal melting and, potentially, soft-sediment deformation and fast flow would therefore be expected. This interpretation is compatible with calculations of ice flow, thermal structure and sediment delivery from Svalbard fjords, such as Isfjorden, where both models and observations suggest fast glacier flow and high sediment delivery rates to the continental margin from ice-sheet drainage basins of $10^3$ $km^2$ (Hooke & Elverhøi 1996; Elverhøi *et al*. 1998).

*Ridges parallel to inferred ice-flow direction*

*Description*. - Individual linear ridges, of tens of kilometres in length and up to between about 40 and 60 m high, have been observed along the lateral margins of cross-shelf troughs in Svalbard. The ridges occur on either one side of a trough or, sometimes, as pairs on both sides. Sub-bottom profilers do not generally achieve acoustic penetration of these ridges, implying that they are made up of relatively coarse diamictic sediments. Examples of these lateral ridges include those at the mouths of Isfjorden, Kongsfjorden and Woodfjorden troughs, as they approach the shelf break west of Svalbard (Ottesen *et al*. 2005a: fig. 6). Beyond the trough-mouths, at the edge of prograding continental shelves, low-gradient submarine fans are found on the continental slope (e.g. Boulton 1990; Vorren & Laberg 1997; Elverhøi *et al*. 1998; Dowdeswell & Elverhøi 2002).

*Interpretation*. - The extensive lateral ridges are interpreted as glacier-derived moraine systems that define the lateral margins of fast-flowing former ice streams. They are found in association with the trough-floor mega-scale glacial lineations described above. Similar features have 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 & Morris 1988; Boulton & Clark 1990; Stokes & Clark 2001), and from along both sides of Trænadjupet, a trough on the Norwegian margin which has mega-scale glacial lineations on its floor (Ottesen *et al*. 2002, 2005b). In both cases, mega-scale glacial lineations were not found beyond the lateral moraine ridges, which thus appeared 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 & Clark (2001), in discussing the geomorphic criteria diagnostic of palaeo-ice streams, noted that these ridges were not always present in the geological record and it is their spatial association with mega-scale lineations that was of particular significance for palaeoenvironmental interpretation.

*Large transverse ridges and grounding-zone wedges*

*Description*. - Large sea-floor ridges orientated transverse to the direction of former ice flow and, therefore, generally parallel to the continental shelf edge, are found both at the shelf edge and more commonly, in the troughs and fjords of Svalbard. These ridges are characteristically tens of metres high, up to several kilometres wide and tens of kilometres long. They are illustrated, for example, by ridges on the outer shelves north of Isfjorden and Kongsfjorden (Figs 3B, 4). Acoustic stratigraphic records, where penetration is achieved, show that the ridges form sedimentary wedges lying above strong basal reflectors (Fig. 4C). Sometimes the sedimentary wedges have only relatively subtle vertical expression on the sea floor, but are nonetheless clearly identifiable on acoustic records. The volume of sediment that they contain may reach a few cubic kilometres.

*Interpretation*. - When located at or near the shelf break around Svalbard, the large transverse ridges are interpreted to be terminal moraines recording the farthest advance of grounded glacial ice across the continental shelf. These terminal moraines are often observed in the areas of the margin between large submarine fans (Elverhøi *et al*. 1998), and have been used to infer the presence of an ice margin that is not fast-flowing (Dowdeswell & Elverhøi 2002). The elongated ridge and wedge in the vicinity of the shelf edge of north-west Svalbard (Fig. 8) is interpreted as a terminal moraine deposited by a rather slow moving ice sheet. Mega-scale lineations, indicative of fast ice flow, are absent from this area. The ridge probably locates the maximum position of the ice sheet in this part of Svalbard during the Last Glacial Maximum (LGM).

Where these extensive ridges and underlying sedimentary wedges are found in the troughs and fjords of Svalbard (Figs 3, 4), they are interpreted to mark major still-stands of the ice margin during general deglaciation (e.g. Powell & Domack 2002; Landvik *et al*. 2005; McMullen *et al*. 2006; Ottesen *et al*. 2005b). This allows time for the sediments to build up to form a grounding zone wedge often tens of metres in thickness. These wedges, which are found as either single features or as a set of large ridges, are sometimes associated with shallower and/or constricted areas of the troughs and fjords of Svalbard, which would have formed natural pinning points for the ice margin during retreat.

*Small transverse ridges*

*Description*. - A further type of transverse ridge is much smaller than those described above. Individual ridges are up to 15 m high, have an average width of about 50-150 m and are spaced a few hundred metres apart. These smaller ridges are fairly evenly-spaced and are almost always found in clusters rather than as isolated individual features. An area of the shelf off Woodfjorden provides a good example, where a series of sub-parallel ridges is located in water depths of up to 150 m (Fig. 5).

*Interpretation*. - Series of smaller transverse ridges found on the continental shelf and in fjords around Svalbard are inferred to be moraines that record brief still-stands or winter-summer ice-front oscillations during general retreat of the ice margin during deglaciation (Nygård *et al*. 2004; Ottesen & Dowdeswell 2006). The fact that these ridges contain much smaller volumes of debris, by several orders of magnitude, than large terminal ridges or grouding-zone wedges suggests that they are generally recording shorter-lived events during deglaciation. These retreat moraines are thought to be formed as push moraines during minor winter readvances of a tidewater ice front when iceberg calving is largely suppressed by the protecting presence of sea ice (Liestøl 1976; Boulton 1986; Ottesen & Dowdeswell 2006).

## Fjords and troughs on the Svalbard margin

The sea-floor morphology of the Svalbard margin west and north of the archipelago is characterised by a series of deep fjord-trough systems separated from one another by intervening shallow banks. This gross topography is a result mainly of glacial activity and the advance of ice sheets and intercalated ice streams to the shelf edge on a number of occasions during the Pleistocene (e.g. Solheim *et al*. 1996; Mangerud *et al*. 1998; Vorren *et al*. 1998). The margin is now described and interpreted in two sections. The first concerns the fjords and adjacent cross-shelf trough systems, and the second considers the shallower banks between. Each of these two morphological zones exhibits a different set of characteristic submarine landforms.

*Bellsund trough and fjord system*

*General description*. - The Bellsund system comprises van Mijenfjorden and van Keulenfjorden, about 60 km long and 10 km wide, with an up to 260 m deep cross-shelf trough ending at the shelf edge 80 km west of the outer coast (Fig. 1). The trough is 15 km wide at the fjord mouth, but widens to about 40 km at the shelf edge. The inner cross-shelf trough is cut into sedimentary bedrock leaving steep walls on both sides. In the outer part of the trough, these side-walls change to more ridge-like Quaternary sedimentary features, 5 km wide, up to 35 km long and several tens of metres high. Our swath-bathymetric data cover only parts of Bellsund Trough and do not extend into the fjords themselves.

*Submarine landforms*. - Mega-scale glacial lineations trending predominantly southwestward are found on the floor of much of the Bellsund Trough (Fig. 2). They are up to 15 km in length, with an amplitude of less than 5 m and an average distance between the ridges of *c*. 200 m. Both the northern and southern sides of Bellsund Trough show ridges running parallel to the lineations for several tens of kilometres (Fig. 1). The ridges are up to 80 m high and 5 km across. Together, the mega-scale glacial lineations and the large sub-parallel ridges extending on either side of them indicate the former presence and dimension of a fast-flowing ice stream that was about 40 km wide at or close to the shelf edge. Beyond the shelf break, a submarine fan has been mapped that indicates the past delivery of several tens of cubic kilometres of glacial sediments over a series of glacial cycles (e.g. Vorren *et al*. 1998).

Superimposed on the mega-scale glacial lineations are several series of relatively small predominantly transverse ridges (Fig. 2). The ridges are up to 5 m high and spaced about 300 m apart. Up to 80 can be counted in a given group. Their superposition implies formation subsequent to the lineations. They are interpreted as push moraines, related to minor readvances during deglaciation after deposition of the mega-scale lineations. Their presence also indicates that the ice margin was grounded during retreat in at least parts of the Bellsund Trough.

*Isfjorden trough and fjord system*

*General description*. **-** The Isfjorden glacial system extends from the fjord heads in the east to the shelf break west of Svalbard, in total about 200 km (Fig. 1). Isfjorden is 10-25 km wide and comprises several basins up to 400 m deep separated by bedrock sills or moraine ridges. The trough beyond the outer coast widens to approximately 50 km close to the shelf edge, and reaches its greatest depth, approximately 350 m, on its northern side (Fig. 1). Beyond the shelf edge, a major trough-mouth fan is present (Elverhøi *et al*. 1998; Vorren *et al*. 1998; Dowdeswell & Elverhøi 2002). Our swath-bathymetric imagery includes most of the trough together with the outermost 40 km of the fjord itself. The inner fjord systems and fjord heads are not imaged acoustically.

*Submarine landforms*. - Mega-scale glacial lineations are observed in much of the trough and the outer fjord (Fig. 3). Some are more than 10 km long, a few metres high, and they show an average spacing between the ridge crests of 200 to 250 m, following the main axis of the fjord. Several bedrock ridges are orientated perpendicular to the fjord axis, and some glacially sculpted bedrock features, probably rock drumlins, are observed. Svendsen *et al*. (1992, 1996) showed that the Late Weichselian ice sheet extended to the mouth of the cross-shelf trough at the LGM, and that a major readvance occurred in the trough during deglaciation. On the southern side of the trough, a curved wide ridge extends all the way to the shelf edge representing the southern limit of the trough (Fig. 1). The ridge has an arcuate form and is interpreted to have been formed at a lateral ice-stream margin, probably deposited during several glaciations, but last modified during the Late Weichselian.

In the Isfjorden trough, a large curved ridge is located transverse to the direction of mega-scale lineations in the trough. It is located 50 km outside the coastline and 15 km southwest of Prins Karls Forland (Fig. 3) showing a width of 10 km and a height of up to 40 m. The ridge crosses most of the trough in water depths between 150 and 250 m. It is interpreted as a grounding-zone wedge. The ridge both overlies mega-scale lineations and has similar features on its surface. The feature is thus similar to grounding-zone wedges reported from both Antarctica and the north Norwegian margin (McMullen *et al*. 2006; Ottesen *et al*. 2005b).

Assuming that the feature represents a still-stand of the ice margin during retreat, we then argue that the ice was grounded and continued to flow rapidly during and after the deposition of the wedge. Thus, the ice stream in Isfjorden was still flowing fast even during deglaciation. No other similar ridges are found between this ridge and inner Isfjorden.

*Kongsfjorden trough and fjord system*

*General description*. - The Kongsfjorden Trough, between the outer coast and the shelf edge, is 10 km wide at its innermost part where it reaches water depths of 350 m. It shallows to 200 m and widens to 30 km across towards the shelf edge (Figs 1, 4). Two major fjords feed into the trough from the interior of north-west Svalbard. Kongsfjorden is about 30 km long, 5-10 km wide with a maximum water depth of 400 m. Krossfjorden, which joins outer Kongsfjorden from the north has about the same length but is narrower and up to 370 m deep (Sexton *et al*. 1992).

*Submarine landforms*. - Mega-scale glacial lineations can be found on most of the sea floor in the Kongsfjorden Trough (Fig. 4). They are generally parallel to the trough axis, but spread out in the outer part as the trough widens towards the shelf edge. In the middle of Kongsfjorden Trough a large N-S-trending ridge occurs (Fig. 4). This ridge is about 5 km wide and up to 30 m high and overlies the lineations, but also has similar features on its surface. The lineations in the outer part of Kongsfjorden Trough were probably formed at the LGM, whereas the lineations in the fjord were probably formed during deglaciation (Landvik *et al*. 2005). At the shelf edge, a trough-mouth fan is present (Fig. 1; Vorren *et al*. 1998).

On the southern side of the trough, a large NE-SW-trending ridge extends to the shelf break. The ridge is up to 50 m high and 5 km wide, and is interpreted as a lateral ice-stream margin, developed in the shear zone between the fast-flowing ice in Kongsfjorden Trough and what was probably thinner, passive ice on the shallow shelf outside Prins Karls Forland. At the shelf break in the southern part of Kongsfjorden Trough, a transverse ridge is present (Fig. 4). The ridge probably marks the maximum position of the ice stream in this area.

*Woodfjorden trough and fjord system*

*General description*. - The Woodfjorden glacial system extends from the fjord heads in the south, across the coast to the shelf break north of Svalbard, in total about 150 km (Fig.1). The whole system widens from 5 km in the inner parts of Woodfjorden to 10 km at the fjord mouth, and further to a maximum of 35 km at the shelf edge. Woodfjorden is an elongate trough with a threshold between Reinsdyrflya and Moffen (Fig. 1). The water depth is generally around 200 m in the cross-shelf trough.

*Submarine landforms*. - Extensive lineations are found in Woodfjorden and the Woodfjorden cross-shelf trough (Fig. 5), orientated generally parallel to the trough axis. The features are clearly imaged, even though Holocene sediment cover is up to about 10 m (Elverhøi *et al*. 1983). Off the mouth of the fjord, the lineations turn towards the NW and continue parallel with the trough axis west of the island of Moffen (Fig. 5A). The lineations are up to several kilometres in length, the average spacing between the ridges is 300 m and their average height is 3 m. In several areas of Woodfjorden cross-shelf trough, series of transverse ridges are found superimposed on the lineated surface (Fig. 5C). The ridges are up to 10 km long and may reach a height of 10 m. A single swath-bathymetry line also shows glacial lineations parallel with the trough axis in the outer part of the cross-shelf trough (Fig. 5D). On both sides of the outer trough, large lateral ridges extend to the shelf edge (Fig. 1). These are at least 30 km long, 5 km wide and up to 50 m in height and are probably ice-stream shear-margin moraines. The curved form of the shelf edge (Fig. 1) suggests that the system terminates in a trough-mouth fan. The glacial lineations, together with the large ice-stream shear-margin moraines in the outer trough, indicate substantial ice flow through this system during the last glacial maximum. The transverse moraine ridges indicate a stepwise ice retreat through the trough.

*Wijdefjorden and Hinlopen trough and fjord system*

*General description*. **-** Wijdefjorden is a 110 km long N-S-trending fjord that continues as a cross-shelf trough east of Moffen, ending as a hanging fjord that enters Hinlopen Trough (Fig. 1). The fjord is 5 km wide in the inner part, 20 km wide at the mouth, with a slightly wider trough crossing the shelf. The water depth is generally less than 200 m in the fjord. Hinlopenstredet is a 110 km long and 5-10 km wide trough between Spitsbergen and Nordaustlandet, continuing north to the shelf edge as a 400 m deep cross-shelf trough (Hinlopen Trough) (Fig. 1). West of Wahlenbergfjorden in Nordaustlandet a shallow bedrock threshold is located (Fig. 6), but north of this threshold the rather narrow trough is *c*. 400 m deep towards a threshold near the shelf edge.

*Submarine landforms*. - The detailed bathymetry of Wijdefjorden reveals an extensive pattern of glacial lineations formed in sedimentary material (Ottesen *et al*. 2005a). The lineations are normally parallel to the fjord and trough axis and may reach lengths up to 20 km and a maximum width of 1 km and up to 20 m in height. The spacing between the ridges varies from 500 m and 1000 m whereas the width of the individual ridges is between 100 and 400 m. In Hinlopenstredet (Figs 6A, B, C) extensive lineations parallel to the trough axis are found. South of the entrance to Hinlopenstredet, off the mouth of Wahlenbergfjorden, lineations with a WSW-ESE trend occur (Fig. 6B).

The pattern of glacial lineations shows that the ice that flowed out Wijdefjorden was confluent with an ice stream in Hinlopen Trough and ended at the shelf break 70 km further north (Fig. 11). The lineations in Hinlopen Trough are interpreted as mega-scale glacial lineations (MSGL) formed by an ice stream flowing through Hinlopenstredet (Fig. 6). South of the entrance to Hinlopenstredet the lineations have a slightly more easterly component, indicating an ice-flow pattern generated by the Barents Sea Ice Sheet. This ice-flow system appears to end with a trough-mouth fan on the basis of the convex form of the shelf edge. However, a large sediment volume of approximately 1350 $km^3$, forming major parts of the depocentre, has been removed by a giant submarine slide below the shelf break, the Hinlopen Slide (Vanneste *et al*. 2006).

## Shallow banks between troughs on the Svalbard margin

*The shelf area west of Prins Karls Forland*

*General description*. - The shelf west of Prins Karls Forland is 20 to 30 km wide, with a water depth between 50 m and 250 m (Fig. 1). The shelf is cross-cut in the north and south by the Kongsfjorden and Isfjorden cross-shelf troughs.

*Submarine landforms*. - The sea-floor morphology of this bank is dominated by a large complex of ridges orientated sub-parallel with the western coastline of Prins Karls Forland (NNW-SSE), known as the Forlandet moraine complex (Landvik *et al*. 2005) (Figs 3, 4). Several other smaller ridges occur both on the outer side and on the inner side of the main ridge complex, which is located 10-20 km west of Prins Karls Forland. The Forlandet moraine complex reaches a length of more than 50 km and a width of up to 1 km. The height of the main ridge reaches a maximum of 50 m. East of the ridge complex, several large depressions are present, up to 6 by 10 km in area and up to 100 m deep (Landvik *et al*. 2005; Ottesen *et al*. 2005a).

The main moraine ridge complex is interpreted to have been deposited at the margin of an ice sheet covering the shelf. This supports the presence of a relatively substantial ice cover on Prins Karls Forland in order to generate westward advance across the shelf (*cf*. Andersson *et al*. 1999). The large depressions east of the main ridge complex are most probably glaciotectonic features developed when the ice front was located at the moraine ridge complex and generated by thrusting of large sediment blocks and incorporating them in the ridge (Ottesen *et al*. 2005a). Alternatively, the depressions may be large blow-out craters, as observed in the Barents Sea shelf areas after the ice retreat (e.g. Mienert & Posewang 1999; Mienert *et al*. 2006). Based on mapping and dating of subglacial till further west, Landvik *et al*. (2005) suggested that the moraine-ridge complex was deposited during a retreat stage from the Late Weichselian maximum ice extent to the shelf edge.

*The shelf area between Kongsfjorden Trough and Amsterdamøya*

*General description*. - This shelf area between the Kongsfjorden trough and Amsterdamøya (Fig. 1) is 50 km wide in the south, but narrows to only 10 km west of Amsterdamøya (Fig. 1). Generally, this part of the shelf is between 50 m and 150 m deep, but the southern part is dominated by Mitragrunnen Bank, which is only 30 m deep and separated from the mainland by a north-south trending trough (Fig. 1).

*Submarine landforms*. - The shallow shelf is dominated by a system of about 40 arcuate ridges up to 35 km long that trend north-south (Fig. 7). The ridges have an average width of *c*. 500 m and are up to 25 m high. Several depressions are located east of the ridges. On the southern part of the outer shelf, the ridges bend eastwards and terminate along the northern slope of Kongsfjorden Trough (Fig. 4).

At the shelf edge west of Danskøya and Amsterdamøya, a very pronounced, elongate and regular single ridge is located and can be followed for several tens of kilometres in 150 to 300 m water depth (Figs. 8A and 8B). It is up to 1500 m wide, with an irregular, hummocky surface. The ridge appears to comprise Quaternary sediments with a wedge-shaped form. It is interpreted as a terminal moraine formed at the grounded margin of a relatively slow-moving ice sheet at the LGM. East of this single ridge, a series of smaller subparallel ridges orientated in a SW-NE direction occurs down to 150 m water depth (Figs. 8A and 8C). The ridges are up to 15 m high, have an average width of 150 m, and a spacing of about 400 m.

*The shelf area between Amsterdamøya and Woodfjorden Trough*

*General description*. - North and east of Amsterdamøya, the shelf widens towards the east to a width of about 30 km (Fig. 1). The water depth is generally less than 150 m in these areas. Northwest of the shelf, the Yermak Plateau is located in water depths deeper than 500 m (Fig. 1). Prominent features of the northwestern part of Svalbard are two south to north-trending fjords, Smeerenburgfjorden and Raudfjorden (Fig. 1). Both continue from the coastal areas as troughs on the inner shelf. The 20 km long Smeerenburgfjorden is located east of Danskøya and Amsterdamøya, and continues for about 10 km north of Amsterdamøya onto the shallow shelf. Raudfjorden is 20 km long, and continues as a trough onto the shelf outside the main coastline for another 10 km.

*Submarine landforms*. - The trough off Smeerenburgfjorden ends with a marked transverse ridge. This is probably the same submarine feature that Liestøl (1972) interpreted as a Late Weichselian maximum moraine ridge deposited by a glacier flowing north from Smeerenburgfjorden. Later, Landvik *et al.* (1998) concluded that the ridge represented a recessional stage during the last deglaciation. The trough off Raudfjorden also ends on the shelf with a marked curved ridge, more than 50 m high.

North and east of Amsterdamøya, a series of transverse ridges occurs (Fig. 9). The ridges have an arcuate form, are generally less than 20 m in height, and stretch from outside Raudfjorden to the western margin of the Woodfjorden cross-shelf trough. Some of the ridges are up to 40 km in length (Fig. 10). We have interpreted the transverse ridges on banks both west and north of Svalbard as series of retreat moraines recording stillstands or ice-front oscillations during the retreat of a grounded ice margin. The position of these moraines has also been used to infer the presence of an ice margin that is not fast-flowing (Dowdeswell & Elverhøi 2002; Landvik *et al*. 2005).

## Distribution of sea-floor landforms and ice-sheet reconstruction

### *Pattern of sea-floor landforms*

We have compiled a geomorphological map of the submarine glacier-influenced landforms around Svalbard (Fig. 10). The areas of our data coverage are given in Table 1, and a number of images are illustrated in subsequent figures, each of which is located in Fig. 1. The most prominent features found on the Svalbard shelf are the large cross-shelf troughs representing the continuation of the major fjords to the shelf break (Fig. 1). The troughs are separated by shallower banks. The most striking feature on the submarine geomorphological map is the pattern of mega-scale glacial lineations located in each of the cross-shelf troughs for which we have high-resolution datasets: Bellsund, Isfjorden, Kongsfjorden, Woodfjorden, Widjefjorden and Hinlopen troughs (Fig. 10). The pattern of lineations generally follows the trough axes. Sometimes the trough margins have linear ridges orientated parallel to former ice flow (Fig. 10).

By contrast, most sets of smaller submarine ridges orientated transverse to past ice-flow direction are found on the relatively shallow banks between the cross-shelf troughs (Fig. 10). These relatively small ridges are occasionally superimposed on mega-scale glacial lineations in the troughs (Fig. 2). Larger transverse ridges, which are usually associated with linear depocentres known as grounding-zone wedges, are less frequently observed, but are found in some mid-shelf trough and fjord settings, such as Isfjorden and Kongsfjorden. Some ridges, up to 40 km long, are also located close to the shelf edge (Fig. 10).

*Reconstruction of the Late Weichselian ice sheet on Svalbard*

A number of geomorphic and stratigraphical studies during the last 20 years, together with glaciological modelling, have established that an ice sheet covered Svalbard, its continental margin and the Barents Sea during the Late Weichselian glacial maximum (e.g. Lambeck 1995, 1996; Andersen *et al*. 1996; Svendsen *et al*. 1996; Landvik *et al*. 1998; Siegert & Dowdeswell 2001). Glaciological and isostatic modelling indicates that this ice sheet was up to about 1500 m thick over the Barents Sea, with a centre positioned east of Kong Karls Land in the northern Barents Sea (e.g. Siegert & Dowdeswell 2001). However, documentation of ice-flow dynamics within the ice sheet has been limited. A large-scale pattern of flow was suggested by Ottesen *et al*. (2005a) who reconstructed palaeo-ice streams along the western margin of the Fennoscandian Ice Sheet and Barents Sea/Svalbard ice sheets. In a study from western Svalbard, Landvik *et al*. (2005) proposed a distribution of palaeo-ice streams separated by areas of dynamically less active glacier ice.

The distribution of submarine landforms in Fig. 10 is used to reconstruct the former ice-flow pattern in the fjords and adjacent shelves of western and northern Svalbard. Mega-scale glacial lineations are assumed to indicate the presence of fast-flowing ice streams within the former ice sheet, and sometimes lateral ridges define their margins (Clark 1993; Ottesen *et al*. 2005a). These palaeo-ice streams are mapped in Fig. 11. The distribution of observed mega-scale glacial lineations shows that ice streams extended across the shelf beyond each of the major fjords of western and northern Svalbard. Along the western coast of Svalbard, sedimentary depocentres or trough-mouth fans also extend into deep water at the termini of cross-shelf troughs (Vorren *et al*. 1998). Vanneste *et al*. (2006) have shown recently that a fan is also present at the mouth of Hinlopen Trough. The Bellsund and Isfjorden trough-mouth fans are the largest, with glacier-derived sediments more than 1000 m thick (Solheim *et al*. 1996). These fans are built up largely from diamictic debris transported to the continental shelf edge by the flow of ice streams (e.g. Andersen *et al*. 1996; Elverhøi *et al*. 1998; Vorren *et al*. 1998).

Radiocarbon dates from cores on the western Svalbard shelf and slope also support the presence of ice to the shelf break at the LGM (e.g. Svendsen *et al*. 1992, 1996; Landvik *et al*. 1998, 2005). In Isfjorden Trough, shells from a stiff diamicton were dated to about 12 500 yr BP, with initial retreat from the outer shelf before about 15 000 yr BP (Svendsen *et al*. 1992, 1996; Elverhøi *et al*. 1995). Dates of 19 200 yr BP from marine sediments underlying one of the glacigenic debris flows on the Isfjorden Fan also show that deposition of diamictic debris was active at the LGM, implying ice at the shelf edge (Andersen *et al*. 1996). In Bellsund Trough, Cadman (1996) dated diamictic deposits overlain by glacimarine sediments to between 16 000 and 13 000 yr BP. High sedimentation rates calculated on the slope off the Isfjorden Trough and the adjacent banks suggest extensive ice-stream flow through that system from about 22 000 yr BP until the onset of deglaciation (Andersen *et al*. 1996; Dowdeswell & Elverhøi 2002). Our work shows the presence of mega-scale glacial lineations in each of the troughs, indicating that ice streams were present under full-glacial conditions (Figs 10, 11).

The other areas of the shelf, largely the shallower banks, are inferred to have been covered by slower-moving ice during the Late Weichselian glaciation, given the lack of streamlined sedimentary bedforms in these areas. The transverse ridges on the banks are assumed to be terminal or deglacial features formed at the margin of the retreating ice sheet. Seismic records from these shallower banks also show moraine ridges with erosion on their proximal sides close to the shelf edge, interpreted as evidence for the presence of ice during the Late Weichselian (Solheim *et al*. 1996). Off Amsterdamøya and Danskøya, for example, a large grounding-zone moraine has been identified at the shelf break (Fig. 8). We propose that it marks the outermost position of the Svalbard Ice Sheet, providing evidence that the ice sheet did not reach the adjacent Yermak Plateau to the north during the Late Weichselian. Such an ice extent is in agreement with higher elevations on Amsterdamøya being ice free, as suggested by Landvik *et al*. (2003) based on exposure age dating.

Our submarine morphological evidence (Fig. 10) supports earlier sedimentological, stratigraphical and chronological studies (e.g. Andersen *et al*. 1996; Elverhøi *et al*. 1995; Landvik *et al*. 1998; Mangerud *et al*. 1998) in demonstrating that a large ice sheet reached the shelf edge around almost all of western and northern Svalbard at the LGM (Fig. 11). The notion of a relatively restricted ice sheet over Svalbard (e.g. Boulton 1979; Troitsky *et al*. 1979), with ice-free conditions in some areas of the west coast at the LGM (e.g. Salvigsen 1977; Miller 1982), is therefore unlikely to be correct.

*Style of deglaciation*

Although the submarine landforms described above offer no new evidence on the absolute timing of deglaciation after the Late Weichselian maximum in Svalbard, they do allow inferences to be made about the ice-margin behaviour during retreat. Geomorphic features on the shelf suggest a complex retreat history in several fjord-trough systems. Variations in the number and spacing of grounding-zone wedges in major troughs indicate that different ice streams behaved independently during their retreat from the shelf. The conspicuous contrast between the cross-shelf troughs and the intermediate shallower bank areas also indicates differences in the nature of deglaciation.

The excellent preservation of mega-scale glacial lineations, when they are not overlain by grounding-zone wedges or sets of smaller retreat moraines, suggests that fast-flowing ice streams, flowing to the shelf edge under full-glacial conditions, underwent rapid deglaciation and retreat through cross-shelf troughs and deep fjords. The ice in these areas may have thinned at the onset of deglaciation, become ungrounded and then retreated rapidly by iceberg calving to leave undisturbed sedimentary lineations. The extensive pattern of mega-scale glacial lineations in Hinlopenstredet provides an example of this situation (Fig. 6), where there are almost no traces of grounding-zone deposits or superimposed moraine ridges, suggesting a rapid retreat through the cross-shelf trough.

Where grounding-zone wedges are present within Svalbard cross-shelf troughs and fjords, episodic ice retreat is indicated between points of relative stability where the ice front remained long enough to build the sediments forming the wedge. Further thinning of the ice then led to another phase of rapid retreat until a new pinning point was reached and another grounding-zone wedge was formed. In Isfjorden and Kongsfjorden troughs, for example, grounding zone wedges are located about midway between the shelf break and the outer coastline (Figs 3A, 4B), indicating a still-stand during deglacial ice retreat. Landvik *et al*. (2005) mapped two additional ridges from seismic profiles nearer the mouth of Kongsfjorden, suggesting further interruptions to ice retreat.

Where series of smaller retreat moraines are found, mainly on the shallower banks between cross-shelf troughs, retreat of the ice front is inferred to be slow but quasi-continuous, relative to areas where occasional larger grounding-zone wedges were formed. These smaller-volume ridges, probably formed from pushing up of sediments during minor readvance each winter superimposed on greater summer retreat due to iceberg calving (Liestøl 1976; Sharp 1984; Boulton 1986), do not need the longer intervals of stability to build up the greater volumes of material that form the larger wedges. Sets of these ridges are most common on the shallow banks between former ice streams, such as the area between Kongsfjorden and Woodfjorden (Figs 7, 9), indicating a slow but fairly uniform rate of retreat. In both Bellsund and Woodfjorden troughs, however, mega-scale glacial lineations are overlain in some areas by series of small transverse ridges (Figs 2, 5C), implying that the pattern of deglaciation was complex. In Woodfjorden Trough, in particular, transverse ridges a few metres high are present in shallower water close to the inferred margins of the former ice stream, suggesting a water-depth dependent influence on the nature of deglaciation.

Several general implications can be drawn from the interpretation of the glacier-derived submarine landforms around Svalbard (Fig. 10). First, the Late Weichselian ice sheet was partitioned into fast-flowing ice streams separated by slower-moving ice (Fig. 11). Secondly, the ice sheet appears to have retreated more rapidly from the cross-shelf troughs and outer fjords, sometimes in a punctuated pattern, and more slowly from the intervening shallower banks. This is to be expected, given that iceberg calving, the main mechanism responsible for rapid mass loss from ice sheets, is known to become greater at increasing water depths (e.g. Pelto & Warren 1991).

## Conclusions

- The continental shelves and major fjords west and north of Svalbard are characterized by submarine bedforms produced by the Late Weichselian ice sheet. Mega-scale glacial lineations result from soft-sediment deformation at the base of fast-flowing ice streams. Extensive lateral ridges are interpreted as glacier-derived moraine systems formed at ice-stream lateral margins. Large transverse ridges at or near the shelf break are interpreted to be terminal moraines, and transverse ridges and sedimentary wedges within troughs and fjords are moraines marking major and minor still-stands and oscillations during ice recession.
- The distribution of glacier-influenced landforms shows mega-scale glacial lineations in each of the major cross-shelf troughs, and smaller submarine ridges on the shallow banks. Large transverse ridges, usually associated with linear grounding-zone wedges, are less frequently observed, but are found in mid-shelf trough and fjord settings, such as Isfjorden and Kongsfjorden.
- Mega-scale glacial lineations indicate the presence of fast-flowing ice streams within the former ice sheet, suggesting that the Late Weichselian ice sheet was partitioned into fast-flowing ice streams separated by slower-moving ice.
- Our submarine morphological evidence (Fig. 10) supports earlier sedimentological, stratigraphical and chronological studies in showing that a large ice sheet reached the shelf edge around almost all of western and northern Svalbard in the Late Weichselian (Fig. 11). The idea of a relatively restricted ice sheet over Svalbard, with ice-free conditions in some areas of the west coast at the LGM, is therefore unlikely to be correct.
- The submarine landforms also allow inferences to be made about the behaviour of the ice margin during retreat. The excellent preservation of mega-scale glacial lineations that are not overlain by grounding-zone wedges or sets of smaller retreat moraines implies that ice streams underwent rapid thinning and retreat through cross-shelf troughs and deep fjords. Where grounding-zone wedges are present in troughs and fjords, episodic ice retreat is indicated. Series of smaller retreat moraines, found mainly on shallower banks between troughs, indicate slow but quasi-continuous ice-front retreat.

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Table 1. Swath-bathymetric datasets from the Svalbard margin used in this study. NHS - Norwegian Hydrographic Service, UiTø - University of Tromsø.

| Location (Fig. 1) | Area $km^2$ | Cell size m | Data source |
|---|---|---|---|
| Bellsund Trough | 590 | 10 | NHS |
| Isfjorden Trough and outer fjord | 3800 | 50 | NHS |
| Shelf west of Prins Karls Forland | 1250 | 50 | NHS |
| Kongsfjorden Trough and outer fjord | 860 | 50 | NHS |
| Kongsfjorden Trough and upper slope | 1500 | 50 | UiTø |
| Shelf north of Kongsfjorden | 1560 | 10 | NHS |
| Shelf north of Svalbard from Danskøya to Woodfjorden Trough | 1160 | 10 | NHS |
| Woodfjorden Trough | 1040 | 10/50 | NHS |
| Outer Woodfjorden Trough | 80 | 10 | UiTø |
| Wijdefjorden | 1000 | 50 | NHS |
| Hinlopen Trough | 1160 | 10 | NHS |
| Total | 14000 | | |

**FIGURE CAPTIONS**

*Fig. 1*. Overview map with regional bathymetry of the fjord and shelf areas around Svalbard. 20 m depth contours. Data from single beam echo-sounder from the Norwegian Hydrographic Service. All data gridded with a cell size of 1 km. A - Amsterdamøya, D -Danskøya, H - Hornsund, HT - Hinlopen Trough, KT - Kongsfjorden Trough, PKF - Prins Karls Forland, R - Raudfjorden, Re - Reinsdyrflya, S - Smeerenburgfjorden, vK- van Keulen fjorden, vM - van Mijenfjorden, W - Woodfjorden, WT - Woodfjorden Trough. Green colour on inset map shows extent of swath bathymetric data coverage and the solid line west of Svalbard is the shelf edge.

*Fig. 2*. A. Detailed swath bathymetry of the Bellsund Trough. The image shows glacial lineations (white lines) in the eastern and lower part with a NNE-SSW direction. A series of recessional moraines is marked with RM. The image is from the deepest part of the Bellsund Trough with water depth between 150 and 260 m. B. Cross-section of the amplitude and wavelength of glacial lineations.

*Fig. 3*. A. Swath bathymetry of Isfjorden (I) and Isfjorden Trough (IT). The dashed line indicates a grounding-zone wedge, which is also described in Svendsen et al. (1992, 1996). B. A series of ridges on the shallower banks north of Isfjorden Trough. C. Mega-scale glacial lineations at the mouth of Isfjorden.

*Fig. 4*. A. Swath bathymetry of the Kongsfjorden – Kongsfjorden Trough system. Extensive glacial lineations are found on the sea floor, generally orientated parallel with trough axes. Outside the curved shelf edge, a series of downslope-orientated features, which may represent glacigenic debris flows related to maximum ice front position, are imaged. B. In the middle of Kongsfjorden Trough a grounding-zone wedge is found (GZW). 5 m depth contour interval. C. Sparker profile NP05-11-10 across the grounding zone wedge.

*Fig. 5*. A. Shaded-relief image of the sea floor of the Woodfjorden cross-shelf trough on the northern side of Svalbard. Glacial lineations follow the long-axis of the trough. B. Vertical profile across a series of glacial lineations in the Woodfjorden trough. C. A series of recessional moraines on a surface with glacial lineations. D. A single multibeam bathymetric line from the outer part of the Woodfjorden cross-shelf trough. Glacial lineations in the deepest part of the trough generally follow the trough axis. Maximum water depth is 200 m.

*Fig. 6*. A. Overview map of the detailed bathymetry of Hinlopenstredet area.

*Fig. 6*. B. Shaded relief image of the sea-floor morphology of the southern part of the Hinlopenstredet with two surface profiles. Extensive glacial lineations (white arrows) show ice movement from ESE into the narrow part of the Hinlopenstredet where it turns parallel to the trough axis towards NW.

*Fig. 6*. C. Shaded relief image of the sea floor morphology of the northern part of the Hinlopenstredet with three surface profiles. Extensive glacial lineations (white arrows) parallel to the main axis of the Hinlopenstredet show ice flow towards northwest.

*Fig*. 7. Detailed swath bathymetry from the shelf areas north of Kongsfjorden Trough (located in Figure 1). A series of up to 40 recessional moraines, generally parallel to the coastline are found.

*Fig*. 8. A. Shaded relief image of the sea floor morphology of the areas outside Danskøya and Amsterdamøya, north-western Svalbard. The marked SW-NE-lineament is a terminal moraine showing the maximum extent of the Svalbard Ice Sheet during the LGM. Assuming the ridge is of LGM age, this implies that the Yermak Plateau was not glaciated during the Late Weichselian. B. Vertical profile across the grounding zone. C. Vertical profile across a series of moraine ridges on the inner shelf.

*Fig*. 9. Detailed swath bathymetry of the shallow banks outside Reinsdyrflya with a series of recessional moraines. The direction of ice recession was from north to south, and the ridges are orientated west to east. A small area of sand waves is shown in the bottom left of the image.

*Fig*. 10. Geomorphic map of the submarine landforms on the Svalbard margin derived from sea-floor imagery.

*Fig*. 11. Reconstruction of ice-sheet flow regime, including ice streams, on the western and northern margin of the Late Weichselian Barents/Svalbard ice sheets. An ice stream is assumed to be present in the fjord of Hornsund and the trough beyond, on the basis of analogy with the other systems of western and northern Svalbard.

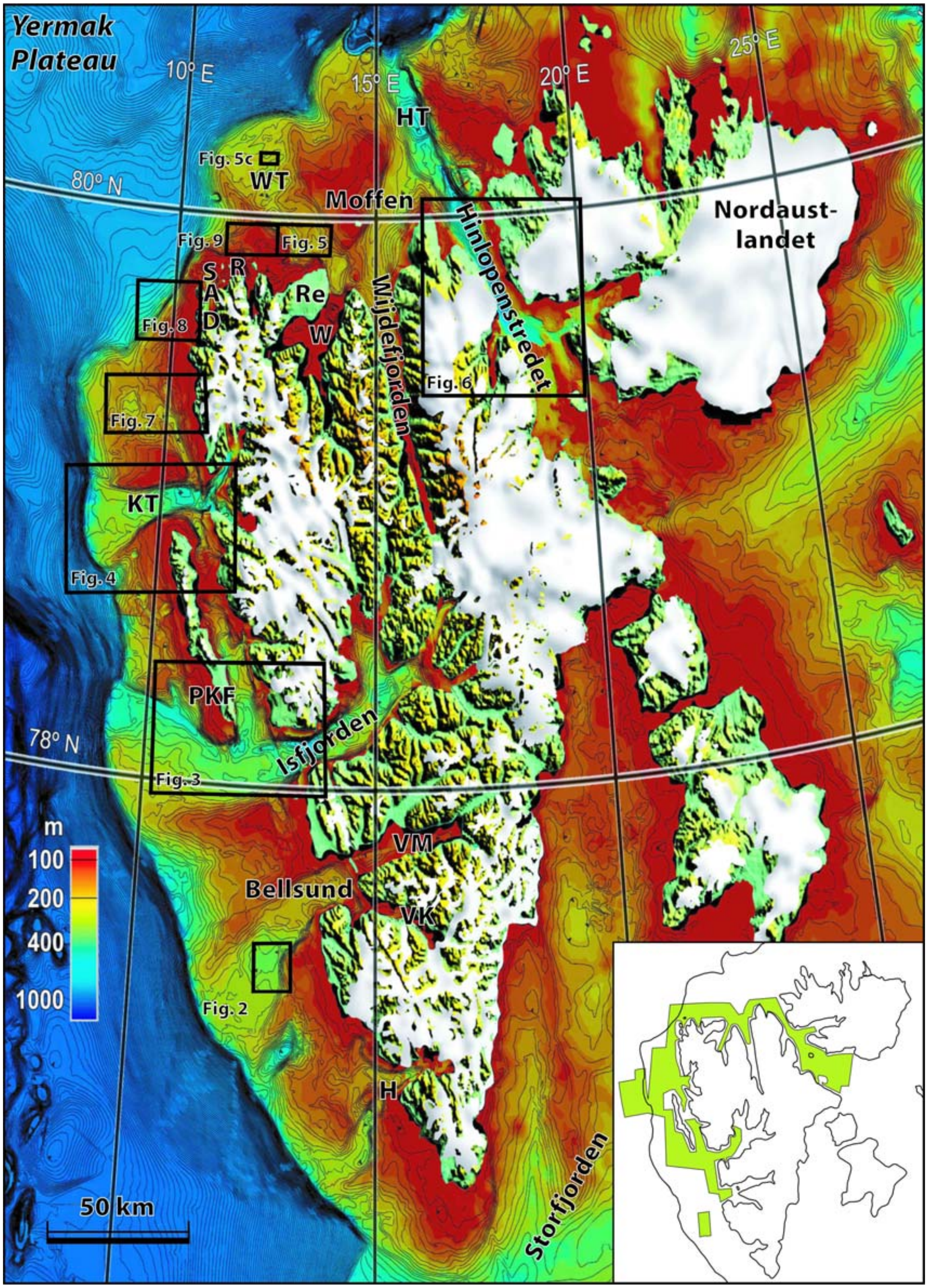

Yermak Plateau
10° E
15° E
20° E
25° E
80° N
78° N
HT
Fig. 5c
WT
Moffen
Nordaust-
landet
Fig. 9
Fig. 5
S
R
A
D
Re
W
Fig. 8
Wijdefjorden
Hinlopenstredet
Fig. 6
Fig. 7
KT
Fig. 4
PKF
Isfjorden
Fig. 3
m
100
200
400
1000
VM
Bellsund
VK
Fig. 2
H
Storfjorden
50 km

Fig. 1

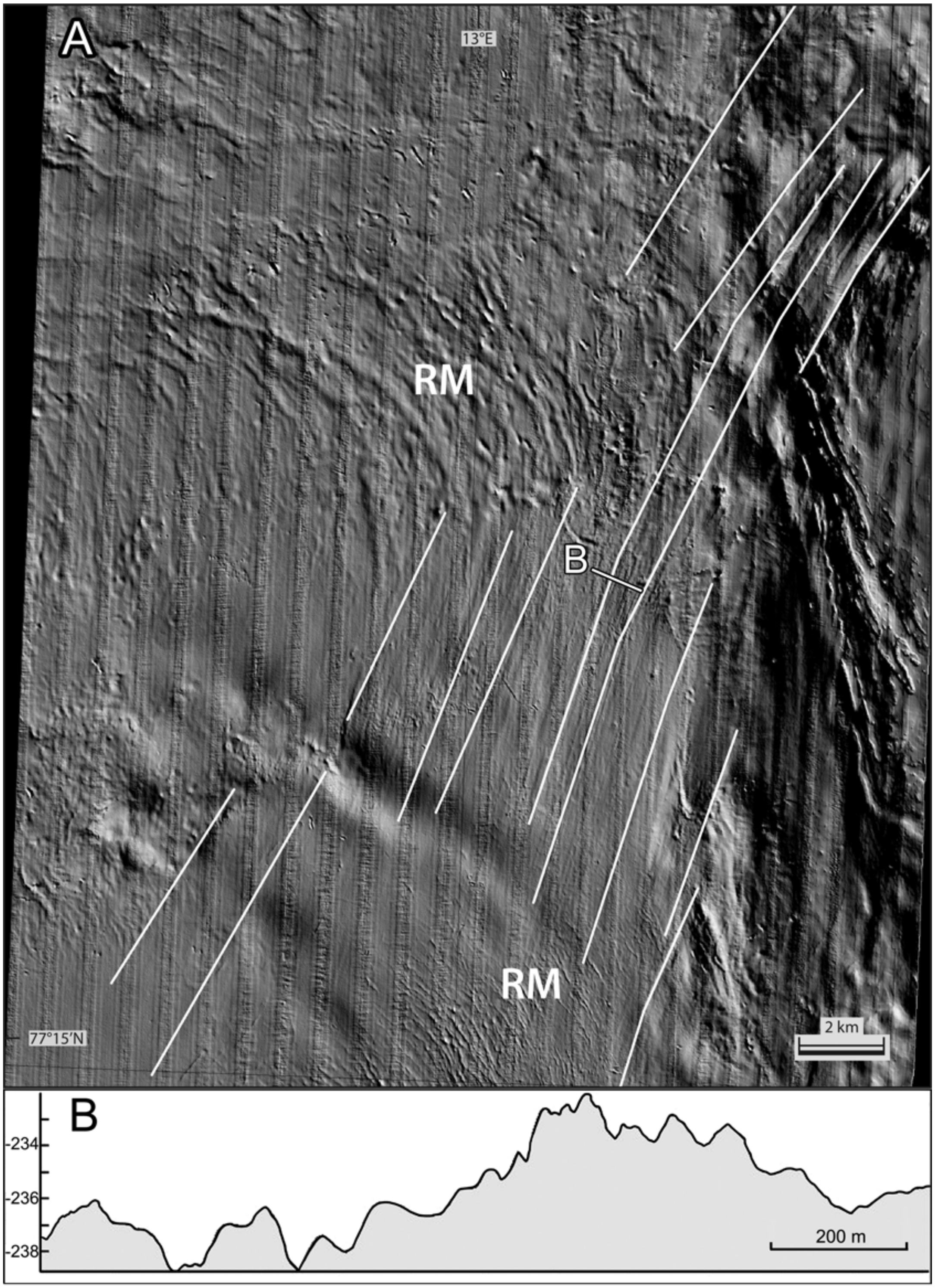
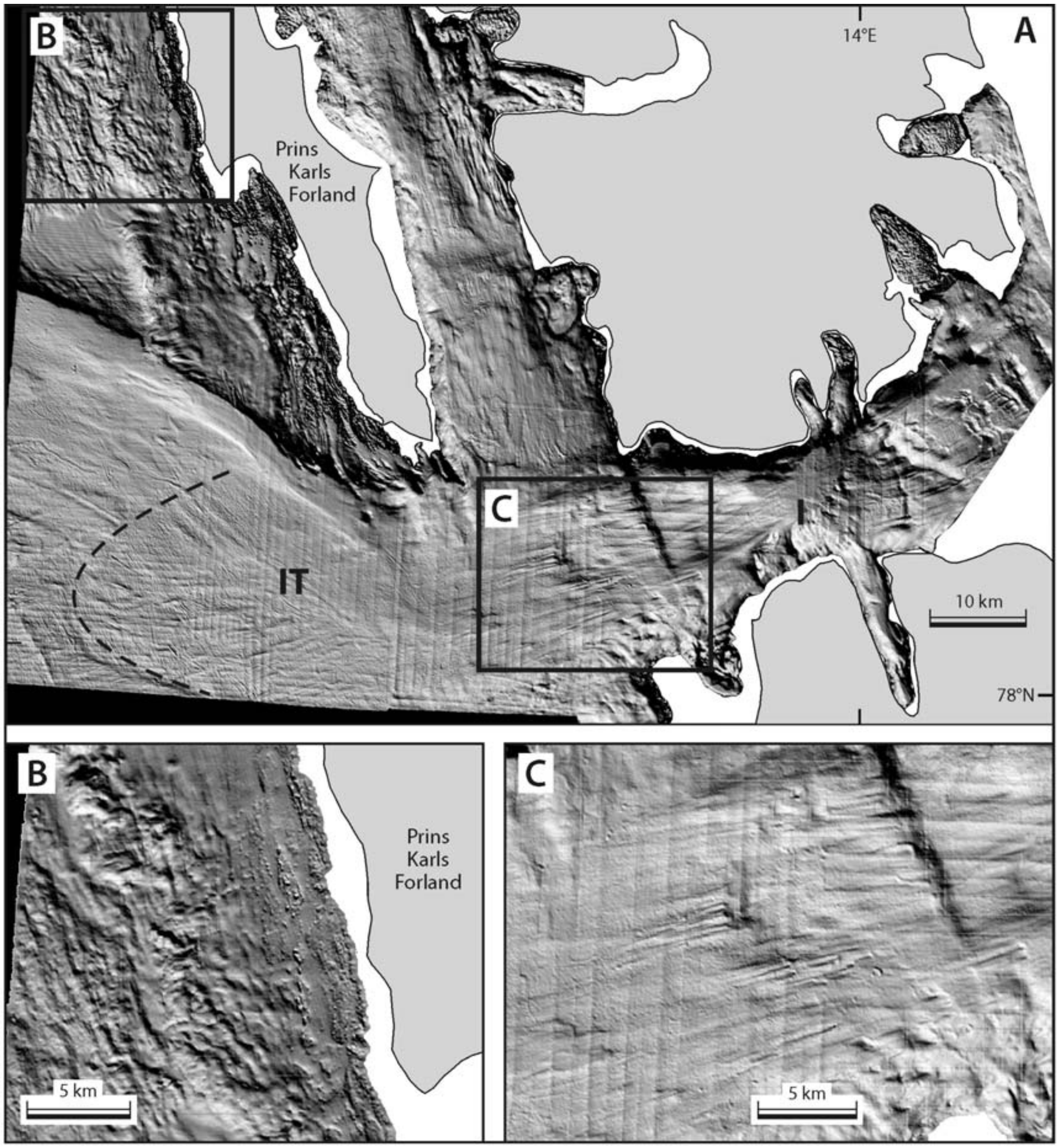
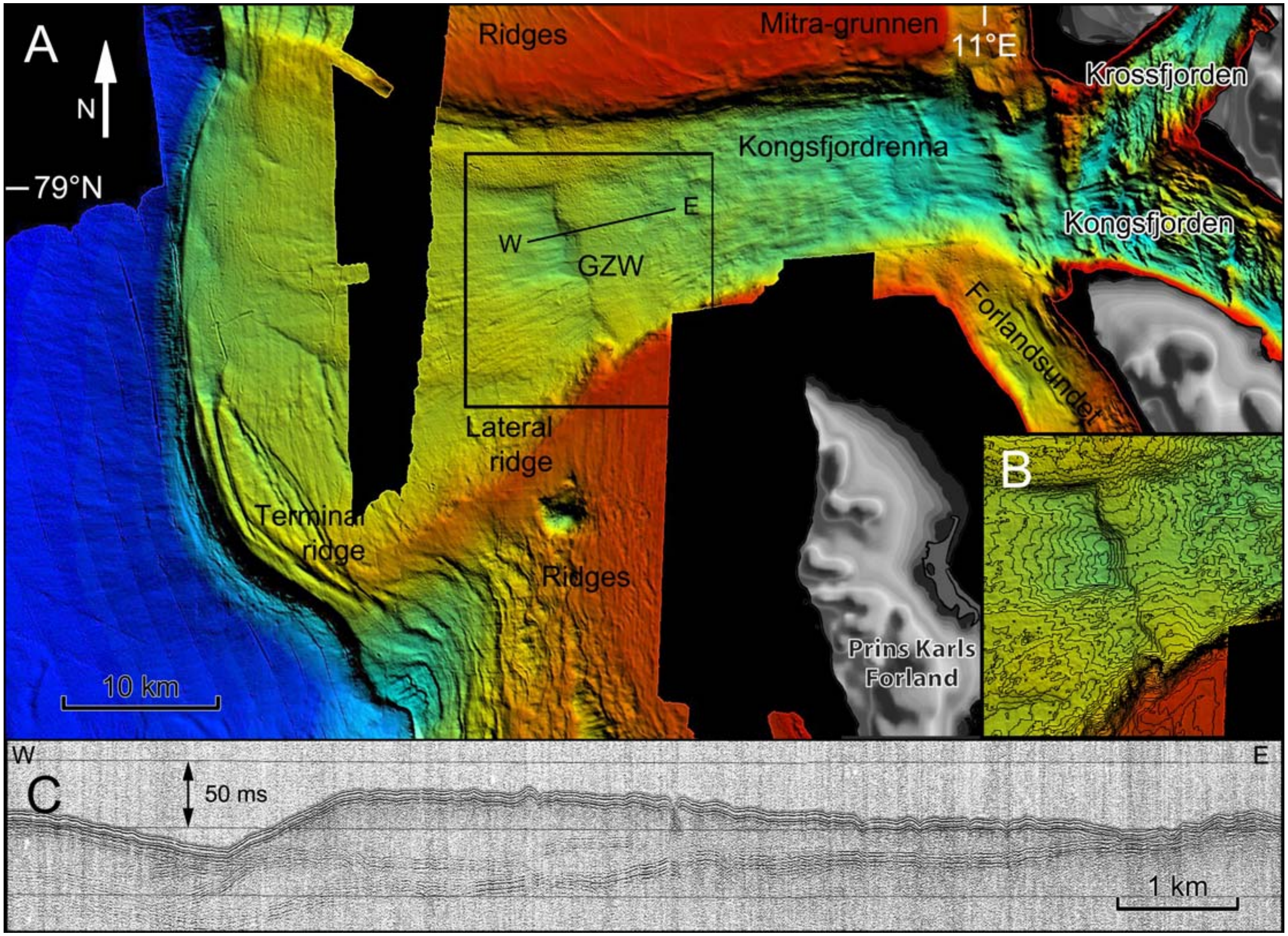



Fig. 2



A
B
C
14°E
78°N
Prins
Karls
Forland
IT
10 km
B
Prins
Karls
Forland
5 km
C
5 km


Fig. 3


A
N
79°N
Ridges
Mitra-grunnen
11°E
Krossfjorden
Kongsfjordrenna
E
W
GZW
Kongsfjorden
Forlandsundet
Lateral ridge
B
Terminal ridge
Ridges
Prins Karls Forland
10 km
W
E
C
50 ms
1 km

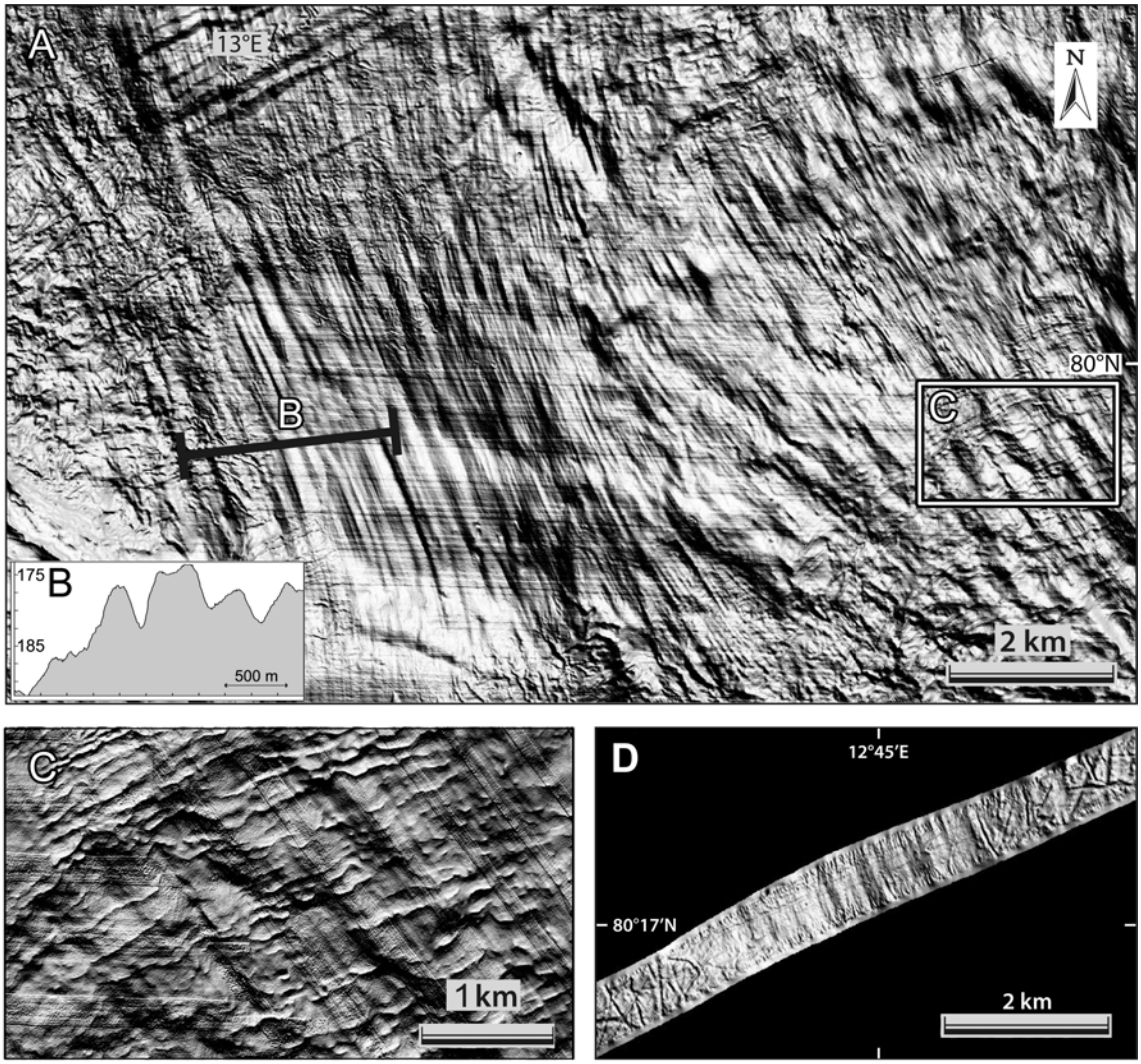



Fig. 5

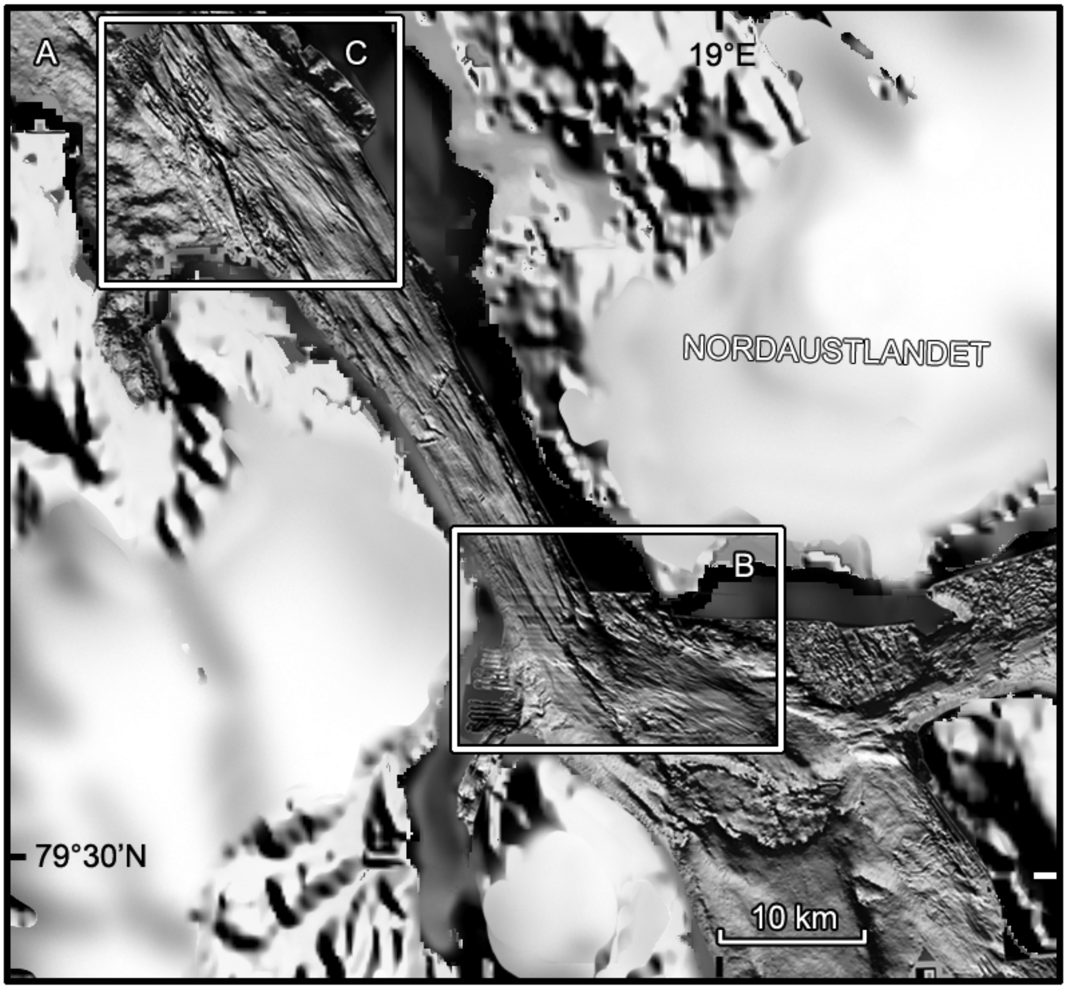



Fig. 6A

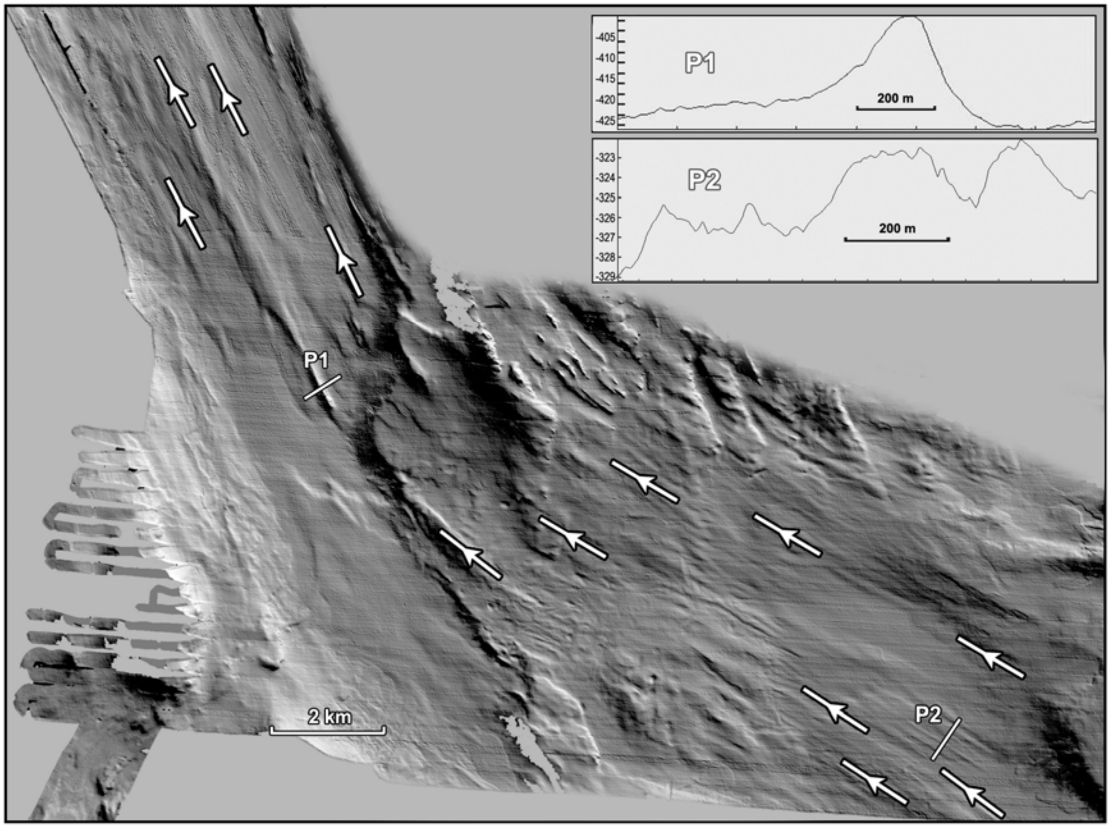

P1
200 m
-405
-410
-415
-420
-425
P2
200 m
-323
-324
-325
-326
-327
-328
-329
P1
P2
2 km

Fig. 6B

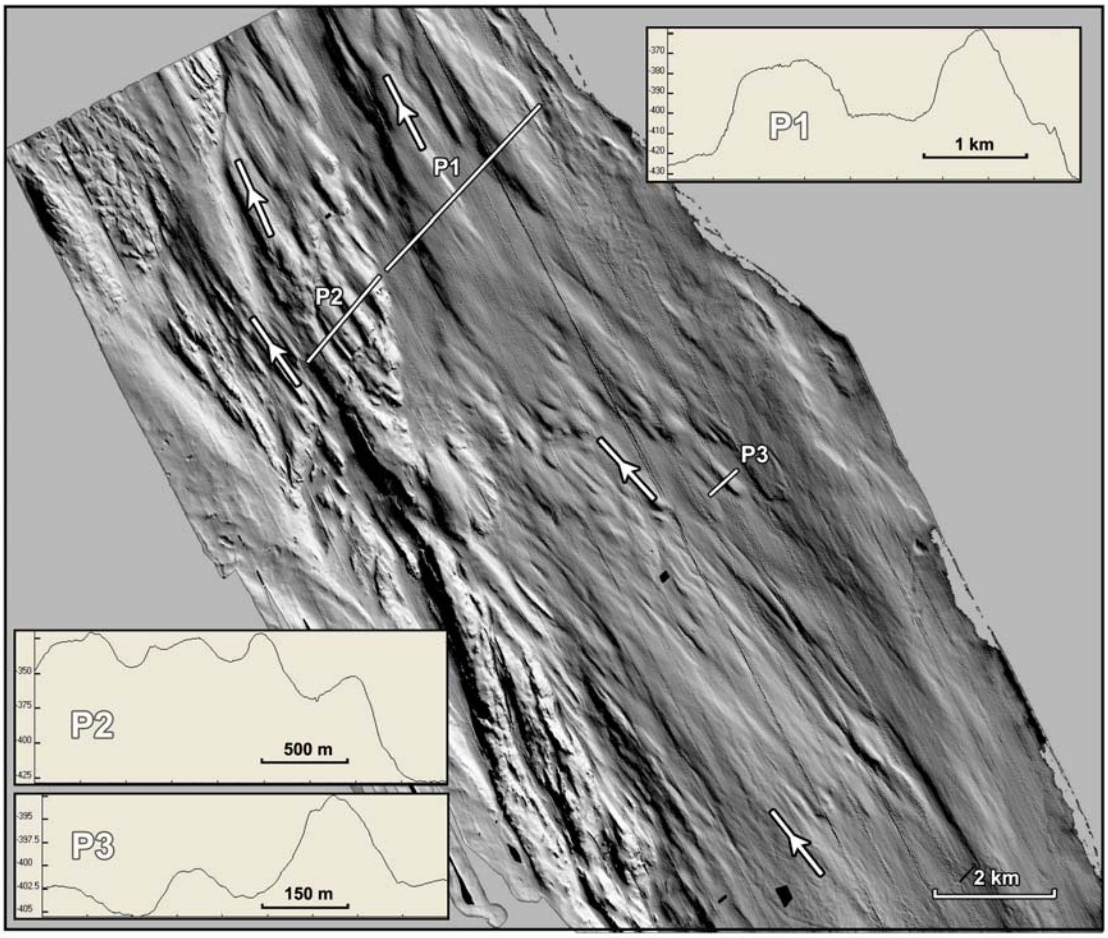



Fig. 6C

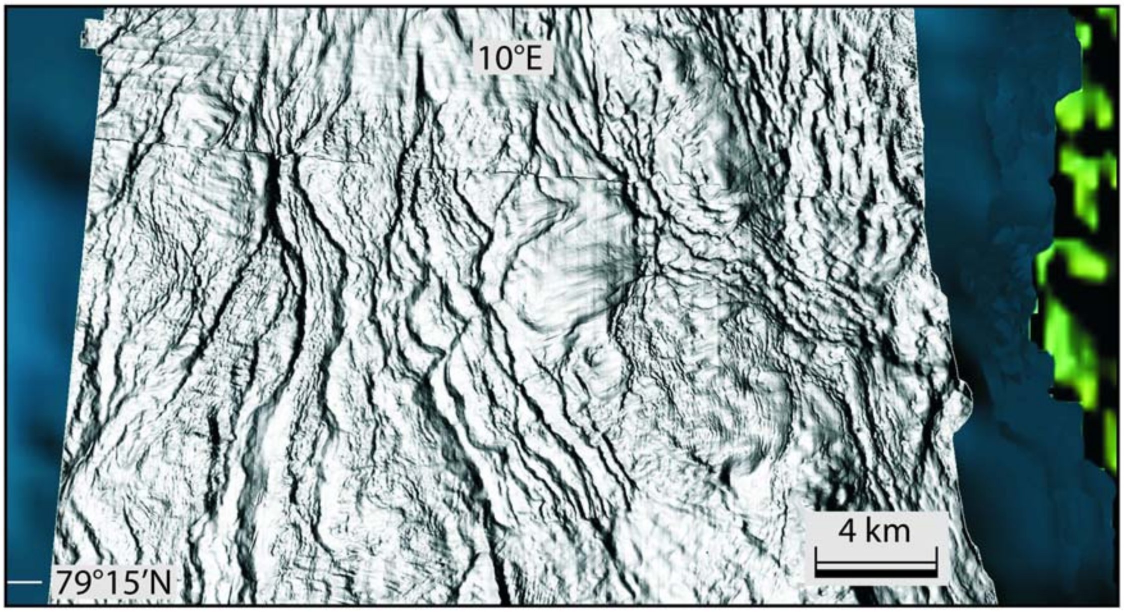



Fig. 7

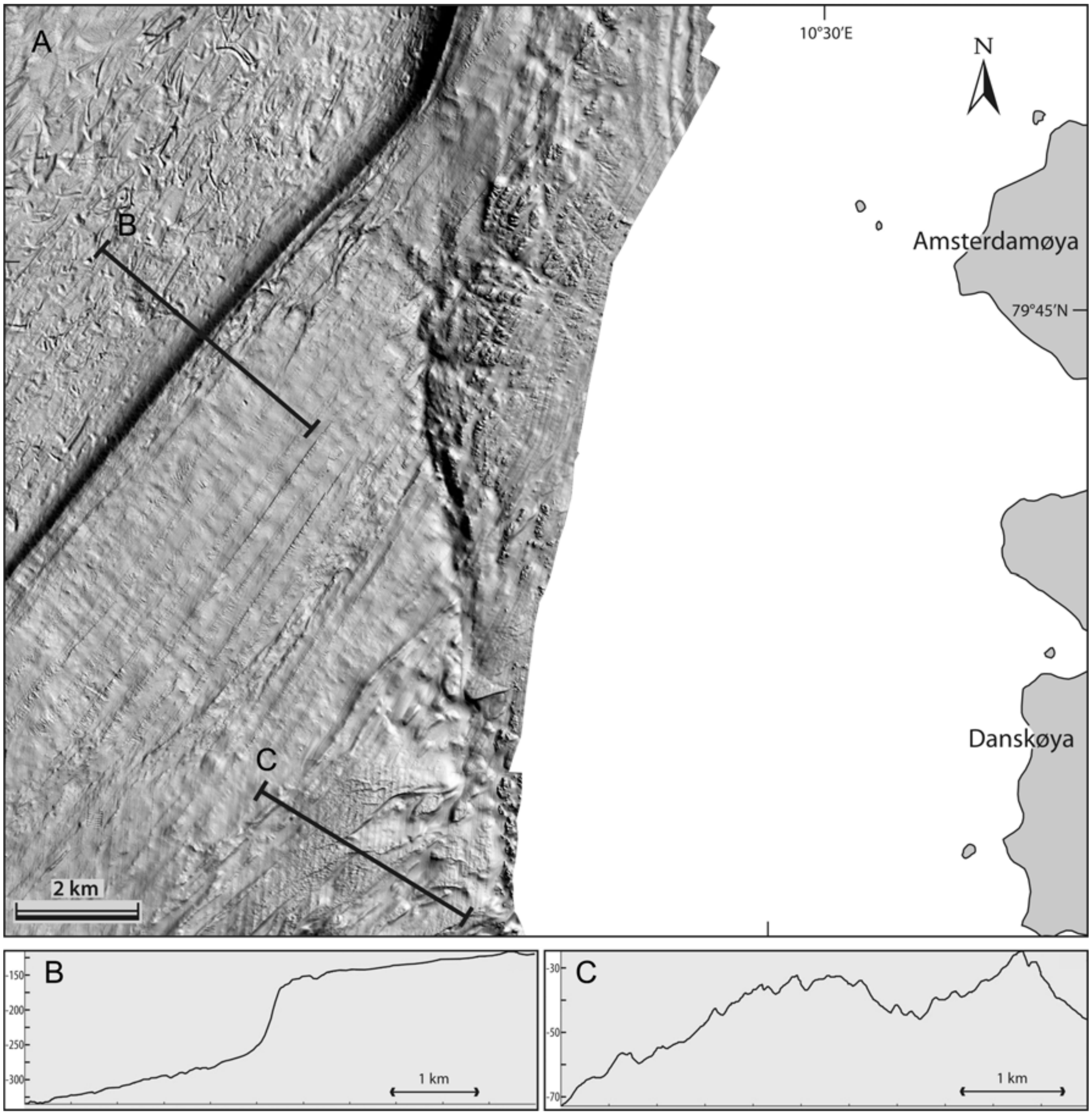

A
B
C
10°30′E
N
Amsterdamøya
79°45′N
Danskøya
2 km
B
-150
-200
-250
-300
1 km
C
-30
-50
-70
1 km

Fig. 8

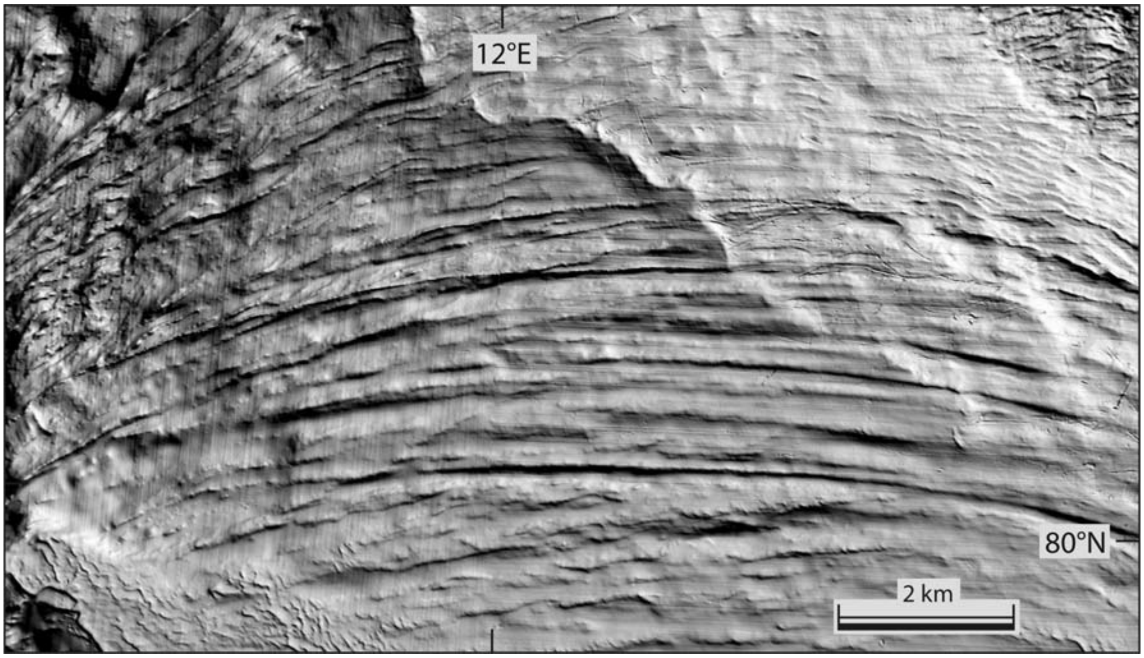



Fig. 9

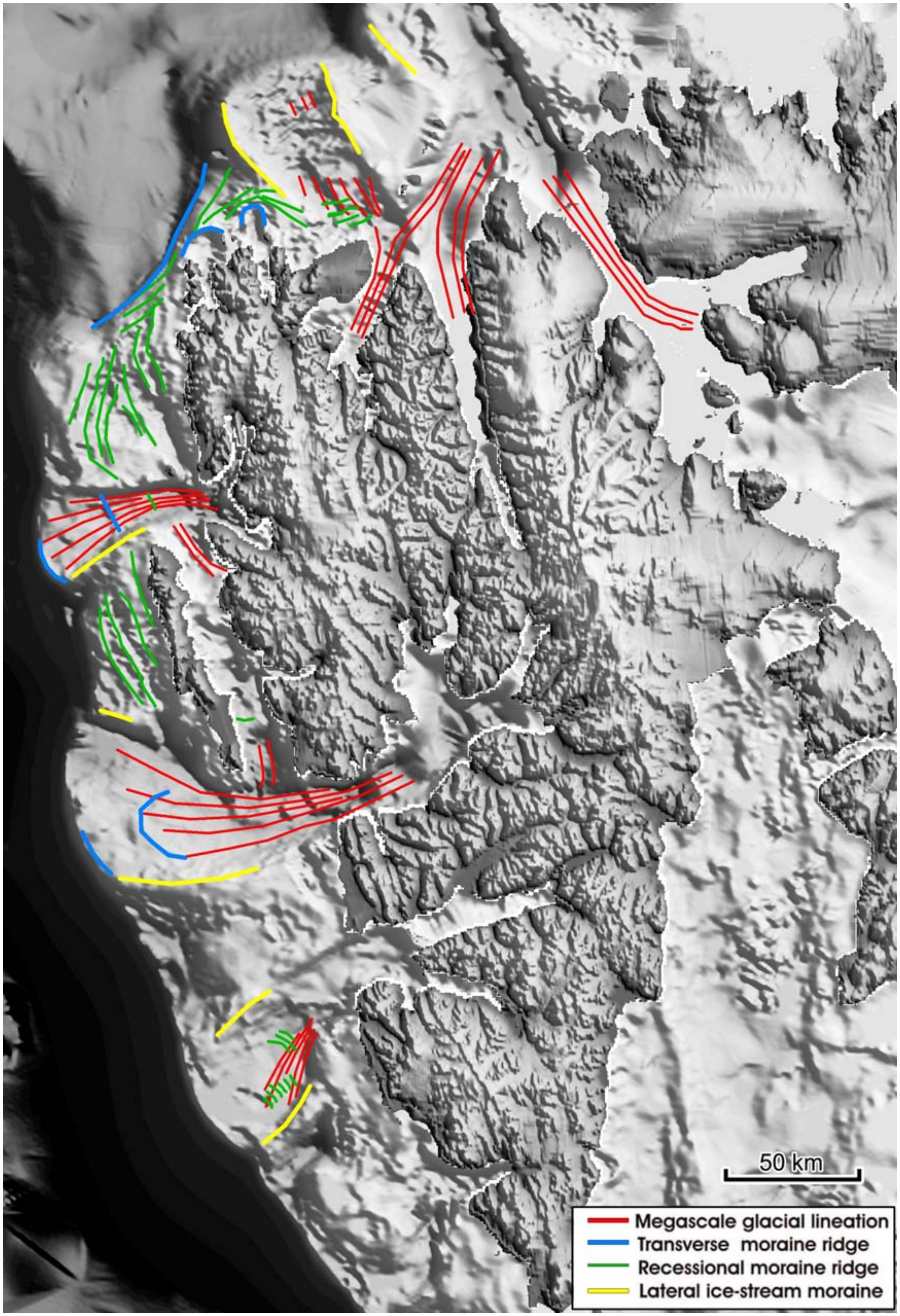

50 km
Megascale glacial lineation
Transverse moraine ridge
Recessional moraine ridge
Lateral ice-stream moraine

Fig. 10

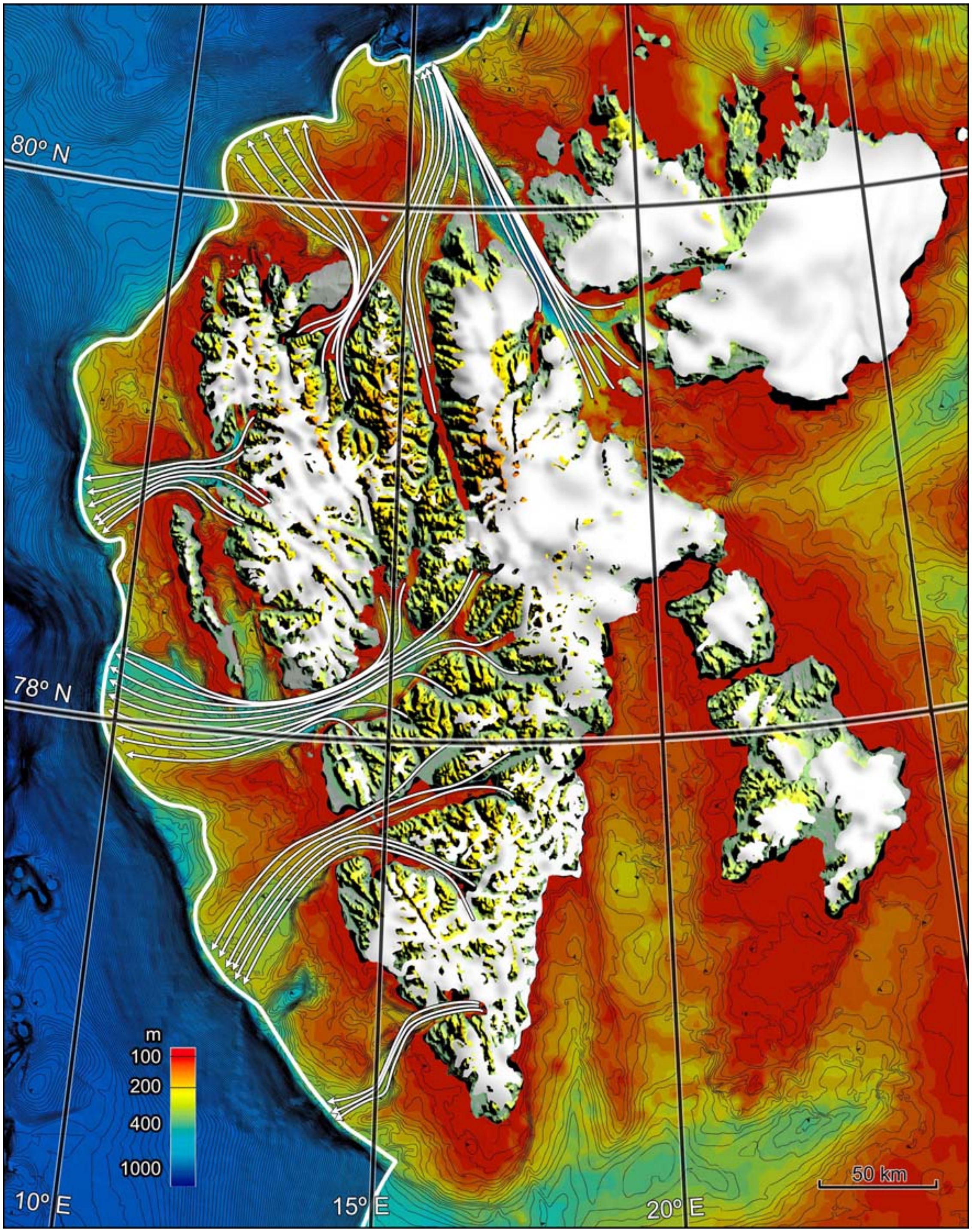



Fig. 11