An inter–ice-stream glaciated margin: Submarine landforms and a geomorphic model based on marine-geophysical data from Svalbard

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An inter–ice-stream glaciated margin: Submarine landforms and a geomorphic model based on marine-geophysical data from Svalbard

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ABSTRACT

Well-preserved submarine landforms from the continental shelf and fjords of northwesternmost Svalbard provide an example of ice-sheet deposition in an inter–ice-stream setting. EM1002 swath-bathymetric imagery covering 1280 km² was examined. At the shelf edge, a distinctive and continuous belt of hummocky topography represents the grounding zone of a slow-moving Late Weichselian ice sheet. Active ice on the outer shelf is inferred from subline lineations orientated parallel to flow. Low-amplitude transverse moraines crosscut the lineations, suggesting ice retreat across the outer shelf with brief stillstands. On the middle and inner shelf, large moraine ridges indicate multiple stillstands during deglaciation. There are arcuate moraine ridges at fjord mouths. Streamlined crag-and-tail landforms are preserved from when active full-glacial ice flowed out of the fjords. Clusters of smaller transverse ridges indicate slow retreat of grounded ice through the fjords. Holocene sedimentation is by rainout from sediment-rich meltwater, producing smooth basin fill. Small slides from the fjord walls are common. Little Ice Age glacier readvance produced another set of terminal moraines and smaller retreat moraines in the innermost fjords. A schematic model of this inter–ice-stream glacial landform assemblage summarizes the geomorphic record. It is compared with a model derived from several Svalbard cross-shelf troughs occupied by fast-flowing Late Weichselian ice streams. In general, the seafloor morphology of continental margins affected by ice streams is dominated by streamlined, subglacially produced landforms oriented in the former ice-flow direction, interrupted by major grounding-zone wedges formed during temporary halts in ice retreat. By contrast, between ice streams, shelf and fjord morphology records submarine landforms of various dimensions oriented mainly transverse to ice flow, produced at slowly retreating, grounded ice-sheet margins. There is little evidence for channeled subglacial water flow in the form of eskers and ice-contact fans on the Svalbard margin, implying that basal water is drained or advedced within soft subglacial sediments.

INTRODUCTION

Ice sheets in both the Arctic and Antarctic have grown and advanced across high-latitude continental shelves to reach the shelf edge a number of times during the Quaternary (e.g., Mangerud et al., 1998; Anderson, 1999). Once ice has retreated to its interglacial position, the dimensions and dynamics of such former ice sheets are reflected in the submarine sediments and landforms preserved on the seafloor of the deglaciated shelves and fjords (e.g., Ottesen et al., 2005; Mosola and Anderson, 2006; Dowdeswell et al., 2008). In addition to this temporal variability in ice extent, almost all ice masses, from major ice sheets to small ice caps of 10³ km², are segmented into fast-flowing ice streams separated by slower flowing ice (e.g., Bamber et al., 2000; Dowdeswell et al., 2002a). The form and flow of ice streams has been a major focus for glaciological and glacial-geological investigations of modern and past ice sheets (e.g., Alley and Bindschadler, 2001; Stokes and Clark, 2001; Anderson et al., 2002; Ó Cofaigh et al., 2003). This is because high ice-stream velocities imply that their marine margins are critical locations for the delivery of icebergs, meltwater, and sediment to the ocean (e.g., Alley et al., 1989; Dowdeswell and Siegert, 1999; Siegert and Dowdeswell, 2002). However, the areas between ice streams, whether in modern or Quaternary ice sheets, have been investigated less systematically, and relatively little evidence and discussion of the submarine landforms produced at the margin and base of such slower flowing ice has been presented.

In this paper, we focus on the shelf and fjords of northwesternmost Spitsbergen, Svalbard (Fig. 1). This area, sandwiched between the flow paths of two large paleo–ice streams (Ottesen et al., 2007), was fed by a relatively restricted ice-sheet drainage basin during both the present interglacial and the Late Weichselian (Figs. 1 and 2B). Well-preserved submarine landforms provide a high-resolution example of ice-sheet deposition in an inter–ice-stream setting. We describe and interpret the submarine landforms from three fjords (Magdalenefjorden, Smeerenburgfjorden, and Raudfjorden) and the morphology of the shelf and shelf-edge to the west and north (Fig. 1). These landforms are then discussed in the context of past ice-sheet dynamics, with particular emphasis on their setting in an area between fast-flowing paleo–ice streams, and their contrast with the morphology of ice-stream–influenced margins.

BACKGROUND: GEOLOGICAL AND GLACIOLOGICAL SETTING

North of Svalbard (Fig. 1), the 30- to 100-km-wide continental shelf ends in a relatively steep continental slope, with gradients up to 20° (mean 4°), that forms the boundary with the Eurasian Basin of the Arctic Ocean. To the west of Svalbard, a 10- to 80-km-wide continental shelf and adjacent slope separates Spitsbergen, the largest island in the Svalbard archipelago, from the structurally complex Knivpovich Ridge. The central part of this ridge is a spreading axis, which is segmented by a transform fault system, the Spitsbergen Fracture Zone. In addition, the northwesternmost corner of the shelf borders the Yermak Plateau (Fig. 1), where the oldest sediments above basement are ~35 m.y. (Jokat et al., 2008). The bedrock of the land areas comprises mainly Precambrian gneisses and migmatises (Hjelle, 1993; Dallmann et al., 2002). In the eastern part of our study area, around Hornemanntoppen, a large body of granite has intruded the surrounding rocks (Fig. 1). The floor and the eastern side of Raudfjorden

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Figure 1. Overview map of the study area in northwesternmost Svalbard, with the glaciers shown. The glacial drainage basins of Magdalenefjorden, Smeerenburgfjorden, and Raudfjorden are marked as blue dotted lines. Red stippled line marks the limit of swath-bathymetric data. The green dotted line marks the shelf edge. The inset map locates the study area in Svalbard and the shelf edge (stippled line). One hundred–meter depth contours are shown for the shelf and fjord areas. Green areas are marginal moraines, and other land areas are yellow. H—Horne- manntoppen, W—Waggonwaybreen.

constitute Devonian sedimentary rocks, mostly conglomerates and sandstones (Hjelle, 1993).

Three main fjords link the continental shelf with the largely ice-covered mountainous interior of northwesternmost Svalbard (Fig. 1)—Magdalenefjorden (10 km long), Smeerenburgfjorden (25 km long), and Raudfjorden (22 km long). The Vasalhavet (halvøya means peninsula in Norwegian) separates Smeerenburgfjorden and Raudfjorden, and the islands of Danskøya and Amsterdamsøya form the western walls of Smeerenburgfjorden. Albert I Land contains many summits around 1000 m high, and most of the area is covered by modern glaciers. Several summits on Vasalhavet reach between 500 and 1000 m, and the highest mountain reaches a little more than 1000 m.

Modern glaciers that flow into the fjords of northwesternmost Spitsbergen are located on Albert I Land and Vasalhavet (Fig. 1). The drainage basin of each of the major tidewater glaciers is shown. The catchment areas of Magdalenefjorden, Smeerenburgfjorden, and Raudfjorden are 150 km², 420 km², and 360 km², respectively, of which 40–60% is ice covered today (Table 1). These drainage basins are an order of magnitude smaller than the catchments draining into Kongsfjorden-Krossfjorden (2700 km²) and Isfjorden (8500 km²) to the south and Woodfjorden-Wijdefjorden (7600 km²) to the east (Table 1 and Fig. 1). It is the Kongsfjorden and Woodfjorden systems that constrain the size of the interior basin feeding into our study area in northwesternmost Svalbard today.

We have also reconstructed the ice-flow directions and locations of fast-flowing ice streams on Svalbard during the last, Late Weichselian glaciation (Fig. 2B; Ottesen et al., 2005, 2007), using streamlined submarine landforms known as megascale glacial lineations (Clark, 1993). Each of these paleo–ice streams was located in a cross-shelf trough. The ice streams to the south and east restrict the size of the full-glacial ice sheet flowing into our study area (Fig. 2B). It is likely that the full-glacial Wijdefjorden-Woodfjorden ice-sheet drainage basin would have been even larger than at present, due to the location of the Late Weichselian ice center east of Svalbard (Forman et al., 2004). It should also be noted that the cross-shelf troughs that link these larger fjords to the continental shelf edge are absent from the shelf of northwesternmost Svalbard.

We calculate the balance flux, Qw, for each of the drainage basins listed in Table 1, to approximate the differences in the volume of ice delivered to the full-glacial margin of each catchment. Balance flux varies with ice-sheet area and accumulation rate, α, and describes the mass discharged at the ice margin so that ice-sheet volume maintains equilibrium with the accumulation rate (Clarke, 1987):

\[ Q_w(x) = \int w(x_c) \alpha(x_c) \delta x_c, \]  

where \( w(x) \) is basin width and \( x \) is position along a basin’s longitudinal axis. If we assume a full-glacial accumulation rate of 0.5 m yr⁻¹ over Svalbard, then the balance flux is ~4 km³ yr⁻¹ for the Isfjorden and Woodfjorden-Wijdefjorden basins, and ~1.5 km³ yr⁻¹ for Kongsfjorden-Krossfjorden. For the smaller northwesternmost Spitsbergen basins, balance flux is an order of magnitude less at no more than 0.2 km³ yr⁻¹, a difference that would be the same independent of the absolute accumulate rate chosen to represent full-glacial conditions. These rough calculations of ice flux make clear that fast flow across the northwesternmost Spitsbergen shelf would be difficult to maintain, and support the view that this part of the Svalbard margin is likely to be an inter–ice-stream area.

Quaternary sediments of glacial origin comprise the seafloor over most of the fjords and adjacent shelves of northwesternmost Svalbard, mainly covered by a thin veneer of Holocene marine mud. Several parts of the study area also reveal exposed bedrock. Liestøl (1972) mapped up to three major moraines extending onto the shelf ~10 km beyond the mouths of Magdalenefjorden, Smeerenburgfjorden, and Raudfjorden on the basis of early regional bathymetric data. In the absence of any chronological control, these moraines were suggested to mark the extent of ice at the Late Weichselian maximum (Liestøl, 1972), although we now know that full-glacial ice reached the shelf edge. Landvik et al. (2003) presented a series of ¹⁰Be exposure ages from bedrock and erratic boulders on Danskøya and Amsterdamsøya (Fig. 1). The cosmogenic ages indicated that these islands had not been completely covered by ice for at least the past 80,000 yr. In addition, the presence of undisturbed block fields on gently sloping plateaus above ~300 m in elevation, and a predominance of sculpted glacial features on bedrock at lower elevations, support this view. This suggests that full-glacial ice was not thick enough to bury the higher mountains and plateaus completely.

**DATA ACQUISITION AND METHODS**

Multibeam or swath-bathymetric data of the seafloor on the northwesternmost Svalbard margin were acquired by the Norwegian Hydrographic Service in the summers of 2003 and 2004. A Kongsberg Simrad EM1002 swath-bathymetry system was used to image most of the fjord and shelf areas, together with part of the upper continental slope down to ~400 m in water depth. The system has a frequency of 97 kHz and emits 111 individual beams. The area of study, between 79°30'N and 80°N and 10°E and 12°15'E, gives a total of ~1280 km² of swath-bathymetric imagery. The whole swath mosaic is shown in Figure 2A.

The swath-bathymetric data were gridded with a 2 m, 5 m, or 10 m horizontal cell size. Errors in vertical elevation of the seafloor were ~0.5% of water depth. The raw multibeam data were processed using Kongsberg Simrad Neptune software, and corrections for tidal variations and the sound-velocity structure of the water column were also applied. Swath data were displayed as black-and-white or color-shaded relief images at different scales. We used ER-Mapper, Geosoft, and ARCGIS software for visualization and interpretation of the data and in the production of the images and bathymetric profiles presented here.

**SWATH IMAGERY OF THE CONTINENTAL SHELF AND SHELF EDGE**

**Shelf Edge and Outer Shelf**

**Description**

The continental shelf edge at the west of the study area is located at water depths between 150 and 290 m (Fig. 1). The shelf edge is well defined and unindented for the 40-km length of our seafloor imagery (Fig. 2A). It has a relatively steep break of slope with the gradient of the continental slope initially at ~20°, decreasing rapidly with distance westward (Figs. 3A and 3C). The outer 10 km or so of the shelf has generally subdued relief with amplitudes of only a few meters. Offshore of Danskøya and Amsterdamsøya, outcropping crystalline bedrock influences the gross shape of the shelf, its western limit marked by a change to more subdued recent sedimentary deposits (Fig. 2A).
Figure 2. (A) Swath bathymetry of the seafloor in the study area. Bathymetric contours are given in the previous figure. C—crystalline bedrock. (B) Distribution of fast-flowing ice streams (subparallel white lines) at the Late Weichselian glacial maximum with individual catchments shown (modified from Ottesen et al., 2007). Is—Isfjorden, Ko—Kongsfjorden, M—Magdalenefjorden, R—Raudfjorden, S—Smeerenburgfjorden, Wo—Woodfjorden, Wi—Wijdefjorden.
Three landform styles are present on the outer shelf. The first is a series of very subdued ridges oriented at right angles to the shelf edge (dotted lines in Fig. 3A). These subdued ridges have amplitudes of less than 1 m and a wavelength of several hundred meters. The second landform type is a well-defined, persistent and linear belt of irregular hummocky terrain about a kilometer in width, which terminates abruptly at the shelf edge (Figs. 3A and 3B). The irregular hummocks and ridges have amplitudes of ~5 m (Fig. 3D). This irregular terrain is less well developed along the southern part of the outermost shelf. Inshore of this hummocky belt, the seafloor is generally smooth but broken by a third set of features—a series of ridges oriented subparallel to the shelf edge (marked with arrows in Fig. 3A). The ridges have amplitudes of 1–3 m and are spaced a few hundred meters apart. Like the shelf edge itself, they are rather straight and unbroken over distances of several kilometers. These ridges also crosscut the subdued ridges described above at ~90°, and therefore postdate them. Finally, in the deeper water beyond the shelf edge, highly irregular furrows that frequently crosscut one another are present (Figs. 2A and 3A). Few such irregular features are seen on the shallower shelf.

Interpretation

Several lines of evidence indicate that ice reached the shelf edge of northwesternmost Svalbard during the last full glacial and then retreated without significant stillstands across the relatively smooth outer shelf. We discuss each of the main submarine landform types in turn.

(1) The subdued ridges, parallel to one another but orthogonal to the shelf edge, are interpreted as indicators of the presence and direction of former ice flow. However, they are neither as long, nor as clearly defined, as the megascale glacial lineations that are typically found in high-latitude cross-shelf troughs and mark the presence of fast-flowing ice streams draining large interior ice-sheet basins (e.g., Stokes and Clark, 2001; Ottesen et al., 2005). As such, they do not provide evidence of ice streams on the northwesternmost Svalbard shelf. A lack of ice-stream activity in the area is also implied by the relatively small dimensions of the catchments draining northwesternmost Svalbard both today and at the Late Weichselian maximum, and the associated balance fluxes (Equation 1), which are an order of magnitude smaller than those supplying ice streams in the Woodfjorden-Wijdefjorden, Kongsfjorden-Krossfjorden, and Isfjorden systems (Table 1 and Fig. 2B).

(2) The well-defined linear belt of hummocky sedimentary terrain at the shelf edge (Figs. 3A and 3B), combined with the steep face of the shelf edge immediately offshore (Fig. 3C), also implies the past presence of ice. The irregular shape of hummocks, ridges, and depressions is typical of glaciated sediments, and it is difficult to see it being produced by marine processes. The ice margin must have been aground to form such features, and we propose that this terrain represents the grounding zone of a tidewater ice margin (e.g., Powell and Domack, 1995). Changes in buoyancy, perhaps tidally induced (Bindschadler et al., 2003), may have produced the observed features in a zone of ice-marginal flexure. They were formed in deformable sediments that could have been molded under the irregular surface of the ice or squeezed upward into basal crevasses. The steep, regular face at the shelf edge also implies the delivery of subglacial deforming sediment to the ice margin along a line source. By contrast, the absence of small ice-contact fans, indicative of delivery from point sources of subglacial meltwater (Boulton, 1986; Powell, 1990), also suggests that channelized basal water was largely absent under full-glacial conditions.

(3) Inshore of the hummocky belt, the subdued outer-shelf topography, broken by low-amplitude ridges, suggests the consistent retreat of grounded ice, perhaps relatively close to buoyancy, with few of the stillstands needed to build larger moraine systems. The lateral continuity of the ridges over a number of kilometers also implies systematic retreat along a wide ice front.

In addition to submarine landforms on the outer shelf, the many irregular and crosscutting furrows in our swath imagery from beyond the shelf edge are interpreted as plowmarks produced by the action of iceberg keels where they impinge on the seafloor (e.g., Woodworth-Lynas et al., 1991). The largest observed plowmark, in the northwest corner of our swath mosaic (Fig. 2A), is 10 m deep, 360 m wide, and at least 6 km long where it disappears beyond the northern limit of swath coverage. The water-depth range of these plowmarks is from 280 m to 420 m (the maximum water depth in the data set). Modern Svalbard glaciers do not generally produce icebergs of this size because they are grounded rather than floating and tend to calve large numbers of relatively small icebergs (Dowdeswell, 1989; Dowdeswell and Forsberg, 1992). These plowmarks are, therefore, likely to be mainly relict features, probably linked to iceberg production during Late Weichselian deglaciation. Iceberg keel plowmarks have been observed on the adjacent Yermak Plateau to water depths of 800 m (Vogt et al., 1994), although they may be from earlier deglacial phases (Flower, 1997).

Middle and Inner Shelf

Description

By contrast with the relatively low amplitude of seafloor features on the outer shelf, the middle and inner shelf of northwesternmost Svalbard has much greater relief (Fig. 2A). Four sets of features are present. The first features, and the most obvious on swath imagery, are several sets of large curvilinear ridges, which tend to form a radial pattern beyond the mouths of the three major fjords. This radial pattern is best developed on the shelf outside Raudfjorden (Fig. 2A). The ridges are illustrated in Figures 4 and 5. They are up to 30 m high and spaced hundreds of meters apart (Figs. 4C and 5B). A second landform type, usually found between and sometimes on the flanks of these large ridges, comprises sets of smaller transverse ridges. These ridges often form clusters of up to about ten which are spaced more closely than the large ridges and have amplitudes usually less than ~10 m (Figs. 4D and 5C). A third submarine feature is represented by flat areas, often on the tops of ridges, with sediment waves on their surfaces (black arrows in Fig. 4B). These features are most clearly developed around the mouths of Smeerenburgfjorden and Raudfjorden at shallow water depth of less than ~45 m (Figs. 4A and 4E). The sediment waves are only a meter or two in amplitude, but the inshore face of the flat sheets can be more than 15 m in height (Fig. 4E). Finally, there are a number of areas on the inner shelf where crystalline bedrock, sometimes with a clear structural control, is present at the seafloor.
Figure 3. (A) Shaded-relief swath bathymetry of the outer shelf and upper slope, showing a well-defined belt of hummocky terrain at the shelf edge (located in Fig. 1). Note the irregular furrows in the deepest water beyond the shelf. The dotted lines indicate two examples of a set of subdued ridges. The arrows mark the crest of two small retreat moraines. (B) Detail of the grounding-zone area immediately inshore of the shelf edge (located in A). (C) Bathymetric profile across the innermost continental slope and shelf-edge grounding zone. (D) Bathymetric profile across the ice-sheet grounding zone.
Figure 4. (A) Shaded-relief swath bathymetry of middle shelf areas, with numerous well-developed ridges north of Smeerenburgfjorden and Raudfjorden (located in Fig. 1). (B) Detail of migrating sand waves on moraine ridges. Black arrows show crest of sand waves. Red arrow indicates general flow direction of bottom currents. (C) and (D) Bathymetric profiles across transverse ridges. (E) Bathymetric profile across sand-wave field.
This is especially obvious in the shallow areas outside Danskøya and Amsterdamøya and south of the entrance to Magdalenefjorden, where the seafloor morphology shows an irregular hummocky pattern of crystalline rocks (Fig. 2A).

**Interpretation**

In addition to exposed bedrock, which we do not discuss further, the three main types of sedimentary feature found on the inner and mid-shelf are interpreted as follows.

1. The relatively large radial ridges are interpreted to be moraine systems, built up during frequent stillstands in ice retreat across the middle and inner shelf during Late Weichselian deglaciation. The radial pattern of the ridges indicates that the ice that produced them derived from the three major fjord systems in the area. These are the moraines that Liestøl (1972) inferred to mark the Late Weichselian maximum. We now know, from the glacial sedimentary features on the outer shelf (Fig. 3), that ice reached beyond the limit of these large moraines at the last full glacial.

2. The smaller ridges, subparallel to the larger moraines, are also inferred to have been produced during ice retreat. They are likely to be small push moraines, associated with short-period, sometimes winter, ice readvance during overall retreat (Boulton, 1986; Ottesen and Dowdeswell, 2006; Ottesen et al., 2008). Similar clusters of small subparallel ridges have been described from troughs in the Ross Sea in Antarctica, the Canadian shelf, and Bellsund in Svalbard, where they are interpreted as indicators of minor readvances of a grounded ice front during overall retreat (Shipp et al., 2002; Todd et al., 2007; Dowdeswell et al., 2008). Their form, and probably also their origin, is therefore similar to that of De Geer moraines (e.g., Lindén and Möller, 2005).

3. The flat areas with surface waves are likely to be made up of sand sorted by relatively strong shallow-water currents (Stride, 1972). The currents responsible for the sand waves appear to be reworking the crests of some larger moraine ridges, and the migrating faces of the sand sheets are steep on bathymetric profiles (Figs. 4B...
and 4E). The well-defined nature of the steep inner edges suggests that the sand waves remain active. The ridges of the sand waves and the free faces of the sheets are orientated parallel to one another (Stride, 1972). The direction of migration, and therefore of current flow, is inferred to be orthogonal to these features (red arrow in Fig. 4B). Their orientation indicates that bottom currents in shallow areas of the inner and mid-shelf are flowing west and southwestward around the northwestern tip of Svalbard. Bottom currents also appear to have flowed into Raudfjorden in particular (Fig. 4A), presumably compensated for by the surface outflow typical of fjord circulation (Syvitski et al., 1987). The flat surfaces on which the sand waves are found may be relict features, formed under a lower sea-level stand during deglaciation, when moraine-ridge crests were beveled off just below the surf zone.

**SWATH IMAGERY OF FJORDS**

**Magdalenefjorden**

**Description**

The most notable feature of the seafloor in Magdalenefjorden is its smoothness (Figs. 6A and 6B). Each of the deeper basins in the fjord has a flat floor, and sediment also appears to infill smaller closed basins and to drape the underlying topography where knobs assumed to be formed of bedrock protrude (B in Fig. 6B). In the outermost part of the fjord, several large transverse sedimentary ridges are present, some of them arcuate (R in Fig. 6A), and at the constriction ~5 km from the inshore limit of our coverage there appears to be a further substantial transverse ridge (Fig. 6A). The deep inner basin of Magdalenefjorden, reaching 130 m, again has a smooth floor. However, it also exhibits a series of scars, and possibly some gullies, on each steep sidewall (Fig. 6C). Some scars appear to be draped by subsequent sedimentation.

The innermost part of the fjord imaged in our swath coverage is ~1 km from the present terminus of a tidewater glacier, Waggongwaybreen. Here, there is a large ridge ~40 m high across the fjord and a series of small ridges, of less than 5 m in amplitude, closer to the modern glacier and subparallel to the larger one (R in Fig. 6C). A similar set of ridges is present offshore of Gullybreen, some 4 km downfjord and on the southern limit of our swath coverage (Fig. 6A).

**Smeerenburgfjorden**

**Description**

Smeerenburgfjorden has three deep basins, reaching up to 200 m in water depth (Fig. 7A). The floors of each basin have mainly flat and smooth surfaces. Large ridges, often arcuate, are found in the mid-fjord separating the middle and outer basins (Fig. 7A). Large arcuate ridges on the inner shelf also define the limit of the outer basin (Fig. 2A). A further arcuate ridge cuts across the fjord adjacent to Svitjodbreen, a glacier that drains from Vasahalvoya on the east side of the fjord (Figs. 1, 7A, and 7B). In the deeper water between them, there are several sets of small transverse ridges, most clearly developed in the outer fjord (R in Fig. 7B). The ridges are typically a few meters high and spaced ~200 m apart. A further set occurs in the shallower waters separating the inner basin from the deep waters of the mid-fjord basin (Fig. 7A).

In the innermost part of the fjord, within 2 km of the present tidewater glacier terminus of Smeerenburgbreen, is a single, 30-m-high ridge running across the fjord (Fig. 8). About 20 smaller ridges, with amplitudes of a few meters and average spacing of 100 m, occur inshore of the larger ridge to the limit of our data coverage (Figs. 8A and 8D). The ice-distal side of the large ridge has a relatively steep slope of ~5° (Fig. 8B) and has a series of gullies running down its face into the flat floor of the inner basin (Figs. 8A and 8C). The gullies are a few meters deep and have a spacing of 50–100 m.

The steep sidewalls of Smeerenburgfjorden also exhibit over 30 slide scars together with associated blocky depositional areas on the fjord floor (Fig. 7). Taking the scars and blocky areas together, typical widths and lengths are 0.2–0.5 km and 0.5–1 km, respectively (Figs. 7C and 7D). The scars are usually a few meters deep, and the blocky areas below them are raised a similar amount above the general level of the seafloor. These features are present on both sides of the fjord.

**Raudfjorden**

**Description**

Several submarine landforms occur in Raudfjorden inshore of the large moraine ridges and associated sand-wave fields on the inner shelf beyond its mouth (Fig. 9A). The deep water down the fjord long-axis is interrupted by a number of outcrops of bedrock, which appear as rough, shallow areas in Figure 9A (marked “B”). Where relatively small bedrock knobs protrude upward they are often linked to streamlined sedimentary features on their down-fjord sides, similar to landforms known as crag-and-tail (Benn and Evans, 1998). Several such features are imaged in detail, especially on the eastern side of the outer fjord, in Figure 9B (marked “C”). Inshore of the large, 40-m-high ridge at the fjord mouth is a series of ~40 smaller subparallel ridges (Figs. 9B–9D).

These ridges have amplitudes from 1 to 5 m and are spaced ~200 m apart. There are additional scattered small ridges on the western side of the fjord and a further cluster at the innermost part of our swath coverage (Fig. 9A). In addition, the deep inner basin of Raudfjorden, which reaches 220 m, is flat and smooth (Fig. 9A). No slide scars are observed on the sidewalls of Raudfjorden.

**Interpretation of Fjord Submarine Landforms**

A number of submarine landforms have been described from swath imagery of the three major fjords in northwesternmost Svalbard (Fig. 2). There are considerable similarities between the features observed in the different fjords, and these landforms are now summarized and interpreted in terms of, first, those produced directly by ice and, secondly, those associated with sediment reworking subsequent to initial glacial deposition. The landforms in the former category are discussed in order of their relative age, with the oldest first.

(1) Crag-and-tail landforms are found only in Raudfjorden (Fig. 9). They are streamlined features produced at the bed of moving ice. Their upstream core is of bedrock, with glacial sediment deposited in the lee of the bedrock knob and extending up to several kilometers downstream before pinching out. They are inferred to be the oldest sedimentary landforms in the fjords because they are the only features formed beneath active ice.

(2) Large and sometimes arcuate sedimentary ridges, often continuous across the fjord axis, are inferred to have formed during stillstands in ice retreat, allowing time for significant sediment deposition to take place. Groups of these moraine ridges are found just beyond the mouths of each fjord (Fig. 2). Arcuate moraine systems are common features at the margins of modern piedmont-glacier lobes that spread out onto lowlands after leaving confining valley walls (e.g., Dowdeswell et al., 2007). Within the fjords, some large ridges occur at lateral and vertical constrictions, which act as pinning points for stillstands of the ice front during retreat.

(3) Inside these large retreat moraines are series of smaller transverse moraines, which are also interpreted to be produced during retreat, but at more frequent intervals. They are assumed to be formed by ice pushing of sediment, including folding, faulting, and even thrusting (Hagen, 1987; Boulton et al., 1996), during minor readvances of grounded ice margins during more general retreat. By analogy with well-dated and very similar landforms in other Spitsbergen fjords, they can be produced.
Figure 6. (A) Shaded-relief swath bathymetry of Magdalenefjorden (located in Fig. 1). G—Gullybreen, R—Ridge. (B) Smooth sedimentary infill of bedrock basins and draping of bedrock in the mid-fjord. B—Bedrock outcrop (located in A). (C) Detail of inner Magdalenefjorden, showing Little Ice Age moraine ridge (at the right marked with R), smaller transverse retreat ridges and slide scars (located in A).
Figure 7. (A) Shaded-relief swath bathymetry of Smeerenburgfjorden (located in Fig. 1). Sv—Svitjodbreen. (B) Outer fjord, showing transverse ridges (marked with R) and basin-fill sediments. (C) Inner fjord showing slide scars on fjord walls and blocky depositional zones on the smooth fjord floor. (D) Bathymetric profile across slide lobe.
Figure 8. (A) Shaded-relief swath bathymetry showing detail of the Little Ice Age moraine and transverse retreat ridges in innermost Smeerenburgfjorden (located in Fig. 1). Note the similarity with innermost Magdalenefjorden (Fig. 6C). (B) Bathymetric profile across major ridge and the set of smaller ridges closer to the modern tidewater glacier, Smeerenburgbreen (located in A). (C) Bathymetric profile across gullies on the ice-distal face of the Little Ice Age moraine ridge (located in A). (D) Bathymetric profile across smaller transverse moraine ridges.
Figure 9. (A) Shaded-relief swath bathymetry of Raudfjorden (located in Fig. 1). B—Bedrock outcrop. (B) Detail of outer fjord showing migrating sand waves, major and smaller scale transverse ridges, and crag-and-tail features (marked with C) (located in A). (C) and (D) Bathymetric profiles (located in B).
as frequently as one per year, although this is not necessarily the case here (Boulton et al., 1996; Ottesen and Dowdeswell, 2006; Ottesen et al., 2007). In Raudfjorden, some sets of small retreat moraines are superimposed on crag-and-tail deposits (Fig. 10B), indicating that they are younger than the subglacially formed features.

(4) In the deep basins of each fjord, but especially well expressed in Magdalenefjorden (Fig. 6B), the flat seafloor is interpreted as fine-grained sediment deposition from glacial meltwater. The meltwater-derived silts and clays rain out slowly on the seafloor and drape the preexisting topography. Acoustically laminated fine-grained hills have been observed in many basins in Spitsbergen fjords (e.g., Elverhøi et al., 1983; Sexton et al., 1992). Furthermore, Spitsbergen fjords are known to be dominated by sediment delivery from subglacially or glaciﬂuvially derived meltwater rather than by iceberg-rafting of debris, which probably accounts for less than 5% of sediment delivery since deglaciation (Dowdeswell and Dowdeswell, 1989). In Magdalenefjorden, in particular, there is morphological evidence that older submarine landforms are being buried by the rainout of such fine-grained sediment. This is a depositional process that continues today at rates of millimeters to centimeters per year, depending on distance from tidewater glacier and glacier-fed river sources (Elverhøi et al., 1980; Dowdeswell and Dowdeswell, 1989).

(5) Although similar landforms to the large and smaller moraine ridges discussed in (2) and (3), the juxtaposition of these two moraine-ridge landform types within a few kilometers of modern tidewater glaciers in Smeerenburgfjorden and Magdalenefjorden justiﬁes further discussion (Fig. 8). The larger moraine ridges are interpreted to mark the Little Ice Age maximum glacier position in Svalbard fjords. Lichenometrically dated moraines on land yield ages of ~120 yr for this maximum on Svalbard (Werner, 1993), and similar lateral moraines at the subaerial margins of many fjords can be traced unambiguously below the seafloor (e.g., Sexton et al., 1992; Ottesen and Dowdeswell, 2006; Ottesen et al., 2007). The smaller moraine ridges, inside the terminal moraine and closer to the modern glacier front, are produced regularly and often annually (Boulton, 1986; Boulton et al., 1996; Ottesen and Dowdeswell, 2006). These are, therefore, the most recent submarine glacial landforms in the fjords.

In addition to these glacial landforms and processes, several mechanisms of sediment mobilization and reworking are also recorded in the fjord landforms. First, the tops of several shallow-water moraine ridges at fjord mouths were probably beveled off during a period of lower deglacial sea level, and current activity continued through the Holocene with migrating sand waves partly obscuring the preexisting glacial topography (Fig. 9). Secondly, submarine mass movements, in the form of slides on steep fjord walls, have produced slide scars and downslope blocky deposits that reach out onto the smooth fjord floor in some places (Fig. 7C). Some slides appear to have overridden small transverse ridges, indicating relatively recent activity (Fig. 10C). Some older slides have, by contrast, been partly buried by subsequent fine-grained sedimentation (Fig. 6C), suggesting that submarine slope failures have continued over an extended period since deglaciation. Finally, isolated plowmarks from grounding iceberg keels are observed in the fjords, although this is a minor process in the three fjords studied here because the tidewater glaciers draining into them have relatively small catchments and produce relatively few larger icebergs.

**INTER-ICE-STREAM SUBMARINE LANDFORMS: DISTRIBUTION AND A SIMPLE MODEL**

**Distribution Pattern of Submarine Landforms**

The distribution of submarine landforms over our whole study area on the shelf and in the fjords of northwesternmost Svalbard, described and interpreted above, is shown in Figure 10A. The distinct belt of hummocky and ridged topography within a kilometer or so of the shelf edge represents the grounding zone of the Late Weichselian ice sheet at its maximum position. The presence of active Late Weichselian ice on the outer shelf is also inferred from subtle but well-deﬁned ridges of sediment orientated in the direction of past ice ﬂow from fjords to shelf edge. Low-amplitude transverse moraines crosscut these ice-ﬂow indicators and suggest ice retreat across the outer shelf with only short-lived stillstands.

On the middle and inner shelf there is much evidence, in the form of large and often arcuate moraine ridges, of multiple stillstands during deglaciation from the Late Weichselian maximum (Fig. 10A). These large moraines are probably not linked to a readvance of ice to the fjord mouths during the Younger Dryas cold phase, given the very small size of Younger Dryas glaciers in western Spitsbergen (Mangerud and Landvik, 2007). The crests of some of these large ridges have been beveled when close to the surf zone during lower deglacial sea-level stands. They continue to be affected by currents and migrating sand-wave fields, indicating west and southwestward flow around the northwestern tip of Svalbard. There are also extensive areas of crystalline bedrock exposed on the shelf (Fig. 10A).

The fjords themselves have large moraine ridges at their mouths, and sometimes at shallows or constrictions within the fjord which are inferred to have acted as pinning points during ice retreat (Fig. 10A). Streamlined crag-and-tail landforms in Raudfjorden are preserved from the time when active full-glacial ice ﬂowed out of the fjord and are crosscut by younger retreat moraines (Fig. 10B). Clusters of smaller transverse ridges indicate the slow retreat of grounded ice through the fjords, where Holocene sedimentation has been dominated by rainout of silts and clays from sediment-rich meltwater to produce ﬂat-floored fjord basins and to drape exposed bedrock topography (Fig. 6). Small slides from the steep fjord sidewalls are common in Smeerenburgfjorden (Fig. 10A). They appear to have formed throughout the period since deglaciation because some are draped by ﬁne-grained sediment whereas others have overridden moraine ridges (Fig. 10C). Ice re-advance during the Little Ice Age has produced a further set of terminal moraines and smaller retreat moraines in the innermost part of the fjords within a few kilometers of modern tide-water glaciers (Figs. 8 and 10A).

**A Simple Model of an Inter–Ice-Stream Glacial Landform Assemblage**

The submarine glacial landforms, mapped in Figure 10A, are illustrated in the form of a simple three-dimensional schematic model in Figure 11A. The assemblage of landforms represents a geomorphic record of ice advance and retreat across a continental shelf to the shelf edge from a mountainous, fjord-dissected landmass. This Late Weichselian ice advance and retreat took place in a glaciological setting where fast-ﬂowing ice streams draining large interior ice-sheet basins were not present. We refer to this suite of submarine landforms as an inter–ice-stream glacial landform assemblage.

There are ﬁve subsets of landforms that make up this assemblage (Fig. 11A), inferred from spatial and crosscutting relationships between landform elements wherever possible. We label the landforms from 1 to 5 in Figure 11A by their relative age of deposition.

(1) *Landforms of ice advance across, and presence at, the shelf edge*: relatively subdued glacial lineations, orientated in the direction of ice flow across the shelf, and a well-deﬁned linear belt of hummocky terrain inferred to represent the shelf-edge ice-grounding zone (Figs. 3 and 11A).
Figure 10. (A) Map of distribution of seafloor features in the shelf-fjord system of northwesternmost Svalbard. (B) Crosscutting relationship between crag-and-tail and younger transverse ridges, Raudfjorden (located in Fig. 9B). (C) Crosscutting relationship between transverse ridges and younger slides, Smeerenburgfjorden (located in Fig. 7A).
Figure 11. Schematic models of submarine landforms produced on continental margins by the action of ice. (A) An inter–ice-stream glacial landform assemblage, located between fast-flowing ice streams, derived from swath-bathymetric data from the shelf and fjords of northwesternmost Svalbard. LIA—Little Ice Age, MSGL—megascale glacial lineations. Note that Landvik et al. (2003) showed, using exposure age dating, that the mountains of NW Svalbard were not completely covered by ice at the Late Weichselian glacial maximum. (B) An ice-stream–glacial landform assemblage, derived from swath bathymetry from major Svalbard fjord systems, where fast-flowing ice was fed from large interior drainage basins (Table 1; Ottesen et al., 2005, 2007).
(2) **Landforms of ice retreat across the shelf during deglaciation:** large and small transverse moraine ridges, the larger probably marking stillstands during retreat of a grounded ice margin (Figs. 4, 5, and 11A), that are sometimes superimposed on glacial lineations (Figs. 3A and 11A).

(3) **Landforms of ice retreat from fjord mouths to fjord heads:** arcuate moraines implying stillstands and/or possible ice readvance to fjord mouths, where ice spread out beyond constraining valley walls (Figs. 9 and 11A); crag-and-tail features (Fig. 9), with transverse ridges superimposed upon them (Fig. 10B), indicating active ice in fjords prior to retreat.

(4) **Landforms produced in the Holocene after major fjord deglaciation:** smooth areas of seafloor, usually in basins within fjords, representing fine-grained sediment deposition linked to the discharge of turbid meltwater from tidewater glacier margins (Figs. 6, 7, 9, and 11A); submarine slides from steep fjord walls, demonstrating slope instability (Figs. 7C, 10C, and 11A).

(5) **Landforms of recent ice readvance and retreat at fjord heads:** large terminal moraines, within a few kilometers of present tidewater glacier margins, recording readvance associated with the cold Little Ice Age and subsequent retreat marked by deposition of small, sometimes annual transverse ridges (Figs. 8 and 11A).

**DISCUSSION**

**Landform Models for Contrasting Ice-Dynamic Settings**

In this paper we have described and interpreted the submarine landforms from a continental margin that is associated with ice draining from relatively restricted catchments, where there is insufficient ice flux to produce fast glacial flow (Fig. 2B and Table 1). We now compare the landform assemblage model produced using our swath-bathymetric data from northwesternmost Svalbard (Fig. 11A) with a similar model derived from earlier swath-bathymetric work from several cross-shelf troughs around Svalbard that were filled with fast-flowing ice streams reaching the shelf edge under full-glacial conditions (Fig. 11B) (Ottesen et al., 2005, 2007). The interior ice-sheet drainage basins feeding these ice streams were an order of magnitude larger than those draining northwesternmost Svalbard (Table 1), providing sufficient flux of ice to sustain fast flow, which was of up to several thousand years duration (Dowdeswell and Elverhøi, 2002).

It is immediately clear that the landform assemblage models derived for these two contrasting ice-dynamic settings are quite different (Fig. 11). Where ice streams occur, cross-shelf troughs are usually present, with shallower banks beyond the trough margins (Fig. 11B). Within the troughs, the seafloor morphology is dominated by megascale glacial lineations (MSGL) that are oriented in the direction of past ice flow (Ottesen et al., 2005, 2007). The MSGL are produced at the deforming bed of active ice streams during full-glacial conditions when ice advances to the shelf edge (e.g., Clark, 1993; Canals et al., 2000; Wellner et al., 2001; Ó Cofaigh et al., 2003; Dowdeswell et al., 2004). Beyond the trough mouth, glaciogenic debris flows are present on the continental slope and transfer diamictic sediments derived from the deforming ice-stream bed downstream to build fan systems (e.g., King et al., 1996; von der Heydt, 1997; Dowdeswell et al., 2002b; Taylor et al., 2002; Nygård et al., 2005). During deglacial ice retreat across the shelf, any stillstands of significant (decadal or greater) duration are marked by transverse grounding-zone wedges (Ottesen et al., 2005, 2007). These diamictic wedges are produced by continuing sediment delivery from the deforming beds of active ice during the stillstands (e.g., McMullen et al., 2006; Mosland and Anderson, 2006; Dowdeswell et al., 2008). Where MSGL are preserved without overprinting by transverse ridges, retreat is assumed to have been rapid and was probably achieved largely by iceberg calving from a buoyant margin (e.g., Dowdeswell et al., 2008; Ó Cofaigh et al., 2008). Where ice retreat is slower, from a grounded margin, smaller transverse ridges are produced, often occurring in sets of tens or even hundreds (e.g., Shipp et al., 2002; Dowdeswell et al., 2008). At ice-stream margins, where there is a strong velocity gradient to slower moving ice, lateral moraines of several tens of kilometers in length are occasionally produced (Fig. 11A) (Ottesen et al., 2005, 2007; Hindmarsh and Stokes, 2008). In shallower water, to either side of cross-shelf troughs, the seafloor is usually heavily scoured by the ploughing action of iceberg keels (e.g., Anderson, 1999; Ó Cofaigh et al., 2002; Ottesen et al., 2005).

In general, therefore, the seafloor morphology of continental margins affected by ice streams is dominated by landforms oriented in the direction of former ice flow, produced by deformation of basal sediments (Clark et al., 2003; Dowdeswell et al., 2004), interrupted mainly by major grounding-zone wedges formed during temporary halts in ice retreat (Dowdeswell et al., 2008) (Fig. 11B). Only where retreat is slow, and the ice is grounded on the seafloor, are sets of small transverse ridges produced. By contrast, in areas between ice streams, the morphology of continental-shelf and fjord floors records landforms of various dimensions oriented mainly transverse to ice flow, produced at ice-sheet margins that are retreating relatively slowly and are usually grounded (Fig. 11A).

Interestingly, there is little evidence for the nature of subglacial water flow in the form of eskers and ice-contact fans, in either of the continental shelf settings described for the Svalbard margin (Figs. 10 and 11). An implication is that basal water is drained mainly by flow within the soft sediments of the former ice-sheet bed and/or advected with the deforming sediment (e.g., Clarke, 2005). In fjords, basin-fill sediments with a smooth surface are often observed in deeper basins. This fine-grained sediment is derived from turbid meltwater draining from Holocene tidewater glaciers (Elverhøi et al., 1980, 1983; Dowdeswell and Dowdeswell, 1989). Eskers and ice-contact fans have been reported from several inner-fjord locations near fjord heads in Svalbard (Boulton, 1986; Ottesen et al., 2008), but we have not observed such features in outer fjord and shelf locations around Svalbard (Ottesen et al., 2005, 2007).

**Ice Thickness and Extent in NW Svalbard at the Late Weichselian Maximum**

Exposure-age dating of glacial erratic blocks from Amsterdamoya and Danskoya in northwesternmost Svalbard (Landvik et al., 2003) showed that Late Weichselian ice was less than ~300 m thick. Given that the shelf edge is less than 10 km west of these islands (Fig. 1), this implies an ice sheet of low surface gradient with motion probably linked to a deformable bed of low shear stress (e.g., Boulton and Jones, 1979). This is consistent with the mainly sedimentary substrate on this part of the Svalbard shelf (Fig. 10). The lack of any net postglacial uplift relating to glacio-isostatic unloading in NW Svalbard also implies that ice was relatively thin during the Late Weichselian full glacial (Forman, 1990). Nunataks and subaerial valley sides would have been present, and the major fjords, therefore, controlled the direction of ice flow inshore of the shelf (Fig. 11A).

In addition, the shelf of northwesternmost Svalbard is also important in a regional context because it provides a constraint on the ice-sheet margin near the Yermak Plateau, close to the Arctic Ocean, where there has been a long debate concerning ice-sheet expansion onto this 500- to 1000-m-deep submarine plateau (Vogt et al., 1994; Flower, 1997; Kristoffersen et al., 2004). Our work showing the position of the grounding line at the shelf edge (Figs. 3 and 10) implies that ice did not flow across the Yermak Plateau during the Late Weichselian glacial maximum.
CONCLUSIONS

- The submarine landforms of the continental shelf and fjords of northwesternmost Svalbard (Fig. 1), which we have investigated using swath-bathymetric methods, provide an exceptionally well-preserved example of ice-sheet deposition in an inter-ice-stream setting. The area lies between the flow paths of two large paleo-ice streams, and this part of the margin was therefore fed by a relatively restricted ice-sheet drainage basin during the Late Weichselian (Fig. 2B).

- The distribution of submarine landforms on the NW Svalbard margin is mapped in Figure 10A. The distinctive belt of hummocky and ridged topography within a kilometer or so of the shelf edge represents the ground zone of the Late Weichselian ice sheet at its maximum position (Fig. 3). Subdued glacial lineations indicate past ice flow across the shelf (Fig. 3A). Ice retreat during deglaciation is recorded by large and small transverse shelf settings described for the Svalbard margin (Figs. 10 and 11). An implication is that basal water was drained mainly by flow or advection within the soft sediments of the former ice-sheet bed.

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A simple, three-dimensional schematic model of an inter-ice-stream glacial landform assemblage is illustrated in Figure 11A. Five subsets of landforms, ordered by relative age, make up this assemblage, inferred from spatial and crosscutting relationships between landform elements. This model is compared with one based on earlier swath-bathymetric work from several cross-shelf troughs around Svalbard that were filled with fast-flowing ice streams reaching the shelf edge under full-glacial conditions (Fig. 11B).

The planform lineament models from these two contrasting ice-dynamic settings are clearly different (Fig. 11). The seafloor morphology of continental margins affected by ice streams is dominated by streamlined landforms oriented in the direction of former ice flow, produced by basal-sediment deformation, and interrupted by major grounding-zone wedges formed during stillstands in ice retreat (Fig. 11B). Ice retreat between these wedges is inferred to be rapid, linked to floation and breakup by iceberg calving. By contrast, on continental shelves between ice streams, seafloor morphology shows landforms of various dimensions oriented mainly transverse to ice flow, produced at ice-sheet margins that retreat relatively slowly and are usually grounded (Fig. 11A).

Finally, there is little evidence of channelized subglacial water flow, in the form of eskers and ice-contact fans, in either of the continental shelf settings described for the Svalbard margin (Figs. 10 and 11). An implication is that basal water was drained mainly by flow or advection within the soft sediments of the former ice-sheet bed.

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Submarine landforms on an inter–ice-stream glaciated margin


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