# Styles of sedimentation beneath Svalbard valley glaciers under changing dynamic and thermal regime

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# Styles of sedimentation beneath Svalbard valley glaciers under changing dynamic and thermal regimes

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**Abstract:** Glacier beds provide crucial information concerning past and present ice dynamics and thermal regime. In this paper we present structural and sedimentological data from four valley glaciers (Austre Lovénbreen, Midtre Lovénbreen, Vestre Lovénbreen and Austre Brøggerbreen) on Brøggerhalvøya, NW Spitsbergen. The main focus of this paper is Midtre and Austre Lovénbreen, two typical High-Arctic land-based polythermal valley glaciers; the former has a long record of documentation regarding its response to twentieth century climatic warming. Structural mapping on the glacier surface and analysis of sediments in the proglacial area of Midtre Lovénbreen indicate that the dynamic regime and thermal structure of the glacier have changed through time. Dynamically, Midtre Lovénbreen was once heavily crevassed and relatively fast moving, but now is virtually crevasse-free and slow moving. The sedimentary record indicates that extensive areas of this glacier were wet-based when it was in a more advanced state, probably at its Neoglacial maximum (late nineteenth/early twentieth centuries). During this advance, a thin deforming layer of diamicton, commonly fluted, was draped over the existing morphology in the presently exposed proglacial area. This morphology consisted of large streamlined ridges aligned parallel to ice flow. Erosion of the underlying bedrock appears to have been limited. Radio-echo soundings of the glacier show that, at present, it is characterized by a polythermal basal thermal regime, with wet-based subglacial conditions only beneath its thicker parts. Modification of the bed is limited under this thermal regime and, as a result, the supraglacial environment dominates modern sedimentation. Comparative studies on Austre Lovénbreen, which also is probably polythermal, indicate similar sedimentary characteristics and facies associations, although here there are much more extensive areas of striated bedrock indicative of former basal sliding. In contrast both Austre Brøggerbreen and, by analogy, Vestre Lovénbreen are known to be predominantly cold-based. Collectively, these four glaciers suggest a trend of glacier recession and thinning accompanied by a change in thermal regime from predominantly wet-based, through partly frozen, to completely frozen. This study suggests that Svalbard valley glaciers have several dynamic modes and that glaciers switch between these modes largely as a reaction to changes in mass balance.

**Keywords:** Svalbard, glacial sedimentation, dynamics, thermal regime, mass balance.

Glaciers in Svalbard (77–80°N) lie in a part of the High-Arctic that is particularly sensitive to climatic change (Dowdeswell 1995; Dowdeswell *et al.* 1997; Fleming *et al.* 1997). Documentation of the changing dynamic regimes of these glaciers and the consequent changes in styles of sedimentation provides valuable insight into the response of former ice masses to rapid climatic warming. The aims of this paper are to describe the pattern of sedimentation associated with four Svalbard valley glaciers, and to explain these patterns with reference to recent changes in their dynamic and thermal regime. The data presented in this paper are primarily from two adjacent valley glaciers (Midtre Lovénbreen and Austre Lovénbreen) on Brøggerhalvøya, on the southern side of Kongsfjorden in NW Spitsbergen. We also draw on data from the neighbouring Vestre Lovénbreen and Austre Brøggerbreen (Fig. 1). Collectively, these four glaciers span a range of dynamic and thermal conditions representative of land-terminating glaciers in Svalbard. These High-Arctic valley glaciers serve as good modern analogues for former mountain glaciers in areas subject to Pleistocene glaciation (Hambrey *et al.* 1997).

## Study area

The Svalbard archipelago is 60% covered by glaciers and is dominated by a maritime-Arctic climate (Hagen *et al.* 1993). Of the glaciers described in this paper (Table 1), Midtre Lovénbreen, a small valley glacier fed by four small tributary cirques, is by far the most extensively studied (e.g. Björnsson *et al.* 1996; Hagen & Liestøl 1990; Lefauconnier *et al.* 1999). Currently the glaciers are largely crevasse-free, except in areas where basal topography changes abruptly and at some points where tributary glaciers enter the main glaciers from steep upper basins. All four glaciers have low-gradient snouts. Measured velocities on the centre-line of Midtre Lovénbreen range from 4.4 to 7.3 m $a^{-1}$ at the equilibrium line (Bjornsson *et al.* 1996; Liestøl 1988). There are no published velocity data for the other studied glaciers.

The Norwegian Polar Research Institute (Norsk Polarinstitutt) monitors mass balance on Austre Brøggerbreen and Midtre Lovénbreen. The records from these glaciers, spanning 34 years, are the longest in Svalbard (Hagen & Liestøl 1990). Statistical analysis of mass balance records and climatic data suggests that the net mass balance of these glaciers has probably been negative in the majority of years since 1900 (Lefauconnier & Hagen 1990). As a result, glaciers on Brøggerhalvøya are currently receding from their Neoglacial maxima (*c.* 1890), and most have receded 1–2 km since that time (Hagen *et al.* 1993). Volume losses since the post-glacial maximal positions have been substantial, possibly

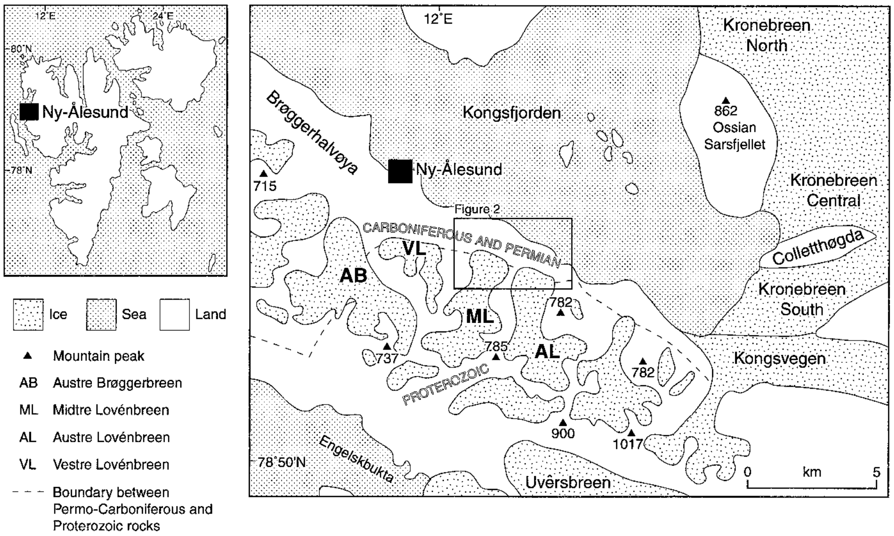


**Fig. 1.** Location of the four glaciers studied on Brøggerhalvøya, NW Spitsbergen. Underlying bedrock geology (from Hjelle 1993) is indicated in the vicinity of the four glaciers.

as much as 25% on the basis of former ice-marginal positions and trim-lines, and Midtre Lovénbreen has receded almost 1000 m since that time (Hansen 1999). Historical and photographic records (e.g. Hamberg 1894) show that at the Neoglacial maximum these glaciers had vertical fronts and were relatively free of surface debris (Liestøl 1988).

Radio-echo soundings of the internal temperature characteristics and bed topography of glaciers in this region, including Midtre Lovénbreen, show that they are polythermal, with extensive areas of temperate ice beneath their accumulation areas, but with their termini frozen to the bed (Hagen & Saetrang 1991; Hagen *et al.* 1991; Ødegård *et al.* 1992; Björnsson *et al.* 1996). Midtre Lovénbreen is frozen to the bed at the snout and margins, but with a warm basal layer (up to 50 m thick) beneath the central part. Extensive icings (sheets of water-ice up to 2 m thick, and characteristic of polythermal glaciers) are present in front of Austre and Midtre Lovénbreen, indicating that winter drainage occurs from both these glaciers. Austre Brøggerbreen, in contrast, is almost entirely cold-based throughout, except for a very restricted basal area in its central region (Hagen *et al.* 1991; Björnsson *et al.* 1996; Hodson *et al.* 1997).

The cirque headwalls and valley walls of all four glaciers are dominated by metamorphic rocks of the Proterozoic Kongsvegen Group (Harland 1997), including phyllites, quartzite, garnet schist, amphibolite and marble. Carboniferous and Permian limestone, chert and dolostone of the Gipsdalen Group occur only in the proglacial areas of Midtre and Austre Lovénbreen (Fig. 1). At Austre Brøggerbreen and Vestre Lovénbreen the geology is more complex, as the Palaeozoic sedimentary rocks were thrust and folded in association with the metamorphic rocks during the Palaeocene West Spitsbergen Orogeny (Harland 1997). Isolated pockets of Palaeocene sandstones of the Ny-Ålesund Subgroup and conglomerates also occur in the proglacial area of Austre Lovénbreen.

**Table 1.** *Selected characteristics of the glaciers studied in this paper*

| Glacier | Area ($km^2$) | Length (km) | Recession (km)* | Thermal regime |
|---|---|---|---|---|
| Austre Brøggerbreen | 11.8 | 6.0 | c. 1 | Cold |
| Vestre Lovénbreen | 2.45 | <2 | c. 0.7 | Cold† |
| Midtre Lovénbreen | 5.95 | 4.8 | c. 1 | Polythermal |
| Austre Lovénbreen | 6.2 | 4.8 | c. 1 | Polythermal† |

*Estimate since Neoglacial maximum.
†Inferred.

## Methods

The geomorphology and sedimentary facies of the proglacial areas of the four glaciers were mapped in the summers of 1999 and 2000. A detailed map of part of the snout and proglacial area of Midtre Lovénbreen was constructed using a Geotronics Total Station in 1999. Stratigraphic logs of proglacial sediments were measured where exposed by stream erosion at Midtre, Austre and Vestre Lovénbreen (Fig. 2). Sedimentary facies were described using a combination of field description, clast macrofabrics, and clast-shape analysis. Poorly-sorted sediments were classified in the field using the Hambrey (1994) scheme. Three-dimensional clast-macrofabric data were collected for samples of 50 prolate clasts and plotted on Lambert equal-area stereographic projections. Clast roundness for samples of 50 clasts is based on a modified Powers (1953) scale. Clast lithological analysis is based upon field identification of hand specimens. The orientations of flutes, linear debris trains/stripes and striations were also recorded.

## Landform/sediment assemblages at Midtre and Austre Lovénbreen: observations

Three landform/sediment assemblages are present at Midtre and Austre Lovénbreen: large streamlined ridges and flutes, linear debris stripes and a moraine-mound complex (Figs 2, 3).

### *Streamlined ridges*

Streamlined ridges are present on the forefield of both glaciers. The largest and best developed are those at the NW margin of Midtre Lovénbreen where the ridges are elongated in the direction of glacier flow. They are between 25 and 50 m wide, up to 200 m in length, and reach 7 m in height (Fig. 3). At the glacier margin, the ridges emerge from beneath the receding glacier (Fig. 4a). The ridges have a broadly consistent stratigraphy, comprising, from bottom to top: muddy-sandy gravel, diamicton, variable gravel and angular gravel (Fig. 5).

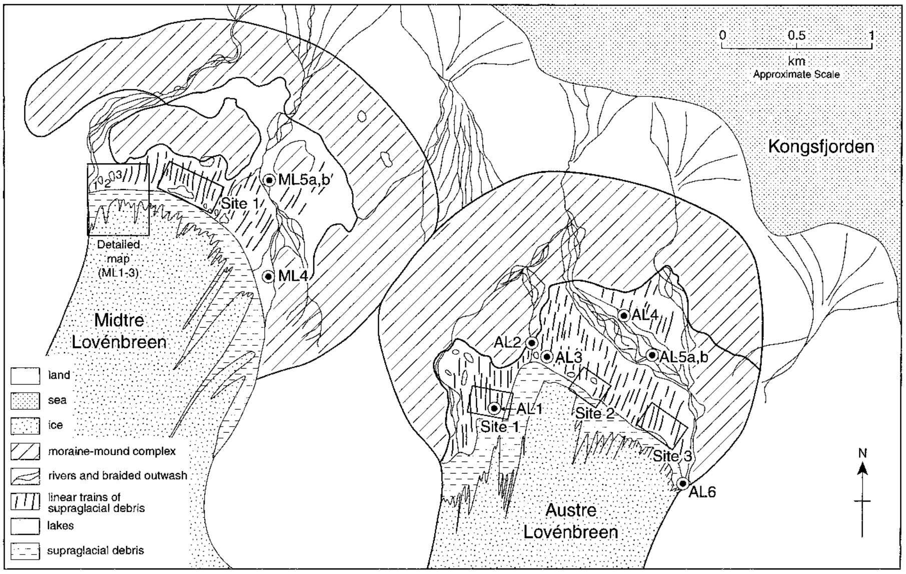


**Fig. 2.** Schematic representation of the glacial geomorphology of the immediate proglacial areas of Midtre and Austre Lovénbreen. Location of logs ML1 to ML5b and AL1 to AL6 (Fig. 6) are indicated. Locations of Site 1 at Midtre Lovénbreen and Sites 1 to 3 at Austre Lovénbreen (Fig. 9) are also indicated.

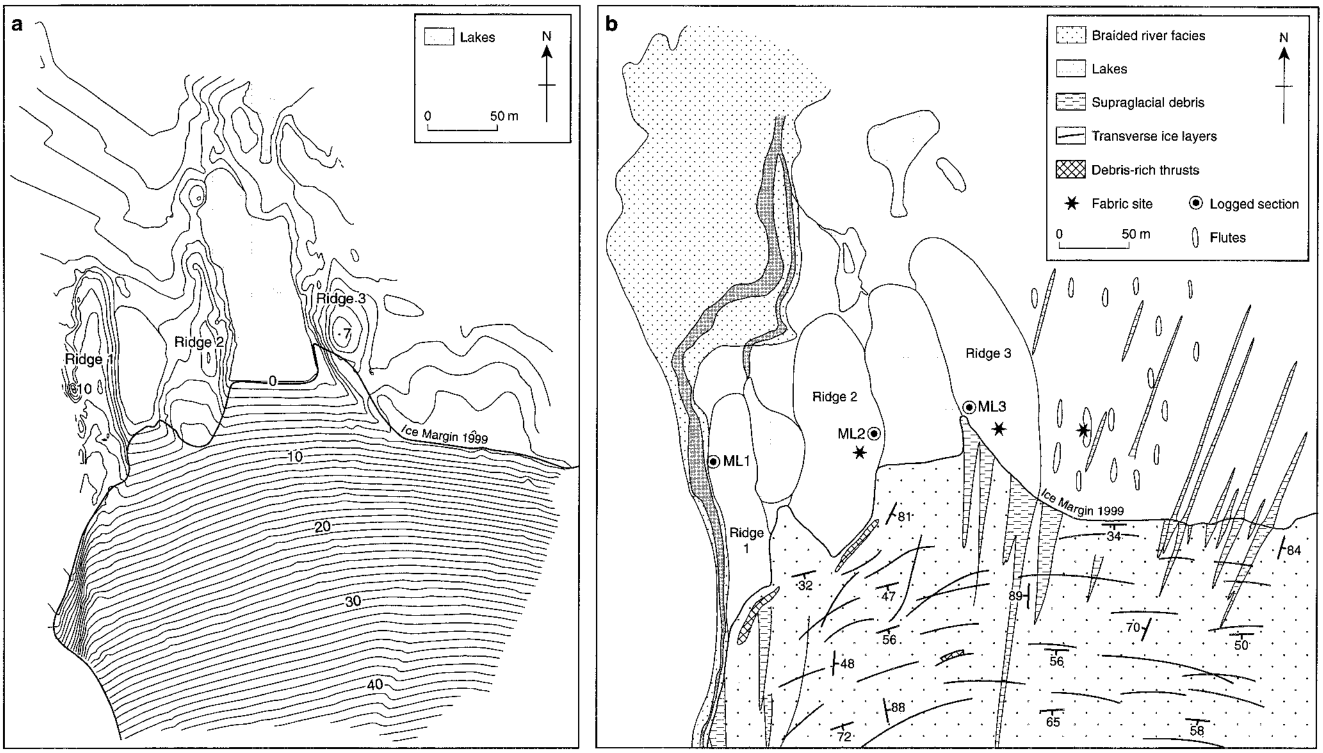


**Fig. 3.** Maps of the NW corner of Midtre Lovénbreen based on a detailed Total Station survey of the area in August 1999. (**a**) Contour map of the glacier snout and immediate proglacial area showing gentle ice-surface gradient and location of Ridges 1 to 3. Contour interval is 1 m, with arbitrary datum at the 1999 ice margin. (**b**) Geomorphological map showing the main components discussed in the text. Tick marks indicate dip angle and strike of structural attributes on the glacier surface. Location of maps indicated on Figure 2.

*Muddy-sandy gravel.* This facies is structureless, typically consisting of 80% gravel, 15% sand and 5% mud. The gravel fraction is dominated by cobble and boulder-sized clasts, many of which are weathered. This facies is of an unknown thickness, but is at least 0.6–1.2 m thick where observed in stream-cut sections (Fig. 6). Clasts are of variable lithology, including a mixture of Proterozoic and Carboniferous lithologies (Fig. 7). Clast roundness peaks are in the subrounded and subangular classes (Fig. 5). Exposures in Ridge 1 show recumbent folding of gravel, sand and mud on a metre scale.

*Diamicton.* The muddy-sandy gravel grades upwards into a thin (0.2–0.75 m) layer of clast-rich muddy diamicton, typically consisting of 40–50% gravel in a sandy, muddy matrix (Fig. 5). In places (e.g. Ridge 1) this deposit varies laterally from clast-rich muddy diamicton to sandy gravel. An anastomosing planar fabric is visible in places. Clasts in this

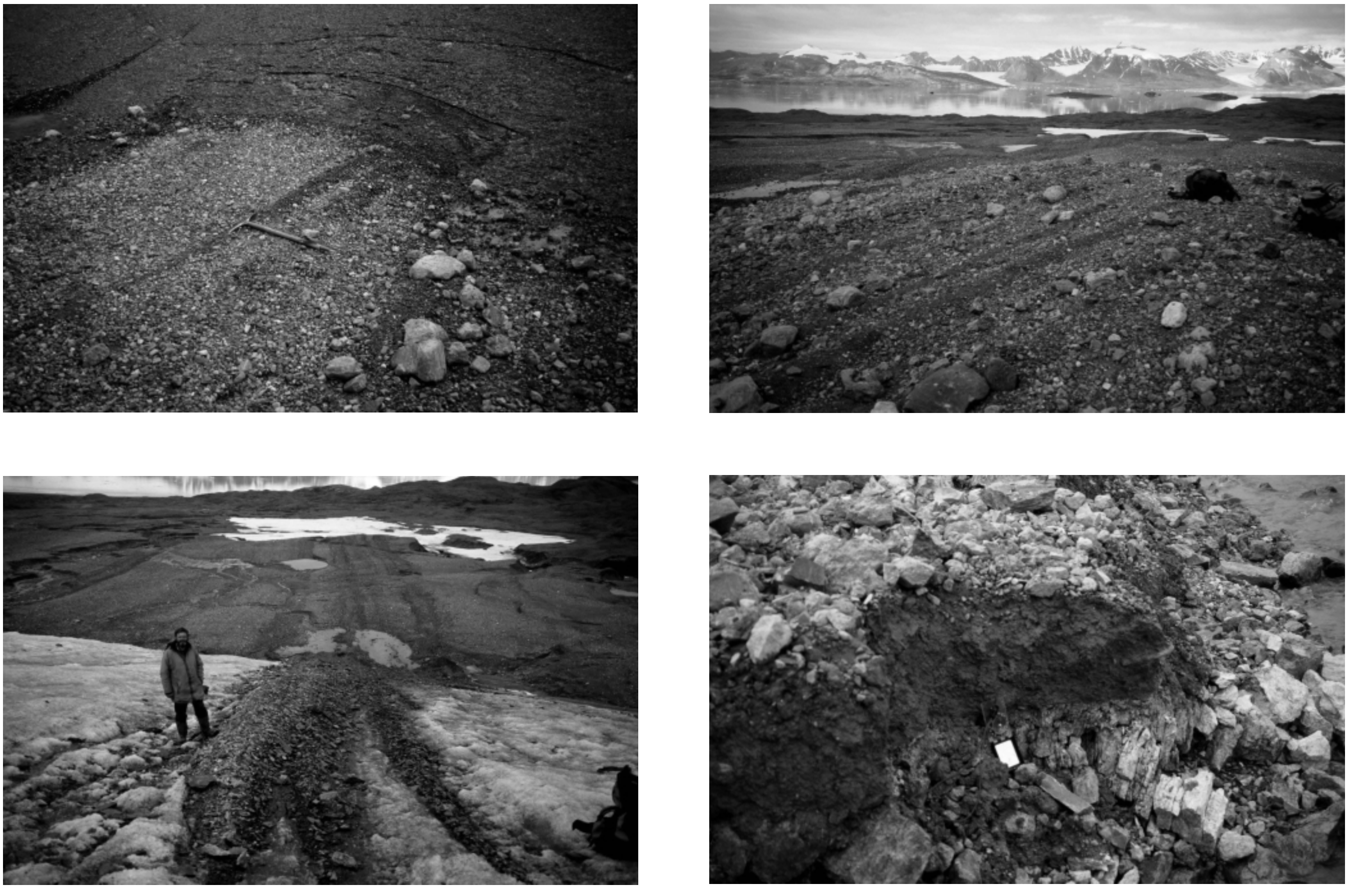

**Fig. 4.** Photographs of Midtre and Austre Lovénbreen. (**a**) Streamlined ridge with two small superimposed flutes emerging from a subglacial position at the receding ice margin, Midtre Lovénbreen. Ice axe for scale. (**b**) Group of small flutes on the forefield of Midtre Lovénbreen. Ice flow was across the photograph from bottom left to top right. Rucksack for scale. (**c**) Linear trains of coarse supraglacial debris arranged in stripes on the surface of Midtre Lovénbreen. Individual stripes can be followed onto the forefield in front of the glacier. (**d**) Diamicton (interpreted as basal till) resting on weathered bedrock on the forefield of Austre Lovénbreen. The till does not penetrate joints in the bedrock but rests cleanly on its upper surface. Compass-clinometer for scale.

facies range from pebble- to boulder-size and include both Proterozoic and Carboniferous lithologies. Clast roundness peaks are in the subrounded and subangular classes (Fig. 7).

*Variable gravel.* The diamicton facies grades upwards into a thin (0.05–0.1 m) layer of moderately well-sorted gravel containing pebbles, cobbles and boulders set in either a sand or mud matrix. Clast lithologies in this facies are similar to those in the diamicton in terms of lithology and roundness classes (Figs 5 & 7). Clast macrofabric data from the surfaces of ridges composed of this facies indicate a strong preferred orientation orthogonal to the ice margin (Fig. 8).

*Angular gravel.* This facies is a veneer of angular cobbles, 1 to 2 clasts in thickness, on the surface of the ridges (Fig. 6). Clasts in this facies are commonly arranged into stripes of a single lithology (typically phyllite, schist, quartzite or marble) and show peaks in the angular and very angular classes (Fig. 5). Boundaries between the angular gravel and the underlying facies are generally sharp (Figs 5 & 6).

The surfaces of the streamlined ridges are generally smooth, although in places incised to depths of up to 1 m along their flanks by small debris-flows scars and silt/gravel depositional lobes. Gently washed surfaces, from which the fines have been removed, and micro-channels up to 0.1 m deep were observed where modern supraglacial streams drain from the glacier onto the upper surface of the ridges. Several depressions 1–2 m deep and 2–3 m across also occur on the ridge crests and flanks. in situations where it is possible to observe the glacier–sediment contact, it is clear that the glacier rests directly on top of the ridges (Fig. 4a).

Smaller streamlined ridges occur in the inner forefield of both Midtre and Austre Lovénbreen. The stratigraphy at the ridge crests is similar to that described above, the most striking feature being the manner in which diamicton drapes over the ridge profiles to a depth of 0.2 to 1.5 m. (Fig. 6). In depressions between the ridges, especially at Austre Lovénbreen, diamicton rests directly on top of either weathered or striated bedrock. In some places the local bedrock is incorporated into the diamicton and fissures in the bedrock are filled with diamicton, whilst in other places the diamicton contains only far-travelled Proterozoic clasts overlying undisturbed weathered Permo-Carboniferous or Tertiary bedrock (Fig. 6). The largest ridges at Austre Lovénbreen are >20 m high and are heavily pitted and dissected by stream erosion. In one case a stream was observed to disappear underground before re-emerging

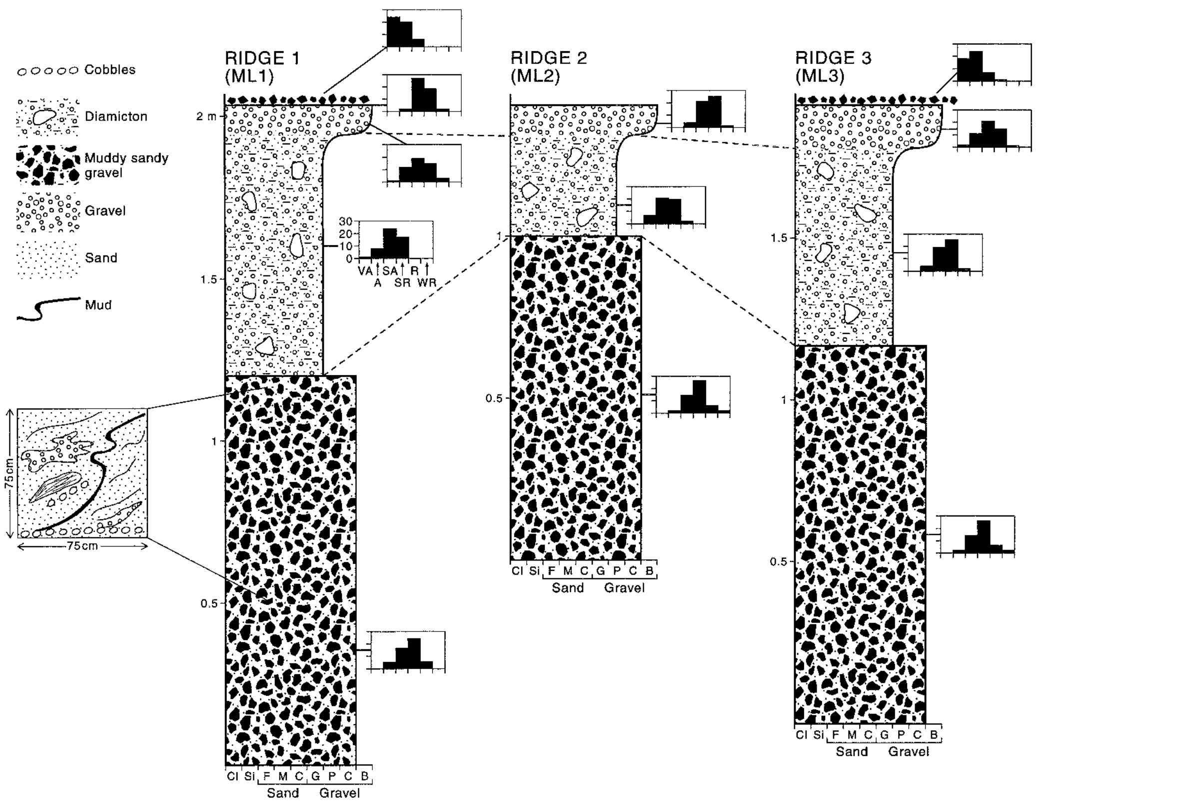


**Fig. 5.** Stratigraphic logs and clast roundness data from Ridges 1 to 3 in the NW corner of Midtre Lovénbreen. Location of logs indicated by ML1 to ML3 on Fig. 3b. Note that each ridge is composed of the same sedimentary facies, irrespective of location on the summit or flanks of the ridge. Clast roundness is based on samples of 50 clasts (VA, very angular; A, angular; SA, subangular; SR, subrounded; R, rounded; WR, well rounded).

beneath candle ice (Aufeis) buried by 3.5 m of muddy-sandy gravel and capped by 1.5 m of diamicton (AL2, Fig. 6). This is the only case where ice has been observed directly beneath sediments in the glacier forefield.

## *Flutes*

Fluted surfaces are developed on the flat areas of the Midtre and Austre Lovénbreen forefields (Fig. 3b). Closest to the ice margins, the ridges form low (<0.5 m high) and elongated (>10 m) fluted ridges ('flutes') composed of diamicton. The majority of these flutes commence in the lee of Carboniferous and Permian boulders, indicative of a local subglacial origin (Fig. 4b). Some boulders are bullet-shaped and striated, whilst others are angular or very angular. Further from the glacier margins, the flutes degrade rapidly and lose much of their surface relief. Similar fluted surfaces are also present on the forefield of the NW arm of Vestre Lovénbreen.

## *Linear debris stripes*

Medial moraines on the surface of all four glaciers can be traced onto the glacier forefield as linear debris stripes (Fig. 4c). These stripes consist of angular or very angular cobbles and boulders (Fig. 7a), and extend for hundreds of metres across the forefield (Fig. 2). Individual stripes rarely exceed 0.5 m in height, forming a drape 1 or 2 clasts thick over the sediments beneath (Fig. 6). Each individual stripe is composed of clasts of either a single lithology or two distinct lithologies (Fig. 7b). Typical lithologies include schist, amphibolite, psammite and marble, matching exposed Proterozoic metamorphic rocks in the headwall and valley walls of Midtre and Austre Lovénbreen. More varied assemblages, including Carboniferous and Tertiary sedimentary rocks are found at Vestre Lovénbreen and Austre Brøggerbreen. Near the central part of Midtre Lovénbreen and the SE part of Austre Lovénbreen, an offset relationship can be observed between debris stripes and flutes (Fig. 9). Linear debris stripes are also well-developed at Austre Brøggerbreen, both on the glacier surface and as ridges several metres in height on the glacier forefield.

## *Moraine-mound complexes*

Between the present-day ice margins and the Neoglacial maxima positions at Midtre Lovénbreen and Austre Lovénbreen are large moraine-mound complexes, braided outwash and lakes (Bennett *et al.* 1996; Hambrey *et al.* 1997). Of these, the moraine-mound complexes are the dominant landscape-forming element. Groups of moraine mounds consist primarily of either stacked or imbricate sheets of sediment of varying composition, including diamicton, sandy gravel, muddy gravel, sand, mud and sand-mud laminites (Huddart & Hambrey 1996; Hambrey *et al.* 1997). Individual mounds are typically short-crested and asymmetric in profile, with rectilinear surfaces (dip typically 25–32°) facing towards the glacier and steeper down-glacier faces (see Hambrey *et al.* 1997 for further details).

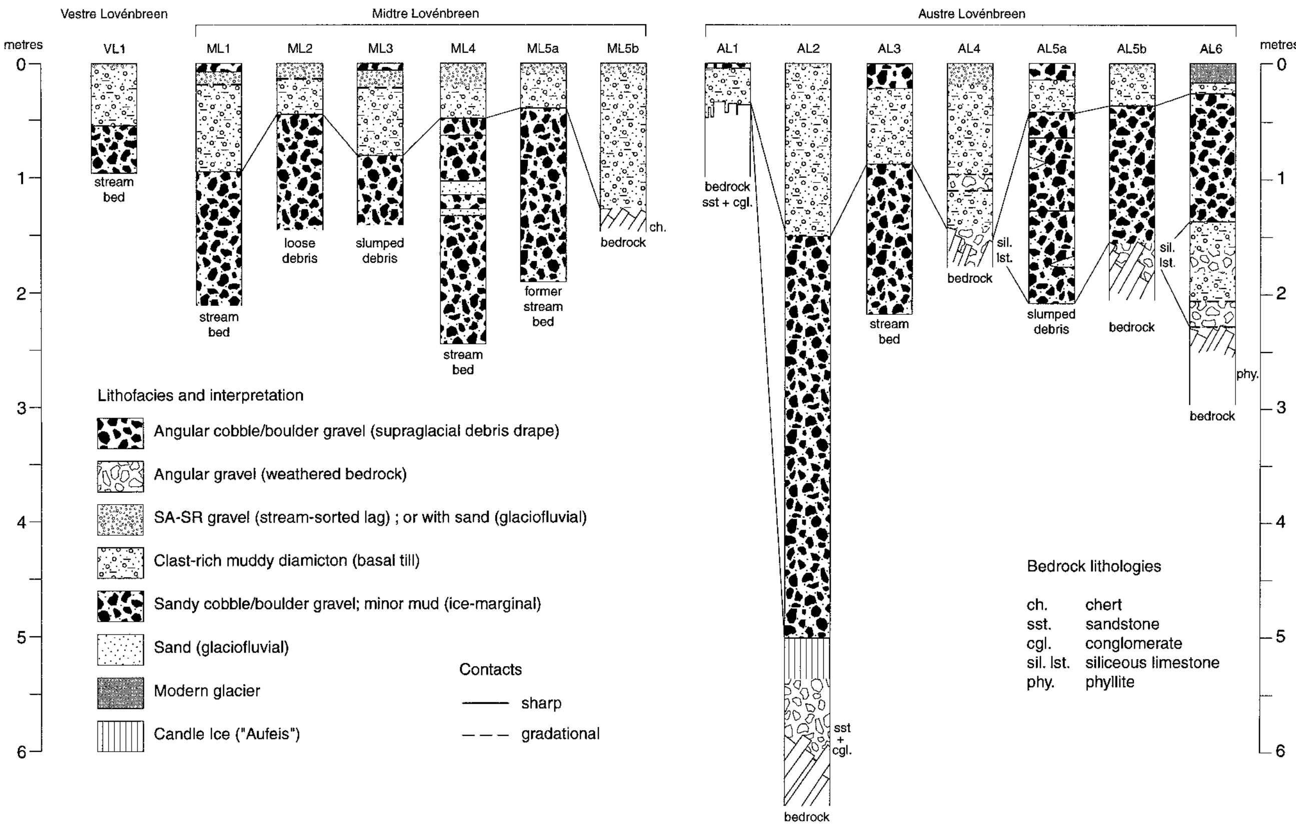


**Fig. 6.** Stratigraphic logs from the forefields of Vestre Lovénbreen (VL1), Midtre Lovénbreen (ML1 to ML5b) and Austre Lovénbreen (AL1 to AL6). The location of the logged sections is indicated on Figures 2 and 3.

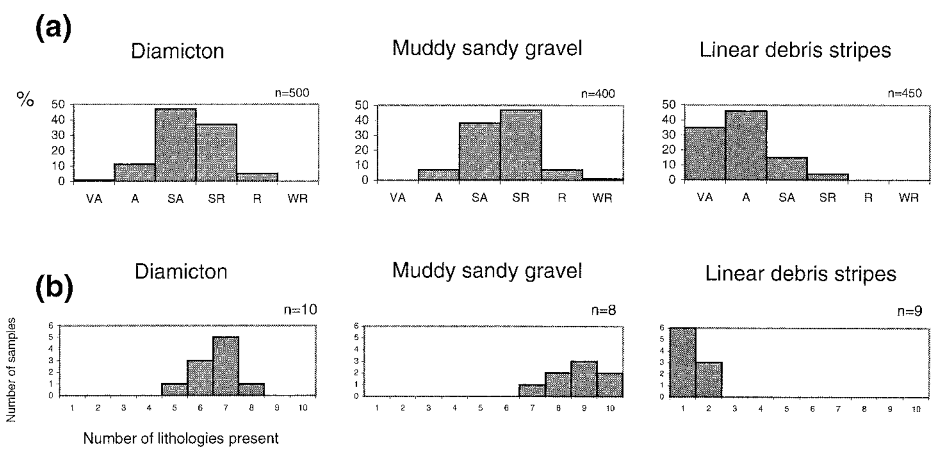


**Fig. 7.** Clast roundness and lithology data for Midtre Lovénbreen. (**a**) Clast roundness data for the three principal facies identified at the glacier (VA, very angular; A, angular; SA, subangular; SR, subrounded; R, rounded; WR, well rounded). Total sample size is indicated in each case. (**b**) The number of different lithologies present in samples of 50 clasts. Total sample size is indicated in each case. Note that the diamicton and muddy-sandy gravel samples show much greater lithological diversity than the linear debris stripes, which are all uni- or bi- lithological.

## *Glacial erosion*

Bedrock in the forefields of Midtre and Austre Lovénbreen is locally either highly weathered or fractured to a depth of several metres (Fig. 4d). Striated bedrock surfaces occur only along the NW flank and in front of Austre Lovénbreen, where measured striation orientations are sub-parallel to flute orientations (Sites 1 and 2, Fig. 9). Extensively striated bedrock surfaces occur beneath dislodged blocks several metres in diameter, and are commonly overlain by diamicton. No striated bedrock was observed at Midtre Lovénbreen or Austre Brøggerbreen, although small exposures occur at Vestre Lovénbreen.

## *Structural glaciology*

The four glaciers exhibit at least five sets of structures that can be mapped in the field: primary stratification, longitudinal foliation, open crevasses, crevasse traces, and thrusts (Fig. 3b). Primary stratification is associated with variable quantities of debris and has been folded about flow-parallel axes, usually into open 'similar' types. Associated with the folding is an axial planar foliation, which is especially strong at flow unit boundaries. The hinges of folded debris layers crop out on the glacier surface as flow-parallel medial moraines, with axes dipping gently up-glacier. Crevasses are currently rare on all four glaciers except in the upper reaches of Midtre

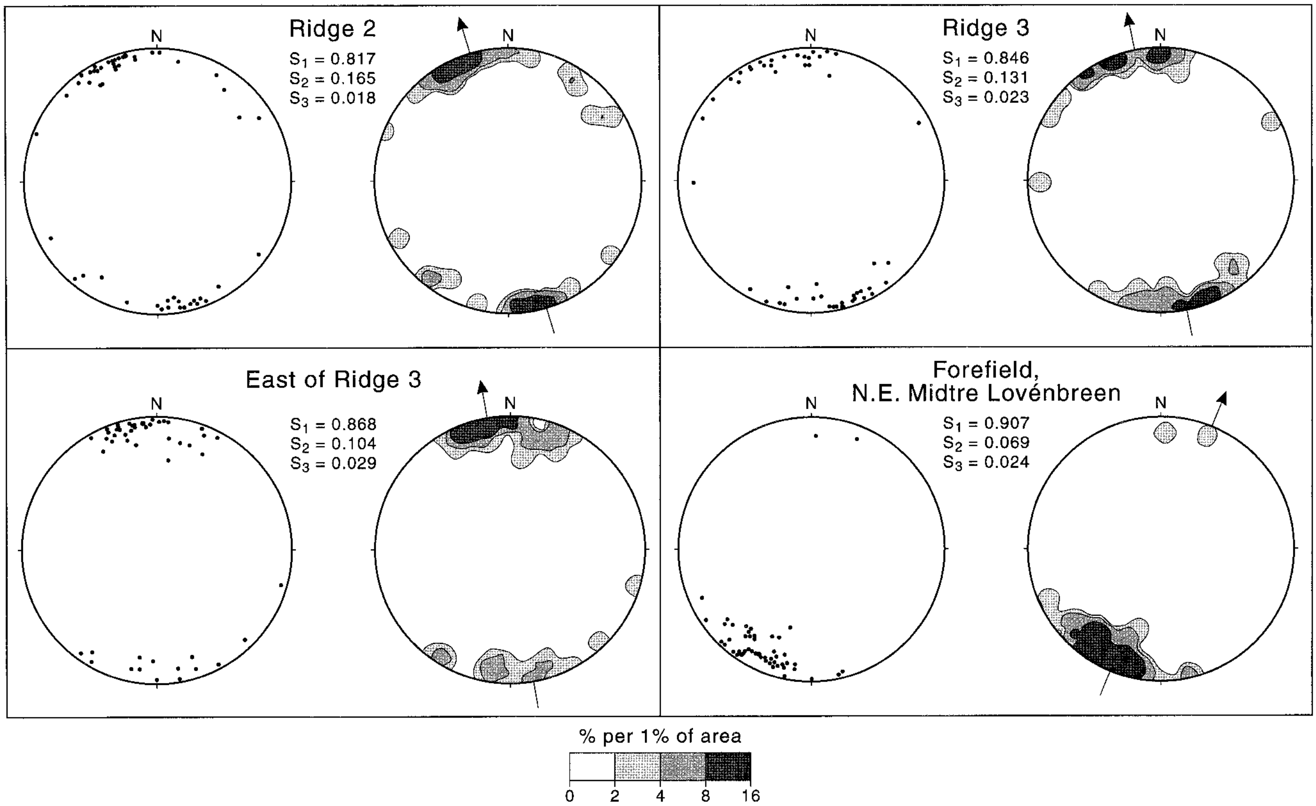


**Fig. 8.** Point and contour plots of three-dimensional clast macrofabric data from the variable gravel facies on the surface of ridges in front of Midtre Lovénbreen plotted on Lambert equal-area projections (lower hemisphere). Fifty clasts were measured in each case; contours at 2%, 4%, 8% and 16% per 1% of area. Eigen vectors and eigenvalues are indicated. The arrow indicates inferred direction of glacier movement.

Lovénbreen, where steep subglacial topography associated with the tributary basins allows open crevasses to form, despite low flow velocities. Downstream of these open crevasses are numerous apparently randomly orientated crevasse traces that represent healed crevasses and tensional veins (Hambrey & Lawson 2000). These crevasse traces can be mapped throughout the entire length of Midtre Lovénbreen, and provide evidence of a formerly more active dynamic regime when the surface of the glacier was extensively crevassed. Across the surface of the glacier in its ablation area are numerous transverse ice layers, interpreted as thrusts, which dip at progressively less steep angles towards the snout (Fig. 3b). Many of these are debris-rich and are associated with debris cones and mounds on the glacier surface. The composition of these debris features is variable, but they typically contain a moderately well-sorted sandy gravel, dominated by subangular or subrounded clasts. Similar features are also present near the snouts of Vestre Lovénbreen, Austre Lovénbreen and Austre Brøggerbreen.

## Landform/sediment assemblages at Midtre and Austre Lovénbreen: interpretation

### *Streamlined ridges and flutes*

The forefields of Midtre, Austre and Vestre Lovénbreen all have streamlined components, varying locally in size from small flutes to large streamlined ridges. The cores of the ridges are composed of muddy-sandy gravel, interpreted as a reworked ice-marginal deposit dominated by glaciofluvial material. This interpretation is based on a sediment texture that is similar to glaciofluvial sediments observed in modern ice-marginal channels, clast roundness peaks in the subrounded class that indicate transport in a glaciofluvial environment (Fig. 7a) and the mixed lithological assemblages indicating a variety of sources for the material (Fig. 7b). This facies may represent material that accumulated in front of an actively advancing ice margin, which was then smoothed by the advancing ice. Draped over the surface of the muddy–sandy gravel is a layer of clast-rich muddy diamicton, interpreted as a basal glacial till. This interpretation is based on a sediment texture that is similar to observed modern *in situ* basal glacial material, the anastomosing planar fabric interpreted here as a shear fabric, the high percentage of subrounded and subangular clasts (Fig. 7a), many bearing striations, and the mixed lithological assemblages (Fig. 7b). The thin layer of variable gravel that forms the surfaces of the large ridges is identical to diamicton in terms of clast roundness, clast lithologies and percentage of striated clasts, but differs texturally in that it lacks fine material. This facies is interpreted as a lag deposit derived from the underlying diamicton by gentle washing out of surface fines by proglacial streams. This process has been observed to occur at the modern ice margin. The angular gravel that in places forms a thin drape over the ridges and flutes is interpreted as supraglacial material let down onto the forefield as a result of ablation of the underlying glacier ice (see linear debris stripes, below).

Streamlined ridges and flutes are interpreted as subglacial bedforms shaped beneath dynamic, wet-based ice. The

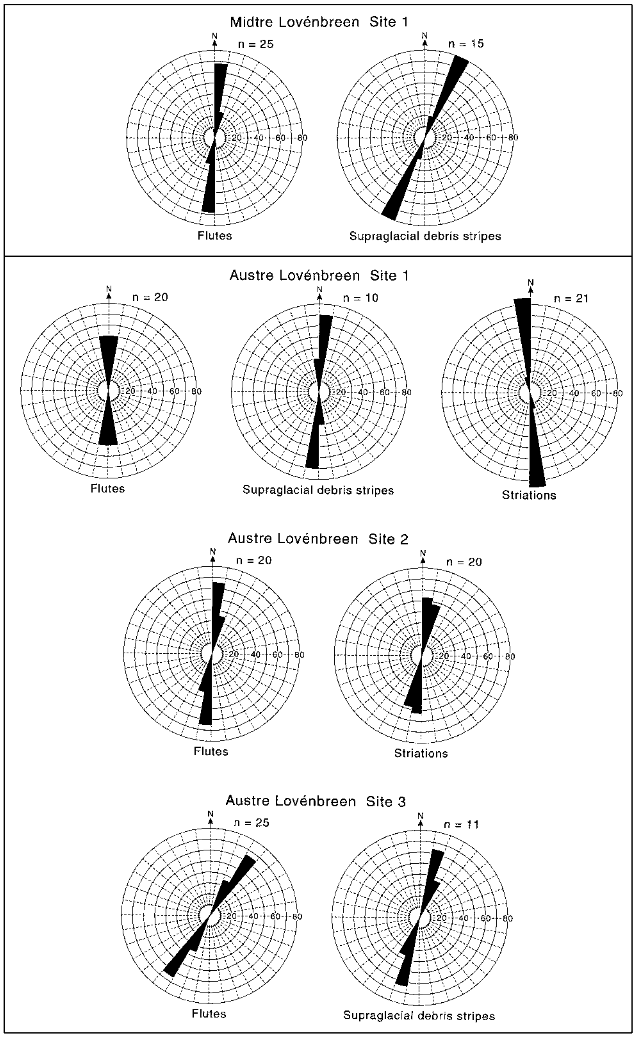


**Fig. 9.** Two-dimensional orientation of striations, clasts in flutes and supraglacial debris stripes on the forefields of Midtre Lovénbreen and Austre Lovénbreen (see Fig. 2 for the location of sample sites). Note the offset relationship (up to 20°) between the flutes and the supraglacial debris stripes at Midtre Lovénbreen Site 1 and Austre Lovénbreen Sites 1 and 3. Note also that the orientation of flutes is similar to that recorded for striations at Austre Lovénbreen Sites 1 and 2. Total sample size is indicated in each case.

strongest evidence for this interpretation is that the ridges can be observed emerging from beneath the modern glacier. Other evidence includes their streamlined morphology and alignment parallel to former glacier flow as indicated by: (i) preferred clast orientations (Fig. 8) and striation orientations (Fig. 9); (ii) clast-roundness values and striated clasts indicative of basal glacial transport and (iii) in the case of flutes, their situation in the lee of subglacially modified boulders, some of which are striated or bullet-shaped (Boulton 1978). Deformation structures in the muddy–sandy gravel at the core of the ridges may indicate soft sediment deformation by overriding ice (Fig. 5). Similar streamlined ridges, fluted moraines and flutes have been described from a variety of glacial environments (Paul & Evans 1974; Boulton 1976; Rose 1989; Bluemle *et al.* 1993; Gordon *et al.* 1992; Benn 1994; Hart 1998) and are regarded as evidence for subglacial sediment deformation during fast ice flow (Hart 1999). The evidence at Midtre and Austre Lovénbreen points to a widespread shaping of subglacial material beneath the glaciers, including the remobilization of glaciofluvial, ice-marginal and basal glacial sediments. As these glaciers are known to be cold-based near their snouts, we can infer that the streamlining process has ceased and the modern glaciers are receding over the proglacial area with little or no modification of the streamlined ridges and flutes.

Long-term preservation of these streamlined features is restricted by fluvial erosion and failure and collapse of the ridges themselves. Aufeis has been observed beneath proglacial sediments at one locality (AL2, Fig. 6), but the overall extent of collapse features suggests that buried glacier ice may also be widespread. If this is the case, then this ice pre-dates the last period of glacier expansion.

### *Linear debris stripes*

The linear debris stripes present at all four glaciers are interpreted as supraglacial/englacial moraines let down onto the forefield as the underlying glacier ice ablates. The strongest evidence for this interpretation is that linear debris stripes can be followed from a supraglacial position on the modern glaciers onto their forefields (Fig. 4c). Stripes are also aligned parallel to modern glacier flow (Fig. 3b), with clast roundness indicative of passive supraglacial or englacial transport (Fig. 7a), and a uni- or bi-modal lithological composition (Fig. 7b). Linear trains of supraglacial debris have been described on the surfaces and forefields of other Svalbard valley glaciers (Glasser *et al.* 1998, 1999; Hambrey *et al.* 1999). They have been explained as debris of supraglacial origin that has been incorporated englacially by folding along flow-parallel axes and the subsequent exposure of the fold-hinges as medial moraines on the glacier surface by ablation.

### *Moraine-mound complexes*

Moraine-mound complexes are characteristic features of the proglacial areas of land-terminating Svalbard valley glaciers (Bennett *et al.* 1996, 1999; Boulton 1970; Boulton *et al.* 1999; Hambrey & Dowdeswell 1997; Hambrey & Huddart 1995; Hambrey *et al.* 1997, 1999; Huddart & Hambrey 1996). Many of these moraine-mound complexes have been interpreted as the product of englacial thrusting in ice that has undergone strong longitudinal compression, especially at the thermal boundary between warm and cold ice (Hambrey *et al.* 1997). Moraine-mound complexes are produced wherever subglacially-derived sediment is elevated into an englacial position at this thermal boundary. Sediment is subsequently released during glacier recession, the rectilinear faces of individual moraine-mounds representing the former thrust planes. Moraine-mounds also form beyond the ice margin as a result of propagation of a basal décollement surface forward of the advancing ice (Hambrey & Huddart 1995; Etzelmüller *et al.* 1996; Boulton *et al.* 1999).

## Discussion

### *Sedimentation and glacier thermal regime*

The nature of erosion and deposition by glaciers and ice sheets is strongly controlled by basal thermal regime (Boulton 1972; Kleman & Borgström 1994; Kleman & Hättestrand 1999). At Midtre, Austre and Vestre Lovénbreen there is evidence for two distinctive styles of sedimentation: one subglacial, the other supraglacial. The subglacial sedimentary environment reflects a period of time when the glaciers were mainly wet-based and dynamic, with active basal sliding over bedrock, subsole deformation, deposition of a thin (*c.* 1 m) layer of diamicton and the development of streamlined bedforms. The supraglacial sedimentary environment reflects a period when the glaciers were characterized by predominantly frozen-bed conditions, when movement was accomplished by internal deformation rather than basal sliding or subsole deformation, and subglacial deposition did not occur. Since polythermal glaciers have areas of both warm- and cold-based ice, styles of sedimentation depend on the proportion of the glacier underlain by these thermal regimes at any one time.

Based on the existing geomorphological and sedimentological evidence we propose the following sequence of events.

(1) During the Neoglacial, glaciers overrode weathered bedrock and ice, depositing several metres of reworked glaciofluvial and basal glacial material. As with other Svalbard glaciers, they were thicker and steeper in their terminal zones at the Neoglacial maximum and the zone of temperate ice expanded to occupy a larger area, with frozen-bed conditions only at the very margin (Hodgkins *et al.* 1999). Moraine-mound complexes formed englacially at this thermal boundary, and the wet-based conditions enabled the glaciers to mobilize and mould the underlying sediment, creating the streamlined ridges and flutes now preserved on the forefields. The orientation of ridges and flutes therefore reflect palaeo-flowlines at the Neoglacial maximum, not present-day flow directions.

(2) With prolonged negative mass-balance conditions in the twentieth century the glaciers began to recede and to thin. Summer air temperature became increasingly important in ablation, and the influence of geothermal and frictional heat declined (Lefauconnier *et al.* 1999). Thus, in the case of Midtre Lovénbreen, the thermal boundary migrated up-glacier to its present position some 1 km from the glacier terminus (Hagen & Saetrang 1991; Björnsson *et al.* 1996). The location of the thermal boundary at Austre Lovénbreen probably migrated in a similar fashion as the glacier thinned. At Austre Brøggerbreen and Vestre Lovénbreen, the glaciers thinned to such an extent that they are now cold-based throughout (Etzelmüller 2000). The contraction and ultimate disappearance of the warm-based zone was accompanied by a change in the style of sedimentation.

(3) Today, mobilization of subglacial sediment is inhibited beneath the glaciers and sedimentation is dominated by the transport and release of englacial and supraglacial debris. As recession continues, remnants of the formerly active subglacial bed emerge from beneath the frozen ice margin, and a drape of supraglacial material is lowered onto the subglacial surface from above. Sedimentation under present-day conditions is dominated by the deposition of supraglacial debris stripes reflecting present day ice-flow directions that differ from the ice-flow directions during the more dynamic phase when basal till was deposited. It follows that changes in the mass balance of the glaciers are reflected in the different styles of sedimentation under changing dynamic and thermal regimes. Figure 10 summarizes our interpretation of the thermal evolution of the valley glaciers on Brøggerhalvøya since their pre-Neoglacial maxima. Immediately before, and during, the Neoglacial maximum the glaciers were characterized by predominantly wet-based conditions. During the initial recession from their Neoglacial maxima, there was a gradual reduction in the extent of this wet-based zone as the glaciers thinned and became dynamically less active. Under present-day conditions, some of the valley glaciers, including Austre Brøggerbreen, are characterized by frozen-bed conditions throughout. The transition between these thermal regimes is important from a landform/sediment perspective because it is largely responsible for changes in the styles of sedimentation as the glaciers recede.

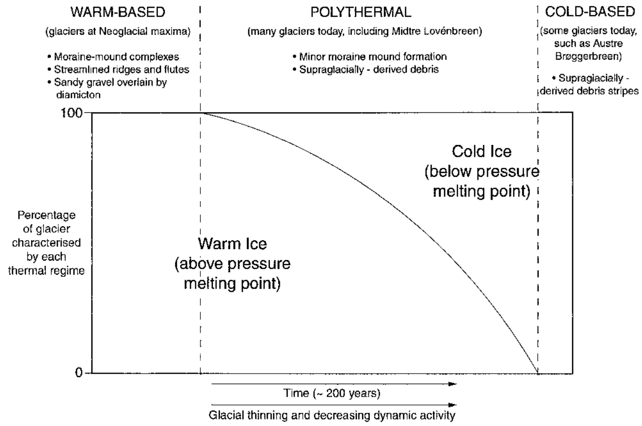


**Fig. 10.** Conceptual model for the thermal evolution of an ideal Svalbard valley glacier over the last 200 years, showing the percentage of the glacier characterised by three possible basal thermal regimes (warm-based, polythermal and cold-based). The transition between these basal thermal regimes is responsible for changes in glacier dynamics and styles of sedimentation.

## *Implications for other ice masses*

The suggestion that the dynamics of polythermal glaciers vary as a result of mass balance has implications for the dynamics of other ice masses, both in Svalbard and globally (Dowdeswell *et al.* 1995). Glaciers that exist close to some critical mass balance threshold will have complex sedimentary histories related to the up-glacier and down-glacier migration of thermal boundaries. Many Svalbard glaciers may also be underlain by deformable sediment that can be remobilized or reactivated during sustained periods of positive mass balance or rapid advances. Equally, changes in the location of this thermal boundary may also help to explain why the velocity of some glaciers appears to be constantly out of equilibrium with the local climate, resulting in rapid oscillations between fast and slow modes of flow, or surges (Budd 1975; Fowler 1987; Murray *et al.* 2000). Since styles of sedimentation are linked to subglacial thermal conditions (Boulton 1972), changes in mass balance may also influence the location of larger fast-flowing outlet glaciers resting on soft sediment such as those that drain the West Antarctic Ice Sheet (Anandakrishnan *et al.* 1998; Bell *et al.* 1998).

## *The nature of the deforming layer at Midtre and Austre Lovénbreen*

The deforming layer at the glaciers investigated in this study is relatively thin (generally $\leq 1$ m). The surface expression of this subsole deformation is a series of ridges and flutes composed of a core of muddy-sandy gravel, overlain by diamicton. Our interpretation of this stratigraphy is that the glaciers flowed over a deforming bed of pre-existing glaciofluvial sediment and deposited a drape of basal glacial deposits over this pre-existing material during glacier flow. The strong clast macrofabrics in the deformed sediments are consistent with the suggestion of Hart (1994) that thin deforming layers possess strong fabrics.

There is also an interesting relationship between the deforming layer and the bedrock, in particular the variable nature of incorporation of weathered bedrock into overlying till (Fig. 4d). In several places no incorporation was observed, but elsewhere there was evidence of till injected into bedrock fractures and bedrock blocks being fractured within the deforming sediment layer (Fig. 6). Till has been observed penetrating joints in bedrock in other settings, suggesting that it has been squeezed under pressure into cracks and joints (Broster 1991; Broster & Park 1993; Evans *et al.* 1998), although this is a locally variable process (Warren 1986). Where there is a lack of interaction between bedrock and the deforming sediment, two possible processes may be involved. Firstly, it is possible that the rapid, frequent and high magnitude basal water pressure fluctuations required for injecting water and sediment into bedrock joints and fractures did not exist in these areas (Iverson 1991). Secondly, it is possible that the interface between deforming sediment and underlying bedrock represents a sporadically developed décollement surface and that till deformed over bedrock without significant incorporation of bedrock, and without being squeezed into fissures within it. The relative importance of these two processes remains to be tested.

## Conclusions

(1) The sedimentary facies indicating former wet-based subglacial conditions in the forefields of Midtre and Austre Lovénbreen include muddy–sandy gravel, diamicton and pebble, cobble and boulder gravels. These facies are commonly shaped into streamlined ridges and flutes.

(2) Landforms indicating supraglacial sedimentation are linear debris stripes composed of angular material that are related to flow-parallel folding high up-glacier. These linear debris stripes are common on Svalbard valley glaciers as medial moraines, emerging from beneath the ice surface close to the snout.

(3) Although the age of the sediments cannot be determined directly, Neoglacial sedimentation at Midtre and Austre Lovénbreen was dominated by a dynamic regime representing widespread wet-based subglacial conditions. Modern sedimentation is dominated by polythermal or frozen-bed conditions. A third stage is displayed at the much-thinned Austre Brøggerbreen and Vestre Lovénbreen, which are believed to be frozen-based throughout.

(4) It is inferred that sediments indicating wet-based subglacial conditions were deposited at the Neoglacial maximum when the glaciers were thicker and more dynamic. At this time the glaciers had greatly enlarged areas of basal melting due to enhanced geothermal and frictional heating.

(5) The Neoglacial advance and sedimentation took place over pre-existing Aufeis or inactive glacier ice, protecting them from further wholesale ablation. Neoglacial sediments overlying these buried ice layers are prone to collapse under present-day climatic conditions.

(6) Changes in glacier thickness and dynamics (and therefore styles of sedimentation) are driven primarily by changes in mass balance. The switch from wet-based subglacial conditions to polythermal or frozen-bed conditions occurs rapidly (within 100 years) in receding Svalbard valley glaciers.

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