The Role of Folding and Foliation Development in the Genesis of Medial Moraines: Examples from Svalbard Glaciers

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ABSTRACT

The structure and debris content of four glaciers in NW Spitsbergen (Svalbard) are described to test the hypothesis that medial moraines are the product of folding, accompanied by the development of longitudinal foliation. Using clast orientation, clast shape, and clast lithological data, combined with measurements of fold axes and foliation in ice, this hypothesis is shown to be applicable to small valley glaciers with multiple basins feeding a narrow tongue, a common situation in Svalbard. The glaciers examined show stratification (commonly incorporating angular rockfall-derived debris) folded to varying degrees along flow-parallel axes throughout the tongue. An axial plane foliation is commonly associated with this folding and attains its greatest strength at flow-unit boundaries. The debris takes a medium-level to high-level transport path through the glacier, emerging at point sources defined by gently dipping fold hinges near the snout. As more of the folded debris layer melts out, downglacier-widening medial moraines are formed. In a few locations, foliation containing basally derived debris also shows an axial planar relationship with folding; this debris typically melts out to produce diamicton with predominantly subrounded and subangular clasts. In this case, it is inferred that subglacial sediment and debris-rich basal ice are folded within the body of the glacier and can reach the surface near the snout. The proglacial areas preserve evidence of medial moraines in the form of trains of coarse angular debris and foliation-parallel ridges of diamicton, although the latter have a poor preservation potential. There is scope for applying these structural glaciological concepts to medial moraines wherever glaciers are fed by multiple basins.

Introduction

The relationships between the various structures in glaciers are complex and involve a range of both ductile and brittle features (Hambrey and Lawson 2000). The role these structures play in the entrainment, transport, and deposition of debris is important in many glaciers. However, until now, the precise relationships between debris and structures within glaciers have not been rigorously defined. Typical ice structure and debris associations, recently hypothesized for several polythermal glaciers in Svalbard, include (1) the relation between debris of supraglacial origin and folding of stratification, a process that is accompanied by the development of an axial plane foliation; (2) the incorporation of basal debris and basal ice, in association with both foliation development; and (3) incorporation of basal debris by thrusting (Glasser et al. 1998; Hambrey et al. 1999; Hambrey and Glasser 2002). These hypotheses were based simply on observed relationships but have yet to be tested using a range of systematically recorded structural data. The aim of this article is to test the validity of folding hypotheses 1 and 2 using structural and sedimentological data from four small valley glaciers in NW Spitsbergen. This approach is particularly relevant to understanding the genesis of medial moraines. The third mode of debris entrainment, by thrusting, is outside the scope of this article but has been described by Hambrey et al. (1997) and Bennett (2000).

This structural glaciological approach has significance in understanding the genesis of landforms developed in the proglacial areas of receding Arctic glaciers. For example, recent work has demonstrated that there is a strong structural glaciological control, notably thrusting or subglacial deformation on the development of moraine-mound com-

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plexes ("hummocky moraine") (Hambrey and Huddart 1995; Van der Wateren 1995; Huddart and Hambrey 1996; Hambrey et al. 1997; Bennett et al. 1999; Boulton et al. 1999; Bennett 2000). Smaller-scale features in Svalbard, such as flow-parallel ridges, include not only the well-known flutes but also "foliation-parallel ridges" of subglacial origin and debris trains of supraglacial derivation (Glasser et al. 1998; Hambrey et al. 1999). In some locations, small-scale transverse moraines of thrust origin intersect flow-parallel structures that may relate to folding in the glacier (Bennett et al. 1996).

Area of Investigation

The four glaciers targeted in this study (austre Brøggerbreen, vestre Lovénbreen, midre Lovénbreen, and austre Lovénbreen) are located on the mountainous peninsula of Brøggerhalvøya, near the research station of Ny-Ålesund (fig. 1) in NW Spitsbergen (Svalbard), at a latitude of approximately 79°55′N. All the glaciers have multiple accumulation basins occupying cirques and are relatively inactive, as evidenced by the low velocities recorded on two of them (austre Brøggerbreen, now largely frozen to its bed, and midre Lovénbreen, with true polythermal characteristics) and a general absence of crevasses on all of them (Hagen et al. 1993). All four glaciers have receded substantially since the Neoglacial maximum of around 1900 A.D., exposing complex sediment/landform assemblages in their proglacial areas (Hambrey et al. 1997; Hansen 1999; Glasser and Hambrey 2001). It is further evident that all these glaciers were formerly much more dynamic and produced structures that are no longer actively forming today. It has been suggested that at their Neoglacial maxima at least some of the Brøggerhalvøya glaciers were surging (Liestøl 1988). However, structures visible in aerial photographs, notably straight (rather than looped or contorted) moraines, indicate that non-surging flow has prevailed throughout the time it has taken for ice to pass through the glacier system.

Each of the glaciers has a receding tongue, at the surface of which flow-parallel lines of debris or medial moraines emerge at point sources. These medial moraines grow into prominent ridges, coalescing downglacier (figs. 2–4). The structural analysis focused primarily on these features.

Methods

A range of mapping and structural geological techniques were used to determine the precise relationships between folding, foliation, and debris layers of supraglacial origin and medial moraines. Sketch maps of the snouts of each glacier were prepared using 1995 vertical aerial photography taken for the Norsk Polarinstitutt. No recent large-scale topographic maps were available, except for midre Lovénbreen (Hansen 1999), but the areal distribution of debris in each case is clear from the photographs. Structural measurements were made on one transect per glacier, each transect linking the debris point sources of all the medial moraines. At each moraine apex, data obtained included the orientation of the axis of folded stratification and of the associated axial planar longitudinal foliation. Other data obtained at representative moraines included the orientation of fold limbs, the long axis of clasts embedded in the ice where medial moraines emerge from beneath the glacier surface, and the shape of clasts according to the Powers roundness classification. Differential weathering of different ice types allowed ready insertion of an ice axe, facilitating the recording of planar features and fold axes. Lithologies making up the moraines were also recorded. Three-dimensional structural data are plotted on lower hemisphere Schmidt equal-area projections, and eigenvalues and eigenvectors have been determined to quantify the strength and preferred orientation of the relevant structures. Clast-orientation data are plotted on rose diagrams and clast shape on histograms according to the Powers roundness categories.

Structural Glaciological Data and Interpretation

The other glaciers investigated appear to show the same structural sequence, except that on austre Brøggerbreen and vestre Lovénbreen the longitudinal foliation is developed mainly in narrow zones, rather than extending across the full width of the glacier. This structural sequence provides a context within which medial moraine formation can be placed. Therefore, the structures that are the focus of this contribution are S_0 and S_1 above, as displayed at the apices of the medial moraines.

Overall Structure of Midre Lovénbreen. The most detailed structural observations were made on midre Lovénbreen, which is typical of many small valley glaciers in Svalbard in having multiple accumulation basins feeding a narrow tongue. Each of the four glaciers studied has a broadly similar suite of planar structures. The sequential development of structures on midre Lovénbreen, which provides a context for folding and medial moraine formation, is as follows:

1. S_0: the stratification of snow, superimposed

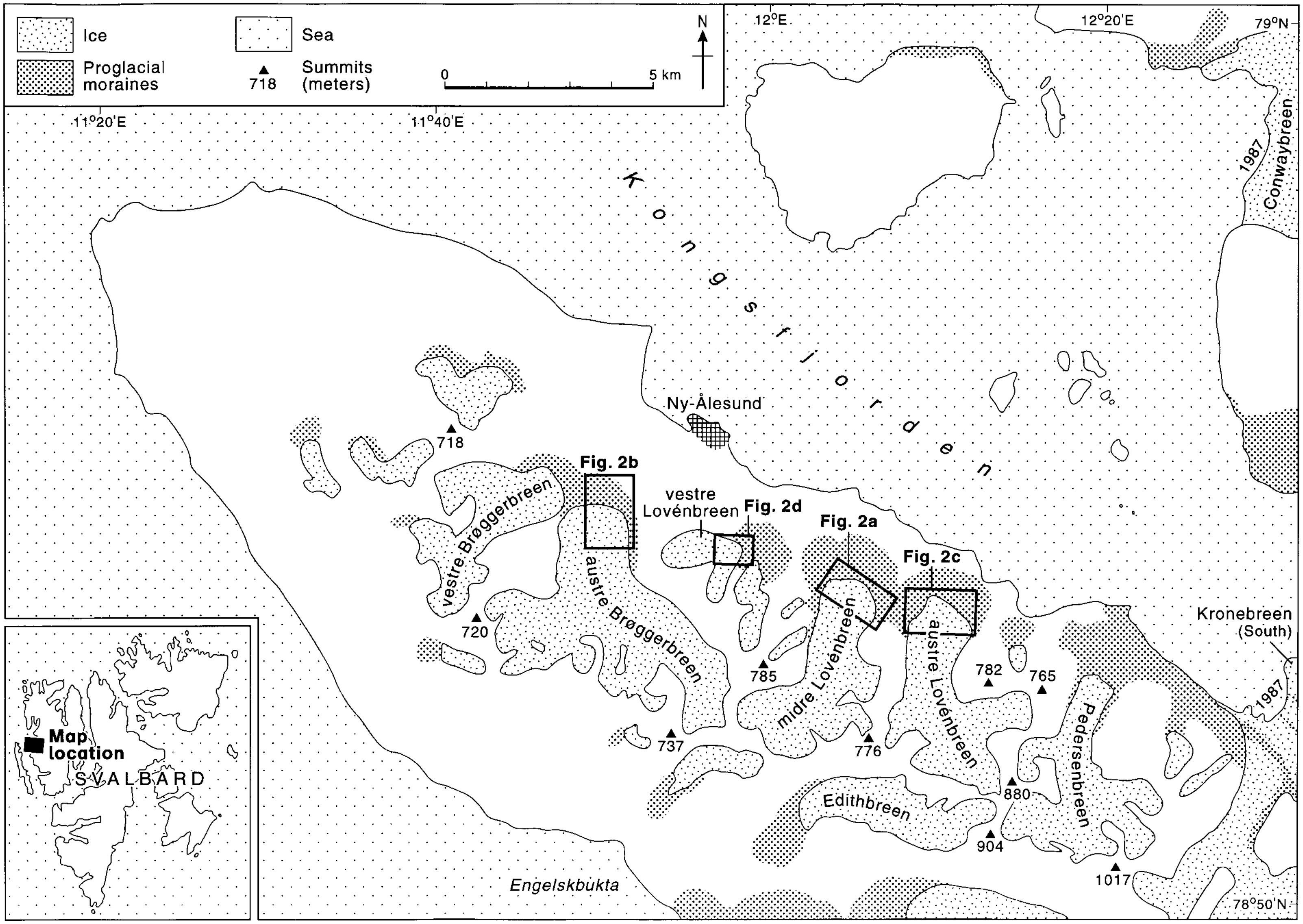


Figure 1. Location map of the four glaciers investigated on the SW flank of Kongsfjorden, NW Spitsbergen

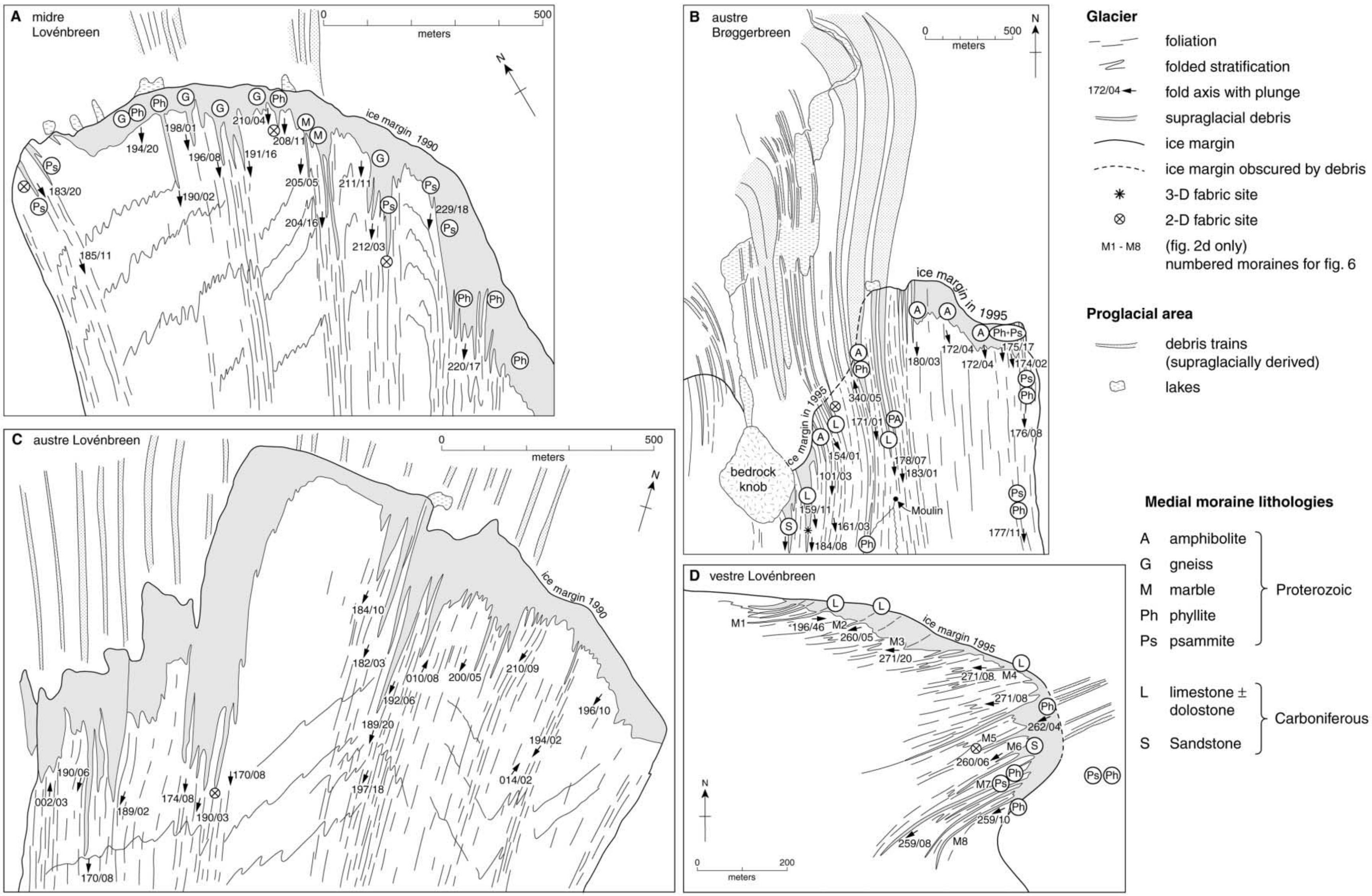


Figure 2. Detailed sketch maps of snout areas of the four glaciers showing the nature of medial moraine development and the relationship with folding and foliation. Drawn from aerial photographs without correction for edge distortion.

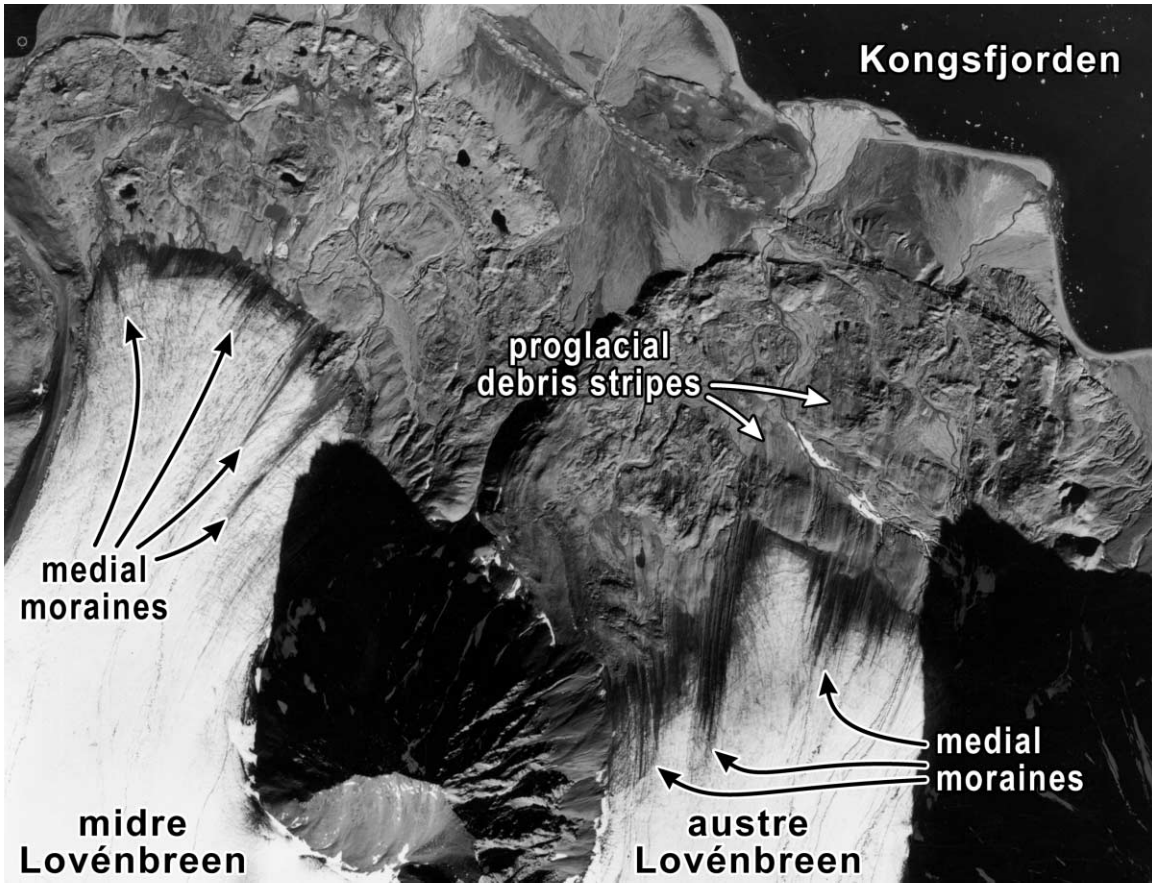


Figure 3. Aerial photograph of midre Lovénbreen (*left*) and austre Lovénbreen (*right*), taken in 1990, illustrating the short medial moraines emerging near the snout and the debris trains extending through the moraine complexes in the proglacial areas. (Reproduced with permission of Norsk Polarinstitutt; photograph S90 5788.)

ice, firn, and ultimately glacier ice. This structure is evident high in the accumulation areas and in former glacier tributaries now disconnected from the main glacier. Discontinuous debris layers derived from the headwall of the glacier are incorporated as an integral part of the stratified ice mass.

2. S_1: the stratified sequence flows out of the individual accumulation basins (of which there are four on this glacier), enters the narrower tongue, and becomes folded. Major folds have amplitudes of 100 m or more and are visible as faint traces on some aerial photographs. Meter-scale parasitic folds occur on the limbs of the major folds (fig. 5*A*). These minor folds are readily visible when standing on the glacier surface, being picked out by differential weathering of contrasting coarse bubbly and coarse clear or dirty ice. Commonly associated with the minor folds is an axial plane foliation (S_1), which is strongest where the folds have low interlimb angles (fig. 5*B*). The foliation is longitudinal in orientation and extends across the glacier for much of its width, although its strength varies markedly and is strongest at flow-unit boundaries.

3. S_2: the numerous crevasse traces intersect S_0, S_1, and each other. They have many orientations and reflect several different stages of fracturing when the glacier was more dynamic. Few crevasses are present today, but at the Neoglacial maximum, ice was probably fast flowing and contained numerous crevasses.

4. S_3: within 100 m of the snout a set of fractures, arcuate in plan, intersect preexisting structures. Some fractures have debris of basal origin entrained along them. These features are interpreted as thrust faults (Hambrey et al. 1997).

Style of Folding and Moraine Emergence. Folding of stratification (F_1) is evident throughout the tongue of each glacier. The style ranges from the "similar" type to isoclinal. Each glacier resembles midre Lovénbreen in terms of fold styles. The dip of the fold limbs is highly variable, but gently inclined (10°–40°) layers are most com-

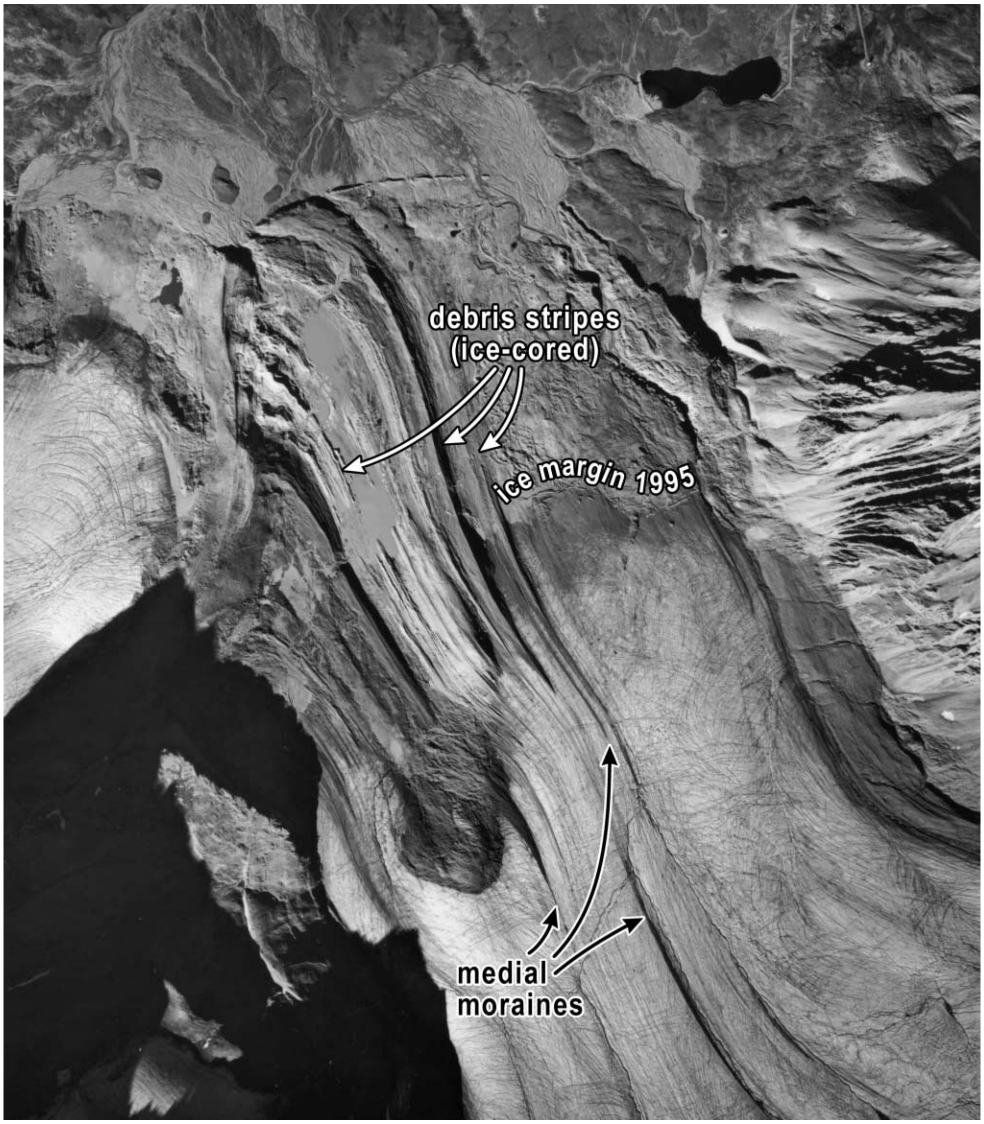
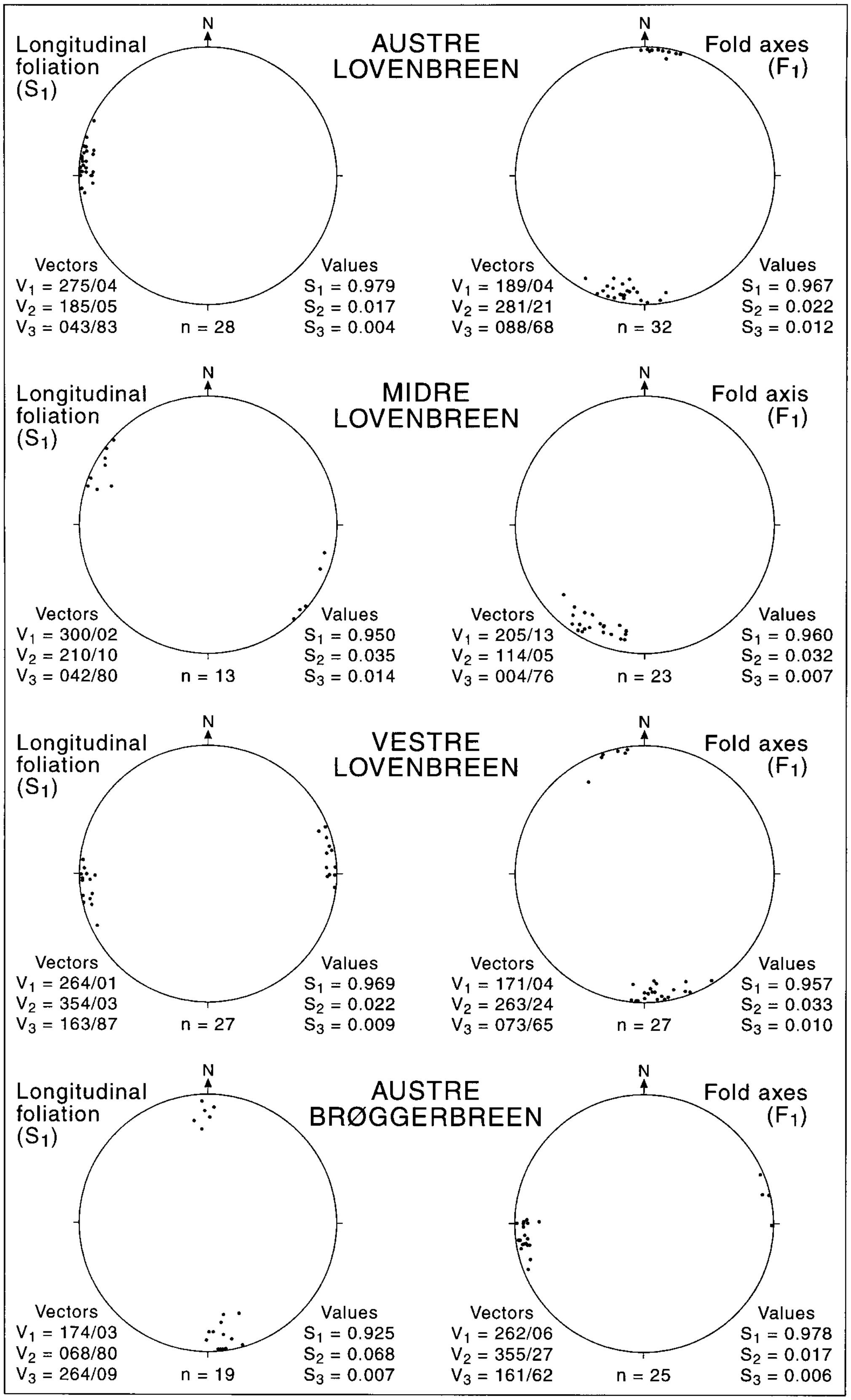


Figure 4. Aerial photograph of austre Brøggerbreen, taken in 1995, illustrating long and short medial moraines and their proglacial continuations as debris trains and ice-cored ridges. (Reproduced with permission of Norsk Polarinstitutt; photograph S95 1087.)

mon. Near flow-unit boundaries, defined by strong longitudinal foliation, the folds become tighter and occasionally isoclinal with steeply inclined limbs. The orientation of the axis of these minor folds is nearly always consistent, that is, parallel to ice flow, and plunging gently upglacier (fig. 6). The orientation of the major folds apparently mirrors that of the minor folds but is not directly measurable. The hinges of folded stratified ice become associated with the emergence of englacial debris within a few hundred meters of each glacier snout. Debris forms discontinuous layers, approximately one clast thick, parallel to the folded stratification; clasts are mainly cobble-sized and boulder-sized. Debris emerges from the ice at a point source and, as more of the layer is exposed, broadens downglacier into a discrete moraine ridge (fig. 5*C*). Each point source effectively represents the fold axis of a debris layer. Numerous point sources, each producing a discrete ridge, are characteristic features of the Svalbard glaciers studied. These ridges commonly coalesce downglacier. The strong clustering of fold axes where debris emerges at the surface is evident both visually in the stereographic projections and statistically in showing S_1 eigenvalues

Figure 5. Structures in glaciers and their relationships with debris. *A*, Debris-free stratification showing parasitic folds on large-amplitude fold, midre Lovénbreen. *B*, Axial planar foliation crosscutting stratification on midre Lovénbreen; ice axe (*ringed*) is inserted along a fold hinge. *C*, Emergence of angular debris and downglacier development of medial moraine ridge, austre Brøggerbreen. *D*, Debris emerging parallel to foliation on austre Brøggerbreen, illustrating clasts of basal affinity and abundant mud matrix (site marked with an asterisk in fig. 2*B*); note alignment of clasts parallel to the foliation. *E*, Emergence of debris of supraglacial origin at a fold hinge defined by the contrast between clean ice and debris-laden ice; the ice axe is placed parallel to the fold axis and the mean orientation of a-axes of clasts.


AUSTRE
LOVENBREEN
N
Longitudinal
foliation
(S1)
Vectors
V1 = 275/04
V2 = 185/05
V3 = 043/83
n = 28
Values
S1 = 0.979
S2 = 0.017
S3 = 0.004
Fold axes
(F1)
Vectors
V1 = 189/04
V2 = 281/21
V3 = 088/68
n = 32
Values
S1 = 0.967
S2 = 0.022
S3 = 0.012
MIDRE
LOVENBREEN
Longitudinal
foliation
(S1)
Vectors
V1 = 300/02
V2 = 210/10
V3 = 042/80
n = 13
Values
S1 = 0.950
S2 = 0.035
S3 = 0.014
Fold axis
(F1)
Vectors
V1 = 205/13
V2 = 114/05
V3 = 004/76
n = 23
Values
S1 = 0.960
S2 = 0.032
S3 = 0.007
VESTRE
LOVENBREEN
Longitudinal
foliation
(S1)
Vectors
V1 = 264/01
V2 = 354/03
V3 = 163/87
n = 27
Values
S1 = 0.969
S2 = 0.022
S3 = 0.009
Fold axes
(F1)
Vectors
V1 = 171/04
V2 = 263/24
V3 = 073/65
n = 27
Values
S1 = 0.957
S2 = 0.033
S3 = 0.010
AUSTRE
BRØGGERBREEN
Longitudinal
foliation
(S1)
Vectors
V1 = 174/03
V2 = 068/80
V3 = 264/09
n = 19
Values
S1 = 0.925
S2 = 0.068
S3 = 0.007
Fold axes
(F1)
Vectors
V1 = 262/06
V2 = 355/27
V3 = 161/62
n = 25
Values
S1 = 0.978
S2 = 0.017
S3 = 0.006

(which measure the strength of the preferred orientation) in excess of 0.9 (fig. 6).

Axial Plane Foliation. Intersecting the F_1 folds is a longitudinal (flow-parallel) foliation (S_1), which has a clearly visible axial plane relationship (fig. 5*B*). The foliation itself is defined by anastomosing layers, approximately a centimeter thick, of coarse bubbly and coarse clear ice and is commonly penetrative across folded S_0 surfaces, although sometimes the intensity of foliation across adjacent folded layers is variable. The crystallographic relationship between S_0 and S_1, however, has yet to be defined. Stereographic projections of poles to foliation show strong clustering and high S_1 eigenvalues (fig. 6). Comparison of eigenvector data confirms the axial planar relationship, as the V_1 values for the plunge of folds and dip direction of the foliation are within a few degrees of being perpendicular to each other (fig. 6). S_1 is best developed where flow units, originating from separate accumulation basins, combine. The strong foliation in such zones is associated with tight folding (interlimb angles of <20°).

Nature of Debris. Debris associated with medial moraines is of two main types, reflecting both supraglacial and subglacial sources.

1. Most debris layers that evolve into medial moraines are composed of either a single lithology or a small range of associated lithologies (fig. 2*A*, 2*B*, 2*D*). Adjacent layers often reveal contrasting lithologies, which in the best example, austre Brøggerbreen, are manifested by both a variety of sedimentary (e.g., Carboniferous limestone and sandstone) and metamorphic lithologies (Proterozoic psammite, phyllite, and gneiss) (fig. 2*B*). Most clasts are boulder sized and cobble sized, with minor proportions by volume of pebbles and sand. Shape histograms for these moraines (group 1, fig. 7) demonstrate that angular and very angular clasts predominate. These clasts bear no features typical of glacial abrasion, such as striae, facets, or chattermarks. These features are consistent with a supraglacial source following comparison with data presented by Bennett et al. (1997) from this part of Svalbard. From observations of in situ rocks in the headwalls of midre Lovénbreen and austre Brøggerbreen, it was possible to link the lithologies in the moraines to their source areas. The varied geological nature of the terrain allows flow paths to be determined with a degree of confidence, aided by inspection of longitudinal foliation traces observable in aerial photographs. Commonly, an individual moraine has its own distinct lithology or small assemblage of lithologies, while its neighbor may have a different lithology. In all cases, contin-

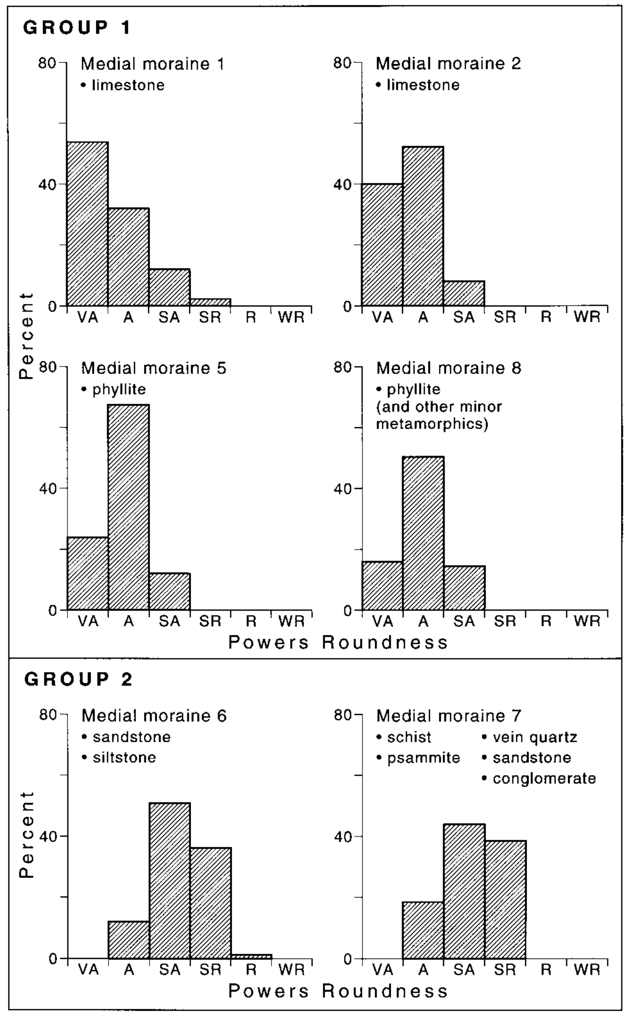


Figure 7. Histograms of two groups of clast-roundness data from the medial moraines of vestre Lovénbreen. Group 1 data represent angular material of supraglacial derivation; group 2 data represent basally derived debris. Fifty clasts were measured in each case.

Figure 6. Schmidt lower hemisphere equal-area projection of structural data from the four glaciers: poles to foliation planes and plunge of fold axes. Orientation of fold axes with respect to ice-flow direction is indicated by parallelism between foliation and expected ice flow. Eigenvectors (*V*) and eigenvalues (*S*) are given.

uation of these medial moraines onto the proglacial areas is evident as prominent debris trains. The relationship between debris and structure in the four glaciers studied has been observed at many other small land-based valley glaciers in Svalbard.

2. In a few medial moraines at vestre Lovénbreen and austre Brøggerbreen, the sedimentological characteristics are quite different from those described earlier. The particle-size distribution ranges from mud size to boulder size, and clasts are predominantly subrounded and subangular (group 2 data, fig. 7). Some fine-grained lithologies (siltstone and limestone) also show facets and striations, and there is a wider variety of lithologies than in those moraines comprising angular debris. The debris melts out from strong longitudinal foliation that has an axial planar relationship with tight similar or isoclinal folds. This foliation is made up of coarse clear ice with disseminated clots of mud and minor amounts of coarse bubbly ice (fig. 5*D*). It resembles closely the regelation layer found in other Arctic glaciers (Knight 1998). The attributes of the foliated and folded ice and of the debris suggest that basal debris has been transferred to a high-level position in the glacier by folding about flow-parallel axes.

Clast Orientation. Where angular debris first reemerges at the glacier surface at the start of a medial moraine, it is apparent that within the first meter or so, the larger clasts have not been disturbed by ablation, and therefore the orientation of their long axes at the surface matches that within the ice. Thus, the long axes of 50 clasts were measured at each of six medial moraines, together with the associated fold axes. The a-axes of clasts are preferentially aligned parallel to the fold axis at each site, although there is considerable variation in the strength of this relationship (fig. 8).

In the case of an example of basally derived debris emerging from near vertical foliation at the start of a moraine on austre Brøggerbreen (see asterisk in fig. 2*B*), an equal-area projection of clast long axes demonstrates a strong fabric almost perfectly parallel to both the longitudinal foliation (S_1) and the associated fold axis (F_1; fig. 9).

Both of these sets of data demonstrate the clear relationship between debris, folded stratification, and foliation, confirming that a common process is involved. An analogy can be drawn between the alignment of clasts in ice and mineral alignment parallel to the fold axis in metamorphic rocks, a feature known as stretching lineation.

Discussion

Evolution of Folds and Medial Moraines. The consistency of structural relations between folded stratification, longitudinal foliation, and the debris layers that evolve into medial moraines suggests that they are associated with a common deformation regime. The location for folding and axial plane foliation development is most likely to be in the zone of strong lateral compression and thickening, where ice from a series of accumulation basins feeds into a relatively narrow tongue. The strain regime within this zone of deformation may be inferred from principles of structural geology (Ramsay and Huber 1983) and presented as a schematic model (fig. 10). Layer-parallel shortening of stratification S_0 (fig. 10*A*) is followed by folding, accompanied by differential shear. The process results in a suite of 100-m-scale similar folds with meter-scale parasitic folds. An axial plane foliation also develops (fig. 10*B*), a structure that is equivalent to schistosity in metamorphic rocks, although it is not known whether realignment and recrystallization of ice crystals takes place in a similar way to those processes in rocks. From that position downglacier, the structures may be modified further if topographic constriction continues, but now the ice is subject to ablation, exposing progressively deeper structures (fig. 10*C*).

The debris that makes up the medial moraines is intimately associated with this structural evolution. The bulk of the debris in a moraine is angular rockfall-derived material and is incorporated within stratification (S_0); it follows a relatively high-level transport path. A few moraines near the snout (although not on all glaciers) are made up of basally derived debris, as inferred from the wide grain size and clast-shape distribution, as well as clast-surface features such as striations. Basal debris is associated with the axial plane foliation (S_1), and its incorporation requires a soft deformable bed. Both S_0-related and S_1-related debris are dominated by clasts that are preferentially aligned parallel to the F_1-fold axes. This feature is equivalent to stretching lineation in rocks (Ramsay and Huber 1983) and represents the maximum extension direction. In terms of the strain ellipsoid, X represents the preferred alignment of clasts and fold axes, whereas the foliation lies in the XY plane (fig. 10). A final phase of debris entrainment, by thrusting, occurs near the snout but is not shown in this model.

The data presented here provide firm quantitative support for the conceptual model of folding in medial moraine generation presented previously (Hambrey et al. 1999). This relationship further demonstrates the remarkable similarity between structural relationships found in ice and in meta-

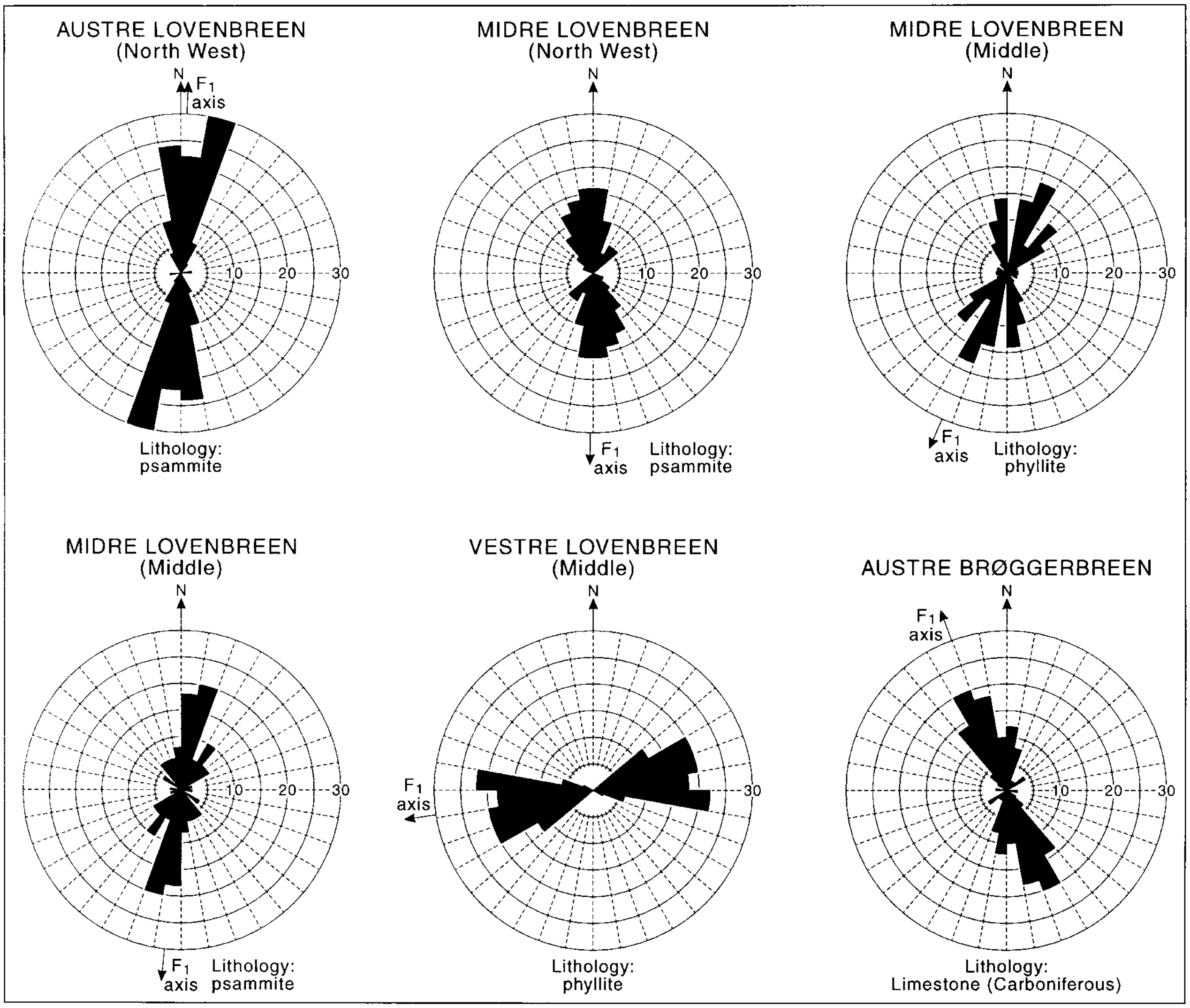


Figure 8. Rose diagrams illustrating the orientation of clast long axes at the point sources of medial moraines comprising angular debris of supraglacial derivation. Fifty clasts were measured in each case and are located on figure 2.

morphic rocks of low to medium grades, such as in slates and schist (Hambrey and Lawson 2000).

Changing Thermal Regime. Basal debris is revealed at the glacier surface where the ice is probably no more than 100 m thick, based on radar profiles (Hagen and Sætrang 1991; Björnsson et al. 1996). Structural evidence suggests that it probably was raised to a relatively high level by folding at the zone of convergence. To incorporate the considerable quantities of debris involved and generate a substantial basal layer, the substrate must have been wet, even in a glacier such as austre Brøggerbreen, which is known to be frozen to its bed. Thus debris incorporation probably took place when the ice was thicker, more dynamic, and sliding on its bed. This inference from structural glaciology is supported by the changing sedimentation regime, which has become apparent as these glaciers have become thinner and colder at the bed (Glasser and Hambrey 2001).

Application of Folding Model to Other Glaciers. Medial moraines are likely to have a number of different origins, but it is clear that the traditional view of a septum of debris between two converged ice-flow units, neatly summarized by Sharp (1988), is too simplistic. A number of studies of medial moraine formation have been undertaken on temperate glaciers. For example, on Berendon Glacier (British Columbia), Eyles and Rogerson (1977) invoked ingestion of basal marginal debris in deep

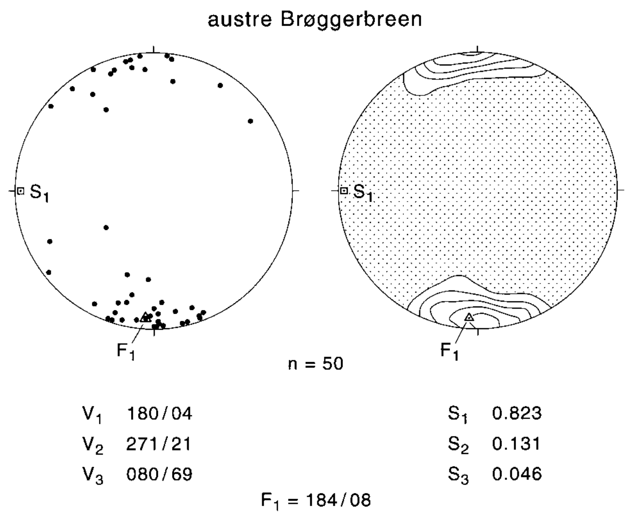


Figure 9. Schmidt lower hemisphere equal-area projection of the long axes of clasts of basal derivation in foliated ice associated within a medial moraine on austre Brøggerbreen (see asterisk in fig. 2*B* for location). The orientations of the associated fold axis (F_1) and foliation (S_1) are also shown. V_1 to V_3 represent eigenvectors and S_1 to S_3 are eigenvalues.

crevasses and redistribution by shearing at the zone of convergence between two flow units. Small et al. (1979), working on medial moraines on glaciers near Arolla, Switzerland, suggested that the debris was derived from "englacial till," having previously been derived from supraglacial point sources within the accumulation zones before being ingested by crevasses. In contrast, in Italy, Smiraglia (1989) stressed the importance of supraglacial debris in the composition of medial moraines on Ghiacciaio dei Forni. A recent theoretical approach to the problem of medial moraine formation explains how moraines widen downglacier (Anderson 2000). However, the assumption is that the debris on the ice surface originates where two flow units merge within the ablation area and is thus redistributed at the surface.

None of these mechanisms explains the relationships observed in the four Svalbard glaciers studied; thus, the folding mechanism represents a new model of medial moraine formation. On the basis of aerial observations of a number of self-contained valley glaciers with multiple accumulation basins in Svalbard, we believe that the processes described herein are widespread in this archipelago. It remains to be seen whether these relationships hold for morphologically similar glaciers elsewhere. However, in the case of at least one temperate Alpine glacier, the Haute Glacier d'Arolla in Switzerland, these structural relationships can already be confirmed (B. Goodsell, pers. comm., 2002), even though previous authors have not noted these links (Small et al. 1979; Gomez and Small 1985).

Proglacial Manifestation of Medial Moraines. The proglacial zone, in the case of the Svalbard glaciers studied, bears the imprint of the folding processes (described earlier) in two ways: (1) as trains of angular debris of single lithology, inferred to be of supraglacial derivation (Glasser and Hambrey 2001), and (2) as "foliation-parallel ridges" (Glasser et al. 1998; Hambrey et al. 1999). From our own observations, the former are common features in the proglacial areas of many Svalbard glaciers, but the latter have been observed only in a few cases. Thus, on a centennial time scale, trains of angular debris have a high preservation potential since they form drapes of angular bouldery debris that contrast markedly with the underlying diamicton of basal glacial origin. Except at austre Brøggerbreen (fig. 4), these drapes generally do not have an obvious ice core but are almost immediately let down onto the substrate. At these Svalbard polythermal glaciers, meltwater tends to emerge in discrete channels at the glacier margins, not from a central portal, so sediments released directly from the ice are not subject to reworking by streams, except adjacent to the channels. In contrast, in temperate alpine regions, the preservation potential of such features is probably low since meltwater discharging from the glacier forms braided river systems, characterized by frequent channel migration, thus tending to rework most of the sediment in the immediate proglacial zone.

Conclusions

Following detailed study of the tongues of four glaciers in Svalbard, where medial moraines emerge at the ice surface, a number of conclusions may be drawn that stress the importance of ice deformation in explaining moraine morphology and the resulting landforms.

1. In Svalbard glaciers with multiple basins feeding a narrow tongue, stratification is folded to varying degrees but is most strongly folded near flow-unit boundaries.

2. An axial plane foliation is commonly associated with this folding and attains its greatest prominence at flow-unit boundaries.

3. The folded stratification incorporates discontinuous layers of angular debris, derived from the glacier headwalls, and the debris is reorganized so that the clast long axes are preferentially aligned

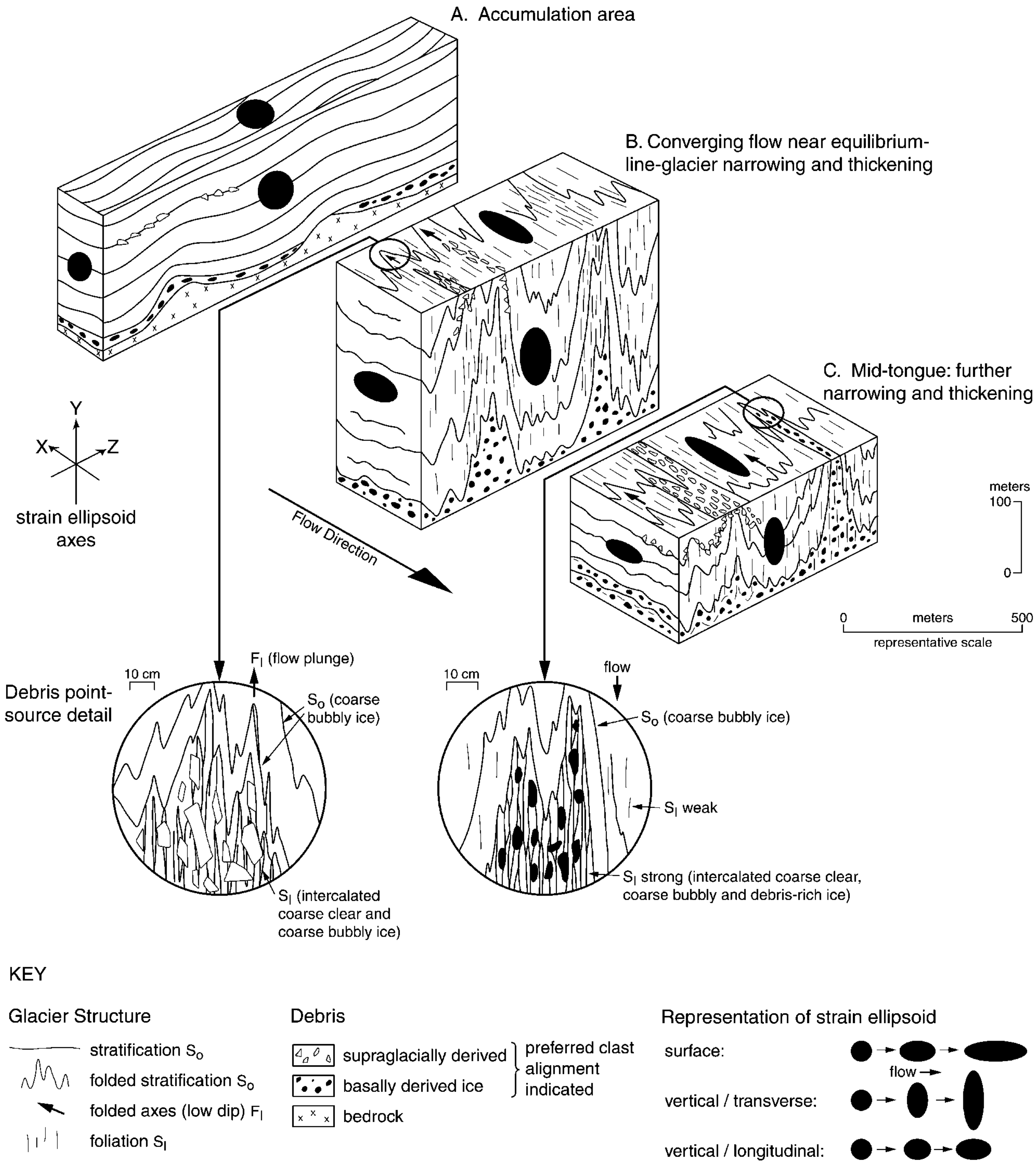


Figure 10. Structural model illustrating the progressive development of medial moraines and their relationship to folding and foliation, representing a segment within the middle portion of a typical Svalbard valley glacier. Enlargements of structural relationships are shown. The cumulative strain ellipsoid is indicated for each successive down-glacier component.

parallel to the fold axis. This debris takes a high-level to intermediate-level englacial path through the glacier, emerging at point sources defined by fold hinges in the tongue, especially near the snout. As more of the folded debris layer melts out, down-glacier-widening medial moraines are formed.

4. Occasionally, examples of basally derived (mainly subangular and subrounded) debris, associated with folding and longitudinal foliation, may be observed; this association requires incorporation of sediment by regelation at a sliding bed and then folding within the body of the glacier to a high-level position.

5. The final stage of structural evolution, thrusting and associated debris entrainment intersects the folds and foliation and has been described elsewhere (Hambrey et al. 1999).

6. These processes may have occurred when glaciers were more dynamic, probably during the Neoglacial maximum, around 1900 A.D.

7. Medial moraines containing angular debris are manifested on the proglacial area by well-preserved debris trains, commonly represented by a single lithology. Those moraines containing basal debris form foliation-parallel ridges, although these have a poor preservation potential.

8. There is considerable scope for applying these structural glaciological concepts to medial moraine and landform genesis in other geographical settings.

9. The main unresolved issue in this investigation is the precise crystallographic relationship between folded stratification and its axial planar foliation. Also, it would be useful to be able to trace the fold structures (with or without debris) accurately to determine the three-dimensional geometry of folds. Application of ground-penetrating radar techniques, which have been useful in defining thrusts in Svalbard glaciers (Murray et al. 1997), have considerable potential in this regard.

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REFERENCES CITED

Anderson, R. S. 2000. A model of ablation-dominated medial moraines and the generation of debris-mantled glacier snouts. J. Glaciol. 46:459–469.

Bennett, M. R. 2000. The morphology, structural evolution and significance of push moraines. Earth Sci. Rev. 53:197–236.

Bennett, M. R.; Hambrey, M. J.; and Huddart, D. 1997. Modification of clast shape in high-arctic glacial environments. J. Sediment. Res. 67:550–559.

Bennett, M. R.; Hambrey, M. J.; Huddart, D.; and Ghienne, J. F. 1996. The formation of geometrical ridge networks ("crevasse-fill" ridges), Kongsvegen, Svalbard. J. Quat. Sci. 11:430–438.

Bennett, M. R.; Hambrey, M. J.; Huddart, D.; Glasser, N. F.; and Crawford, K. 1999. The landform and sediment assemblage produced by a tidewater glacier surge in Kongsfjorden, Svalbard. Quat. Sci. Rev. 18:1213–1246.

Björnsson, H.; Gjessing, Y.; Hamran, S.-E.; Hagen, J. O.; Pálsson, F.; and Erlingsson, B. 1996. The thermal regime of sub-polar glaciers mapped by multi-frequency radio-echo sounding. J. Glaciol. 42:23–32.

Boulton, G. S.; van der Meer, J. J. M.; Beets, D. J.; Hart, J. K.; and Ruegg, G. H. J. 1999. The sedimentary and structural evolution of a recent moraine complex, Holmstrømbreen, Spitsbergen. Quat. Sci. Rev. 18: 339–371.

Eyles, N., and Rogerson, R. J. 1977. Glacier movement, ice structures, and medial moraine formation at a glacier confluence, Berenden Glacier, British Columbia, Canada. Can. J. Earth Sci. 14:2807–2816.

Glasser, N. F., and Hambrey, M. J. 2001. Styles of sedimentation beneath Svalbard valley glaciers under changing dynamic and thermal regimes. J. Geol. Soc. Lond. 158:697–707.

Glasser, N. F.; Hambrey, M. J.; Crawford, K. R.; Bennett, M. R.; and Huddart, D. 1998. The structural glaciology of Kongsvegen, Svalbard and its role in landform genesis. J. Glaciol. 44:136–148.

Gomez, B., and Small, R. J. 1985. Medial moraines of the Haut Glacier d'Arolla, Valais, Switzerland: debris supply and implications for moraine formation. J. Glaciol. 31:303–307.

Hagen, J. O.; Liestøl, O.; Roland, E.; and Jørgensen, T. 1993. Glacier atlas of Svalbard and Jan Mayen. Nor. Polarinst. Medd. 129.

Hagen, J. O., and Sætrang, A. 1991. Radio-echo soundings of sub-polar glaciers with low-frequency radar. Polar Res. 9:99–107.

Hambrey, M. J.; Bennett, M. R.; Dowdeswell, J. A.; Glasser, N. F.; and Huddart, D. 1999. Debris entrainment and transfer in polythermal valley glaciers. J. Glaciol. 45:69–86.

Hambrey, M. J., and Glasser, N. F. 2002. Development of landform and sediment assemblages at maritime

High-Arctic glaciers. *In* Hewitt, K., eds. Landscapes in transition. Rotterdam, Kluwer.

Hambrey, M. J., and Huddart, D. 1995. Englacial and proglacial glaciotectonic processes at the snout of a thermally complex glacier in Svalbard. J. Quat. Sci. 10: 313–326.

Hambrey, M. J.; Huddart, D.; Bennett, M. R.; and Glasser, N. F. 1997. Genesis of "hummocky moraines" by thrusting in glacier ice: evidence from Svalbard and Britain. J. Geol. Soc. Lond. 154:623–632.

Hambrey, M. J., and Lawson, W. J. 2000. Structural styles and deformation fields in glaciers: a review. *In* Maltman, A. J.; Hubbard, B.; and Hambrey, M. J., eds. Deformation of glacial materials. Spec. Pub. Geol. Soc. Lond. 176:59–83.

Hansen, S. 1999. A photogrammetrical, climate-statistical and geomorphological approach to the post Little Ice Age changes of the Midre Lovénbreen glacier, Svalbard. M.S. thesis, University of Copenhagen, 84 p.

Huddart, D., and Hambrey, M. J. 1996. Sedimentary and tectonic development of a high-arctic, thrust moraine complex, Comfortlessbreen, Svalbard. Boreas 25: 227–243.

Knight, P. G. 1998. The basal ice layers of glaciers and ice sheets. Quat. Sci. Rev. 16:975–993.

Liestøl, O. 1988. The glaciers in the Kongsvegen area, Spitsbergen. Nor. Geogr. Tidsskr. 42:231–238.

Murray, T.; Gooch, D. L.; and Smart, G. W. 1997. Structures within the surge-front at Bakaninbreen, Svalbard, using ground penetrating radar. Ann. Glaciol. 24: 122–129.

Ramsay, J. G., and Huber, M. 1983. The techniques of modern structural geology. Vol. 1. Strain analysis. London, Academic Press, 307 p.

Sharp, R. P. 1988. Living ice. Cambridge, Cambridge University Press, 225 p.

Small, R. J.; Clark, M. J.; and Cawse, T. J. P. 1979. The formation of medial moraines on alpine glaciers. J. Glaciol. 22:43–52.

Smiraglia, C. 1989. The medial moraines of Ghiacciaio dei Forni, Valtellina, Italy: morphology and sedimentology. J. Glaciol. 35:81–84.

Van der Wateren, D. F. M. 1995. Structural geology and sedimentology of push moraines: processes of soft sediment deformation in a glacial environment and the distribution of glaciotectonic styles. Meded. Rijks. Geol. 54.