Two-facies interpretation of the basal layer of the Greenland ice sheet contributes to a unified model of basal ice formation

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ABSTRACT

Two exposures of basal ice in Alaska and Greenland, which have previously provided the basis for contrasting models of basal-ice development, are in fact directly comparable. Reinterpretation of previous field descriptions, combined with new structural and sedimentological data from West Greenland, facilitates a simple unification of previous models of basal-ice development and a common terminology for the field description of basal-ice sequences. The stratigraphy of the basal-ice sequence at any site indicates the subglacial conditions and processes operating up-glacier of that site. Presented here are interpretations of the major sequence types.

INTRODUCTION

Understanding the origin of debris-bearing basal ice in glaciers and ice sheets is crucially important to glacier studies. The basal layer reflects processes operating at the glacier bed and determines many rheological and geomorphological properties of glaciers. A series of earlier papers has described basal ice exposed at the margin of the Greenland ice sheet (e.g., Knight, 1987a, 1989; Sugden et al., 1987; Knight et al., 1994) and has suggested that the basal-ice layer exposed there differs from exposures in other locations, such as the well-known sequence at the Matanuska glacier in Alaska (Lawson and Kulla, 1978; Lawson, 1979). This paper demonstrates that the two exposures of basal ice in Greenland and Alaska, which have previously provided the basis for contrasting models of basal-ice development, are in fact directly comparable. My reinterpretation of the basal ice exposed at the margin of the Greenland ice sheet draws together interpretations by several previous authors and suggests a high degree of equivalence and comparability between this and the basal-ice layer described at the Matanuska glacier. The significance of this reinterpretation is twofold. First, it permits a unification of previously competing models of basal-ice development that have been discussed in recent literature (e.g., Hubbard and Sharp, 1989) and opens the way toward a simple general model of basal-ice development. Second, it facilitates the development of a common terminology for the field description of basal-ice sequences, a need for which has frequently been identified (e.g., Hubbard and Sharp, 1989; Knight, 1993).

PREVIOUS DESCRIPTIONS OF THE BASAL-ICE LAYER

Hubbard and Sharp (1989) reviewed the many published reports of debris-bearing basal ice. The most influential classification has been that of Lawson (1979). On the basis of observations at the Matanuska glacier, Lawson proposed a twofold classification involving a lower stratified facies and an upper dispersed facies (Fig. 1A). The stratified facies is characterized by lenses, pods, and discontinuous layers of debris-rich and debris-poor ice in three complexly distributed subfacies. The dispersed facies, separated from the stratified facies by a well-defined boundary, is characterized by a uniform distribution of debris in the ice. Lawson's (1979) terminology has been applied in descriptions of basal sequences in many other locations (e.g., Souchez and Lorrain, 1991).

From observations at the Greenland ice-sheet margin, Knight (1987a, 1987b) and Knight et al. (1994) described a three-facies basal-ice sequence, with a lower "solid" family of ice types, a middle "banded" layer, and an upper "clotted" layer (Fig. 1B). The solid family consists of complexly interbedded ice types including old snow and cavity-floor ice. The banded sequence is characterized by discrete layers of debris separated by thicker layers of cleaner ice. The clotted ice consists of debris particles and particle aggregates suspended in relatively clean ice. Sugden et al. (1987) described the banded and clotted layers of the sequence at that site in detail, and Souchez and Lorrain (1991) interpreted those two layers to be equivalent to Lawson's (1979) stratified and dispersed facies.

PROBABLE EQUIVALENCE OF PREVIOUS DESCRIPTIONS

The three-facies sequence observed in Greenland can be compared directly with the two-facies sequence in Alaska that was described by Lawson (1979). Differences between the two sequences can be attributed to the glaciological characteristics of the two sites rather than to fundamentally different styles of basal-ice development.

Stratified Facies

Lawson (1979) attributed the stratified facies to the freezing of meltwater to the glacier sole. This assessment was based on isotopic enrichment in ^{18}O, indicating an origin different from snow diagen-

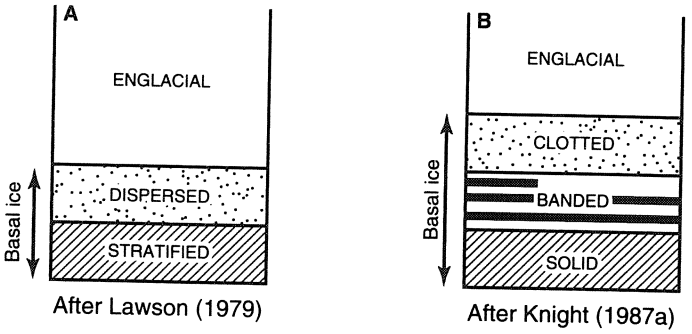

Figure 1. Schematic sections of basal-ice facies at (A) Matanuska glacier and (B) margin of Greenland ice sheet.

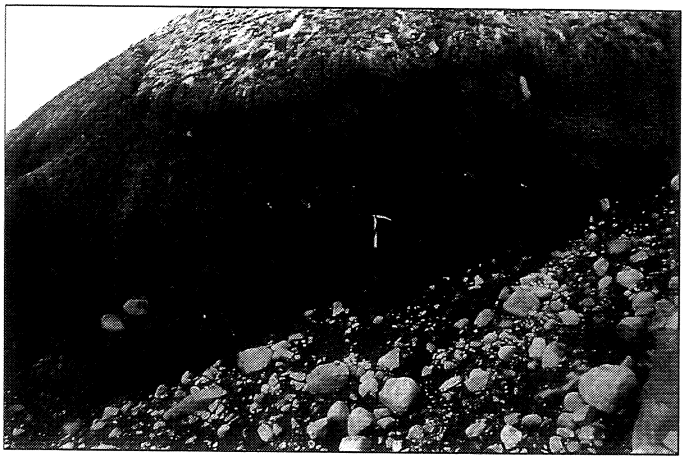

Figure 2. Photograph showing structural connection between debris bands and stratified facies (solid family) at margin of Greenland ice sheet. Pick is 70 cm long.

esis; physical characteristics of ice and debris, indicating a subglacial origin; and radiocarbon ages of wood taken from the ice, indicating a young age for the ice and thus an origin relatively close to the margin. Knight (1987b) attributed the solid family in Greenland to freezing on of subglacial material close to the margin, partly on the basis of a $\delta D/^{18}O$ ratio characteristic of refrozen rather than meteoric water and partly on the basis of the physical and structural characteristics of the ice and debris. Although some differences of detail exist between the sites, there are no points of contradiction in the descriptions and no obstacles to the unification of the classifications. The stratified basal facies from the Matanuska glacier and the solid basal family from the Greenland ice sheet can probably be considered as examples of the same type of debris-bearing basal-ice layer. The term "stratified facies" can appropriately be applied to both. Differences of detail can be described in terms of subfacies and attributed to variations in site characteristics.

Dispersed Facies

On the basis of $\delta^{18}O$ characteristics, Lawson (1979) attributed ice in the dispersed facies to snow diagenesis in the accumulation zone. However, he attributed debris in the dispersed facies primarily to subglacial entrainment, with only limited input from the accumulation zone. He suggested entrainment by localized pressure melting and freezing on, without water loss, of individual particles from the glacier bed, combined with limited upward dispersion associated with particle interactions or flow-related vertical strains. For the clotted ice, Sugden et al. (1987) and Souchez et al. (1990) suggested a similar process of small-scale bump-related regelation, and Knight (1987a) suggested the possibility of dispersal of debris away from the bed. Souchez and Lorrain (1991) suggested that the clotted ice is probably equivalent to Lawson's (1979) dispersed facies. There is sufficient similarity both in what is known and in what remains puzzling about the clotted and dispersed facies to consider the two ice types as probably equivalent. The debris in the dispersed facies at Matanuska is more coarse grained than that in the clotted ice in Greenland, but this may be attributable to the component derived from supraglacial sources, to the distance traveled by the ice, or to the characteristics of the sediment available for entrainment at the two sites. Specific characteristics of the clotted ice, such as the vertical variation in clot size and bubble characteristics described by Knight et al. (1994), were not included in the description of the Matanuska site, but would be less evident at that site because the dispersed facies is not as thick there. Variation in thickness can be explained by the different flow and thermal regimes of the two sites; for example, the longer flow lines in Greenland permit more extensive regelation zones and greater thickening of the layer by deformation around obstacles.

Banded Sequence

Knight (1987a) and Knight et al. (1994) considered the banded sequence as a distinctive basal-ice type not described at the Matanuska glacier. Sugden et al. (1987) considered the banded sequence without specific reference to the solid family, as did Souchez and Lorrain (1991), who nevertheless equated the debris bands with Lawson's (1979) stratified facies.

Ice and debris in the banded sequence are closely related to ice and debris in the stratified facies at the same site in terms of structural, sedimentological, and stable isotope characteristics. Knight (1987b, 1989) has demonstrated that the debris bands and parts of the solid family are isotopically consistent with freezing of basal meltwater, just as Lawson and Kulla (1978) and Lawson (1979) showed for the stratified facies at Matanuska. Figure 2 illustrates the structural connection that is often recognizable between the stratified facies and the banded sequence. Sedimentological data from Greenland (Fig. 3) show a clear equivalence between the material in ice-debris laminations in the stratified facies and the material in ice-debris laminations in the debris bands immediately above, and these data illustrate the equivalence of the two categories. A T-test statistical analysis indicates that the ice-debris laminations in the stratified and in the banded facies are sedimentologically indistinguishable at a 95% confidence level. On these grounds, the banded sequence can be seen as an extension of the stratified facies, intercalated with the overlying dispersed-facies ice by processes of deformation within the ice. The hypothesis that the banded sequence originated by freezing on of alternate layers of clean and dirty ice has been falsified previously (Knight, 1989), and the deformation hypothesis is supported by structural relations clearly visible at the margin (Fig. 2) and by strain-net evidence of compressive flow in the marginal zone (Knight, 1992).

MODEL OF BASAL-ICE DEVELOPMENT

A unified classification of the basal-ice sequence can be created by synthesizing the classifications based on the Greenland and Alaska site descriptions (Fig. 4). The stratified and dispersed facies are the basic components of the sequence, and the banded sequence is effectively a zone of overlap between those two components, formed by the deformational intercalation of stratified ice with ice higher in the sequence.

Stratified Facies

The stratified facies is entrained largely by adhesion of material to the base of the glacier by freezing-on. Clean and dirty water and subglacial sediment (e.g., Weertman, 1961), cavity-floor ice and debris (e.g., Theakestone, 1967; Tison and Lorrain, 1987), proglacially derived material such as snow (e.g., Shaw, 1977), and marginal superimposed ice (e.g., Hooke, 1973) can all be entrained. Although material from the basal transport layer might be entrained by tractional and deformational processes including folding, thrusting (e.g., Goldthwaite, 1951), and regelation-related envelopment (e.g., Iverson, 1993) without large-scale refreezing, refrozen meltwater rather than meteoric ice will normally be the principal element of the stratified facies. Compressional fold structures commonly exist in the stratified facies, and particular structures might indicate particular subglacial conditions.

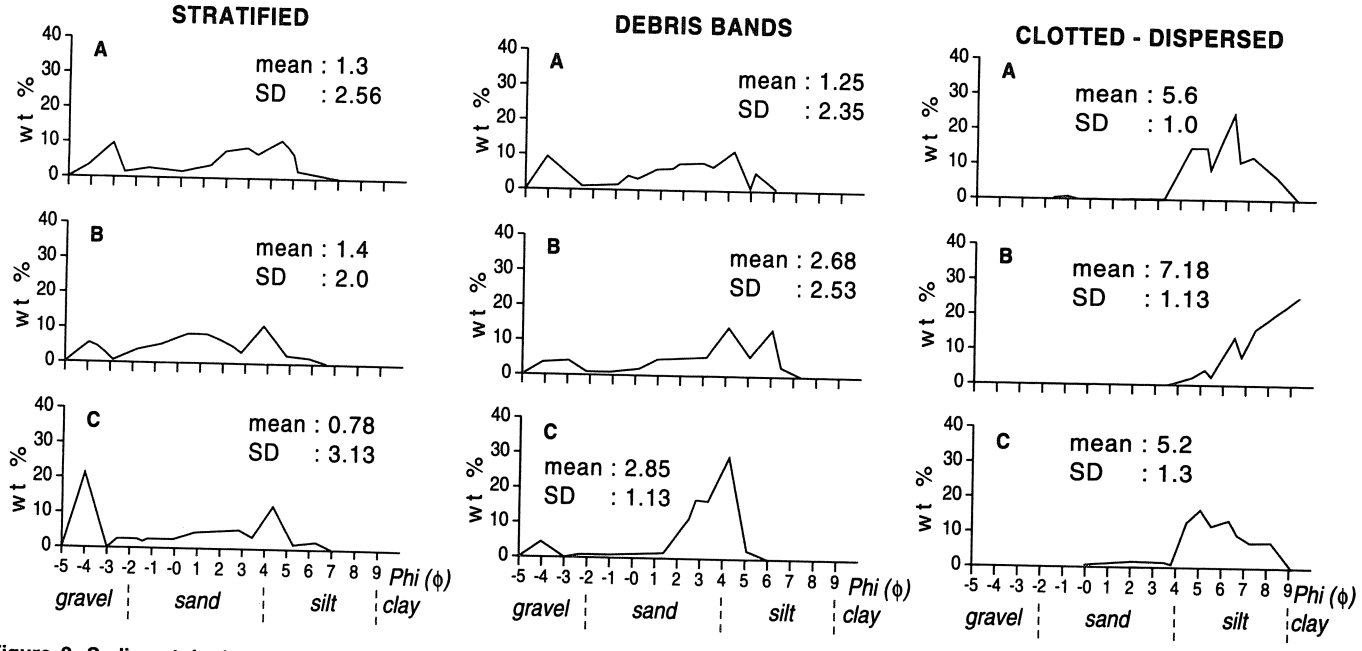

Figure 3. Sedimentological characteristics of solid, banded, and clotted basal-ice layers in West Greenland. Graphs show particle-size distribution in samples from each facies at three sites (A, B, and C) with mean particle size and standard deviation (SD).

Banded Sequence

The banded sequence is a structural extension of the stratified facies, formed by compressional deformation. Connections are sometimes visible in the field between elements of the banded sequence and compressional structures in the stratified facies. The characteristics of the ice and debris in the bands are equivalent to material in the stratified ice.

Dispersed Facies

The origin of the dispersed facies remains elusive. It differs both from englacial ice derived from accumulation at the glacier surface and from the stratified basal facies derived from freezing-on at the bed. Many of the characteristics of the dispersed facies could be explained by small-scale regelation associated with ice flow across an uneven bed in a zone of sliding close to the melting point in the interior of the glacier. This remains the foremost hypothesis for the origin of the dispersed facies. However, some characteristics of the dispersed facies described in Greenland, particularly the narrow range of particle sizes, the vertical size grading of both particles and particle aggregates, and the vertical transition in gas characteristics, call for more detailed explanation, which is the focus of ongoing research. Alternative hypotheses include thorough mixing of stratified ice from the interior of the glacier with overlying nonbasal ice and the diffusion of debris along crystal boundaries in response to thermal, pressure, or strain gradients.

INTERPRETATION OF BASAL-ICE SEQUENCES

Because the principal elements of a basal-ice sequence involve different entrainment processes operating in different glaciological settings, the basal-ice sequence at a site can provide a record of subglacial conditions and processes up-glacier of that site. On the basis of the model proposed in this paper, a sevenfold categorization of possible basal-ice sequences can be envisaged (Fig. 5), and the sequences interpreted as follows.

Type 0. Where no basal ice is present, either none is formed upflow of the point of observation, or whatever has been formed has

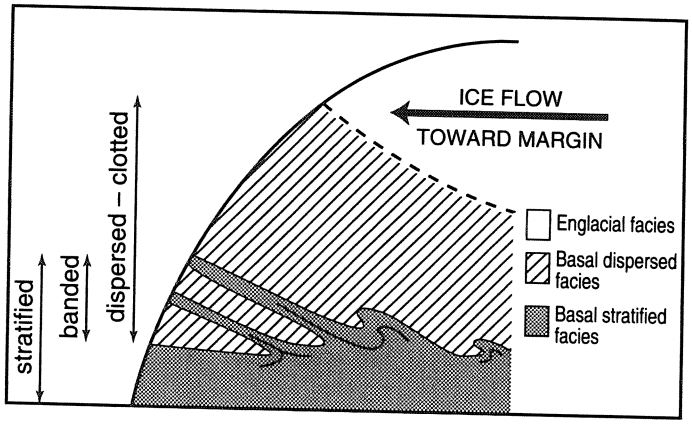

Figure 4. Schematic section combining descriptions of basal-ice sequences in Alaska and Greenland. Debris bands are seen as extension of stratified facies.

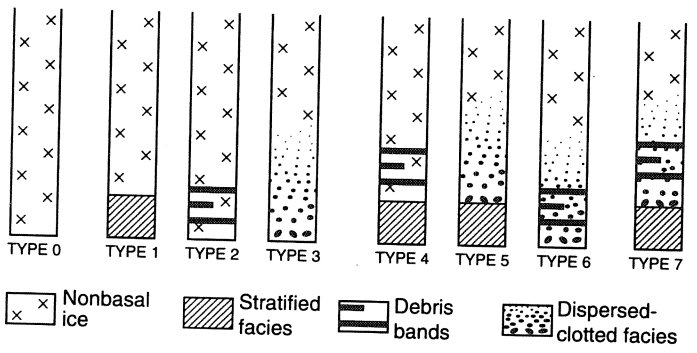

Figure 5. Basic sequences that might be observed in field exposures of basal ice.