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The influence of tectonic deformation on facies variability in stratified debris-rich basal ice

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Abstract

Facies variability displayed within basal ice has hitherto been widely interpreted as a reflection of spatial variation in the processes of ice formation, the basal boundary conditions, or a combination of both. Recent literature has consequently been characterised by attempts to derive a genetic classification of basal ice facies, applicable to different types of glacier. We present new observations made at the Russell Glacier (Greenland), which suggest that any such genetic classification must take account of post-formational deformation occurring within basal ice. All the ice sub-facies occurring within the stratified basal ice are explained in terms of two sets of processes: the initial entrainment of a debris-rich basal layer; and subsequent flow-related tectonic deformation of that layer to produce distinctive, tectonically-derived sub-facies. The evolution, appearance, and composition of some elements of the basal ice layer are therefore argued to be controlled primarily by post-formational, flow-related deformation. Any useful genetic classification of basal ice facies must therefore include criteria able to distinguish between characteristics derived from the mechanism of ice formation, and those that are tectonically derived. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Many glaciers display a basal zone, up to tens of metres in thickness, in which the ice is characterised by a high debris content, a distinctive chemical and isotopic composition, and a highly variable structure (Hubbard and Sharp, 1989; Knight, 1997). This basal layer commonly comprises a complex assemblage of layers and lenses of distinctive types of ice (e.g. Lawson, 1979; Knight, 1987; Hubbard and Sharp, 1995).

Most research on basal ice has focused upon establishing the subglacial processes and bed conditions responsible for the formation of the different basal ice facies that comprise the basal ice layer. For example, attempts have been made to specify facies characteristics associated with small-scale regelation processes and large-scale basal adfreezing; with rigid beds and soft beds; and with closed and open-system water supplies (e.g. Lawson and Kulla, 1978; Gow et al., 1979; Jouzel and Souchez, 1982). This research focus has led to attempts to create 'genetic' basal ice classifications (e.g. Knight, 1994; Hubbard and Sharp, 1995; Knight and Hubbard, 2000), in which the presence or absence of certain facies is used to make inferences about subglacial conditions. There is, however, a growing body of evidence that basal ice characteristics derive not simply from the process of initial entrainment of the ice and included debris, but also from strain-induced processes that occur during the post-formational flow and deformation of basal ice. This paper builds upon the work of Hart (1995) by developing a model that incorporates post-formational tectonic deformation into the interpretive analysis of basal ice.

Structures indicative of both ductile and brittle styles of deformation have been previously described at a number of sites (e.g. Hudleston, 1976; Lorrain et al., 1981; Boulton and Spring, 1986; Hart, 1995). Indeed, folding and thrusting within the basal layer of glaciers has been postulated as a means of raising debris from the bed, and shearing is one of the oldest hypotheses concerning debris entrainment (e.g. Chamberlin, 1895). Deformation due to simple shear is particularly intense in the basal region of ice-masses (Hooke, 1973). Despite this, the specific characteristics associated with tectonically-derived basal ice facies have not been explored. This paper describes characteristics of stratified facies basal ice from

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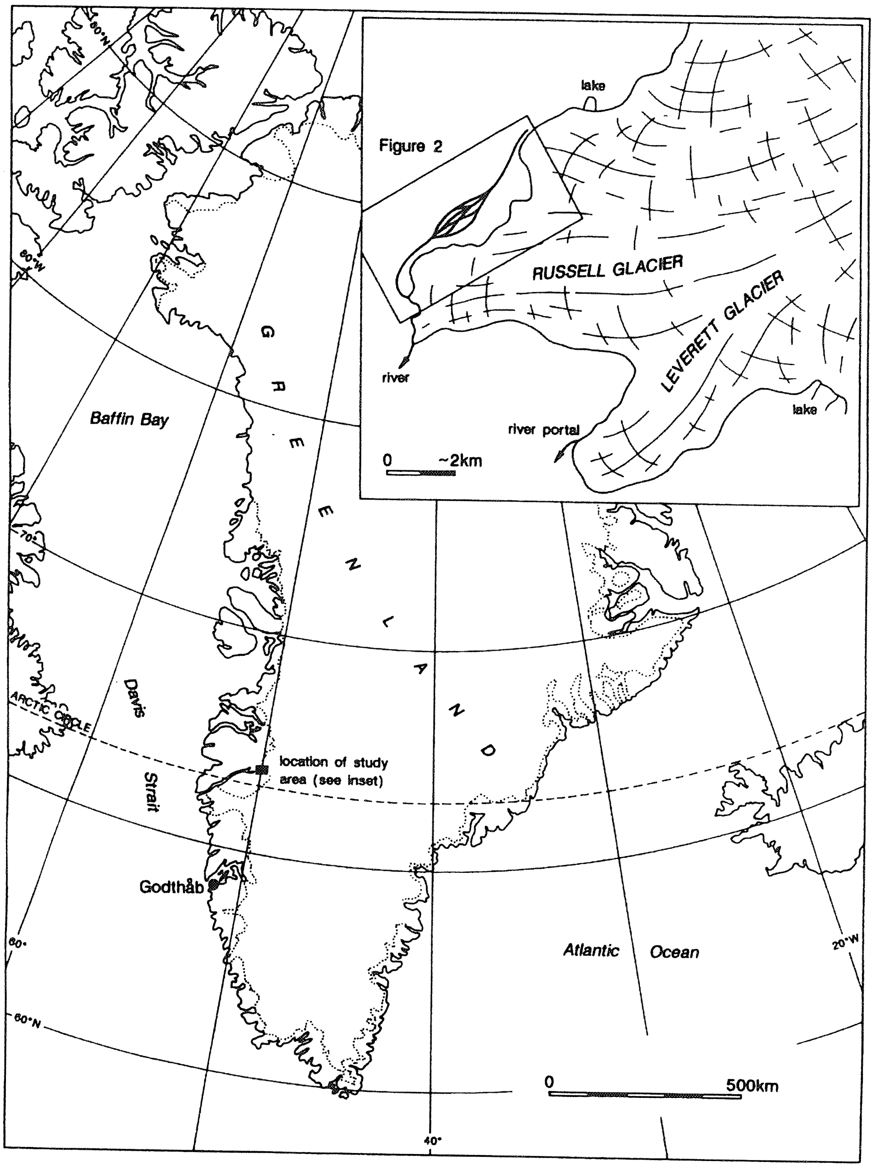

Fig. 1. Location of Russell glacier.

the Russell Glacier, West Greenland, and relates the characteristics of its constituent sub-facies to specific styles of deformation and strain histories.

2. The study site

The field observations described here were made at the northern margin of the Russell Glacier in south-west Greenland (67° 06′N, 50° 15′E). Situated approximately 15 km to the east of Kangerlussuaq (Fig. 1), the glacier is part of a small lobe on the mid-western margin of the Greenland Ice Sheet. The glacier is thought to be polythermal, being characterised at least seasonally by a cold-based margin (van Tatenhove, 1995). Along with the Matanuska Glacier in Alaska, the Russell Glacier is one of the most intensively studied sites of basal ice research. Work by Knight (1987, 1989, 1994), Sugden et al. (1987), and Knight et al., (1994) has established the stratigraphy, sedimentology and ice characteristics of the extensive basal ice layer exposed at the glacier margin.

Fieldwork involved examination of the extent and composition of the stratified facies of the basal ice layer and the subjacent bed at five locations (Fig. 2). The primary focus of the observations concerned the distribution of, and interaction between, the different basal sub-facies comprising the stratified facies, and the structural associations between ice and sediment. Subsequent laboratory analyses of the sediment incorporated within the basal ice included particle-size analysis of the fine fraction (< 2 mm), performed using a Coulter LS100 laser sizer.

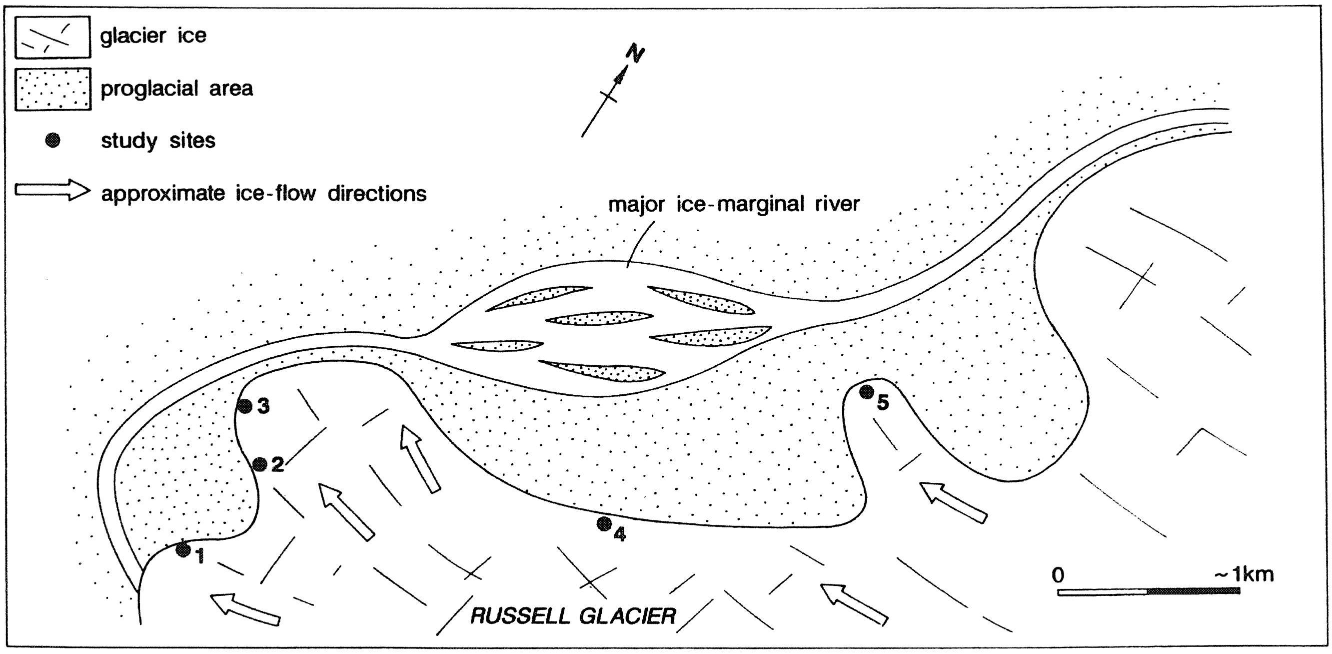

Fig. 2. Location of the study sites.

3. The observed basal ice facies

The basal ice layer exposed throughout the study area was described according to the classification scheme devised by Lawson (1979) and recommended by Knight (1994, 1997). The facies recognised and the terms employed are defined in Tables 1 and 2. The base of the glacier in the study area was characterised by a conspicuous and widespread debris-rich stratified facies, which contrasted strongly with the overlying debris-poor dispersed facies (Fig. 3A). In addition, a variety of debris-rich bands penetrated upwards from the upper boundary of the stratified facies, through the overlying dispersed facies, to outcrop at the glacier surface. The characteristics of the dispersed facies have been described in detail by Knight et al. (1994). The dispersed facies, and the characteristics of the sub-facies of the stratified facies, which constitute the primary focus of this paper, are described below. The results of particle-size analysis of the fine sediment fractions contained within the various basal ice facies are reported in the following section.

3.1. The stratified facies

The stratified facies occurred at the very base of the glacier and was in general characterised by a high debris content, a low bubble content and a fine crystal structure: all features commonly associated with basal ice (Hubbard and Sharp, 1989). The facies as a whole displayed considerable variation, and was composed of a frequently complex assemblage of the following sub-facies.

Table 1
Description of the terminology employed in this paper

Term	Description
Debris lamination	A thin layer of debris of between c. 1–2 mm in thickness. These laminations characterise the discontinuous sub-facies and are laterally discontinuous
Debris-band	Much thicker layers of debris of between c. 10–200 cm in thickness. These features are also more laterally continuous than the debris laminae, often extending laterally along the glacier margin for hundreds of metres. The debris-bands contain a variety of sediments, including fine-grained sorted sediments and diamictons with clasts up to 200 cm in length
Aggregate	A small, rounded body of debris, c. 1–2 mm in diameter and comprised of a range of particle sizes and rock types
Clot	Larger, more irregularly shaped bodies of debris up to c. 2 cm in diameter. They display a characteristic light grey colouration and are comprised of predominantly silt-sized sediment. See Knight (1987) and Sugden et al. (1987) for fuller descriptions

3.1.1. The solid sub-facies

This was typically composed of frozen debris cemented by interstitial ice, although it contained occasional small lenses of debris-free ice (Fig. 3B). This sub-facies yielded a mean debris content of 47% by volume ($n = 5$). The entrained debris was generally diamictic in nature, with an abundance of small clasts up to c. 2 cm in length, and

Table 2
Origin of the basal ice facies according to the tectonic model[a]

Basal ice facies	Subfacies	Interpretation
Stratified	Solid	Represents unconsolidated sediment adfrozen onto the sole of the glacier near the margin (Sugden et al., 1987)
	Discontinuous	Created by flow-related deformation and attenuation of non-cohesive blocks of solid sub-facies ice
	Suspended	Created by flow-related deformation and attenuation of cohesive blocks of solid sub-facies ice
Dispersed		A far-travelled facies, originally entrained by closed-system regelation in the ice-sheet interior (Sugden et al., 1987)

[a] Note: Basal ice classification as per Lawson (1979).

occasional boulders up to c. 30 cm in length, situated within a predominantly sand-sized matrix. These clasts also comprised a variety of different rock types. Solid sub-facies ice was most commonly observed at the very base of the glacier, but was also observed intercalated with other stratified sub-facies, usually occurring as layers and lenses between 1–2 cm and 100 cm in thickness.

3.1.2. *The discontinuous sub-facies*

This sub-facies usually occurred interstratified with layers and lenses of solid sub-facies ice, and was characterised by laterally discontinuous debris laminae c. 0.5 – 2 mm in thickness, occurring within a matrix of cleaner ice (Fig. 3C). The discontinuous sub-facies appeared to be much less debris-rich than the solid sub-facies, and yielded a mean debris content of 22% by volume ($n = 5$). The ice between the debris laminae was bubble-poor, and appeared to be fine-grained in nature. In combination with the solid sub-facies, the discontinuous sub-facies comprised the majority of the stratified facies.

3.1.3. *The suspended sub-facies*

This sub-facies was characterised by a high density of small debris 'aggregates' between 1–2 mm in diameter (Table 1). The incorporated debris was similar in composition to the material occurring within the discontinuous and solid sub-facies ice, comprising a variety of particle sizes and rock types. The ice itself was generally bubble poor and fine grained. The high density of sediment aggregates contained within this facies is reflected by a mean debris content of 30% by volume ($n = 5$). This sub-facies occurred at or close to the upper boundary of the stratified facies.

3.2. *The dispersed facies*

The dispersed facies was characterised by a dispersed arrangement of debris within the host ice. It comprised a low density of 'clots', very different in nature from the more densely packed 'aggregates' contained within the stratified suspended sub-facies (Table 1). In comparison to the stratified basal ice facies (with the exception of the solid sub-facies), the ice itself was relatively bubble rich and coarse grained. This facies usually occurred at the top of the basal ice sequence, superjacent to the stratified facies, and yielded a mean debris content of under 1% by volume ($n = 3$), considerably lower than that recorded from the stratified suspended sub-facies.

4. Observed facies architecture

Detailed observations of the basal ice facies and their architecture were made at five sites within the study area (Fig. 2). The observations made at each site are described below. In addition, the results of the particle-size analysis of sediment samples recovered from the basal ice facies present at site 1 are reported.

4.1. *Site 1*

Site 1 was located on the side of a small lobe that constituted the snout of the Russell Glacier (Fig. 2). The basal ice layer at this site was characterised by a layer of stratified facies ice up to 1 m in thickness. This layer was dominated by layers and lenses of solid sub-facies ice, comprising frozen diamicton with a sand and fine gravel matrix, and an abundance of rounded pebbles, with a range of *a*-axes of approximately 5–20 cm. Intercalated between these lenses of solid sub-facies ice were layers of discontinuous sub-facies ice between 10 and 20 cm in thickness and composed of a series of thin (approximately 1 mm thick), sub-parallel, debris laminations. These laminations displayed distinctive structural features, and were intimately associated with the bodies of solid sub-facies ice. These relationships are summarised schematically in Fig. 4. Firstly, individual laminations could be traced back to blocks of frozen sediment (i.e. solid sub-facies ice), and appeared to be attenuated from them (Fig. 4A). Secondly, the laminations were deflected around obstacles, such as large clasts or units of solid-sub-facies ice (Figs. 4B and C). Finally, the laminations were often folded, both into gentle, open folds and recumbent, isoclinal folds (Figs. 3D and 4D).

The results of particle-size analysis of the fine sediment fraction contained within the solid sub-facies, discontinuous sub-facies and dispersed facies ice are displayed in Fig. 5. All three samples display unimodal particle-size distributions with well-defined peaks. In addition to these maxima, all three samples contain significant

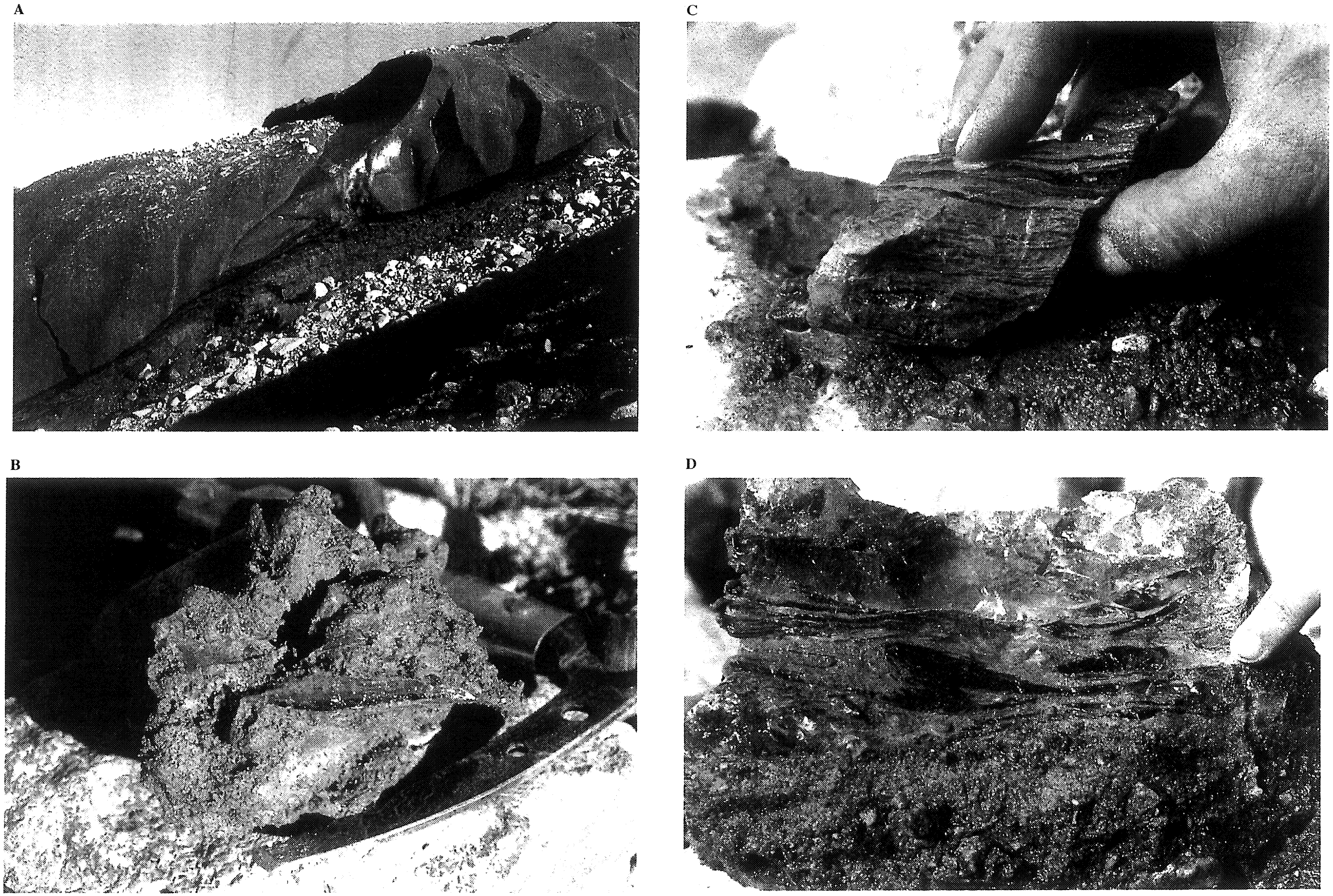

Fig. 3. (A) A layer of stratified facies basal ice at the base of the ice lobe that constituted site 5. (B) Small block of solid sub-facies ice containing a lens of debris-free ice. The block is approximately 7 cm across. (C) Small block of discontinuous sub-facies ice. (D) Block of ice illustrating the interactions between the laminations of the discontinuous sub-facies and the frozen sediment of the solid sub-facies. Note the recumbent flow fold in the centre-left of the figure.

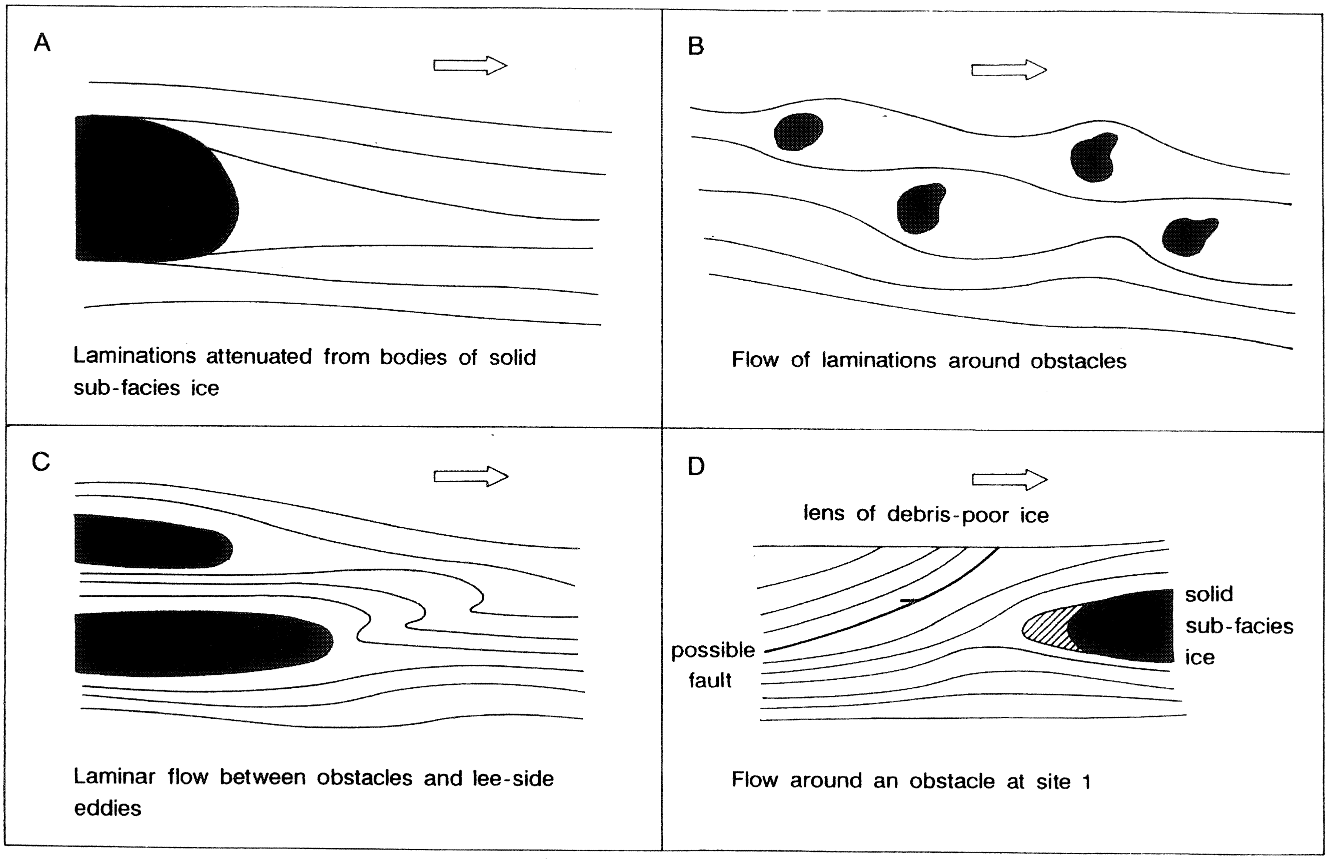

Fig. 4. Schematic diagram summarising the relationships between the debris laminations and obstacles observed within the basal ice layer at Site 1. Arrows indicate the ice-flow direction. Captions A to C depict areas approximately 10 cm across, whilst caption D is approximately 1 m across.

volumes of clay-sized sediment (< 3.9 μm), whilst the sample taken from the dispersed facies also features a minor peak in the fine sand fraction. Within the fine sediment fraction studied, the solid sub-facies sample displays the highest mean particle size (52 μm), the discontinuous sub-facies the intermediate mean value (28 μm), and the dispersed facies, the lowest (20 μm).

4.2. Site 2

At Site 2, a subglacial cavity allowed the three-dimensional structure of the basal ice layer to be examined, by providing access to the base of a crevasse orientated obliquely to the glacier margin (Fig. 2). This crevasse cut into the basal ice layer and allowed observation of the upper surface of the boundary between the debris-rich stratified facies ice and the overlying debris-poor dispersed facies ice.

The basal part of the glacier, exposed within the cavity, comprised a widespread layer of stratified, solid sub-facies ice, composed of frozen diamicton. The boundary between the debris-rich, stratified facies ice, and the overlying debris poor, dispersed facies ice, was gently undulating in appearance. The contact also displayed planes of sediment, composed both of debris laminations and aggregates, appearing to be 'rafted' from the upper surface of the stratified facies into the overlying dispersed facies (Fig. 6). This produced a transitional zone between the two facies, characterised by complex interfingering of debris poor ice and thin (c. 1–2 mm thick) sheets of debris

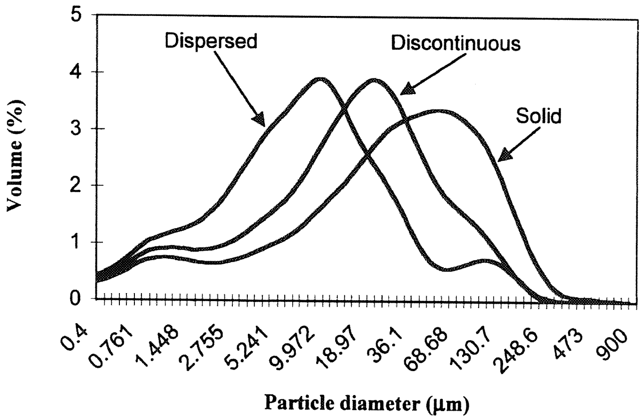

Fig. 5. Particle-size distribution of the fine-grained sediment (< 2 mm particle diameter) contained within the stratified solid and discontinuous sub-facies ice, and dispersed facies ice at Site 1.

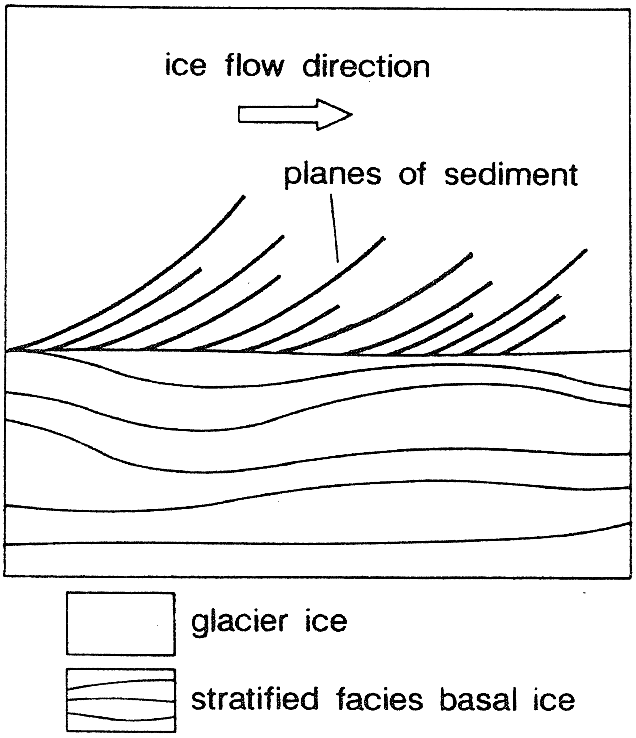

Fig. 6. Schematic diagram illustrating the upper boundary of the stratified facies at Site 2 in two dimensions.

(i.e. the debris laminations or lines of aggregates exposed in three dimensions).

A large recumbent fold exposed in three dimensions and verging towards the glacier margin was also observed within the cavity. The axial plane of the fold was horizontal and the feature was approximately 1 m in thickness orthogonal to this plane. The fold displayed a core of solid sub-facies ice surrounded by a folded layer of discontinuous sub-facies ice. The laminations within the latter were orientated parallel to the fold surface.

4.3. Site 3

Site 3 was located on the snout of the same lobe as Site 2 (Fig. 2). The snout displayed a series of debris bands (Table 1), which outcropped parallel to the local margin, and brought a significant amount of sediment to the glacier surface (Fig. 7A).

The apparent base of the glacier was composed of solid sub-facies ice. This unit appeared similar to the solid sub-facies ice observed elsewhere, although it lacked any large clasts. In this respect, it reflected the nature of the local subglacial sediment, which comprised sorted sands and silts.

One exposure revealed a unit of fine grained basal ice, located in between two thin layers of solid sub-facies ice, and characterised by a crudely laminated sequence of sediment aggregates of variable elongation. In some areas the aggregates were not elongated, and the ice resembled suspended sub-facies ice (Fig. 7B). In other areas however, the aggregates appeared to be attenuated in a common direction, and were more laminated in appearance (Fig. 7C). Close observation of the base of this unit suggested the aggregates were derived from the subjacent layer of solid sub-facies ice, with lines of aggregates appearing to be entrained from its upper surface (Fig. 7D).

4.4. Site 4

The basal ice layer at site 4 was dominated by stratified, discontinuous sub-facies ice, characterised by predominantly sub-parallel debris laminations. The basal ice layer was also relatively homogeneous, with few large clasts and no solid sub-facies ice evident. Coincident with the dominance of discontinuous sub-facies ice was a paucity of subglacial sediment. The glacier margin in this region rested directly upon bedrock with only a sparse veneer of debris.

A short distance to the east, however, the glacier once again terminated over a considerable thickness of subglacial sediment. This change in the nature of the subglacial substrate was accompanied by a reappearance of solid sub-facies ice up to 2 m in thickness.

4.5. Site 5

Site 5 was located at a thin and steep, debris-covered ice lobe. Observations were made within a cavity under the frontal margin (Fig. 3A). At the base of the glacier there was a layer of stratified, solid sub-facies ice up to 1 m in thickness. Above this occurred a layer of predominantly stratified, discontinuous sub-facies ice, with occasional lenses of stratified, suspended sub-facies ice, again approximately 1 m in thickness. Finally, the sequence was capped by a layer of dispersed facies ice at least 5 m thick. Observations of the upper surface of the stratified facies ice, revealed planes of debris being incorporated into the overlying dispersed facies ice, as seen previously at Site 2 (Fig. 6).

In addition to these distinct planes of debris, the ice immediately overlying the solid sub-facies ice displayed a high density of sediment aggregates, which appeared to extend a number of metres into the dispersed facies ice. The ice also contained distinct clots more characteristic of the dispersed facies. Consequently, the dispersed facies displayed a general decrease in sediment content with height, and a transition from densely packed sediment aggregates to diffuse sediment clots.

5. Interpretation: a tectonic model

The observations reported here, describing the sub-facies variability within the stratified facies of the basal

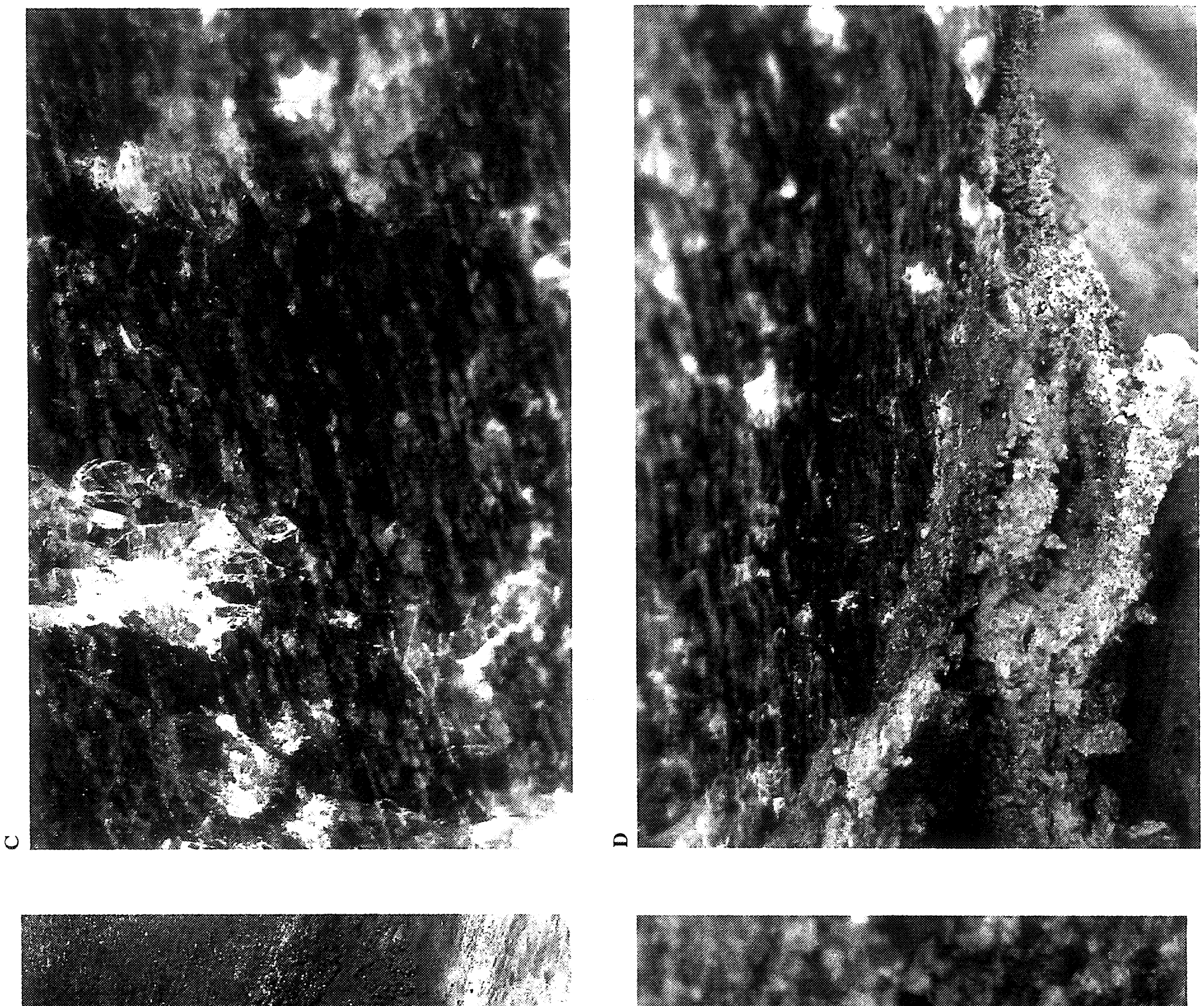

Fig. 7. (A) Debris-band outcropping on the surface of the glacier at Site 3. (B) Dispersed sediment aggregates contained within the basal ice intercalated between two layers of solid sub-facies ice at Site 3. The area depicted is c. 10 cm in length. (C) Lines of more elongate sediment aggregates located within the same unit at Site 3. The area depicted is c. 10 cm in length. (D) Photograph of the basal part of the intercalated ice unit and the upper part of the subjacent layer of solid sub-facies ice. Sediment aggregates appear to be sheared from the upper boundary of the solid sub-facies ice and entrained into the overlying ice. The photograph covers an area approximately 15 cm across and ice flow is from left to right.

ice layer, can be interpreted as illustrating the influence of glaciotectonic deformation. Flow-related tectonism causes the appearance of the basal ice layer to evolve as deformation progresses, leading to substantial variability in its characteristics. We propose a simple model for the origin of the stratified facies, including all its constituent sub-facies variability, that can be reduced conceptually to a single entrainment mechanism combined with the effects of flow deformation.

Unconsolidated subglacial sediment is initially entrained onto the base of the glacier, to produce a widespread and very debris-rich basal ice layer. This results in the formation of a basal layer of stratified, solid sub-facies ice, composed largely of frozen sediment with only interstitial ice, and a lithological character similar to the source sediment (Fig. 8 – part 1). This type of basal layer was particularly well displayed at sites 2 and 5 (Fig. 2). The most likely entrainment mechanism in the case of a polythermal glacier such as the Russell Glacier, involves large-scale, net basal adfreezing (Weertman, 1961). In this case, unconsolidated, saturated sediment is frozen onto the glacier sole, down-glacier of the boundary between the warm-based interior ice, and cold-based marginal ice (Sugden et al., 1987; van Tatenhove, 1995). Alternative mechanisms, such as regelation into a soft-bed (Iverson, 1993; Iverson and Semmens, 1995) might also be able to create a basal layer of debris-rich ice. However, a plentiful supply of subglacial sediment is an essential prerequisite. Some heterogeneity may be introduced into the stratified facies at this formative stage in the form of lenses of debris-free ice (Fig. 3b), resulting from ice segregation within the subglacial sediment (e.g. Mackay, 1971, 1989).

Once this basal layer of sediment is entrained, it is subjected to flow-induced shear strains. This type of strain regime is particularly intense at the base of ice masses where the differential velocity is at its greatest, causing rotation of the strain ellipsoid into parallelism with the direction of movement (Hooke, 1973; Hooke and Hudleston, 1978). Under these conditions, the debris structures observed within the basal ice are likely to evolve as the ice deforms. The imposition of intense shear stresses causes the basal layer of frozen sediment to fracture along lines of weakness, and to disaggregate under the imposed stresses. In this respect, Echelmeyer and Zhongxiang (1987) have measured rates of displacement of up to 2.5 mm/d occurring across discrete "shear bands" within frozen subglacial sediment beneath Urumqi Glacier No. 1, China.

As a result of thrusting and folding, the disaggregated frozen debris and cleaner ice above, become intermixed. In addition, pervasive creep within the frozen debris itself may lead to regelation around sediment particles and lead to the formation of ice lenses (Echelmeyer and Zhongxiang, 1987; Lawson, 1996). Wherever there is a boundary between debris-rich, stratified, solid sub-facies ice and cleaner ice, debris is attenuated from the former into the latter to form fine debris laminations (c. 0.5–2 mm in thickness). As these laminations are continually attenuated from the diminishing bodies of solid sub-facies ice, they progressively form stratified, discontinuous sub-facies ice (Fig. 8 – part 2). In view of this structural association with, and derivation from, bodies of frozen sediment, this facies is considered tectonic in nature. It is not therefore, necessarily indicative of the initial mechanism of debris entrainment, as for instance suggested by Kamb and La Chappelle (1964), Hubbard and Sharp (1995) and Lawson et al. (1998). Where this process of sediment attenuation occurs at the boundary between different basal ice facies, such as the stratified facies ice and overlying dispersed facies ice at sites 2 and 5, laminations occur as sheets of debris being intruded into the overlying ice (Fig. 6). In addition, sediment was observed being sheared and attenuated from the upper surface of a thin band of solid sub-facies ice at site 3 (Fig. 7D). In all cases, the laminations or sheets of debris were listric in appearance, and therefore similar in disposition to the debris-bands observed on the glacier surface at site 3. After formation, the laminations act as useful indicators of flow patterns occurring within the basal ice layer, often flowing around obstacles such as clasts and bodies of solid sub-facies ice (Fig. 4), and revealing flow irregularities around these obstacles in the form of recumbent flow folds (Fig. 3D).

If discontinuous sub-facies ice is tectonically derived from solid sub-facies ice, then the particle size distribution of the sediment contained within both sub-facies should display no significant difference. This hypothesis can be tested using the data collected at site 1. Fig. 5 indicates that the debris contained within the solid and discontinuous sub-facies at this site is similar in terms of its particle size character. The only difference is that the sediment recovered from the discontinuous sub-facies is generally finer, with the whole curve being located closer to the finer end of the particle size spectrum. This finer distribution might reflect shear-related particle comminution.

Variation in the cohesive strength of the solid sub-facies ice may lead to the formation of tectonically derived facies with differing characteristics. Where the solid sub-facies is more cohesive, perhaps because of a high concentration of fine-grained sediments, simple shear might result in the formation of suspended rather than discontinuous sub-facies ice. In this case, the ice surrounding the bodies of frozen debris is not laminated in appearance, but characterised by a collection of dispersed sediment aggregates (Table 1). It is suggested that the crudely laminated ice described at site 3 (Fig. 7b) represents suspended sub-facies ice tectonically derived from subjacent solid sub-facies ice composed of cohesive sediment. However, in the absence of firm evidence, this association between the sedimentary character of solid

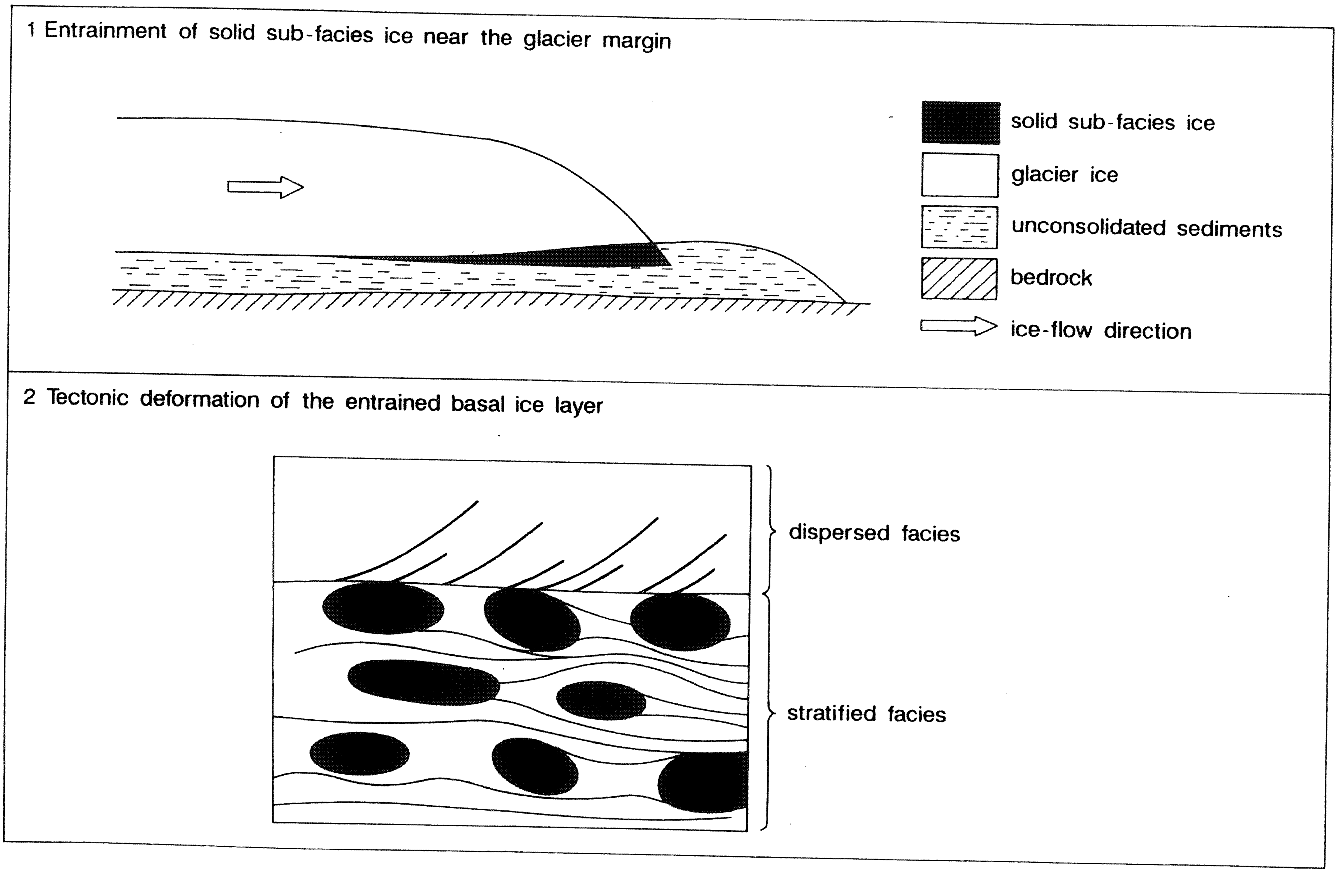

Fig. 8. Schematic diagram illustrating the operation of the 'tectonic model' at the Russell glacier.

sub-facies ice, and the character of the tectonically derived ice facies, remains an educated hypothesis.

The model presented here differs from the conventional interpretational framework (e.g. Lawson, 1979; Knight, 1987; Sugden et al., 1987; Hubbard and Sharp, 1995), in that it attempts to explain the facies variability within the stratified facies solely in terms of tectonic processes, and not via recourse to a wide range of distinctive entrainment mechanisms. The resulting interpretation of the stratified basal ice facies and sub-facies occurring at the Russell Glacier according to this model is summarised in Table 2. Two fundamental differences with existing explanatory models include: (1) the interpretation of discontinuous (and possibly suspended) sub-facies ice as being tectonic in origin; and (2) the emphasis upon *temporal* evolution controlling the appearance and composition of the basal ice layer, rather than *spatial* variation in the entrainment processes or bed conditions.

6. Discussion

The suggestion that the appearance of basal ice facies evolve in response to imposed shear strains is not entirely new. Many authors have noted the influence of glaciotectonic deformation, either upon the basal layer of ice-masses (Lorrain et al., 1981; Boulton and Spring, 1986; Hubbard and Sharp, 1995), or within the subjacent materials, whether frozen (Astakhov et al., 1996) or unfrozen (e.g. Hart et al., 1990). Hart (1995) has suggested explicit similarities between the basal ice layer and the subglacial deforming-layer in her "deforming-layer/debris-rich basal ice continuum". Both are characterised by simple shear, and comprise a mixture of units with differing mechanical and rheological attributes, producing an inhomogeneous deforming medium.

It is useful to conceptualise the basal ice layer as a glaciological 'shear zone', in which deformation is concentrated into a relatively narrow zone. The concept and existence of shear zones within a geological context is well established. In addition, glacier ice and hard rock are widely believed to represent comparable deforming media (e.g. Hambrey and Milnes, 1977). It is therefore to be expected that shear zones, similar in character to those reported within hard rock environments, are likely to occur within glaciers. Indeed, Hudleston (1976) has described small shear zones occurring within the Barnes Ice Cap, whilst Echelmeyer and Zhongxiang (1987) inferred the existence of a basal shear zone beneath Urumqi Glacier No. 1, in which c. 60% of the overall motion occurred with a layer 35 cm thick. The prevalence of what are interpreted as tectonic laminations within the basal ice layer at the Russell Glacier might indicate that the shear zone is in this instance predominantly ductile in nature. Discrete shear may also occur within the basal ice layer, as suggested by Echelmeyer and Zhongxiang (1987), suggesting a brittle–ductile character in which both brittle and ductile mechanisms occur. However, further work is required to establish the degree of rheological similarity between the glaciological and geological environments, and the extent to which the results from one environment can be applied to the other.

The 'tectonic model' described in this paper is proposed as an alternative explanation for some, but not necessarily all, the basal ice facies traditionally interpreted as reflecting the operation of specific processes of ice accretion, or the existence of particular bed conditions. It does not seek to falsify previously advocated interpretations of basal ice facies. Rather it aims to provide a plausible complementary theory.

Given the possibility that basal ice facies with similar appearances may have a number of different origins, it brings into question the completeness of previous attempts to devise genetic classifications, that seek to make inferences about subglacial processes and conditions (Sharp et al., 1994; Hubbard and Sharp, 1995). We suggest that such classifications must incorporate the potential influence of strain-induced tectonic evolution of the basal layer. Useful modifications to existing classification schemes might include the sub-division of the stratified discontinous and suspended sub-facies into two types; one in which the character of the ice is genetically derived (i.e. related to the initial process of formation), and the other in which the character of the ice is tectonically derived (i.e. reflective of post-formational tectonism).

The conditions most likely to favour the formation of basal ice facies by tectonic processes, or to lead to the tectonic 'overprinting' of basal ice facies reflecting other processes, involve the development of a basal zone characterised by relatively high rates and amounts of shear strain. Such a situation is likely to be promoted by the existence of high basal shear stresses, a lack of deformation within subjacent materials (i.e. low rates of basal sliding and bed deformation), or a combination of both. In addition, the basal ice layer must persist for an amount of time sufficient to attain significant finite strains and develop tectonic structures.

Two developments are required to test the validity of this model. Firstly, the development of a set of criteria which can be used to distinguish between facies whose characteristics relate to the process of entrainment, and those whose characteristics are tectonic in origin. A possibility lies in the small-scale application of co-isotopic analysis. Laminated ice resulting from closed-system regelation is thought to produce a series of laminae that are compositionally distinct (Boulton and Spring, 1986; Hubbard and Sharp, 1993). In contrast, there is no reason to believe the tectonic mode of formation will lead to isotopic fractionation and the formation of a similar isotopic profile. Secondly, the "tectonic model" needs to be applied to other glaciers that also display inhomogeneous basal ice layers, to test whether the model provides a plausible explanation at sites other than the Russell Glacier.

7. Conclusions

The following points emerge from observations made at the Russell Glacier in Greenland. Firstly, that it is possible to explain the facies variability displayed within stratified facies basal ice, by a process of initial sediment entrainment, followed by flow-related, tectonic deformation. In the case of the Russell Glacier, it is suggested that net basal adfreezing close to the glacier margin results in the formation of a basal layer of stratified, solid subfacies ice. This is disaggregated into blocks of frozen debris, situated within a matrix of debris-poorer ice. These blocks are then progressively attenuated into stratified, discontinuous and suspended sub-facies basal ice, depending upon the cohesivity of the parent sediment. Secondly, that the 'tectonic model' provides a complementary hypothesis with which to explain the facies variability displayed by many basal ice layers. If correct, it challenges the assumption that facies variability solely relates to spatial variation in the processes of formation and subglacial bed conditions, which forms the basis of genetic classification schemes. To establish its validity however, further research is required to establish key criteria able to distinguish between facies whose appearance is related to its process of formation, and those whose appearance is reflective of subsequent tectonism.

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