Debris entrainment and polythermal structure in the terminus of Storglaciären

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Abstract Ground penetrating radar recordings and measurements of ice motion have provided a detailed picture of movement and internal structure of the terminus of Storglaciären, Sweden. The glacier is polythermal with a cold surface layer resulting in a frozen rim along the glacier margins and terminus. Englacial debris layers emerge at the glacier surface, forming supra-glacial ice-cored ridges. Measurements show that surface velocity decreases sharply by ~50% across the ridge line. The transport mechanism through the cold ice to the surface is inferred to be through shearing of clean ice intercalated with the debris layers and not along discrete “shear planes”. The sediment is likely frozen on at the glacier bed. However, the way in which the sediment layers are brought up into the ice and sandwiched between clean ice layers is not answered.

INTRODUCTION

Many glaciers have extensive debris-covered termini. The debris cover is of interest since it alters ablation and complicates the glaciers response to climate change. In Scandinavia ice cored lateral moraines have survived almost 100 years without being noticeably affected by the climate change driving general glacier retreat over the last century (Östrem, 1964). In areas with large debris-covered glaciers, such as the Himalaya, debris affects assessment of freshwater resources (Nakawo et al., 1999).

In many cases the debris cover is mainly derived from rockfalls (e.g. Nakawo et al., 1999). However, much uncertainty revolves around the mechanics of entrainment of debris at the base of a glacier and subsequent transport of such debris towards the surface in narrow bands (e.g. Hambrey et al., 1999). The fact that debris can be entrained in the basal ice has been shown from theory and observations for both cold and temperate ice (e.g. Alley et al., 1997). The problem lies in the mechanisms responsible for moving basically entrained material towards the glacier surface in discrete bands (discussions in Weertman, 1961; Alley et al., 1997; Hambrey et al., 1999).

This paper deals with the internal structure of a cold-based terminus with emerging debris bands and the associated ice flow in order to better define the processes involved in bringing basal debris into the glacier and up to its surface.

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DEBRIS PLANES AND DEBRIS-COVERED RIDGES

The incorporation of debris into basal ice and mechanisms for transporting such debris to the glacier surface has been discussed by many authors (e.g. Alley et al., 1997; Hambrey et al., 1999 and references therein). Whereas processes for basal entrainment of till into ice are generally accepted, processes for subsequent lifting and transport in the glacier ice are still under debate. Weertman (1961) argued forcibly against the so-called shear plane mechanism. Hooke et al. (1972) and Nickling & Bennett (1974) found additional evidence against shearing within sediment-rich layers from laboratory experiments. Their results showed that the creep rate and shear strength of ice increase with increasing sediment concentration. However, with a very small volume fraction of sediment, creep rates are higher than both for clean ice and for higher volume fractions (Hooke et al., 1972). Yet, many still argue for shear motion along discrete sediment-rich planes (e.g. Clarke & Blake, 1991; Murray et al., 1997; Hambrey et al., 1999).

The occurrence of debris-rich layers is common in polythermal glaciers (Boulton, 1970). Entrainment of debris under temperate ice conditions has traditionally been associated with regelation. Walder (1986), theoretically, and Iverson (1993), experimentally, showed that ice can regelate into subglacial debris. Knight (1989) found that isotopic composition of ice in a stacked sequence of debris bands indicated regelation whereas intercalated ice was isotopically similar to glacier ice above the sequence and hence not formed by regelation.

In addition to the processes described above, folding (e.g. Hudleston, 1976) and englacial drainage (Kirkbride & Spedding, 1996; Näslund & Hassinen, 1996) have also been suggested as means of incorporating and, perhaps primarily, transporting debris towards the glacier surface.

STORGLACIÄREN

Storglaciären, northern Sweden, (Fig. 1) is extensively studied (e.g. Jansson, 1996) including annual glacier mass balance measurements since 1946 (e.g. Holmlund & Jansson, 1999). The retreat of the glacier in response to a rise in air temperature around 1910 (Holmlund, 1987) has halted partly due to positive mass balance on the glacier during the last decade (Holmlund & Jansson, 1999). Steepening of the terminus indicates that an advance may be imminent. The glacier is polythermal with a cold surface layer of varying thickness (≤60 m) in the ablation area (Holmlund & Eriksson, 1989). The glacier margins and a frontal zone of ≤200 m width is frozen to the glacier bed (Holmlund et al., 1996). Hence any glacier advance will have to occur over a frozen terminus region. The glacier is underlain by a till layer which has been shown to deform (e.g. Iverson et al., 1994).

SUPRAGLACIAL DEBRIS ON STORGLACIÄREN

Several englacial debris bands emerged on the surface near the terminus in 1994 and formed ice-cored ridges as a result of differential melting (Fig. 2). The debris bands are parallel to foliation in the ice and hence have an arcuate shape (Figs 1 and 2). Between
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Fig. 1 Map of Storglaciären showing surface and bed topography. Inset shows location of debris-covered ridges and of surveyed stakes and fixed points used in this study.

the debris bands there is cleaner ice that can be divided into two types: (a) largely bubble-free ice consisting of large crystals and (b) ice rich in bubbles elongated in the plane of foliation along the direction of flow. Bubble-free ice occurs immediately below the sediment layers whereas bubble-rich ice is found immediately above the layers. Typically, large crystals indicate non-deforming ice whereas elongated bubbles are an indication of actively deforming ice. A bulk sample from one debris band gave a sediment concentration of 78% by weight or ~51% by volume assuming an average density of 2.65 kg m$^{-3}$. The debris is unsorted, somewhat rounded, and devoid of clasts $>$0.1–0.2 m. Rockfall debris typically contains more angular particles and also larger concentrations of coarse particles relative to typical subglacially worked tills (Boulton, 1978). Hence, the origin of material in the debris bands is inferred to be of subglacial origin.

GROUND-PENETRATING RADAR OBSERVATIONS

Detailed surveying of bed topography and the internal structure of the glacier was carried out during the fall of 1995 with a continuous wave step-frequency ground-penetrating radar (based on a Hewlett Packard Network Analyzer, HP8753B). The equipment sends out a continuous sine wave at 201 frequencies evenly distributed over a user-defined bandwidth. The signal penetration depth varies depending on the frequencies covered by the bandwidth (780–1080 MHz in our case). The radar system thus allows recording of both thermal structure and ice thickness although not necessarily simultaneously. Details of the equipment can be found in Hamran et al. (1995) and Richardson et al. (1997). For the present study the radar system was mounted on a sled and pulled by hand. During the survey an approximately constant travel speed was maintained between stakes along the survey line. In interpreting the
radar image we consider travel speed between individual stakes to be constant. Since stake positions are known, they constitute known reference points along the profile. In the case of a somewhat varying travel velocity between different sets of stakes, these reference points aided in the interpretation of the radar image.

Fig. 2 (a) The moraine ridges seen from fixed point A-95 (northern moraine) in fall 1995. (b) Close up of the ridge looking south. The ridge is approximately 1 m high.
Figure 3(a) shows a radar image of the glacier terminus. The uppermost strong horizontal reflection is the upper ice surface. The glacier surface is not corrected for topography and therefore appears flat. The depth scale, calculated from a radar signal travel velocity of 168 m μs⁻¹, is shown relative to the ice surface. An automatic gain control was applied in the data processing. Internal structures are readily seen in the terminus (Fig. 3(a)) that show thermal zonation, debris bands and possibly water pockets. Figure 3(b) shows the interpretation of the profile in Fig. 3(a). For easier evaluation, data have here been adjusted to show true surface topography.

The radar image shows a strong sharp bed reflection close to the terminus where the ice-bed interface is frozen. The transition from cold-based to wet-based conditions occurs at ~200 m from the terminus (Holmlund et al., 1996, fig. 6, p. 152). Upstream from this point, bed reflection weakens considerably. Instead the radar image shows the englacial transition from cold surface layer to temperate ice below as a less sharp, diffuse reflection (Fig. 3). Here, the strength of the signal that reaches and returns from the bed is drastically reduced due to scattering of the radar signal by liquid water within the temperate ice body that obscures the bed. Another strong reflector can be followed from the location of the debris-covered ridges to a point near the cold-temperate transition at the bed. This reflector is interpreted as a continuous debris

![Figure 3](image-url)
band, emanating from the base of the glacier and reaching the surface at the ridges. The radar image also shows a second englacial reflector further up-glacier, which terminates before reaching the surface. This feature is interpreted to be a second debris band that should soon emerge on the glacier surface between stake U100 and U150 (Fig. 3). To date no sign of this inferred second debris band has appeared on the glacier surface.

SURFACE VELOCITY

Repeated surveys of nine stakes (Fig. 1) were made in 1995 from the fixed point A-95 using standard surveying techniques (Geodimeter™ 440 total station: ±0.0005° for angles and ±5mm + 10 ppm for distances). The errors in calculated velocities are negligible due to the length of the survey period. The velocity along the profile is shown in Fig. 4. As expected from continuity, horizontal surface velocity, \( u_H \), decreases towards the terminus. However, across the point of emergence of the debris bands \( u_H \) decreases from 9.1 to 3.6 m year\(^{-1} \) (>50% reduction in \( u_H \)) over a distance of 50 m. The vertical velocity \( u_V \) is variable and close to zero along the profile.

Emergence velocity \( u_E \) gives the vertical flux of ice that interacts with the net balance to determine the evolution of the surface profile. For most of the measured stake profile \( u_E \) is \(-2.5\) to \(-3.5\) m year\(^{-1} \) (Fig. 4). The lowermost stakes yield \( u_E \) near zero. Typical net balance in this region is \(-2\) to \(-3\) m year\(^{-1} \) and varies by \(-0.2\) to \(-0.4\) m year\(^{-1} \) over the area covered by the stake profile. Thus, the terminus is near a balanced state. The lowermost section of the profile, on the other hand, is in a state of strong wastage, caused by a lack of influx of ice into the section. The emerging debris bands separate the two dynamic regimes observed on the terminus. It therefore seems reasonable to
conclude that the ice down-glacier of the ridges is stagnant or moving very slowly. This is not surprising since no or very little sliding can occur in this area because of the frozen bed. The ice up-glacier from the emerging debris bands is part of the active glacier that is now responding to changes in net balance.

**OBSERVATIONS VERSUS THEORY**

Our study of the terminus region of Storglaciären suggests that the ice wedge down-glacier and possibly beneath the debris band is slower moving (cf. Nye, 1967). The ice up-glacier of the debris bands is active and approximately in balance with the local net balance of the glacier indicating near steady-state conditions or, possibly, glacier growth. Extrapolating the debris band reflection back towards the bed indicates that it originates at or near the current transition between temperate and cold basal conditions. Thus, it is possible to suggest, as did Clarke & Blake (1991), that the debris bands are forming where this transition occurs. The transport to the glacier surface would take ~14 years at the present surface velocity. This is a conservative estimate since the speed at depth is slower than at the surface. Since Storglaciären has been in steady retreat for most of the twentieth century, it is likely that the cold–temperate transition has retreated with the glacier terminus. Hence, it is not certain that the debris was entrained at the cold–temperate transition. If the second reflector, visible in the radar images at a location ~100 m upstream from the emerging debris bands, also constitutes a debris band, the cold–temperate transition cannot be the only location for incorporation and additional mechanisms must be sought.

With the relatively high concentrations of debris in the debris bands on Storglaciären, the difference in competence (e.g. Hobbs et al., 1976, p. 67) between the debris bands and the intercalated ice is quite large. Any shear deformation occurring in and around these bands must therefore occur in the cleaner ice. The observations of bubble orientation in the bubble-rich ice in our section supports this idea. The strong velocity gradient observed across the sequence also indicates that significant shearing occurs in this zone of the glacier. However, a significant portion of apparently non-shearing ice (i.e. bubble-free layer) is also moved along beneath the debris band. Knight (1989) concluded that the debris-rich and debris-poor layers in a stacked sequence had different origins, the debris-rich parts being consistent with freezing-on and the debris-poor being similar to overlying glacier ice. It seems likely that the observed sequence on Storglaciären is similar, except for the possible division of the debris-free layers into deforming and non-deforming layers.

In order for debris bands to be carried to the surface it is necessary for ice below the debris band to maintain a significant degree of shear motion. However, that presents a problem at the base of the glacier. Suppose that debris is frozen on as a result of cooling of temperate ice flowing into the region of the cold–temperate transition. Furthermore, re-freezing of relatively clean ice must occur as well in order to maintain an ice layer sufficiently weak for shearing beneath the debris. However, this combination does not seem possible if we assume that the quasi-steady-state location of the cold–temperate transition dips down into the till and underlying bedrock in the down-glacier direction. This would give a situation where subglacial water cannot reach beyond the debris band, resulting in no re-freezing beneath the
debris band. If the mechanism outlined above was in operation, the result would be a slow depletion of the ice wedge beneath the debris band. The effect of this process on a glacier in steady-state will be that the emergence point of the debris band would move further down-glacier and closer to the bed and eventually consume the wedge.

With our current knowledge, the layers emerging on the surface of Storglaciären are difficult to explain in terms of the entrainment process. Obviously further investigations into the origin of ice surrounding the layers are needed. However, the process of entrainment of till into the ice evidently is associated with phase changes either due to a cold–temperate transition at the bed or regelation, while the process by which debris is lifted off the bed remains poorly known.

CONCLUSIONS

Debris emerging on the terminus of Storglaciären that forms ice-cored supra-glacial ridges can be traced into the glacier as a reflector in radar images. Velocity measurements show a more than 50% drop in surface velocity over a distance of ~50 m across the ridges in the down-glacier direction. The emerging debris layer is complex and shows a very distinct repetitive sequence of ice containing numerous bubbles elongated in the direction of foliation indicating shearing, debris bands with ~50% by volume sediment content, and coarse-grained bubble-free ice indicating no shearing. The structure in the ice is similar to other debris bands described in the literature where sediment is frozen on at the base of the glacier and where the intercalated ice is glacier ice brought up with the entrained sediment layer. However, the question regarding the process by which the sediment is lifted and brought up from the base into the ice remains unanswered.

Acknowledgements The careful reviews by Dr U. H. Fischer and one anonymous reviewer significantly helped us improve the paper. We are most grateful to Prof. C. F. Raymond who provided additional suggestions, well beyond his duties as scientific editor, to help us focus the paper further.

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