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Preservation of basal-ice sediment texture in ice-sheet moraines

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Abstract

Ice-sheet moraines near Kangerlussuaq in west Greenland inherit distinctive particle-size distributions from basal ice, although debris structures from the basal ice are commonly destroyed by deposition and resedimentation processes. The abundance of clay and silt in the "dispersed facies" basal ice at the ice-sheet margin is clearly reflected in the sedimentology of the ice-sheet moraine. Geographical variations in the texture or grain size of moraine sediments may thus reflect geographical variations in basal ice. This offers a new approach to reconstructing the basal-ice characteristics, and hence the thermal and dynamic properties, of former ice sheets. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Subglacial debris is entrained into the lowest few metres of ice sheets by processes that vary with basal temperature and pressure, so the characteristics of basal ice can be used to infer subglacial conditions (Knight, 1997). Previous attempts to reconstruct basal-ice characteristics from melt-out tills have focused on the potential preservation of diagnostic glacially derived structures (e.g. Shaw, 1977a, b, 1979; Haldorsen and Shaw, 1982; Lawson, 1979a, 1981; Ham and Mickelson, 1994). However, englacial fabrics and structures are often modified by post-depositional reworking, are ambiguous, and cannot reliably be interpreted from the sedimentary record (e.g. Paul and Eyles, 1990; Bennett et al., 1999). It would therefore be valuable to identify basal-ice characteristics that reflect subglacial conditions and also survive robustly in postglacial sediments. Knight et al. (1994) demonstrated that different basal-ice facies at the margin of the Greenland ice sheet were characterised by distinctive particle-size characteristics. The aim of this research is to evaluate whether these distinctive characteristics can be retained in postglacial sediments even where structures such as laminae and englacial debris fabrics are destroyed.

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2. Study site and methods

Our observations were made at the terminus and northern margin of the Russell Glacier, on the western margin of the Greenland ice sheet near Kangerlussuaq (67° north, 50° west) in September 1999. The characteristics and origin of the basal ice at this site have been described in several previous studies (e.g. Sugden et al., 1987; Knight, 1994; Knight et al., 1994). The basal ice is up to 35 m thick, and comprises two facies (Lawson, 1979b) that include debris with distinctive particle-size characteristics. The stratified facies is formed by subglacial freezing near the margin, and presents a virtually ubiquitous bottom layer averaging 1.5 m in thickness throughout this area of the ice-sheet margin. Debris in the stratified facies is dominated by sand, gravel and boulder-sized material. By contrast, debris in the overlying dispersed facies comprises mainly silt and clay-sized material, and occurs only in certain locations where a specific combination of subglacial conditions apply: the basal temperature is close to the pressure melting point in the interior of the ice sheet where the dispersed facies forms; no substantial subglacial melting occurs downglacier from its point of formation; and ice flow is not divided around large subglacial obstacles close to the margin. The occurrence of dispersed facies basal ice at the margin thus indicates a specific geography of subglacial conditions, making it a potentially valuable marker facies.

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Our observations of the basal ice and moraine sediments were based on a complete survey of 2 km of the ice margin at a site where the glacier was overtopping a complex of multiple moraine ridges up to 30 m high. The sediment and water discharge were dominated by local ablation from the marginal zone, and no major meltwater outlets affected the site. To determine whether the geographical distribution of dispersed facies basal ice was reflected in the sedimentary properties of the moraine, we measured the composition of the debris in the two basal-ice facies, calculated the sediment flux through these facies, traced the routing of silt and clay-sized material from the basal ice into the moraine, and characterised the debris composition of sediment stores within the moraine complex.

The basal ice was exposed in a near vertical ice-front cliff, in crevasse walls, and in the ceilings of cavities, permitting a three-dimensional analysis based on c. 8000 m^2 of exposure. The moraine surface was completely exposed over an area of c. 100,000 m^2, and nine major gullies and moraine breaches provided cross-sections through the interior of the moraine. Ice and sediment samples were collected at the end of the field season, after the site-specific sediment-transfer processes and sediment routing had been established. Each stage of the ice-moraine sediment-transfer pathway was sampled systematically along transects where the entire pathway was accessible, with the specific aim of recognising the extent to which fine-grained glacier-derived material was being stored within the moraine. Samples of 100–200 g were taken from the source ice facies, from ice-front debris accumulations, from intra-moraine stream channels and pond deposits, from the surface and interior of the moraine ridges, and from debris fans at the distal limit of moraine breaches. Samples were split, and used in 50 g batches for particle-size analysis following procedures described by Hobbs (1998), combining hydrometer and sieving. Sampling avoided clasts over 5 cm, and the proportion of the deposits that comprised clasts of this size or larger was calculated by field measurement and photographic analysis of large vertical exposures of sediment. The percentage of the moraine surface that was covered by specific materials was measured both by ground survey and by analysis of vertical photographs. We use the terms clay (< 2 μm) silt (2–63 μm) and sand (63 μm–2 mm) to denote grain sizes of sediment following conventions reviewed by Jones et al. (1999).

3. Observations

The stratified and dispersed facies displayed distinctive debris-content and particle-size characteristics (Fig. 1). The stratified facies basal ice had a mean thickness of 1.5 m, and a mean debris concentration of 30% by volume. It comprised 1.5% clay (< 2 μm), 13.5% silt

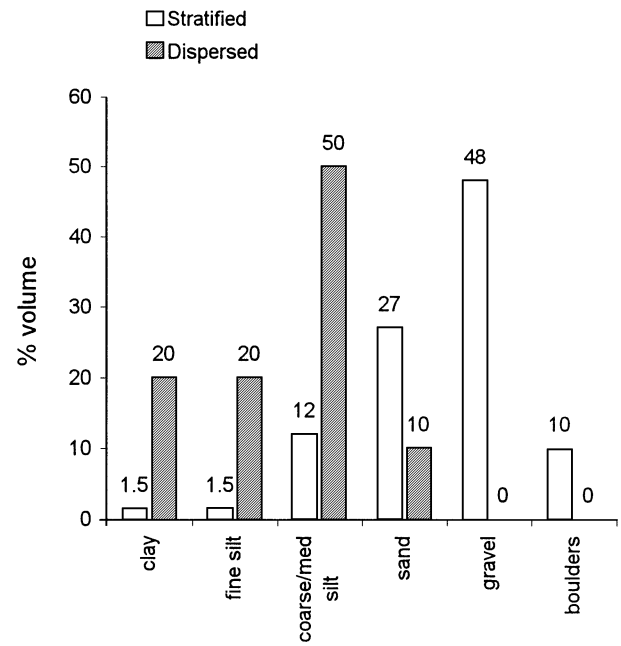

Fig. 1. Relative proportions of different particle sizes in the dispersed and stratified basal-ice facies. Data are presented as bars for direct comparison with Fig. 2.

(2–63 μm) and 85% coarser material (> 63 μm). By contrast, the dispersed facies basal ice had a mean thickness of 15 m, and a mean debris concentration of only 2% by volume. It comprised 20% clay, 70% silt and 10% sand, with the debris concentrated in lenticular particle aggregates or "nodules" (Sugden et al., 1987) up to 15 cm in diameter dispersed in a matrix of debris-free ice. The non-basal ice was virtually debris free. These measurements are consistent with previous measurements at the same site reported by Sugden et al. (1987) and Knight et al. (1994).

Sediment production at the glacier margin was derived almost entirely from melt-out of debris from the basal ice. Aeolian and fluvial inputs to the moraine were negligible, and there was no significant subglacial deforming layer. Subglacial streams may discharge a substantial proportion of the total glacial debris flux, but no such streams affected moraines within our study area. Subglacial melt-out till in areas of well-developed dispersed facies ice comprised 25–44% silt and clay (mean 31% < 63 μm). This is less than the 90% silt and clay content of the dispersed facies ice from which it was derived, suggesting preferential removal of fines by meltwater, but higher than the 15% total silt and clay content of the stratified facies. Silt and clay was transferred from the glacier to the moraine both in meltwater and by dropping of silt/clay nodules onto the moraine surface by ablation of dispersed facies ice. At locations that were freshly exposed by seasonal retreat of the ice margin, up to 35% of the moraine surface directly in front of the glacier was covered in recently deposited nodules. These nodules quickly (days–weeks) disaggregated after their release to produce a silt-clay layer on the moraine surface. Where this was buried by continued deposition, or reworked by dry mass movements, it was incorporated into the moraine. Where it was redistributed by water or fluid mass movements, some was redeposited in intramoraine sediment traps such as ponds debris fans, and some was removed from the area in outflowing streams. Mean suspended sediment content of the main outlet stream from the section of ice margin that we studied was 10 g l^{-1}. Much of the remainder was trapped in tiered systems of sedimentary basins that constituted 40–50% of the area of intramoraine channels, and contained waterlain clay, silt and sand in volumes of up to 240 m^3 per basin, comprising on average 50% silt and clay. In areas where the dispersed facies was well developed, drapes, lenses and laminae of silt and clay derived from it constituted a clearly identifiable component of the moraine, both in present-day deposits and in ancient sediments within the moraine complex.

Debris flux through the ice can be calculated from the ice flux and the debris content. The local ice flux, estimated from measurements of annual ablation, ice front recession and advance, and surface and basal velocity measurements (Knight, 1987, 1992), is equivalent to ice movement of $\sim 24 \text{ m y}^{-1}$. The calculated annual debris flux through the different basal ice facies is shown in Fig. 2. Because of the differences in the thickness of the two basal ice facies, and because of the much higher silt and clay content of the dispersed facies, the discharge of clay and silt from the basal ice was spatially very variable, primarily reflecting the variations in thickness of the dispersed facies. Discharge of clay and silt was 20 times higher at locations with a thick (30 m) dispersed facies than at locations with no dispersed facies. Direct deposition of silt and clay onto the moraine surface in sufficient amounts to create distinctive silt/clay layers in the moraine occurred only at locations where the dispersed facies was relatively thick (> 10 m).

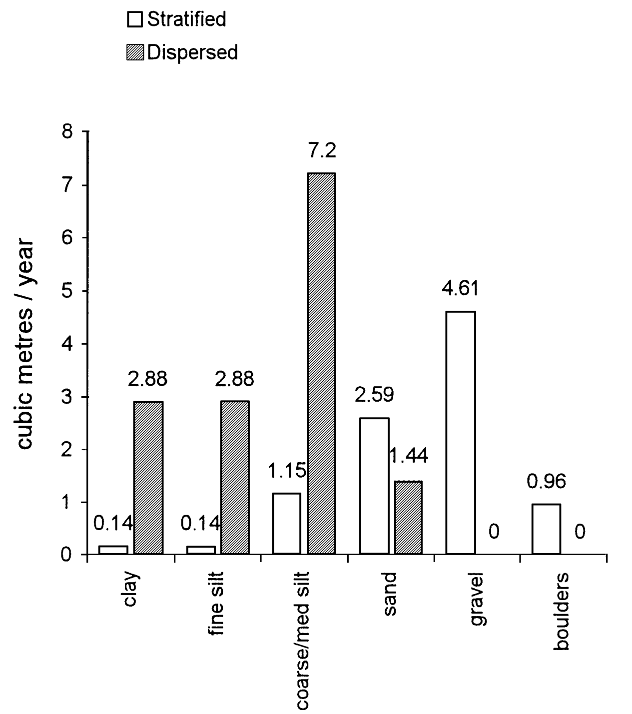

Fig. 2. Annual flux of debris of different grain sizes from the stratified and dispersed basal ice facies, per linear metre of ice margin.

4. Discussion

Our measurements of particle sizes in the two basal-ice facies (Fig. 1) demonstrate that the dispersed and stratified facies have clearly distinguishable particle-size characteristics. The dispersed facies basal ice is the dominant source of fine-grained material for the ice-marginal moraine, and its distribution controls the amount of clay and silt released to the moraine. It is clear from the sedimentology of intra-moraine sediment traps such as river channels, lake basins, debris fans and moraine ridges that some of the clay and silt that is released from the ice is held in storage within the ice-marginal moraine. These observations indicate that it is possible to use geographical variations in the debris composition of ice-marginal moraines to reconstruct the spatial distribution of dispersed facies ice at the glacier margin. Because the reconstruction is based on the relative abundance of diagnostic particle sizes, rather than on the preservation of fragile englacial debris structures, this approach can be used in circumstances where characteristics such as till fabric or inherited basal-ice structures cannot reliably be interpreted. It is widely recognised (e.g. Lawson, 1979a, b) that ice-marginal resedimentation can lead to sorting and redistribution of glacial sediments, so structures and local textural characteristics may not survive robustly. However, our results indicate that in specific circumstances where distinctive particle sizes are produced by different facies, the presence or absence of distinctive facies can be reflected in the presence of distinctive moraine characteristics. However, the distinctive particle-size distributions observed at the Russell glacier may not be widespread in other locations, and this approach needs to be elaborated to account for the range of grain sizes delivered by local basal-ice discharge. The approach depends on the long-term survival of the particle-size signal in the proglacial environment. In glacier forelands dominated by fluvial processes this is unlikely, but in situations where material is deposited directly to moraine ridges that are unaffected by meltwater activity, survival appears to be possible. Since the dispersed facies has been shown to reflect subglacial thermal and dynamic conditions (Knight et al., 1994), this is a potentially valuable reconstructive tool. Knight (1994) described how specific basal-ice sequences could be created in response to specific distributions of subglacial thermal and dynamic conditions. If the sedimentological characteristics of moraines associated with these sequences could be identified, then former subglacial conditions could be deduced from moraine sedimentology in a range of different glaciological settings. Our present results indicate that at least one of the key basal facies indicative of subglacial processes does leave a sedimentological imprint in ice-sheet moraines.

5. Conclusions

We conclude that (1) basal ice at this location exhibits a very high degree of particle-size sorting between facies; (2) particle-size characteristics of basal ice can be transferred to and preserved in ice-marginal moraines; (3) moraine sediments can thus be used to infer the presence or absence of distinctive basal facies in former ice masses; and (4) distributions of clay and silt in moraines thus have the potential to be used to reconstruct patterns of subglacial thermal regime and ice flow in former glaciers. However (5), this approach may be limited to areas where particularly distinctive basal-ice facies exist, and where the foreland of the glacier includes local sediment traps such as moraine ridges and closed basins that prevent the complete removal of diagnostic particle sizes by outflowing streams.

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