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Identification of basal layer debris in ice-marginal moraines, Russell Glacier, West Greenland

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Abstract

Different processes of ice formation and deformation at the glacier bed create distinctive basal ice facies. The geographical distribution of these facies at the glacier margin can indicate the distribution of subglacial environments. Previous research has shown that debris in dispersed facies basal ice at the margin of the Greenland ice sheet has a distinctive particle-size distribution that can also be recognised in moraines deposited where the dispersed facies is present. This permits reconstruction of the distribution of basal ice characteristics and subglacial conditions from moraine sediments. Here, we study stratified and debris-band facies of the basal ice layer at the same site. We find that, contrary to previous suggestions, these two facies can also be distinguished sedimentologically. Co-variant plots of the C_{40} (aggregate shape) and RA (aggregate roundness) indices show that pebble and cobble sized clasts (-2ϕ to -7ϕ) in the debris bands are statistically more angular than those in the stratified facies. Sedimentological characteristics of the parent facies are retained in ice-marginal moraines. Combined with previous work, these new observations suggest that the geographical distribution of basal ice facies at a glacier margin can be reconstructed from sedimentological characteristics preserved in moraines.

1. Introduction

Structural and sedimentological characteristics of basal ice in glaciers and ice sheets are influenced by processes at the glacier bed, and can therefore be used to recognise processes in inaccessible subglacial areas (Lawson, 1979a; Hubbard and Sharp, 1989; Knight, 1997). Two distinctive facies can be recognised from most descriptions of basal ice sequences. The stratified facies typically occurs at the base of the sequence and is dominated by pebble and cobble-sized debris (85% $>$ 0.063 mm) with small amounts of silt and clay (Knight et al., 2000). The dispersed facies, which is not ubiquitous, typically overlies the stratified facies and is dominated by silt and clay (90% $<$ 0.063 mm) (Knight et al., 2000). In some locations, debris bands 0.1–0.2 m thick extend upwards from the stratified facies into overlying ice. Knight (1994) suggested that debris bands are a structural extension of the stratified facies generated by folding or thrusting, and demonstrated that the stratified facies and the debris bands were indistinguishable in terms of their particle size distribution.

Knight et al. (2000) showed that the distinctive clay-rich sediment signature of the dispersed facies could be preserved within ice marginal moraines. This suggested that relict Quaternary ice marginal moraines could be used to indicate the distribution of dispersed facies ice in the basal layer of former glaciers. Extending this approach to other facies, our objective is to ascertain whether sedimentological differences can be identified between the stratified facies and the debris bands and, if so, whether they can also be recognised in ice-marginal moraines dominated by sediment supply from each facies.

2. Methods and study site

Fieldwork was carried out at Russell Glacier, on the western margin of the Greenland Ice Sheet (Fig. 1). Basal ice at this site has been described previously by Knight (1987, 1994) and Knight et al. (1994, 2000).

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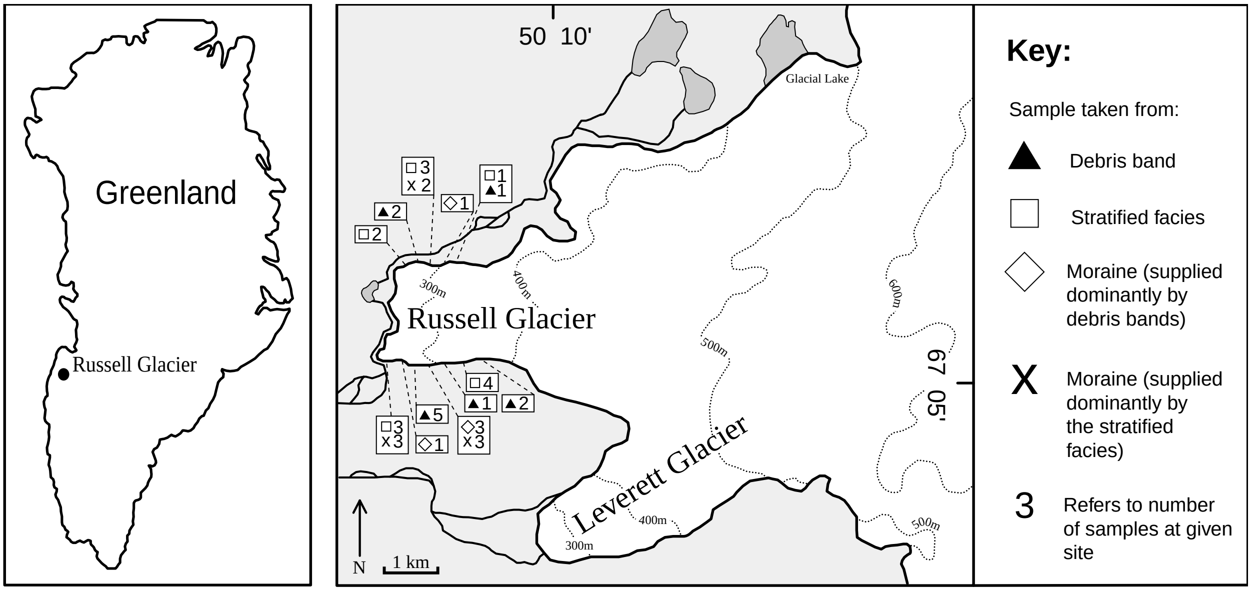


(a) (b)

Fig. 1. (a) and (b) Location map of Greenland and Russell Glacier with sampling points.

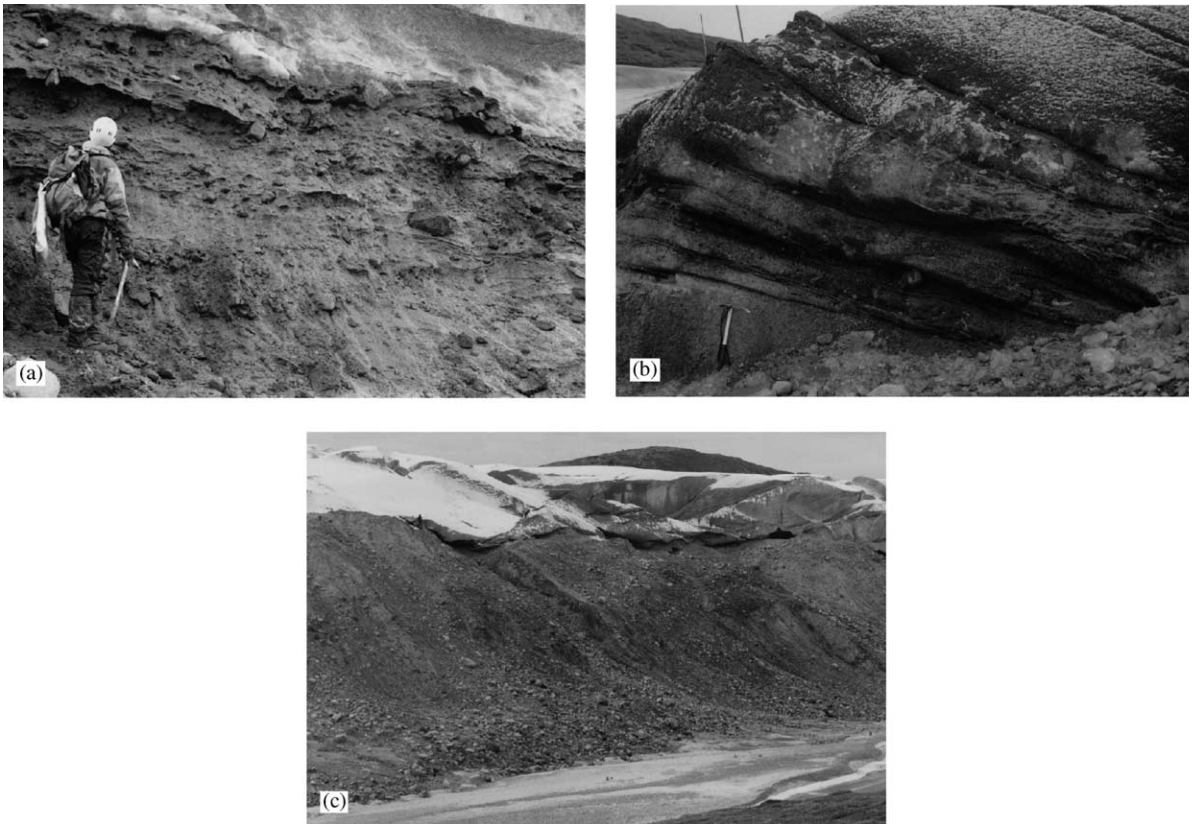


Fig. 2. (a) Typical section of stratified facies basal ice at Russell Glacier; (b) typical section of debris bands at the Russell Glacier, debris bands start above the ice axe; and (c) typical section of moraine at the Russell Glacier, person for scale in upper left corner.

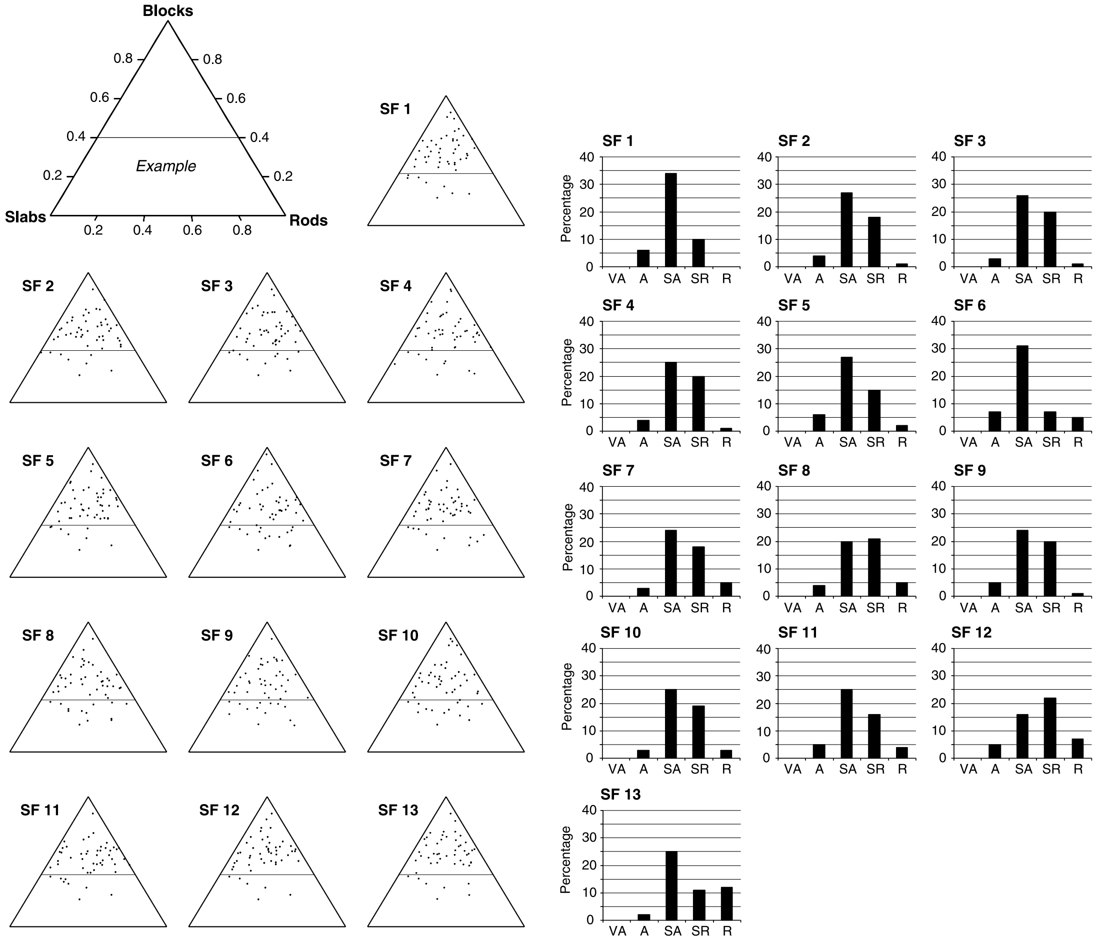
Debris supplied to the ice-marginal moraine is derived almost entirely from the basal ice layer (Fig. 2), with a negligible contribution from englacial and supraglacial routes (Knight et al., 2002). Debris in the basal layer is dominated by locally derived gneiss, with a minor component of distally derived granite. The facies composition of the basal ice varies around the margin, and moraines were sampled at locations where the debris supply was dominated by a single facies rather than a combination of facies (Fig. 1b).

Aggregate shape and roundness characteristics of clasts from the basal ice and from the moraine were analysed by a procedure previously used by Benn and Ballantyne (1994) and Hambrey et al. (1999) to differentiate glacial sediment facies. This involved analysis of the co-variance of the C_{40} index and the RA index of pebble and cobble sized debris (4–128 mm) in each population. The C_{40} index is the percentage of clasts with c/a ratios $\leqslant 0.4$. Clasts that display slab or rod characteristics are more likely to have a C_{40} value of $\leqslant 0.4$ than clasts that display cubic characteristics. The RA index is the percentage of very angular and angular clasts in a sample. Each sample required measurement of a (long), b (intermediate) and c (short) axes of 50 clasts. Each clast was assigned a roundness value using descriptive criteria provided by Benn and Ballantyne (1994), modified from Powers (1953).

3. Results

Twenty-five samples (of 50 clasts each) were collected from basal ice, and 13 from the moraine. Ternary diagrams and clast-roundness histograms display the shape and roundness of clasts collected at each sample location (Figs. 3–5).

Ternary diagrams for the stratified facies indicate that the clast shape is varied, while the histograms display a negative skew that indicates a low proportion of angular and very angular debris (Figs. 3a and b). Ternary diagrams and clast-roundness histograms for the debris bands indicate a more normal distribution because of a higher representation of angular and very angular clasts (Figs. 4a and b). For moraine samples from sites where the stratified facies was the dominant source of sediment, the ternary diagrams and clast roundness histograms are similar to those for basal ice samples that were taken from the stratified facies. Likewise, for moraine samples from sites where debris bands were the dominant source, the ternary diagrams and clast



(a) (b)

Fig. 3. (a) Ternary diagrams displaying clast shape of the stratified facies, and (b) histograms displaying the roundness of clasts from the stratified facies.

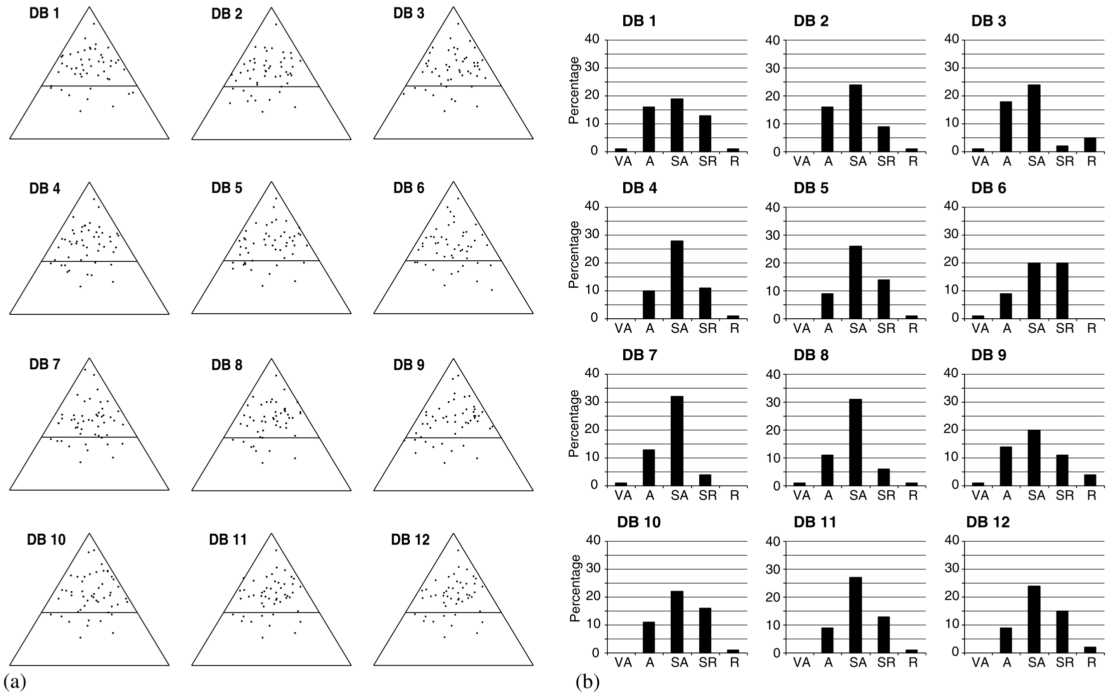


Fig. 4. (a) Ternary diagrams displaying clast shape of the debris bands, and (b) histograms displaying the roundness of clasts from debris bands.

roundness histograms are similar to those for basal ice samples that were taken from the debris bands (Figs. 5a and b).

A co-variant plot of C_{40} and RA values indicates that the C_{40} values of the stratified facies and the debris bands overlap (Fig. 6a). However, the RA index values of the two facies form two distinct populations on the co-variant plot. The difference between the two RA index values of the two facies is significant at the 99.9% confidence level according to a Mann–Whitney U-test. The co-variant plot presented in Fig. 6b displays data from the stratified facies and debris bands alongside samples collected from moraines. A clear difference (significant at the 99.9% confidence level) exists between samples taken from moraines supplied predominantly by debris bands and by the stratified facies. However, there is no significant difference between the proportion of lithologies between the stratified facies and the debris bands at each sample site (Fig. 7).

Although Fig. 8 indicates an apparent difference between the proportions of faceted clasts in the stratified facies (mean = 25.2%) and debris bands (mean = 18.2%), a Mann–Whitney U-test indicated that, at the 99.9% confidence level, the difference was not significant.

From all the clasts measured, from both facies, few had striations present. It is suggested that this is due to gneiss and granite being unsuitable lithologies for recording striations upon each other.

4. Discussion

These results indicate that there is a morphological difference between the pebble-sized debris in the stratified facies and in the debris bands of the basal ice layer. This difference also occurs in moraines supplied dominantly by debris from each of these basal ice facies. These results have implications for the reconstruction of basal ice layers in Quaternary glaciers and ice sheets, the formation of debris bands, basal ice layer processes and the method of analysing the co-variance of the C_{40} and RA indices.

This research demonstrates that Benn and Ballantyne's (1994) technique of analysing the co-variance of the C_{40} and RA indices can also be used to analyse the debris within the basal layer and to discriminate between basal layer facies within sediments in the ice-marginal moraine. Previous sedimentological research on the reconstruction of basal ice layer characteristics has been predominantly based on the interpretation of subglacial melt-out tills (Shaw, 1977a, b; Lawson, 1979a, b) and has relied on the preservation of diagnostic basal layer features, such as well-defined layering and folding of strata in the stratified facies. However, post-depositional reworking destroys many of these features, and the reliability of interpretations from glacigenic sediment flows has been questioned by Paul and Eyles (1990) and Bennett et al. (1999). Analysis of sediments derived from basal ice provides an alternative route to Quaternary reconstruction, and the Benn and Ballantyne (1994)

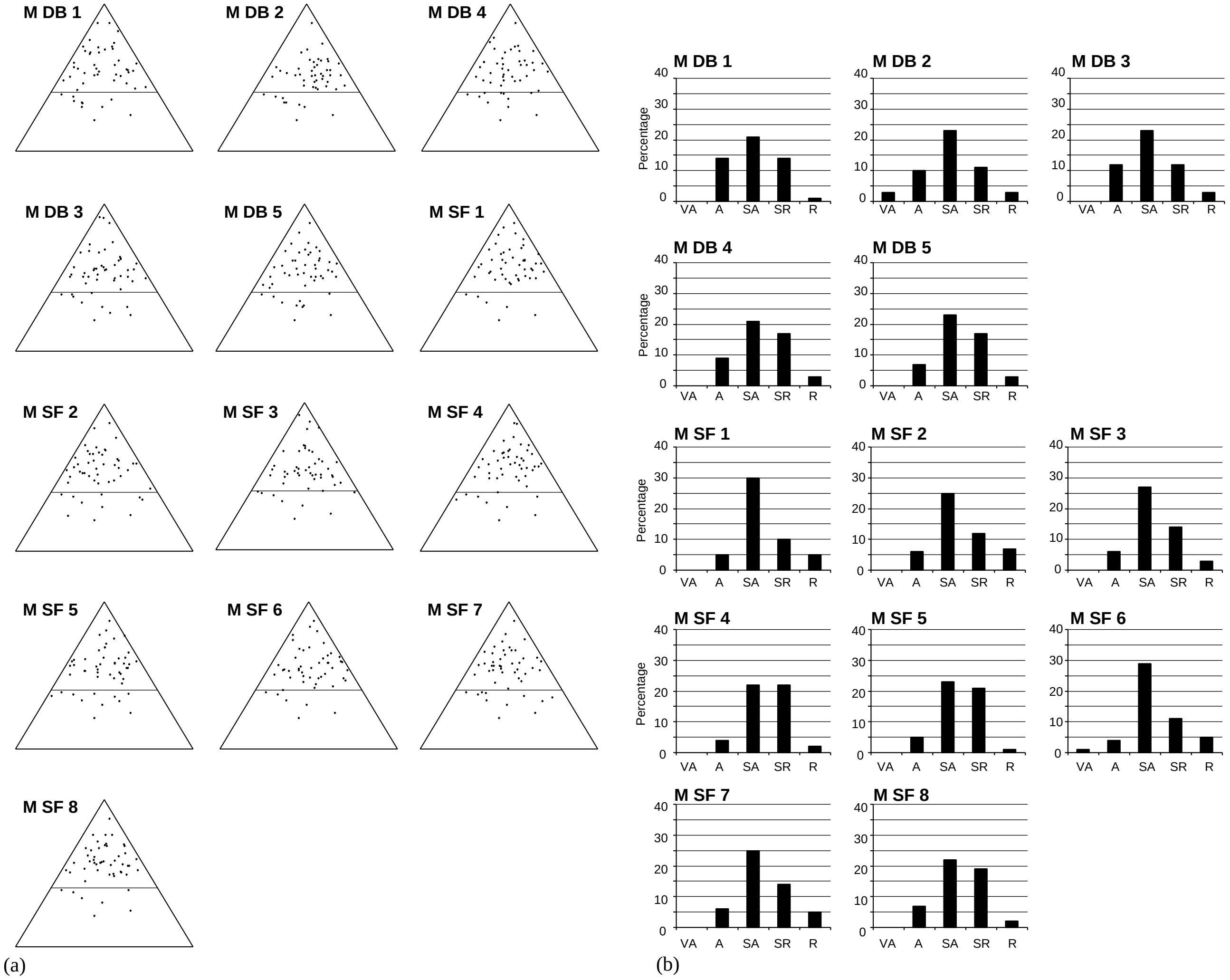


Fig. 5. (a) Ternary diagrams displaying clast shape of the moraine, and (b) histograms displaying the roundness of clasts from the moraine.

technique provides a method by which this can be achieved.

Hambrey et al. (1999) used Benn and Ballantyne's (1994) technique to describe the pebble- and cobble-sized debris within basal debris and subglacially derived thrust debris in 12 glaciers in Svalbard. However, the RA/C_{40} co-variant results that they reported are quite different from those presented here. In Svalbard the subglacially derived thrust debris had very low C_{40} and RA values, whereas the basal debris had higher C_{40} values and slightly higher RA values. In Greenland we found that stratified facies samples had very low RA and C_{40} values while debris band samples displayed higher RA values with C_{40} values similar to the stratified facies. This difference in the C_{40} and RA values between sediment samples at the Russell Glacier and those presented by Hambrey et al. (1999) may be explained by processes operating within surge glaciers, but data available from Svalbard do not differentiate samples from surge-type and non-surge-type glaciers.

It is significant that investigations at different types of glaciers in Greenland and in Svalbard, including an ice-sheet outlet, small mountain and valley glaciers, and both surge-type and non-surge-type glaciers, both demonstrated sedimentological distinctions between the stratified facies and debris bands. Further applications of the Benn and Ballantyne (1994) technique to different glacial environments may help to distinguish between the sedimentological signatures of different glacial processes.

It has been suggested that the presence or absence of debris bands in basal ice implies specific subglacial conditions (Knight, 1994). Reverse slopes, surging and frozen margins have all been suggested to be responsible for thrusting and the subsequent formation of debris bands in both modern glaciers (Clarke and Blake, 1991; Hambrey and Huddart, 1995; Hambrey et al., 1996, 1999; Bennett et al., 1998; Hambrey and Lawson, 2000; Glasser and Hambrey, 2002) and Late Pleistocene glaciers (Graham and Midgley, 2000; Hambrey et al.,

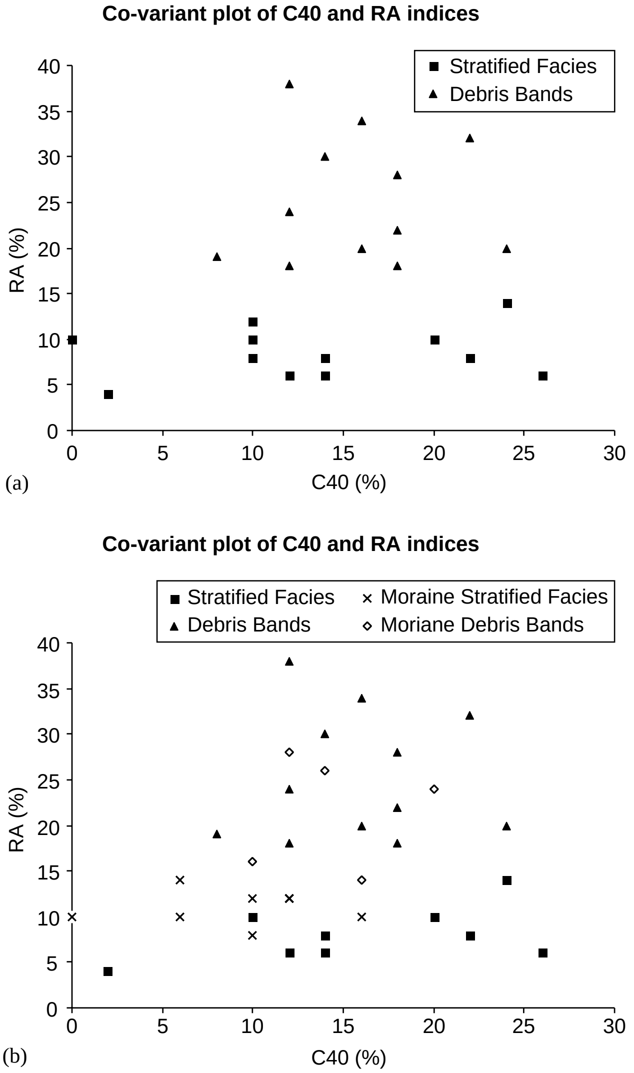


Fig. 6. (a) Scatter plot of C_{40} and RA values, with samples from stratified facies and debris bands, and (b) scatter plot of C_{40} and RA values, with samples from stratified facies, debris bands and samples from the moraines.

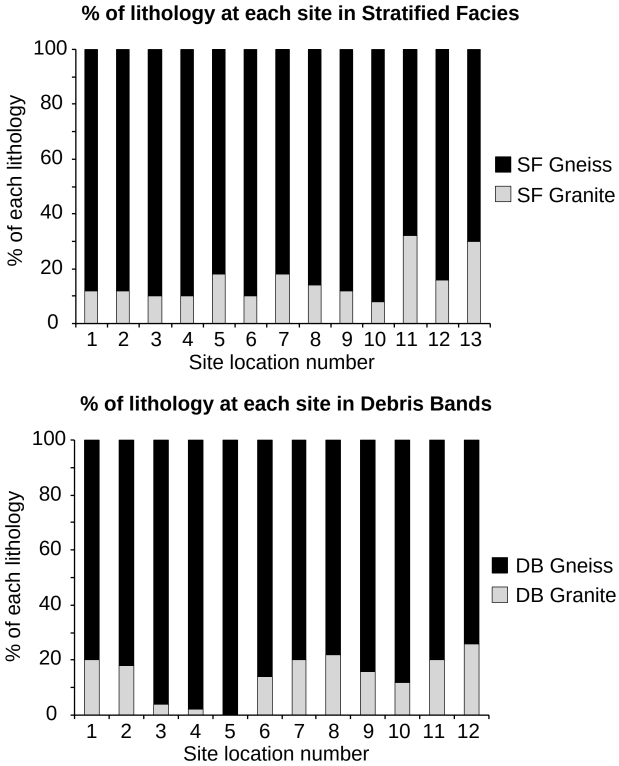


Fig. 7. Percentage of each lithology at all the sampled locations.

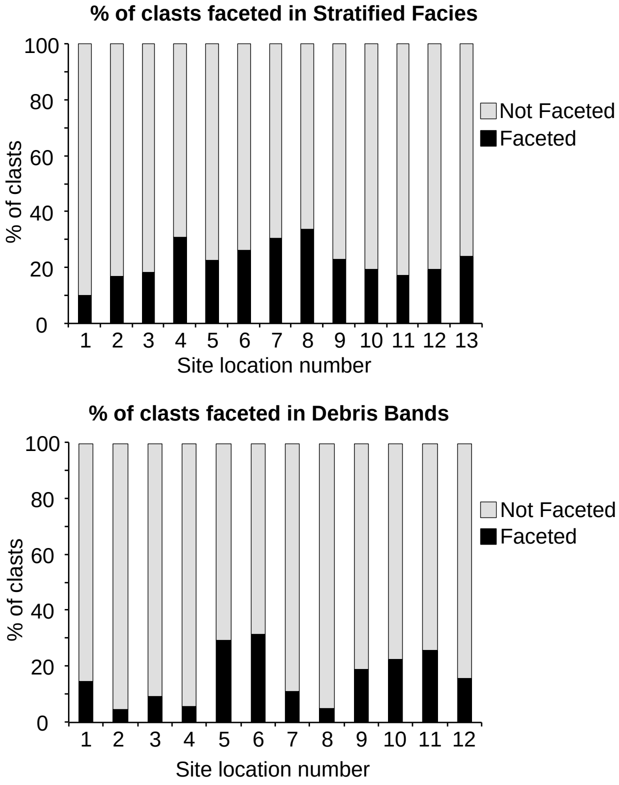


Fig. 8. Percentage of clasts faceted at each sample site.

1997). This proposed thrusting mechanism could be responsible for the difference between the RA index values of the debris bands and the stratified facies. It has previously been suggested that debris bands are formed close to the glacier margin (Knight, 1987; Knight, 1994; Bennett et al., 1997, 1998; Hambrey et al., 1999) and that they may be derived tectonically from the stratified facies (Knight, 1994). This hypothesis is supported by the similar proportions of distal lithology (granite, <30%) and local lithology (gneiss, >70%) in both the stratified facies and the debris bands. If the debris bands formed in the interior of the ice they would be composed predominantly of the distal lithology. Ensminger et al. (2001) also suggested that debris bands at the Matanuska Glacier (Alaska) can be traced downwards into the stratified facies. However, they found that the debris bands at the Matanuska Glacier contain sediments that range only from coarse silt to very fine sand, whereas the sediments within debris bands at the Russell Glacier range from clay to very large boulders.

Since the stratified facies at the two sites are sedimentologically similar, this difference in the debris-band material suggests that different processes create the debris bands at the two sites. Ensminger et al. (2001) suggested that the debris bands at the Matanuska Glacier are formed as a result of rapid injection of turbid super-cooled meltwater into basal crevasses. However, there is no evidence of extensive basal crevasses at Russell Glacier or field evidence, of the type suggested by Evenson et al. (1999), to indicate that super-cooling is taking place at the Russell Glacier.

As has been discussed, Hambrey et al. (1999) supplied evidence that a sedimentological difference may exist between debris bands and the stratified basal ice facies in different glacial environments. It would be prudent to suggest that different glacial environments may yield different values using the Benn and Ballantyne (1994) technique. However, these values, once recorded, could build up a global representation of the sedimentological characteristics of the basal layer. This would allow reconstruction of the basal layer in various past environments.

5. Conclusions

1. It is possible to discriminate between the stratified facies and debris bands in the basal ice layer by applying Benn and Ballantyne's (1994) technique of using the C_{40} and RA indices that describe the aggregate shape and roundness characteristics of clasts.
2. The distinctive difference between debris from the stratified facies and from debris bands can also be recognised in moraines to which debris bands or stratified facies are the dominant sources of sediment.
3. Combining these results with previous work (Knight et al., 2000), it appears to be possible that basal ice layers of former glaciers can be reconstructed from relict ice-marginal moraines. Previous work showed that this was possible for dispersed facies ice; this work extends the technique to stratified facies and debris bands.

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