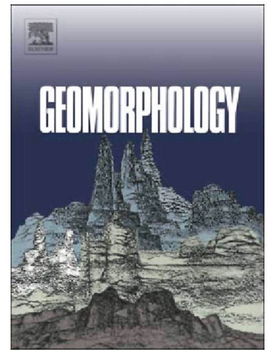
Accepted Manuscript



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PII: S0169-555X(10)00400-9
DOI: doi: 10.1016/j.geomorph.2010.08.018
Reference: GEOMOR 3371

To appear in: *Geomorphology*

Received date: 5 January 2010
Revised date: 25 August 2010
Accepted date: 27 August 2010

Please cite this article as: Cook, Simon J., Graham, David J., Swift, Darrel A., Midgley, Nicholas G., Adam, William G., Sedimentary signatures of basal ice formation and their preservation in ice-marginal sediments, *Geomorphology* (2010), doi: 10.1016/j.geomorph.2010.08.018

Sedimentary signatures of basal ice formation and their preservation in ice-marginal sediments

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Abstract

Reconstruction of subglacial processes from sedimentological evidence is central to our understanding of glaciological conditions beneath former ice masses. At Svínafellsjökull, southeast Iceland, we assess the extent to which two different processes of basal ice formation (regelation and glaciohydraulic supercooling) can be identified from ice-marginal sediments. Our results indicate that the sedimentary characteristics of deposits produced by these two processes can be distinguished from one another and that it may be possible to recognise evidence of these processes in Quaternary sediments and to reconstruct their spatial pervasiveness. Sediments derived from the melting of regelation basal ice have (i) a massive structure; (ii) a sediment matrix (0 to 10Φ) dominated by coarse sand; and (iii) a higher proportion of angular clasts than supercool basal ice and associated sediments. Sediments derived from "supercool" basal ice (i) can be either massive or layered; (ii) tend to have a silt-dominated matrix; and (iii) contain a slightly higher proportion of rounded and well-rounded clasts than regelation basal ice and sediments. Previous studies indicate that the dominance of silt within supercool basal ice may be unique to this process, and hence, supercooling should leave a readily recognisable signature in the sedimentary record. Our results from Svínafellsjökull lend support to that idea, although we suggest that further work is required to assess whether silt dominance is a process signature diagnostic of supercooling, and in particular, the extent to which subglacial sediment supply determines the sedimentary character of basal ice facies and associated sediments.

Keywords: basal ice; glaciohydraulic supercooling; ice-marginal sediments; melt-out till; Quaternary; regelation; subglacial sediment

1. Introduction

Our ability to reconstruct conditions and processes beneath former ice masses from sedimentological evidence is key to our understanding of the controls on palaeo-ice mass behaviour. In modern glacial environments, the basal ice layer exposed at the glacier margin provides a window into the relatively inaccessible subglacial environment, providing a wealth of evidence concerning the nature of the ice-bed interface, including thermal conditions, hydrology, and the mechanisms of ice flow (Hubbard and Sharp, 1989; Knight, 1997). Sediments deposited during melt-out of the basal layer of former ice masses offer similar opportunities for the reconstruction of subglacial processes, provided that appropriate models are available to link the properties of different types of basal ice to their associated sedimentary products. At Svínafellsjökull, southeast Iceland, we assess the extent to which the distinctive characteristics of "stratified" (i.e., visibly layered and debris-laden) basal ice produced by two different subglacial processes (regelation and glaciohydraulic supercooling) are preserved in ice-marginal sediments and, hence, whether the influence of such processes might be identifiable within the sedimentary record. Svínafellsjökull represents an ideal study site because the origins and spatial distribution of basal ice facies are well known (Cook et al., 2007, 2010), enabling subglacial processes to be related directly to ice-marginal sediments.

2. Research context

Whilst many studies have sought to determine which gross sedimentary characteristics are reliably preserved in ice-marginal sediments (e.g., clast shape and roundness, clast fabric, and grain size distribution; Lawson, 1981;

Ham and Mickelson, 1994; Knight et al., 2000; Adam and Knight, 2003), very few studies have assessed the extent to which different processes of basal ice formation can be inferred from analysis of ice-marginal sediments (e.g., Larson et al., 2006). Consequently, we have examined the sedimentary products of the melt-out of basal ice produced by two processes that reflect two very different basal regimes: regelation and glaciohydraulic supercooling.

Regelation is the pressure melting and refreezing of ice around bedrock obstacles, during which loose sediment may be entrained (Weertman, 1957; Kamb and LaChapelle, 1964; Hubbard and Sharp, 1993), and hence the presence of regelation ice is important evidence for basal sliding. Regelation ice tends to (i) be visibly layered from multiple episodes of melting and refreezing around bedrock obstacles; (ii) have low debris concentrations of ~ 5% by volume; (iii) contain polymodal grain size distributions; and (iv) contain dominantly basally worked clasts with occasional sharp-edged fracture planes (e.g., Kamb and LaChapelle, 1964; Boulton, 1978; Hubbard and Sharp, 1993, 1995; Alley et al., 1997). The sedimentary products of regelation basal ice have only rarely been described from modern glacial environments, although the process has been inferred from post-glacial sediments (e.g., Kemmis, 1981; Hughes et al., 1985; Domack et al., 1998). Regelation operates across small bedrock obstacles (up to 50 cm in amplitude), being remelted at the next bump; and hence basal ice layers formed by regelation should be only millimetres to decimetres thick and therefore of limited significance in glacial sediment budgets (Hubbard and Sharp, 1993; Alley et al., 1997). Nevertheless, tectonic thickening of basal layers (e.g., Sharp et al., 1994) can result in metres-thick sequences of regelation ice that may contribute significantly to moraine-building and till deposition (e.g., Spedding and Evans, 2002).

Glaciohydraulic supercooling occurs when the pressure melting point of water ascending the adverse slope of a subglacial overdeepening rises faster than the water is heated by viscous dissipation (Alley et al., 1998; Lawson et al., 1998). This causes water to freeze to the base of the glacier as frazil and anchor ice, producing very distinctive ice facies that commonly have (i) visible layers as a result of successive episodes of freeze-on of water and sediment to the glacier base; (ii) sediment concentrations averaging ~ 30% by volume; (iii) high proportions of silt as a result of preferential filtering of silt from subglacial water by frazil ice growth; and (iv) a high proportion of fluvially worked clasts as a result of sediment transport by water (Alley et al., 1998; Lawson et al., 1998; Larson et al., 2006). Although Larson et al. (2006) proposed a landform–sediment assemblage that is diagnostic of supercooling (including hummocky moraine, debris flow deposits, and melt-out tills), the power of such an approach has been criticised because the assemblage is too similar to those produced by a range of other glaciological processes (Evans, 2009). Furthermore, diagnostic sedimentary criteria, such as the dominance of silt in basal ice produced by glaciohydraulic supercooling (hereafter referred to as “supercool” basal ice), have been based on research at just one glacier (Matanuska Glacier, Alaska).

The process implications of regelation versus supercooling mean that the development of robust diagnostic sedimentary criteria would significantly enhance our understanding of former ice mass behaviour. For example, sediments derived from regelation basal ice would indicate glacier motion through basal sliding over bedrock. Sediments derived from supercool basal ice would indicate the presence of water at the glacier base, which would also influence glacier motion (e.g., by allowing ice-bed separation) and would also indicate specific subglacial hydrological configurations beneath the glacier (i.e., supercooling is typically associated with distributed, rather than channelised, routing of subglacial water; Lawson et al., 1998). Sedimentary analyses have already been used to invoke supercooling as a central process in the formation of a wide range of Quaternary landforms and sediments, including melt-out tills (e.g., Kristensen et al., 2008), moraines (e.g., Lawson et al., 1998), and Heinrich layers (e.g., Roberts et al., 2002). However, it is first essential that these criteria, and the limitations of their preservation in the sedimentary record, are tested at other modern glaciers (Cook and Knight, 2009).

3. Field site and methods

Ice-marginal sediments derived from the melt-out of stratified basal ice were investigated in summer 2007 at Svínafellsjökull (63°59’ N., 16°52’ W.), a temperate outlet glacier of the Oræfajökull ice cap, southeast Iceland (Fig. 1). Mapping and analyses of stratified basal ice facies in 2004 and 2005 (Cook et al., 2007, 2010) enabled investigation to be focused in areas where sediment supply to the ice-marginal environment was known to be dominated by melting of facies formed by regelation and tectonic thickening (subfacies A and B of Cook et al., 2007, 2010) and facies formed by glaciohydraulic supercooling (subfacies C and E). Three sites were investigated where basal ice and ice-marginal sediments were related to supercooling (sites 1, 2 and 3), and two sites were investigated where basal ice and ice-marginal sediments were related to regelation (sites 4 and 5) (Fig. 1; Table 1). Sites were selected where inputs from other sediment sources (e.g., supraglacial) were minimal.

Fig. 1.

Table 1.

Basal ice and ice-marginal sediments were described and logged following standard techniques (e.g., Lawson, 1979; Evans and Benn, 2004). At each site, between one and eleven samples of 50 basalt clasts were extracted from basal ice layers, and between one and eight samples were collected from adjacent ice-marginal sediments (Table 1). These samples were analysed for shape and roundness using standard techniques described by Benn (2004). The Tri-Plot program of Graham and Midgley (2000) was used to derive C40 indices for each sample (i.e., the proportion of clasts with a *c*:*a* axial ratio of ≤ 0.4). Plots of C40 versus relative angularity (i.e., the proportion of very angular and angular clasts) and C40 versus relative roundness (i.e., the proportion of well-rounded and rounded clasts) were then used to assess the extent to which different basal ice origins could be inferred from clast characteristics of melt-out sediments.

Sediment samples (Table 1) were also taken from basal ice layers and adjacent ice-marginal sediments for particle size determination to enable assessment of whether ice and sediment types can be differentiated on the basis of silt concentration. Size was determined using a laser granulometer (size range 0 to 10 Φ) after removing sediment coarser than 0 Φ by wet sieving. Sediment size description was assisted by use of the GRADISTAT package (Blott and Pye, 2001).

4. Results

4.1. Basal ice composition

Basal ice formed by supercooling, previously identified and mapped by Cook et al. (2007, 2010), was present at sites 1, 2, and 3 (Fig. 1). At all three sites, the ice was dominated by subfacies C (using the classification scheme of Cook et al., 2007, 2010), which can be classified as banded solid (BSo) basal cryofacies according to the scheme proposed by Hubbard et al. (2009).

At site 1, 0.9 m of subfacies C basal ice was observed in summer 2003 that thickened as it dipped upglacier beneath the lake surface (Fig. 2A). This ice contained angular aggregates of predominantly silt-sized material (Fig. 2B) within a clean ice matrix and had a mean debris concentration of 28% by volume. Subhorizontal layers persisted throughout that were clearly picked out by differences in debris concentration and distribution, although individual layers were laterally discontinuous. Rapid recession of the ice margin into the lake (Fig. 2A) meant that basal ice was no longer accessible by 2004.

Up to 1.9 m of subfacies C ice was observed at site 2 in 2004 and 2005 (Fig. 2C) along with a thick sediment layer that appeared to be melting-out in situ. Excavation below ground level revealed buried subfacies C ice with a total thickness approaching ~ 4 m. Again, recession of the ice margin into the lake meant that by 2007 the stratified basal ice layer was inaccessible. At site 3, up to 0.7 m of subfacies C basal ice was observed in 2005 when the ice was just overtopping a moraine; and again this basal ice was no longer accessible by 2007.

Fig. 2.

Facies demonstrated to have formed by regelation and tectonic thickening (Cook et al., 2010) were present at sites 4 and 5. Exposures of subfacies A up to 2 m thick were observed at these sites in 2004, 2005, and 2007, with a minor component of subfacies B at site 5 (Fig. 2D). Subfacies A comprises alternating, debris-rich and debris-poor laminae, with low debris concentrations (< 6% by volume). Subfacies B is composed of dispersed particles and debris aggregates within a clean ice matrix with debris concentrations below 4% by volume. This layered basal ice with low debris content can be classified as banded dispersed (BD) basal cryofacies according to the scheme of Hubbard et al. (2009).

4.2. Composition of ice-marginal sediments

At site 1 where melt-out of subfacies C ice had been observed in 2003, the area comprised several low profile (i.e., < 0.5 m height) moraine mounds, with long axes that were formed parallel to the former ice margin. Two of the mounds were logged (Fig. 3, log 1 and log 2) from trenches cut across the long axis. The first mound was composed primarily of alternating layers of stratified or laminated muddy diamict; layers of laminated fine to medium sand, with occasional lenses of fine to medium sand or granule gravel, were also observed. The composition of the second mound was similar but overlain by up to 0.15 m of massive diamicton and included occasional layers or lenses of granule gravel not more than 0.04 m in thickness and not more than 0.2 m in lateral extent. We note here that diamicton appeared structureless to the naked eye (and hence is coded as massive) although it is not possible to say with certainty that it did not contain micro-scale structures because we did not undertake micromorphological analyses. The same can be said for all subsequent descriptions of apparently massive diamictons.

Fig. 3.

Sediments at site 2 had been observed to be melting-out in situ in 2004 and 2005 and could be observed in section. Fig. 3 demonstrates that these sediments were composed of muddy diamicton with a structure that ranged from weakly stratified to laminated. The top of the sequence was capped by a 0.07-m layer of massive medium sand that had been eroded from a nearby moraine. At site 3, a small excavation was made into the crest of the moraine on the ice-proximal side of the apex, which demonstrated sediments composed almost entirely of muddy diamicton with an occasional weakly stratified structure (Fig. 3).

Sites 4 and 5 were both situated at the crest of small (~1.5 m high) moraines that had been in contact with the glacier in 2004 and 2005, although the size of the moraines probably reflects their origin as seasonal-readvance moraines rather than entirely by the debris flux provided by the ice. Sediments at site 4 were composed primarily of apparently massive diamicton, although weak stratification was noted near the base of the excavated section (Fig. 3); a 0.04-m gravel layer separated the upper and lower diamictons. Site 5 was composed almost entirely of apparently massive, clast-rich sandy diamicton with very weak visible stratification between 0.6 and 0.7 m depth (Fig. 3).

4.3. Sediment particle size distribution

Having given some overall description of ice-marginal sediments and particle size in Fig. 3, we focus here on the sediment particle size distributions of the matrix between 0 and 10 Φ (Fig. 4).

Fig. 4.

Basal ice and ice-marginal sediments associated with supercooling (sites 1, 2 and 3) tend to have finer grained sediment particle size distributions than basal ice and sediments associated with regelation (Table 1; Fig. 4). At sites 2 and 3, mean basal ice particle size distributions were 3.9 Φ (very fine sand) and 5.4 Φ (coarse silt), respectively. So despite the overall fine-grained nature of the basal ice, some variability exists between sites. No basal ice particle size samples could be obtained at site 1 as a result of the recession of the ice margin into the lake.

Ice-marginal sediments associated with supercooling had similar particle size distributions to the parent basal ice (Table 1; Fig. 4). Although no direct comparisons between basal ice and ice-marginal sediments at site 1 can be made, the ice-marginal sediments had a very similar particle size distribution to basal ice and sediments at site 2 (Table 1; Fig. 4).

Basal ice and ice-marginal sediments associated with regelation at sites 4 and 5 had coarser particle size distributions (i.e., mean between 2.6 and 3.3 Φ; Table 1; Fig. 4). Although the mean particle size of regelation-related basal ice and ice-marginal sediments at site 4 is similar to that of supercooling-related basal ice and sediments at sites 1 and 2, the modal particle size of the two populations is visibly different, with a coarse skew for regelation-related basal ice and sediments (Fig. 4).

4.4. Clast characteristics

Figs. 5A and 5B presents covariant plots of clast shape (C40) versus relative angularity (proportion of very angular and angular clasts) for sites 1, 2, and 3 (supercool) and sites 4 and 5 (regelation), respectively; and Figs. 5C and 5D presents C40 versus relative roundness (proportion of well-rounded and rounded clasts) for sites 1, 2, and 3 and sites 4 and 5, respectively.

Fig. 5.

We can clearly see from Fig. 5 and Table 1 that at all sites, both in areas that are dominated by supercool and by regelation basal ice, the clast shape and angularity/roundness characteristics of basal ice and associated ice-marginal sediments are similar. There is a slightly higher proportion of angular clasts within basal ice (mean = 15.3%) and ice-marginal sediments (mean = 15.3%) at sites 4 and 5 than at sites 1, 2, and 3 (basal ice mean = 12.5%; ice-marginal sediments mean = 11.8%) (Fig. 5A and 5B; Table 1). Equally, there is a slightly higher proportion of rounded clasts within basal ice (mean = 17.4%) and ice-marginal sediments (mean = 8.1%) at sites 1, 2, and 3 than at sites 4 and 5 (basal ice mean = 5.8%; ice-marginal sediments mean = 7%). A Mann-Whitney U-test reveals that there is a significant difference between supercool (sites 1, 2, and 3) and regelation basal ice (sites 4 and 5) in terms of the proportion of rounded clasts (at 99% significance), although not for the proportion of angular clasts (at either 95% or 99% significance). However, the difference in roundness between basal ice populations is not observed in the ice-marginal sediments where a Mann-Whitney U-test revealed no statistical difference between ice-marginal sediments of supercooling or regelation origin, either for roundness or angularity.

Clast shape (C40) appears not to be able to differentiate between sediments of different origins because there is a similar range of C40 values in each of the plots on Fig. 5 (see also Table 1). There is some suggestion that there may be a difference in shape between supercooling- and regelation-derived ice-marginal sediments because a Mann-Whitney U-test reveals a difference at 95% significance. However, this difference is not observed between basal ice populations of different origins.

5. Discussion

We discuss first the extent to which the sedimentary characteristics of basal ice of different origins have been preserved within ice-marginal sediments at Svínafellsjökull, followed by a discussion of the significance of our results for the reconstruction of conditions and processes beneath former ice masses.

5.1. Supercool sediments

On the basis of previous research at the Matanuska Glacier, Alaska, basal ice produced by glaciohydraulic supercooling is considered to be characterised by a layered appearance, high debris content, the dominance of silt-sized sediment, and a high proportion of fluvially worked clasts (Alley et al., 1998; Lawson et al., 1998; Larson et al., 2006). Some of these characteristics are consistent with basal ice of the same origin at Svínafellsjökull (Cook et al., 2007, 2010). Supercool (subfacies C) basal ice at sites 1, 2, and 3 is characterised by a layered appearance (Figs. 2A-C) with a high debris content (~ 28% by volume on average) and a high proportion of coarse silt and very fine sand (Fig. 4; Table 1). There is a statistical difference in clast roundness between supercool and regelation basal ice, with generally more rounded clasts in supercool basal ice.

At the Matanuska Glacier, and for some sites once covered by ice in North America and Scandinavia, it has been suggested that the distinctive sedimentary characteristics of supercool basal ice have been preserved in sediments derived from basal ice melt-out (Larson et al., 2006; Kristensen et al., 2008). However, these supercooling signatures have lacked verification from other modern sites. Our results from Svínafellsjökull indicate (i) that ice-marginal sediments do occasionally preserve sedimentary layering inherited from supercool basal ice; (ii) that the conspicuous dominance of silt and very fine sand in supercool basal ice is preserved in ice-marginal sediments; and (iii) that the large proportion of fluvially rounded clasts found within supercool basal ice is not always reflected in ice-marginal sediments and, hence, may not be a reliable indicator of supercooling (although this last finding is based on a relatively small number of samples).

At Svínafellsjökull, the layered appearance of the basal ice appears to have been preserved within ice-marginal sediments in some situations (Figs. 2 and 3). At site 1, the layering within ice-marginal sediments probably does not record the structure of the basal ice. We observed reworking of melt-out sediments by flow along a shallow gradient toward what is now a large proglacial lake. Hence, sediment flow likely contributed to the layered appearance of the sediments here (cf. Lawson, 1982). Site 2 provides the best example of a true melt-out till at Svínafellsjökull because conditions at this location favoured development of such a till (flat area at the base of a moraine slope that washed insulating sediment on top of melting basal ice). Under these circumstances basal ice was allowed to melt-out in situ; and so layering was preserved in ice-marginal sediments. At site 3, there is only very faint layering evident within an otherwise apparently massive till, indicating that layering was destroyed as basal ice melted onto a steep moraine slope. So, in general, the preservation of the distinctive layered appearance of supercool basal ice depends largely on the conditions under which it melts, and hence this signature can vary significantly around the glacier margin. Lawson (1979) found that melt-out tills only accounted for around 5% of the deposits at the Matanuska Glacier, and our observations are broadly consistent with that.

The dominance of silt and very fine sand within supercool basal ice was recorded within ice-marginal sediments at sites 2 and 3, although such an assessment was not possible at site 1 (Fig. 4; Table 1). Although the particle size distributions of basal ice and ice-marginal sediments at sites 1 and 2 are all similar, the particle size distributions of basal ice and ice-marginal sediments at site 3 are different, being more fine-grained. Nonetheless, the dominance of silt and very fine sand in basal ice and melt-out sediments is clear and is distinctively more fine-grained than regelation basal ice and sediments at sites 4 and 5. This result is consistent with previous reports of silt-dominated basal ice and sediments associated with supercooling (e.g., Larson et al., 2006).

Although there is a statistical difference between supercool basal ice and regelation basal ice in terms of clast roundness, the same trend was not observed in ice-marginal sediments. Inspection of Fig. 5C and Table 1 reveals that there was significant variability in basal ice clast roundness between sites 1, 2, and 3; and hence, the preservation of a clast morphology signature of supercooling in ice-marginal sediments appears unlikely. The reasons for the lack of a consistent clast morphology signature are unclear, but we suggest that the subglacial supply of rounded clasts could be variable. Lawson et al. (1998) described concentrations of sorted gravels with rounded clasts within basal ice, perhaps related to channel fill beneath the glacier. Swift et al. (2006) also regarded the basal sediment within overdeepenings to be a mixture of subglacially and fluvially transported material, and hence it should be expected that sediment within basal ice will exhibit heterogeneous characteristics. It seems likely, therefore, that although basal ice contained concentrations of rounded clasts where sampled, ice-marginal sediments may have formed from basal ice that contained more mixed clast characteristics. Clast shape (C40), in this study, also appears not to be able to discriminate reliably between populations derived from basal ice of different origins (Fig. 5; Table 1).

5.2. Regelation sediments

Regelation basal ice has been described in numerous studies and is generally considered to be layered, to contain low concentrations of debris, to contain a range of grain sizes, and to be dominated by basally worked clasts that may show signs of fracture and angularity (e.g., Kamb and LaChapelle, 1964; Boulton, 1978; Hubbard and Sharp, 1993, 1995; Sharp et al., 1994; Alley et al., 1997). Basal ice at sites 4 and 5 is broadly consistent with these previous descriptions, being characterised by a layered appearance, low debris contents (~ 5% by volume on average), dominated by coarse sand (Figs. 2D and 4; Table 1), and containing a higher proportion of angular clasts than rounded clasts. Few studies have considered the sedimentary products of regelation ice from modern environments, although this process has been invoked to explain the origin or development of some post-glacial sediments (e.g., Kemmis, 1981; Hughes et al., 1985; Domack et al., 1998).

Overall, our results indicate (i) that sedimentary layering from regelation ice is not preserved in ice-marginal sediments; (ii) the sandy texture of the basal ice is preserved in ice-marginal sediments and is distinct from sediments derived from supercooling; and (iii) that the higher proportion of angular clasts within regelation basal ice is preserved in ice-marginal sediments, although it has not been possible to differentiate ice-marginal sediments of different origins on the basis of clast morphology.

The high ice to debris ratio of regelation basal ice means that the preservation of layering within ice-marginal sediments is very unlikely (Paul and Eyles, 1990; Evans et al., 2006). Therefore, the very faint layering within ice-marginal sediments at sites 4 and 5 (Fig. 3; Table 1) probably represents layering from sediment flow or from reworking by a seasonal glacier readvance rather than from direct melt-out of basal ice in situ.

The sediment particle size distribution of basal ice at sites 4 and 5, dominated by coarse sand, is preserved within ice-marginal sediments and is similar between sites (Fig. 4, Table 1). This coarse sediment signature is notably different from the fine-grained supercool basal ice and sediments. The extent to which a coarse sand texture can be considered as diagnostic of regelation, and hence of importance in evaluating the extent of basal sliding beneath palaeo-ice masses, is uncertain. Regelation basal ice and sediments from nearby Breiðamerkurjökull, Iceland, described by Boulton et al. (1974) are similarly dominated by sand. However, Domack et al. (1998) suggested that clots of frozen clay within Prydz Bay marine sediments, Antarctica, resulted from regelation entrainment of a mud-rich slurry. Sediment supply and bedrock lithology may play significant roles in determining the particle size distribution of regelation basal ice and melt-out sediments.

In general, samples of basal ice at sites 4 and 5 contained higher proportions of angular clasts than they did rounded clasts (Fig. 5, Table 1), and this pattern was also true for ice-marginal sediments. These properties reflect the active subglacial transport of sediment in the basal traction zone (e.g., Boulton, 1978).

5.3. Recognising basal processes in formerly glaciated environments: problems and progress

Our results from Svínafellsjökull indicate the potential to identify the former operation of supercooling and regelation from Quaternary sediments, enabling important insight into the conditions beneath former ice masses. For example, correct identification of regelation from Quaternary glacial sediments is important in assessing the potential for glacier motion through basal sliding, and identification of glaciohydraulic supercooling allows inferences to be made about the nature of subglacial hydrology. Furthermore, because of the strong spatial differences in the occurrence of different basal ice facies and subglacial processes (Cook et al., 2007), it may be possible to reconstruct the spatial distribution of basal ice compositions and subglacial processes from post-glacial sediments (Knight et al., 2000; Adam and Knight, 2003). The most robust method of differentiation between sediments of different origins would appear to be on the basis of particle size distribution, although our work does show some variability in particle size distribution of supercool ice facies and sediments around the glacier margin. Where conditions allow it, sedimentary stratification may also be preserved, but this is the exception rather than the norm. Clast shape and roundness/angularity analysis was found to be less reliable in differentiating between sediments of different origins because of significant overlap between populations of regelation-related and supercooling-related sediments.

Particle size distributions of sediments derived from basal ice melt-out survive robustly in the absence of significant agents of sediment reworking, such as glaciofluvial activity (Knight et al., 2000). Hence the distinctive silt-dominated particle size distribution of ice-marginal sediments derived from supercooling may be recognised relatively easily in post-glacial sediments (Larson et al., 2006; Kristensen et al., 2008). The sedimentary characteristics of regelation sediments, whilst being distinct from sediments derived from supercooling, may not be so easily distinguished from sediments derived from other processes of basal ice formation whereby there is no selective entrainment of a specific sediment particle size. Cook et al. (2010) demonstrated that supercool basal ice facies contributed around five times more debris to the ice-marginal environment at Svínafellsjökull than did regelation basal ice. Hence the preservation potential of a supercooling signature is likely to be greater than for a regelation signature. Nonetheless, some studies have reported the influence of regelation through analysis of post-glacial sediments (e.g., Kemmis, 1981; Hughes et al., 1985; Domack et al., 1998), and such sedimentary signatures and geomorphic impact may be enhanced where debris-laden regelation layers are thickened through glaciotectonic deformation (e.g., Sharp et al., 1994) as at Svínafellsjökull.

There are significant challenges to be met in order to be able to differentiate between the influences of different subglacial processes, including processes of basal ice formation, within the sedimentary record of past glaciations. Different criteria used to elucidate the origins of sediments (including clast fabric analysis, sedimentary layering, preservation of englacial structures, etc.) have all been criticised and the data can sometimes be equivocal (Paul and Eyles, 1990; Boulton, 1996; Hart, 1998; Bennett et al., 1999; Evans et al., 2006). For example, while Larson et al. (2006) suggested a landform–sediment assemblage indicative of the influence of supercooling (including melt-out tills, sediment flow deposits, hummocky moraine), other workers have criticised these criteria suggesting that they are not unique to this process (Evans, 2009).

Some hope may then come from analysis of the sediments themselves. Larson et al. (2006) suggested that the dominance of silt within basal ice produced by supercooling may be unique to this process. Some subsequent studies (e.g., Kristensen et al., 2008) have also related silt-dominated sediments to a supercooling origin. Until now, the idea that basal ice and ice-marginal sediments produced by supercooling should necessarily be silt-dominated has been based solely on observations at the Matanuska Glacier (Alley et al., 1998; Lawson et al., 1998; Larson et al., 2006). Our study at Svínafellsjökull lends some support to this suggestion. However, the extent to which particle size distributions record a subglacial process signature has been questioned previously. For example, Haldorsen (1982) suggested that melt-out till and lodgement till necessarily had different particle size distributions as a consequence of their different origins. Hart (1998) criticised this assertion suggesting instead that grain size differences merely reflect variations in the nature of the subglacial environment rather than any process signature. It is reasonable to speculate then as to whether silt dominance within supercool basal ice is a function of the supercooling process itself (i.e., preferential filtering of silt by frazil ice during supercooled freeze-on) or of some other factor such as sediment supply, or both (Cook and Knight, 2009).

We advance a hypothesis for how silt-dominated basal ice and sediments might result irrespective of the nature of supercooled freeze-on. The fact that supercooling relies upon the presence of an overdeepening means that, during times when the glacier recedes into the overdeepening, a lake will form in front of the glacier allowing fine-grained sediments to accumulate. When the glacier subsequently advances into the lake and supercooled freeze-on resumes, the system is already primed so that basal ice will entrain the local supply of silt. Thus silt-dominance may be an overdeepening-specific sediment signature rather than, or in addition to, a supercooling-specific signature. The variability in the clast morphology data across parts of Svínafellsjökull that overly an overdeepening (i.e., where supercool basal ice is dominant; Fig. 1) also suggests that sediment supply is spatially variable and thus, in part, controls the sedimentary character of the basal ice and resultant sediments. Bedrock lithology may also vary beneath different parts of the glacier providing variable sediment supply.

There are other possible causes of the dominance of silt within supercool basal ice or the relative silt deficiency within regelation basal ice. Eyles and Menzies (1983) proposed that bed roughness plays an important role such that smoothed beds promote efficient comminution and enhanced abrasion of rock particles to give fine-grained particle size distributions, whereas rough beds promote grain crushing and a lower proportion of fine-grained products. Eyles and Menzies (1983) also suggested that fine-grained sediments are more likely to become lodged against bedrock obstacles during the regelation process, and hence become removed from debris transport. Boulton (1975) showed that regelation flow occurred around individual particles resulting in only limited entrainment of silt and clay particles. Likewise, particles larger than pebble size would tend not to be entrained because ice is able to deform around them. The issue of whether silt dominance can be regarded as a supercooling signature merits further research, and we invite the testing of our hypothesis for the accumulation of silts within overdeepenings.

Whatever the cause of silt dominance within supercool basal ice, the recognition of silt-dominated tills in the glacial sedimentary record could be significant to interpretations of their genesis. For example, basal ice produced within overdeepenings can reach several metres in thickness, either by supercooling or through enhanced thickening of preexisting basal ice against a reverse bedslope (e.g., Lawson et al., 1998; Swift et al., 2006). Hence the interpretation of till sequences as the product of the melt-out of such basal ice offers an important alternative explanation to their interpretation as the products of processes such as subglacial sediment deformation (see Boulton, 1996; Hart, 1998; Piotrowski et al., 2001; Evans et al., 2006). A number of workers have already begun to attribute the formation of some melt-out tills and also Heinrich layers to the supercooling process and to the presence of overdeepenings (Lawson et al., 1998; Roberts et al., 2002; Larsen et al., 2004; Larson et al., 2006; Kristensen et al., 2008). It is essential then that potentially diagnostic subglacial process signatures preserved in the sedimentary record are tested further so that we can be confident in our interpretation of sediment origins in a range of different situations.

6. Conclusions

Our results from Svínafellsjökull indicate that the distinctive sedimentary characteristics of basal ice produced by two different processes (glaciohydraulic supercooling and regelation) are preserved within ice-marginal sediments during basal ice melt-out. Furthermore, the spatial distribution of basal ice types of different origins may be reconstructed from post-glacial sediments (e.g., Knight et al., 2000; Adam and Knight, 2003). There are key differences between these sediments that may make it possible to differentiate between the influences of these two processes in the sedimentary record of past glaciations. Sediments derived from the melting of basal ice produced by supercooling tend to be silt-dominated with a slightly higher proportion of rounded and well-rounded clasts compared to regelation basal ice and sediments. Where supercool basal ice melts-out in situ, the sedimentary stratification observed in the basal ice is also preserved within ice-marginal sediments, although this is rare. Sediments derived from the melting of basal ice produced by regelation tend to be dominated by coarse sand with a slightly higher proportion of angular and very angular clasts than supercool basal ice and sediments. There is very little evidence of the preservation of basal ice sedimentary stratification within ice-marginal sediments because of the high ratio of ice to sediment within regelation ice.

We find that sediment particle size analysis provides the most robust method of differentiating between basal processes from ice-marginal sediments. Because of its higher sediment content, the preservation potential of a supercool basal ice signature in post-glacial sediments is greater than for regelation basal ice, although where regelation ice is tectonically thickened its impact on proglacial sedimentology and geomorphology might be more easily recognised in post-glacial sediments. Until now the assumption that supercooling necessarily produces silt-dominated basal ice and sediments has been based on results at only one glacier (e.g., Lawson et al., 1998). Results from Svínafellsjökull lend support to this idea. However, further research is required in order to assess whether the dominance of silt-sized material within basal ice produced by supercooling, and hence within melt-out sediments, is a function of the supercooling processes itself (i.e., silt filtered from subglacial water during percolation through frazil ice) or of sediment supply. Likewise, sediment supply may play a role in determining the sedimentary character of regelation basal ice and associated ice-marginal sediments. In the case of explaining silt-dominated basal ice and sediments through supercooling, we hypothesise that subglacial overdeepenings may trap significant quantities of silt during times of reduced glacier extent when the overdeepening becomes a proglacial lake. This would provide a ready supply of silt for basal ice accretion when the overdeepening is subsequently inundated once more during times of greater glacier extent. Either way, silt-dominated till may be strongly indicative either of the influence of overdeepenings and/or of supercooling in glacial sediment entrainment and may be developed as a diagnostic tool to aid the interpretation of till genesis.

Acknowledgements

SJC gratefully acknowledges funding from the Royal Geographical Society. This research benefited from aerial photographs acquired by the NERC Airborne Research and Survey Facility in 2007. We thank Richard Waller for the photograph used in Fig. 2a. This manuscript benefitted from helpful reviews from an anonymous reviewer and the editor Richard Marston.

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FIG. 1. The location (inset) and ice-marginal environment of Svínafellsjökull, including the distribution of stratified basal ice facies, prominent ice-marginal geomorphological features, and sample locations for analysis of ice-marginal sediments derived from stratified basal ice.

Fig. 2. Basal ice composition at Svínafellsjökull. (A) Supercool basal ice (subfacies C) at site 1 (photograph by Richard Waller); (B) close-up of supercool basal ice at site 2 including angular aggregates of silt-dominated sediment; (C) section of supercool basal ice at site 2; (D) section of regelation basal ice at site 5 composed primarily of subfacies A, with a 20-cm-thick lens of subfacies B immediately below the ice axe head.

Fig. 3. Sedimentary logs for ice-marginal sediments at each site.

Fig. 4. Particle size distributions of the sediment matrices (0 to 10 Φ) of basal ice and ice-marginal sediments. Error bars indicate ± one standard deviation.

Fig. 5. Covariant plots of clast shape versus relative angularity (RA) (A and B) and relative roundness (RR) (C and D). Plots (A) and (C) compare basal ice and ice-marginal sediments from areas of the glacier where basal ice formation is dominated by glaciohydraulic supercooling (i.e., sites 1, 2, and 3); and plots (B) and (D) compare basal ice and ice-marginal sediments from areas where basal ice formation is dominated by regelation (i.e., sites 4 and 5).

List of Tables

Table 1. Summary of site characteristics and sedimentary characteristics of stratified basal ice and ice-marginal sediments.

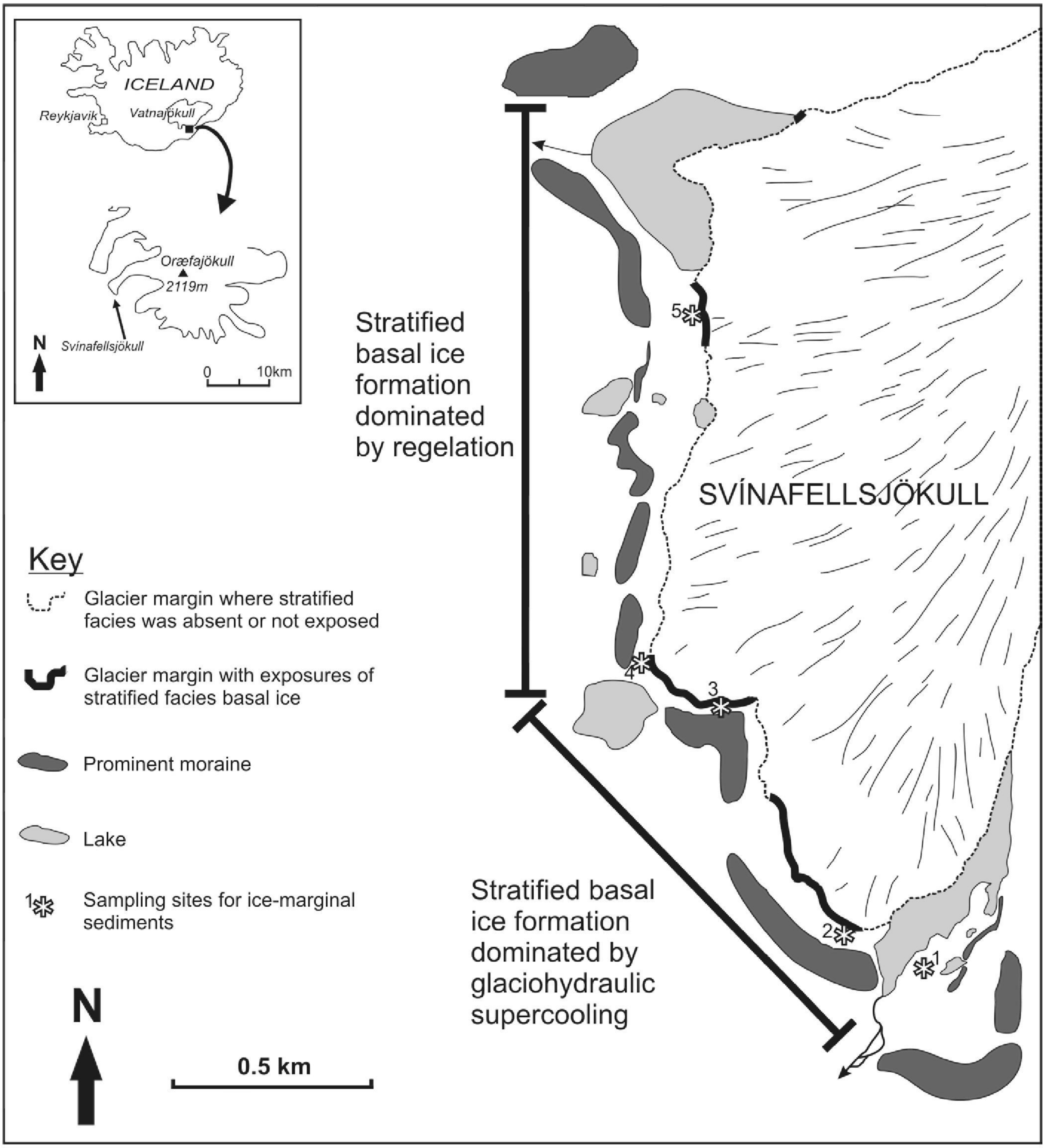
ICELAND
Reykjavik
Vatnajökull
Oræfajökull
2119m
Svínafellsjökull
N
0
10km
Stratified
basal ice
formation
dominated
by regelation
SVÍNAFELLSJÖKULL
Key
Glacier margin where stratified facies was absent or not exposed
Glacier margin with exposures of stratified facies basal ice
Prominent moraine
Lake
Sampling sites for ice-marginal sediments
Stratified basal ice formation dominated by glaciohydraulic supercooling
N
0.5 km
1
2
3
4
5

Fig. 1

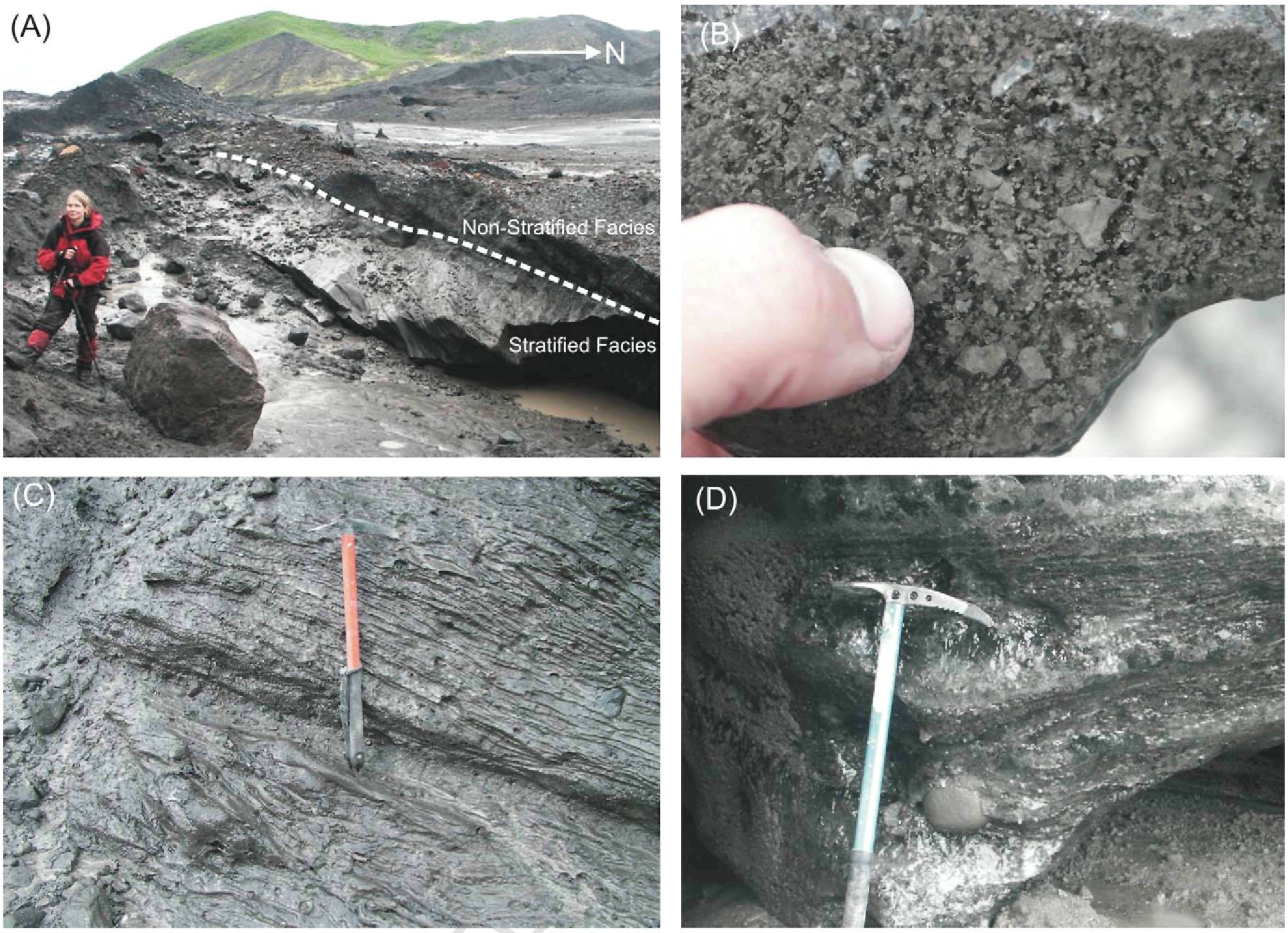

Fig. 2

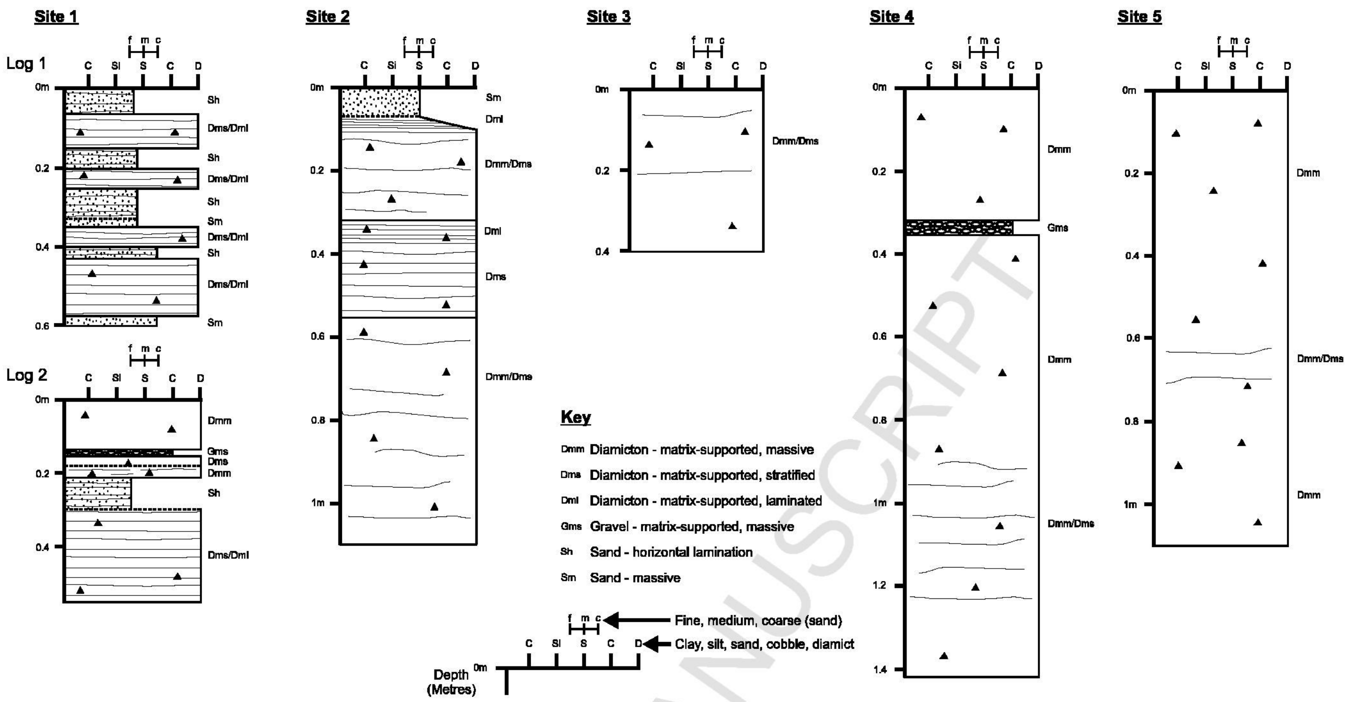
Site 1
Log 1
Log 2
Site 2
Site 3
Site 4
Site 5
Key
Dmm Diamicton - matrix-supported, massive
Dms Diamicton - matrix-supported, stratified
Dml Diamicton - matrix-supported, laminated
Gms Gravel - matrix-supported, massive
Sh Sand - horizontal lamination
Sm Sand - massive
Fine, medium, coarse (sand)
Clay, silt, sand, cobble, diamict
Depth (Metres)

Fig. 3

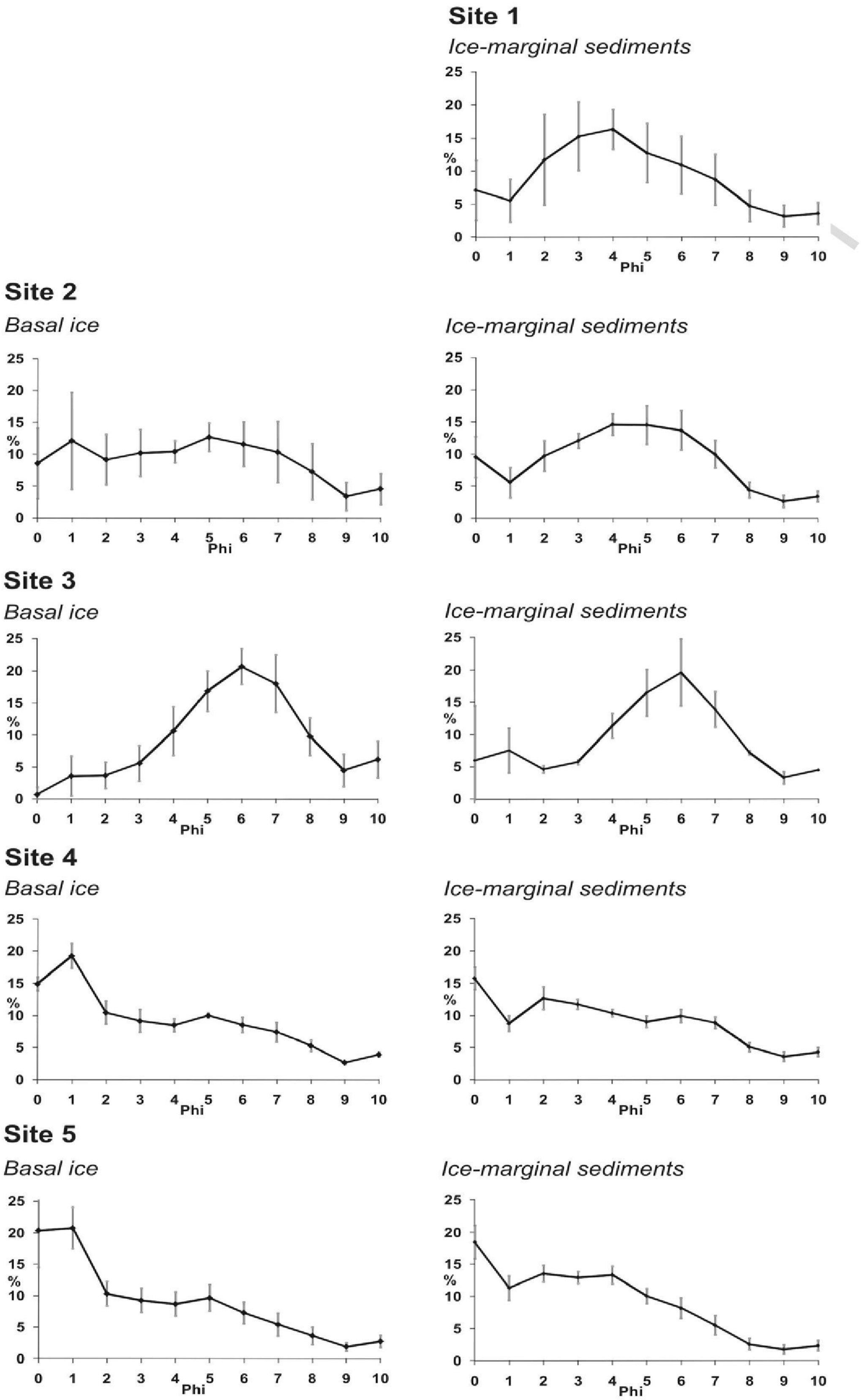
Site 1
Ice-marginal sediments
Site 2
Basal ice
Ice-marginal sediments
Site 3
Basal ice
Ice-marginal sediments
Site 4
Basal ice
Ice-marginal sediments
Site 5
Basal ice
Ice-marginal sediments
%
Phi
0 5 10 15 20 25
0 1 2 3 4 5 6 7 8 9 10

Fig. 4

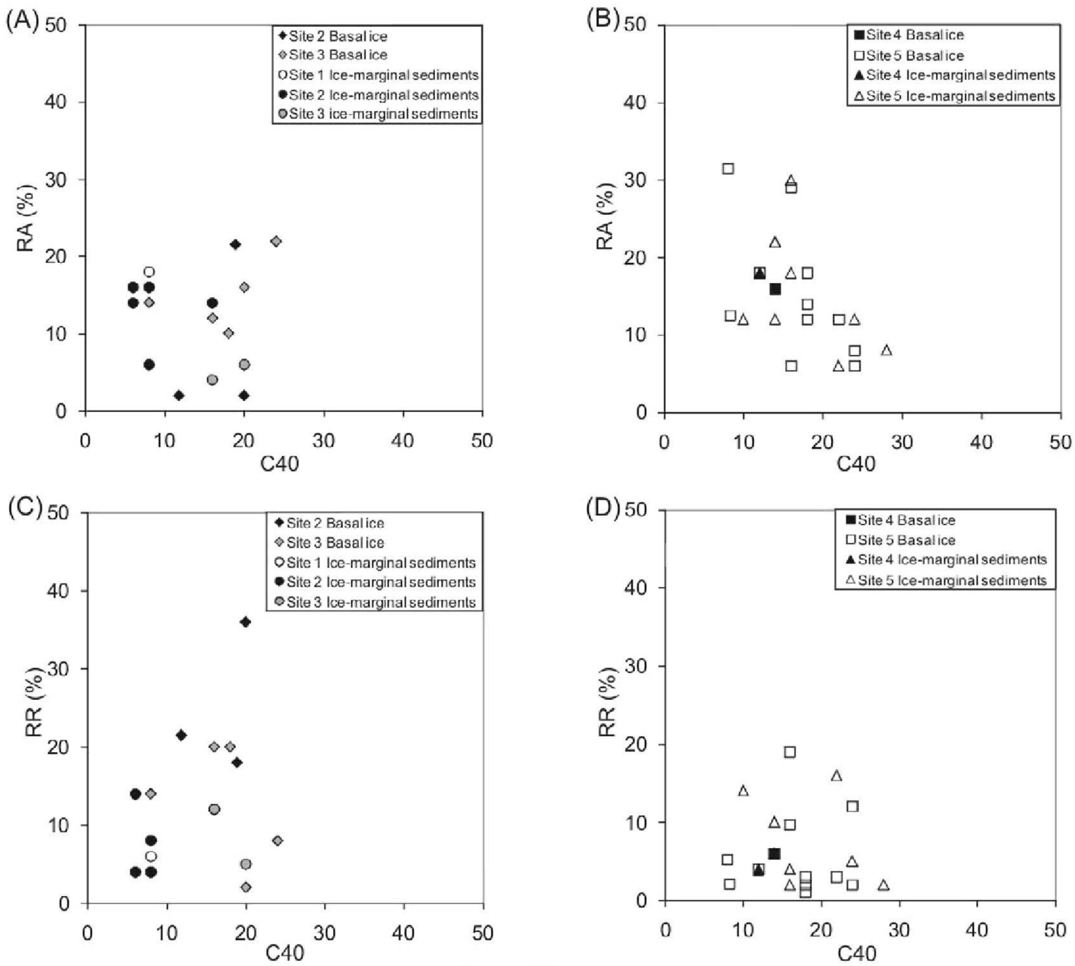
(A)
RA (%)
C40
Site 2 Basal ice
Site 3 Basal ice
Site 1 Ice-marginal sediments
Site 2 Ice-marginal sediments
Site 3 ice-marginal sediments
(B)
RA (%)
C40
Site 4 Basal ice
Site 5 Basal ice
Site 4 Ice-marginal sediments
Site 5 Ice-marginal sediments
(C)
RR (%)
C40
Site 2 Basal ice
Site 3 Basal ice
Site 1 Ice-marginal sediments
Site 2 Ice-marginal sediments
Site 3 Ice-marginal sediments
(D)
RR (%)
C40
Site 4 Basal ice
Site 5 Basal ice
Site 4 Ice-marginal sediments
Site 5 Ice-marginal sediments

Fig. 5

Table 1

Summary of site characteristics and sedimentary characteristics of stratified basal ice and ice-marginal sediments.

Site	Dominant basal ice facies	Basal ice				Ice-marginal sediments			
		Mean particle size (Φ)	***Mean C40***	***Mean relative angularity (%)***	***Mean relative roundness (%)***	***Mean particle size (Φ)***	***Mean C40***	***Mean relative angularity (%)***	***Mean relative roundness (%)***
1	Supercool (subfacies C)	-	-	-	-	3.9 (very fine sand) n=11	8.0 n=1	18.0	6.0
2	Supercool (subacies C)	3.9 (very fine sand) n=11	16.9 n=3	8.5	25.2	3.9 (very fine sand) n=6	8.8 n=5	13.2	8.4
3	Supercool (subfacies C)	5.4 (coarse silt) n=3	17.2 n=5	14.8	12.8	4.5 (very coarse silt) n=2	18.0 n=2	5.0	8.5
4	Regelation (subfacies A)	3.1 (very fine sand) n=5	14.0 n=1	16.0	6.0	3.3 (very fine sand) n=10	12.0 n=1	18.0	4.0
5	Regelation (subfacies A)	2.6 (fine sand) n=18	16.8 n=11	15.2	5.7	2.7 (fine sand) n=6	18.0 n=8	15.0	7.4