Origin and significance of ‘dispersed facies’ basal ice: Svínafellsjökull, Iceland

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ABSTRACT. Dispersed facies basal ice – massive (i.e. structureless) ice with dispersed debris aggregates – is present at the margins of many glaciers and, as a product of internal glacial processes, has the potential to provide important information about the mechanisms of glacier flow and the nature of the subglacial environment. The origin of dispersed facies is poorly understood, with several hypotheses having been advanced for its formation, and there is disagreement as to whether it is largely a sedimentary or a tectonic feature. We test these established hypotheses at the temperate glacier Svínafellsjökull, Iceland, and find that none fully account for dispersed facies characteristics at this location. Instead, dispersed facies physical, sedimentological and stable-isotope (δ^{18}O, δD) characteristics favour a predominantly tectonic origin that we suggest comprises the regelation and strain-induced metamorphism of debris-rich basal ice that has been entrained into an englacial position by tectonic processes operating at the base of an icefall. Further thickening of the resultant dispersed facies may also occur tectonically as a result of ice flow against the reverse bed slope of a terminal overdeepening. Lack of efficient subglacial drainage in the region of the overdeepening may limit basal melting and thus favour basal ice preservation, including the preservation of dispersed facies. Despite the relatively low sediment content of dispersed facies (~1.6% by volume), its thickness (up to 25 m) and ubiquity at Svínafellsjökull results in a significant contribution to annual sediment discharge (1635–3270 $\mathrm{m^3\,a^{-1}}$) that is ~6.5 times that contributed by debris-rich stratified facies basal ice.

INTRODUCTION

Understanding the origin and characteristics of basal ice beneath glaciers and ice sheets is important for glaciologists and geomorphologists because basal ice influences ice motion, provides information on glaciological processes and conditions at the base of ice masses, and is important for glacial sediment entrainment, transfer and deposition (Hubbard and Sharp, 1989; Knight, 1997). Dispersed facies basal ice (defined as dispersed debris particles and aggregates within a clean ice matrix, using the terminology of Lawson, 1979) is of particular interest because it has commonly been associated with formation in the deep interior of ice masses and is therefore potentially important in conveying information about subglacial processes and conditions in highly inaccessible locations (e.g. Sugden and others, 1987). Furthermore, numerous studies have described a basal ice facies at many different ice masses, which is descriptively similar at all sites, and could be classified as dispersed facies basal ice (hereafter referred to simply as ‘dispersed facies’), although several different names have been applied (e.g. the ‘dispersed facies’ of Lawson (1979), the ‘clotted facies’ of Knight and others (1994) and the ‘clear facies’ of Hubbard and others (2000); Table 1).

Basal ice stratigraphy around glacier margins can be very variable, but the generalized stratigraphy proposed by Knight (1994) is of a lowermost, debris-rich, layered facies termed ‘stratified facies’ overlain unconformably by dispersed facies. Dispersed facies is in turn typically overlain by meteorically derived glacier ice (englacial facies), although the contact between these facies is typically diffuse, leading several authors to propose a genetic relationship between the two (e.g. Lawson, 1979). It is also common to find debris bands (sometimes referred to as ‘banded facies’; Knight, 1987, 1994) intercalated with dispersed facies or englacial facies. Debris bands have been suggested to be tectonically attenuated debris-rich ice derived from the stratified facies or from underlying subglacial sediments (e.g. Hart, 1995, 1998; Waller and others, 2000). Though basal ice is important for transferring debris through the glacier system and for building till sequences and moraines (e.g. Lawson, 1979; Knight and others, 2002), estimates of debris flux in basal ice layers are not common, and have largely been made for debris-rich stratified facies basal ice (e.g. Larson and others, 2006; Cook and others, 2010), with few measurements made of dispersed facies (e.g. Knight and others, 2002).

Despite its potential importance and apparent ubiquity, the dispersed facies remains enigmatic, with several hypotheses proposed for its formation. Hypothesized mechanisms include those of a broadly sedimentological nature in which the dispersed facies is passively emplaced, including freezing-on of ice and sediment subglacially (Christoffersen and others, 2006), passive burial of sediment deposited supraglacially in the accumulation area (Koerner, 1989), and transport of sediment through the intercrystalline vein network (Knight and Knight, 1994) by water generated by rigid-bed regelation (Knight, 1987; Sugden and others, 1987). Other mechanisms have been of a largely tectonic nature in which dispersed facies is the end-product of strain-induced metamorphism of another ice facies, including englacial ice (Sharp and others, 1994; Hubbard and others, 2000) or debris-rich stratified facies basal ice (Hart, 1995).

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Table 1. Key characteristics of dispersed facies basal ice (and descriptively similar basal ice facies with different names) outlined in previous studies

Study	Facies name	Thickness	Key characteristics	Proposed origin
Matanuska Glacier, Alaska (Lawson, 1979)	Dispersed facies	0.2–8 m	Massive with scattered clay- to pebble-sized debris particles and aggregates Mean debris concentration 3.8% by volume (range 0.04–8.4%) Isotope composition similar to overlying glacier ice Crystal size 1–4 cm Fewer bubbles than overlying glacier ice Bubble-poor	Combination of surface (firnification) and basal influences (e.g. regelation)
Russell Glacier, Greenland (Knight, 1987; Sugden and others, 1987)	Clotted ice	Up to several tens of metres	Clear ice containing suspended nodules of debris up to 8 cm in diameter found at triple-grain crystal boundaries. Size and concentration of clots decreases towards top of sequence, merging into overlying glacier ice Debris concentration 0.001–8% by weight Isotope composition intermediate between glacier ice and stratified facies Crystal size 2–5 cm Bubble-poor	Regelation around bedrock obstacles in ice-sheet interior
Laboratory simulations of clotted ice formation (at Russell Glacier, Greenland) (Knight and Knight, 1994)	Clotted ice	As Knight (1987); Sugden and others (1987)	As Knight(1987); Sugden and others (1987)	Clotted ice formed as a consequence of regelation. Silt-laden water squeezed along pressure gradient from bed into overlying ice through intercrystalline vein network
Exit, Childs and Matanuska Glaciers, Alaska (Hart, 1995)	Clean ice or low debris/ ice ratio layer	As Lawson (1979)	As Lawson (1979)	Initial entrainment by regelation or basal adfreezing. Reduction in clot size with height due to tectonic deformation, i.e. lowermost debris layers attenuated to a thinner layer, then to a clot, then to a particle
Variegated Glacier, Alaska (Sharp and others, 1994)	Clear ice	Decimetres thick	Low concentrations of incorporated debris and gas bubbles. Grit particles to clasts dispersed throughout ice Mean debris concentration 0.4% by volume Isotope composition intermediate between glacier ice and debris-rich basal ice Crystal size up to 4 cm Bubble-poor	Metamorphism of glacier ice under variable pressure close to the glacier bed
European Alps (Hubbard and Sharp, 1995; Hubbard and others, 2000)	Clear ice	0.1–10 m	Translucent ice layers with dispersed debris Mean debris concentration 4.1 g L^{-1} Bubble-poor	Strain-induced metamorphism of firnified glacier ice Isotope composition similar to overlying glacier ice
Greenland and Canadian Arctic ice cores (Koerner, 1989)	Basal ice (i.e. not divided into facies)	Metres to tens of metres	Ice containing basal debris ranging from individual particles to rare pebble-sized material, sometimes found as silty clots Camp Century core has mean debris concentration of 0.24% by weight Bubble-poor	Superimposed ice charged with wind-blown debris formed during the last interglacial when ice-sheet extent was much reduced
Kamb Ice Stream, West Antarctica (Christoffersen and others, 2006)	Clear ice; Clean ice	6–12 m	Clean, transparent ice that sometimes contains dispersed debris or mud clots Debris content <1% by volume	Growth of accreted ice, possibly from supercooled groundwater, in the ice-sheet interior
Meserve Glacier, Antarctica (Holdsworth, 1974; Cuffey and others, 2000; Samyn and others, 2005)	Amber ice	Metres to tens of metres	Bubble-free and amber in colour Includes mud-rich debris although contains a range of grain sizes. Typical debris concentration ~15 g L^{-1}	Regelation around bedrock at subfreezing temperatures or accretion of ice during glacier advance into a lake

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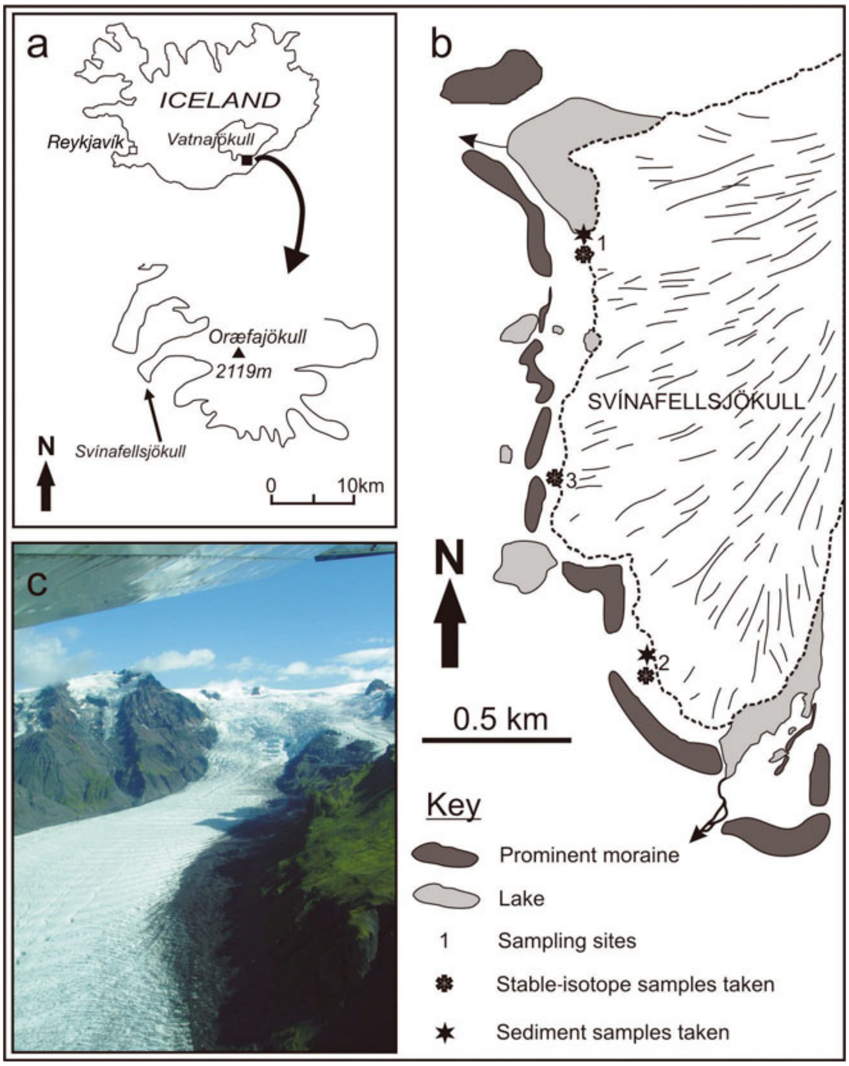

Fig. 1. (a) Regional context of Svínafellsjökull. (b) Map of Svínafellsjökull terminus including sampling locations for sediment particle size and stable-isotope analyses. (c) View of the icefall and ogives.

Table 1 summarizes the key characteristics and proposed mechanisms of formation for the dispersed facies from a number of key studies.

The first aim of our study is to elucidate the origin of the dispersed facies at the temperate glacier Svínafellsjökull, southeast Iceland (Fig. 1). The presence of an icefall and a terminal subglacial overdeepening at Svínafellsjökull may contribute importantly to the origin of dispersed facies at this location in ways that have not been examined. Goodsell and others (2002) demonstrated that basal materials could be elevated into englacial and even supraglacial positions in folds generated by intense compression at the base of an icefall, with dark ogive bands, which reflect areas of particularly dense foliation, forming planes of weakness along which strain can also be accommodated by thrusting on the scale of the glacier thickness. Spedding and Evans (2002) suggested that the presence of a terminal overdeepening may further enhance the elevation of basal material as a result of ice flow against the adverse slope. Swift and others (2006) speculated that this might also reactivate thrusting along dark ogive bands to form prominent outcrops of very debris-rich ice in supraglacial locations down-glacier of the overdeepening. Similar processes may influence basal ice formation at Svínafellsjökull.

Our second aim is to assess the contribution of dispersed facies to sediment transfer at Svínafellsjökull following calculations made by Cook and others (2010) of debris transfer by the more debris-rich stratified facies at the same glacier.

STUDY SITE AND METHODS

Dispersed facies was examined at Svínafellsjökull (63°59′ N, 16°52′ W), a temperate outlet glacier of the Oræfajökull ice cap, southeast Iceland (Fig. 1). Typically the dispersed facies is found in metres-thick exposures at the terminus in direct contact with the substrate (glacial moraine/till), although it is occasionally found to be underlain by the more debris-rich and visibly layered stratified facies. The stratified facies has been examined in detail by Cook and others (2007, 2010), who attributed its formation to the tectonic thickening of regelation ice and, in the southern part of the glacier terminus, to freeze-on of water and sediment as a result of glaciohydraulic supercooling.

Many glaciers in this region terminate in overdeepenings (Knudsen and others, 2001; Roberts and others, 2002; Spedding and Evans, 2002), and an overdeepening at Svínafellsjökull has been inferred from the distribution of

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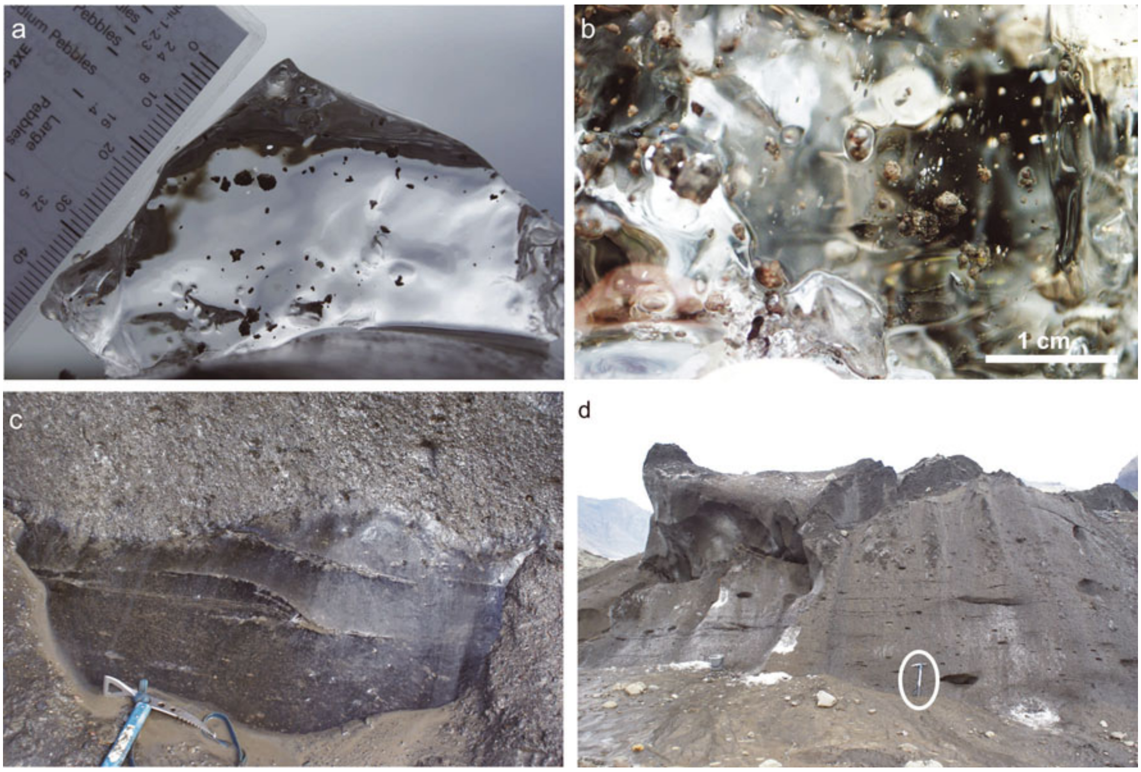

Fig. 2. Typical characteristics of the dispersed facies including (a, b) dispersed debris aggregates and particles (a) in thin section and (b) in situ, (c) occasional debris-rich planes and (d) the crudely layered structure of the ice.

features known to be associated with glaciohydraulic supercooling (Cook and others, 2007). These included vents of upwelling supercooled water, the presence of anchor-ice terraces and frazil-ice flocs in and adjacent to vents, and crevasses or fractures filled with platy ice (Evenson and others, 1999). Also in common with other glaciers in the region is the prominent icefall located ~6 km from the terminus, a position that coincides with the approximate altitude of the equilibrium line in this region (Spedding and Evans, 2002). Ogives appear immediately down-glacier from the icefall spaced on average at a 35 m interval (Fig. 1c; King and Ives, 1956), the arcuate dark ogive bands being composed of strongly foliated ice that occasionally contains subglacially worked clasts. The association of ogives with icefalls and subglacial debris is common to many glaciers in this region (Ives and King, 1954; King and Ives, 1956; Swift and others, 2006).

Dispersed facies was characterized and logged following Lawson (1979), with description of facies thickness, physical appearance, mean crystal diameter, debris distribution and debris concentration. Measurements of crystal size were facilitated by thin-sectioning blocks of ice to ~1–2 mm thickness on a hot plate and viewing the thin section through cross-polarizing lenses. Decimetre-scale samples of dispersed facies were removed using an ice axe, after removing the top 20–30 cm of rotted ice. These were taken from sections with a massive structureless appearance with no debris bands present. Sediment samples were extracted from melted ice blocks by filtering. Sediment size distribution was characterized by wet sieving (–4 to 0Φ) and laser granulometry (0–10Φ). Descriptive statistics (e.g. Φ is defined as $\log_2 d$, where d is particle diameter (mm)) and sediment classifications for particle size distributions were produced using the GRADISTAT package (Blott and Pye, 2001).

Stable-isotope analysis of dispersed facies followed similar methods to previous research (e.g. Cook and others, 2010). Before sampling the ice, the top 20–30 cm of ice was removed to extract ice unaffected by surficial melting and contamination resulting from the movement of surface meltwater along crystal boundaries. Blocks of ice of ~30–100 mL were removed (i.e. typically decimetre-scale samples, although occasionally centimetre-scale) and allowed to melt in sealed sample bags. Samples were then filtered through 0.45 μm nitrocellulose filter papers and subsequently stored in airtight bottles. Stable-isotope analysis was undertaken on a GV Instruments Isoprime continuous-flow mass spectrometer. Standardization was carried out by calibration against laboratory and International Atomic Energy Agency (IAEA) reference standards. All analyses were duplicated and internal precision was 0.4% for hydrogen and 0.08% for oxygen, with external precision estimated to be approximately twice these values.

RESULTS

Physical attributes and facies classification

Dispersed facies ice was characterized by a low mean debris concentration of 1.6% by volume (std dev. 2.0%; $n = 48$) dispersed throughout a clean ice matrix (Fig. 2a and b). Measured debris concentrations ranged from 0.2% to 9.7% by volume. Debris occurred either as individual particles or as irregular-shaped aggregates (typically less than ~5 mm in diameter) and generally had a polymodal grain-size distribution (see below). Thin sections of the ice revealed that debris was typically found within the ice crystals (i.e. intracrystalline) rather than at crystal boundaries (Fig. 2a). Debris was occasionally concentrated along debris planes

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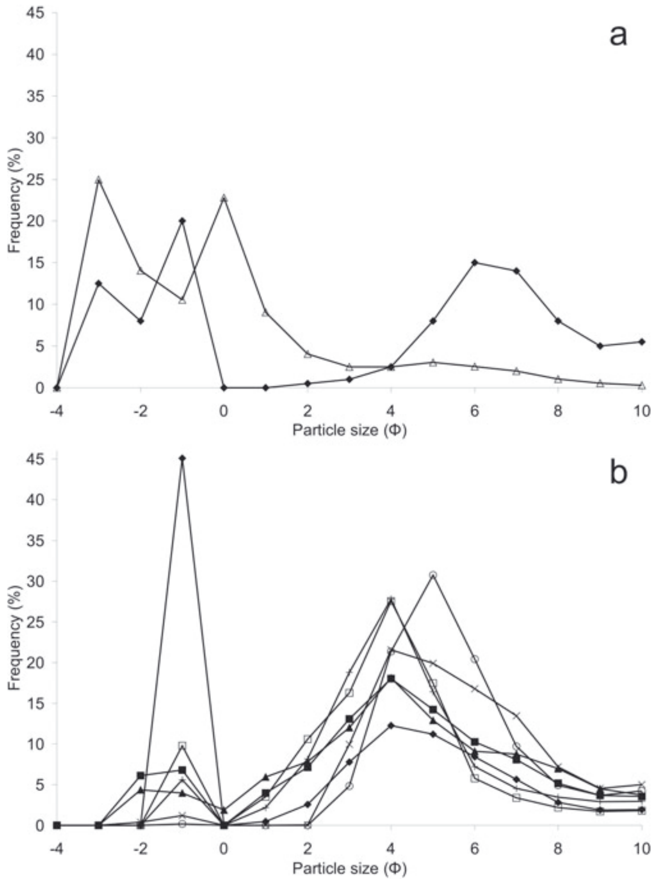

Fig. 3. Particle size distributions for (a) site 1 and (b) site 2 (see Fig. 1b for site locations).

separated by the more typical arrangement of uniformly distributed debris (Fig. 2c). Viewed at the centimetre to decimetre scale, dispersed facies appeared massive and structureless, although at the decimetre to metre scale it sometimes exhibited weak layering (Fig. 2d). Bubbles were rare, although where they did exist they were deformed and flattened, and generally less than ~3 mm in length. Crystal diameters ranged from 0.8 to 6.8 cm, with a mean of 2.9 cm (std dev. 1.5 cm; $n = 37$).

The underlying stratified facies was generally more debris-rich (3–30% sediment by volume), equally bubble-poor and generally had smaller crystal sizes (0.4–1.8 cm). For detailed comparison with the characteristics of the stratified facies, we refer the reader to Cook and others (2007, 2010). Overlying glacier ice (englacial facies) was characteristically blue or white, with a high concentration of bubbles and low debris content (0.04% by volume; $n = 4$). Glacier ice crystal diameters were larger on average than dispersed facies crystals, 1.8–7.5 cm with a mean diameter of 3.8 cm (std dev. 1.5 cm; $n = 20$). Debris was similarly polymodal, although insufficient debris was recovered from glacier ice to allow detailed particle size analysis.

Exposures of dispersed facies were typically sub-vertical at the glacier margin, with exposures of 0.5–15 m in height. In most cases, the base of the dispersed facies could be seen, except in the southern portion of the glacier where it is receding into an overdeepening. Dispersed facies could be traced up-glacier across the glacier surface for several tens of metres. Foliation planes within the dispersed facies and overlying glacier ice typically dipped up-glacier at 10–20°, so true thicknesses in this area were up to ~25 m. Dispersed facies ice was also observed within laterally discontinuous bands that outcropped up to ~400 m up-glacier of the main ice-marginal exposures. These bands contained aggregates or angular clasts of yellow or red tephra or rock, and were not sampled for sediment or isotope analyses.

The naming of different basal ice facies has been inconsistent between studies (Hubbard and others, 2009). We have adopted the term ‘dispersed facies’ of Lawson (1979) because it is the most widely used. However, to facilitate future comparisons between similar ice facies at other glaciers, we classify dispersed facies basal ice at Svínafellsjökull according to the unified basal ice facies classification scheme of Hubbard and others (2009). As such, dispersed facies at Svínafellsjökull includes Dispersed (D) (where no layering is visible), Dispersed Stratified (DSt) (where layering is on the scale of metres) and Dispersed Banded (DB) (where layering is on the scale of decimetres) basal cryofacies.

Spatial distribution

Dispersed facies occurred almost ubiquitously around the glacier terminus. It was found either in direct contact with the substrate or was separated from it by a layer of debris-rich stratified facies. Where they were found together, dispersed facies and stratified facies had a sharp, unconformable contact. Bubble-foliated glacier ice derived from meteoric sources lay stratigraphically above the dispersed facies, and the boundary between the two ice types was diffuse. Fractures filled with platy ice were common in the southern reaches of the glacier (Cook and others, 2007) and represent the injection of supercooled water along with sediment into crevasses and fractures where the glacier enters an overdeepening. These structures have been injected into and cross-cut the dispersed facies, suggesting that the dispersed facies developed up-glacier of the terminal overdeepening.

Sediment characteristics

Figure 3 presents sediment particle size distributions for dispersed facies from two locations. There was significant variability between individual particle size distributions, which were generally polymodal. Samples at site 1 (location in Fig. 1b) both contained high proportions of pebbles, granules and coarse sand, and one of the two samples contained a high proportion of silt (Fig. 3a). At site 2 (Fig. 3b), there was a much lower proportion of pebbles, granules and coarse sand, with samples generally dominated by fine sand and silt. The mean particle size for the dispersed facies at Svínafellsjökull was $2.95 \pm 3.62\Phi$ (fine sand; $n = 9$). Figure 4 demonstrates that debris volumes measured through the thickness of dispersed facies at the glacier margin did not vary systematically with height above the glacier bed over scales of metres (Fig. 4a–e) to tens of metres (Fig. 4f).

Stable-isotope analysis

Figure 5 presents stable-isotope plots of $\delta^{18}O$ against δD for dispersed facies, and results are summarized in Table 2. A local meteoric waterline (LMWL) is plotted on each graph in Figure 5 based on the data of Robinson (2003) and Robinson and others (2009) from nearby Skeiðarárjökull (~10.5 km west of Svínafellsjökull). This was also used as a reference water composition for Svínafellsjökull by Cook and others

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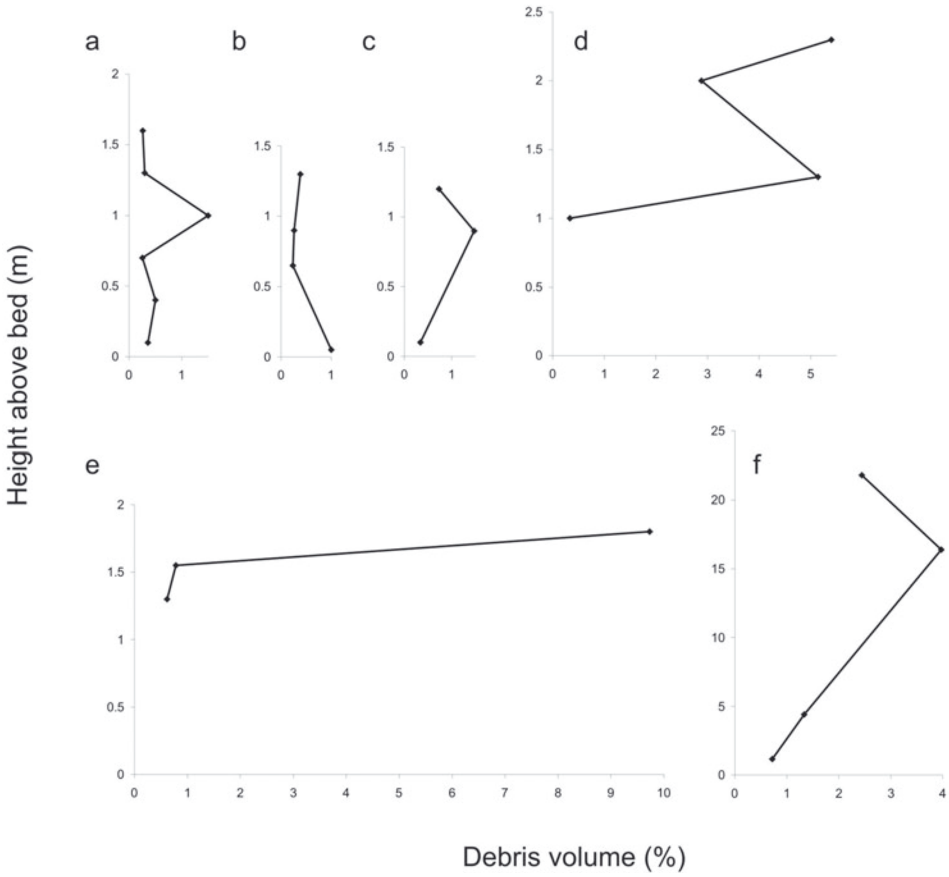

Fig. 4. Change in debris volume within dispersed facies with height above the glacier bed, from site 1 (a–c), site 3 (d, e) and site 2 (f).

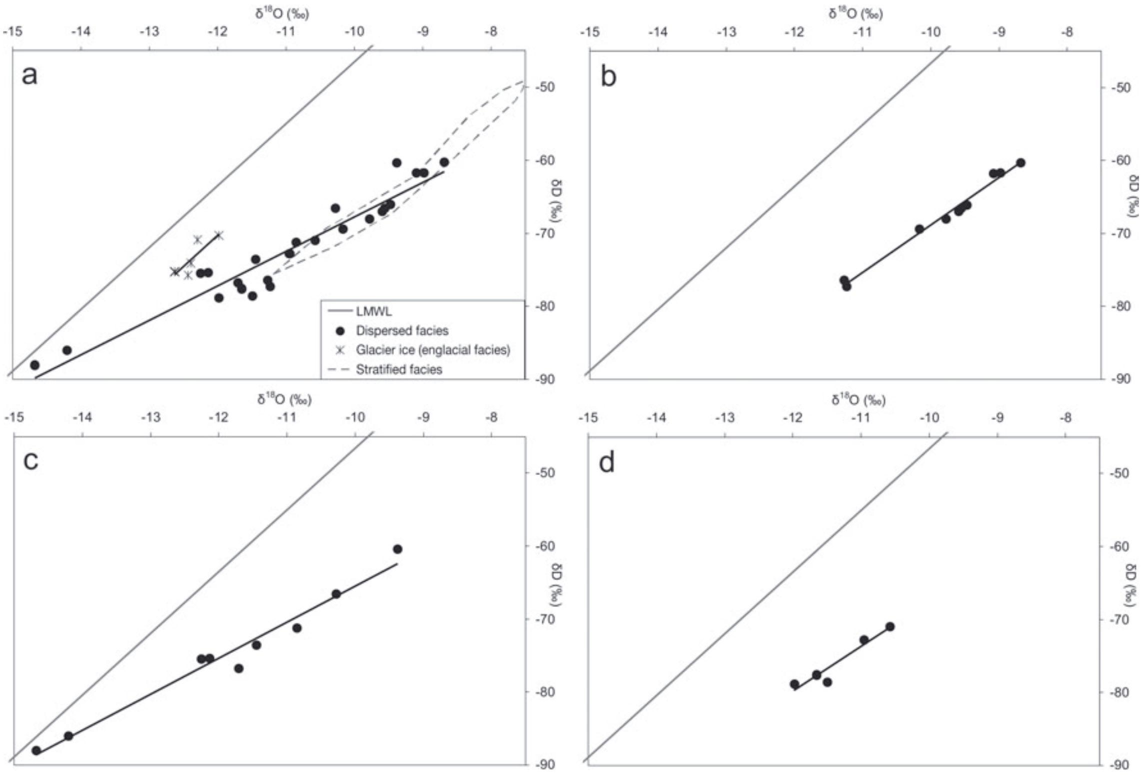

Fig. 5. Stable-isotope composition of dispersed facies: (a) composition of all dispersed facies, glacier ice and stratified facies samples; (b–d) composition of dispersed facies samples at (b) site 1, (c) site 2 and (d) site 3.

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Table 2. Summary of the stable-isotope compositions of dispersed facies and glacier ice samples

Sample	*n*	Mean $\delta^{18}O$	Range $\delta^{18}O$	Mean δD	Range δD	Slope of regression line and error	r^2
		‰	‰	‰	‰		
Glacier ice	6	–12.4	–12.6 to –12.0	–73.6	–75.7 to –70.3	8.6 ± 2.5	0.74
Dispersed facies (All)	24	–10.9	–14.7 to –8.7	–71.9	–88.0 to –60.3	4.7 ± 0.3	0.92
Dispersed facies (site 1)	10	–9.8	–11.3 to –8.7	–67.4	–77.3 to –60.3	6.5 ± 0.3	0.99
Dispersed facies (site 2)	9	–11.9	–14.7 to –9.4	–74.8	–88.0 to 60.4	5.0 ± 0.3	0.97
Dispersed facies (site 3)	5	–11.3	–12.0 to –10.6	–75.8	–78.8 to –71.0	6.1 ± 1.1	0.91

(2010). This LMWL has a slope of 8.46 and is plotted through the lightest values in the dataset to facilitate comparison with dispersed facies ice compositions (i.e. it is an adjusted LMWL). An envelope encapsulating the isotope compositions of stratified facies samples is plotted for comparison based on the data of Cook and others (2010).

Figure 5a shows all stable-isotope data for dispersed facies and glacier ice. Dispersed facies compositions plot with a regression slope of 4.7 ($r^2 = 0.92$; Table 2). Glacier ice compositions plot with a regression slope of 8.6 ($r^2 = 0.74$), similar to the adjusted LMWL and typical of ice derived directly from meteoric sources (e.g. Jouzel and Souchez, 1982). Dispersed facies samples generally have a lighter composition than stratified facies samples, although there is overlap between compositions. Comparison between Figure 5b, c and d (see also Table 2) shows that there was some compositional variability of dispersed facies between sites 1, 2 and 3, respectively. However, at all sites, data plot along regression slopes of 5.0–6.5, with high r^2 values (0.91–0.99). The isotope composition of dispersed facies, plotting along a line of lower slope than meteorically derived glacier ice samples, is therefore consistent with isotope fractionation during closed-system freezing (Jouzel and Souchez, 1982).

DISCUSSION

Evaluation of existing theories for dispersed facies formation at Svínafellsjökull

Any theory for the origin of dispersed facies basal ice at Svínafellsjökull must account for the development of its key characteristics. Dispersed facies: (1) is massive (i.e. structureless), with low debris concentrations (mean 1.6% by volume), low bubble content, and crystal size intermediate between that of overlying glacier ice and underlying stratified facies; (2) is almost ubiquitous around the glacier margin and in thicknesses of metres to tens of metres; (3) contains sediment sizes ranging from clay to pebble; (4) shows no systematic decrease or increase in sediment concentration with height above the bed, although it does have a diffuse contact with overlying glacier ice; and (5) has a stable-isotope composition consistent with closed-system freezing. Overall, our results indicate that no single existing theory of dispersed facies formation can fully account for the characteristics of dispersed facies basal ice at Svínafellsjökull. We consider each existing hypothesis in turn, highlighting the reasons for these hypotheses being discounted.

The model of clotted facies formation at Russell Glacier, West Greenland, proposed by Sugden and others (1987), involving alteration of glacier ice by regelation in the interior of the ice mass (Table 1) can explain a number of features of the dispersed facies at Svínafellsjökull. For example, Svínafellsjökull is a temperate glacier that likely moves in part through basal sliding around bedrock obstacles, so the basal layer should be expected to have been affected by regelation (Cook and others, 2010). The low debris concentration, diffuse contact with glacier ice, polymodal sediment size distribution and closed freezing system isotope composition are all consistent with an origin through regelation. It is difficult, however, to explain the distribution and full suite of characteristics of dispersed facies through regelation alone. Regelation typically only produces basal ice layers on the order of millimetres to decimetres thickness (e.g. Kamb and LaChapelle, 1964; Hubbard and Sharp, 1993), whereas dispersed facies at Svínafellsjökull is typically several metres to tens of metres thick. Thus, to explain the thickness of dispersed facies through regelation requires regelation ice to have been thickened tectonically.

Tectonic thickening can happen in one of two ways. Firstly, Knight and others (1994) suggested that variation in the spatial distribution of clotted ice at Russell Glacier may represent thickening of a regelation layer by plastic flow around large bedrock obstacles close to the ice-sheet margin. Such obstacles are not evident at the margin of Svínafellsjökull. Likewise, the variability in distribution and thickness of the clotted facies at Russell Glacier is not observed for the dispersed facies at Svínafellsjökull. Secondly, tectonic thickening could occur against the adverse slope of the overdeepening. Regelation layers up to 2 m thick were observed within the stratified facies by Cook and others (2007, 2010), with some regelation layers displaying evidence of having been thickened (i.e. the presence of folds and faults). This, however, was limited to the stratified facies and to a scale that could not explain the observed thicknesses of dispersed facies, and fracture-fills that cross-cut the dispersed facies do not show evidence of deformation. It therefore seems unlikely that regelation and tectonic thickening in the terminal region of the glacier are sufficient to explain the thickness of dispersed facies at Svínafellsjökull.

Another possible formation mechanism that is closely related to the rigid-bed regelation hypothesis is the generation of clots as a result of water and sediment being squeezed away from bedrock obstacles into the intercrystalline vein network (Table 1). This leads to the accumulation of fine-grained sediments between crystal boundaries (Knight and Knight, 1994). Spedding and Evans (2002) suggested that basal ice at nearby Kvíárjökull was formed in this manner, with the additional effect of tectonic thickening as a consequence of compressive flow near the terminus.

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This hypothesis is refuted because: (1) dispersed facies debris at Svínafellsjökull includes pebbles and coarse sand, which are too coarse to be transported through the intercrystalline vein network (Fig. 3); (2) this debris is often found within crystals, rather than at triple-grain boundaries (Fig. 2); and (3) there is no systematic reduction in sediment concentration with height above the bed (Fig. 4), as would be expected if water had been squeezed upward from an underlying sediment source or debris-rich ice layer.

Hart (1995) suggested an alternative model of dispersed facies formation involving the tectonic attenuation of debris from a lowermost debris-rich basal ice or subglacial sediment layer into the overlying glacier ice (Table 1). This hypothesis is also rejected at Svínafellsjökull. Firstly, Hart (1995) suggested that debris concentration and debris aggregate size should reduce with height above the bed, which is inconsistent with the irregular changes in debris concentration with height above the bed observed at Svínafellsjökull (Fig. 4). Secondly, this model presumes that the host ice facies into which debris-rich basal ice or subglacial sediment has been entrained is meteorically derived englacial facies glacier ice, the isotope composition of which should plot along a line of similar slope to that of the LMWL. At Svínafellsjökull the samples of this ice plot along a freezing slope of lower gradient (Fig. 5; Table 2), implying a different origin.

Another tectonic mechanism has been proposed by Hubbard and others (2000) for the 'clear facies' at Tsanfleuron, Switzerland, in which meteorically derived glacier ice is metamorphosed by internal deformation close to the ice/bedrock interface (Table 1). Comparison of the characteristics of dispersed facies at Svínafellsjökull with the clear facies at Tsanfleuron indicates that this model does indeed account for many of the characteristics of the ice, including the low bubble concentrations, occasionally deformed and flattened bubbles, metre thicknesses of massive structureless basal ice, and the diffuse boundary with overlying glacier ice. However, it would be expected that this process would produce ice with an isotope composition similar to that of the LMWL, whereas dispersed facies samples from Svínafellsjökull plot instead along a closed-system freezing slope (Fig. 5; Table 2), and so this hypothesis is also rejected.

The interpretation by Koerner (1989) of basal ice in cores from Canadian Arctic islands and from Greenland as buried superimposed ice containing wind-blown sediment raises another potential mechanism: the incorporation of surficial sediment. Some englacial debris at Svínafellsjökull undoubtedly enters the glacier via crevasses, especially those formed at the icefall, some of which may penetrate to considerable depth. This is supported by the presence of laterally discontinuous bands of dispersed facies at Svínafellsjökull containing red and yellow angular tephra/rock that presumably reflect individual rockfall events from the valley sidewalls. The critical test of this mechanism is that the isotope composition of the host ice must be consistent with that of meteorically derived englacial facies glacier ice, which is not the case (Fig. 5; Table 2). Further, it is not clear how debris derived from rockfall or aeolian deposition could form such a homogeneous and discrete layer close to the glacier bed.

Finally, processes of basal adfreezing must also be considered, as these have been invoked in other studies to explain the origin of facies similar to dispersed facies. Christoffersen and others (2006) showed that freeze-on of pore-water from subglacial sediments can produce 'clean' or 'clear' facies (the authors use the terms interchangeably) beneath Antarctic ice streams. However, it is unlikely that such processes operate to produce metres to tens of metres of basal ice beneath temperate valley glaciers where environmental conditions are quite different to those beneath Antarctic ice streams. Further, since Souchez and others (2004) have predicted that the stable-isotope composition of basal ice produced by adfreezing would not show isotope fractionation, isotopic composition again provides a critical test which leads us to refute this hypothesis, specifically because samples from Svínafellsjökull plot along a freezing slope (Fig. 5; Table 2).

Though not considered to be an established mechanism of dispersed facies formation, glaciohydraulic supercooling has previously been linked to the formation of metres thicknesses of basal ice (e.g. Lawson and others, 1998; Cook and others, 2010), and it is therefore important to carefully exclude this as a potential mechanism. Firstly, features associated with supercooling (e.g. fracture-fills) always cross-cut dispersed facies or underlie dispersed facies with an unconformable contact (e.g. stratified facies), indicating that dispersed facies is formed by a separate process that operates up-glacier of the overdeepening. Secondly, the isotope composition of dispersed facies ice is different from basal ice types formed by supercooling, in that it plots along a freezing slope of lower gradient than the LMWL (Fig. 5; Table 2) (cf. Cook and others, 2010). It is of course possible that supercool ice forms a small component of the dispersed facies, especially if there are multiple overdeepenings along the glacier length, and that subsequent strain and/or regelation is sufficient to alter significantly the debris distribution and isotope composition. Nevertheless, supercooling is typically only locally significant (e.g. Spedding and Evans, 2002; Tweed and others, 2005; Cook and others, 2007, 2010), whereas dispersed facies at Svínafellsjökull is ubiquitous, making it difficult to envisage supercooling as the primary source.

A model of dispersed facies formation at Svínafellsjökull

None of the aforementioned theories of dispersed facies formation satisfactorily explains the origin of dispersed facies at Svínafellsjökull. Perhaps the most striking observation at Svínafellsjökull is that the dispersed facies is almost ubiquitous around the glacier margin and occurs in metres-thick sequences. Hence, the mechanism(s) responsible for its formation must operate pervasively across the glacier width, and up to tens of metres at the glacier base. We therefore illustrate a new model for dispersed facies formation that is partly dependent on the glacier-wide elevation of basal debris throughout the glacier thickness by processes operating at the base of the icefall (Fig. 6) (cf. Goodsell and others, 2002; Swift and others, 2006).

The processes of entrainment envisaged in this model have previously been inferred by Goodsell and others (2002) from observations of ogive formation at Bas Glacier d'Arolla, Switzerland (Fig. 6a). Notably, Goodsell and others (2002) found that folding at the base of the icefall generated areas of particularly dense foliation (i.e. dark ogive bands) that formed planes of weakness along which folding and thrusting had entrained both basal ice and debris. Swift and others (2006) later adapted this model to explain the formation of englacial debris-rich basal ice bands at

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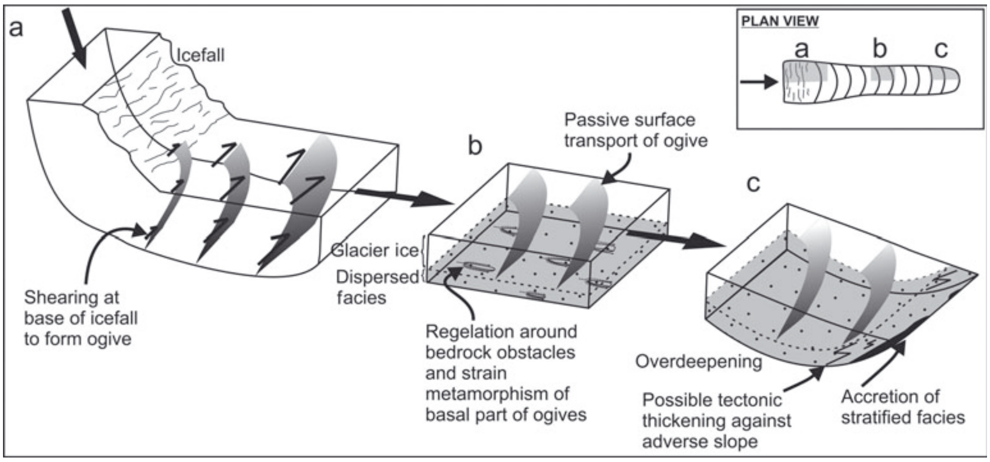

Fig. 6. Conceptual model of dispersed facies formation through entrainment of sediment at the base of an icefall followed by ice metamorphism. (a) Sediment entrainment at the base of an icefall through shearing and folding to form ogives. (b) Basal part of ogive is metamorphosed through regelation and strain to form dispersed facies basal ice. (c) Final stratigraphy at glacier terminus includes stratified facies accreted from supercooled water in the overdeepening, the possible tectonic thickening of basal ice as the glacier flows against the reverse slope of the overdeepening, and the possible effect of inefficient subglacial drainage across the overdeepening, allowing basal ice to survive in metres thicknesses.

Kvíárjökull. They argued that initial folding at the base of an icefall could be followed by shearing of the fold structures and the direct entrainment of basal ice and debris along the shear zone. This results in a series of parallel arcuate glacier-wide folds containing basal ice and debris, with central debris-rich thrust planes, that are relatively broad at the base and thin towards the surface (Swift and others, 2006, fig. 7b). The presence of ogives immediately down-glacier of the icefall implies similar mechanisms of debris elevation at Svínafellsjökull (Fig. 1c). Debris from surficial sources (tephra, wind-blown dust, rockfall from valley sides) may also be incorporated into the ice via open crevasses in the region of the icefall.

Following initial entrainment at or near the icefall, our model envisages metamorphosis and mixing of the englacially elevated basal ice and adjacent englacial ice as a result of regelation and strain experienced during the ~6 km of ice flow between the icefall and the terminus. The closed-system freezing origin, indicated by the stable-isotope composition, is consistent with the influence of regelation (e.g. Hubbard and Sharp, 1993), while occasional deformed and flattened bubbles indicate the influence of strain. Both these processes have been invoked separately to explain tens of metres of dispersed-type ice (e.g. Sugden and others, 1987; Hubbard and others, 2000). In combination they will allow the mixing and metamorphosis of ice to several metres or even tens of metres above the bed, producing the uniform massive structure of the dispersed facies and characteristic diffuse interface with the overlying glacier ice (Fig. 6b), and with the surface expression of the ogives remaining largely unchanged. Other studies too have considered dispersed facies to have been generated by high strain following initial sediment entrainment into englacial ice (e.g. Hart, 1995, 1998; Waller and others, 2000).

It is also possible that dispersed facies characteristics consistent with regelation (e.g. closed-system isotope composition) are inherited from the entrainment of regelation basal ice into thrusts and folds at the icefall. Furthermore, between the thrust planes that penetrate to the glacier surface to form ogives, there are likely to be a number of minor thrusts and folds. These will not reach the glacier surface, but may elevate basal ice and sediment to several metres or tens of metres above the glacier bed. These smaller tectonic features generated at the base of the icefall may also be important in the generation of dispersed facies, and will also experience strain and regelation with transport to the terminus.

The terminal overdeepening may also play a role in the development of dispersed facies at Svínafellsjökull (Swift and others, 2006), although the evidence for such an influence is less convincing (Fig. 6c). It is possible that glacier flow against the adverse slope of the overdeepening has caused tectonic thickening of the dispersed facies (or has done in the recent past). Notably, tectonic features such as shear planes and overturned folds (nappes) have been observed in the stratified facies (Cook and others, 2010), and seem to explain the thickening of centimetre- and decimetre-scale regelation layers to metre-scale layers. However, there is little direct evidence for the thickening of such layers on the scale of many metres. Furthermore, the dispersed facies is cross-cut by features associated with the operation of glaciohydraulic supercooling in the overdeepening (e.g. fractures filled with platy ice; Cook and others, 2007) that do not display any tectonic disturbance. This suggests that dispersed facies develop to their full extent before reaching the terminal overdeepening.

A further factor likely to favour thick dispersed facies is the possible lack of efficient subglacial drainage in the region of the overdeepening, which should allow basal ice to survive in greater thicknesses (e.g. Spedding, 2000; Spedding and Evans, 2002). The nature of the subglacial drainage system at Svínafellsjökull remains unknown, but it is likely that the presence of an inefficient subglacial drainage system is important in enabling the development of the significant thicknesses of dispersed facies at this location.

Significance of dispersed facies at Svínafellsjökull

Relatively few studies have quantified sediment fluxes from the basal ice layer, and fewer still have quantified this for individual basal ice facies. We use the steady-state sediment

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flux equation of Cook and others (2010) to quantify sediment flux for the dispersed facies. In our calculation we use a mean dispersed facies thickness of 3.5 m across the 2 km of the glacier margin, a mean sediment content of 1.6% by volume, and measured glacier terminus velocity of 14.6–29.2 m a^{-1}. This gives a sediment flux of 0.81–1.62 $m^3\,m^{-1}\,a^{-1}$. This value is lower than that calculated by Cook and others (2010) for the stratified basal ice produced by supercooling and by regelation which has sediment fluxes of 4.8–9.6 and 1.0–2.0 $m^3\,m^{-1}\,a^{-1}$ respectively. Therefore, on a local scale, dispersed facies contributes much less sediment to the proglacial environment during melt-out than does stratified facies. Knight and others (2002) measured a debris flux of 7.2 $m^3\,m^{-1}\,a^{-1}$ for the dispersed facies of Russell Glacier. This value is higher than our calculated sediment flux for dispersed facies at Svínafellsjökull largely because of the higher mean thickness (15 m) of dispersed facies measured by Knight and others (2002) at Russell Glacier.

Using the above parameters, we calculate that dispersed facies has a total sediment discharge of 1635–3270 $m^3\,a^{-1}$. Using the data in Cook and others (2010), we calculate that the total sediment discharge for supercool stratified facies is 207–414 $m^3\,a^{-1}$ and for regelation stratified facies is 42–84 $m^3\,a^{-1}$ (i.e. a total of 249–498 $m^3\,a^{-1}$ for stratified facies). Thus, despite its low sediment content, dispersed facies transports ~6.5 times as much sediment to the proglacial environment as does stratified facies, because of its consistently higher thickness and ubiquity around the glacier margin.

Tectonic processes are typically thought not to be significant for glacier and ice-sheet sediment budgets, except for surging, advancing and polythermal glaciers (e.g. Alley and others, 1997). However, our results indicate that thrusting and folding on glacier-thickness scales, generated at the base of an icefall, serve to significantly enhance sediment entrainment and transport even at temperate glaciers, in accordance with other recent work (e.g. Goodsell and others, 2002; Swift and others, 2006). The effect of tectonic processes on the development of basal ice may have been overlooked in previous studies because the basal ice visible at the glacier margin may not show much (or any) clear evidence for tectonic entrainment of sediment. Such evidence would be removed from the basal ice or overprinted by other processes (e.g. regelation, melting, refreezing, water percolation, strain metamorphism, etc.). We suggest, therefore, that tectonic entrainment of material in the deep interior of glaciers and ice sheets may be more widespread than previously envisaged, but that the influence of such processes in the development of basal ice is not observable, nor is there sufficient detail on bed topography beneath many ice masses to be able to identify areas where such processes may operate (i.e. situations similar to an icefall or overdeepening, but beneath several hundred metres or several kilometres of ice).

CONCLUSIONS

At Svínafellsjökull we have tested existing hypotheses for the origin of dispersed facies basal ice which is found almost ubiquitously around the glacier margin in thicknesses of up to ~25 m. These existing theories included regelation around bedrock obstacles with associated flow of sediment-laden water through the intercrystalline vein network, tectonic attenuation of underlying sediment or sediment-rich basal ice, strain-induced metamorphism of firnified glacier ice, basal adfreezing of subglacial water, and inputs from surface ice and sediment sources. Analysis of physical, sedimentological and stable-isotope characteristics of the dispersed facies at Svínafellsjökull reveals that none of these existing hypotheses can fully account for the origin of dispersed facies here. Instead we propose that dispersed facies forms by regelation and strain-induced metamorphism of the lowermost parts of band ogives. These ogives form at the base of a prominent icefall where compression leads to the elevation of basal sediment through the glacier thickness and across the glacier width by folding and thrusting. Minor folds and thrusts at the glacier base between ogive bands may also entrain significant amounts of sediment, and will also be subject to regelation and strain during transport to the glacier terminus. The presence of a terminal overdeepening beneath the glacier may also promote the thickening of dispersed facies by (1) allowing ice flow against a reverse bed slope, thereby enhancing tectonic thickening of the basal ice, and (2) preventing significant basal melt as a consequence of the operation of an inefficient subglacial drainage system.

Dispersed facies is calculated to have a sediment flux of 0.81–1.62 $m^3\,m^{-1}\,a^{-1}$ (dependent on glacier velocity) which is lower than that measured for the underlying debris-rich stratified facies by Cook and others (2010). However, because the dispersed facies is thick (~3.5 m on average) and almost ubiquitous around the glacier margin, it has a total sediment discharge of 1635–3270 $m^3\,a^{-1}$. This value is ~6.5 times greater than that of the stratified facies. The dispersed facies owes its origin and sediment content to tectonic entrainment of sediment at the base of an icefall. Tectonic processes of sediment entrainment have often been overlooked or considered not to significantly influence the sediment budgets of glaciers and ice sheets. Our results, however, indicate that tectonic processes significantly enhance sediment entrainment and the development of basal ice.

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