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Supercooled meltwater discharge from Skeiðarárjökull and Skaftafellsjökull and associated glacial debris entrainment

Fiona S. Tweed[1], Andrew J. Russell[2] Tim Harris[1] and Matthew Roberts[3]

[1]Geography, Staffordshire University, College Road, Stoke-on-Trent, Staffordshire, ST4 2DE, UK.
[2]School of Geography, Politics and Sociology, University of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU.
[3]Veðurstofa Íslands, Bústaðavegi 7- 9, 108 Reykjavík, Iceland.

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1. Introduction

Glaciers and ice sheets entrain large quantities of sediment and processes by which they do so continue to be debated. Knowledge of glacial sediment entrainment processes is crucial to understanding past and present sediment fluxes and the sedimentary record. Glaciohydraulic supercooling has been identified as an active sediment entrainment mechanism at glaciers in Alaska (e.g. Lawson *et al.*, 1998; Evenson *et al.*, 1999) and was subsequently documented at several temperate Icelandic glaciers (e.g. Roberts *et al.*, 2002; Tweed *et al.*, 2005; Cook *et al.*, 2007, 2010; Larson *et al.*, 2010). It has also been suggested that that rapid discharge of supercooled meltwater from the base of over-deepened ice sheet basins during the Quaternary constitutes a plausible mechanism for entraining extensive amounts of sediment in the Laurentide Ice Sheet (Alley *et al.*, 1998, 1999; Roberts *et al.*, 2002; Larson *et al.*, 2006). There has been a tendency for the process to be uncritically accepted and the controls on the spatial and temporal variability of glaciohydraulic supercooling have yet to be thoroughly investigated; even at sites that fulfil the physical requirements to enable the process to occur, researchers report inconsistency in the presence of field evidence and the supercooled signature in meltwater temperature measurements (e.g. Tweed *et al*., 2005). Over the last fifteen years there has been robust debate regarding i) the link between glaciohydraulic supercooling and the formation of thick sequences of basal ice (e.g. Cook *et al*., 2007; Larson *et al.*, 2010; Cook *et al.*, 2010, 2011), iii) the potential for silt dominance in basal ice sequences to be used as a diagnostic indicator of the process (e.g. Evenson *et al.*, 1999; Larson *et al.*, 2006; Cook *et al.*, 2011, 2012) and iii) the degree to which landform-sediment assemblages can be attributed to supercooling (e.g. Larson *et al.*, 2006; Evans, 2009). Some of these issues are considered elsewhere in this volume. Here we summarise evidence of supercooling from Skeiðarárjökull and Skaftafellsjökull during a range of hydrological conditions and present evidence of associated glacial sediment entrainment.

2. Glaciohydraulic supercooling - basic principles

Glaciohydraulic supercooling occurs when the rate of basal meltwater ascent outstrips the rate at which meltwater temperature can rise by heat convection due to latent heat of fusion as frictional ice melt occurs (Alley *et al.*, 1998). Supercooling and associated ice growth are dependent on a large enough meltwater flow rising at a suitably steep angle (> 1.2 to 2.0 times that of the ice surface slope), commonly on ascent from overdeepened glacier basins (Alley *et al.*, 1998). Frazil ice is produced during meltwater depressurisation trapping sediment as it forms. Anchor ice accretes onto the walls of conduits and forms terraces at the sites of vent upwellings (Lawson et al., 1998; Evenson *et al.*, 1999; Tweed *et al.*, 2005; Larson *et al.*, 2010). Such terraces are morphologically similar to tufa or travertine deposits (see Ford and Pedley, 1996). Frazil ice circulates in meltwater and freezes onto the glacier forming substantial accretions of debris-rich ice.

3. Skeiðarárjökull and Skaftafellsjökull

Skeiðarárjökull (~1500 km^2) is a temperate, surge-type piedmont glacier draining from the southern side of the Vatnajökull ice cap, southeast Iceland (Björnsson, 1982) (Figure 1).

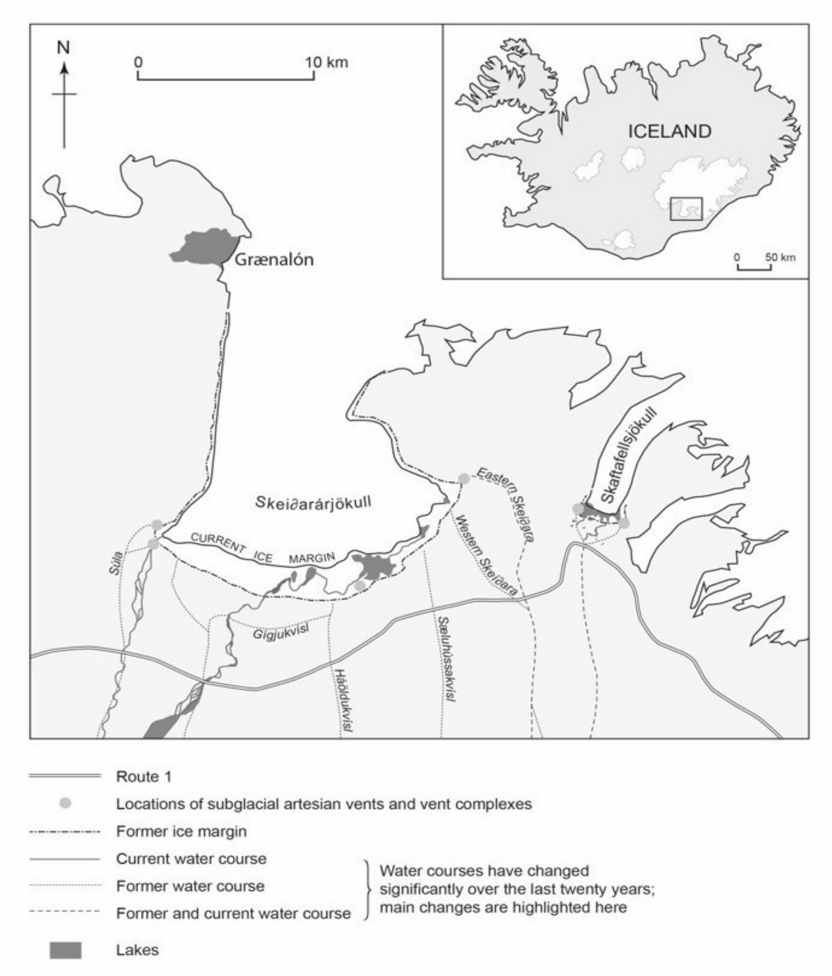

Figure 1: Skeiðarárjökull and Skaftafellsjökull, illustrating the locations of artesian vent complexes.

Temperate valley glacier Skaftafellsjökull (~100 km2) is fed by ice from Vatnajökull, with the addition of some ice from the northern flank of Öræfajökull. Skeiðarárjökull frequently releases jökulhlaups from Grímsvötn and from several ice-marginal lakes, including Grænalón (Figure 1). In common with many southern glaciers of Vatnajökull, Skeiðarárjökull and Skaftafellsjökull have been retreating into overdeepened basins since the late 1990s, forming negative ice-surface slopes close to their termini. Both glaciers now exhibit submerged snouts with proglacial lakes developing and coalescing along their frontal margins. Radio-echo sounding data confirms the existence of terminal overdeepenings at both sites (Björnsson et al., 1999, 2003). When compared to ice-surface elevation data, it is evident that termini of Skeiðarárjökull and Skaftafellsjökull fulfil the physical conditions for glaciohydraulic supercooling (Tweed et al., 2005; Larson et al., 2010).

4. Field evidence for glaciohydraulic supercooling at Skaftafellsjökull

Repeated field observations made in summer and winter from 2000-2009 confirmed that extensive terraces of frazil ice formed around turbid artesian vents where meltwater discharged under pressure at Skaftafellsjökull (see Figures 1, 2 and 3). These locations are now submerged by proglacial lakes as the glacier retreats. Artesian vent complexes were present at the eastern and western margins of Skaftafellsjökull, where meltwater discharge was vigorous in summertime. Frazil ice flocs and aggregates were frequently abundant, floating in meltwater discharged from vents. During lower flow conditions, the morphology of vents became visible (see for example, Figure 2) revealing risers of debris-rich ice over which meltwater flowed. During supercooling, progressive growth of frazil ice in vents and crevasses trapped sediment from turbid meltwater discharge, resulting in debris-rich ice accretions adjacent to vent complexes. Excavations below the water line in the proximity of vents and at crevasse upwellings revealed frazil ice accretions. Analysis of frazil ice samples recovered from artesian vent structures or from meltwater circulating in water close to vents (Figure 4) frequently yielded sediment concentrations in excess of 25% by volume, testifying to the efficacy of sediment entrainment. Field evidence for supercooling at this site is further discussed in Roberts *et al.* (2002) and Tweed *et al.* (2005).

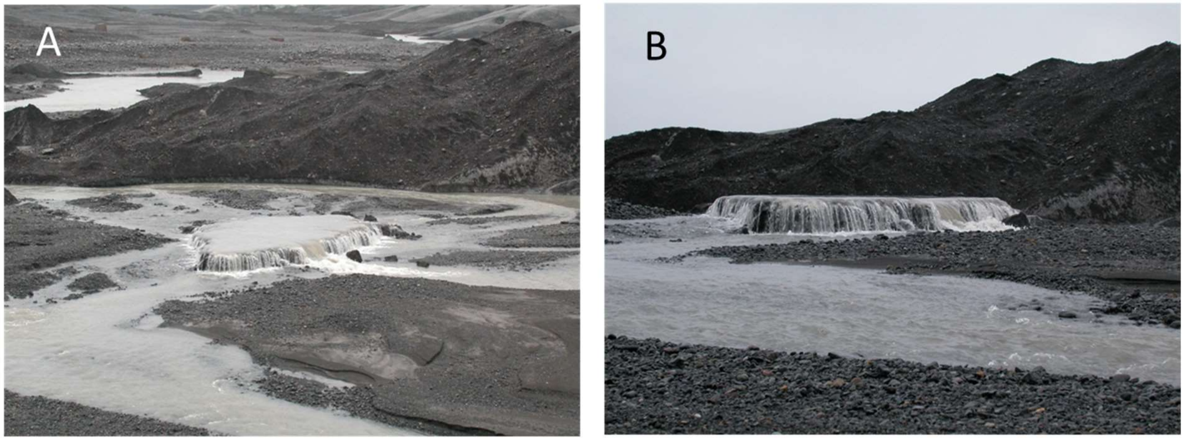

Figure 2: a) Artesian vent at the eastern margin of Skaftafellsjökull, 2003, discharging supercooled meltwater; debris-covered glacial ice in the background. b) The vent lip is composed of frazil ice incorporating sediment from turbid meltwater discharge. The form of the vent exhibits vertical walls (risers) similar to those of terraced travertine systems. c) Deploying a roped and weighted temperature probe to monitor meltwater temperature in the vent.

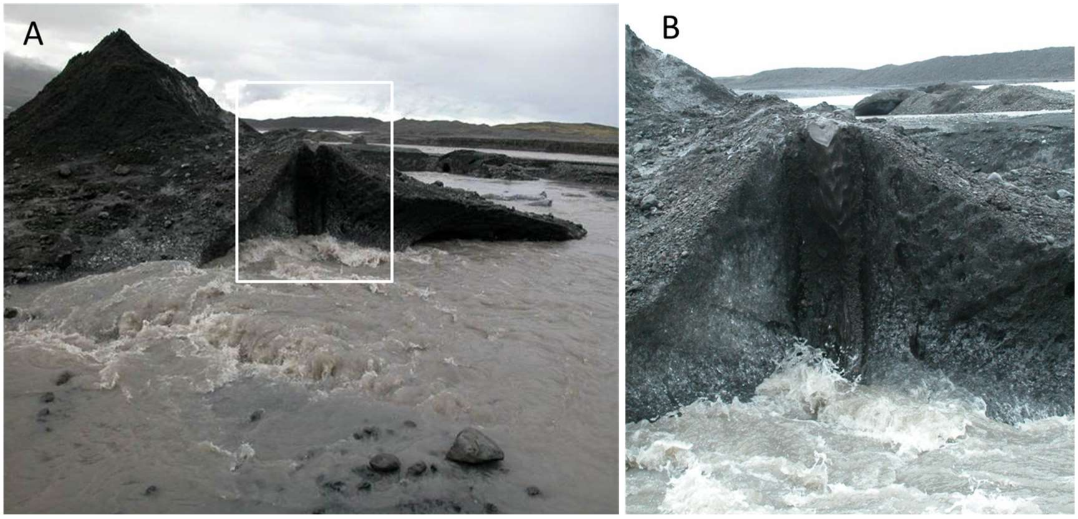

Figure 3: a) Submerged artesian vent at the western margin of Skaftafellsjökull, 2004; note debris-rich ice plugging a crevasse. b) Close up of debris-rich ice which has accreted as a consequence of supercooled meltwater discharge trapping sediment as it freezes. Note that in a) the site of upwelling has migrated to the foreground as a consequence. Images © Tim Harris.

Figure 4: Debris-rich ice samples retrieved from the mouths of artesian vents at Skaftafellsjökull. Note the fine grained nature of the ice crystals.

5. Field evidence for supercooling at Skeiðarárjökull during normal flow and jökulhlaups

Observations from successive summers at Skeiðarárjökull, especially at vents feeding the Súla and Skeiðará (see Figure 1), repeatedly identified evidence of supercooling (Tweed *et al.*, 2005). Terraces of anchor ice were present at the head of the Súla outlet 2000 and flocs of debris-laden frazil ice were observed to adhere to glacier ice. Between 2001 and 2002 the vent complex at the head of the Sula moved eastwards to the head of the Blautakvísl (Figure 1) where similar observations of field evidence of supercooling were made (Tweed *et al.*, 2005).

Glaciohydraulic supercooling has been documented during floods from Skeiðarárjökull, notably the November 1996 jökulhlaup on Skeiðarársandur (see Roberts *et al.*, 2001, 2002) and floods from Grænalón ice-dammed lake (Roberts *et al.*, 2005). The November 1996 jökulhlaup generated sufficient basal water pressure to hydraulically fracture glacier ice, producing multiple supraglacial floodwater outlets across Skeiðarárjökull at distances of up to 5km from the glacier snout (Roberts *et al.*, 2000, 2002). 'Blind' fractures that propagated from the glacier bed, but did not reach the glacier surface, were also generated. High basal water pressures and associated hydrofracture development during the 1996 jökulhlaup led to englacial sediment deposition forming 'fracture-fill' deposits within Skeiðarárjökull (Roberts *et al.*, 2001). These deposits comprised stratified sands with no evidence of post-depositional modification. Significantly, fracture fills contained consistently frozen sediment with sporadic lozenge-shaped platelets of bubble-free ice, which themselves contained silt in pore spaces (see Roberts *et al.*, 2002). Ice platelets retrieved from jökulhlaup fracture fills were crystallographically identical to frazil ice that was found in subglacial vents at Skeiðarárjökull and Skaftafellsjökull. The presence of primary bedforms associated with vertical sedimentation in near-vertical hydrofractures is consistent with glacio-hydraulic freeze-on (Roberts et al., 2001; Russell et al., 2005, 2006) (Figures 5 and 6). In addition, sintered frazil pans were observed in the ice-proximal reaches of the Skeiðará; these have been attributed to the growth of ice in supercooled floodwater (Roberts *et al.*, 2002).

The October 2004 jökulhlaup from Grímsvötn subglacial lake had a peak discharge of ~3000 m^3s^{-1} and drained through Skeiðarárjökull's overdeepening exiting its eastern margin (Einarsson et al., 2016). Observations of jökulhlaup vents in March 2005 revealed large amounts of debris-rich frazil ice accreted within the vent rims and in nearby radiating crevasses (Figure 7).

Several floods from ice-dammed lake Grænalón have occurred during which supercooling has been evident. A group of high capacity artesian vents was observed to appear along the western margin of Skeiðarárjökull in association with several Grænalón floods from 2001-2005. Roberts *et al.*, (2005) established that floodwater from Grænalón drained into Skeiðarárjökull's overdeepened basin, travelling 13.4km beneath the glacier to the snout. Negative effective pressure drove floodwater towards the margin of the glacier and it became supercooled as it ascended from the overdeepening. In July 2002, abandoned conduits plugged with debris-rich frazil ice were identified during waning stage flow from a Grænalón jökulhlaup; these were attributed to supercooled ice accretion. Figure 8 illustrates coarse-grained and fine-grained accretion of sediment associated with vent-related meltwater discharge during a jökulhlaup from Grænalón in

July 2005. Images constrain event-related sediment entrainment, as the deposits have accreted around giant slabs of ice removed by the flood.

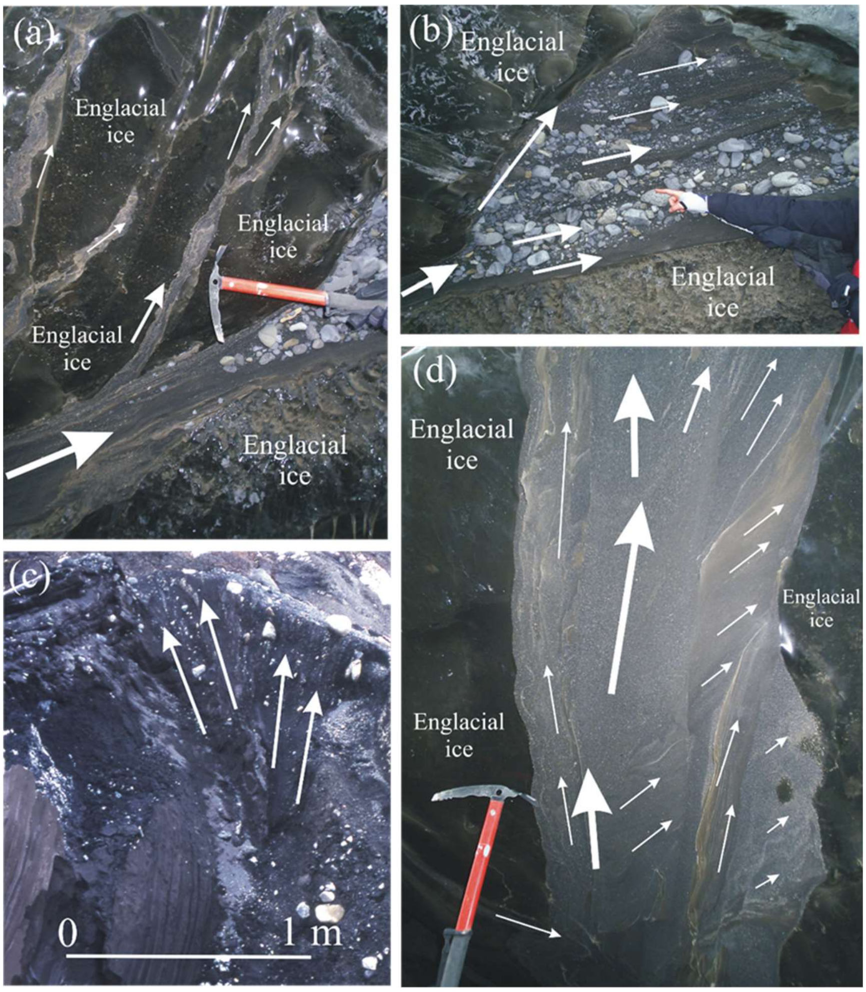

Figure 5: Englacial jökulhlaup deposits at Skeiðarárjökull, although having a low preservation potential, provide an intriguing insight into fluvial sedimentary processes within pressurised fracture networks. Englacial sedimentation is thought to be enhanced by highly supercooled meltwater that allows sediment accretion to vertical ice walls (Roberts et al., 2001, 2002). Sediment emplaced in photographs (a), (b) and (d) would have been at least 50 m below the surface of Skeiðarárjökull in November 1996. (a) Hydrofractures commonly bifurcate as they propagate upwards forming a complex network of branches. In this case meltwater has deposited progressively finer sediment within a series of branch fractures. Ice axe is 70 cm in length; (b) Sedimentation also occurs within englacial voids dissected by hydrofractures. The presence of coarse-grained sediment also indicates that hydrofracture networks had to be sufficiently dilated to allow transit through the glacier (Roberts et al., 2001); (c) Typical upward-fanning or 'mushroom' structures are seen within shallower ice near the Súla vents on the western margin of Skeiðarársandur. These beds are accreted by hydraulically supercooled and sediment charged meltwater; (d) A medium-sized fracture is packed with frozen fluvial sediment that displays a variety of sedimentary structures including: cross-stratification, planar and wavy bedding. Sedimentary structures indicate that accretion was initiated along the flanks of the fracture and that several phases of sedimentation occurred. (Figure from Russell et al., 2006 © Elsevier B.V. reproduced with permission.)

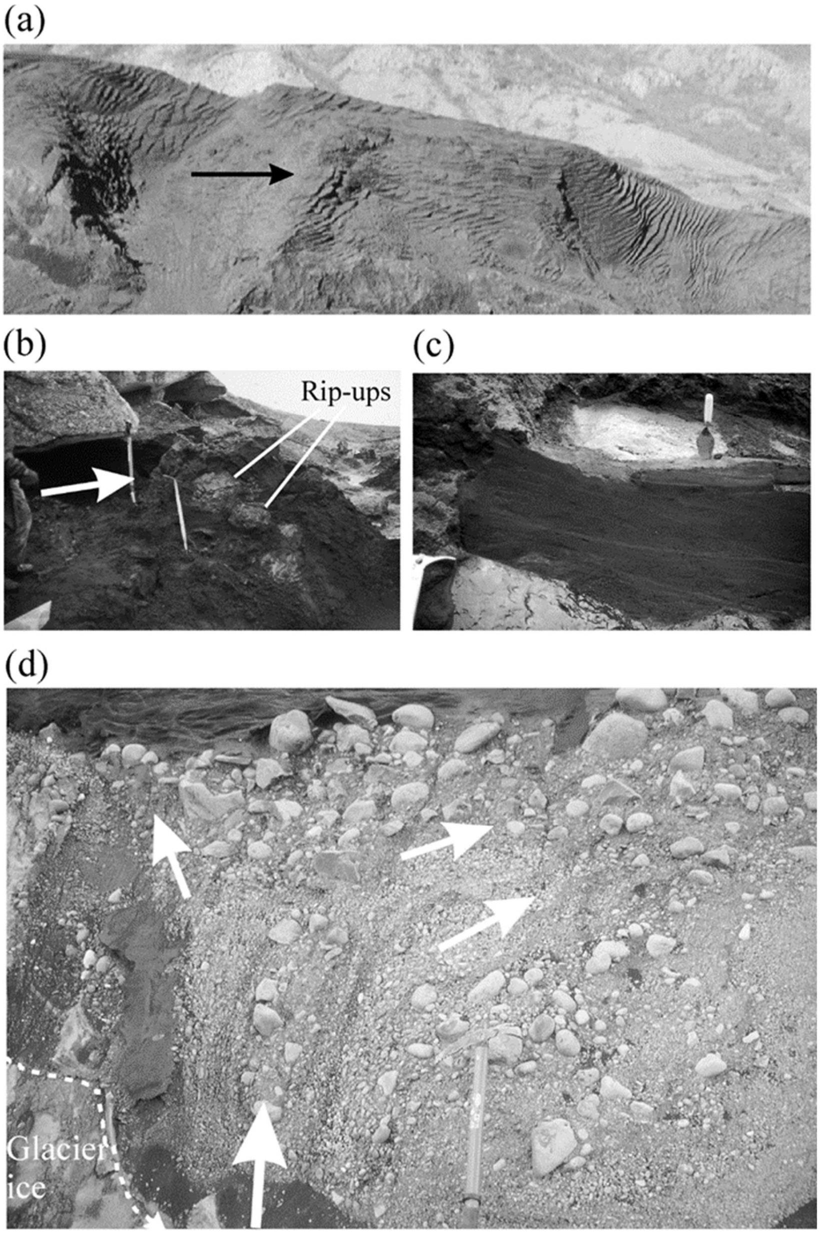

Figure 6: Englacial sedimentary structures of jökulhlaup origin: (a) 4 m thick climbing ripple sequence deposited englacially during the November 1996 jökulhlaup, Skeiðarárjökull. Deposits suggest rapid aggradation under moderate-low energy conditions; (b) Intra-clasts contained within November 1996 jökulhlaup deposits emplaced within a large jökulhlaup-generated fracture on Skeiðarárjökull; (c) November 1996 jökulhlaup fracture fill displaying crudely bedded sands and silts deposited englacially under moderate-low energy conditions; (d) High energy coarse-grained November 1996 jökulhlaup sediments, deposited within Skeiðarárjökull. Vertical bedding and upward-fanning of strata indicate deposition from a flow rising vertically. High angle of bedding may also be diagnostic of sediment accretion within supercooled meltwater. (Figure from Russell et al., 2005 © Elsevier B.V. reproduced with permission.)

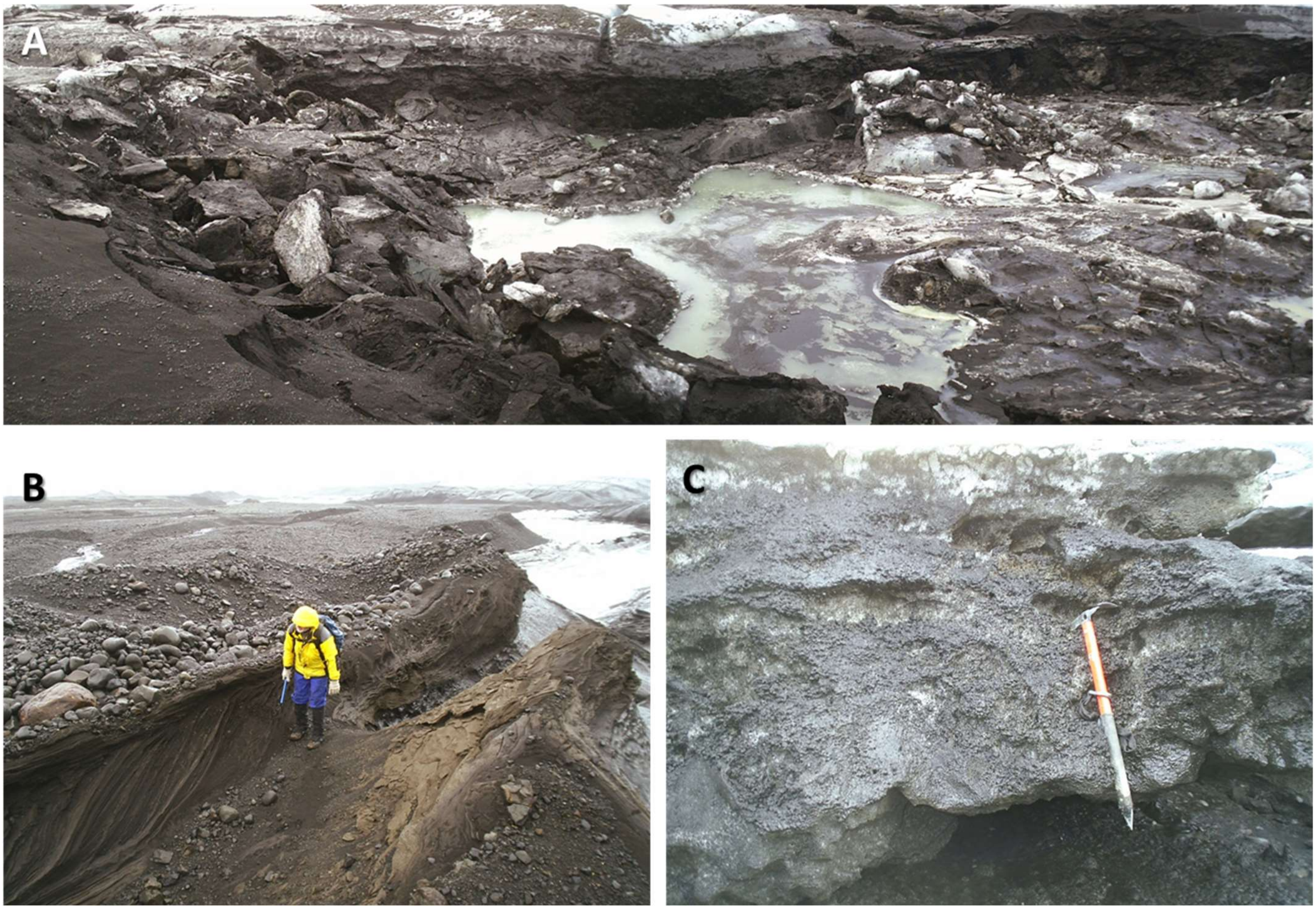

Figure 7: (a) Large (~100 m diameter) artesian vent complex on the eastern margin of Skeiðarárjökull generated by the relatively low magnitude 2004 jökulhlaup from Grímsvötn. Note large collapsed fragments of debris-rich frazil ice within the vent; (b) pervasively frozen supraglacial jökulhlaup deposits within a crevasse fill radiating from a jökulhlaup vent; (c) Debris -rich frazil ice accretion with artesian vent.

6. Temperature measurements

Temperature probes have been used to record water temperatures in turbid artesian vents at Skaftafellsjökull and Skeiðarárjökull during a range of hydrological conditions. Hydrologic monitoring of meltwater exiting vents undertaken on several occasions between July 2000 and 2004 at Skeiðarárjökull and Skaftafellsjökull demonstrated that discharge was supercooled. Temperature data are presented in Roberts *et al.*, (2002), Tweed *et al.*, (2005) and Roberts *et al.*, (2005) illustrating the measurement of sub-zero temperatures during a range of hydrological conditions, including jökulhlaups from Grænalón and a small flood from Grímsvötn in March 2002. These temperatures were recorded despite air temperatures being well above freezing on all occasions. Such meltwater temperature measurements corroborate the field evidence of the occurrence of supercooling. However, it should be noted that, despite the presence of field evidence of supercooling, not all of the vents monitored returned supercooled temperature records each time they were measured. It could be that supercooled meltwater was being diluted by other meltwater inputs, temperature probes were not sufficiently immersed to pick up the supercooling signature or that supercooling was temporally variable due to meltwater discharge fluctuations (see Tweed *et al.*, 2005; Cook *et al.*, 2010).

7. Supercooled sediment entrainment and sediment fluxes

Figure 9 provides further illustration of the field evidence for supercooled sediment entrainment close to areas where turbid meltwater discharged at Skaftafellsjökull. Sediment-filled crevasses and plugged meltwater conduits were frequently observed at the western margin of the glacier between 2000 and 2009. Observations at both Skaftafellsjökull and Skeiðarárjökull have also revealed debris-rich ice exposures of several metres in thickness close to artesian vent complexes. Such exposures exhibit no signs of structural deformation (e.g. faulting or folding); instead they are characterised by channel fills, bedforms and coarse particle clusters indicative of deposition by high-energy turbulent meltwater flows.

At Skeiðarárjökull and Skaftafellsjökull, *in situ* melting of debris-rich ice created thick, frequently laminated, melt-out till deposits that could be traced laterally into ice-marginal ridges in the proglacial zones of both glaciers (see Figure 10). Although preservation potential is an area that merits further investigation, it is evident that ice-marginal ridges and hummocky deposits are better preserved away from areas of meltwater discharge. Annual inspection of sites between 2000 and 2009 also confirmed that primary structures in the sediments can survive melt-out, although thaw-induced slumping and degradation of units was common. At least 180 x 10^6 tonnes of sediment were transported during the 1996 jökulhlaup (Jónsson *et al.*, 1998; Roberts, 2005). Given the density of hydro-fracturing and supraglacial outbursts documented at Skeiðarárjökull (Roberts *et al.*, 2001), millions of tonnes of sediment were deposited within Skeiðarárjökull in 1996. Post-flood emergence of this debris is still occurring, exerting a strong control on sediment supply to the proglacial zone. Glaciohydraulic supercooling is implicated in the development of debris-rich (basal) ice in sub- and englacial locations (see Cook *et al.*, 2010, 2011; Larson *et al.*, 2010), although the link between supercooling and the development of specific basal ice facies remains an area of ongoing research. Such sediment accretion acts as a temporary sink until the time that such debris-rich ice ablates. Continued glacial retreat is likely to expose successive units of debris-rich ice to melt-out, thus supplying glacio-fluvial and aeolian systems with sediment.

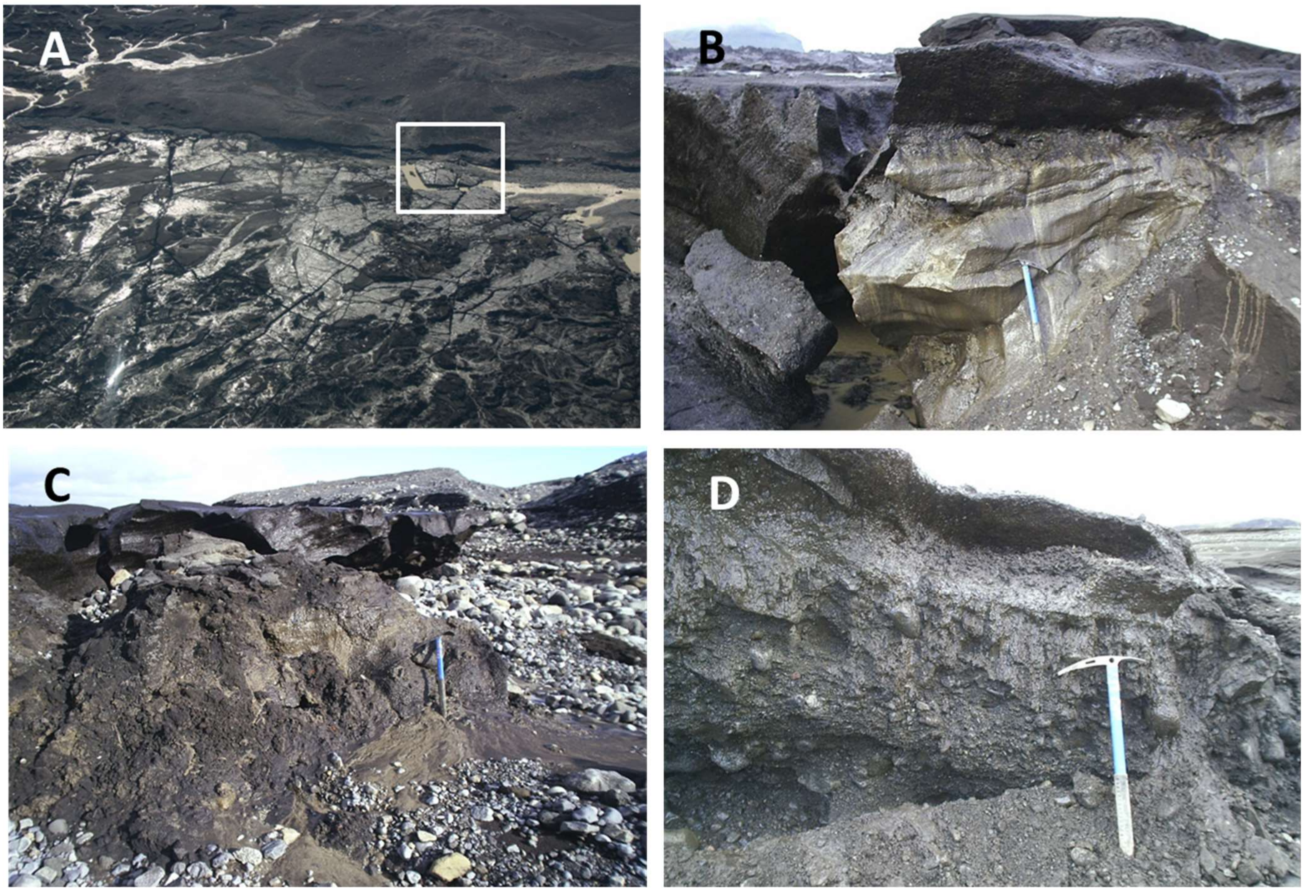

Figure 8: Supercooled sediment accretion during a flood from Grænalón ice-dammed lake. a) An aerial view of one of the main outlets of the July 2005 jökulhlaup from Grænalón (image ©Hazen Russell); note extensive ice fracturing and evidence of supraglacial floodwater discharge. Rectangle delimits the locations of images b and c. b) Accretion at the base of a large flood-transported ice slab; c) Vent-related debris-rich ice accretion and melt-out. d) Coarse-grained frozen jökulhlaup gravels accreted to the underside of a jökulhlaup displaced fragment of glacier ice. The very poorly sorted gravel unit contains silt sized sediment and displays poorly-defined imbrication, individual clasts are coated in ice armour and the deposit is ice-cemented. It is possible that the gravel component of the deposit is local to the ice margin and the englacial system supplies the finer grained material.

Figure 9: Evidence of debris-rich ice accretion from Skaftafellsjökull: a) Frazil ice accreting debris in a crevasse. b) Fine-grained debris-rich ice plugging a former glacial meltwater conduit. c) Debris-rich ice in a crevasse that formerly discharged turbid meltwater (image from Tweed et al., 2005 © Elsevier B.V. reproduced with permission). d) Debris-rich ice in a former crevasse-upwelling.

Figure 10: The melt-out of debris-rich ice. The contact between the debris-rich ice (right of each image) and remaining sediment (left of each image) is clearly defined in both cases.

8. Summary

Field evidence for supercooling at the margins of Skaftafellsjökull and Skeiðarárjökull over a range of hydrological regimes, including jökulhlaups, has been supported by the quantification of supercooled meltwater temperatures. Rapid discharge of supercooled meltwater and associated growth of frazil ice is an effective sediment entrainment mechanism, dominantly accreting suspended silts and sediment of larger calibre during floods. *In situ* melting of debris-rich ice creates thick deposits that can be traced laterally into ice-marginal ridges and hummocky terrain. Continued ablation will expose debris-rich ice and fracture fill debris to melt-out, thus supplying glacio-fluvial and aeolian systems with sediment. Supercooled sediment entrainment has the potential to exert a strong control on sediment fluxes from the margins glaciers, past, present and future, but the exact nature of its contribution remains an area to be more thoroughly investigated.

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