# Correspondence

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*Rapid sediment entrainment and englacial deposition during jökulhlaups*

Englacial water flow is a commonly invoked hypothesis to account for the presence of water-worked sediment at high elevations within glaciers (e.g. Kirkbride and Spedding, 1996; Näslund and Hassinen, 1996; Glasser and others, 1999). However, subscribers to this hypothesis lack evidence for sediment entrainment by englacial water flow. Here we present direct field evidence for supraglacial outbursts and rapid englacial fluvial sediment deposition during two recent Icelandic jökulhlaups. Both of these jökulhlaups generated basal water pressures in excess of ice overburden, which fractured overlying ice, allowing sediment to be fluvially emplaced at high elevations within each glacier. Although these jökulhlaups were hydrologically extreme, similar short-term rates of increase in basal hydraulic pressure may be generated during lower-magnitude hydrological events. The recent Icelandic jökulhlaups therefore provide us with a direct insight into rapid sediment entrainment and englacial deposition, a process that could be applied to other high-water-pressure events.

On 5 November 1996, Skeiðarárjökull, an outlet glacier of the Vatnajökull ice cap, was inundated by a jökulhlaup; within 14 hours, discharge had peaked at 45 000–53 000 $m^3 s^{-1}$ (Snorrason and others, 1997; Björnsson, 1998). On 18 July 1999, a volcanically induced jökulhlaup burst from Sólheimajökull, an outlet glacier of the Mýrdalsjökull ice cap (Russell and others, 1999; Sigurðsson, 1999). Peak jökulhlaup discharge is estimated to have been of the order of $10^3 m^3 s^{-1}$ (Russell and others, 1999); eyewitness accounts suggest a flood duration of around 6 hours (Sigurðsson, 1999). Both jökulhlaups were exceptional due to their rapid rate of discharge increase, and are not typical Icelandic jökulhlaups (see Björnsson, 1992). These events may, however, be part of a continuum of glacier response to sudden increases in intraglacial hydraulic pressure.

During the relatively short duration of flooding at Skeiðarárjökull and Sólheimajökull, multiple floodwater outlets developed. Early rising-stage discharge produced remarkable supraglacial outbursts of basal floodwater up to 3.5 km from the snout of each glacier (Figs 1 and 2). According to Björnsson (1998) and Mackintosh and others (in press), ice depth in the regions where these supraglacial outbursts developed is about 200 m. At both field sites, most of the floodwater discharged onto the ice surface through complex assemblages of up-glacier dipping fractures (Fig. 2). These fractures were rapidly sediment-filled during the jökulhlaups to produce extensive "fracture fills" encased within the glaciers. Most fracture fills contained locally structureless, massive and stratified coarse-grained sands, which were interbedded with occasionally well-rounded, cobble-sized clasts. Where stratified, bedding was concordant to fracture inclination.

Fieldwork in 1999 revealed that the entire 23 km margin

*Fig. 1. Oblique view of the surface of Skeiðarárjökull during the rising stage of the November 1996 jökulhlaup. Floodwater is bursting from a series of fractures parallel to the ice margin; uppermost fractures are 2.2 km from the snout. Photograph courtesy of Þ. E. Pétursson.*

of Skeiðarárjökull contained fracture fills. Identification of fracture fills as relating to the November 1996 jökulhlaup was made only where it was possible to visually trace fracture fills from known floodwater outlets. Fracture outlets were identified from oblique video footage taken during the flood. Field surveys revealed that fracture fills extended into zones of Skeiðarárjökull that were assumed to have been unaffected by the jökulhlaup. Such a widespread occurrence of fracture outlets was not observed on jökulhlaup aerial footage. This suggests that many fractures did not reach the surface during the flood and that fracture sedimentation was able to take place within the glacier. Work by Ensminger and others (1999) has shown that it is possible for debris-laden meltwater to be injected into "blind" basal crevasses during high water pressure. This lends credibility to the hypothesis that fracture sedimentation at Skeiðarárjökull was able to occur without a hydraulic link to the glacier surface. This mechanism of englacial sedimentation would account for the ubiquitous presence of fracture-fill deposits at Skeiðarárjökull in 1999, indicating that ice fracturing was extremely pervasive during the November 1996 jökulhlaup.

Given that supraglacial outlets developed in over 200 m of ice at both field sites, it is unlikely that any large-scale fracture or hydraulic feature extended through the entirety of both ice masses. We therefore need to identify a process capable of rapidly transporting large volumes of subglacial floodwater to the surface of glaciers. A sudden influx of water to the glacier bed can generate basal hydraulic pressures greater than ice overburden pressure. This process is commonly observed during surging (Iken and others, 1983), spring events (Skidmore and Sharp, 1999), intense rainfall (Barrett and Collins, 1997) and jökulhlaups (Warburton and Fenn, 1994). If the rate of increase in hydraulic pressure is exponential, it is possible to generate massive short-term deficits between overburden and hydraulic pressure (Bindschadler, 1983), creating ideal conditions for fracturing by hydraulic action. The prerequisite for hydraulic fracturing is sustained water pressure in excess of ice overburden pressure and a component of the confining tensile strength of ice (Mandl and Harkness, 1987). To achieve this threshold, water must be supplied to intraglacial drainage at a rate faster than

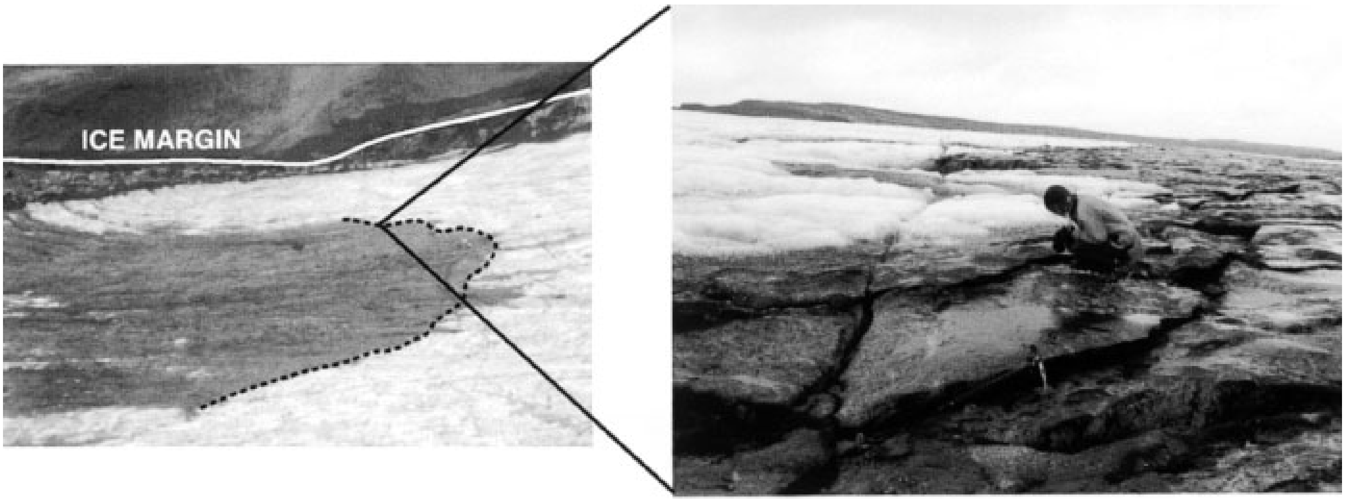


*Fig. 2. Oblique view of a supraglacial fracture outlet formed during the July 1999 jökulhlaup at Sólheimajökull; the outlet is 3 km from the snout and 0.5 km from the lateral margin. Note down-glacier surface staining. Dashed line indicates the uppermost fracture outlet, which is about 250 m long. Inset shows a profile view of an up-glacier dipping fracture complex. Note person for scale.*

it can escape (Röthlisberger and Lang, 1987). Given a rapid increase in basal water pressure, the threshold for hydraulic fracturing can easily be achieved (see Warburton and Fenn, 1994). Therefore, the key determinant for hydraulic fracturing is the rate of increase in intraglacial water pressure, and not the overall magnitude of flooding. This means that hydraulic fracturing is not confined to high-magnitude jökulhlaups, and has the potential to occur during any event involving a sudden increase in basal water pressure.

New field evidence presented here may also help to clarify the debate between Näslund and Hassinen (1996) and Krüger and Aber (1999), who have discussed processes of sediment supply and deposition at high elevations on the surface of Kötlujökull, an outlet glacier of the Mýrdalsjökull ice cap, Iceland. Their debate focuses on a concentration of supraglacial debris which originally appeared high on Kötlujökull. Both sets of authors agree that this supraglacial deposit is glaciofluvial; the difficulty lies in how the material reached the surface. Näslund and Hassinen (1996, p. 192) suggested that the debated glaciofluvial material travelled rapidly to the surface of Kötlujökull by water flow in englacial conduits at high elevations, possibly during a jökulhlaup. Krüger and Aber (1999, p. 402) stated that the specific glaciofluvial sediment discussed by Näslund and Hassinen (1996) actively reaches the surface of Kötlujökull along debris bands and thrust planes, and not by water flow in modern high-level englacial conduits. Krüger and Aber (1999) acknowledge that the original englacial debris load of Kötlujökull may have been emplaced by a jökulhlaup produced by the 1918 Katla eruption. However, they believe that subsequent transport of the debated sediment has been within debris bands and thrust planes.

Since neither set of authors was able to demonstrate exactly how the debated debris reached the surface of Kötlujökull, it is wise to consider hydraulic fracturing as a mechanism for rapidly entraining sediment. This process would mimic the morphology and sedimentology of the debris-laden thrust planes described by Krüger and Aber (1999). According to Näslund and Hassinen (1996), the original sediment accumulation appeared high on Kötlujökull, at an ice depth of about 150 m. Given that Kötlujökull is entirely temperate and has a relatively flat bed (Näslund and Hassinen, 1996), it is unlikely that thrusting elevated the debated glaciofluvial sediment.

The debris-rich nature of 1918 jökulhlaup floodwaters (Jóhannsson, 1919; Jónsson, 1983; Tómasson, 1996) means that englacial deposits are most likely to have been preserved in discrete bands, similar to fracture fills at Skeiðarárjökull. Näslund and Hassinen (1996) state that the sediment accumulation originated at least 2.5 km from the snout of Kötlujökull. When compared to figure 1 of Tómasson (1996), it is clear that this sediment accumulation was above one of the intraglacial route ways for 1918 jökulhlaup floodwater, as suggested by Krüger and Aber (1999). This area may have been exposed to ice fracturing and mass sediment entrainment during the onset of the jökulhlaup. Given that 1918 floodwater burst through the surface of Kötlujökull 12 km from the snout (Tómasson, 1996, fig. 1), it is likely that 1918 flood sediments are still preserved within fracture fills that once connected with the bed of Kötlujökull. The outcropping glaciofluvial sediment, although morphologically similar to thrust planes, may have been directly emplaced during the 1918 jökulhlaup. The morphology of the sediment accumulations may therefore have resulted from the ablation of relict fracture fills, which means that the debated sediment may still be directly attributable to water flow at high elevations. However, we do not dismiss the possibility of debris transfer along thrust planes, as advocated by Krüger and Aber (1999). Instead, we have suggested an alternative process that could apply to Kötlujökull.

In summary, field observations from Skeiðarárjökull and Sólheimajökull confirm that jökulhlaups with a rapid rate of discharge increase can inject floodwater and sediment to high elevations within glaciers. We suggest that direct high-level fluvial emplacement of englacial debris be considered as an entrainment hypothesis for Kötlujökull and other glaciers subject to sudden jökulhlaups or abrupt rises in basal water pressure.

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