Controls on the development of supraglacial floodwater outlets during jökulhlaups

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Abstract Recent field observations have revealed that jökulhlaups with a near-instantaneous rise to peak discharge can generate temporary hydraulic pressures capable of forcing floodwater through the surface of glaciers. This paper identifies and explains the controls on the development of supraglacial jökulhlaup outlets. Field evidence is presented from two recent Icelandic jökulhlaups, which produced multiple supraglacial outbursts. Subglacial hydraulic pressure increase is identified as the principal control on supraglacial outlet development during jökulhlaups. A near-instantaneous rise to peak subglacial water pressure can produce supraglacial outbursts by hydrofracturing. Pressure increases below the hydrofracturing threshold, but above ice overburden pressure, can back-feed pre-existing drainage, resulting in outbursts from moulins and crevasses. Hydrofracture outbursts can route water to areas of the glacier not normally inundated by floods, and can control the spatial distribution of ice block release.

Key words jökulhlaup; subglacial hydrology; flood routing; hydrofracturing; supraglacial; Iceland

BACKGROUND, RATIONALE AND AIMS

Previous studies of glacial outburst floods (jökulhlaups) assume that floodwater is transported through glaciers in isolated conduits, to emerge from pre-existing ice-marginal outlets (e.g. Nye, 1976). Although most jökulhlaups conform to this theory, recent field observations from Iceland demonstrate that jökulhlaups with exceptionally rapid rates of rising stage discharge increase, can produce supraglacial outlets at high ice surface elevations. As the shape of the jökulhlaup hydrograph is largely determined

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by the reaction of intraglacial drainage to rapid influxes of floodwater (Björnsson, 1992, 1998; Tweed & Russell, 1999), it is important to gain a greater understanding of the controls on supraglacial outlet development. This paper aims to identify and explain the controls on the development of supraglacial jökulhlaup outlets.

FIELD SITES AND METHODS

Fieldwork was conducted at Skeiðarárjökull and Sólheimajökull, Iceland, temperate outlet glaciers draining from the Vatnajökull and Myrdalsjökull ice caps, respectively (Fig. 1). Both glaciers were recently inundated by jökulhlaups that generated supraglacial outbursts. On 5 November 1996, a jökulhlaup burst from Skeiðarárjökull, having drained from the Grimsvötn subglacial caldera. Within 14 h, discharge had peaked at 45 000–53 000 m$^3$s$^{-1}$ (Snorrason et al., 1997; Björnsson, 1998). On 18 July 1999, a volcanically induced jökulhlaup drained from Sólheimajökull. Peak discharge is estimated at $10^3$ m$^3$s$^{-1}$, with a flood duration of around 6 h (Sigurðsson, 1999).

Fieldwork was conducted annually at Skeiðarárjökull Glacier between 1996 and 2000 and at Sólheimajökull Glacier in 1999. Aerial video footage and photographs were taken before, during and immediately after the Skeiðarárjökull Glacier jökulhlaup, and directly after the Sólheimajökull Glacier jökulhlaup. These media allowed the reconstruction of spatial and temporal changes in supraglacial outlets. Post-flood surveys were conducted at both field sites.

SUPRAGLACIAL OUTLET DEVELOPMENT AT SKEIÐÁRÁRJÖKULL

At c. 07:10 h on 5 November 1996, a flood wave burst from the Skeiðará outlet, located to the extreme east of the snout (Fig. 1). At c. 07:20 h, two 760-m-long fracture outlets burst through c. 350 m of ice, 3 km up-glacier from the Skeiðará outlet
(Roberts et al., 2000b). Both fractures were orientated roughly parallel to the snout, and rapidly discharged floodwater across Skeiðarárjökull. Similar fracture outlets developed progressively across the snout. By 16:30 h on 5 November, ice-marginal and supraglacial outlets occupied a 2-km-wide belt of the 23-km-wide snout. Flow duration from the majority of supraglacial outlets was on a time scale of minutes to hours. At c. 17:00 h on 5 November, after most supraglacial outbursts had ceased, floodwater was observed pouring from two isolated supraglacial fractures, 0.8 km from the ice margin (Fig. 2(a)). On the following day, c. 17 h later, a large supraglacial ice-walled canyon had been incised into the glacier (Roberts et al., 2000b) (Fig. 2(b)). The headwalls of the canyon were defined by the former position of the two isolated fracture outlets observed on the previous day. Russell et al. (1999) estimate that over $5.7 \times 10^6$ m$^3$ of ice were removed from the supraglacial canyon during its formation.

Former sites of supraglacial outflow at Skeiðarárjökull were characterized by incised chambers, eroded into the ice surface by hydraulic removal of fragmented ice during the jökulhlaup. Supraglacial outlets contained complex networks of up-glacier dipping debris-laden fractures (Fig. 3(a)), interpreted as jökulhlaup fracture fills by Roberts et al. (2000a,b). Fracture fills were characterized by a main arterial fracture that radiated out of the glacier and fed an assemblage of densely packed fractures, located immediately down-glacier (Fig. 3(a)).

**SUPRAGLACIAL OUTLET DEVELOPMENT AT SÓLHEIMAJÖKULL**

During the short duration of flooding at Sólheimajökull, water discharged from moulins, crevasses, and multiple supraglacial fractures. The most prominent fracture outlet was located over 3 km up-glacier from the snout, where ice depth exceeds 200 m. The fracture outlet had a semi-elliptical plan form, c. 250 m long (Roberts et al., 2000b). An immediate post-flood survey of this outlet uncovered a dense network of reverse-dendritic fractures that dipped gently up-glacier. At Sólheimajökull, ice blocks had been removed from outlets by water flow along networks of fractures that dipped up-glacier at shallow angles; this contrasts with the hydraulic excavation of fracture outlets at Skeiðarárjökull. Such an oblique intersection with the ice surface allowed floodwater to undermine overlying ice, producing ice blocks by localized collapse (Fig. 3(b)).
Fig. 3 Controls on the development of supraglacial jökulhlaup outlets. Insets illustrate schematic profile views of fracture outlet development. The hydrofracture threshold has been exceeded in both insets; however, subglacial water pressure is much greater in A than B.
DISCUSSION

The recent Icelandic jökulhlaups produced supraglacial outbursts through ice thicknesses in excess of 200 m. Although supraglacial outbursts are atypical of previously reported jökulhlaups (e.g. Björnsson, 1992), they may represent extreme responses to sudden increases in glaciohydraulic pressure during flooding (Roberts et al., 2000a). Given the extremely short rising stage of both floods, and the morphology of the outlets, it is unlikely that floodwater reached the surface of the glaciers by englacial conduit migration. Video footage from Skeiðarárjökull testifies to the rapidity of fracture outlet formation in the region of the Skeiðará outlet, suggesting that floodwater was forced to the ice surface within 20 min of ice-marginal outflow. We therefore need to explain how supraglacial fracture outlets developed in deep sections of ice. Roberts et al. (2000b) identified hydrofracturing as a mechanism for elevating water swiftly to the surface of glaciers during rapid increases in jökulhlaup discharge. However, this process will only operate when water pressure exceeds both ice overburden pressure and a component of the tensile strength of ice (Mandl & Harkness, 1987). The identification of different degrees to which water pressure exceeds ice overburden pressure permits differentiation between supraglacial outlet types.

Fracture outlets at Skeiðarárjökull were markedly different from outlets at Sólheimajökull due to the presence of distinctive ice chambers, indicative of hydraulic fracturing and ice block removal by floodwater. In contrast, fracture outlets at Sólheimajökull did not display deeply erosive ice chambers, suggesting that although hydraulic pressure had reached the threshold for hydrofracturing, water pressure was not high enough to force networks of fractures to migrate from the main arterial fracture. This indicates that once water pressure has exceeded the threshold for hydrofracturing, the principal control on subsequent fracture outlet development is the excess of glaciohydraulic pressure over the hydrofracture threshold (Fig. 3). Hydraulic pressure in excess of the hydrofracture threshold will produce incised ice chambers, as displayed at Skeiðarárjökull (Fig. 3(a)). Water pressures slightly above the hydrofracture threshold will produce outlets similar to those observed at Sólheimajökull (Fig. 3(b)). When glaciohydraulic pressure exceeds the weight of a water column extending from the bed to the ice surface, but fails to reach the hydrofracture threshold, water can be back-fed through pre-existing drainage, as illustrated at Sólheimajökull (Fig. 3).

CONCLUSIONS AND WIDER IMPLICATIONS

Recent outburst floods from Skeiðarárjökull and Sólheimajökull demonstrate that a near-instantaneous rise to peak discharge can force floodwater through the surface of glaciers. Subglacial water pressures slightly above the weight of a water column rising through the glacier will back-feed pre-existing englacial drainage. Glaciohydraulic pressure in excess of ice overburden and a component of the tensile strength of ice create ideal conditions for supraglacial outbursts by hydrofracturing. Future studies need to recognize that supraglacial outbursts can:
(a) route floodwater to areas of the glacier and ice margin not normally inundated by floods; and
(b) control the spatial distribution of ice block release, which in turn has major implications for proglacial flood impact.

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