Tunnel channel formation during the November 1996 jökulhlaup, Skeiðarárjökull, Iceland

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ABSTRACT. Despite the ubiquity of tunnel channels and valleys within formerly glaciated areas, their origin remains enigmatic. Few modern analogues exist for event-related subglacial erosion. This paper presents evidence of subglacial meltwater erosion and tunnel channel formation during the November 1996 jökulhlaup, Skeiðarárjökull, Iceland. The jökulhlaup reached a peak discharge of 45 000 to 50 000 $m^3 s^{-1}$, with flood outbursts emanating from multiple outlets across the entire 23 km wide glacier snout. Subsequent retreat of the southeast margin of Skeiðarárjökull has revealed a tunnel channel excavated into the surrounding moraine sediment and ascending 11.5 m over a distance of 160 m from a larger trough to join the apex of an ice-contact fan formed in November 1996. The tunnel channel formed via hydro-mechanical erosion of 14 000 m^3 to 24 000 m^3 of unconsolidated glacier substrate, evidenced by copious rip-up clasts within the ice-contact fan. Flow reconstruction provides peak discharge estimates of $680 \pm 140\,m^3 s^{-1}$. The tunnel channel orientation, oblique to local ice flow direction and within a col, suggests that local jökulhlaup routing was controlled by (a) subglacial topography and (b) the presence of a nearby proglacial lake. We describe the first modern example of tunnel channel formation and illustrate the importance of pressurized subglacial jökulhlaup flow for tunnel channel formation.

INTRODUCTION

Tunnel valleys and tunnel channels are common within the Quaternary landform and sedimentary record of North American and European ice sheet margins (e.g. Wright, 1973; Ehlers and Linke, 1989; Brennand and Shaw, 1994; Clayton and others, 1999; Jørgensen and Sandersen, 2006). Tunnel valley networks and sedimentary fills have been identified within Late Ordovician and Late Paleozoic successions (Ghienne and Deynoux, 1998; Eyles and de Broekert, 2001). Tunnel valleys are elongate depressions cut into unconsolidated sediment or bedrock, with typical lengths of 1–100 km, widths of up to 4 km and depths of up to 400 m. Tunnel valleys can either be infilled with sediment or remain unfilled, forming an unfilled channel (O'Cofaigh, 1996; Russell and others, 2003; Jørgensen and Sandersen, 2006; Hooke and Jennings, 2006). Although tunnel valleys are known to have a subglacial genesis, numerous mechanisms have been proposed to explain their origin. Boulton and Hindmarsh (1987) proposed that deforming subglacial sediment would flow towards low-pressure zones around conduits, allowing progressive evacuation of subglacial sediment and tunnel valley generation. Piotrowski (1997) argued that, for glacially-charged aquifers, groundwater flux alone was incapable of instantaneously discharging large meltwater volumes and suggested instead that excess meltwater accumulation at the glacier bed resulted in periodic jökulhlaups, which excavate subglacial sediments to produce tunnel valleys. While large-scale sedimentary structures within some tunnel valley sediment fills indicate time-transgressive formation (Praeg, 2003), fluvial excavation remains one of the most frequently proposed hypotheses to explain the origin and characteristics of tunnel valley systems (e.g. Wingfield, 1989, 1990; Ghienne and Deynoux, 1998; Huuse and Lykke-Andersen, 2000; Jørgensen and Sandersen, 2006; Hooke and Jennings, 2006). Tunnel valleys may be modified by numerous processes acting over considerable time spans. Björnsson (1996) for example has highlighted the role of meltwater in excavating a 300 m deep subglacial trough at Breiðamerkurjökull, Iceland, since the Little Ice Age glacier advance. Tunnel channels, by contrast, are thought to be created by bank-full flow conditions (Brennand and Shaw, 1994; Clayton and others, 1999; Beaney, 2002; Cutler and others, 2002; Sjogren and others, 2002; Smith, 2004; Fisher and others, 2005). Tunnel channel systems are commonly tens of kilometres in length orientated towards former ice margins directly into proglacial outwash deposits (Clayton and others, 1999; Cutler and others, 2002; Kozlowski and others, 2005). Many tunnel channels ascend adverse bed topography suggesting that subglacial flow within the channels was pressurized and flowing down a hydraulic gradient controlled by ice-surface elevation (Clayton and others, 1999; Johnson, 1999; Cutler and others, 2002; Hooke and Jennings, 2006; Jørgensen and Sandersen, 2006). In the literature there is considerable debate as to the magnitude and frequency of tunnel channel forming flows. Hypotheses include a sudden or catastrophic origin during glacier outburst floods, or more steady-state conditions associated with progressive headward sapping by deformable bed sediment or seasonal meltwater flows (e.g. Mooers, 1989; Wright, 1973; Hooke and Jennings, 2006). Recent research along the Laurentide Ice Sheet margin suggests periodic glacier outbursts associated with meltwater storage and release behind zones of frozen glacier bed (Clayton and others, 1999; Cutler and others, 2002; Hooke and Jennings, 2006).

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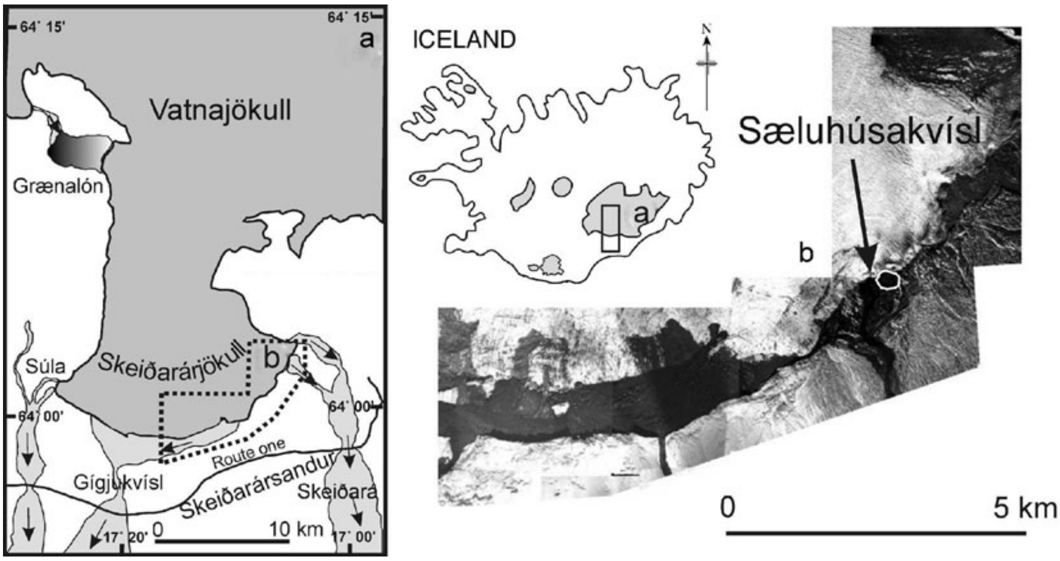

Fig. 1. (a) Location of Skeiðarárjökull and Skeiðarársandur within Iceland and in relation to Vatnajökull ice cap. (b) Aerial photograph of waning stage jökulhlaup flows within the Gígjukvísl channel system at 12:00 on 6 November 1996. The location of Sæluhúsakvísl outlet and Sæluhúsavatn lake basin are indicated.

Despite the relative abundance of literature concerning Quaternary tunnel channel genesis, there are no examples of tunnel-channel formation within contemporary glacial systems. This gap has commonly been attributed to a lack of appropriate modern conditions for tunnel channel genesis or the inaccessibility of the subglacial environment (Jørgensen and Sandersen, 2006). This paper addresses this lacuna and presents the first modern example of tunnel channel formation during a glacier outburst flood or 'jökulhlaup' under well-constrained event magnitude, duration and impact.

Aims

The aims of this paper are: (1) to present new evidence of subglacial meltwater erosion and tunnel channel formation during the November 1996 jökulhlaup, Skeiðarárjökull, Iceland; and (2) from this evidence, determine the controls on tunnel channel routing and morphology.

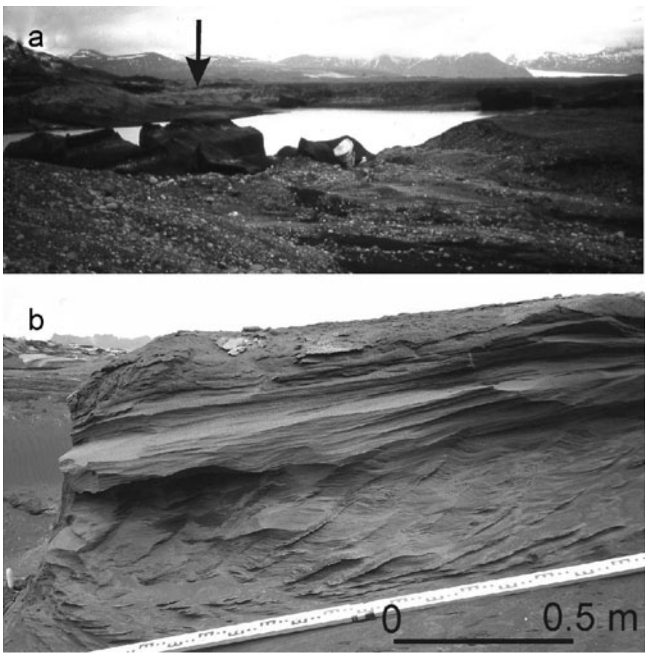

Fig. 2. (a) View of the upper Sæluhúsavatn basin in April 1997. Perched delta on the far side of the lake basin and stranded ice blocks indicate higher lake levels prevailed during the jökulhlaup. (b) Climbing ripple sequence exposed within the upper Sæluhúsavatn, approximately 50 m from the position of the 1996 ice margin. Climbing ripples indicate very high sedimentation rates and a flow direction directly away from the glacier margin.

NOVEMBER 1996 JÖKULHLAUP

A volcanic eruption beneath the Vatnajökull ice cap began on 30 September 1996 (Guðmundsson and others, 1997). Over the following month, 3.8 km^3 of meltwater travelled subglacially into the Grímsvötn subglacial lake until it reached a critical level for drainage (Björnsson, 2002). The resulting jökulhlaup began in Skeiðará, the most easterly river draining Skeiðarárjökull (Fig. 1), on the morning of 5 November, and reached a peak discharge of 45–53 $\times$ 10^3 m^3 s^{-1} within 14 hours (Björnsson, 2002; Snorrason and others, 1997, 2002). After its release from Grímsvötn, the jökulhlaup propagated as a high-pressure subglacial flood wave taking 10.5 hours to reach the glacier snout (Roberts and others, 2000; Jóhannesson, 2002; Roberts, 2005; Flowers and others, 2004). Floodwater burst from numerous outlets across the entire 23 km wide ice margin (Russell and Knudsen, 1999; Roberts and others, 2000) (Fig. 1). As the jökulhlaup progressed, discharge from the glacier became progressively focussed on major conduit outlets (Roberts and others, 2000; Roberts, 2005; Flowers and others, 2004). Notably, to exit the glacier, floodwaters had to ascend about 300 m to the sandur surface (Björnsson, 1998; Roberts and others, 2002).

Evidence for large-scale erosion of glacier substrate during the November 1996 jökulhlaup takes the form of copious numbers of intraclasts or rip-ups found in en- and proglacial jökulhlaup deposits (Russell and Knudsen, 1999; Roberts and others, 2001; Waller and others, 2001; Russell

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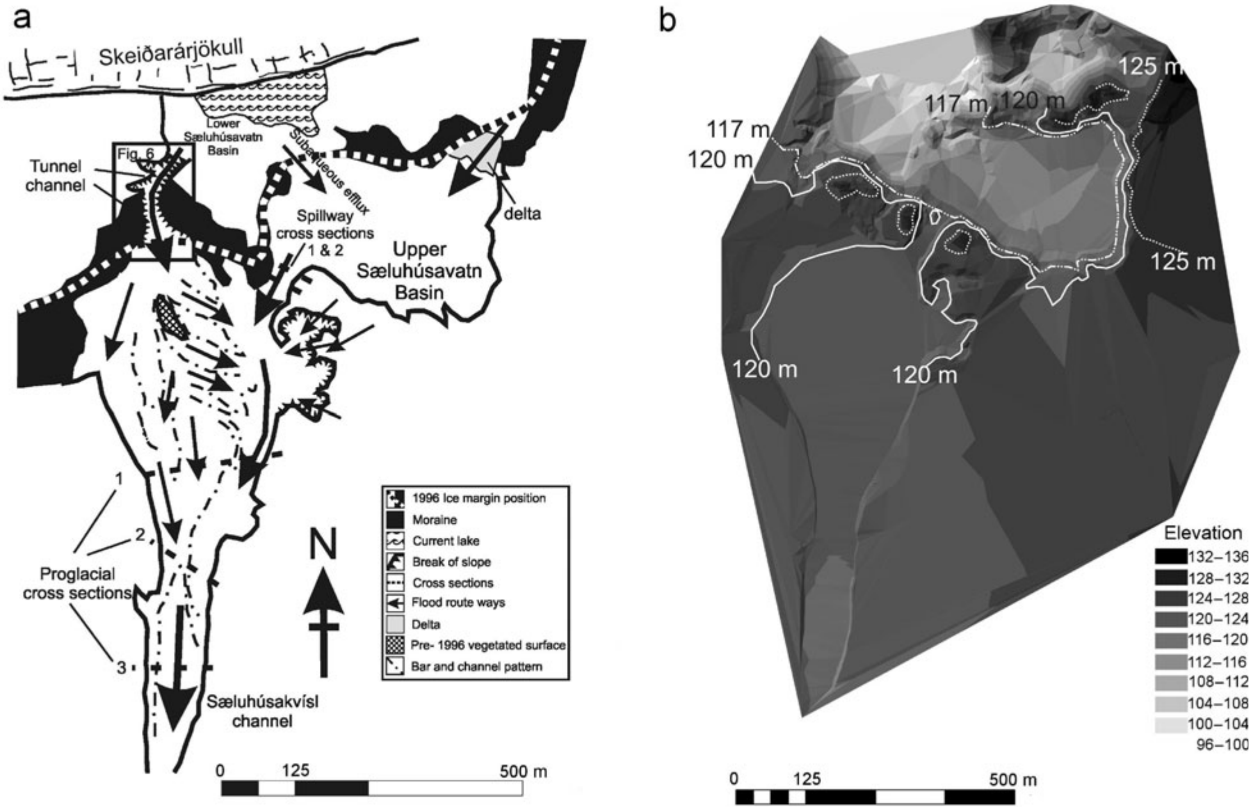

Fig. 3. (a) Map of the field area, indicating the location of channel and spillway cross-sections used to reconstruct 1996 jökulhlaup discharge for this system. (b) Elevation model for the field area derived from over 2000 DGPS survey points.

and others, 2006). The event-based erosion is also seen in published sediment budget calculations for the proglacial area (Roberts, 2005; Russell and others, 2006). As Grímsvötn subglacial lake acted as a sediment trap for coarse-grained eruption products, the entire solid sediment load of the jökulhlaup downstream of Grímsvötn was solely derived from fluvial erosion of older volcaniclastic, glacial and glaciofluvial sediments (Stefánsdóttir and others, 1999). The estimated total sediment flux during the 1996 jökulhlaup of $1.8 \times 10^8\,m^3$ suggests tunnel channel excavation may have occurred (Roberts, 2005). Although it is known that subglacial erosion took place during the November 1996 jökulhlaup, no knowledge exists of the spatial distribution and geomorphological expression of erosion. It is notable, however, that between 1996 and 2006, the snout of Skeiðarárjökull thinned by about 100 m and retreated by up to 1 km. In particular, ice margin retreat near the Sæluhúsavatn proglacial lake has progressively revealed a subglacial feeder channel to Sæluhúsakvísl, one of the November 1996 jökulhlaup outlets (Figs 1 and 2).

METHODS

Fieldwork was undertaken in the Sæluhúsakvísl area of Skeiðarársandur in April 1997, March 2004, July 2005 and April 2006 (Fig. 1). The site was surveyed using Differential Global Positioning System (DGPS) allowing construction of a terrain model of the field area (2331 points) and the mapping of flood wash limits and flood channel morphology (165 points). Within-channel surface grain sizes and bedforms were noted at regular intervals to allow characterization of grain and form roughness. Channel cross-sectional areas, water surface slopes and roughness were used to reconstruct peak jökulhlaup discharge within the Sæluhúsakvísl tunnel channel and Sæluhúsavatn proglacial lake outflow channels.

SÆLUHÚSAVATN PROGLACIAL LAKE BASIN

The Sæluhúsavatn upper basin was full of water prior to and immediately following the November 1996 jökulhlaup (Figs 2a, 3 and 4). Stranded ice blocks and silt deposits observed in April 1997 indicated that lake levels rose by several metres during the jökulhlaup (Figs 2a and 3b). A coarse-grained boulder delta deposited on the eastern margin of the lake indicates subaerial jökulhlaup influx to the basin (Figs 2a and 3). Sedimentary infill of the upper Sæluhúsavatn basin includes a 1–2 m thick unit of sandy climbing ripples capped by laminated silt (Fig. 2b). Palaeocurrent direction is directly away from the former glacier margin (Figs 2b and 4a). Other sedimentary facies include massive sand units containing out-sized cobbles and intraclasts composed of laminated silts. Located within 50 m of the 1996 glacier margin, all of these facies are the product of high sedimentation rates and rapid reworking within a lacustrine environment (Allen, 1982a, b; Ashley and others, 1982). This finding is consistent with subaqueous jökulhlaup efflux into the upper Sæluhúsavatn lake basin (Fig. 4). Jökulhlaup water exited the Sæluhúsavatn basin initially through a number of spillway channels on the western margin of the lake basin, generating a series of cataracts (Figs 3b and 4). Progressive spillway erosion during a later stage of the jökulhlaup accounted for most of the lake outflow.

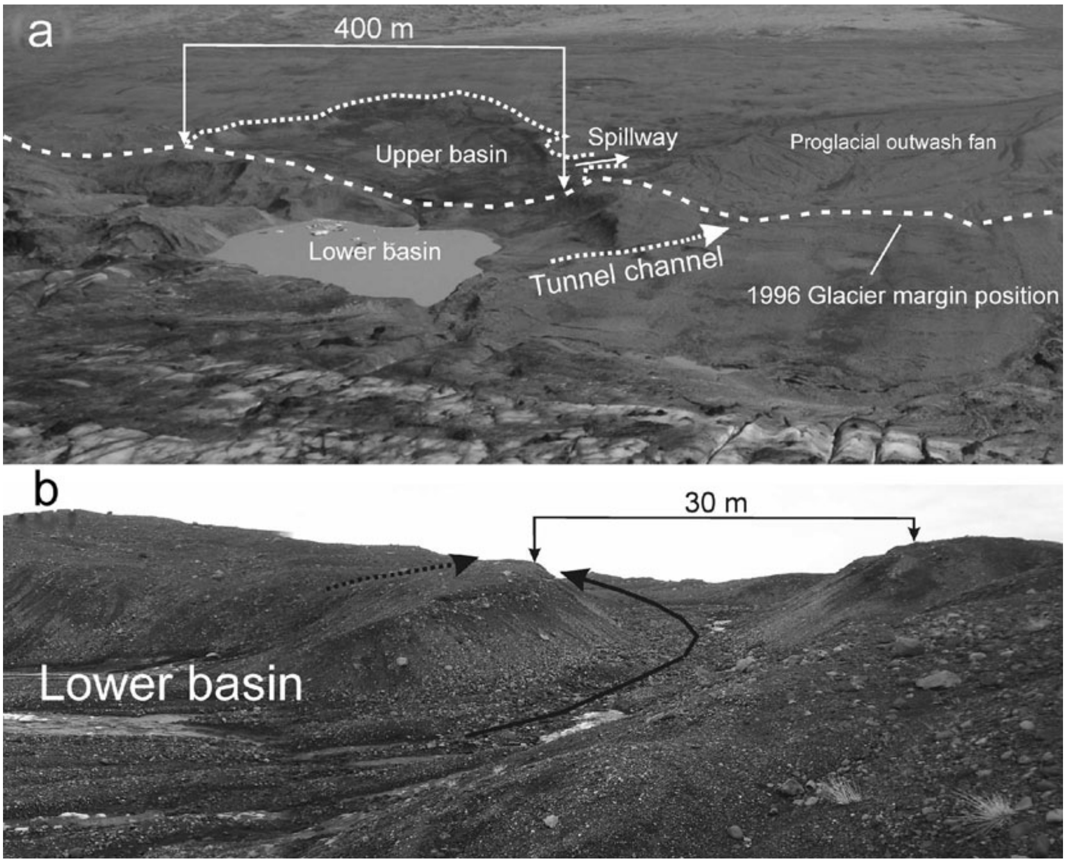

Fig. 4. (a) Oblique aerial photograph taken in August 2005 indicates the location of the tunnel channel in relation to the 1996 glacier margin position, proglacial outwash fan and lower Sæluhúsavatn basin. View is from the glacier (in foreground) towards the proglacial area. (b) View from lower Sæluhúsavatn basin up the tunnel channel towards the former ice margin. A smaller channel is truncated by the main tunnel channel.

REVERSE-GRADIENT CHANNEL AND PROGLACIAL OUTWASH FAN

A channel ascends from the lower Sæluhúsavatn basin directly to the head of a distinctive proglacial outwash fan deposited by the 1996 jökulhlaup (Figs 4a and b). Post-jökulhlaup observations reveal a broad, low channel-shaped depression excavated into the surrounding moraine sediment rather than into the overlying ice (Figs 5a–c). The channel bottom ascends 11.5 m over a distance of 160 m and has an average reverse gradient of 0.07 (m/m) (Figs 3b, 4a, 4b and 6). The channel bed becomes shallower as it ascends (Fig. 6). Two tributary gullies entering the channel on its western margin represent post-jökulhlaup meltwater reworking during deglaciation of the channel area (Figs 3b, 4 and 6). In order to avoid these post-jökulhlaup channel modification zones, cross-sectional profiles were surveyed between the tributary gullies and the 1996 ice margin (Figs 3b and 6). Bank-full channel cross-sectional areas of between 50 m^2 and 90 m^2 were derived from channel widths of 25–40 m respectively (Fig. 6). The channel base has a relatively smooth appearance when compared to adjacent moraine deposits and the channel margins are characterized by clear breaks of slope in the surrounding moraine sediment (Fig. 5b). With depths restricted to 0.7–2.2 m, the main channel is characteristically wide and shallow, and truncates another shallow channel ascending from the lower Sæluhúsavatn basin (Figs 4b and 6). A figure for the volume of eroded sediment of 14 000 m^3 was derived by extrapolating surveyed cross-sectional areas (90 m^2) along the channel length of 160 m. However, a greater channel cross-sectional area (190 m^2) within the first 100 m of the channel as it ascends from the lower Sæluhúsavatn basin suggests that a total of 24 000 m^3 of sediment was eroded (Figs 4b and 6).

The bar pattern of the proglacial outwash fan indicates rapid flow expansion from the former channel portal, with the upper fan surfaces sloping in a radial fashion away from the channel portal (Figs 3a and 4a). The centre of the fan is incised to a depth of 4 m to the pre-jökulhlaup surface (Russell and Knudsen, 2002) (Figs 5a and b). Copious numbers of rip-ups or intraclasts composed of glaciofluvial sediment are found on the fan, which also contains sediment of up to boulder size (Figs 5a and b). Relatively few ice block obstacle marks are found on the fan compared with other 1996 jökulhlaup outwash fans (Russell and Knudsen, 1999, 2002; Fay, 2002). The fan has an estimated volume of 70 000 m^3 based on an average thickness of 2 m and an area of 35 000 m^2.

FLOW RECONSTRUCTION

Peak jökulhlaup discharge was estimated within the Sæluhúsakvísl proglacial channel using four variants of the slope-area technique. Flows were reconstructed at three proglacial channel cross-sections and a further two cross-sections within a spillway channel exiting the Sæluhúsavatn proglacial lake basin (Figs 3a and 6). The proglacial channel cross-sections were inundated solely by jökulhlaup flow

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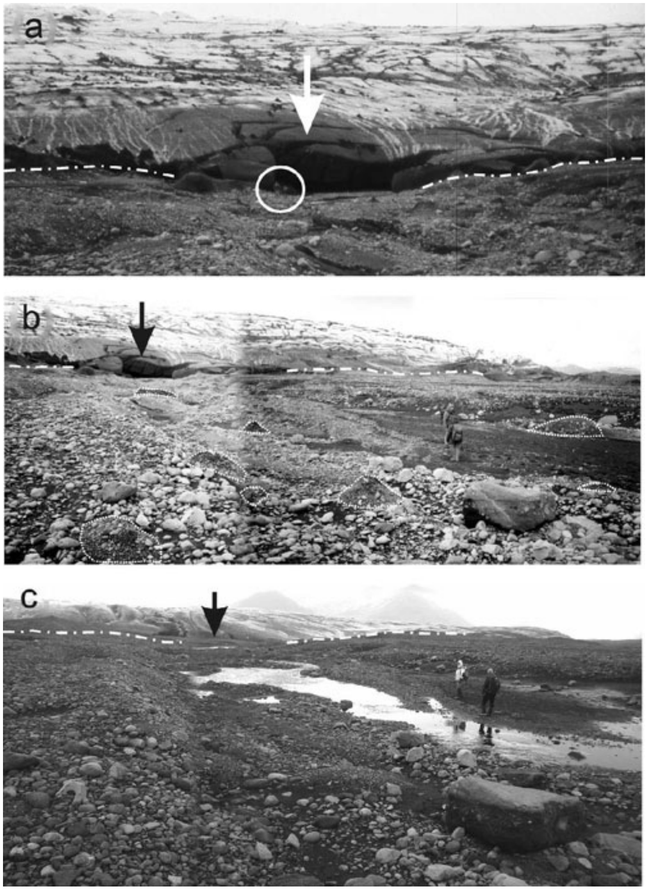

Fig. 5. (a) View of the mouth of the Sæluhúsakvísl outlet in April 1997 illustrating channel incision into moraines on either side (note people for scale). Waning stage erosion dissecting rising stage jökulhlaup deposits, creating a prominent proglacial channel leading towards the viewer. (b) Taken in April 1997 this view shows the central portion of the proglacial outwash fan littered with numerous rip-ups or intraclasts. Waning stage fan incision has exhumed the pre-jökulhlaup vegetated surface near to the people. (c) The same view as in (b) taken in March 2004, illustrating degradation of the intraclasts on an otherwise unaltered surface. Ice margin retreat shows the mouth of the tunnel channel cutting through adjacent moraine ridges.

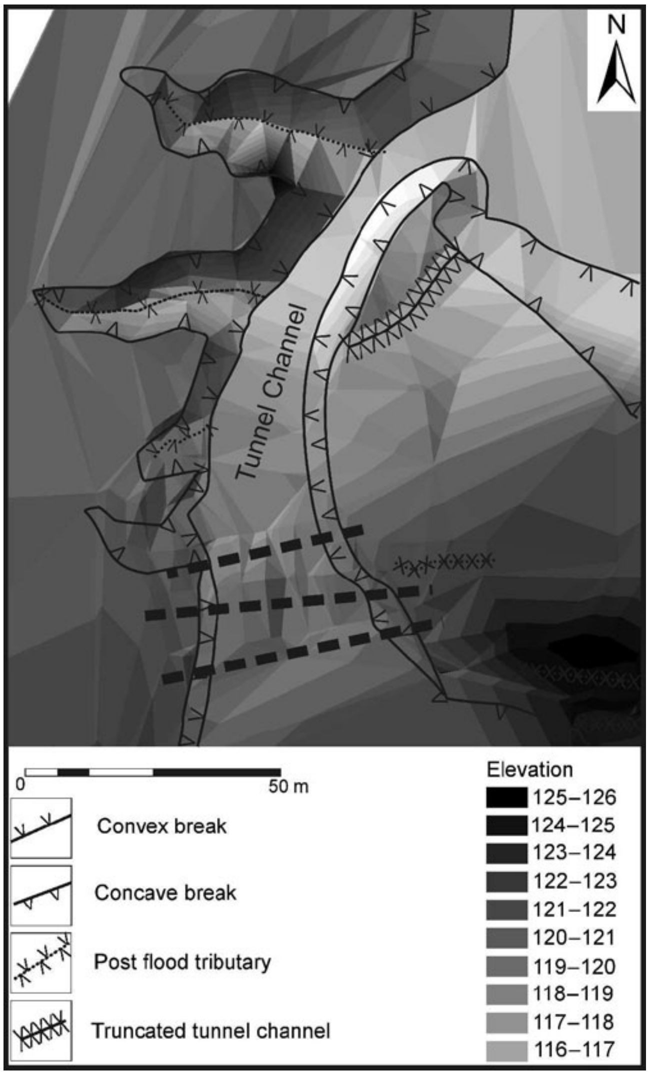

Fig. 6. Geomorphological map of the tunnel channel area indicating the location of the cross-sections used to infer flow conditions.

exiting the Sæluhúsavatn proglacial lake and the main tunnel channel portal to the west of Sæluhúsavatn (Fig. 4a).

Mean flow velocities for each channel cross-section were calculated using three variants of the standard Manning resistance equation as well as an adaptation of the Keulegan equation (Thompson and Campbell, 1979; Russell and others, 1999). The Manning and Keulegan resistance equations required the following input data: (1) the energy gradient or water surface slope; (2) channel hydraulic radius and (3) grain roughness (Chow, 1959; Henderson, 1966; Maizels, 1983). Four methods were used to characterize grain and form roughness in order to identify potential problems of incorporating the channel resistance. Wash limits were located with the help of aerial photographs taken during the jökulhlaup waning stage on 6 November 1996 and surveyed using DGPS. Channel hydraulic radius was calculated from cross-sectional areas and wetted-perimeters derived from surveyed channel cross-sections (Table 1). Channel roughness was characterized by the Darcy-Weisbach friction factor f and Manning's n. The modified Keulegan equation proposed by Thompson and Campbell (1979), being the least empirical and least site-specific, was used to calculate the friction factor f in the Darcy-Weisbach equation (Church and others, 1990). The Darcy-Weisbach equation was used to obtain mean velocity values:

$$v = \sqrt{\frac{8gds}{f}} \tag{1}$$

where s is the slope, d is the flow depth (m), g is the acceleration due to gravity (9.81 m s^{-2}) and f is the friction factor calculated using Thompson and Campbell's 1979 equation:

$$\frac{1}{\sqrt{f}} = \left(1 - \frac{k_s}{10R}\right) \times 2\log_{10}\left(\frac{12R}{k_s}\right) \tag{2}$$

where R is the hydraulic radius and k_s is the size of the roughness elements equal to 4.5 times the boulder size D_i. In this case, we calculated k_s as the proportion of the flow depth d occupied by flow resistance elements ΔA:

$$k_s = 4.5\, d\, \Delta A \tag{3}$$

The proportion of the flow depth occupied by flow resistance elements was estimated visually. A single f value was calculated for each cross-section. Calculated f values were

Table 1. Input data for flow reconstruction

	Channel cross-section 1	Channel cross-section 2	Channel cross-section 3	Spillway cross-section 1	Spillway cross-section 2
Cross-sectional area (m^2)	520	334	260	220	170
Hydraulic Radius (m)	2.42	3.60	2.59	2.88	2.99
Slope (mm^{-1})	0.006	0.008	0.01	0.01	0.01
Width (m)	210	85	95	70	50
Average depth (m)	2.48	3.93	2.74	3.14	3.40
Grain size D_{84} (m)	0.55	0.55	0.55	0.75	0.75
Grain size D_{90} (m)	0.6	0.6	0.6	0.8	0.8
% reduction in cross-section area due to roughness	5	5	5	10	10

converted to Manning's n using an equation presented by Richards (1982):

$$n = \sqrt{\frac{fR^{1/3}}{8g}} \tag{4}$$

Manning's n values were calculated from grain size characteristics using the Manning-Limerinos and Manning-Strickler equations (Equations 5 and 6), which required estimates of the D_{84} and D_{90} percentiles of the grain size distribution (Maizels, 1983; Ryder and Church, 1986; Russell, 1994):

$$n = 0.038 D_{90}^{1/6} \tag{5}$$

$$\frac{n}{d^{1/6}} = \frac{0.113}{1.16 + 2.0 \log(d/D_{84})} \tag{6}$$

where d is flow depth and D_{84} and D_{90} are the 84th and 90th percentile grain-size values, respectively. D_{84} and D_{90} percentiles were derived for each cross-section from estimates of surface grain sizes. However, n values calculated from grain-size distributions were compared with those derived solely from water surface slope and the hydraulic radius using Jarrett's equation (Jarrett, 1984):

$$n = 0.32\, S^{0.38} R^{-0.16} \tag{7}$$

where R is the hydraulic radius (m) and S is the energy slope. Mean flow velocities were derived for each proglacial channel cross-section using each of the four variants of the slope-area technique presented above. Peak flood discharges were derived by multiplying mean flow velocities by channel cross-sectional areas.

Average peak jökulhlaup discharge for the Sæluhúsakvísl proglacial channel was reconstructed as $1560 \pm 310\,m^3\,s^{-1}$ (Table 2). Average peak discharge from the main spillway channel exiting the Sæluhúsavatn was reconstructed as $870 \pm 170\,m^3\,s^{-1}$ (Table 2). There is good correspondence of discharge values derived from the various techniques (Table 2). Sensitivity of peak discharge estimates to changes in water surface slope, channel cross-sectional area and grain roughness are presented in Table 3. Slope-area discharge estimates are sensitive to channel cross-sectional area as discharge is the product of resistance-based velocities and cross-sectional areas (Table 3). Although variation of water surface slope and grain roughness has a significant impact on discharge, these parameters can be constrained reliably. The estimated error for each discharge measurement using the slope-area technique is estimated to be $\pm 20\%$. The difference in average reconstructed discharge between the proglacial and spillway channels ($690\,m^3\,s^{-1}$) exceeds the likely errors at each site.

If peak discharge within the proglacial and spillway channels was synchronous, then peak flow exiting the tunnel channel would be $680\,m^3\,s^{-1}$ (Table 2). Dominance of proglacial bars and channels emanating from the tunnel channel portal, however, suggest that flows from the tunnel channel peaked later than those exiting the Sæluhúsavatn basin (Figs 3a and 4a). The peak discharge of $680\,m^3\,s^{-1}$ for the tunnel channel should therefore be regarded as a minimum figure.

Average peak flow velocities within the tunnel channel of $8–14\,m\,s^{-1}$ are derived by dividing peak discharge, calculated from the proglacial hydraulic reconstructions, by the surveyed channel cross-sectional area. This assumes that the tunnel channel was subject to bank-full conditions and that there was no tunnel roof expansion. Observations of the

Table 2. Discharge estimates

	Channel cross-section 1 $m^3\,s^{-1}$	Channel cross-section 2 $m^3\,s^{-1}$	Channel cross-section 3 $m^3\,s^{-1}$	Spillway cross-section 1 $m^3\,s^{-1}$	Spillway cross-section 2 $m^3\,s^{-1}$
Darcy-Weisbach	1880 ± 380	1730 ± 350	1270 ± 250	910 ± 180	720 ± 140
Manning-Limerinos	1370 ± 270	1420 ± 280	940 ± 190	800 ± 160	650 ± 130
Manning-Strickler	2090 ± 420	2020 ± 400	1410 ± 280	1220 ± 240	970 ± 190
Jarrett	1830 ± 370	1700 ± 340	1030 ± 210	950 ± 190	760 ± 150
Average	1790 ± 360	1720 ± 340	1160 ± 230	970 ± 190	770 ± 150
Proglacial average	1560 ± 310				
Spillway average	870 ± 170				
Tunnel channel component	680 ± 140				

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Table 3. Sensitivity of discharge reconstruction techniques to changes in input parameters

	+0.01 slope	+10 m^2 cross-sectional area	+10 cm grain roughness
% discharge increase in main channel	+5.3	+4.7	−2.5
% discharge increase in spillway channel	+4.0	+8.6	−4.8

outlet in April 1997 indicate that the conduit was mainly sediment-walled, showing little upward expansion into the glacier (Fig. 5a).

DISCUSSION

The case for a tunnel channel feeding the Sæluhúsakvísl proglacial outwash fan is supported by: (1) the clear association of the freshly cut channel ascending from the lower Sæluhúsavatn basin and the proglacial outwash fan (Figs 3, 4 and 6); (2) the lack of any major meltwater outlet or proglacial outwash fan in the Sæluhúsakvísl area prior to the jökulhlaup as indicated by oblique aerial photos taken in August 1996; (3) repeated ground and aerial observations since 1996 that do not indicate any major meltwater flow from the 1996 ice margin towards the upper Sæluhúsavatn basin capable of generating the channel system (Figs 3a and 4a) and (4) observations of the outlet channel cutting through adjacent moraine deposits in April 1997 (Figs 5a and b). The presence of numerous rip-up clasts on the proglacial fan surface confirms that major subglacial excavation took place at this location during the 1996 jökulhlaup (Figs 5b and c). Estimated volumes of sediment eroded from the tunnel channel account for 20 to 34% of the volume of the proglacial outwash fan, highlighting the importance of subglacial tunnel channel erosion as a source of sediment to the jökulhlaup at this site. Many of the outwash fans draining the eastern side of Skeiðarárjökull are heavily incised by waning stage flows implying rapid and marked reductions in sediment supply (Russell and Knudsen, 2002; Russell and others, 2006).

Although there is evidence of subaqueous jökulhlaup efflux into the upper Sæluhúsavatn basin at an elevation of 110 m, a substantial discharge ascended the flanks of the lower basin through the tunnel channel to exit at an elevation of 120 m (Fig. 3). Aided by subaerial and the aforementioned subaqueous jökulhlaup influx, the level of the Sæluhúsavatn rose from 117 m to 125 m allowing the formation of a delta graded to a lake level of 125 m (Fig. 2a). The temporarily raised proglacial lake levels acted as a hydraulic dam deflecting subglacial jökulhlaup flow up the western flank of the upper basin to exit the glacier margin at an elevation of 120 m (Figs 3, 4 and 6). Within-flood changes in hydraulic conditions can therefore be seen to have a significant impact on meltwater flow routing and tunnel channel trajectory. In addition, the presence of a smaller truncated tunnel channel ascending from the upper Sæluhúsavatn basin suggests progressive channel evolution, possibly from an anastomosing to a single channel (cf. Brennand and others, 2006).

The Sæluhúsakvísl tunnel channel and proglacial outwash fan described in this paper show many similarities to those described from Quaternary ice marginal zones (e.g. Clayton and others, 1999; Cutler and others, 2002; Kozlowski and others, 2005; Jørgensen and Sandersen, 2006). Similarities between the Sæluhúsakvísl and Quaternary tunnel channel systems include: up-glacier slopes; associated outwash fans displaying rapid downstream fining and apex incision; dissection of end moraines and a characteristic 'box' shape (Clayton and others, 1999; Cutler and others, 2002; Kozlowski and others, 2005). Clayton and others (1999) and Cutler and others (2002) attributed channels cut into outwash fan apexes in Wisconsin to erosion during the waning stage of a tunnel-channel flood. Absence of ice-block obstacle marks or kettle-holes on proglacial outwash fans led Cutler and others (2002) to conclude that tunnel discharge had been relatively modest or that they had been covered by deposits of later lower magnitude flows. Interestingly, 1996 jökulhlaup flows within the Sæluhúsakvísl channel were noted to have a modest number of ice blocks when compared to adjacent outlets. Flood flow within sediment-walled tunnel channels will not result in as much ice removal as en- or supraglacial conduits which are subject to vigorous erosion processes during jökulhlaups (Roberts and others, 2001; Roberts, 2005).

Our modern analogue has demonstrated a close relationship between tunnel channel erosion and proglacial outwash deposition. The data presented clearly demonstrate the ability of meltwater, under these conditions, to erode under appropriate local hydraulic gradients and in the presence of erodible glacier substrate. Tunnel channel formation in Iceland takes place beneath temperate glacier ice in the absence of permafrost. The November 1996 jökulhlaup had a sufficiently rapid onset to induce water pressures high enough to force large volumes of water to ascend from a heavily over-deepened glacier basin. Many Quaternary tunnel channels ascend to ice margins from over-deepened basins (Clayton and others, 1999; Cutler and others, 2002; Jørgensen and Sandersen, 2006). Over-deepened basins may encourage tunnel channel formation as ascending subglacial meltwater will seek the most efficient route through highly erodible and complex glacier substrate. The presence of an over-deepened basin may also help retain meltwater within subglacial lakes (e.g. Shoemaker, 1992; Alley and others, 2006; Domack and others, 2006) thereby providing a source of water for release during tunnel channel forming bursts.

CONCLUSIONS AND WIDER IMPLICATIONS

For the first time at a contemporary glacial margin, we have demonstrated that glacier outburst floods are capable of generating tunnel channels. In our Icelandic example, tunnel channel routing is controlled by subglacial topography and rapid changes in subglacial and proglacial hydraulic gradients during the 1996 jökulhlaup. One cannot explain the location or trajectory of the tunnel channel discussed in this paper without recourse to transient ice-marginal hydraulic conditions during the 1996 jökulhlaup.

This paper demonstrates the need for greater attention to be paid to the interaction of proglacial lakes as a control on subglacial meltwater flow routing (see also Brennand, 2000). We suggest that the presence of proglacial lakes will increase the variability of geomorphologic response and sedimentary signature of glacier outburst floods over distances as little as a few hundred metres. Our study highlights the importance of meltwater outbursts as agents of tunnel channel formation and provides a valuable modern analogue for a process which has until now only been inferred from the Quaternary record. Further research is required to determine the origin of the lower Sæluhúsavatn basin which, being of composite origin, can be classified as a tunnel valley.

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