The role of hydrograph shape in controlling glacier outburst flood (jökulhlaup) sedimentation

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Abstract Glacial outburst floods (jökulhlaups) play an important part in proglacial geomorphology and sedimentology. Research on the impact of floods has made assumptions by associating jökulhlaup sedimentary successions with distinctive hydrograph shapes and flow rheology. However, jökulhlaup hydrograph shape alone is thought to have a significant impact on proglacial sedimentology. To date, little information exists concerning the role of hydrograph shape as a control on the sedimentological and geomorphological impact of jökulhlaups. This paper illustrates how field interpretation of flood deposits can be related to specific hydrograph shapes, and outlines how flume experiments can be used to assess the extent to which hydrograph shape exerts a control on jökulhlaup sedimentology.

Key words jökulhlaups; sedimentary successions; hydrograph shape; field prototypes; flume modelling; Iceland

BACKGROUND

Jökulhlaups (glacier outburst floods) are common in proglacial areas and have significant impact on fluvial sedimentology (Maizels, 1995). To date, research on jökulhlaups has concentrated upon interpretation of sedimentary successions and geomorphological impact. Variation in the characteristics of flood deposits has led researchers to associate different jökulhlaup successions with distinctive hydrograph shapes and sediment supply conditions (Maizels, 1993, 1997; Maizels & Russell, 1992). Maizels (1993) presented a model of how flow rheology, hydrograph shape and sediment supply control the characteristics of Icelandic jökulhlaup deposits. The model was based upon interpretation of the sedimentary record, and not on observation of process. Jökulhlaup hydrograph shape is controlled largely by flood generation mechanisms and floodwater routing (Clarke, 1982; Haeberli, 1983; Walder & Costa 1996; Tweed & Russell, 1999). Hydrograph shape alone is thought to have a significant impact on the rates of sediment acquisition, channel adjustment patterns, channel erosion and subsequent deposition during flood conditions (Walder & Costa, 1996; Russell & Knudsen, 1999a). However, little attention has been paid to the role of flood hydrograph shape in controlling the physical characteristics of sedimentary successions.

This paper presents the rationale for a combined fieldwork and laboratory flume project, which aims to determine the role of hydrograph shape in controlling the sedimentary characteristics of jökulhlaup deposits. This paper aims to justify field prototype data to be scaled-down for a series of future flume-based experiments, the results of which will be presented elsewhere.

METHODS

Two recent Icelandic jökulhlaups were used as prototypes to compare the sedimentological impact of jökulhlaups with contrasting hydrograph shapes. These particular jökulhlaups were chosen because they constitute excellent examples of two very distinctive jökulhlaup hydrograph shapes produced by different flood drainage mechanisms.

Vertical sedimentary sections were logged allowing the vertical and (where possible) three-dimensional architecture of sedimentary successions to be determined. Grain-size analysis, clast sorting and orientation were noted in the field. Samples were collected for grain-size laboratory analysis. Sedimentary sections were studied during fieldwork that took place from 1996 up until 2001.

FIELD-SITES AND HYDROGRAPH SHAPES

The two glaciers used as prototypes for this study are Sólheimajökull, southern Iceland, and Skeiðarárjökull, southeast Iceland (Fig. 1). The contrasting hydrograph shapes associated with the two jökulhlaups are illustrated in Fig. 2. Table 1 presents the characteristics of the two Icelandic jökulhlaups. Although there is some uncertainty

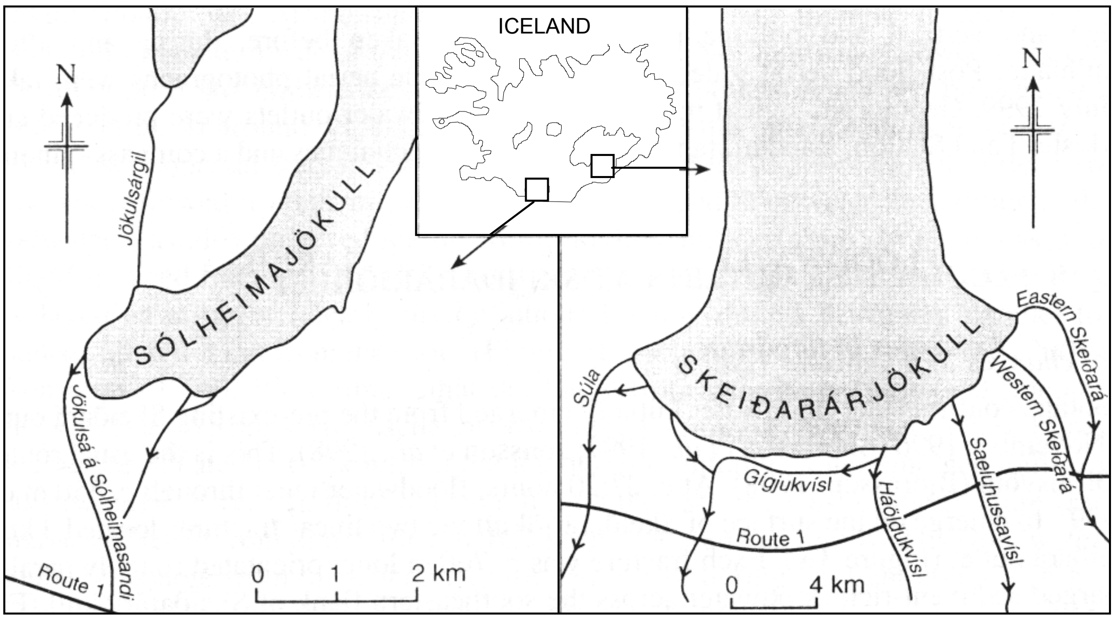
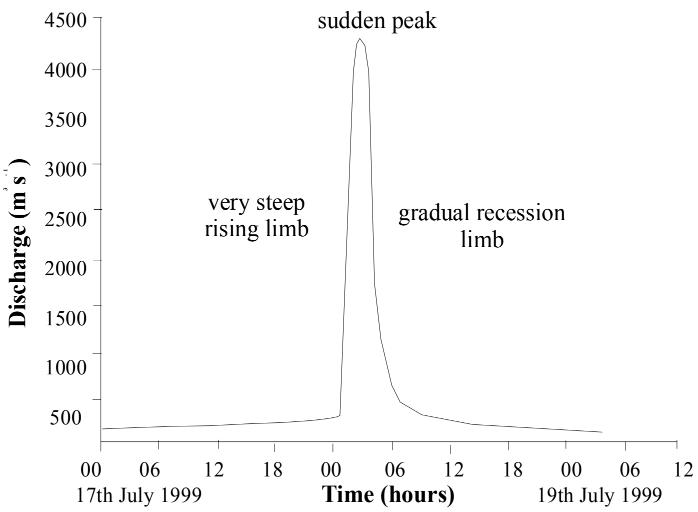


Fig. 1 Location of Sólheimajökull and Skeiðarárjökull, Iceland.



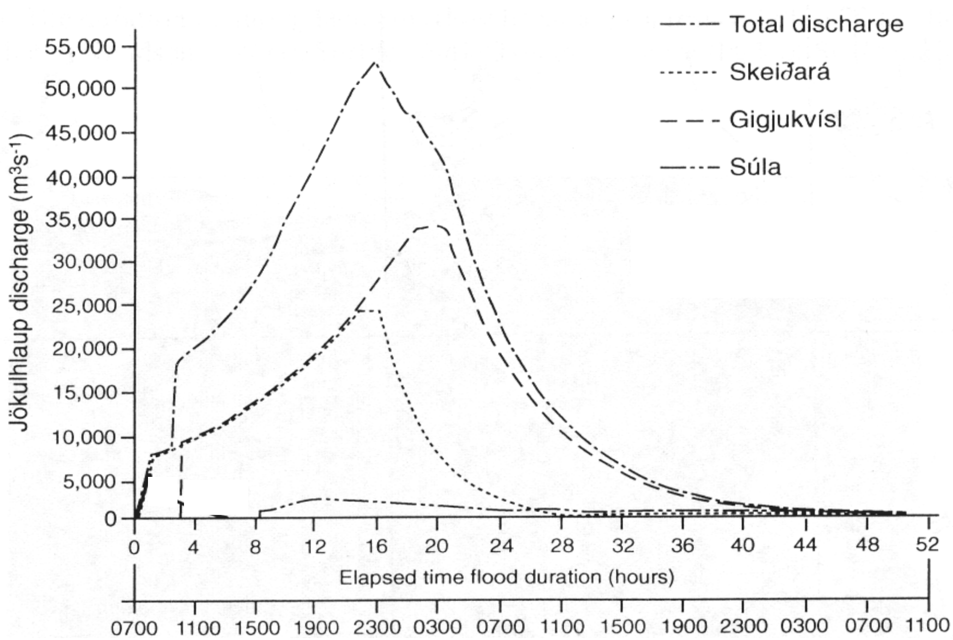


Fig. 2 Hydrographs associated with the July 1999 jökulhlaup at Sólheimajökull, southern Iceland, adapted from Sigurðsson *et al.* (2000), and the November 1996 jökulhlaup at Skeiðarárjökull, southeastern Iceland, adapted from Snorrason *et al.* (1997).

regarding the exact nature of the November 1996 hydrograph, Grímsvötn jökulhlaups are commonly characterized by an exponential rising stage, characteristic of the process of tunnel enlargement by thermal erosion (Björnsson, 1974; Walder & Costa, 1996), which is thought by Snorasson *et al.* (1997) to have dominated the bulk of the rising stage of the hydrograph.

JÖKULHLAUP IMPACT ON SÓLHEIMAJÖKULL

The July 1999 jökulhlaup at Sólheimajökull had a significant erosional and depositional impact. Jökulhlaup flow exited the glacier via tunnels located across the margin. The

Table 1 The characteristics of jökulhlaups with contrasting hydrograph shapes from Sólheimajökull and Skeiðarárjökull, Iceland.

Field location	Sólheimajökull (Fig. 1)	Skeiðarárjökull (Fig. 1)
Hydrograph shape	asymmetrical (Fig. 2)	symmetrical (Fig. 2)
Date	17–18 July 1999	5–7 November 1996
Cause	volcanic activity from the Katla subglacial volcano	subglacial eruption led to drainage of the subglacial lake, Grímsvötn
Peak discharge	4500 $m^3 s^{-1}$ in <1 h	30 000 $m^3 s^{-1}$ in 20 h
Rate of rising discharge	75 $m^3 s^{-1}$ per minute	25 $m^3 s^{-1}$ per minute
Rate of falling discharge	9 $m^3 s^{-1}$ per minute	25 $m^3 s^{-1}$ per minute

majority of rising stage flow issued from the western margin, a central tunnel conveying most of the waning stage flow whilst smaller flows exited the eastern margin (Russell *et al.*, 2001). The jökulhlaup flow cut through moraine ridges and fluvial deposits. Boulders up to 10 m in diameter were deposited simultaneously with ice blocks in front of the western margin (Fig. 3). A 1200-m^2 boulder bar was deposited in front of the main jökulhlaup conduit (see Fig. 2(a)–(g) Russell *et al.*, 2002). This boulder bar extended to a thickness of 6 m reducing to 1.5 m within 500 m downstream and was deposited on top of older vegetated surfaces (Russell *et al.*, 2000). Boulder bar deposits comprise structureless, inversely-graded, crudely bedded, matrix-supported gravels (see Fig. 2(c)–(g) Russell *et al.*, 2002) indicative of rapid deposition during the rising flow stage. Although waning stage reworking of bar surface lead to the development of chute channels and imbrication clusters, the deposited surface generally lacked an armoured layer. Waning stage erosion was triggered by scour around large ice block obstacle marks. Circular pits within fine-grained sediments indicate the melt-out of completely buried ice blocks.

Fig. 3 Ice blocks and boulders (10 m) deposited simultaneously near the ice margin at Sólheimajökull.

JÖKULHLAUP IMPACT ON SKEIÐARÁRJÖKULL

During the November 1996 jökulhlaup at Skeiðarárjökull, flood waters exited the glacier via multiple outlets, although the Gígjukvísl channel conveyed most of the late rising and waning stage flows (Russell & Knudsen, 1999a). The initial flood wave was dominated by a debris rich flow, however the main flood consisted of turbulent flow conditions (Russell & Knudsen, 1999a). A large proglacial outwash fan was deposited in the Gígjukvísl channel possessing a coarse-grained, well-armoured surface. This proglacial outwash fan comprised a range of sedimentary structures at a variety of scales. Deposits include (a) coarsening upward successions showing a transition from horizontally-bedded, matrix-supported gravels to gravel and boulder clast-rich sediments (see Fig. 6 Russell & Knudsen, 2002); (b) polymodal, matrix-supported deposits with large scale cross stratification (Fig. 4) and (c) clast rich, crudely horizontally bedded deposits. The large range of deposits located within the Gígjukvísl channel are associated with sediment reworking and winnowing of finer sediments as the flow depths and transport capacities decreased during the waning stage flow. Ice blocks were released, transported and deposited across the outwash fan during the late rising and waning stage flows producing a heavily kettled topography (Fay, 2002). Rip-up clasts were produced by rapid deposition during hyperconcentrated flow conditions (Russell & Knudsen, 1999a).

Fig. 4 Polymodal matrix-supported deposits with upstream dipping beds (10–15°) on the outwash fan deposited in the Gígjukvísl channel, proglacial outwash fan Skeiðarárjökull. Former flow direction is away from viewer.

DISCUSSION

Sediment flux during the Sólheimahlaup (jökulhlaup at Sólheimajökull)

At Sólheimajökull, large volumes of sediment were readily available throughout the rising stage. Large amounts of sediment were evacuated from the subglacial system and the erosion of moraines and older fluvial deposits during the rapid rising stage (Russell *et al*., 2002). Peak flood discharge decreased from 4780 $m^3 s^{-1}$ at the glacier snout to 1943 $m^3 s^{-1}$ 6 km downstream (Russell *et al*., 2002). This rapid downstream hydrograph attenuation was mirrored by a downstream reduction of the erosional and depositional impact of the jökulhlaup. The presence of structureless, inversely-graded, crudely bedded, matrix-supported gravel units at Sólheimajökull are indicative of rapid deposition from a fluidal rising stage flow with a high sediment concentration (Russell *et al*., 2000). The presence of poorly defined clusters of boulders and ice blocks suggests concurrent and very rapid deposition from a sediment-rich flow (Fig. 4) indicating high sediment flux at the time of deposition (Russell *et al*., 2002). The presence of circular pits within fine-grained sediments indicates simultaneous deposition of sediment and ice blocks from a sediment-rich flow. Waning stage sediment reworking was confined to pre-existing channels, therefore restricting the lateral extent of waning stage erosion. The fact that a boulder bar was deposited on older vegetated surfaces confirms rapid deposition of large amounts of sediment within the immediate proglacial zone (Russell *et al*., 2000).

Flow duration of the Sólheimahlaup

The very short duration of the rising stage of the hydrograph during the jökulhlaup inhibited the development of well-structured bedforms. The presence of relatively immature surface armouring and clast bedform development confirms that very little time was available for such bedforms to develop as flow stage waned. The rapid rise to peak discharge allowed simultaneous deposition of ice blocks and boulders.

Sediment flux during the Skeiðarárhlaup

During the November 1996 jökulhlaup at Skeiðarárjökull, high sediment flux and prolonged flow conditions were maintained during the rising and waning stage in the main Gígjukvísl channel (Snorrason et al., 1997; Russell & Knudsen, 1999a). High sediment fluxes reflect continuous subglacial sediment supply (Russell & Knudsen, 1999a). The presence of upward-coarsening successions reflect a progressive supply of coarser grained sediment as stage increased (Russell & Knudsen, 2002). On the western side of Skeiðarárjökull, shorter flow duration and sediment supply exhaustion were reflected by the erosional impact of waning stage flows (Russell & Knudsen, 1999a). Incision of the proglacial outwash fan was inhibited by the high sediment flux maintained throughout the waning stage flow (Russell & Knudsen, 1999b). Waning stage sediment reworking led to incision of higher stage deposits. Waning stage winnowing was suggested by the presence of the armoured surface on the proglacial outwash fan, reflecting an overall transition of deposition from suspended load to traction load (Russell & Knudsen, 1999a).

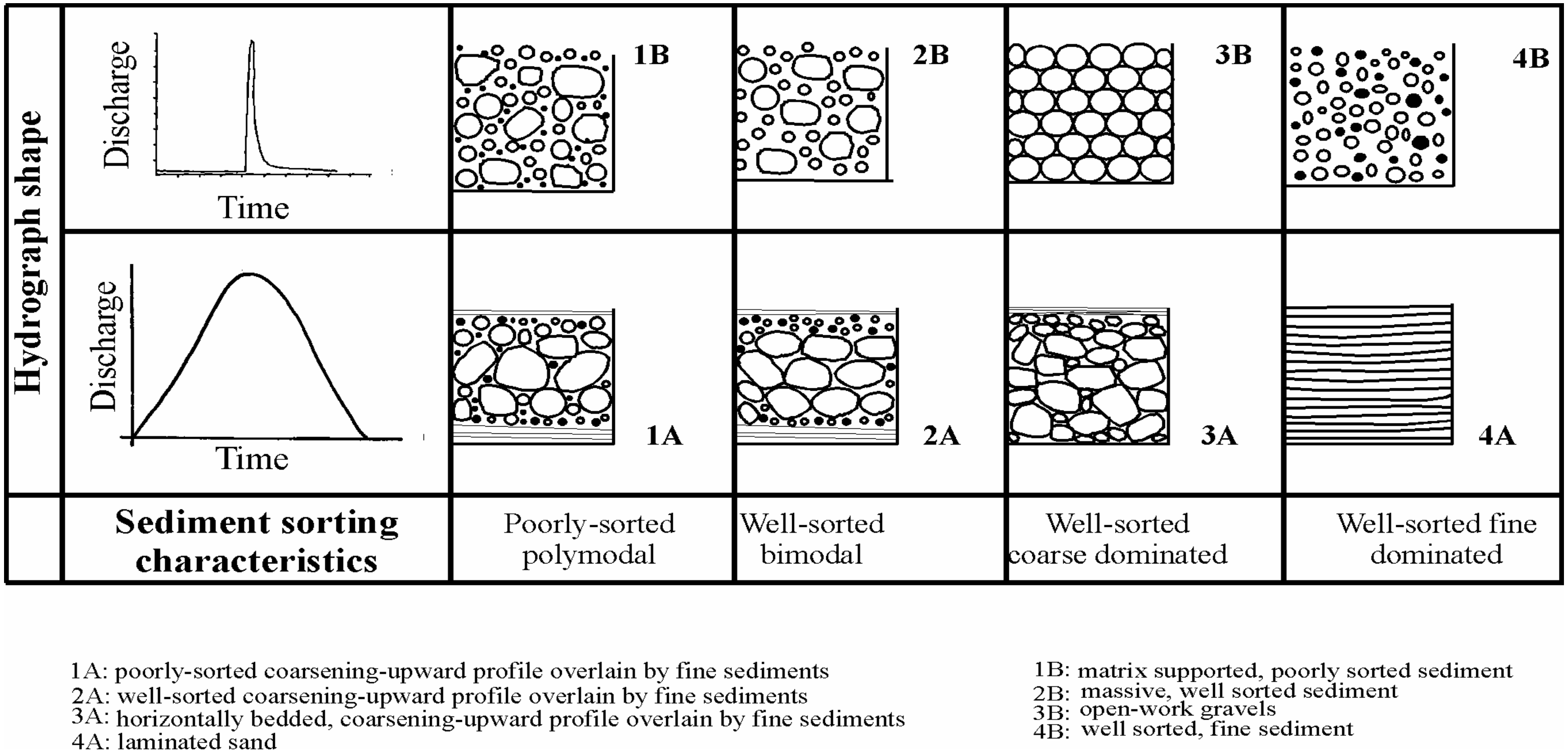


Fig. 5 Conceptual model showing the expected controls of hydrograph shape and sediment sorting characteristics on jökulhlaup sedimentation.

Flow conditions during the Skeiðarárhlaup

The prolonged rising and waning flow stage of this jökulhlaup allowed enough time for bedforms and well-organized sedimentary successions to be deposited. Large-scale high angled (~15–20°) downstream and upstream dipping beds identified in exposed sediment sections indicate the migration of large-scale gravel bars and bedforms under prolonged, relatively deep flow conditions. Lower-angled (~5–10°) upstream and downstream dipping beds are interpreted as the product of shallower waning stage flows. The heavily armoured surface layer of the Gígjukvísl outwash fan highlights the importance of armouring and winnowing processes during the prolonged waning stage (Russell & Knudsen, 1999a, 2002). Deposition took place long enough to allow stage-related changes in flow conditions to be preserved in the sedimentary record. The presence of upward-coarsening units on the Gígjukvísl outwash fan reflect the longer rising flow stage, which allowed more time for bedforms and structure to develop within the deposits. This contrasts with the jökulhlaup at Sólheimajökull.

The interpretation of field data in relation to hydrograph shape has allowed a conceptual model to be developed (Fig. 5) which summarizes the expected controls that hydrograph shape has upon jökulhlaup sedimentation. This model remains to be tested through the use of hydraulic flume modelling techniques.

CONCLUSIONS AND FUTURE WORK

This study has concentrated upon the similarities and differences of vertical sedimentary successions from fieldwork studies that are associated with contrasting jökulhlaup hydrograph shapes. Using two Icelandic case studies it has been observed that the rate of rising and falling stages during a jökulhlaup has a significant effect on proglacial sedimentology. It is clear that the depositional impact of each jökulhlaup varied considerably in the creation of distinctive sedimentary successions associated with major contrasts in their hydrograph shape.

In conclusion, jökulhlaups characterized by a rapid rise to peak discharge result in high rates of sediment acquisition and deposition, and inhibit the development of well-defined bedforms. In contrast, the prolonged rising and falling limbs of jökulhlaups characterized by a symmetrical hydrograph shape, allow time for large-scale bedforms to develop and processes such as winnowing and bed armouring to occur, resulting in distinctive sedimentary sequences.

Hydraulic modelling techniques and field interpretation of jökulhlaup deposits will contribute knowledge and understanding of the role of hydrograph shape in controlling jökulhlaup sedimentation. Future research will test a conceptual model through a series of flume experiments aiming to explain how jökulhlaup hydrograph shape influences the vertical, two- and three-dimensional nature, internal geometry and architecture of jökulhlaup sedimentary successions.

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