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Discharge magnitude and frequency as a control on proglacial fluvial sedimentary systems

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Abstract Recent work on active, inactive and Quaternary proglacial outwash plains or *sandur*, subjected to contrasting magnitude and frequency regimes has yielded new insights into the controls on sandur evolution. This paper provides a review of recent research on magnitude and frequency in proglacial systems. The primary objective of this paper is to demonstrate that sandur influenced by repeated high magnitude flooding (jökulhlaups) are dominated by large-scale bar systems (jökulhlaup bars), which are unrelated to normal, low magnitude–high frequency flows which occur between floods. Jökulhlaup bars scale to flood-channel widths, and their upper surfaces are topographically higher than, and unaffected by, between-flood flows. Large gravel bars are distinctive from large bars in sandy braided rivers, where the dominant discharge is less than bankfull, and large bars grow by amalgamation of smaller bars.

Key words sandur; braided river; jökulhlaup; floods; glacial meltwater; sedimentology; geomorphology; Iceland

INTRODUCTION

The issue of magnitude and frequency in fluvial geomorphology has been a persistent problem for many years. The debate as to whether most work is done by frequent events of moderate magnitude or infrequent high magnitude events has seen advocates for both cases. Opinions generally vary depending on how "work" is defined, and what climatic-hydrological regime is being considered (Wolman & Miller, 1960; Dury, 1973; Wolman & Gerson, 1978; Kochel, 1988). Generally, when work is defined as sediment transport, and when temperate–humid environments are considered, low magnitude–high frequency events are considered dominant (Wolman & Miller, 1960; Dury, 1973). When work is defined in terms of "irreparable" modifications to the landscape, and when arid, semiarid and tropical–humid regions are considered, high magnitude–low frequency events are generally considered dominant (Wolman & Gerson, 1978; Gupta, 1983; Kochel, 1988).

The nival region, where there is snow cover for more than one month for greater than 50% of years (Church, 1988) is often omitted from studies of magnitude and frequency. However, extreme seasonal discharge variability and the occurrence of high magnitude floods from a number of sources makes the landscape response of the nival region similar to dryland regions in many respects. This paper is concerned with the

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issue of magnitude and frequency in proglacial settings, an end-member of the nival region where discharges are controlled by the presence of permanent snow and ice and where there is greater potential for the release of stored water.

The aims of this paper are to review the range of discharge magnitude and frequencies which occur in proglacial settings, and to demonstrate that proglacial systems subjected to repeated high magnitude floods have a distinctive geomorphological form. This study focuses on mid-channel bars in proglacial rivers subjected to high magnitude glacial floods. "Jökulhlaup bars" from the Skeiðará River in southeast Iceland are shown to be formed by flood-related discharges, and are unrelated to normal, low magnitude–high frequency flows which occur between floods.

DISCHARGE IN PROGLACIAL REGIONS

Controls on meltwater discharge have been reviewed previously (Maizels, 1995) and are only briefly reviewed here. In general, glacial meltwater discharge is characterized by cyclic variability at various scales. At the smallest scale, diurnal variations are controlled by daily temperature changes. Diurnal variations are more marked in alpine than Arctic glacial drainage basins and small glacierized basins display larger diurnal variations than large basins.

Diurnal variations are superimposed onto a seasonal cycle. Winter low-flow is followed by a spring melt event. Snowmelt occurs first followed by ice melt. Discharge reaches a peak during the summer. Discharges decrease from late summer onwards, through to winter low-flow. Maximum discharge is controlled by the size of the glacier. Consequently, discharges increase during glacier advance, and generally decrease during glacier retreat. For short time intervals, discharges can increase during retreat due to periods of rapid melting.

High magnitude–low frequency floods are an additional source of meltwater input to the proglacial environment. High magnitude glacial floods can have a number of causes. In small drainage basins, rainstorms can be significant (Warburton, 1994). The largest and most geomorphologically effective glacial floods are caused by the sudden release of water from glacier-impounded lakes and from subglacial volcanic eruptions (Tweed & Russell, 1999). These floods are generally known by the Icelandic term *jökulhlaup* (glacier-burst). The geomorphological and sedimentological effects of jökulhlaups on proglacial fluvial systems can be considerable (Maizels, 1997). Jökulhlaup behaviour can also be cyclic, as ice-dammed lake size and stability tends to increase as glaciers become larger, and decrease as glaciers thin and become less efficient dams (Thorarinsson, 1939; Evans & Clague, 1994).

THE GEOMORPHOLOGICAL EFFECT OF REPEATED, HIGH MAGNITUDE FLOODS: JÖKULHLAUP BARS

Many studies of jökulhlaup impact have been concerned with one-off events, or the impact in areas that had previously been unaffected by flood flows (e.g. Russell *et al.*, 2001). However, as indicated above, many proglacial rivers are likely to have cycles of repeated high magnitude floods superimposed onto the normal seasonal and diurnal cycles. Understanding and recognizing the impact of repeated flooding has important implications for management and utilization of proglacial rivers in terms of engineering structures (roads, bridges, flood defences) and hydroelectric schemes.

Fahnestock & Bradley (1973) were the first to recognize that braided rivers subjected to repeated flooding have a different, distinctive channel pattern compared to normal braided rivers. They describe two adjacent rivers, one subjected to 40 years of annual jökulhlaups, the other to normal flows during the same period. The "normal" river had an intricate braided system, which changed location across the sandur many times during the investigated period. The flood-impacted river had a very simple braided system, dominated by large bars, 100s to 1000s of metres long. The bars stand up to 5 m above the active channels, and the surfaces of the bars were only marginally altered during the 40-year period. The intervening channels were in more or less the same locations throughout the investigation period.

Since then, Russell (1993) and Russell & Marren (1999) have described a bar in Greenland that has been subjected to regular jökulhlaups with only minor adjustments to its form, primarily related to flow and deposition around ice blocks stranded by jökulhlaups. Fahnestock & Bradley (1973) also noted the predominance of ice block hollows and obstacle marks on the surface of the flood-impacted bars. Nicholas & Sambrook Smith (1998) noted that sediment transport rates around a bar in Iceland during a normal melt season were incompatible with the size of the bar and the sediments within it. Nicholas & Sambrook Smith (1998) concluded that the bar and sandur were formed by jökulhlaup flows, and that present-day channels and sediment transport are unrelated to the bars they flow around.

THE SKEIÐARÁ RIVER: "TYPE-SITE" FOR THE JÖKULHLAUP BAR?

The Skeiðará River in south Iceland (Fig. 1), located on Skeiðarársandur, the largest active outwash plain in the world has a history of jökulhlaups extending back to the twelfth century (Þórarinsson, 1974). During the twentieth century, jökulhlaups from the subglacial Lake Grímsvötn occurred approximately every 10 years until 1940, with discharges of 25 000–30 000 $m^3 s^{-1}$, and approximately every 5 years since 1940, with discharges of 1000 to 10 000 $m^3 s^{-1}$ (Guðmundsson *et al.*, 1995; Björnsson, 1997). In addition, large jökulhlaups related to subglacial volcanic eruptions, with discharges of 40 000–50 000 $m^3 s^{-1}$ occurred in 1934, 1938 and 1996 (Þórarinsson, 1974; Björnsson, 1997). The normal discharge of the Skeiðará River is 200–400 $m^3 s^{-1}$ (Boothroyd & Nummedal, 1978; Snorrason *et al.*, 1997). During the 1996 jökulhlaup the discharge in the Skeiðará was 15 000 to 20 000 $m^3 s^{-1}$ (Snorrason *et al.*, 1997) with the remaining water occupying other proglacial river channels.

Ground surveys, aerial photograph interpretation and field reconnaissance of a jökulhlaup bar were carried out on Skeiðarársandur during the summers of 2000–2001. Surveys were carried out using a SOKKIA SET4C Total Station, and were made relative to the Route 1 bridge, which crosses the river 10 km downstream of the glacier. All of the bar surfaces between the glacier and the Route 1 bridge were examined from the air, from aerial photographs, and where possible, on the ground. The maximum flooded area during the 1996 jökulhlaup was determined from aerial photographs taken during the flood. Post-flood reworking was determined from aerial

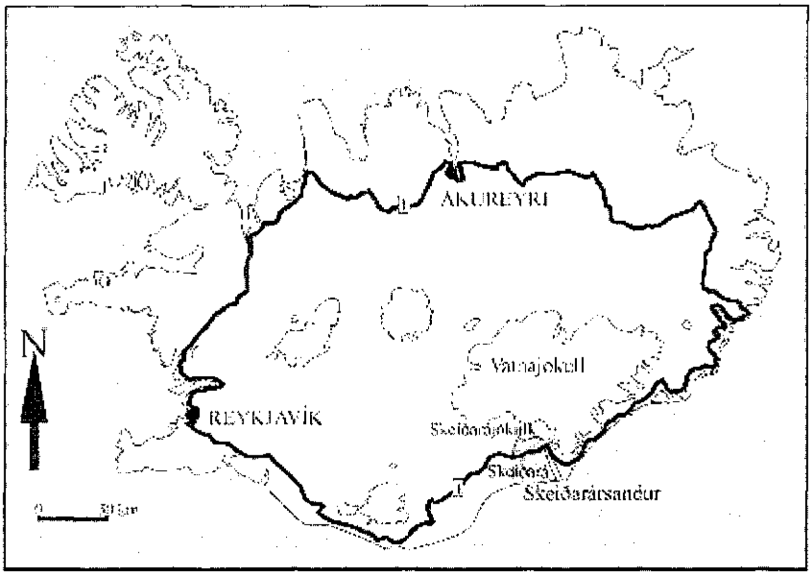

Fig. 1 Location map of Skeiðarársandur, and the Skeiðará River in Iceland.

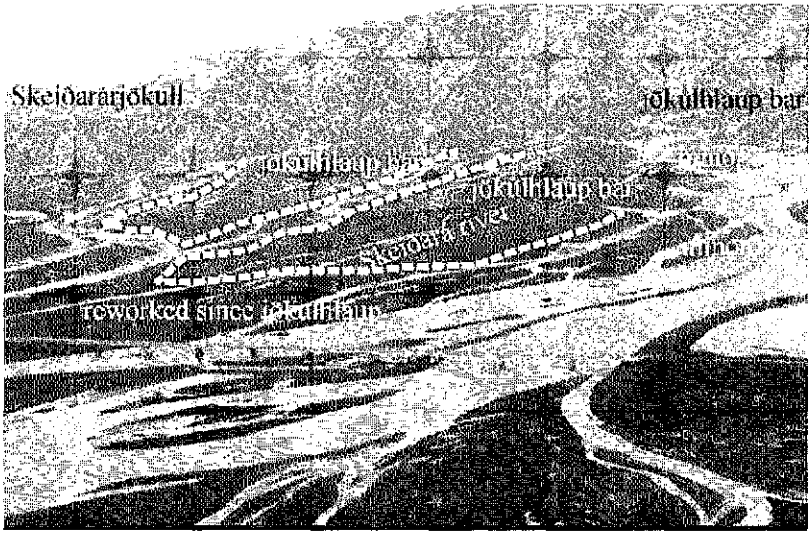

Fig. 2 View of bars in the Skeiðará. Note presence of large gravel bars, and smaller bars in the channels flowing around the larger bars.

photographs taken during 1997, and by field examination. Flood affected areas which hadn't been reworked were easily identifiable due to the presence of numerous ice block obstacle marks. Bar surfaces reworked since the 1996 jökulhlaup were identifiable by the presence of erosion scarps, falling stage drapes and by the presence of a poorly sorted, imbricated bar surface, which contrasts with the flood surface where imbrication is absent.

Figure 2 is a view of the proximal bar pattern of the Skeiðará. The presence of two scales of bar development can be clearly seen. The largest bars are topographically higher than the active channel, and feature numerous ice block obstacle marks. The smaller bars occur *within* the active channel, are at similar levels to the channel, and do not have ice block obstacle marks. The proximal braiding on Skeiðarársandur has been termed "coarse-braided" by Boothroyd & Nummedal (1978). It is suggested by Boothroyd & Nummedal (1978) that coarse-braiding occurs because the coarse gravel it is found in conjunction with inhibits the formation of active braid bars. It is suggested here that this channel pattern is due to the formation of large bars during jökulhlaup flows.

A means of testing this hypothesis is to determine what channel sizes the various scales of bar are related to. Figure 3 compares late July water levels (surveyed 25–31 July 2001), with the height of bar surfaces which were inundated by peak flows since the 1996 jökulhlaup, and the height of bar surfaces formed or modified during the 1996 jökulhlaup. Difficulties of access means that smaller bars within the main channel are excluded from this analysis. Bar surfaces from the 1996 jökulhlaup are 2.5–3 m higher than surfaces affected by any flows since the flood. Flows since the 1996 jökulhlaup include the peak summer flows, which have been higher in other years, and were 0.5 m higher in mid-August 2001 than surveyed here, and a small Skeiðarárhlaup that occurred in August 2000. Lateral migration is likely to be the main cause of bar migration over longer time periods but at present the main Skeiðará channel is relatively stable.

Bars are generally scaled to the width of the channel they are formed in. This appears to be true for the Skeiðará. The length of a bar tends to be approximately 1.5 times the width of its corresponding channel. This rule holds true for channels and bars at all scales within the Skeiðará. The largest bars in the Skeiðará are scaled to the width of the channel during flood conditions, which were up to twice as wide as the present channel. In other words, assuming the relationship between channel width and bar length observed here is valid, many of the jökulhlaup bars are too long for the width of channel they currently occupy.

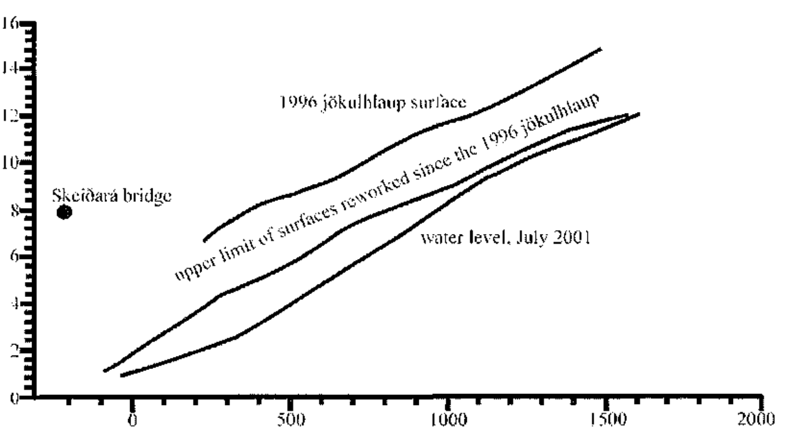

Fig. 3 Long profile of bars in the proximal Skeiðará River, showing hierarchy of bar and channels associated with different discharges of varying magnitude and frequency.

DISCUSSION

The empirical relationship between bar length and channel width observed here contrasts with Yalin's (1977) equation where the scaling ratio is π (3.142). At present no explanation can be offered for this difference. An important first step will be to determine if bars in other jökulhlaup-affected rivers show the same bar length to channel width relationship.

The hierarchy of bars, channels and topographic surfaces described here is distinctive for a gravel-bed braided river. The hierarchical scheme of Williams & Rust (1969) is only applicable if jökulhlaup flows are considered, otherwise there is no relationship between bar and channel size. There are more similarities with the channel ordering scheme devised by Bristow (1987) for the Brahmaputra River, in that the largest bars are semipermanent features related to the first-order channel. Like the Brahmaputra River, the largest bars on Skeiðarársandur are modified and partly dissected by lower-order channels and bars, but still retain their general shape over long time periods. However, a key difference is that whilst the largest bars on the Brahmaputra form through amalgamation of smaller bars and the dominant discharge is less than bankfull (Thorne *et al.*, 1993), the bars on Skeiðarársandur appear to be directly formed by high magnitude floods. Later floods may then modify the surface of bars on Skeiðarársandur although the general form and location are maintained.

CONCLUSIONS

This paper has shown that the coarse-braided reach described by Boothroyd & Nummedal (1978) coincides with those locations where bar lengths are scaled to jökulhlaup-related channel widths and depths. Coarse-braiding may therefore be related to the formation of jökulhlaup bars during floods, rather than the coarse grain size of the proximal reach *per se*. The jökulhlaup bars on Skeiðarársandur are similar to those described by Fahnestock & Bradley (1973) in that they are significantly topographically higher than normal peak discharge channels, and their surfaces preserve flood related features such as ice-block obstacle marks.

An important next step in evaluating the distinctive nature of jökulhlaup bars will be to examine their internal sedimentology and architecture. At present no detailed description of the large-scale architecture or sedimentology of a jökulhlaup bar exists. It is therefore uncertain how the distinctive surface morphology of jökulhlaup bars will be reflected in the subsurface sedimentology. This has implications for identification of Quaternary jökulhlaup bars. Groundwater flow through sandur systems is also likely to be affected by the presence of jökulhlaup bars. In order to further understand the internal structure of jökulhlaup bars, ground penetrating radar surveys of a jökulhlaup bar on Skeiðarársandur were undertaken during the summer of 2001, and will form the basis of a future publication.

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