Glacier outburst floods and outwash plain development: Skeiðarársandur, Iceland

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ABSTRACT

Outwash plains, such as Skeiðarársandur, serve as prototypes for braided river facies and analogs for the Mars Pathfinder and Viking 1 landing sites on the margins of the Chryse Basin. Glacier outburst floods (jökulhlaups) have generated some of the largest known terrestrial freshwater flows and recent studies suggest that the stratigraphy of outwash plains (sandur) is dominated by sedimentary sequences laid down during jökulhlaups, rather than by braided river facies produced by an ablation-related flow regime. The modern point-source drainage configuration on Skeiðarársandur evolved from a diffuse, multipoint distributary system during glacier retreat, when meltwater began to be routed parallel to the ice front. The contemporary pattern of water and sediment dispersal across Skeiðarársandur differs from the conditions that prevailed when the ice front was coupled to the sandur, and the November 5–6 1996 outburst flood from Skeiðarárjökull had little impact on the proximal surface of Skeiðarársandur beyond the confines of the entrenched channels that traverse it. Thus, the point-source dispersal system on Skeiðarársandur may not provide an exact analogue for the pattern of meltwater dispersal responsible for the sediment assemblage laid down during past jökulhlaups, and caution may be required when comparing conditions on Skeiðarársandur to those presumed to have been experienced during massive outburst floods elsewhere.

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Introduction

Distributary channels on outwash plains, or sandur, are employed as prototypes of braided river systems, and information about fluvial processes and lithofacies, derived from studies of active sandur, underpins depositional models of braided alluvium (Rust, 1978). Patterns of erosion and deposition on sandur also provide analogs for the Martian surface in the vicinity of the Viking 1 and Mars Pathfinder landing sites (Rice and Edgett, 1997). Glacier outburst floods, or jökulhlaups, have generated some of the largest known terrestrial freshwater flows, and in locales where large volumes of sediment are flushed from beneath glaciers they are instrumental in creating outwash plains, or sandur. Sandur appear to be dominated by sediments laid down during jökulhlaups rather than by braided river facies (Maizels, 1991, 1997). However, field observations have focused on the ablation-related flow regime (cf. Boothroyd and Nummedal, 1978), and little is known about how the meltwater dispersal system functions during jökulhlaups.

Satellite synthetic aperture radar (SAR) images and aerial photographs acquired immediately after and during the November 1996 jökulhlaup on Skeiðarársandur (Figs 1 and 2), provide a synoptic perspective of the drainage network during a large glacier outburst flood. This data, together with information derived from the literature, sequential aerial photographs (1945–97) and a postevent field survey, allow us to develop a conceptual model to illustrate how the geometry of the proglacial drainage system has developed over time.

Study area

Skeiðarársandur has an area of 1350 km^2 and is the largest active glacial outwash plain on Earth. It is being constructed by braided rivers that emanate from Skeiðarárjökull, an outlet glacier on the southern margin of the Vatnajökull ice cap (Fig. 1). Meltwater emerges through numerous subglacial tunnels at the ice front (Rist, 1955; Churski, 1973). Three large braided stream systems channel water and sediment from the glacier onto Skeiðarársandur (Figs 1 and 2). The Skeiðará and Núpsvötn rivers route run off from the glacier margins directly onto the sandur. The Gígjukvísl River is fed by meltwater from the central and west-central sections of Skeiðarárjökull, which collects in the proglacial zone before being routed on to the sandur. Overflow channels, such as the Háöldukvísl and Seluhússkvisl, are activated during jökulhlaups when water ponds in the proglacial zone.

The proglacial zone behind the terminal moraine complex is widest in the west, where a ~ 1 km wide, Ç25 m deep ice-marginal depression developed between 1931 and 1960 (Fig. 2). The ice front is Ç15 m lower than the proximal sandur surface, except along Skeiðarárjökull's east-central margin. The moraine complex also becomes topographically less distinct toward the east, where it is being overridden. No terminal moraine is preserved beyond Skeiðarárjökull's eastern margin, where the ice-marginal depression is Ç250 m wide and Ç14 m deep. An incised braided channel system is preserved on the T3 surface east of the ice-marginal depression. Further west, where the moraine complex is present, the T3 surface comprises an apron of small, coalescing, coarse-grained outwash fans that merge with the sandur surface at a point Ç4 km beyond the gaps from which the feeder channels emerge (Klimek, 1973).

Active channels beyond the proglacial zone are entrenched and bordered by a sequence of three terraces. The (highest) T3 terrace surface lies between 13 and 20 m above the floors of these channels (Fig. 2). The active channel area of the Skeiðará, Núpsvötn, and Gígjukvísl rivers becomes

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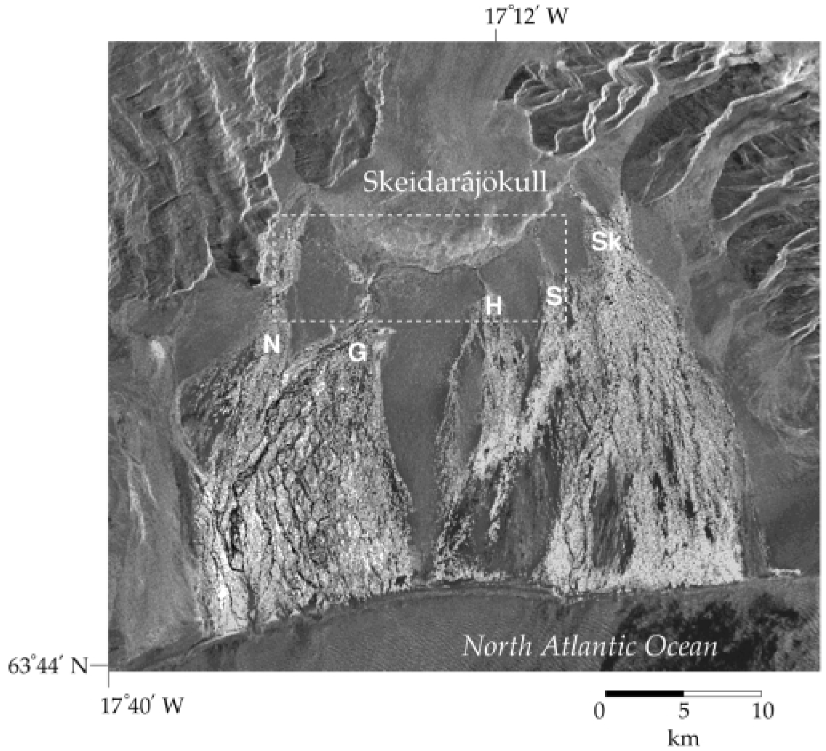

Fig. 1 ERS-2 SAR intensity (backscatter) image of Skeiðarársandur, acquired on November 7 1996. The maximum extent of the outbust flood is indicated by high levels of radar backscatter, which are probably caused by enhanced surface moisture levels and/or frozen floodwater. Flow across the sandur is from North to South. Meltwater supplied from the point-source distributary system can be seen to spread out over an increasingly large area down-sandur once the channels that traverse the proximal zone, which are incised 13 and 20 m below the highest T3 terrace surface (delineated by low levels of radar backscatter), merge with the sandur surface. N = Núpsvötn, G = Gígjukvísl, and Sk = Skeiðará rivers. H = Háöldukvísl and S = Seluhússkvisl overflow channels. The dashed rectangle delimits the detail of the proximal zone and ice-marginal depression shown in Fig. 2.

progressively wider and less well-defined down-sandur. A complex system of shifting braid channels develops within 3–8 km from the ice front, as the channels merge with the sandur surface, and in the distal zone the flow is transformed into a shallow, discontinuous sheet of water. When the three river systems merge during high flows, the intermediate and distal portions of Skeiðarársandur are almost completely inundated (Figs 1 and 3).

The largest outburst floods on Skeiðarársandur are associated with volcanic eruptions beneath Vatnajökull (Björnsson, 1988). They usually start in the Skeiðará River, although at their peak meltwater emerges from multiple outlets along the 28 km wide ice front (Rist, 1955). The November 1996 jökulhlaup was conspicuous for its short duration and extraordinary magnitude. In two days Ç3.8 km^3 of water drained from Grímsvötn. The cumulative peak discharge was Ç4.5 $\times$ 10^4 m^3 s^{-1} (Snorrason *et al.*, 1997). Field survey and correlation mapping using temporal sequences of SAR images revealed that during the 1996 jökulhlaup, patterns of erosion and deposition in the proglacial zone were highly localized (Russell *et al.*, 1999; Gomez *et al.* in press; Smith *et al.* 2000). The ice-marginal depression and ice-parallel drainage network also regulate the size of the sediment supplied to the proximal portion of the sandur. This engenders a corresponding change in the slope of the rivers that traverse the proximal zone, which occurs in the absence of any change in the meltwater flow or sediment supply regimes. The bed material fines rapidly with increasing distance from the ice front and the slope of the Gígjukvísl River is lower than that of: (i) the Skeiðará Rivers (whose meltwater sources are not buffered by the ice-marginal drainage system); (ii) the slope of the main ice-marginal channel within the proglacial zone (where much coarse sediment was deposited); and (iii) the slope of the T3 terrace surface which was active when the ice front was coupled to the sandur (Fig. 4).

Despite the high discharge and although the Háöldukvísl and Seluhússkvisl overflow channels were activated, only Ç24% of the proximal zone was inundated (Figs 2 and 3). In effect, the entrenched channels permitted the event to bypass the proximal zone. The geometry of the distributary channels, patterns of erosion and deposition, and presence of inactive surfaces in the proximal zone during the 1996 outburst flood, thus contrast with the historical and stratigraphic evidence for a complex braided channel network and system of coalescing outwash fans coupled to the ice margin (Churski, 1973; Maizels, 1991), and require explanation.

Proglacial drainage evolution

In the case of glaciers flowing over an unlithified sediment bed, the potential for evacuating large amounts of sediment from beneath the ice front increases during jökulhlaups, when the flow in the vicinity of the ice margin is dispersed across the bed (Rist, 1955; Björnsson, 1998). By contrast, during surges, basal drainage beneath Skeiðarárjökull occurs through a distributed network of passageways (Björnsson, 1998). At times when the position of the ice margin is relatively stable, the removal of sediment by repeated jökulhlaups, in combination with periodic surges, may facilitate lowering of the ice front and the elevation of meltwater outlets (Jónsson, 1955; Gustavason and Boothroyd, 1987). Once the base of the glacier drops below the elevation of the proximal sandur surface, meltwater which previously flowed directly onto the sandur is diverted parallel to the ice front. Evidence that erosion (rather than a drop in the rate of deposition, or aggradation and the construction of a high relief proximal surface during the time the glacier was coupled to the sandur) precipitated the change in the elevation of the ice front and was responsible for the formation of the depression is provided by the T2

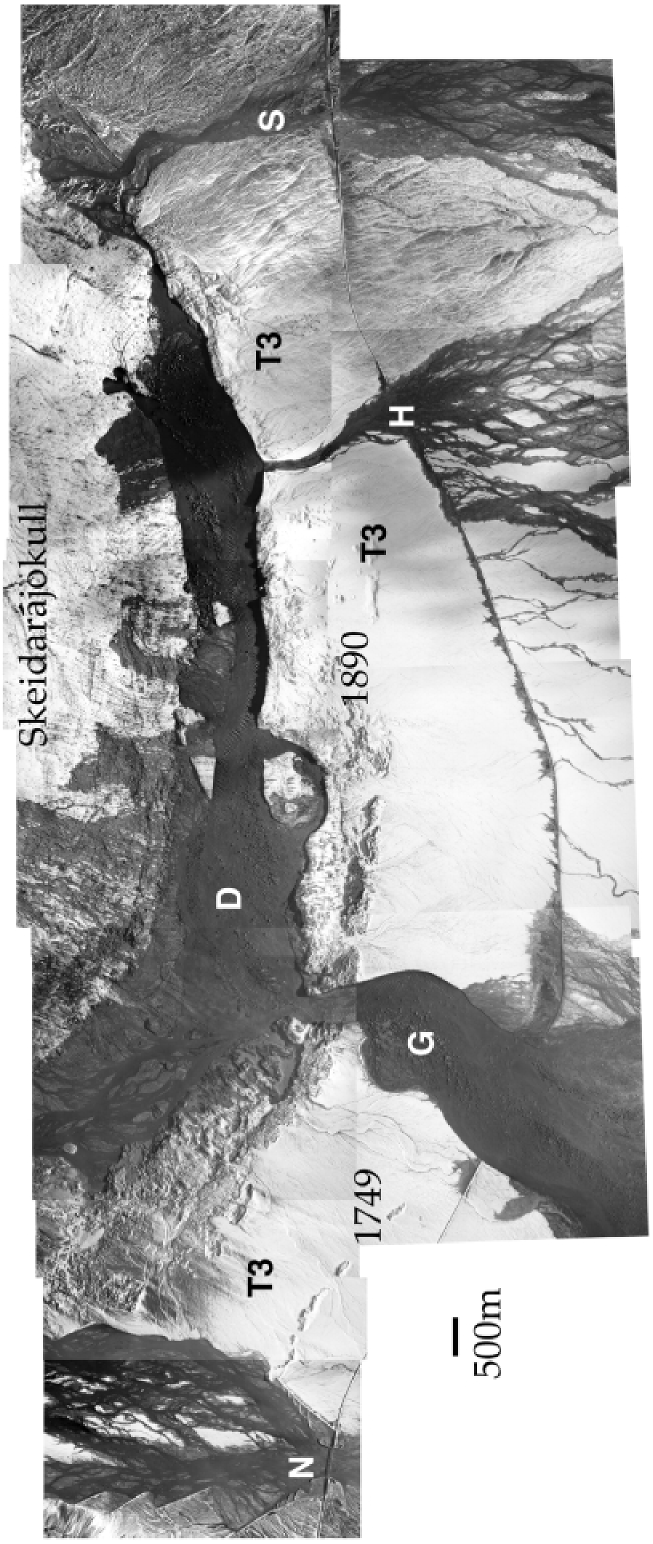

Fig. 2 The ice margin, flooded ice-marginal depression (D), and proximal sandur (T3 terrace) surface between the Gígjukvísl River and Seluhússkvísl overflow channel during the jökulhlaup (11 : 45, November 6 1996). N = Núpsvötn, G = Gígjukvísl, and Sk = Skeiðará rivers. The Háöldukvísl and Seluhússkvísl overflow channels are indicated by H and S, and the approximate position of the ice front in 1749 and 1890 by terminal moraines. The peak discharge in the Gígjukvísl River (G), which conveyed about 60% of the total volume of floodwater, was Ç1.9 × 10^4 m^3 s^{-1} (Snorrason *et al.*, 1997; Russell *et al.*, 1999). Inactive braided channels on the T3 terrace surface West of the Seluhússkvísl overflow channel are highlighted by the light snow cover. Compiled from aerial photographs ©National Land Survey of Iceland.

and T1 terrace surfaces, which border all the incised channels that traverse the proximal zone and are also present within the ice marginal depression.

Channels in the proximal zone that are not regulated by proglacial lakes respond to variations in the rate of glacier recession and sudden changes in the elevation of meltwater outlets around the ice margin by downcutting. Downcutting may be initiated by jökulhlaups and occur in a stepwise manner as the glacier recedes, or by the alternation of debris and water across a fan surface (Hooke, 1967; Thompson and Jones, 1986). It will be amplified by disturbances to the fan-source system, or by floods that exceed the threshold for channel entrenchment and, at times when active sliding cannot be sustained, may be encouraged by the presence of a tunnel drainage system that focuses subglacial drainage lines on a few outlets. There is also a commensurate drop in the level of the groundwater table beneath the sandur that modifies the runoff system, and helps isolate channels on the proximal surface by shifting the point at which effluent seepage contributes to the braided distributary system downslope (Churski, 1973). The potentiometric surface is lowered further as the ice front thins during periods of glacier retreat. In this manner we envisage that the diffuse, multipoint distributary system on the proximal portion of Skeiðarársandur (cf. Rist, 1955) was gradually transformed into the contemporary, integrated proglacial drainage network that is dominated by a few major outlets flowing through prominent topographic lows (Fig. 5).

Our interpretation of the sequence of proglacial drainage differs from that proposed for neighbouring outlet glaciers (Price and Howarth, 1970; Thompson, 1988), and other locales where rivers in the proglacial zone have been dammed or diverted by Little Ice Age deposits. This is because we do not consider that the change from a diffuse to an integrated distributary system is conditional upon the presence of a terminal moraine complex. The disintegration of the diffuse, multipoint distributary system may have been facilitated by the development of the system of high capacity subglacial tunnels that currently focus drainage on a few outlets and are maintained at times when active sliding does not occur (Björnsson, 1998). The terminal moraine complex also helped direct runoff parallel to the ice front (Galon, 1973). However, we believe the crucial factor affecting the evolution of the contemporary ice-marginal drainage system in front of Skeiðarárjökull is the behaviour of the ice front; specifically the lowering of the glacier bed below the elevation of the proximal sandur surface. Once initiated, the topographic discontinuity prevents meltwater from flowing directly onto the proximal surface, regardless of whether flow beneath the ice margin is dispersed or focused on a few outlets, and even during jökulhlaups runoff continues to be diverted parallel to the ice front (Figs 2 and 5).

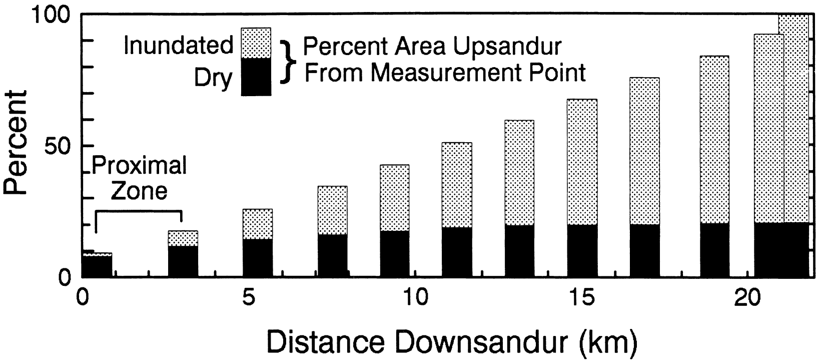

Fig. 3 Cumulative percent of Skeiðarársandur inundated by meltwater or remaining dry during the November 5–6 jökulhlaup estimated from the ERS-2 SAR intensity image of Skeiðarársandur, acquired November 7, 1996 (Fig. 1).

There are several indicators of the timing of the adjustment. Thórarinsson (1939) noted that although the active sandur surface began directly in front of Skeiðarárjökull it was Ç15 m higher than the glacier bed; some of the distributary channels on the T3 surface were also still active in 1945 (Churski, 1973). At that time, the ice front was located Ç1 km behind the 1890 moraine, several proglacial lakes were in evidence behind the moraine complex, and a rudimentary lateral ice-marginal drainage system had been established that routed flow to the Háöldukvísl channel. The Gígjukvísl River and numerous other topographic lows in the moraine complex were fully functional as overflow channels, routing water and sediment directly on to the sandur surface beyond the 1890 moraine. Jökulhlaups that occurred in 1945 and 1954 likely encouraged the development of an integrated proglacial drainage system. During the 1954 event, a coherent ice-marginal drainage system routed floodwater originating from beneath the centre section of Skeiðarárjökull along the ice front and into the Gígjukvísl River, which assumed its present course through the terminal moraine complex during the earlier 1945 jökulhlaup (Rist, 1955). The pattern of glacier retreat from the late C19 moraines in front of Skeiðarárjökull is replicated throughout south-east Iceland, and aerial photographs show that Skeiðarárjökull retreated 0.5–1.5 km in the period 1945–60. Krigström (1962) reported that groundwater supported a steam system beyond the western margin of terminal moraine complex, but by 1960 a completely integrated, ice-marginal drainage system that directed flow to the Skeiðará, Gígjukvísl and Núpsvötn

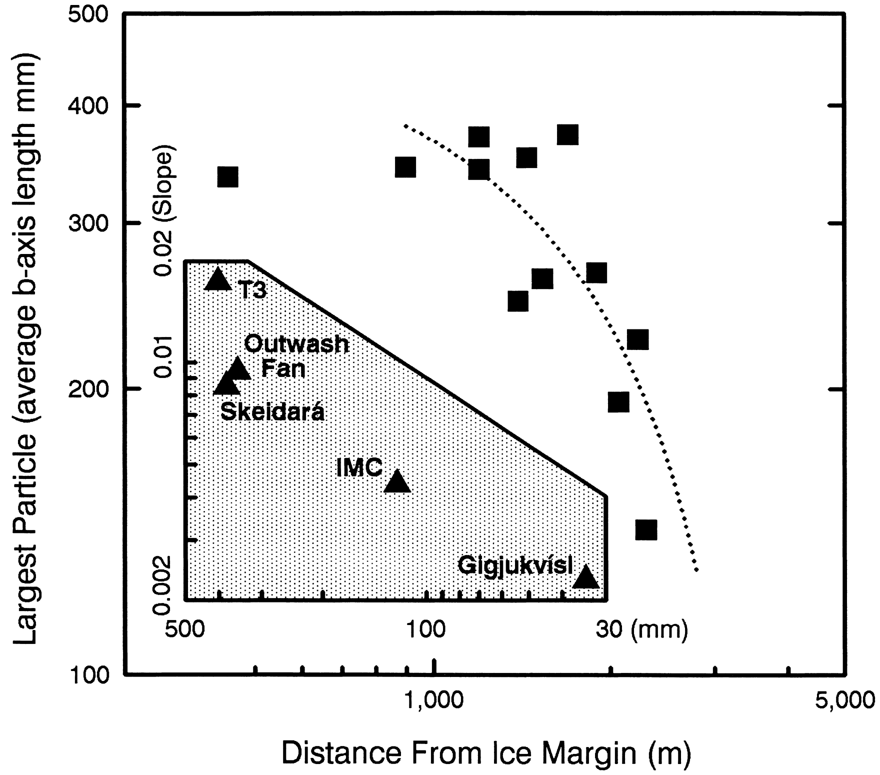

Fig. 4 Variation in average maximum particle size (derived from pebble counts) with distance from the ice margin on the outwash fan associated with the major subglacial outlet at the ice margin to the north-east of the Háöldukvísl overflow channel (see Fig. 2 for location). Inset: variation of slope with average maximum particle size for the T3 terrace surface between the Háöldukvísl and Seluhússkvisl overflow channels, the outwash fan, the Skeiðará River, the ice-marginal channel (IMC) downstream from the fan, and the Gígjukvísl River.

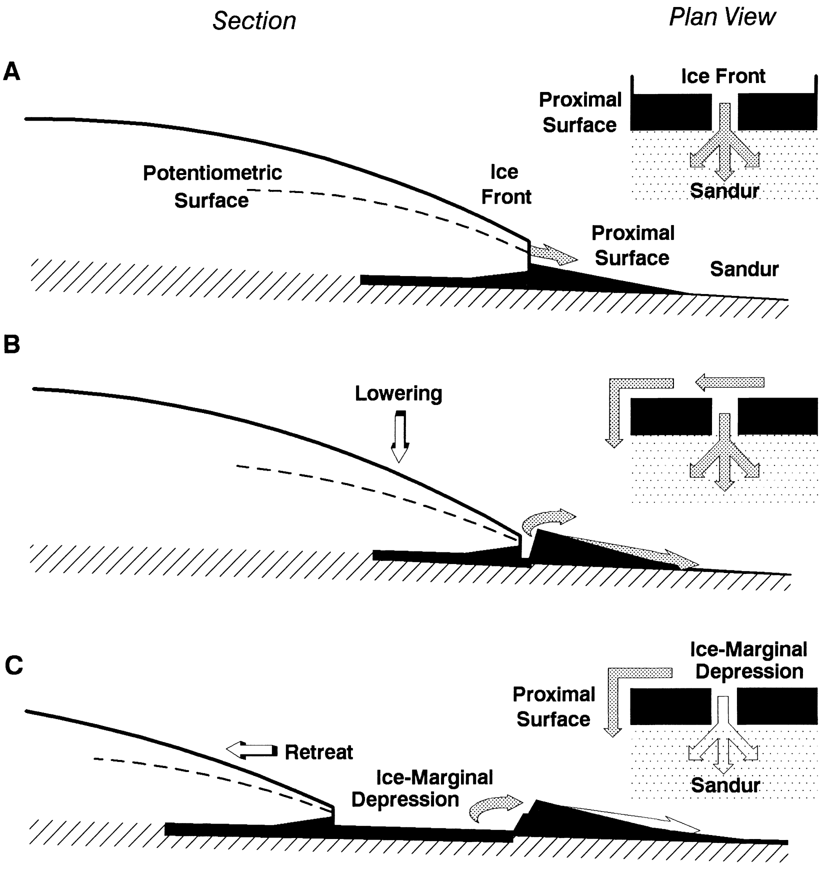

Fig. 5 Model for the metamorphosis of a distributed meltwater drainage system, beyond an initially stagnant, then retreating, ice front into a point-source network (see text for details). Stippled arrows signify active channels and open arrows overflow channels. (**A**) Glacier is coupled to the sandur and meltwater is routed directly on to the proximal sandur surface through a diffuse network of distributary channels. (**B**) Beneath a stagnant ice front, evacuation of sediment by meltwater under hydrostatic pressure creates an ice-marginal depression and lowers the elevation of the ice front. As the base of the glacier drops below the elevation of the proximal sandur surface meltwater is diverted parallel to the ice front as well as being routed to the distributary channels on proximal sandur surface. (**C**) Progressive lowering and retreat of the ice front isolate the distributary channels on the proximal sandur surface, and a lateral ice marginal drainage network develops that is dominated by a small number of primary outlets.

rivers had evolved, and the glacier had been almost completely decoupled from the proximal sandur surface. A diffuse proglacial meltwater dispersal system may re-emerge in the future and reactivate the proximal surface if the ice-marginal depression is infilled, the T3 surface is eroded, and/or Skeiðarárjökull readvances and thickens.

Conclusion

The contemporary configuration of channels in the proximal zone of Skeiðarársandur is atypical, since a diffuse, multipoint distributary system is required to sustain active accretion over the entire outwash plain (cf. Krigström, 1962). The shift from a diffuse to a channelized (point-source) distributary system on Skeiðarársandur appears to have had a significant impact on the magnitude and style of sedimentation in the proximal zone. This has implications for the interpretation of vertical and lateral lithofacies successions on Skeiðarársandur, and the development of a general facies model. The lateral lithofacies are a product of the contemporary meltwater distributary system, which by-passes the proximal zone during both low and high flows, and is dominated by a few large braided rivers that emerge from point sources to deposit their sediment load on the distal portions of the sandur, in a predictable pattern downstream (cf. Boothroyd and Nummedal, 1978). Maizels (1991, 1997) has argued that sandur are dominated by sedimentary sequences laid down during jökulhlaups rather than by braided river facies generated by an ablation-related flow regime, but the vertical lithofacies succession apparently reflects past conditions when the ice front was coupled to the sandur and a diffuse, multipoint meltwater distributary system supplied water and sediment to numerous coarse-grained outwash fans in the proximal zone (cf. Churski, 1973). Moreover, because coarse sediment is filtered out by channelized flows in the proglacial zone (Fig. 4), the development of a point-source dispersal system may give the appearance of increasingly distal conditions at any given locale in the proximal zone (cf. Maizels, 1997).

Observations of contemporary sediments and processes inevitably are used as analogues for ancient deposits. However, the hypothetical alluvial sequences generated for the proximal zone of Skeiðarársandur suggest that the previous pattern of sediment dispersal across the sandur differs from the sediment assemblage in the contemporary braided river systems. This is because the channels in the proglacial zone affect both the flow regime and spatial extent of discharge on to the sandur, and influence patterns of erosion and deposition and the preservation potential of sediment sequences (Maizels, 1997). Given the disposition of the active channels, facies exposed on the surface of Skeiðarársandur, especially in the proximal zone and mid-sandur region, are unlikely to be a product of contemporary fluvial processes. Moreover, care should be taken when employing the contemporary conditions and distribution of facies in active channels crossing Skeiðarársandur as an analogue for sedimentary deposits that are presumed to have been caused by catastrophic flooding in other locales, including planetary surfaces.

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