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F. J. Magilligan
Dartmouth College

B. Gomez
Indiana State University

L. A. K. Mertes
University of California, Santa Barbara, CA

L. C. Smith
University of California, Los Angeles, CA

Norman D. Smith
University of Nebraska-Lincoln, nsmith3@unl.edu

See next page for additional authors

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Authors

F. J. Magilligan, B. Gomez, L. A. K. Mertes, L. C. Smith, Norman D. Smith, D. Finnegan, and J. B. Garvin



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Geomorphic effectiveness, sandur development, and the pattern of landscape response during jökulhlaups: Skeiðarársandur, southeastern Iceland

F.J. Magilligan^{a,*}, B. Gomez^b, L.A.K. Mertes^c, L.C. Smith^d,
N.D. Smith^e, D. Finnegan^b, J.B. Garvin^f

^a*Department of Geography, Dartmouth College, 6017 Fairchild, Hanover, NH 03755, USA*

^b*Geomorphology Laboratory, Indiana State University, Terre Haute, IN 47809, USA*

^c*Department of Geography, University of California, Santa Barbara, CA 93106, USA*

^d*Department of Geography, University of California, Los Angeles, CA 90095, USA*

^e*Department of Geosciences, University of Nebraska, Lincoln, NE 68508, USA*

^f*NASA/GSFC, Code 921, Greenbelt, MD 20771, USA*

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Abstract

By contrast with other historical outburst floods on Skeiðarársandur, the 1996 jökulhlaup was unprecedented in its magnitude and duration, attaining a peak discharge of $\sim 53,000 \text{ m}^3/\text{s}$ in $<17 \text{ h}$. Using a combination of field sampling and remote sensing techniques (Landsat TM, SAR interferometry, airphotos, and laser altimetry), we document the sandur-wide geomorphic impacts of this event. These impacts varied widely across the Skeiðarársandur and cannot be singularly attributed to jökulhlaup magnitude because pre-jökulhlaup glacial dynamics and the extant setting largely conditioned the spatial pattern, type, and magnitude of these impacts. Topographic lowering and asymmetric retreat of the ice front during the late twentieth century has decoupled the ice sheet from the moraine/sandur complex along the central and western sandur. This glacial control, in combination with the convex topography of the proximal sandur, promoted a shift from a primarily diffuse-source braided outwash system to a more point-sourced, channelized discharge of water and sediment. Deposition dominated within the proglacial depression, with approximately $3.8 \times 10^7 \text{ m}^3$ of sediment, and along channel systems that remained connected to subglacial sediment supplies. This shift to a laterally dissimilar, channelized routing system creates a more varied depositional pattern that is not explicitly controlled by the concave longitudinal profile down-sandur. Laterally contiguous units, therefore, may vary greatly in age and sediment character, suggesting that current facies models inadequately characterize sediment transfers when the ice front is decoupled from its sandur. Water was routed onto the sandur in a highly organized fashion; and this jökulhlaup generated major geomorphic changes, including sandur incision in normally aggradational distal settings and eradication of proximal glacial landforms dating to $\sim \text{A.D. 1892}$. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Floods; Jökulhlaups; Facies models; Outwash; Sediment

* Corresponding author. Tel.: +1-603-646-1475.

E-mail address: Magilligan@dartmouth.edu (F.J. Magilligan).

1. Introduction

During the past several decades, geomorphologists have reevaluated the association of extreme floods and landscape/landform development. Research in the 1960s and early 1970s examined the spectrum of geomorphic change of riparian and floodplain systems broadly within the rubric of magnitude–frequency relationships, generally focusing on alluvial response to instantaneous peak discharges generated by precipitation-driven events (Wolman and Miller, 1960; Dury, 1973). Shortly thereafter, focus shifted to a more inclusive incorporation of nonprecipitation-driven outburst floods, such as those usually associated with catastrophic drainage of Pleistocene glacial lakes (Baker, 1973; Kehew and Lord, 1987; Jarrett and Malde, 1987; Baker and O'Connor, 1992), jökulhlaups (Church, 1972; Maizels, 1989), and/or dam-failure floods (Costa and O'Connor, 1995). These thematic shifts redirected attention away from a somewhat restrictive and possibly inappropriate magnitude–frequency paradigm where statistical assumptions of extreme value analysis of annual floods poorly correspond to the nature of the driving mechanism, the time scale in question, or even to the appropriate metric of a flood's magnitude.

Rather than focusing on discharge to express driving inputs of potential change, many geomorphologists instead use hydraulic expressions of energy availability and dissipation to characterize flood magnitude (Baker and Costa, 1987) and have broadened the analysis to examine the geomorphic legacy and overall effectiveness of floods (Wolman and Gerson, 1978), especially those not related to rainfall–runoff events. Recent research has further shown that the type and magnitude of geomorphic effects may also be controlled by the duration of maximum energy expenditure. Analyzing the geomorphic effects of two large dam-burst floods in the western US, Costa and O'Connor (1995) demonstrated the minimal geomorphic impacts of these short-lived floods. Although these catastrophic floods attained maximum flood powers commonly associated with major riparian change (Kochel, 1988), minimal geomorphic impacts occurred as the flood hydrograph was of minimal duration. Thus, the geomorphic effectiveness of a flood depends upon both energy availability and flood duration, with the former controlled by both water-

shed scale (drainage area, drainage density, etc.) and local effects (valley slope, valley constraints, channel conveyance) and the latter controlled in part by the flood-producing mechanism.

In this paper, we analyze the geomorphic impacts of the 1996 jökulhlaup (Icelandic term for sub-glacially generated outburst floods) on Skeiðarársandur in SE Iceland and embed the hydro-geomorphic impacts of this flood within the broader Holocene and late historical development of the Skeiðarársandur. This flood provides a rare opportunity to examine the geomorphic impacts of an event of unusual scale, providing a potential analog for unmeasured historical and Pleistocene events. By using remote sensing techniques including satellite synthetic aperture radar (SAR), Landsat TM, and laser altimetry in combination with field-based methodologies, we discuss the geomorphic signature of this catastrophic flood that generated extreme peak discharges $>5 \cdot 10^4 \text{ m}^3/\text{s}$, maximum localized stream power of $>4 \cdot 10^4 \text{ W/m}^2$ (Russell and Knudsen, 1999a,b), and an extremely rapid time to peak hydrograph of approximately 17 h (Snorrason et al., 1997).

The peak discharge of this recent jökulhlaup ranks it as one of the largest historical floods and as great as some of the largest paleo-floods ever estimated. The estimated maximum discharge of $5.3 \cdot 10^4 \text{ m}^3/\text{s}$ for the 1996 jökulhlaup exceeds the Mississippi River flood of 1993, which had a peak discharge of $1.2 \cdot 10^4 \text{ m}^3/\text{s}$. In many ways, this jökulhlaup mimics the type of floods analyzed by Costa and O'Connor (1995): it is a single-source flood of extreme runoff. Despite its enormous discharge and high maximum flood power, the geomorphic impacts of this jökulhlaup are difficult to ascertain and contextualize, in part because establishing what constitutes catastrophic change in these alluvial settings is somewhat unclear. Most fluvial definitions of catastrophic relate to alluvial channels contained within valleys; and they generally use geomorphic indices such as significant channel erosion (Kochel, 1988), floodplain stripping (Nanson, 1986), or interruption of floodplain fining-upwards sequences by overbank gravel deposition (Ritter, 1975) to characterize the destabilizing nature of the flood. However, such analyses have hitherto not been performed for unconfined flows across glacial outwash plains (“sandur” in Icelandic). Characterizing a flood as catastrophic in these alluvial settings lacks appropriate

metrics in part because such floods have rarely been observed or because insufficient analogs exist. Because of the distinct suite of geomorphic influences, this flood generated significant depositional and erosional features in both proximal and distal settings. As presented herein, the pre-jökulhlaup pattern of ice retreat and the extant sandur depositional setting largely conditioned the spatial pattern, type, and magnitude of these impacts. The broader spatial dimension provided by remote sensing techniques, combined with pre- and post-jökulhlaup topographic information across the sandur, provides us the opportunity to explain the impacts of this flood in relation to the late Holocene depositional history of the sandur and the hydrologic conditions occurring during the event itself.

2. Geomorphic setting

The Skeiðarársandur, Iceland's largest (1300 km²) glacial outwash plain, has been well-studied, and there is a long record of jökulhlaups and ice front positions (Thórarinnsson, 1939; Thórarinnsson et al., 1974; Maizels, 1991, 1997; Gudmundsson et al., 1995, 1997; Williams et al., 1997). Water and sediment delivered to the sandur are derived from Skeiðarájökull, a lobate outlet glacier of the Vatnajökull ice cap (Fig. 1). Seasonal meltwater generally contributes to sediment transport, but episodic jökulhlaups exert the dominant control on its long-term development (Maizels, 1991, 1997). On Skeiðarársandur, the largest jökulhlaups result from eruptions beneath Vatnajökull that raise the level of a subglacial lake within the Grimsvötn caldera, which then drains catastrophically (Fowler, 1999). Although jökulhlaups commonly occur on the Skeiðarársandur, the 1996 jökulhlaup was unprecedented in its discharge and time to peak for historically occurring events (Tweed and Russell, 1999) exceeding the discharge of some of the largest jökulhlaups across Skeiðarársandur during the past 100 years (Rist, 1957; Nummedal et al., 1987). The November 1996 event was preceded several months earlier by significant subglacial volcanic and hydrologic activity, including changes in ice topography and sliding velocities (Gudmundsson et al., 1997; Alsdorf and Smith, 1999) and the development of a subglacial hyaloclastite ridge, caused by the phreatomagmatic eruption (an explosive magma–water interaction), approximately 6–7 km

long and 200 m. By early November, approximately 3.5 km³ of water was stored within the subglacial lake of the Grimsvötn caldera. The lake ultimately failed on November 4, and the water took ~10 h to reach the glacier terminus.

Although the Skeiðarársandur developed primarily during the Holocene, the impact of the 1996 jökulhlaup is better contextualized relative to late historical ice dynamics. The recent array of subglacial and proximal proglacial processes and deposits largely governs the resulting geomorphic impacts. The Skeiðarájökull, and thus the loci for sediment and water discharge, has shifted considerably over the past 350 years. All but obliterated or buried across the sandur, a small patch of a late Holocene (Little Ice Age?) moraine exists on the western edge of the sandur ~2 km beyond the A.D. 1892 end moraine. The lee of the younger, proximal moraine contains major outwash channels; and, where dissected, these notches typically possess an easily recognized stepped sequence of largely unpaired terraces. Eight terrace flights, with the oldest dated to ~A.D. 1892, are recognized along the Kotá River on the far eastern end of the Skeiðarársandur. Because these terraces are strongly linked to localized ice dynamics and not necessarily to shifts in sediment supply and delivery (Thompson and Jones, 1986), correlation between even adjacent drainages may not occur. For our study area of the Skeiðarársandur, three to four terrace sequences commonly exist with at least 20 m of relief from the lowest (T1) to the highest (T3) terrace, with strong differences in gradient and particle size occurring.

Despite its recent recessional history, the Skeiðarájökull has experienced major advances and still-stands in the past 100+ years, with a well-recorded surge in 1991 (Williams et al., 1997; Björnsson, 1998). The position of the ice front has been spatially irregular, and a well-pronounced asymmetry exists between the 1892 moraine and the modern ice terminus generating a wedge-shaped proglacial zone widening to the west (Klimek, 1973). The proximal proglacial zone is 2–3 km wide in the western portion of the sandur, but the eastern part of the ice sheet by the Skeiðará River currently abuts the moraine and sandur. The decoupling of the ice front from its sandur and moraine in the central and western part of Skeiðarársandur creates a prominent proglacial depression at least 50 m below the moraine crest, with the

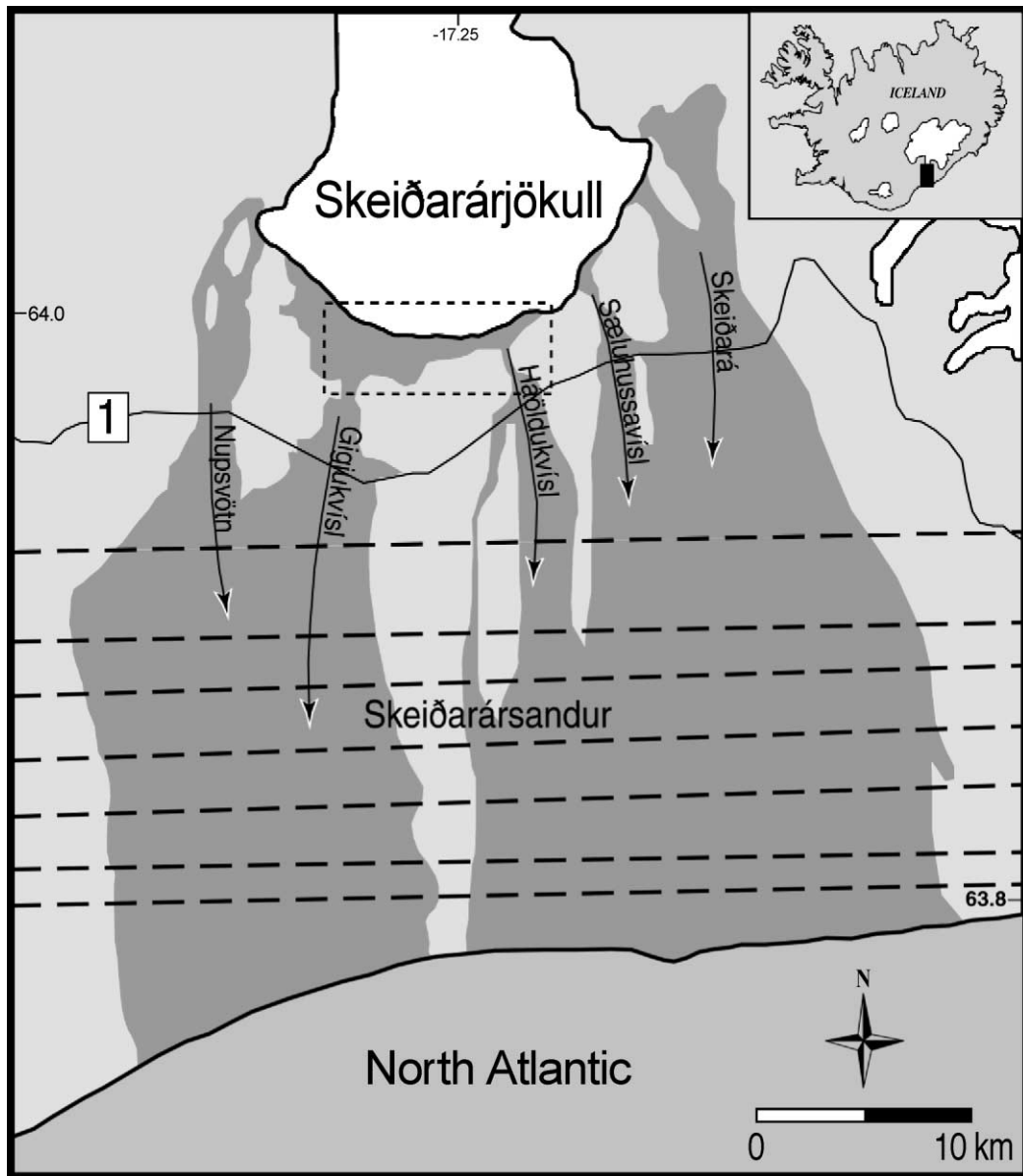


Fig. 1. Location map of field area in southeastern Iceland. Dashed lines across sandur indicate the flight lines for the laser altimetry profiling. Dark shaded areas on sandur show the areas inundated during the peak discharge. Note that the upper sandur, especially in the proximal sandur, remained relatively water-free. Dashed box near ice shows area in airphoto in Fig. 4.

ice front and its attendant drainage well below the elevation of the central sandur (Gomez et al., 2000). The position of the ice front relative to the moraine-sandur complex figures prominently in the geomorphic impacts of the jökulhlaup. This connection is further exacerbated by subglacial processes, espe-

cially in the eastern portion by the Skeiðará River where a well-developed ice tunnel runs directly from the overspill channel of the subglacial Lake Grímsvötn onto the sandur surface. This ice tunnel, estimated to be ~30 m in diameter, generates peak velocities of approximately 5–10 m/s during jökulh-

laups (Björnsson, 1998). Lacking the direct conduit to the jökulhlaup source, the central and western portions depend more on smaller subglacial channels that operate only during jökulhlaups to transport water and sediment. These subglacial processes, in combination with the proglacial proximal geometry, condition the modern development of the Skeiðarársandur and help explain the magnitude and type of geomorphic impacts of the 1996 jökulhlaup.

3. Methods

3.1. Remote sensing

3.1.1. SAR interferometry

Repeat-pass satellite synthetic aperture radar interferometry was used to estimate the distribution and net budget of sediment eroded or deposited by the jökulhlaup. Interferometric synthetic aperture radar (InSAR) is a recently developed geodetic technique that uses the phase information in two or more radar images to estimate topographic relief (with meter-scale precision) or displacement (millimeter- to centimeter-scale precision). Using data from the European ERS-1 and ERS-2 satellites, we constructed pre-flood and post-flood topography of the sandur using image pairs collected October 21–22, 1996 and January 1–2, 1997. Following a correction procedure to mitigate errors introduced by atmospheric and geometric noise, pre- and post-flood topography may be subtracted to yield a map of net topographic change caused by the flood (cf. Smith et al., 2000). This map was subsequently superimposed onto post-flood topography. Note that this image represents changes in surface elevation only. Positive values (net topographic increase) correspond with total depositional thickness only where sediment is deposited directly onto an original surface. Where scour occurred immediately prior to deposition, elevation change is reduced by the depth of scour. Integrating the net topographic change image over defined regions of the sandur allows estimation of topographic budgets representing net gain or loss of sediment from the 1996 jökulhlaup. Net topographic budgets were constructed for (i) the ice-marginal trench between the ice terminus and its moraine (13.8 km²); (ii) downstream area between the terminal moraine and Iceland's Highway 1 (25.8 km²); (iii) flow in breakout channels (4.2 km²);

and (iv) the entire proglacial zone, defined as the area between the ice terminus and Iceland's Highway 1 (39.5 km²).

3.1.2. Landsat TM

Remote sensing analysis of the sandur environment was possible using optical data from the Landsat Thematic Mapper collected prior to (September 11, 1996) and after (June 3, 1997) the flooding event. After coregistration of the images, change detection analysis was accomplished using a standard principal components analysis for temporal difference (Richards, 1993). The best bands for this analysis were Bands 7, 6, and 5. The results were coded by color to show the areas where the greatest amount of change had occurred.

3.1.3. Laser altimetry

The use of conventional remote sensing imagery for estimation of surface topography is often restricted by the lack of a third vertical dimension and is constrained to the horizontal resolution (m/pixel) of the imaging sensor (e.g., Landsat 30 m, Radarsat 25 m, and AVHRR 1.1 km). Conventional methodology involves combining image data with digital elevation models (DEM) in order to enhance surface topography, which in turn is limited to DEM availability. Alternatively, NASA's Airborne Topographic Mapper Laser Altimeter (ATM) sensor is an airborne-based laser altimeter providing high-resolution topographic data. The ATM sensor aboard NASA's P-3B aircraft operates at 2000–5000 pulses/s at a frequency-doubled wavelength of 523 nm in the blue–green spectral region, which is rotated along an elliptical (scanning) or direct sampling (profiling) pattern beneath the aircraft. By recording the round-trip time of the laser pulse, an estimated range measurement is received. During post flight processing, concurrent aircraft and airport kinematic differential GPS measurements are combined with the laser ranging data and aircraft roll, pitch, and heading parameters. This technique provides highly precise horizontal (~2 m) and vertical height locations (~100–200 mm) at ranges in excess of 1000 km from a GPS base station.

East-to-west-trending ATM profiles were acquired over Skeiðarársandur during the summer field seasons of 1996, 1997, and 1998. Preliminary cross-sections traversing the mid- and distal sandur were first

acquired in 1996. Repeat-pass profiles of the 1996 flight lines were reacquired in the early spring of 1997, capturing geomorphic development following the November jökulhlaup. In addition, new profiles of the upper and lower sandur latitudes were obtained, bringing the total cross profile count to seven.

Profile segments were initially reduced to the essential data elements (longitude, latitude, and elevation), sorted, and then filtered to remove outlier data points that resulted from laser interaction with atmosphere triggers (e.g., clouds, water, etc.) and vegetation. Fortunately, on Skeiðarársandur, the harsh climate and anthropogenic activity in the historical period have minimized vegetation growth, making the arduous task of vegetation filtering unnecessary. Once sorted and filtered, the data can then be represented in user-defined plots such as the cross-sectional plots located across the medial and distal sections of the sandur (Fig. 2).

3.2. Field methods

3.2.1. Sediment sampling

Sediment was sampled on freshly deposited surfaces across the sandur and down the main outlet channels. In the proglacial depression, coarse particles were measured on an ice-contact outlet fan immediately north of the Háöldukvísl spillway channel and also across several densely kettled ice-proximal bars. Sampling was undertaken as far east as the Skeiðará outlet and as far west as the Nupsvötn channel but was especially concentrated in proximal locations where the coarsest deposits occurred. For the Skeiðará River, over 80 coarse particles were sampled from the ice-contact source and from 20 km downstream. We further collected matrix samples across the sandur for textural analysis.

Sediment deposition was evaluated by several techniques, but primarily by repeat pass SAR interferometry. Remote sensing methods were combined with, and validated by, estimates of minimum sedimentation from kettle depths concentrated in three major zones: the proglacial depression ($63^{\circ}58.21' - 63^{\circ}59.32' \text{ N}$), the ice proximal Skeiðará River channel ($63^{\circ}59.32' - 64^{\circ}2.00' \text{ N}$), and down the Gígjukvísl channel beyond the moraine notch ($63^{\circ}54.11' - 63^{\circ}57.19' \text{ N}$). Sediment accumulation around stranded ice blocks provided a minimum depth of deposition during the jökulhlaup. In cases where the kettle occurred near a

fresh terrace, the terrace thickness was added to the kettle depth to generate total sediment thickness. Otherwise, the kettle depth alone was considered to represent sediment thickness.

3.2.2. Surveying

Surface transects across the sandur and terrace surfaces were measured with a TOPCON total station and prism. To facilitate reconstruction of the circum-Icelandic Highway following the jökulhlaup, the Icelandic Department of Highways placed numerous bench marks throughout the proximal sandur that were used to establish absolute elevations for our surveying. The total station was used to measure gradients of the sandur, terraces across the sandur, and channel profiles; and it was also used to tie in elevation of high-water marks and other critical control points. Cross-channel profiles were measured at the Gígjukvísl notch and the Háöldukvísl spillway channel. In combination with a well-established high-water mark, these cross-section data for the Háöldukvísl channel were input into HEC-RAS to model discharges through the spillway. HEC-RAS, developed by the US Army Corps of Engineers, calculates discharge and other hydraulic variables from field-derived channel data using a standard-step iterative process to reconstruct water surface profiles (cf. Hoggan, 1989).

GPS measurements were taken at survey stations and at numerous control points that could be easily identified on remote sensed images. GPS coordinates were recorded for all sediment sampling locations. A base station was maintained at the field camp, and data from the roving hand-held receivers were downloaded and differentially corrected daily.

4. Results

The geomorphic impacts of jökulhlaups have been generally documented by other workers, but our broad spatial coverage provided by remote sensing (combined with pre- and post-jökulhlaup data) allow a detailed analysis of the geomorphic impacts of the 1996 jökulhlaup. Jökulhlaups are common phenomena across the Skeiðarsandur and have had major effects on the alluvial architecture and geomorphology (Maizels, 1993b, 1997). The geomorphic impacts of the 1996 flood, however, are best appreciated relative

to the erosional and depositional setting existing prior to its occurrence.

4.1. Pre-1996 jökulhlaup setting

The shifting depositional loci across the sandur have generated prominent geomorphic variations both along and orthogonal to orientation of the major outwash channels (cf. Price and Howarth, 1970). Cross-sandur topography profiled by laser altimetry (Fig. 2) details a pronounced asymmetric convexity in the upper sandur, with the Háöldukvísl and Skeiðará Rivers in the central and eastern sections of the sandur, respectively, representing the major sediment point sources. Maximum elevations exist in the central portions, suggesting that the Háöldukvísl was the major point source of sediment during most of the late Holocene development. At present, however, the Háöldukvísl spillway channel is removed from the ice front by >1 km; and it lies 30 m above the present elevation of the proglacial outwash channel, effectively curtailing further sediment contribution to the sandur.

Recent aggradation is greatest in the eastern portion of the sandur. For an equal distance from the sandur

mid-section, the eastern half is topographically higher than the western half. This increased aggradation manifests in other geomorphic indices across the sandur. For example, our field surveys of alluvial surfaces predating and unaffected by the 1996 jökulhlaup further show that down-sandur gradients increase progressively eastward across the pre-1996 outwash terraces. Although particle size and gradient decrease downstream for each younger terrace, similar age terraces are steeper on the eastern edge (Fig. 3). Cross-sandur sedimentological differences also existed before the 1996 jökulhlaup. Sampling over 20 years earlier by Boothroyd and Nummedal (1978) revealed that for an equal distance downstream from the glacier terminus, bed material of the Skeiðará River was significantly coarser than the Gígjukvísl River on the western side.

The proximal proglacial topography was also significantly different prior to the 1996-jökulhlaup. Before 1996, the zone behind the A.D. 1892 moraine contained a distinct proglacial outwash channel and lake (Fig. 4). Immediately downstream of the proglacial lake, the outwash channels from the western and central sections of the Skeiðarájökull converged to form the Gígjukvísl River, which, prior to the jökulh-

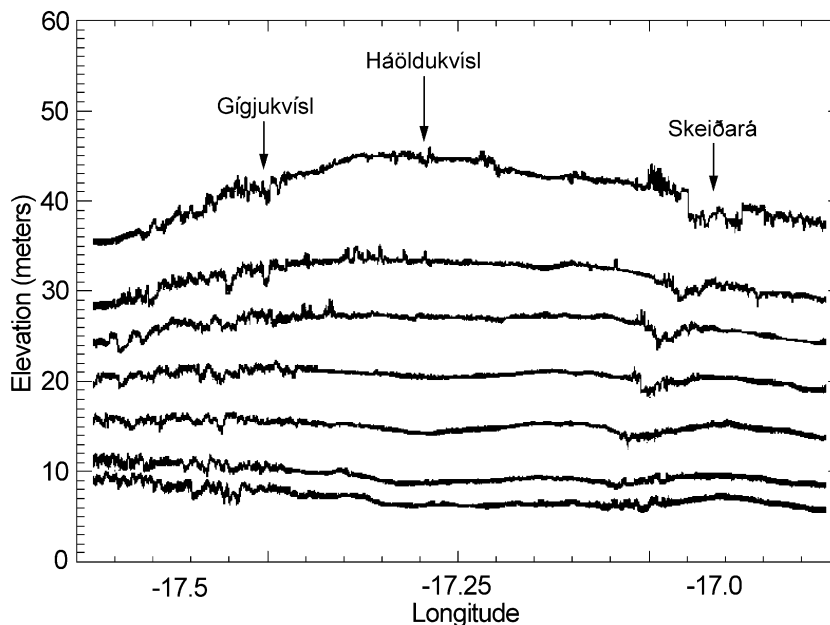


Fig. 2. Cross-sandur topographic profiles from laser altimetry for successive down-sandur transects (see Fig. 1 for locations).

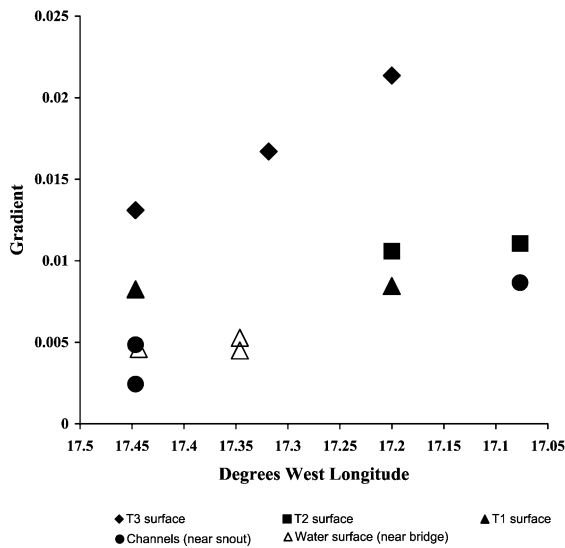


Fig. 3. Gradients for terraces (T1, T2, and T3), sandur surfaces and channels plotted against longitude. Trends demonstrate that for a given surface, gradients are progressively steeper moving eastward across the sandur.

laup, then flowed through an ~ 250 m wide gap in the ice-cored moraine (Bogacki, 1973).

4.2. Effects of the 1996 jökulhlaup

By approximately 7:20 a.m. on November 4, water and sediment discharged directly onto the sandur surface via the Skeiðará River, following the course of the ice tunnel link to the subglacial lake. During the next 9 h, discharge points developed progressively westward, with the peak total discharge of $53,000 \text{ m}^3/\text{s}$ being reached within 17 h (Sigurdsson et al., 1998). As the discharge outlets opened diachronously westward, water and sediment flowed directly from the ice terminus and upwards through crevasses several km upstream of the terminus. Subglacial water pressures detached the glacier from its bed, facilitating the calving of abundant ice blocks (several exceeding 30 m in length) and opening two large embayments several kilometers east of the Háöldukvísl spillway channel. These embayments enlarged up-glacier following existing tunnels and became the major sources of water and sediment to the proglacial depression. Using paleo-velocity techniques on bar and fan sediments immediately following the jökulhlaup, Russell and Knudsen (1999a,b) estimated peak velocities of ~ 10 m/s and

peak stream powers of $4 \cdot 10^4 \text{ W/m}^2$ for flows emanating from these embayments. Fan sedimentology evidences the intensely hyperconcentrated flows throughout the jökulhlaup, with poorly stratified to massive coarsening-upwards sequences deposited during the rising limb followed by hyperconcentrated waning-stage sequences of reworked sediments (Russell and Knudsen, 1999a,b; Russell et al., 1999).

Discharge onto and across the sandur surface was both temporally and spatially variable (Fig. 5). The asynchronous and spatially variable discharge pattern resulted from the varying degrees of connectivity to the subglacial lake, the existence of the pronounced proglacial depression, the narrow notch at the Gígjukvísl control point, and the topographic convexity of the sandur. Because of its topographic convexity and location of discharge points, not all of the sandur surface was inundated (Fig. 1). Large sections of the proximal sandur surface remained unflooded, especially in the central portions; and many other areas received flow only late in the flood. The Skeiðará River peaked early, while flooding to the west was delayed because flows started later and because considerable time was required to fill the proglacial depression. The Háöldukvísl channel in the central portion did not start to discharge until flood stages reached the spillway elevation, and our post-flood field surveys indicate that the water stage in this outlet channel was only 4 m above the spillway bed. The narrow pre-flood channel of the Gígjukvísl River limited flow onto the western region, further delaying the westward shift of the peak flow. The channel (which was cut into the ice-cored moraine) quickly widened increasing from a pre-jökulhlaup width of approximately 250 m (Bogacki, 1973; Galon, 1973) to over 500 m during the jökulhlaup. Once widened, the Gígjukvísl notch became a major source of water, sediment, and ice blocks, with flows sustained well after the Skeiðará River waned.

The spatial and temporal sequencing largely explains the variety of geomorphic impacts. To best describe and explain these impacts, we will examine these erosional and depositional impacts in proximal, medial, and distal sandur settings.

4.3. Proximal zone

The near-ice impacts varied spatially along an east–west gradient. The proximal zone can be sub-

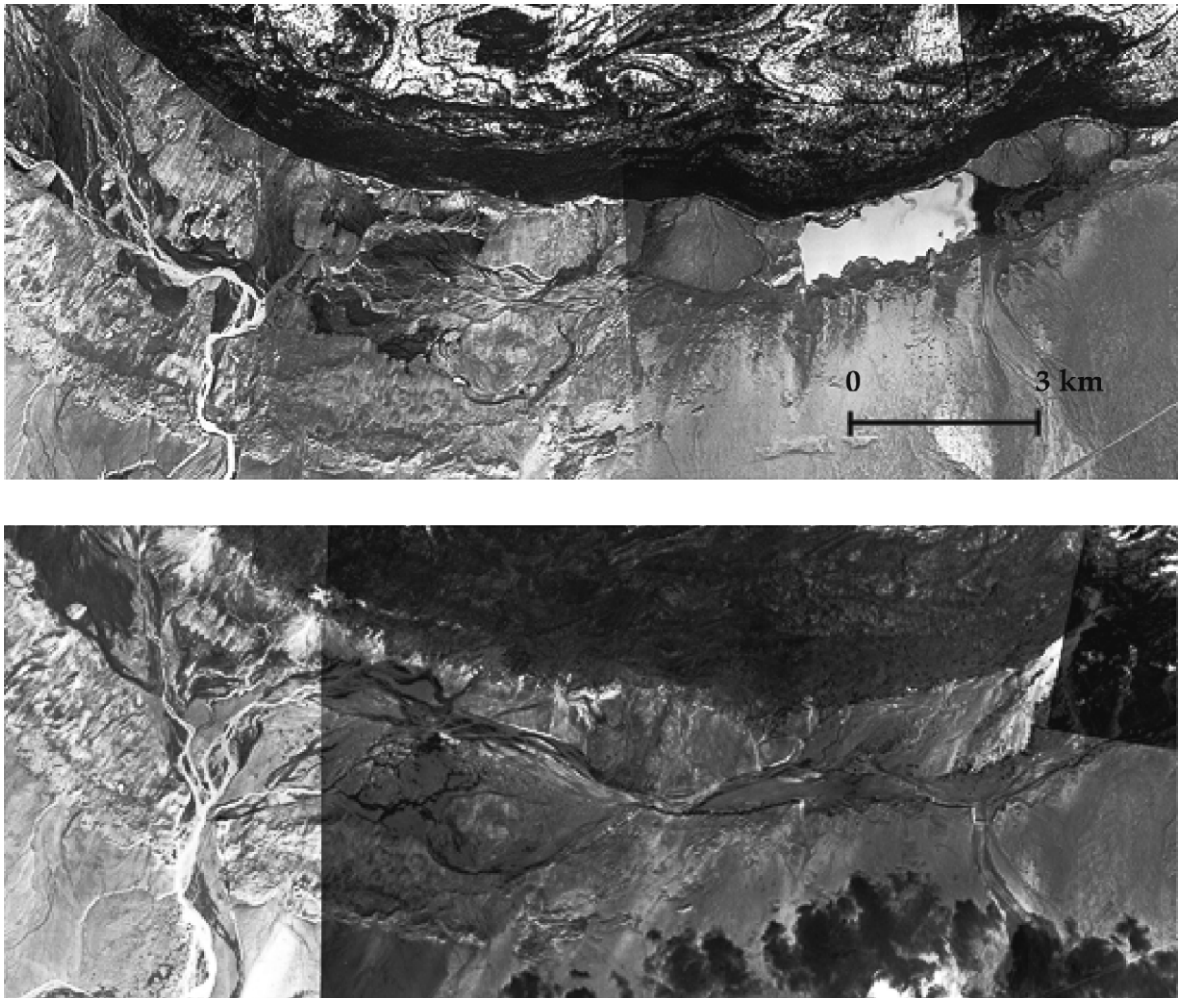


Fig. 4. Airphotos for the proximal sandur. Upper photo-mosaic is from 1992, 4 years before the jökulhlaup, and shows the proglacial topography and well-developed lakes. The bottom photo-mosaic was taken in April 1997, several months after the jökulhlaup, and shows the complete restructuring of the proglacial zone.

divided into the proglacial depression and the ice-contact moraine-sandur complex in the east. For the central and western portions, the end moraine and the proglacial depression significantly affected the deposition and erosional patterns. One of the more dominant effects was the complete restructuring of the proglacial proximal zone by both erosional and depositional processes. Pre- and post-jökulhlaup interferometry indicate that, for this zone, approximately $3.8 \times 10^7 \text{ m}^3$ of net deposition occurred (Table 1). This deposition was concentrated primarily in two 3-km long segments near the Háöldukvísl and Gígjukvísl

notch sites, with net increases in surface elevation exceeding 10 m near the embayment north of the Háöldukvísl spillway and immediately upstream of the Gígjukvísl river. Significant erosion of ice and sediment occurred in the Gígjukvísl River (particularly along the east bank, downstream of the ice-cored moraine), in outlet channels, and along both sides of the proglacial trench. Also, proglacial lakes evident in previous field mapping (Galon, 1973), in pre-flood InSAR data, and in airphotos were completely destroyed during the 1996 jökulhlaup. The complete modification of the proglacial zone attests to the

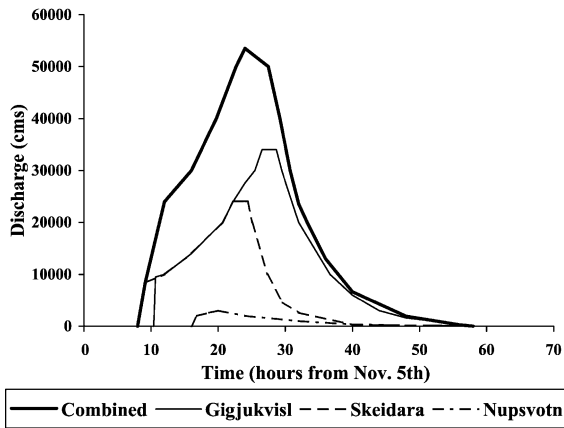


Fig. 5. Jökulhlaup hydrographs from the three major drainages (the Nupsvötn, the Gígjukvísl, and the Skeiðará) and the combined hydrograph (data from the Icelandic Department of Energy).

extreme magnitude of this event. Churski (1973) used the presence of the proglacial landforms upstream of the Gígjukvísl notch to argue that large jökulhlaups rarely emanate from the Gígjukvísl ice front source, yet the 1996 jökulhlaup completely eradicated these previous landforms.

Because of the extensive wedge-shaped proglacial depression and narrow Gígjukvísl notch, a strong backwater effect occurred, greatly enhancing deposi-

Table 1

Estimates of deposition and erosion from InSar (adapted from Smith et al., 2000)

	Area (km ²)	Depth (m)	Volume ($\times 10^6$ m ³)
<i>(1) North of Moraine (pro-glacial depression in proximal zone)</i>			
Erosion	5.9	-6.0	-35.3
Deposition	7.9	+9.2	+72.9
Net	3.8	+2.7	+37.6
<i>(2) South of Moraine (proximal zone beyond moraine)</i>			
Erosion	15.4	-3.20	-49.3
Deposition	10.3	+2.4	+24.5
Net	25.8	-1.0	-24.8
<i>(3) Entire proximal zone</i>			
Erosion	21.2	-4.0	-84.4
Deposition	18.2	+5.3	+97.2
Net	39.5	+0.3	+12.8
<i>(4) Breakout channels</i>			
Erosion	2.6	-4.1	-10.8
Deposition	1.6	+3.3	+5.3
Net	4.2	-1.3	-5.5

tion. Our field interpretations of sedimentary deposits support the interpretations of Russell and Knudsen (2001), who also found numerous deltaic facies assemblages throughout the proglacial zone. Most coarse-grained fluvial deposits that were formed during the initial stages of the jökulhlaup are capped by foreset and topset sequences, reflecting the waning stage flows generated into standing water in the proglacial depression. Our field mapping across broad fan-like deposits in the proglacial depression immediately north of the Háöldukvísl notch shows the relatively coarse-grained nature of the surface and its down-fan fining. Although deposited during waning flow stages, surface gradients across the 1000-m long fan remained relatively steep ($\sim 0.9\%$) with proximal maximum particle sizes of ~ 350 mm fining to 140 mm at the fan toe. Using data spanning the entire proglacial zone, a strong downstream-fining relationship exists (Fig. 6).

Sediment deposition dominated the ice-proximal zone. However, other significant geomorphic adjustments also occurred, including the major restructuring of the proglacial zone (Fig. 4) and the deposition of variously sized ice blocks (many exceeding 15 m) following the development of two large embayments in the center of the ice front. These stranded ice blocks generated kettle holes throughout the proglacial

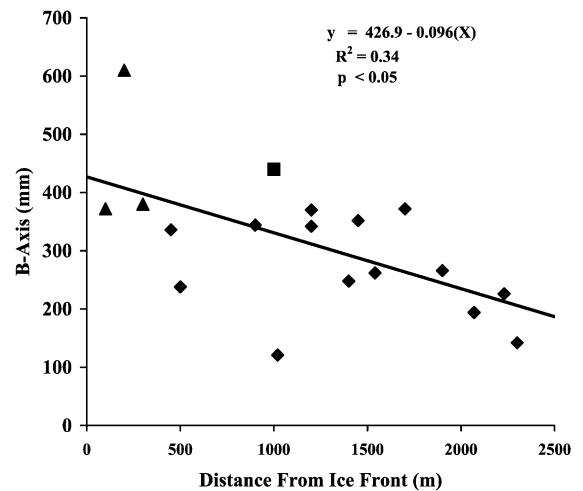


Fig. 6. Maximum particle size (*b*-axis) plotted against distance from ice for the ice proximal zone. Triangles are for the Skeiðará river source, squares are for the Nupsvötn, and the diamonds are for the pro-glacial zone due north of the Háöldukvísl notch.

depression. Although these kettles occur throughout the proglacial zone, the supply of ice blocks was generally restricted to a small area north of the Háöldukvísl notch in the sandur's center. Most of the calving occurred in two large embayments, ca. 140 m in diameter, which ultimately join to form a single channel in the ice front, ca. 150 m long and 80 m wide. Because the present ice terminus is significantly withdrawn from the A.D. 1892 moraine at this location, the ice blocks could only be transported within the proglacial depression or either deposited in or eventually routed out the Gígjukvísl notch. Once flushed through the notch, many of these ice blocks were deposited in a large expansion zone immediately downstream of the Gígjukvísl notch (Fig. 7). Many others, however, were transported and deposited more than 7 km downstream of the moraine. This irregular spatial pattern contrasts strongly with the kettle pattern observable on the A.D. 1892 moraine and higher T3 surfaces. Airphoto and field evidence across the moraine show a more uniformed but densely kettled surface. This more uniformed kettle distribution

resulted when the ice front was in contact with the moraine and proximal sandur. Because the proximal sandur and moraine are currently decoupled from the ice front, and a single dominant source of ice blocks existed during the 1996 jökulhlaup, a much more spatially restricted kettle distribution occurs, with mainly the proglacial depression and Gígjukvísl channel exhibiting ice-block depressions (Fig. 8). Numerous ice blocks were also stranded near the Skeiðará River source, but fewer ice blocks were calved in this section, resulting in a less kettled surface topography.

4.4. Channel impacts down sandur

The decoupling of the moraine from the current ice terminus left many of the proximal and medial sections of the sandur unaffected by the jökulhlaup. Because of sandur convexity, shifting sources of water and sediment discharge, and the asymmetric glacial retreat history during the twentieth century, sandur-spanning flood waters did not occur until well down the medial section (Fig. 1). The only continuous

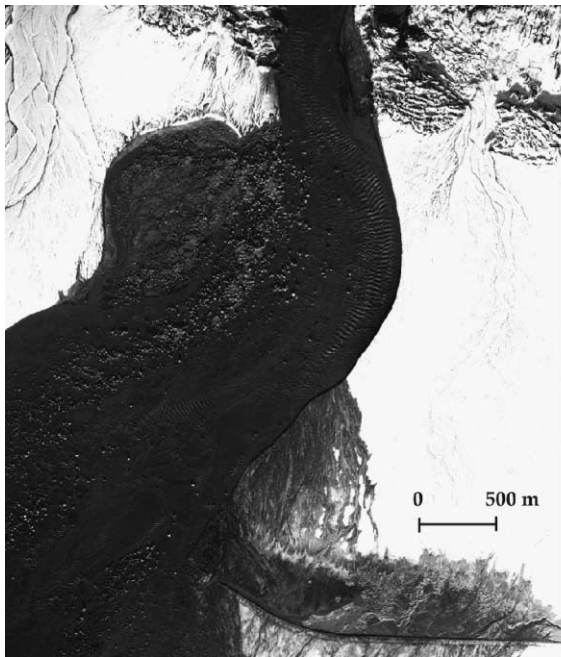


Fig. 7. Airphotos of ice blocks downstream of Gígjukvísl notch. Photo on left was taken on November 5, 1996, slightly after the peak discharge. Note the concentration of ice blocks in the expansion zone immediately downstream of the notch. Blocks are stranded on a large bar deposited in expansion zone. Photo on right is from December 12, 1997, and shows the deeply kettled depositional zone downstream of the notch and Highway 1.

Table 2

Results from HEC-RAS modeling for Háöldukvísl spillway channel

Discharge (m ³ /s)	1175.00
Mean velocity (m/s)	3.33
Maximum depth (m)	3.94
Minimum channel elevation (m)	85.34
Hydraulic radius (m)	2.91
Top width (m)	129.21
Channel cross-sectional area (m ²)	351.92
Energy grade line slope	0.0079
Water surface elevation (masl)	89.27
Shear stress (N/m ²)	230.90
Froude number	0.63
Unit stream power (W/m ²)	768.50

Mean for two cross-sections ~242 m apart.

down-sandur water sources were the Gígjukvísl, Skeiðará, Háöldukvísl, and Nupsvötn Rivers. The Háöldukvísl River, now acting solely as a spillway channel, can only be activated when the proglacial depression fills up to the Háöldukvísl notch (~88 masl). Even at its peak, estimates from high water marks indicate a maximum discharge of only 1175 m³/s (Table 2). Its

elevated spillway notch above the proglacial depression also precludes any significant sediment transport onto the sandur.

The Skeiðará and Gígjukvísl Rivers were the dominant point sources of water and sediment, but each possessed a distinctive geomorphic signature. With its point source in contact with the sandur, the Skeiðará River was able to transport and deposit sediment directly onto the sandur. Boulders with intermediate axes of ~500 mm were transported over 2 km from the ice front. Field sampling of bed material down the Skeiðará River revealed a prominent down-channel fining trend (Fig. 9). The downstream fining evident in the 1996 deposits differed slightly from bed samples collected over 20 years earlier by Boothroyd and Nummedal (1978). Although similar particle sizes occur in the medial and distal channel settings, our sampling indicated both coarser and finer material in proximal locations. Differences probably result primarily from our more inclusive sampling design where we sampled all coarse clasts ($n=80$) in reaches asso-



Fig. 8. Photo of kettles ~2 km south of Highway 1, downstream of the Gígjukvísl notch shown in Fig. 7.

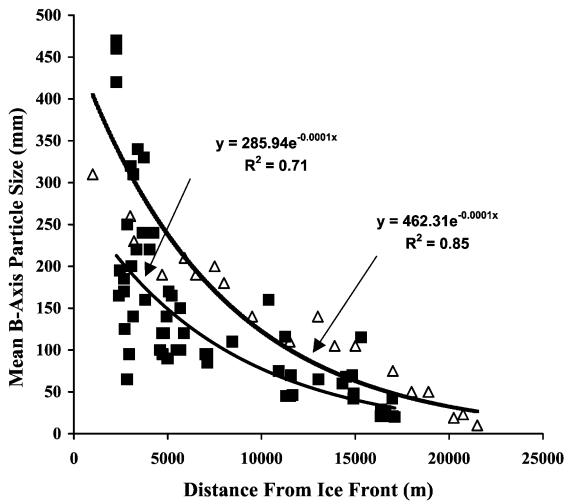


Fig. 9. Fining relationship down the Skeiðará River for coarse particles. Open triangles are from Boothroyd and Nummedal (1978), and solid squares are from our 1997 field sampling.

ciated with the flood, rather than their sampling of the single largest clast in a reach ($n=20$) that may not have been related to a single event.

A much different transport and aggradational regime occurred on the more western margins of the sandur. The backwater effect moderated transfer of sediment onto the western area, especially of coarser material. The asymmetric proglacial zone stored considerable volumes of sediment, and our estimates derived from pre- and post-flood interferometry suggest that this zone accounted for approximately $3.8 \times 10^7 \text{ m}^3$ of sedimentation (Table 1). Downstream of the Gígjukvísl notch, most of the aggraded material was gravel-sized and finer. Assuming kettle hole depth represents minimum thickness of aggradation, mean sediment thicknesses ranged from 1.05 to 1.57 m (Table 3), with the mean accumulation beyond the Gígjukvísl notch being significantly less than the mean depth of aggradation in the proglacial zone (at $\alpha < 0.05$). The planimetric characteristics of the kettles across the proximal sandur varied less than the depths, with the largest kettles being ~ 22 m in length by 14 m wide (Table 3). Grab samples of surface sediments downstream of the Gígjukvísl notch indicates that most of the material was sand (median particle size = 1.90ϕ), with less than 1.5% clay. This matrix differs somewhat from grab samples both on the

eastern sandur by the Skeiðará and from samples near the coast at the distal Gígjukvísl outwash. The eastern sandur has a somewhat coarser matrix (median particle size = 1.65ϕ), while the most distal sample has at least 10% clay and a finer overall matrix (median particle size = 1.84ϕ).

4.5. Geomorphic changes in distal settings

Because of the long distances from the source and the generally unconfined flow, most distal reaches are dominantly aggradational. Detailed cross-sandur profiling from laser altimetry across the medial and distal locations, in combination with Landsat imagery for the entire sandur reveals a dynamic sandur history. These broad coverages further demonstrate the shifting loci of activity and the occurrence of major channel development in these usually depositional settings. The asymmetric topographic convexity evident in the proximal and medial locations attenuates dramatically down sandur (Fig. 2) reflecting the new point sources of sediment supply. The topographically high mid-section bordering the present Háöldukvísl channel becomes topographically lower than the eastern and western margins at the sandur toe. This topographic inversion results primarily because the Háöldukvísl channel is currently cut off from the glacial sediment source. Conversely, the eastern areas supplied by the Skeiðará River remain in contact with the glacial water and sediment source, and the western areas are supplied by the Gígjukvísl River, which is linked

Table 3
Kettle dimensions and measured sediment thickness

	Kettle depth	Measured sediment thickness	Kettle length	Kettle width
<i>(A) Pro-glacial depression</i>				
Mean (m)	1.17	1.57	22.54	14.95
St. Dev. (m)	0.35	0.37	14.95	9.41
<i>(B) Skeiðára River (near ice front)</i>				
Mean (m)	1.08	1.66	22.85	13.71
St. Dev. (m)	0.44	0.76	17.56	8.06
<i>(C) Gígjukvísl (downstream of notch)</i>				
Mean (m)	0.80	1.05	18.28	18.89
St. Dev. (m)	0.33	0.52	n.a.	n.a.

Samples were taken throughout the pro-glacial depression, near the Skeiðará source, and downstream of the Gígjukvísl notch.

to the glacial sediment source although the widened proglacial depression inhibits significant coarse sediment transfer down sandur.

In addition to deposition, significant channel development occurred in the western and central portions of the distal sandur between the Gígjukvísl and Háöldukvísl outwash channels (Fig. 10). Such channel development in this normally aggradational setting attests not only to the catastrophic nature of the 1996 jökulhlaup but also to the role of relict features on the

sandur and to the twentieth century glacial retreat history. The lack of a direct and uninterrupted sediment source from the ice front greatly limits sediment supply; and flows here may have become sediment-starved, especially with the addition of sediment-free water from the Háöldukvísl spillway channel. Furthermore, the topographically higher mid-sandur may have acted to constrain the flow in this normally diffuse flow section, thus contributing to incision into the distal sandur.

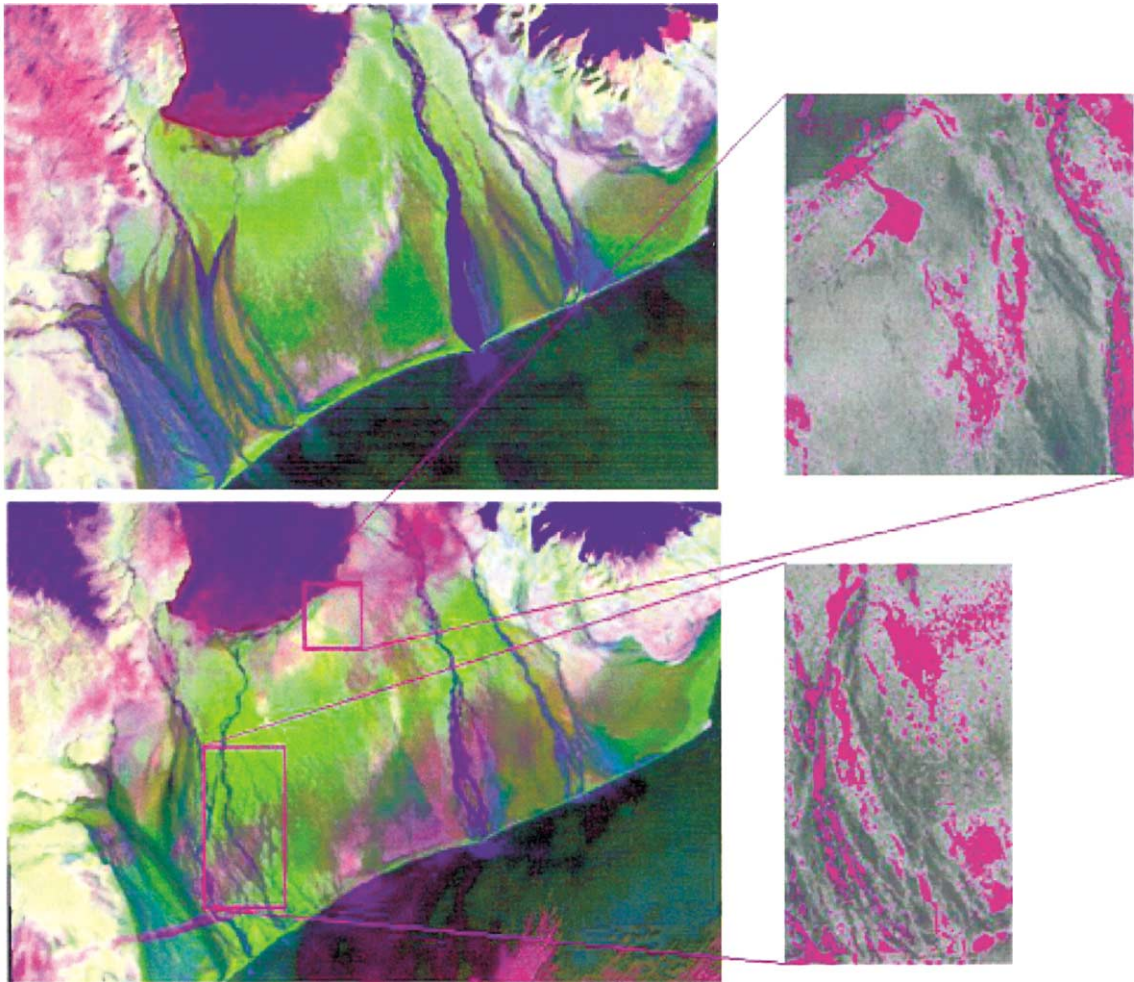


Fig. 10. Color composite images shown as red, green, and blue for TM Bands 746 for September 11, 1996 and June 3, 1997. The 746-color composite was selected to enhance the thermal differences (Band 6) because of the presence of glaciers and snow in the area. The detailed insets are color-sliced principal components images, where pink shows the areas that experienced the greatest amount of surface change between acquisition of the two images. In particular, the northern image shows the spillway notch of the Háöldukvísl River where new channels can be seen forming downstream of the outlet area. The southeastern image shows the area of formation of depositional features and channel carving off of the west bank of the Gígjukvísl River.

5. Discussion

The type, magnitude, and spatial patterns of geomorphic adjustments presented herein all point to the integrated controls of jökulhlaup magnitude, its occurrence relative to the ice front position, and the subglacial routes of water and sediment to the terminus. For the 1996 jökulhlaup, the pattern of erosion and sedimentation across the Skeiðarársandur was largely effected by the unusually large magnitude of the jökulhlaup and its rapid time-to-peak and was preconditioned by pre-event geomorphology, especially the asymmetric detachment of the glacier from its moraine. These controls combined to provide a patchy and spatially irregular pattern of erosion and deposition. This patchiness, however, does not imply randomness, as locations of geomorphic activity accord well with the location and type of controls. The dominant control on sandur development from the 1996 jökulhlaup is the shift from a diffuse, braided river system across the sandur to a more channelized, point source routing of sediment and water down-sandur. This shift away from a diffuse source flow ultimately left many areas of the sandur unaffected by the jökulhlaup and intensified the geomorphic effects in other areas.

5.1. Jökulhlaups and sandur development

The broad pattern of effects resulting from the 1996 jökulhlaup suggests a different conceptual model of sandur development. The typical diffuse and unchannelized flow across sandur has been frequently used as a prototype of the braided stream facies environment (Krigström, 1962; Bluck, 1974; Rust, 1978) and has been commonly associated with alluvial fan depositional models (Boothroyd and Nummedal, 1978). Our results point to several major differences in the conceptualization and application of these models. In particular, the down-sandur lithofacies pattern evoked by Boothroyd and Nummedal (1978) may only represent sandur development when the ice is coupled with its moraine/sandur complex and the jökulhlaup disperses relatively evenly across the sandur. Depending largely on the systematic decrease in both gradient and particle size down-sandur, their model assumes a smooth, concave longitudinal profile that is laterally continuous down-sandur. When the ice front is decoupled from the

moraine, however, the more channelized flow pattern creates an irregular depositional pattern that poorly resembles the smooth cross-sandur pattern envisioned by Boothroyd and Nummedal (1978). In our decoupled model, the proglacial depression becomes a major sediment sink that stores large sediment volumes for potential subsequent evacuation. Furthermore, the patchiness of water and sediment discharge across the sandur leaves large areas unaffected by the jökulhlaup and concentrates sediment transport and deposition down distinct sandur-marginal channels. Unlike the Boothroyd and Nummedal (1978) model, cross-sandur surface texture can be radically different, with sedimentologically similar surfaces being longitudinally dispersed down-sandur.

Comparison to alluvial fan deposition is not necessarily rejected with this decoupling model; however, a different analog is needed. The dynamic nature of ice retreat and jökulhlaup occurrence, in the context of existing sandur geomorphology, is perhaps more analogous to an avulsing and incising channel system across a previously aggraded fan surface. Similar to the alluvial fan depositional model proposed by Dorn (1988) and Hooke (1967), different age surfaces are preserved on the sandur surface and remain unaffected by floods/jökulhlaups. Thus, for a given downstream distance on the fan/sandur, significantly different deposits may occur, both in age and sedimentology. In this decoupling model, sedimentological and geomorphic variation may be more pronounced in the cross-sandur direction than down-sandur.

Lastly, channel network development in the distal sandur contrasts significantly from facies modeling in these sections. Sedimentological analyses in distal settings generally portray a dominantly aggradational regime (Maizels, 1989, 1993a,b). Down-sandur lithofacies assemblages generally consist of stacked vertical sequences generated by varying flow pulses occurring during the jökulhlaup and commonly result in cross-bedded and horizontally bedded units at the surface (Type “B3” lithofacies of Maizels, 1993a,b). Although these lithofacies models account for distal flow constrictions, large-scale channel network development (as occurred during the 1996 jökulhlaup) is not necessarily considered. Distal channel development revealed by laser altimetry and Landsat imagery suggests that incisional episodes may occur, contributing to the development of cut-and-fill sedimentary

sequences in these usually aggradational settings (Fig. 10). Channel incision may not always occur during jökulhlaups, but specific conditions may exist to engender their occurrence. Conditions for incision may be enhanced in a decoupled system where the flows become more channelized and when large sediment volumes are deposited and stored in the immediate proglacial depression.

5.2. *Geomorphic effectiveness and landscape persistence*

Evaluating and representing the magnitude or frequency of the extraordinary 1996 jökulhlaup is somewhat difficult. Unlike the geomorphic impacts of catastrophic floods in alluvial settings where a channel is confined within a valley, few analogs exist for jökulhlaups. These events also lack portrayal by traditional magnitude–frequency relationships that depend on extreme value theory of annual maximum floods. The closest comparisons are Pleistocene outburst floods, especially those unconfined in valleys, and of course other jökulhlaups across sandar. Major depositional features like large-scale bars and dunes, common in Pleistocene outburst floods (Baker, 1973; Lord and Kehew, 1987; Carling, 1996), are generally absent for the 1996 jökulhlaup. Broad, ice-contact lobate fans commonly occurred with maximum particle sizes >500 mm, but these landforms were generally restricted to the immediate proglacial zone.

Other measures, however, exist to represent the enormity of this flood, both in regard to its impact on the Skeiðarársandur and within broader geomorphic theory. Magnitude–frequency concepts are essentially irrelevant, and perhaps erroneous, here. A more appropriate measure of this jökulhlaup's impact and rarity is its overall effectiveness in molding the landscape and generating landscape features that will persist well into the future. Volcano-glacial jökulhlaups across sandar are not unlike hydrologic regimes and geomorphic conditions existing in semi-arid regions where large floods with enormous flood powers occur and are followed by long periods of inactivity. As Baker (1977) points out, deposits remain for considerable time in many alluvial settings in the SW United States as the necessary competency to mobilize large boulders can only be attained by infrequent flash floods. In geomorphic settings char-

acterized by a highly variable hydrologic regime and a high response threshold, the potential exists to transfer coarse sediment, but the long time between high magnitude events generates landforms and deposits that may have tremendous persistence. Thus, the effectiveness of an event needs to be evaluated both by what was accomplished during the event as well as its resulting geomorphic legacy (Anderson and Calver, 1977; Wolman and Gerson, 1978).

The effectiveness of this jökulhlaup and the persistence of its suite of landforms and deposits have long-term implications for the sedimentological development of the Skeiðarársandur. Sandar are frequently used as prototypes of braided river lithofacies assemblages, but Maizels (1993a,b, 1997) demonstrates that jökulhlaup occurrence is a critical, yet overlooked, component in facies development, primarily through their episodic contributions of alluvium. The sporadic sediment transfer down-sandur is systematically exacerbated in situations where the ice is decoupled from the moraine–sandur complex, as currently exists on the Skeiðarársandur. The persistence and legacy of the voluminous deposits in the proglacial zone has, and will have, profound implications for the resulting alluvial architecture down-sandur. Although significant down-sandur transfers of glacially derived material occurred during the 1996 jökulhlaup, sediment trapped within the proglacial depression will require $\sim 10^1$ – 10^2 (or longer) years to be effectively transmitted through the sandur system because the diffuse point source directly onto the sandur has currently been eliminated. Because of this decoupling, subsequent jökulhlaups may not have the capacity to transport the material to medial and distal settings, thus underscoring the geomorphic legacy of this event.

Another way to represent the geomorphic effectiveness of this flood is to characterize its erosional effects. Since gaging records are not adequate to develop accurate magnitude–frequency relationships in this hydro-geomorphic regime, determining its frequency is best established relative to the jökulhlaup's ability to modify or eradicate geomorphic landforms of known general age. Although jökulhlaups commonly occur on Skeiðarársandur, this is the first one in the twentieth century that greatly modified glacial features dating to the late nineteenth century (Churski, 1973). The ice-cored moraine at the Gígjukvísl notch widened over 100% from a pre-jökulhlaup width of ~ 250 m (Galon,

1973) to over 500 m, and ice proximal glacial deposits were completely eradicated during this jökulhlaup. These erosional impacts would therefore suggest an event of an occurrence of once, on average, in ~ 100 years. However, the channel development in the distal sandur may be an occurrence requiring a much greater recurrence interval. These surfaces are of unknown age but are probably at least late Holocene (Maizels, 1989). Erosion at the sandur toe would suggest an occurrence of approximately once in 10^3 years, but this is only an extreme estimate of the frequency of this impact.

6. Conclusions

The panoply of sedimentary and geomorphic features distributed throughout the sandur demonstrates a more dynamic picture of sandur development than previously recognized. The geomorphic impacts of the 1996 jökulhlaup cannot be explained solely by the magnitude of the jökulhlaup itself but must be combined with the conditions existing at the time of its occurrence, specifically the asymmetric decoupling of the ice front from the sandur during the recent recession. The magnitude and time-to-peak of this jökulhlaup may have been unprecedented in historical times, but the type and pattern of geomorphic impacts cannot be exclusively ascribed to the hydrologic characteristics of the jökulhlaup. The concentration of water and sediment discharge into distinct channels, especially on the eastern margins along the Skeiðará River, governed the geomorphic pattern. The greater sediment flux along the Skeiðará can be seen in the coarser sizes of channel bed sediment, relative to the Gígjukvísl River, and the down-sandur sediment wedge revealed by laser altimetry (Fig. 2). Due to a well-developed pro-glacial depression, sediment storage dominated in the central and western portions of the proximal sandur, although the Gígjukvísl River had sufficient capacity to transport considerable volumes of finer material beyond the moraine. The ice-marginal drainage that developed during ice retreat has now abandoned the topographically higher sandur mid-section by the Háöldukvísl spillway channel, previously the major outlet for water and sediment.

The decoupling of the ice front from the sandur and concomitant ice-marginal drainage development in the central and western margins establishes a depositional

pattern across the sandur that cannot be explained by existing facies models for sandar. This shift to a laterally dissimilar, channelized routing system creates a more varied depositional pattern that is not explicitly controlled by the concave longitudinal profile down-sandur. Laterally contiguous units, therefore, may vary greatly in age and sedimentology.

Dismissing our observations and conceptual model, inasmuch as they are based on a sandur strongly affected by glacial recession, may be tempting; however, observations of circum-polar ice positions and mass balances indicate that recession has been an ongoing recent process (Dowdeswell et al., 1997), especially in many other areas of SE Iceland (Price and Howarth, 1970; Thompson, 1988). Furthermore, with global warming projections indicating that higher latitude regions will be disproportionately affected, the tendency for continued recession is greatly enhanced. Our conceptual model developed for an icefront decoupled from its moraine may provide an analog for geomorphic impacts in these recessional settings, including the style of geomorphic impacts occurring during the retreat of the Laurentide ice sheet (cf. Gustavason and Boothroyd, 1987; Lord and Kehew, 1987; Kehew and Teller, 1994).

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