Changes in the Gígjukvísl river channel during the November 1996 jökulhlaup, Skeiðarársandur, Iceland

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Abstract — *Aerial photographs taken in 1992 and 1997 enabled the production of maps of Skeiðarársandur before and after the November 1996 jökulhlaup. This paper presents pre- and post-jökulhlaup maps of the Gígjukvísl river channel, providing an excellent opportunity to examine geomorphological change resulting from the jökulhlaup. The Gígjukvísl channel system underwent spectacular transformation from a complex system of low capacity channels and proglacial lakes to a large high capacity channel, scaled to the November 1996 jökulhlaup flows. The overall size of the Gígjukvísl channel increased, reducing flood flow resistance and decreasing future potential for the formation of backwater lakes. Specific change within the Gígjukvísl channel, upstream of the Little Ice Age moraines, consists of bank erosion of up to 300 m at the main Gígjukvísl outlet and within channel deposition of between 6 and 12 m. Downstream of the Little Ice Age moraines channel change consists of bank erosion of 600 m and localised within–channel aggradation of 4 m. Comparison of 1992 and 1997 aerial photographs also provides a clear picture of the glacier snout retreat of 300 m and thinning of 50–60 m during this period. Drastic change within the Gígjukvísl channel was brought about by the recent (post-1954) creation of a proglacial trench within the river system. Prior to the November 1996 jökulhlaup, the proximal Gígjukvísl river channel had never experienced a high–magnitude jökulhlaup. Extensive bank erosion during the jökulhlaup drasticly changed the channel so it is now well–adjusted to high–magnitude flood flows reducing the geomorphological impact of future jökulhlaups.*

INTRODUCTION

There are many areas in Iceland where changes in landscape are, or can be expected to be, rapid even within the typical design lifetime (50–100 years) of man-made structures. Understanding and monitoring these changes is necessary for the design and maintenance of these structures. Recently, the Public Roads Administration has produced maps of some of the areas where rapid natural changes can influence road transportation. Maps have been produced of Breiðamerkursandur (aerial photographs from August, 1996, height of flight 5500 m), Skeiðarársandur (aerial photographs from August, 1997, height of flight 3000 m) and Mýrdalssandur (aerial photographs from September, 1997, height of flight 3000 m). These areas are large glacial outwash plains as indicated by the Icelandic word *sandur*.

On Breiðamerkursandur (Figure 1) the glacier has retreated throughout the last century and a proglacial lake, Jökulsárlón, has emerged (Price, 1982). As the proglacial lake emerged, the sediment load carried by the river, Jökulsá, to the sea changed from approximately 9 million m^3 per year to a negligible amount (Björnsson, 1996). This is the cause of coastal ero-

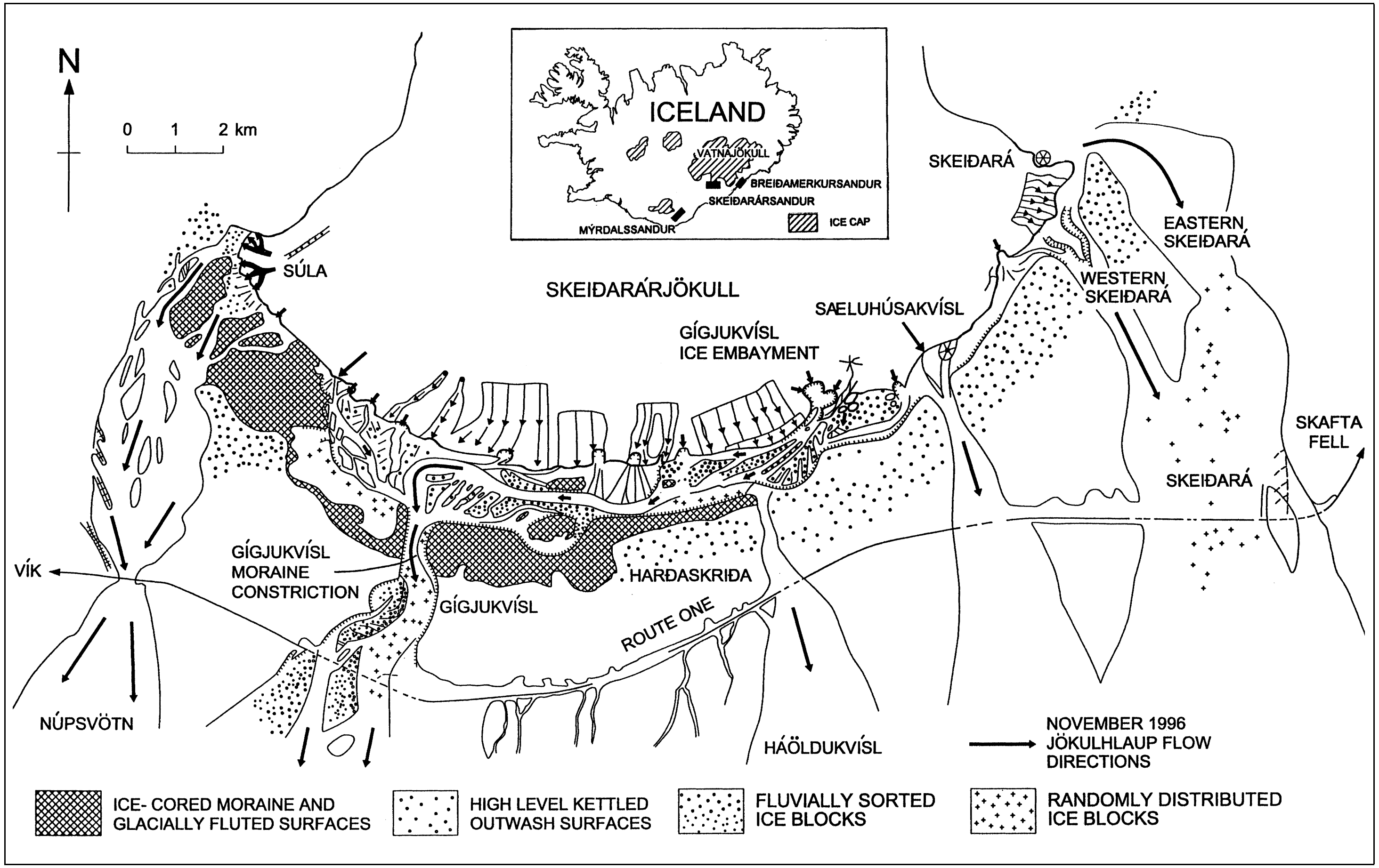

Figure 1. Location of the study area within Iceland (insert) and the Gígjukvísl channel in relation to the margin of Skeiðarárjökull. – *Kort af farvegi Gígjukvíslar og jaðri Skeiðarárjökuls.*

sion at the Jökulsá River outlet of about 8.5 m per year. This erosion threatens the road (Route One) and two powerlines as discussed by Jóhannesson (1994, 1995). Mýrdalssandur (Figure 1) has been created by jökulhlaups from the Katla volcano, with peak discharge of the order of 100,000-300,000 $m^3 s^{-1}$ (Jónsson, 1982; Maizels, 1989a,b, 1991, 1993a,b, 1995; Tómasson, 1996). The 34 km long road across Mýrdalssandur (Route One) is not designed to withstand such an event.

Skeiðarársandur (Figure 1) in southeast Iceland is the "typesite" for jökulhlaups (Thórarinsson, 1939, 1974; Churski, 1973; Björnsson, 1988, 1992; Guðmundsson *et al.*, 1995), and different features of their impact have been recorded by Klimek (1972, 1973), Galon (1973), Nummedal *et al.* (1987), Boothroyd and Nummedal (1978), Maizels (1991,1993a,b) and Russell and Marren (1999). These studies describe the sedimentology and geomorphology of Skeiðarársandur without isolating the geomorphic change caused by a single jökulhlaup. The November 1996 jökulhlaup is thus unique as it is the first large jökulhlaup on Skeiðarársandur since 1938 and the geomorphic conditions before and after the jökulhlaup are well documented.

The November 1996 jökulhlaup on Skeiðarársandur caused damage to roads and bridges which has been estimated at about 1,000 million ISK (15 million USD). The main geomorphic impact of the jökulhlaup occurred within the Gígjukvísl channel (Figure 1). This river captures water drained from outlets at the central part of the glacier, whereas the two rivers to the east and west of Gígjukvísl, the Súla and Skeiðará respectively, emerge from single lateral conduits. Both these lateral channels have previously conveyed numerous jökulhlaups and therefore the geomorphic change during the 1996 event was minimal. The sediments produced by this jökulhlaup have been described by Russell and Knudsen (1999a,b). This paper presents maps of the Gígjukvísl channel before and after the November 1996 jökulhlaup. Herein, these maps are used to give an overview of the geomorphic changes within the Gígjukvísl river channel during the jökulhlaup.

THE NOVEMBER 1996 JÖKULHLAUP

A volcanic eruption beneath the Vatnajökull ice cap began on September 30th, 1996 (Guðmundsson *et al.*, 1997). Meltwater travelled subglacially into the Grímsvötn subglacial caldera lake until it reached a critical level for drainage (Björnsson, 1997). The jökulhlaup began on the most easterly outlet river, the Skeiðará, at 0730h on November 5th. The jökulhlaup began in the Gígjukvísl river at around 1015h on November 5th and reached the Súla bridge at 1613h on November 5th (Snorrason *et al.*, 1997) (Figure 1). The jökulhlaup in the Súla river had the shortest duration and was observed from aerial photographs to have waned considerably by 1200h on November 6th. The jökulhlaup had its longest duration in the Gígjukvísl river channel persisting well into November 7th (Snorrason *et al.*, 1997). The flood reached a peak discharge of 40,000–50,000 $m^3 s^{-1}$ within 15 hours, forming the shortest rising limb on discharge charts for any jökulhlaup recorded from the Grímsvötn caldera (Björnsson, 1997). In this flood, 3.2 km^3 of water drained from the Grímsvötn caldera within a period of 40 hours (Björnsson, 1997). At the flood peak, a backwater lake containing 0.06–0.1 km^3 of water was temporarily stored upstream of the Gígjukvísl moraine constriction (Russell *et al.*, 1999, Russell and Knudsen, 1999a) (Figure 1).

The 1996 jökulhlaup was similar in magnitude to the 1934 and 1938 jökulhlaups which drained 4.5 km^3 and 4.7 km^3, respectively, with peak discharges of 25,000–30,000 $m^3 s^{-1}$ (Björnsson 1992; Guðmundsson *et al.*, 1995).

PRODUCTION OF THE MAPS

A map of Skeiðarársandur, based on the August, 1997 aerial photographs, was produced by Ísgraf for the Public Roads Administration following a tender. The map covers the total width of Skeiðarársandur from just south of Route One to just north of the Skeiðarárjökull glacier terminus (Figure 1). The work included aerial photography and the production of gridpoints with 10 m spacing. In the tender documents the height of flight is required to be 3000 m. Average error, as specified in the tender documents, was required to be less than ± 0.5 m for plan coordinates (x, y) and less than ±0.7 m for elevation (z). To be able to produce a map with this accuracy, model points must be measured by ground survey and the location of these points marked on the ground prior to taking the aerial photographs. The model points can then be identified on the aerial photographs. For this map 39 points were measured with a GPS Trimble 4000 SSi (error in plan coordinates less than 0.02 m and error in elevation less than 0.05 m) and their location marked on the ground.

Since the main geomorphic impact of the November 1996 jökulhlaup on Skeiðarársandur was concentrated within the Gígjukvísl channel, the Public Roads Administration commissioned Ísgraf to produce a similar map of this particular area based on aerial photographs from August, 1992 (height of flight 5500 m, National Land Survey of Iceland). Common points on these two sets of aerial photographs were identified. The coordinates of these points were measured by ground survey. For the 1992 map 16 points were measured with a GPS Trimble 4000 SSi. It was possible to produce this map with about the same accuracy as the 1997 map by using information from the 1997 map in the production of the 1992 map.

Due to the data being digital, maps of any scale can be produced. At present, maps of scale 1:10,000 with 2 m contour lines have been produced. Maps of the channel of Gígjukvísl in 1992 and 1997 with a 10 m contour interval are shown in Figures 2 and 3.

GEOMORPHIC CHANGES WITHIN THE GÍGJUKVÍSL RIVER CHANNEL

The geomorphic impact of the November 1996 jökulhlaup within the Gígjukvísl channel is revealed by comparing the 1992 and 1997 maps. This comparison is complemented by our sedimentological studies in the area before, during and after the jökulhlaup. The location and surface elevation of selected transects are shown in Figures 4 and 5. The first three transects reach the glacier, which retreated by about 300 m between 1992 and 1997 and thinned by 50–60 m at the snout.

The Skeiðarárjökull glacier advanced up to 1 km during a surge and a small jökulhlaup in 1991 (Pálsson *et al.*, 1992; Björnsson, 1998). This glacier advance closed the former northwest outlet of the Háöldulón lake resulting in the reactivation of an older and higher level outlet as can be seen by comparing Figures 2 and 6. The advance of the glacier caused geomorphic changes within the Gígjukvísl channel that influenced the patterns and processes of erosion and sedimentation during the November 1996 jökulhlaup. An overview of these changes is summarised below.

Transect 1

This transect crosses the Gígjukvísl channel from the Háöldukvísl channel mouth (left bank) to the glacier (right bank) (Figures 4 and 5). It is characterised by a depression between the ice margin and older pitted sandur surface of higher elevation, Harðaskriða, (Figure 1) a jökulhlaup fan, possibly dating back to 1922. Prior to the November 1996 jökulhlaup, the Háöldukvísl channel was last flooded during the 1945 jökulhlaup (Ragnar Stefánsson, former warden of the Skaftafell National Park, *personal communication*, 1990).

The erosion of the left bank amounted to 300 m and the pre-existing channel aggraded by 6–12 m. Net sediment deposition in the trench between the 1992 glacier margin and the pre-jökulhlaup 1996 margin exceeds 12 m (Figure 5). It is possible that much of the extreme northern part of this cross–section is still underlain by sediment–covered ice from the glacier retreat since 1991. The channel profile deepens towards the south (Figure 5) where flows in the November 1996 jökulhlaup were concentrated along the left bank, enhancing the erosional process.

The region between Gígjukvísl and transect 1

In 1992 this area was characterised by two alluvial fans, each with an area of ca. 0.6 km^2 (B and C on Figure 2), which formed during the 1991 surge. Similar fans have been reported from the 1890 and 1964 surges of Brúarjökull (Knudsen, 1995). The fans were located at a poorly defined inter–lobate recess in the snout of Skeiðarárjökull, in the same area as the largest November 1996 jökulhlaup outlet.

The main Gígjukvísl outlet was described by Russell *et al.* (2001) who differentiated between the rising (R on Figure 3) and waning–stage fans (W on Figure 3). Between 8 and 9 m of sediments were deposited downstream of the surge–related fans (B and C on

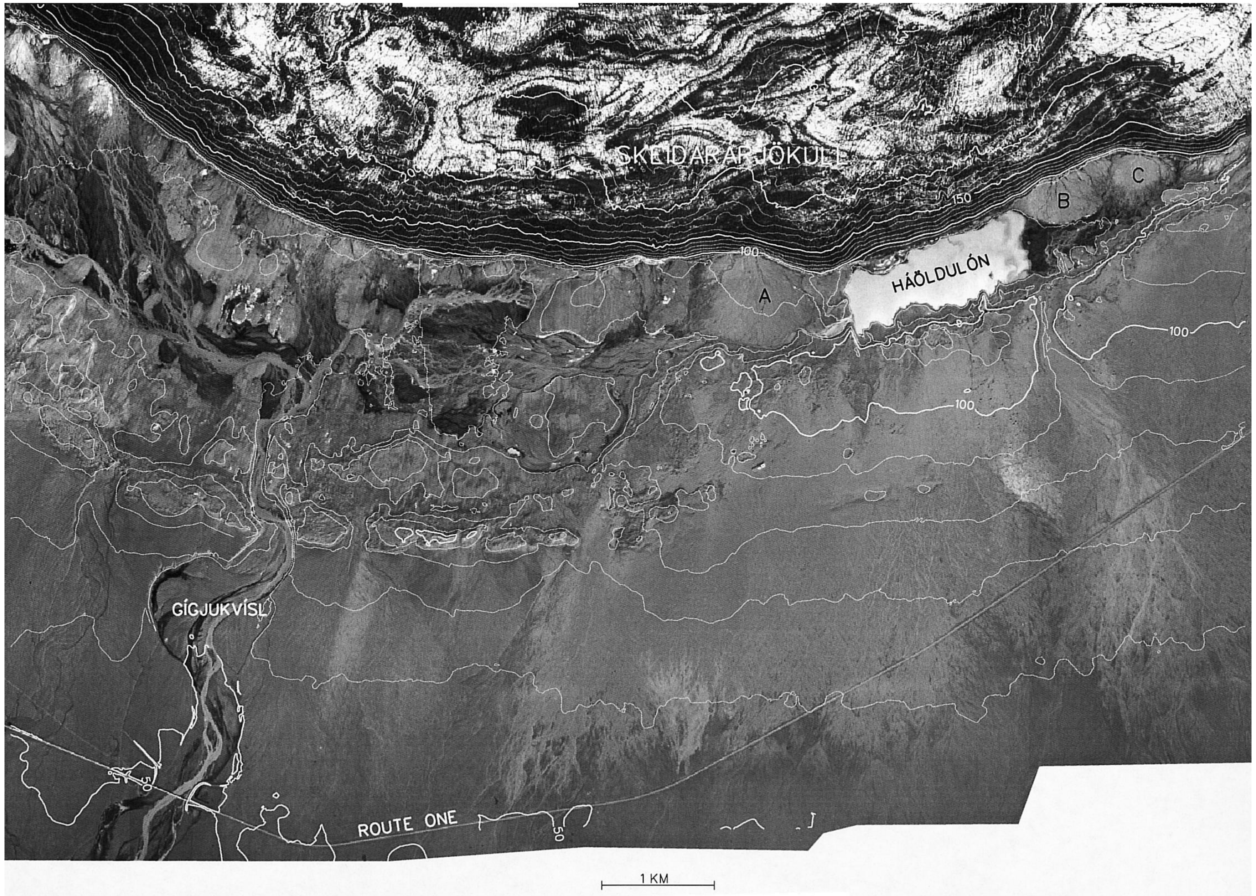

Figure 2. Map of the Gígjukvísl channel in 1992. Contour interval is 10 meters. The fans marked A, B and C formed during the 1991 surge of Skeiðarárjökull. – *Kort af farvegi Gígjukvíslar árið 1992. Hæðarlínubil er 10 m. Framburðarkeilurnar sem merktar eru A, B, C mynduðust í tengslum við framhlaup Skeiðarárjökuls árið 1991.*

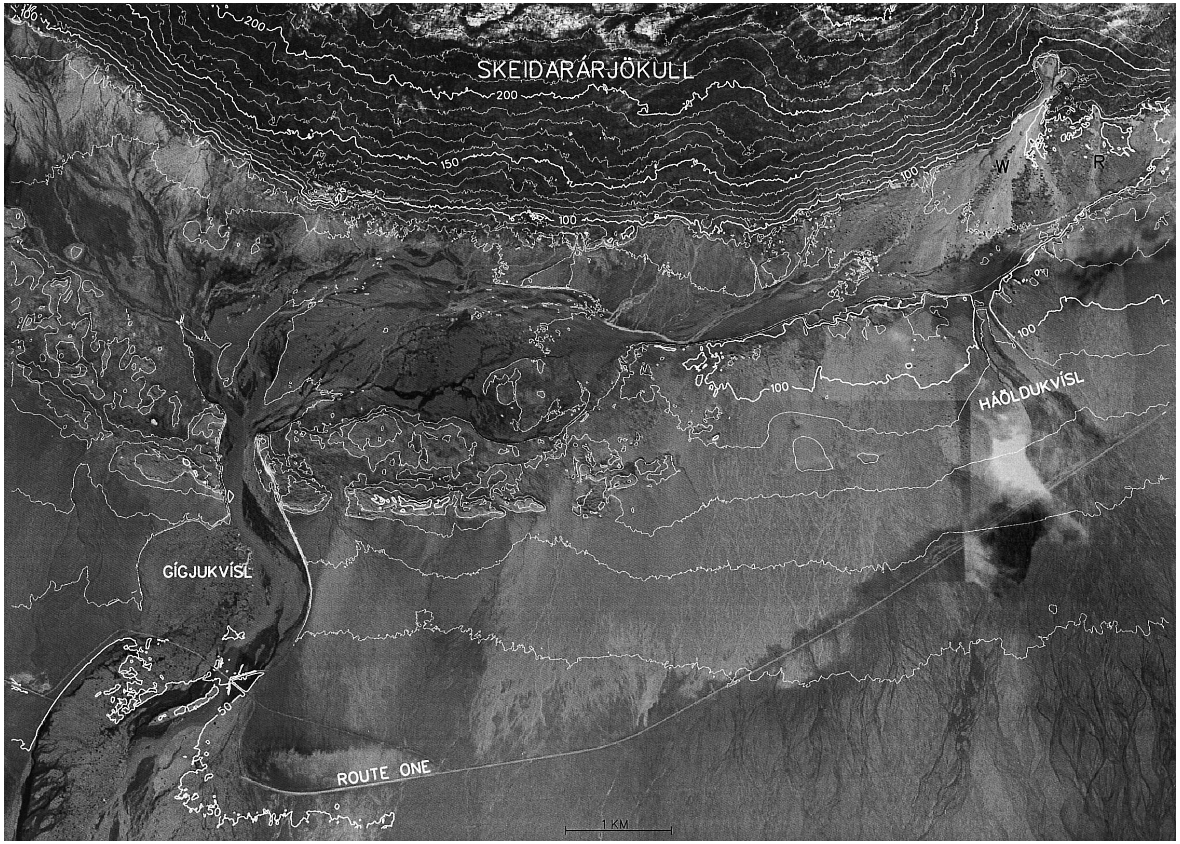

Figure 3. Map of the Gígjukvísl channel in 1997. Contour interval is 10 meters. The outlet fan marked R formed on November 5th, 1996 and was active during the rising–stage of the jökulhlaup. The fan marked W formed on the morning of November 6th, 1996 and was active during the waning–stage of the jökulhlaup. – *Kort af farvegi Gígjukvíslar árið 1997. Hæðarlínubil er 10 m. Framburðarkeilan sem merkt er R myndaðist 5. nóvember 1996 á meðan rennslið í hlaupinu óx. Framburðarkeilan sem merkt er W myndaðist að morgni 6. nóvember 1996 þegar rennslið í hlaupinu rénaði.*

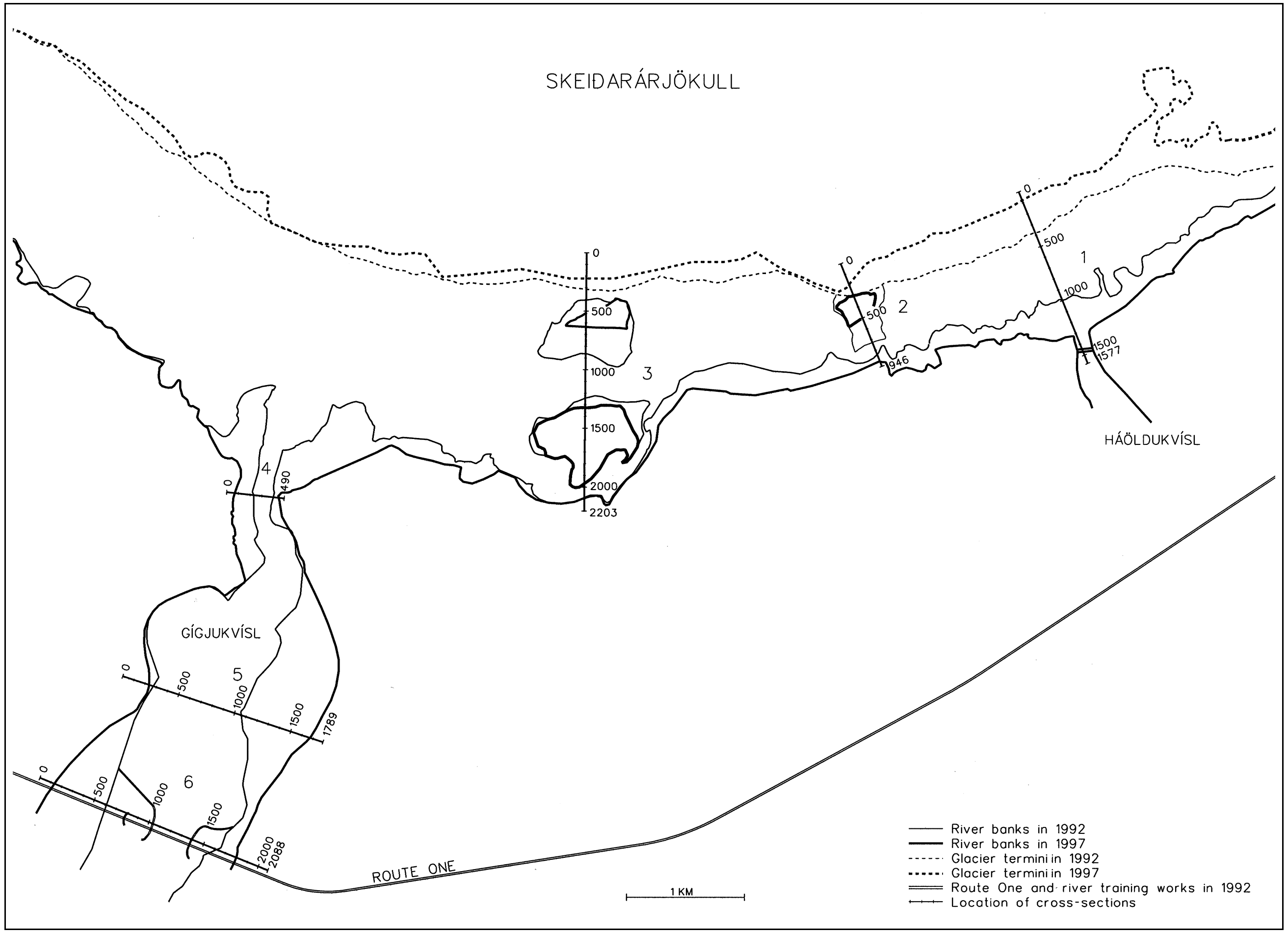

Figure 4. The banks of the Gígjukvísl channel and Skeiðarárjökull termini in 1992 and 1997. – *Bakkar Gígjukvíslar og jaðar Skeiðarárjökuls árin 1992 og 1997.*

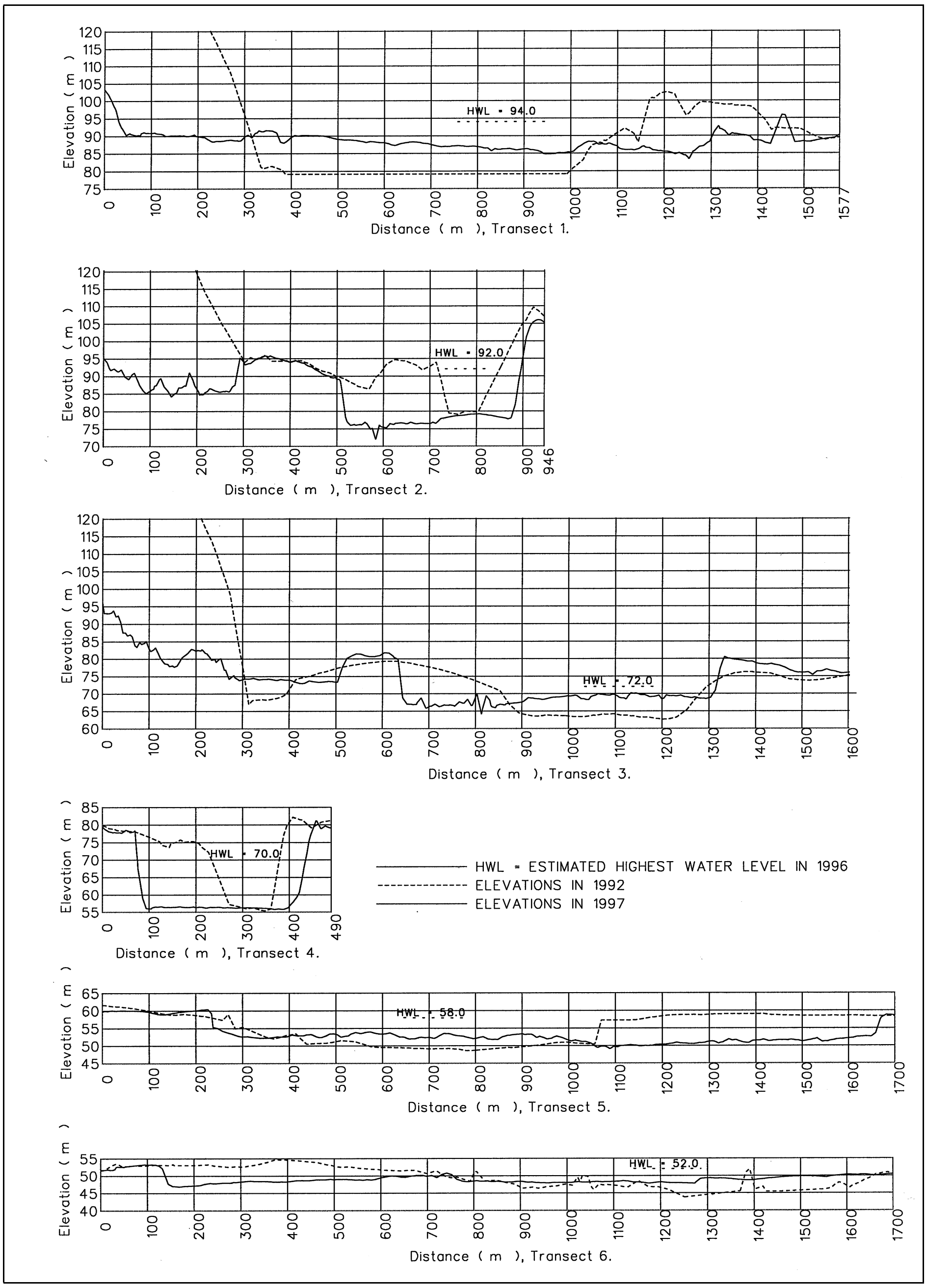

Figure 5. Surface elevations at selected transects (an upstream view). The locations of the transects are shown in Figure 4. – *Hæð í völdum þversniðum (horft er upp farveginn). Staðsetning þversniðanna er sýnd á mynd 4.*

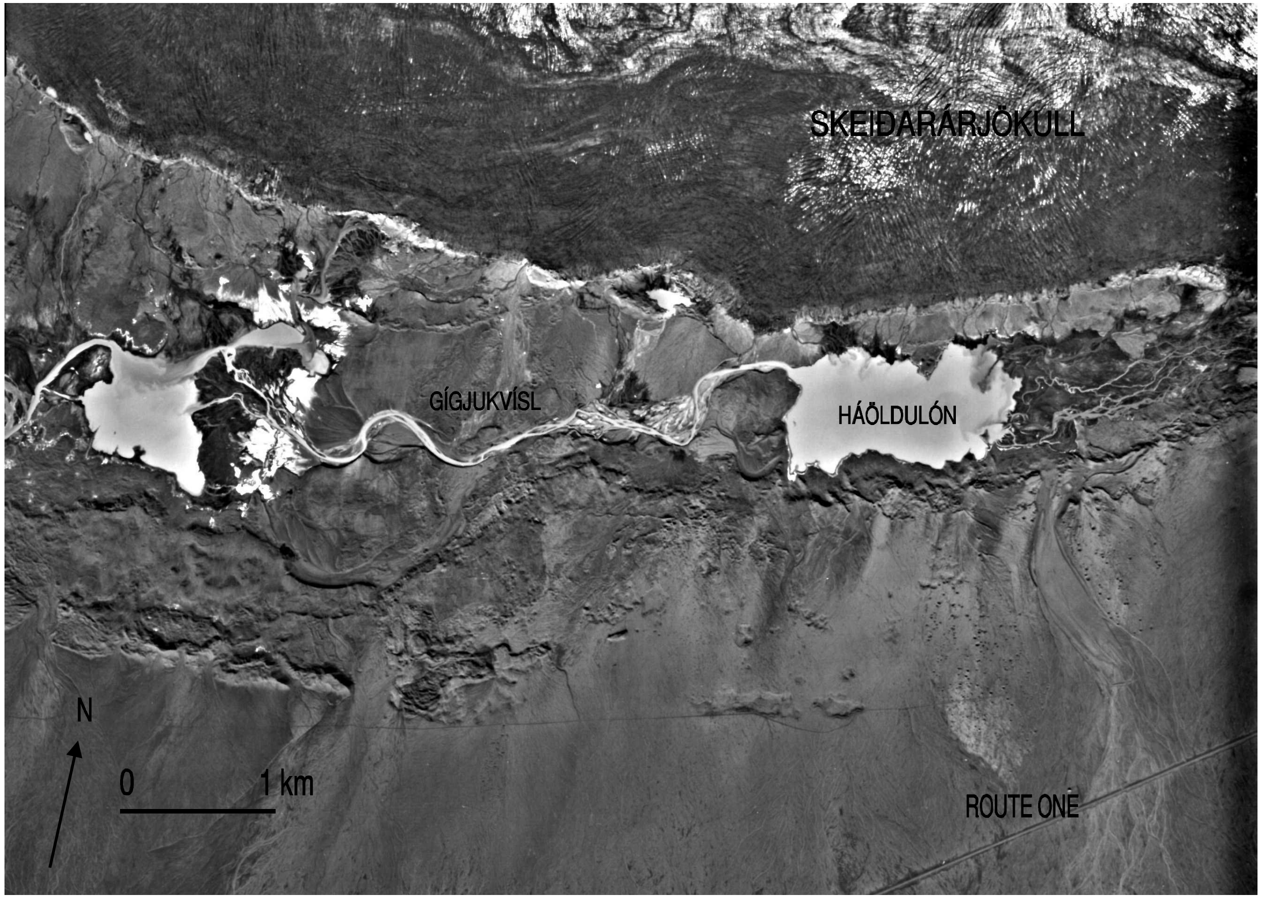

Figure 6. Aerial photograph of the Gígjukvísl channel from September 12th, 1986. The outlet of lake Háöldulón that was active in 1986 was closed during the 1991 surge (Figure 2). Published with the permission of the Icelandic Geodetic Survey. – *Loftmynd af farvegi Gígjukvíslar frá 12. september 1986. Útfall Háöldulóns, sem var virkt 1986, lokaðist í framhlaupi Skeiðarárjökuls 1991 (2. mynd). Birt með leyfi Landmælinga Íslands.*

Figure 2) between 1992 and 1997. The bed elevations of the eastern margin of the waning–stage jökulhlaup fan (W) change from 80 m to 92–94 m during the same period. The greatest aggradation (16 m) occurred in the vicinity of the rising–stage fan (R), creating the greatest potential of complete burial of ice blocks, as demonstrated by numerous kettle–holes in this region (Fay, in press). With this high aggradation, the two 1991 surge fans (B and C on Figure 2) were probably completely buried during the 1996 jökulhlaup, although parts of these fans may have been eroded during the rising–stage of the flood. The apex of these fans in 1992 was at an elevation of 88 m, whilst the jökulhlaup fan elevations at the same locations were 98–100 m in 1997. High sediment flux during the waning jökulhlaup flow stage may have buried the 1991 western surge fan (B). Localised backwater conditions early in the rising flow stage, combined with high sediment flux within the flow, may have resulted in the burial of the eastern surge fan (C). The small sandur to the east of the rising–stage fan aggraded from an elevation of 90 m in 1992 to 100 m in 1997.

Transect 2

This transect shows cross-profile changes within one of the narrowest November 1996 proglacial channels. Major erosion of the island at the central part of this transect (distance 300-700 m, Figure 5) was observed during the rising flow stage on November 5th, 1996. This erosion resulted in marked lowering of the level of a large backwater lake which accumulated upstream during the early rising flow stage. The erosion concentrated mainly on the right bank where it amounted to 220 m. In contrast, erosion of the left bank was only 50 m (Figure 5). Such high erosion rates on the right bank could be due to the presence of relatively easily eroded fluvial and glacial sediments, as opposed to the buried glacier ice within the left bank. The area at the glacier margin (distance 0–300 m, Figure 5) was over-washed during the jökulhlaup. Therefore, some of the distinctive troughs may represent channels occupied by 1996 jökulhlaup water flowing obliquely around the island. The elevation of the main channel was 80 m in 1992 and 78 m in 1997.

The region between transects 1 and 2

The proglacial lake Háöldulón (Figure 2) dominated this area in 1992. The lake was noticeably altered by the 1992 surge when the glacier advanced 200 m into it during a total advance of about 700 m in this region (Pálsson *et al.*, 1992). The surge closed the former northwest outlet of Háöldulón resulting in the reactivation of an older and higher level outlet and about 2 m increase of the lake level (Figures 2 and 6). Transect 2 crosses the outlet that was reactivated during the 1991 surge.

The former area of Háöldulón has been completely filled with sediments and is now occupied by the westernmost part of the waning–stage Gígjukvísl jökulhlaup fan (fan W in Figure 3). The former lake basin is now 80 m a.s.l. just upstream of transect 2 and 85–90 m a.s.l. at transect 2, whereas the lake level was 79 m a.s.l. in 1992.

Transect 3

This transect shows a combination of erosion and deposition. Erosion of the right bank of the main channel was 220 m, whilst erosion of the left bank was only 50 m. The pre-existing channel area aggraded by about 6 m. The northern bank of the island (distance 500 m, Figure 5) was also eroded by jökulhlaup flows exiting the glacier from the north. These flows also resulted in the infill of a well–defined channel cut by 1991 surge–related flows exiting the ice margin. The irregular topography on the northern 300 m of this profile represents jökulhlaup deposition on top of the ice–marginal landscape created by meltout from the 1991 surge.

The region between transects 2 and 3

This area is located downstream of lake Háöldulón and contains the largest fan formed during the 1991 surge (fan A). The three fans (A, B and C in Figure 2) indicate where bedload–rich flows escaped the glacier at the end of the surge. In 1992 the river flowed along the southern fringe of fan A and eroded the north side of Harðaskriða. The 1992 Gígjukvísl channel was braided from the fan to transect 4, but before the surge the channel was incised and sinuous (Figure 6). The pre–surge channel width at transect 2 was 50 m, but increased to about 100 m (Figure 5) during the surge and jökulhlaup in 1991.

The large surge-related fan downstream of transect 2 (A in Figure 2) has a similar morphology when the 1992 and 1997 maps are compared. However, the 80 m contour line is less fan-like on the 1997 map and has a more glacier–parallel orientation (Figures 2 and 3). Several November 1996 jökulhlaup outlets extend in a line westward from transect 2 (Figure 3). Flows from these outlets modified the clearly defined shape of the 1992 fan and infilled an area immediately to the west of transect 2. Although some kettles formed following the 1996 jökulhlaup on the lower portions of the 1991 surge fan, the bulk of the fan has survived intact.

The island on transect 3 (at a distance of 400-900 m, Figure 4) underwent major erosion during the November 1996 jökulhlaup (Figure 3), truncating a distinctive anatomising esker system. The erosion of the right bank of the main channel cuts through a portion of the 1991 surge–fan (fan A in Figure 2) as well as older sediments. The jökulhlaup flows also reworked the northwestern side of the island.

Transect 4

This transect is located where the Gígjukvísl river runs through a large moraine constriction. The snout of Skeiðarárjökull was situated at these moraines in 1904 (map from Danish Geodetic Institute, 1:50.000, based on measurements from 1904, published in 1941). The moraine is presently ice–cored (Kaldal, 1997; Russell *et al.*, 1999). Despite erosion of the right bank by 170 m and the left bank by 50 m, the riverbed elevation remained unchanged.

Transect 4 controlled the level of the backwater lake which developed upstream. At its peak this backwater lake temporarily stored 60–120$\times$10^6 m^3 of water (Russell and Knudsen, 1999a). As the ice–cored moraine ridges on either side of the river channel eroded, the capacity of the cross-section increased, lowering the level of the backwater lake even when the discharge was increasing.

The region between transect 3 and 4

Prior to 1991 this area was the site of a lake (Figure 6) which filled with sediments during the surge. In 1992 the Gígjukvísl river had a braided course in this region becoming channelised where it turns south. From there the river flows through moraines situated at the ice margin in 1904.

A heavily kettled “expansion bar” downstream of the south island at transect 3 (at a distance of 1200–2000 m, Figure 5) had a surface elevation between 66 and 68 m in 1997, whilst only 60 m in 1992. Some of the largest kettle–holes on this bar resulting from the November 1996 jökulhlaup extend through the entire bar thickness.

In the centre of the Gígjukvísl channel, north of the moraine gap (transect 4), the jökulhlaup bar surfaces have an elevation between 62 and 64 m in 1997, compared to 60 m in 1992. The 1997 channels at this location are, however, at an elevation of 60 m. This may suggest waning–stage scour to pre–jökulhlaup elevations at this location.

The western part of the Gígjukvísl catchment, west of the moraine gap, contains a southeastward–draining confluent river system, which is flowing around a series of older fluted surfaces. Comparison of the 1992 and 1997 photos reveals very little change in this area, with the same patterns of fluted surfaces being clearly visible on both photographs. The 70 m contour across this system has not changed its position between 1992 and 1997. The greatest change during this period is concentrated along the ice–marginal zone where a series of new kettled–outwash fans provide evidence of ice–proximal aggradation, confined to a distance of less than 500 m from the glacier margin. The extent of ice-proximal aggradation coincides with an elevation of approximately 70 m. The limited extent of jökulhlaup fans in this region could be due to a combination of both limited flow duration and limited sediment availability for the western Gígjukvísl outlets. The backwater lake may have also limited the transport of jökulhlaup sediment from this section of the glacier margin.

The region south of transect 4

At transect 5 the erosion of the right bank was 50 m and the erosion of the left bank was 600 m during the November 1996 jökulhlaup. The riverbed is 4 m higher in 1997 than in 1992 (Figure 5). At transect 6 the erosion of the right bank was 500 m and the erosion of the left bank was 200 m. At the eastern end of the former bridge, as well as further east, the bed elevation was 4–5 m higher in 1997 than in 1992. The bed elevation west of the former bridge was unchanged (Figure 5).

Whereas this part of the Gígjukvísl river channel was virtually unaffected by the 1991 surge and jökulhlaup, it underwent an overall widening and shallowing during the 1996 jökulhlaup. Downstream of the moraine constriction the erosion was concentrated on the left bank. At transect 6 the erosion has shifted to the right bank. Net deposition dominates the old channel course with 3–4 m of aggradation.

CONCLUSIONS

This paper presents maps that show the channel of Gígjukvísl after the 1991 surge of Skeiðarárjökull and following the November 1996 jökulhlaup. These maps have been used to measure changes in the Gígjukvísl channel resulting from the jökulhlaup. The main geomorphic impact consists of channel change brought about by bank erosion of up to 300 m at the main Gígjukvísl outlet (transect 1) and within–channel deposition between 6 and 12 m. Aggradation rates decrease markedly downstream, with bank erosion of 600 m downstream of the moraine constriction (transect 5) accompanied by localised within–channel aggradation of only 4 m. Comparison of 1992 and 1997 aerial photographs also provides a clear picture of 300 m of glacier snout retreat and thinning of 50-60 m during the study period.

The Gígjukvísl channel system underwent spectacular transformation from a complex system of low capacity channels and proglacial lakes to a large, high capacity channel scaled to November 1996 jökulhlaup flows. The overall size of the Gígjukvísl channel increased, reducing flood–flow resistance and decreasing future potential for the formation of backwater lakes. The drastic change within the Gígjukvísl channel was brought about by the fact that the proglacial trench in which the river system is located had only recently (post–1954) been created. As such, the proximal Gígjukvísl channel had never experienced a high magnitude jökulhlaup, in contrast to the Skeiðará channel system, which had adjusted to successive jökulhlaups over the previous decades, and where the overall geomorphic impact of the November 1996 jökulhlaup was much less spectacular. Due to the extensive bank erosion during the jökulhlaup, the present Gígjukvísl channel is now well–adjusted to high magnitude flood flows reducing the geomorphological impact of any subsequent jökulhlaups.

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ÁGRIP

BREYTINGAR Á FARVEGI GÍGJUKVÍSLAR Í JÖKULHLAUPINU Í NÓVEMBER 1996

Ný kort af farvegi Gígjukvíslar eftir framhlaup Skeiðarárjökuls árið 1991 og eftir hlaupið í nóvember 1996 eru notuð til að leggja mat á breytingar á farvegi Gígjukvíslar sem áttu sér stað í hlaupinu í nóvember 1996. Helstu breytingar á farveginum eru allt að 300 m rof á árbakka á móts við stærsta útfall hlaupsins (snið 1) og hækkun á árbotni þar á bilinu 6 til 12 m. Botninn á farveginum hækkar minna eftir því sem neðar dregur og í sniði 5 var rof á árbakka 600 m en botnhækkunin aðeins 4 m. Við samanburð á kortunum má sjá að jaðar jökulsins hefur hopað um 300 m og lækkað um 50-60 m á árabilinu 1992 og 1997. Þær miklu breytingar sem urðu á farvegi Gígjukvíslar stafa af því að lægðin sem áin rennur í meðfram jökuljaðrinum er nýleg og hefur myndast við hop jökulsins eftir 1954. Farvegur Gígjukvíslar hafði því aldrei áður tekið við vatnsmagni úr stóru jökulhlaupi, ólíkt farvegi Skeiðarár sem hefur mótast af mörgum stórum jökulhlaupum á undanförnum áratugum enda urðu breytingar á farvegi Skeiðarár í hlaupinu í nóvember 1996 mun minni en breytingarnar á farvegi Gígjukvíslar. Vegna hins mikla rofs á árbökkum Gígjukvíslar í hlaupinu í nóvember 1996 þá getur núverandi farvegur Gígjukvíslar flutt meira vatnsmagn en áður og því má búast við minni breytingum í næstu jökulhlaupum.

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