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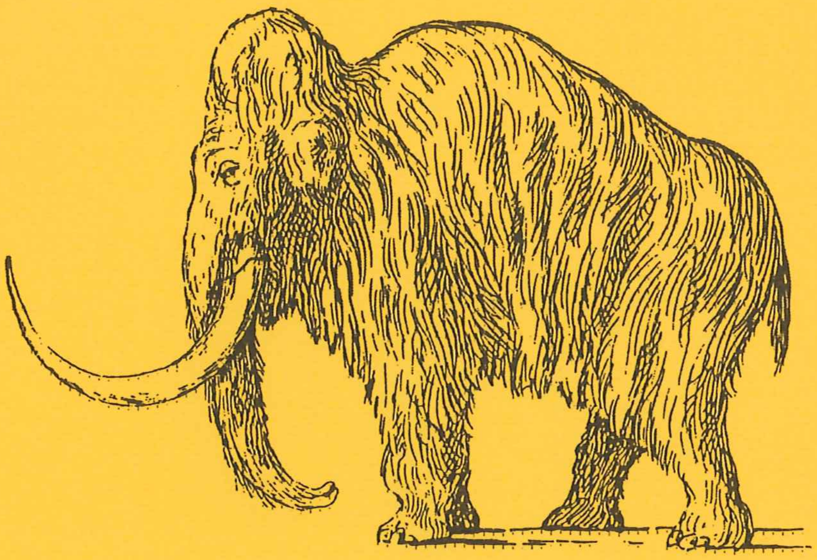

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Lina Sultan

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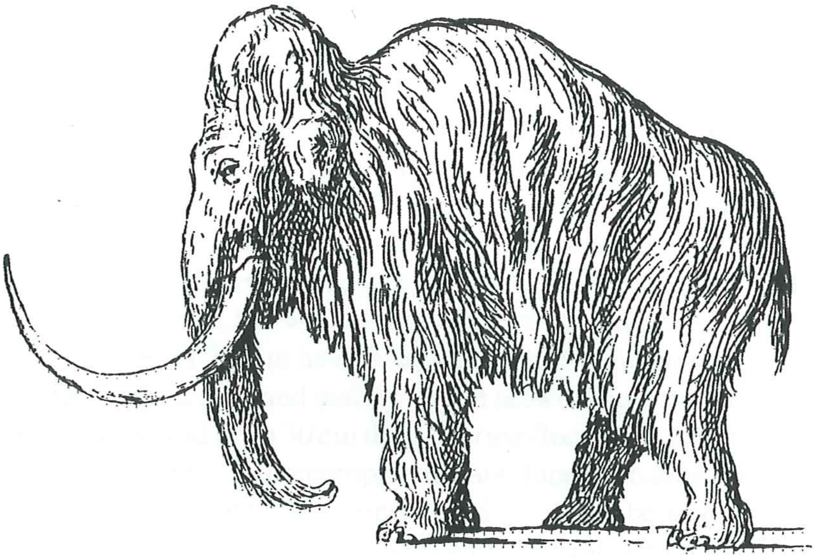

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Proglacial environments are an integrated part of the glacier landscape, housing a variety of landforms fed by glacier meltwater. Their appearance is dependent on a number of factors, such as the variability of source material and processes active during the transportation and deposition.

The present work aims to investigate two such terrestrial outwash successions from the terminus region of the Mýrdalsjökull ice cap, south Iceland; respectively in a modern and an ancient setting. Both deposits are described in detail regarding their architecture and sedimentology, compared with each other and finally classified as alluvial fans of the Hochsander type. The modern fan formed during the 1980s in association with an advancing glacier with a steep, debris-covered frontal slope, while the fossil fan developed as a consequence of the 934-938 AD Eldgjá fire releasing huge quantities of tephra over the glacier surface. Supraglacial material feeding the fans was collected in drainage paths and transported off the glacier surface on to the forefield, either directly dispersed or transported downstream in incised channels, before spreading at an intersection point. Average daily sedimentation rates of 2.5 cm have been measured for the most active time of development of the modern fan. Deposition occurred mainly within networks of laterally migrating braided streams, generally 0.1-0.5 m wide and up to 30 cm deep. During floodings sheetflows, sometimes transformed into hyperconcentrated flows, and accompanying antidune formation dominated. Collectively, these depositional processes generated fans constructed of planar-bedded sands and low-angled cross-bedded sands interbedded with thin gravelbeds and occasional mud-drapes, related to subaerial fan exposure. The material of Hochsanders is generally moderately to poorly sorted, mainly belonging to the middle sand fractions. Architecturally, the fans have all the characteristics of an alluvial fan, with a semiconical shape, a plano-convex cross-profile, a slope ranging from 1-5° and a radial length of 1-1.5 km.

It is concluded that Hochsanders are highly influential on the architecture of superimposed landforms. Moreover, their presence may give valuable information about local palaeo-climate and the transition from ice marginal to proglacial environments.

Key words: Alluvial fans, Hochsanders, sediment architecture, supraglacial material, tephra, Iceland

Lina Sultan, Department of Geology - Quarternary Geology, Lund University, Sölvegatan 13, SE-223 62 Lund, Sweden.

Rekonstruktion av konformade smältvattens-successioner framför Mýrdalsjökull, Island: Arkitektur och sedimentations stil

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En proglacial miljö är en integrerad del av ett glacialt landskap, där smältvattensavlagrade landformer är vanligt förekommande. Deras utseende är beroende av ett antal olika faktorer, så som processer aktiva under transport och deposition samt ursprungsmaterialets karaktär.

Denna artikel syftar till att undersöka två terrestra smältvattens-successioner från de terminala delarna av glaciären Mýrdalsjökull, södra Island: respektive i en nutida och i en fossil miljö. Båda avlagringarna är beskrivna i detalj angående arkitektur och sedimentologi, jämförda med varandra och slutligen klassificerade som alluvialkoner av 'Hochsander'-typ. Den moderna konen bildades under 1980-talet i samband med en framryckning av en glaciär med brant, materialrik främre kant. Den fossila konen bildades som en konsekvens av Eldgjá-utbrottet 934-938 e.Kr., då enorma kvantiteter tefra spreds över glaciärytan och det proglaciala förlandet. Supraglacialt material samlades i dränerings rännor och transporterades från isytan till området framför iskappan, där det antingen spreds direkt eller fördes vidare nedströms i kanaler, innan det spreds ut vid skärningspunkten. En genomsnittlig daglig sedimentationshastighet på 2.5 cm uppmättes under den mest aktiva bildningstiden av den moderna konen. Depositionen skedde huvudsakligen inom ett nätverk av lateralt migrerande flätfloder, generellt 0.1-0.5 m breda och upp till 30 cm djupa. Under översvämningar dominerade okanaliserade flöden, delvis omvandlade till hyperkoncentrerade flöden, och tillhörande antidyn formationer. Sammantaget genererade dessa processer landformer uppbyggda av planbäddad sand och lågvinklig korsskiktad sand mellanlagrad av tunna grusbäddar och ett mindre antal lerdraperingar, relaterade till subaeril ytexponering. Materialet i Hochsander koner är vanligtvis moderat- till dåligt sorterat, mestadels av medelsand kornstorlek. Arkitektoniskt sett har avlagringarna alla utmärkande drag hos en alluvialkon, med en semikonisk form, en plano-konvex genomskärning, en lutning på 1-5° och en radial längd på 1-1.5 km.

Sammanfattningsvis kan sägas att Hochsander-koner har ett stort inflytande över arkitekturen av pålagrade landformer. Dessutom kan deras närvaro ge värdefull information om lokalt palaeoklimat och ismarginala- till proglaciala övergångszoner.

Lina Sultan, Department of Geology - Quarternary Geology, Lund University, Sölvegatan 13, SE-223 62 Lund, Sweden.

CONTENTS

1. Introduction

As meltwater emerges from a glacier to its forefield sediment may accumulate rapidly, forming proglacial outwash successions. Depending, however, on the variability of source material, the structure of the ice front and processes acting during transportation and deposition the resulting landforms will appear differently; sedimentologically and morphologically. Commonly, alluvial fans will form where streams are topographically confined to drainage routes (Clague 1973; Stanistreet & McCarty 1993). Contrary, where material is mainly subglacially derived or uniformly washed off the glacier surface broad, low-angled outwash plains, also known by their Icelandic term 'sandar', are likely to develop (e.g. Boulton 1986).

Alluvial fans formed beyond a glacier margin or in connection with a mountain massif have attracted much attention since the 18th century and many scientists, including Smith (1754) in Blair & McPherson (1994) and more recently Boothroyd & Ashley (1973), Boothroyd & Nummerdal (1978), Miall (1996) and Zielinski & Gozdnik (2001), have investigated their character and importance. Lately, attention has been directed towards the formation of extensive, subglacially fed outwash successions, often associated with catastrophic jökulhlaup-events (Maizels 1993; Russel & Knudsen 1999; Roberts *et al.* 2001) and surging glaciers (Russel *et al.* 2001). In general, subglacially fed deposits consist of coarse-grained material in the proximal parts with a marked decrease in grainsize towards more distal parts.

In contrast to these, minor supraglacially fed fans consisting of sand-sized material have attracted less attention and, hence, they are not fully understood. Such Hochsander fans can be distinguished from other alluvial fans based on a distinct set of characteristics, including facies, sedimentary structures and mean grainsize (Gripp 1975). Nevertheless, few researchers have thoroughly described the sedimentology of these alluvial fans, mainly presented by Heim (1983,1992) and Krüger (1994,1997). The latter two studies comprise brief information on the hydraulics and sedimentary processes active on modern Hochsander fans. However, sedimentological characteristics and architecture of fossil landforms are not discussed satisfactory. Thus, further research on the relationship between active processes and resulting sedimentary structures and facies is of importance for an improved understanding and a more substantiated identification of fossil Hochsander fans. This to avoid confusion with other similar proglacial landforms.

The present paper aims to reconstruct the architecture and style of sedimentation of two outwash fans at the proglacial area of the Mýrdalsjökull ice cap in central south Iceland. Comparisons are made between an identified fossil outwash succession and a possible modern analogue. Furthermore, a sedimentological model is presented that tries to evaluate some of the events generating the formation of supraglacially fed outwash fans. Finally, an attempt is made to assess the significance of Hochsanders in the proglacial landsystem and the influence they might have on the internal architecture of a glacier forefield.

This work is based on field studies carried out during the period July 28th - August 30th 2001. A total amount of 30 days were spent in Iceland, of which 21 days consisted of actual fieldwork, 5 days were spent on transport and preparations and the remaining 4 days no fieldwork could be carried out on account of heavy rainfalls.

2. Setting

Two selected study areas are located in central south Iceland in the terminus region of the Mýrdalsjökull ice cap, c. 150 km east-southeast of Reykjavík (Fig. 1). The areas are situated in the forefields of Slettjökull and Kötlujökull, two ice margins subjected to distinctly different types of recession; the northern margin of Mýrdalsjökull (Slettjökull) is submitted to frontal retreat, while the eastern flank (Kötlujökull) retreats areally by detachment of stagnant ice fields. Like all Icelandic ice caps the glacier is of temperate type, implying large quantities of

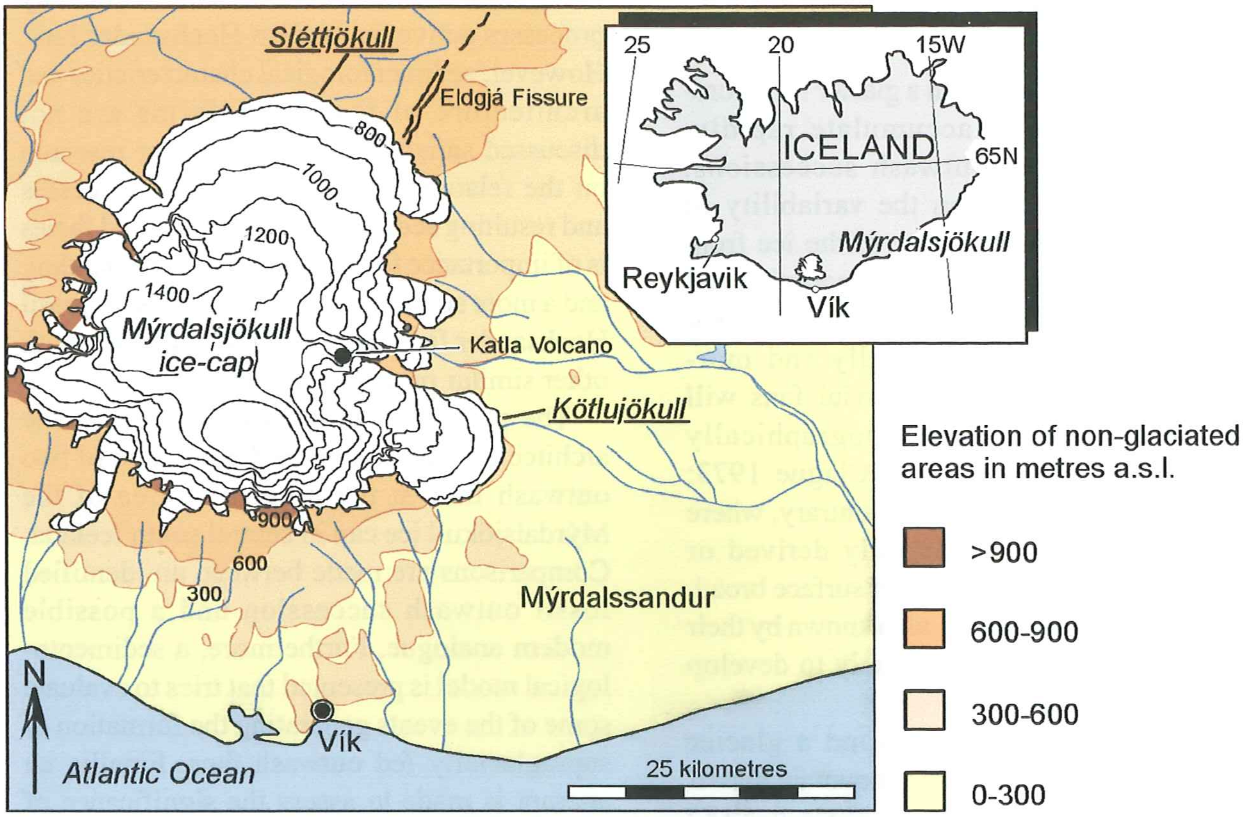

Fig. 1. Location map showing the Mýrdalsjökull ice cap in southern central Iceland and its outlet glaciers Kötlujökull and Slettjökull. The position of the subglacial volcano Katla and the Eldgjá fissure swarm is also shown.

meltwater are being produced annually. The central part of the ice cap, covering c. 600 km², forms a plateau at an elevation of about 1300 m, where the two highest rims of the ice-cap are situated. They reach a level of 1497 and 1505 m a.s.l, respectively, surrounding a peripheral zone of outlet glaciers (Björnsson *et al.* 2000). One broad continuous lobe, terminating at 550-600 m a.s.l, covers the northern flank of the ice cap, while the eastern side is split into several minor outlet glaciers. The largest outlet glacier of the eastern side of Mýrdalsjökull is a piedmont foot outlet glacier that extends towards southeast and terminates approximately 220 m a.s.l. On the southern and western flanks steep outlet glaciers flow in narrow confining valleys down to 100-800 m a.s.l.

An average ice-thickness of 230 m has been recorded, ranging from a few metres up to 740 m. The maximum thickness was measured within a 100 km² caldera, found beneath the central part of the ice-cap. An elliptical rim, cut by several glacially eroded passes, frames the c. 700 m deep caldera and through one of the lowest passes of the rim Kötlujökull drains towards southeast (Björnsson *et al.* 2000). North of the caldera the relief of the subglacial bedrock is smoothened, sloping gently towards northeast.

The caldera contains the circular subglacial volcano Katla, which has been active over several hundred thousand years (Larsen 2000). The volcano Katla is part of the larger Katla volcanic system, also containing the Eldgjá fissure. Twenty eruptions have been recorded during the last 11 centuries, i.e. an average of two eruptions a century, causing a great deal of damage to south Iceland. Not only in respect of ash falls and lava flows, but also by succeeding catastrophic glacier outbursts of large quantities of meltwater – jökulhlaups. One of the largest Holocene eruptions within the volcanic system is the 10th century Eldgjá fire, which opened up a >75 km long linear eruptive fissure striking NE-SW parallel to ridges and craters northeast of the ice-cap. The last great eruption, distributing tephra over an area exceeding 50.000 km² on land, occurred in 1918 (Larsen 2000). Tephra-derived layers, interbedded in the outwash plains surrounding Mýrdalsjökull often comprise a distinct chemical signature, allowing them to be used as marker horizons.

Apart from tephra, Holocene lavas and Pleistocene grey basalts and hyaloclastites, mostly pillow lavas, tuffs and breccias, represent the main bedrock geology of the area. Outwash plains of various sizes enclose the ice cap, spreading out in all directions. The largest, the Myrdalssandur outwash plain, covers most of the 15-25 km long lowland area between the Atlantic coast and the southeastern front of the glacier (Maizels 2000).

The area of Mýrdalsjökull receives heavy winter precipitation and high rates of summer melting, with an ablation period extending from early May to early October. Based on reports of the Icelandic Meteorological Office, Krüger (1994) summarised the climatic conditions as follows: the coastal lowland has a mean air temperature of 4-5°C and an average annual precipitation of about 2,260 mm, while the highland at the north margin has a somewhat lower mean air temperature, 0 to -1°C, and an annual precipitation of at least 2,000 mm. Kötlujökull terminus is situated in the area of highest precipitation of Iceland, dominated by highly oceanic climate. An average precipitation of about 5000 mm per year was estimated along the margin between 1995 and 1998 (Krüger & Kjær 2000).

3. Methods

Along the northern margin of Slettjökull a buried fossil outwash deposit was studied in detail. To establish the subsurface relief of the deposit 266 pits were excavated through the overlying diamicts down to the glaciofluvial sediments. Based on a fixed reference point a coordinate system was set up running parallel respective perpendicular to the present-glacier margin. The intention was to generate a grid of points with an interval of 50 m, covering the entire study area of about 1200 m². Unfortunately, it proved difficult to distribute the measuring points evenly because of the nature of the terrain surface. Numerous supraglacial meltwater streams had cut down into sediments of the glacier forefield and extended downslope towards more distal regions. As a result, sediments were eroded and the terrain dissected and, accordingly, the grid was adjusted. Mapping was completed by precision levelling using a GTS-6 Topcon instrument with minimum accuracy of ± 1 mm. It is presented here as a plan view and a three-dimensional model (Fig. 8 and 9). The topographical model is created by an ordinary krieging interpolation system using a surfer platform. The krieging interpolation system was selected based on its high standards when plotting unevenly spread measuring points. The present-day terrain surface was established using stereo-pars of 1:15000 aerial photographs (from Landmaelingar Islands July, 1996). A B8-machine was employed for the mapping of the terrain (equidistance 1 meter). After drawing, the map was digitalized using an Arch8 computer program. At ten sites, spread over the study area, natural exposures in glaciofluvial sediments were cleaned, described, photographed and logged (scale 1:20). Fourteen 1 kg samples were collected along two transects following the terrain gradient downglacier. The sites of the logs and the three profiles were also sampled both above and below a tephra marker horizon, if identified. The classification of the fluvial deposits largely follows the lithofacies code system suggested by Miall (1978, 1996) and overlying diamicts are classified according to the recommendations by Krüger & Kjær (2000).

At Kötlujökull glaciofluvial sediments of a modern supraglacial outwash fan was studied, although no natural exposures were available here. The central part of the fan surface was levelled along with the flow direction, using the same techniques as previously mentioned. Three large pits were excavated in the proximal, middle and distal parts of the fan and a log was recorded from each pit (scale 1:10). 1 kg samples were collected from the lower, middle and upper part of the wall in each excavation. The grain size analyses are statistically evaluated in accordance with Folk & Ward (1957). They are presented in diagrams involving calculations of average grain-size and sorting coefficient.

Sixteen tephra-samples were collected at Slettjökull, spread along the margin from the Eldgjá fissure and westwards. 5 g pulp samples were sent to ACME Analytical Laboratories in Vancouver for chemical analysis of whole rock-samples by ICP (Inductively Coupled Plasma), an instrument that is capable of determining the concentrations of 40 to 70 elements simultaneously. For the purpose of this study the concentrations of 20 elements were determined, including both major elements and common trace elements (Appendix).

4. Kötlujökull

4.1. Geomorphology of the forefield

On the eastern flank of the Mýrdalsjökull ice-cap Kötlujökull, a 15 km long and 3-7,5 km broad outlet glacier descends from an elevation of 1200 to 220 m a.s.l., forming a piedmont foot outlet glacier below 600 m a.s.l. The glacier snout, covered with glacier debris and volcanic ashes, terminates on the Mýrdalsjökull outwash plain, which slopes gently towards the Atlantic coast.

Figure 2A shows the large-scale geomorphology of the forefield beyond Kötlujökull. A girdle of marginal ridges, dating back to an ice-advance around 1900, extends c. 2 km beyond the present-day front of the active glacier (Heim 1983; Krüger 1994). It separates the glacier forefield from the Myrdalssandur outwash plain. Behind the outermost reach several readvances of Kötlujökull, terminating in 1940, 1955 and 1987, have produced a complex pattern of irregular ice-marginal ridges. These readvances were not conformably distributed as some areas advanced further than others, which imply end-moraine ridges of different ages cross cut each other. Remnants of ice-free moraine from the 1940s ice-stagnation still persists at some places along the margin, although heavily dissected and partially overridden by later glacier advances. The mid-1950s end-moraine system can be seen in the northern part of the study area, cut by both active and abandoned meltwater streams and minor supraglacially fed outwash fans. The most recent girdle of ice-marginal ridges was formed during the late 1980s, when a segment of Kötlujökull advanced, producing a frontal push-moraine ridge in 1987. This well-defined end-moraine system separates an area of fully ice-cored moraine from the part of the forefield dominated by partially ice-cored moraine, slightly fluted ground moraine, hummocky moraine and outwash deposits. The fully ice-cored moraine extends c. 400-500 m beyond the active front of the glacier.

A c. 120 m² outwash fan is situated in the centre of the study area. The fan extends immediately beyond the fully ice-cored moraine through a gap in the mid-1950s marginal moraine ridge, situated about 100 m in front of the fully ice cored moraine. Thereafter it spreads out, forming a fan sloping towards southeast. Following the gradient of the terrain a minor streamlet can be seen running across the southeastern side of the bare fan surface. The inclination is highest in the proximal parts with a 5° dip and decreases to 2° towards more distal areas (Fig. 2B). The difference in altitude between the proximal and distal part of the fan surface is c. 11 m over a 380 m distance.

4.2. Glacier fluctuations and development of a minor outwash fan

Throughout the 1970s and 1980s, the development of a minor, supraglacially fed outwash fan was monitored along the margin of Kötlujökull (Krüger 1994, 1997). During this period the ice front advanced across the glacier forefield, producing a frontal moraine-ridge. Immediately outside the steep ice-front a minor fan was being deposited, extending through a gap in the 1955 end-moraine across an area with morainic terrain (fig 2A). After 1980, the proximal 100-125 m of the fan was seen pushed and successively overridden by the advancing glacier (Krüger et al. in press).

Figure 3 shows the situation of the area at three occasions: In 1979, prior to the fan development, the gap in the 1955 moraine-ridge

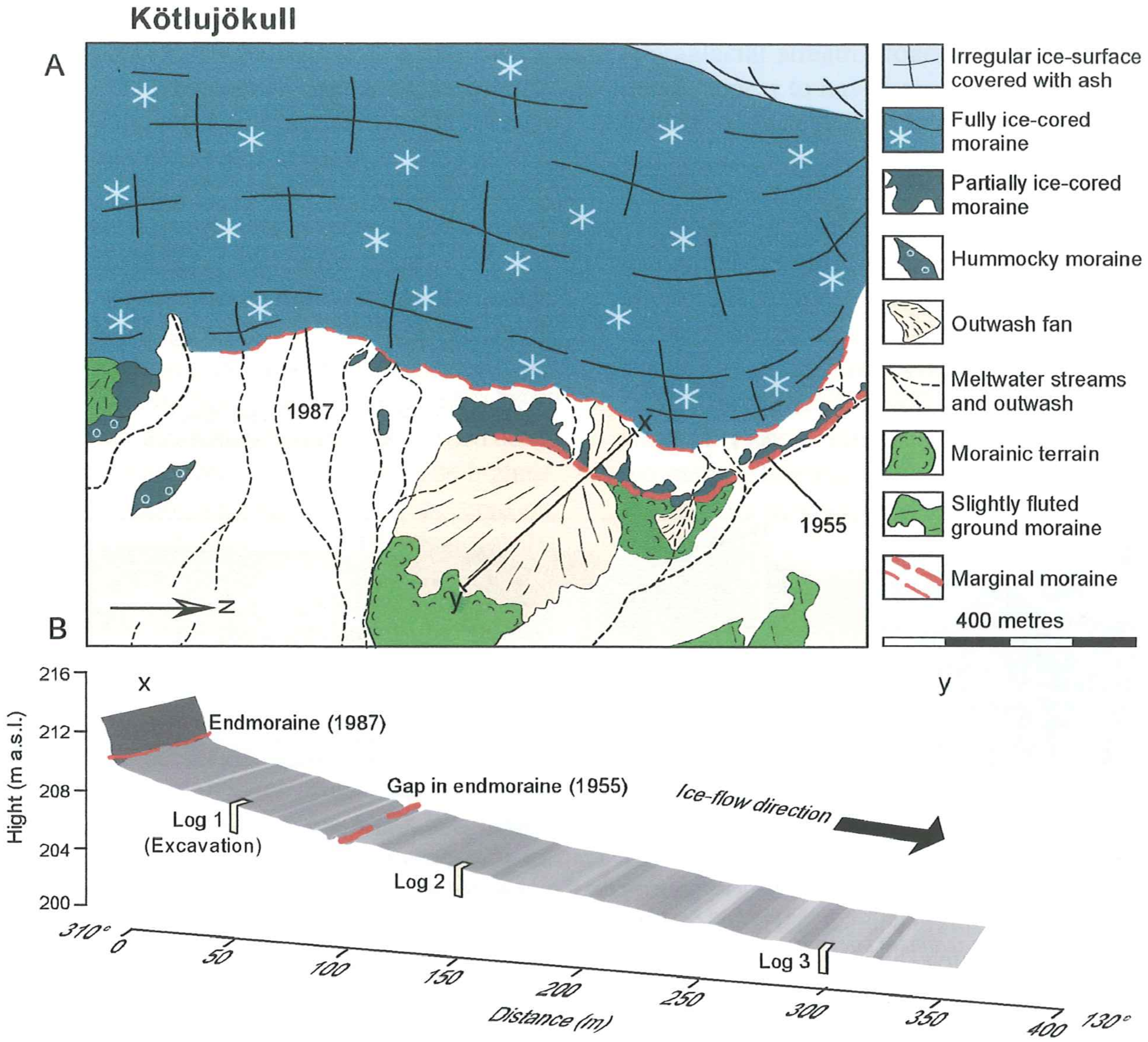

Fig. 2. Geomorphological map. A) The forefield of Kötlujökull with the studied outwash fan located in the centre. The x-y profile-line is shown in fig. 2B. Based on aerial photographs by Landmaelingars Islands (1996). B) Profile line along the outwash fan following the palaeo-current direction downslope towards southeast. The positions of logs are displayed as well as the location of the 1987- and 1955 end-moraine ridges.

appeared as an abandoned boulder-paved meltwater channel (Fig. 3A); in 1986 two thirds of the fan, 1.5 m, was deposited (Fig. 3B); and in August 2001 the sediment thickness at the gap had risen to c. 2.5 m (Fig. 3C). Furthermore, Figure 3 demonstrates the correspondence between the rates of end-moraine progression related to a fixed reference point and sediment accumulation at the middle part of the fan. The displayed data have been extracted and compiled from field observations by J. Krüger 1979-2001 (pers. comm.). Between 1979 and 1982 the ice front advanced by a mean distance of 10 m per year, significantly increasing during 1982 to an annual progression of 32 m. The increase in glacier dynamic was reflected in a steepening of the frontal ice slope. Two years later, the end-moraine progression decreased to an average of 20 m per year. As the glacier slowed down a differentiation of progression rates occurred between frontal movements relative to the ice surface velocity due to higher friction at the front. As the ice did not compensate for the more rapid upglacier movement, it fractured and started to move along thrust-planes, resulting in the formation of overhanging walls or steep frontal ice-cliffs. In 1986, the rate of frontal advance decreased to c. 4 m per year, ceasing between 1987-1989. The stabile ice-marginal position gave rise to a reduction in the steepness of the frontal slope (Krüger *et al.* in press).

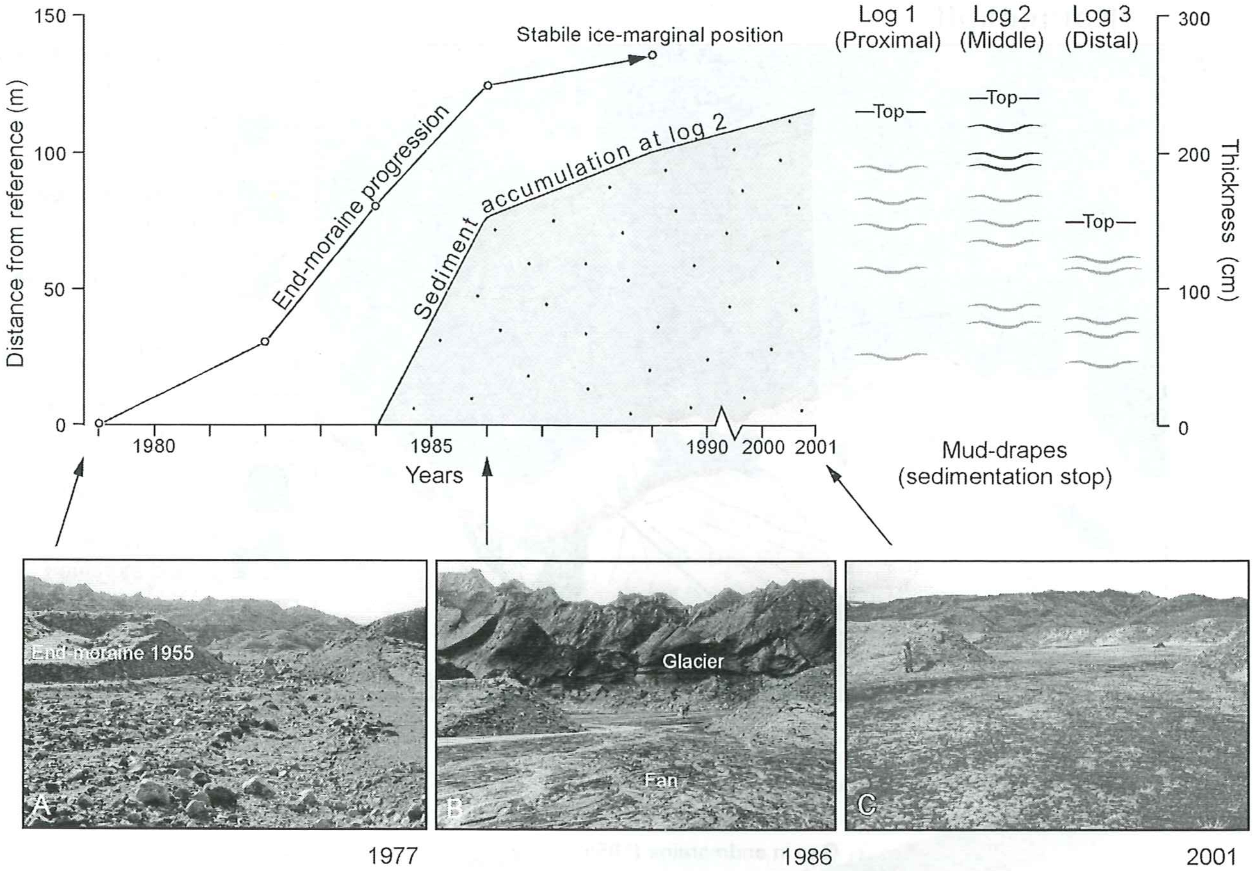

Fig. 3. Diagram showing the correspondence between end-moraine progression and sediment accumulation at the monitored fan, from 1979-2001. The photos show the fan viewed across a gap in the 1955 end-moraine at three occasions: A) In 1977, prior to the fan development, the fan appeared as an abandoned boulder-paved meltwater channel; B) in 1986 two thirds of the fan had been deposited and it was covered in a network of braided streams; C) in August 2001 the sediment thickness of the fan had risen to a total thickness of c. 2.5 m. See person for scale. On the right-hand side of the diagram, the occurrences of mud-drapes in each log are shown. Data have been extracted and compiled from field observations by J. Krüger 1979-2001 (pers. comm.).

The initial high slope gradient combined with a coherent heavily sediment-laden fully ice-cored moraine facilitated the transport of supraglacial material beyond the glacier, where it accumulated as outwash fans. When the ice margin stagnated, on the other hand, the ice-cored moraine collapsed, resulting in a lowering of the frontal slope gradient. Thus, instead of spreading out on the glacier forefield, the supraglacial material was chiefly trapped in topographical lows within the existing dead-ice field. The material that reached the forefield was subjected to a series of resedimentation cycles successively reworking the sediment within the ice-cored moraine. In general, the reworking started with backwasting, defined by Kjær and Krüger (2001) as the 'sub-horizontal retreat of near-vertical free ice-walls, or steep ice-cored slopes'. Following this process sediment rolled, fell or slid downslope. Rainwater or meltwater occasionally oversaturated the sediments, triggering slurry-like sediment movements. Accordingly, meltwater streams cutting down in the material transported sand and gravel off the glacier surface on to the fans. On average, the sediment cover was reworked up to two times during a single ablation period, resulting in a downslope sorting of the bulk sediment. Such processes were favoured by the extreme climate of Kötlujökull, with high annual precipitation and large summer melting.

The material, transported in the described manner, originated from three known sources: (i) Sorted sand emerged from numerous englacial dirt bands all over the glacier snout. This material may represent old ablation surfaces or originate form volcanic eruptions or dust storms. (ii) Diamict material, consisting mainly of gravel-silt-sand, emerged from debris-loaded thrust-planes and (iii) water worked sediments, comprising poorly sorted gravely sand, emerged higher up on the glacier. These water worked material may date back to the catastrophic Katla eruption in 1918, which triggered a large bursts of meltwater transporting huge amounts of material both across the glacier surface and englacially.

The sedimentation rate of the outwash fans along the margin of Kötlujökull was extremely high, resulting in fans of several hundred square-metres being deposited within a few years time. Krüger (1994, 1997) recorded daily sedimentation rates up to 2.5 cm. The highest sedimentation rates seem to have occured on days of high precipitation, immediately following one or two days of moderate rainfall. The material was 'prepared', i.e. oversaturated with water, which facilitated a downslope transportation. Cloudy periods and days of moderate rainfall seem to have reduced the input of water and sediment to the main streams and also the meltwater production. Extended sunny periods, on the other hand, intensified the meltwater production, but because of temporary slope stability only small amounts of sediment, mostly silt, sand and fine gravel, moved downslope.

Although the fans are situated adjacent to the glacier margin, they display sedimentary textures and grainsize composition common for distal regions of outwash fans (Krüger 1997). Instead of the coarse-grained material seen in fans fed by subglacial streams, they comprise mainly sand-sized facies interbedded with thin laminae of gravel and occasional mud-drapes. Because of the low transport capacity of the supraglacial streams coarser components of debris appear to have been left behind on the glacier, while mostly sand and some silt and gravel were drained off the surface and deposited in front of the glacier.

Krüger (1994) termed these fans Hochsander fans, originally defined by Gripp (1975). Heim (1992) suggested following definition of Hochsander fans: 'sand- or sand-gravel bodies, which material is derived from glaciofluvial outwash of supra- to englacial meltwater, deposited immediately in front of the ice-margin, beyond its marginal moraine or up to a maximum of a few hundred meters in front of it'.

4.3. Sediment description and interpretation

The studied fan rests on a coarse-grained lag covered with moss, which has been preserved under the fan sediments. Dense basalts and porous basaltic tuffs are the dominating rock-particles and the average grainsize ranges from coarse sand to fine sand, with a mean of medium sand for entire fan. The sorting seems to be consistently low throughout the reach of the fan, dominated by poorly sorted material (coefficient 1-2), with occasional layers of moderately sorted sediments (coefficient 0.7-1). As seen in figure 4 no clear pattern concerning the mean grainsize or the spreading about the average can be recognized between

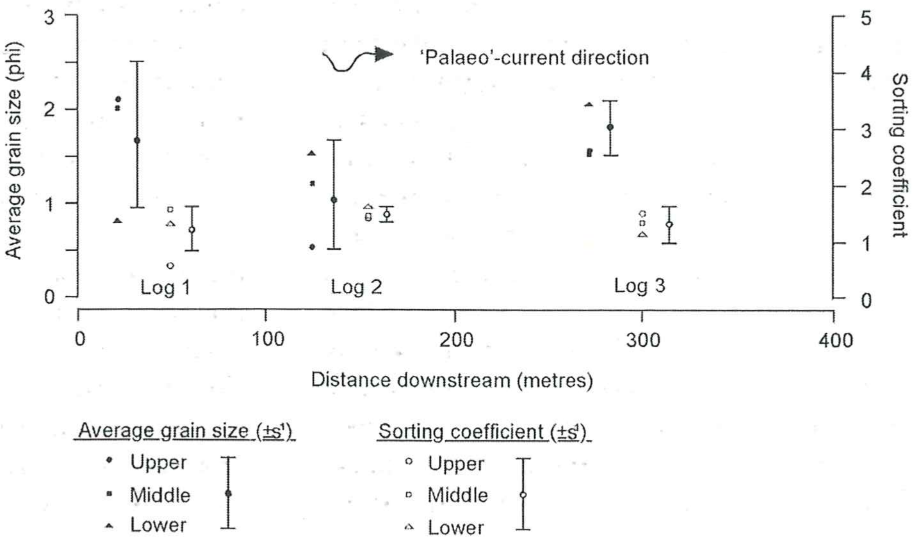

Fig. 4. Diagram of average grainsize and sorting measured in the proximal (log 1), middle (log 2) and distal (log 3) part of the fan. One standard deviation = s^1.

the proximal, middle and distal part.

Eleven lithofacies have been identified within the three logs of the fan in front of the 1987 marginal moraine. The sedimentological characteristics of these lithofacies are firstly described and secondly the processes are presented. Photo documentation and field observations of processes active during the fan-development have provided valuable information that further substantiates the interpretations of the lithofacies (Krüger pers. comm.).

*Boulders (*Bl*) and gravels (*G*)*

***Description*.** Gravel facies typically comprise loose, clast-supported, fine to coarse gravels. Individual horizons rarely exceed a few centimetres, forming discontinuous, massive or crudely horizontally bedded layers within thicker sand units. Indistinct lines of scarcely scattered gravel particles occur frequently throughout the reach of the fan. *Gm*, massive or crudely bedded gravel, generally consists of poorly sorted, heterogeneous, matrix-supported units. Two good examples can be seen in log 1 at 0.9 m and 1.2 m, respectively (Fig. 5). *Gh*, horizontally bedded gravel, is present as erosive beds cutting sandy units at low angles (<10º). These facies occur locally as lenses, e.g. in the lower bottom of log 3, typically with a lateral distribution of up to 0.5 m. Although, gravel beds commonly show limited internal structures or grading, some exhibit cross-bedding. *Gp*, plane cross-bedded gravel, seems to be chiefly located to the middle part of log 2 and 3. Generally, the beds do not exceed 5 cm in thickness and they are characterized by a lateral distribution of less than 2 metres. At one location, situated in the uppermost part of log 1, a minor layer of possible *Gt*, trough cross-bedded gravel, was recognized. This erosive facies was no more than a few centimetres thick and the internal structure was indistinct.

***Interpretation*.** Massive or crudely bedded gravel, *Gm*, is interpreted as the product of rapid deposition within streams, due to episodic overcharging of the flow with sediment load, associated with summer rainstorms (Miall 1996). A temporarily enhanced transport capacity induced by an increase in water- and sediment supply may have triggered the transport of gravel and rare pebbles on to the glacier forefield. The transport capacity does not seem to have been sufficient for transporting larger boulders though. The clast-supported framework of the gravel facies reflects grain-by-grain deposition from bedload (Brayshaw 1984). *Gh*, the discontinuous beds and lenses of horizontally bedded gravel, most likely represent infilling of flat, shallow channels (Miall 1996). Small changes in transport capacity of the streams have resulted in an indistinct horizontal lamination of the sediments. The erosive nature of *Gh* is also attributed to this pulse-like flow style with rapidly changing flow capacity. Formation of antidunes, characteristic of braided streamlets during the ablation period, were observed throughout the course of the fan development. The rare cross-bedded gravel facies, *Gp* and possibly *Gt*, are thought to represent migrating antidunes, formed within the major channel-network. Migration of different types of dunes is common in both meandering and braided streams. An alternative origin for *Gp* is from the migration of linguoid bars during flood stages, but it does not seem likely since large bars were rarely formed within this system of shallow, low-energy braided streamlets.

*Sands (*S*)*

***Description*.** The sand lithofacies predominate the fan deposits. They generally comprise thin heterogeneous units (2 cm to 0.1 m) of horizontally bedded sands, often occurring as centimetre-thick fining-upward sequences of coarse to fine sands. Percentages of silt and clay tend to be consistently low (<5%). Two closely resembling sandfacies have been distinguished; *Sh* and *Sl*. *Sh* is a "normal", laterally continuous horizontally bedded unit, commonly interbedded with numerous millimetre-thin gravel horizons. The sorting varies from moderately sorted beds to heterogeneous silty-gravely-sandy beds. Indistinct fining-upward successions and sub-successions, often forming repeated graded beds, occur frequently within this facies. A representative example can be

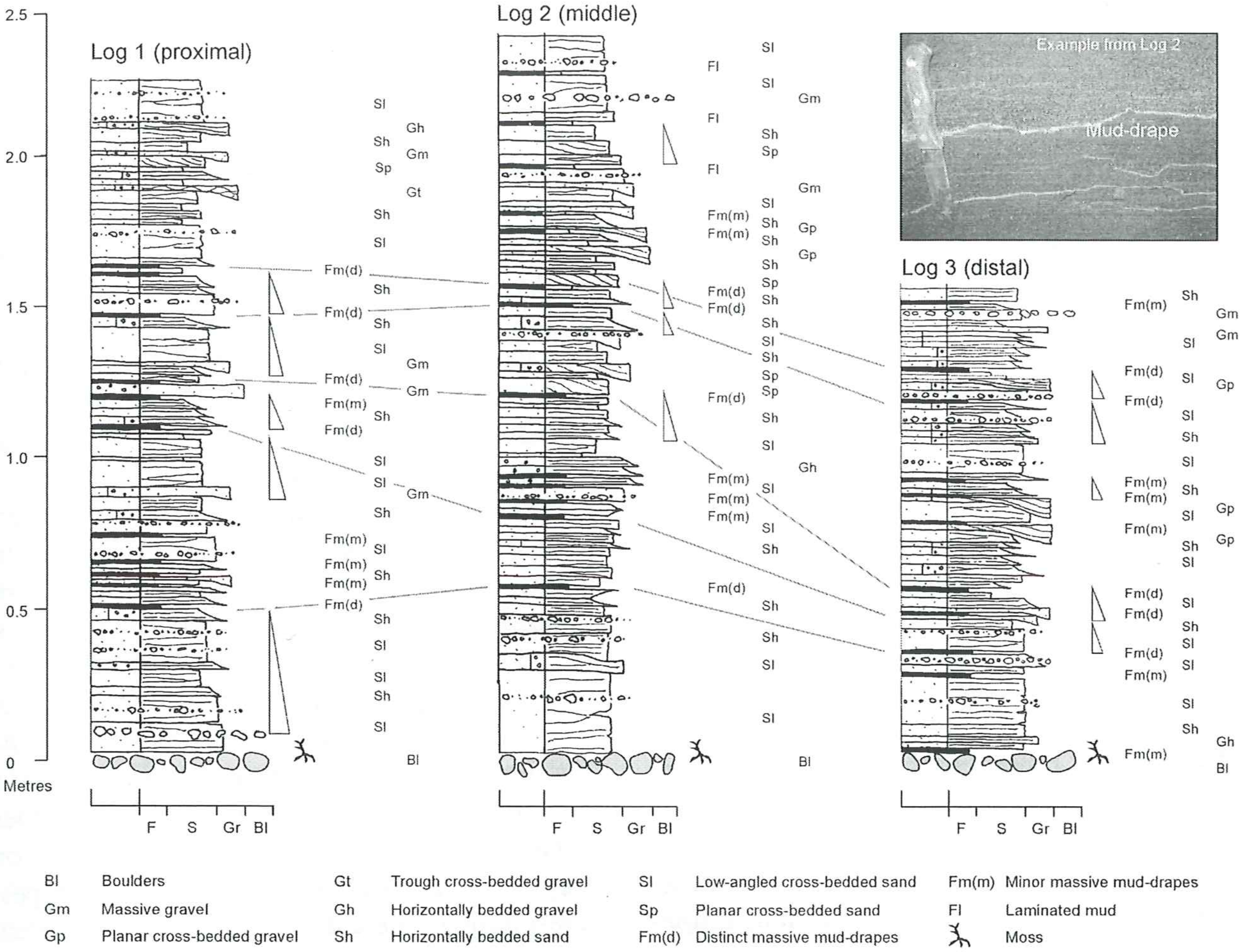

Fig. 5. Sedimentological logs A) Logs from the proximal, middle and distal parts of the fan showing lithology and primary sedimentary structures. Distinct mud-drapes are accentuated by connecting lines. The photo displays an example of yellowish, massive mud-drapes from the middle part of the fan.

seen in log 1 between 1.1 m and 1.2 m (Fig. 5). Coarsening-upward successions can be found locally. *Sl* (low-angled cross-bedded sand), the most common sand facies, closely resembles *Sh*, with the exception of its lateral distribution. This facies typically has a laterally distribution of less than one metre. The thin, discontinuous, alternating coarser and finer layers cut underlying layers at low angles (<10°), forming beds between a few centimetres up to approximately 0.5 m thick. The thickest *Sl* beds are located to the lowermost parts of each log. *Sp*, plane cross-bedded sand, is not as common as *Sh* and *Sl*, but does occur occasionally. Log 2 comprises the highest number of *Sp* facies, especially in the upper half section. These erosive facies rarely exceed 0.1 m and typically comprise sandy layers interbedded with gravely lags.

Interpretation. The predominance of horizontally bedded sands and low-angled cross-bedded sands is typical for shallow, laterally unstable streamlets (Miall 1996). Laminated sand beds may, apart from being deposited within the braided network of shallow streams, also be deposited by flashy, ephemeral sheetflows as summarised by e.g. Landvik & Mangerud (1985) and Miall (1996). These periodical floodings seem to have occurred diurnally along the margin of Kötlujökull during the ablation period. *Sh* is interpreted as sand being deposited mainly under upper stage flow regimes within shallow streams, up to 5 cm deep, from relatively steadily flowing water with only minor fluctuations in transport capacity. Alternatively, *Sh* is associated with sheetflow deposition during the periodical floodings. Probably, both processes worked simultaneously, enhanced by the increased meltwater supply in the afternoons that caused floodings as well as the migration of streams. *Sl*, on the other hand, was presumably deposited by pulsed flows within wider, shallow channels, each flow eroding the upper surface of underlying layers. Repetitive couplets of normal grading (e.g. the middle part of log 2) point to frequent short-term fluctuations of the flows, associated with waning flood conditions. These fluctuations are due either to abandonment of laterally migrating braided streams or variations in the transport capacity following changing water influx. Observations show that both processes were active simultaneously. Plane cross-bedded sand, *Sp*, may originate from migration of minor sandy bars and shallow, narrow channels with an approximate width of 0.5 m.

Fines (silts and clays) (F)

Description. Fines represent the least common lithofacies type within the recorded sandur succession. It includes massive and laminated mud, present as thin beds draping underlying facies. The yellowish massive mud-drapes (*Fm*) vary in thickness from a few millimetres up to one or two centimetres at the most (Fig. 5). They appear to be mainly structureless, even though some lamination is visible at places. Five clay-drapes in each log are considered to be distinct, *Fm(d)*. These facies, located at 0.6 m, 0.8 m, 1.2 m, 1.5 m and 1.6 m in the middle part of the fan are laterally continuous for at least 2 m, i.e. at the scale of the excavations. *Fm(m)* facies, on the other hand, are laterally discontinuous and therefore termed minor massive mud-drapes. They typically have a lateral distribution of less than 1.5 m. Three beds at log 2 are distinguished from other fines by their colour and structure. These layers (*Fl*), displaying various shades of brown, are clearly laminated and occur only at the top one metre of the middle part of the fan (Fig. 3).

Interpretation. The brownish laminated mud of the upper part of log 2 is interpreted as pond-sediments, probably formed when a minor depression in the ground became water-filled. More complex in their nature are the yellowish mud-drapes, seen at different levels in all three logs. Heim (1983) interpreted similar mud-drapes as the result of melting of ice-remnants interbedded in the fan sediments. Krüger (1994) observed how the fan surface was periodically flooded by a thin cover of meltwater heavily loaded with fines. He interpreted that as the result of occasional influx of fines to the proglacial area, due to drainage of small supraglacial lakes on the ice surface. I propose that the mud-drapes represent the last stage of successions associated with waning floods. The drapes are predominately seen ending fining-upward successions, implying they are the final product of a certain course of events. At times when the water flow ceased, following a decrease in sediment supply, the finest particles of the suspension load could be slowly deposited, draping underlying layers. The lateral persistence of the distinct layers, *Fm(d)*, imply they originate from longer periods of sedimentation stops compared to the minor clay-drapes, *Fm(m)*. An alternative interpretation may be that the minor drapes have been subject to a more pronounced erosion by overlying sediments than the distinct drapes, resulting in solely thin layers being preserved. Upward escape of fine particles is excluded as a possible origin of the mud-drapes. This since photographical evidence and field observations show streams draped with a thin cover of mud surrounded by non-muddy areas, a situation that would not appear if the mud had migrated upwards from within already deposited sediments.

4.4. Depositional environment: Kötlujökull as a facies model

By definition, Hochsander fans are non-erosive deposits that fill up depressions in the morainic terrain in front of glacier margins, or rest on the proximal part of old outwash plains (Heim 1992). The observed supraglacially fed outwash fan at Kötlujökull consists mainly of planar-bedded, normal graded, coarse- to medium sands interbedded with thin laminae of fine gravels and occasional mud-drapes. Poorly sorted material, mainly belonging to the middle sand fractions, dominates in both proximal and distal regions. Hochsanders have all the architectural characteristics of an ordinary alluvial fan, with a typical semiconical shape, a slope of 2-5° and a radius of c. 400 m.

The fan at Kötlujökull developed during the 1980s in a humid climate in front of a steep, debris-covered, advancing or stationary glacier margin. Sediment exposed on the ice surface was collected in drainage paths and transported downslope in mass-movement dominated resedimentation cycles. At this particular fan sorted sand emerged from englacial dirt bands, diamict material from debris-laden thrust-planes and water worked sands and gravels from higher up on the glacier. However, for Hochsanders to form the origin of the material does not seem to matter, as long as it is exposed on the ice surface. During the downward transport of sediment, coarse components apparently were left on the glacier, while mostly sand, fines and some gravel were transported off the surface on to the forefield in a network of braided streamlets. The 0.1-0.5 m wide and up to 30 cm deep streams were laterally unstable and flooded in accordance with the diurnal ablation cycle. During floodings in the afternoons sheetflows were generated, temporarily transformed into hyperconcentrated flows where the sediment/water ratio was disproportional. Occasionally, minor feeder channels seem to have worked their way through the terminal ice wall and formed incised channels cutting down in the surface of the newly deposited fan sediments. Rapid changes in stream transport capacity, due to short-term variations of water influx controlled by weather changes, induced deposition of alternating thin horizons of sand and fine gravel. During heavy rainstorm events, an increased water and sediment supply enhanced the transport capacity and thereby coarse sand and gravel could be transported on to the forefield. On the other hand, a lowering of the stream depth followed by an increased sediment concentration generated deposition of fining-upward successions ranging from fine gravel to medium or fine sand draped with mud. These events are associated with waning floods during dry, sunny periods or periods of moderate rainfall. When the flow concentration reached a critical limit, the sediment concentration appeared to have been sufficient to form hyperconcentrated grain flows (Jonsson 1982; Maizels 1993). Observations in field show that at this point porous gravel particles started to roll downslope over the surface, resulting in deposition of thin gravel sheets noted below and above the mud-drapes. The final phase involved a complete sedimentation stop, when the finest material could be deposited as mud-drapes.

5. Slettjökull

5.1 Geomorphology of the forefield

The northern margin of the Mýrdalsjökull ice cap has the shape of a 20 km broad lobe: Slettjökull, terminating at 550-600 m a.s.l. The margin is split into two discrete sub-lobes, separated by an obsidian-dominated medial moraine c. 1.2 km east of the study area. The gently sloping glacier surface is almost clean and debris-free, except for a few outcropping ash-layers, sloping 3-6°. Sharp-edged dirt cones positioned parallel to the ice margin are seen in relation to these layers. A relatively newly exposed c. 100 m² bedrock knob situated immediately east of the study area can be seen breaking the monotony of the outermost ice front (figure 6). Further upglacier a few minor nunataks are visible, around which the ice adjust as indicated by the crevasse pattern.

Figure 6 shows the overall geomorphology of the glacier forefield beyond Slettjökull. The forefield has been modelled by at least two advances of the ice front and finally exposed by glacier retreat in this century. Two systems of marginal ridges have been preserved in the forefield of Slettjökull. A complex series of three to six sub-parallel marginal moraine ridges, dating back to a glacier advance around the turn of the previous century extends 1.5-2 km beyond the present-day margin. These slightly curved ridges separate the proglacial landsystem of outwash deposits from the glacier forefield, dominated by clast-paved fluted ground-moraine cut by braided stream channels. Up to 50 m wide depressions, partly

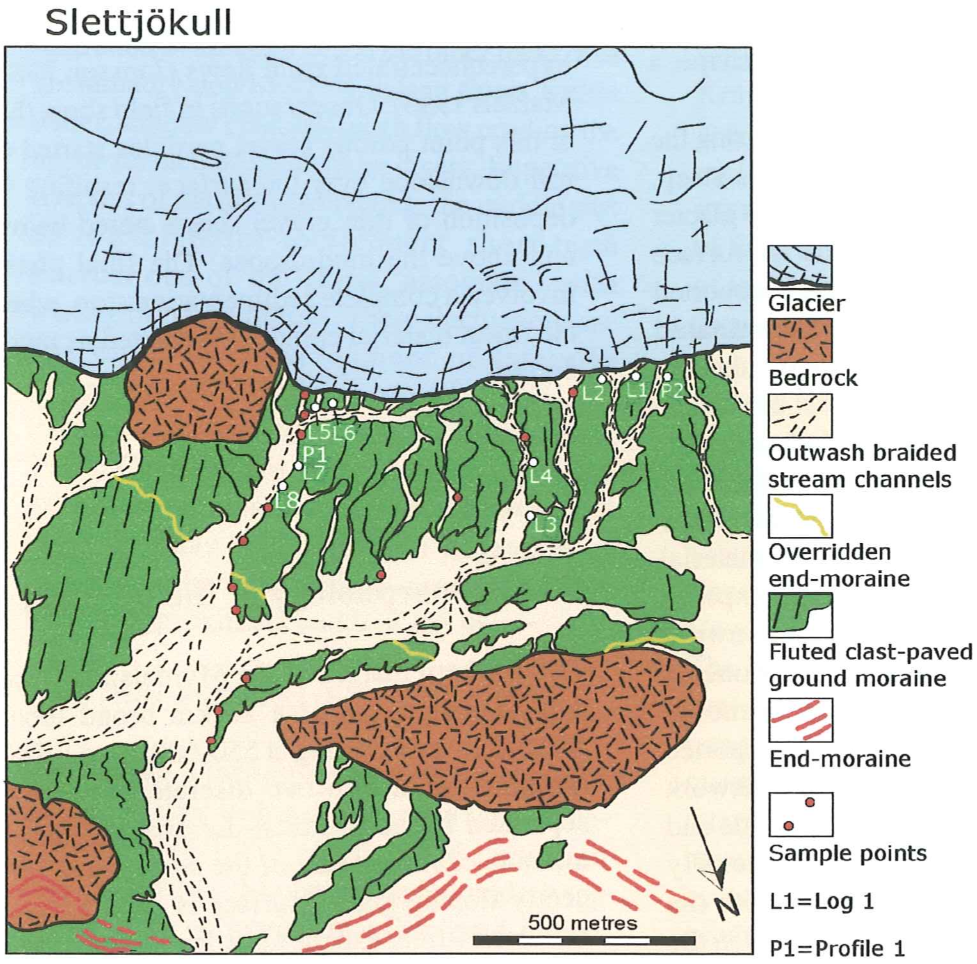

Fig. 6. Geomorphological map showing the forefield of Slettjökull. The locations of logs and profiles are shown as white circles. Sample points from grainsize analysis are shown as red circles, positioned as two transects. Based on aerial photographs from Landmaelingars Islands (1996).

filled with ground moraine or outwash sediments, separate each line of ridges (Krüger 1994). A glacier stagnation, dating back to about 1900 is represented by an overridden push-moraine situated approximately 200 to 600 m beyond the present-day ice-margin, i.e. in the centre of the forefield. Immediately north of the study area, this particular ridge climbs the flank of a large bedrock knob. Closest to the glacier margin a series of c. 50 identified annual moraine ridges were produced and preserved during the past eight decades, since 1928 (Krüger 1994). The positions of these annual moraines indicate a continuous frontal glacier retreat with some variation, ranging from 10-50 m per year and finally balanced with the climate. A temporary stagnation of the glacier around 1989 resulted in repeated stacking of annual moraines, leading to the formation of a more composite moraine ridge seen c. 10 m in front of the present-day ice front. The partly fluted, clast-paved ground moraine present in the forefield is heavily dissected in the proximal high-lying regions. It is cut by up to 4 m deep gullies located perpendicular to the ice front, formed when meltwater transported from the glacier cut down in the forefield. This undulating terrain is clearly drumlinized and partly covered with flutings present as distinct ridges or stone stripes striking parallel with the former ice flow direction. Farther away from the glacier toe the ground moraine is more smooth, forming a flat and low-lying terrain relief, cut by a few main channels. A gradual westward transition from areas of heavily dissected ground moraine towards more coherent morainic terrain is present within the study area. Where the till cover has been eroded outwash sediments are exposed. Scattered on the ground moraine surface small depressions have been filled with eolian sand, downwash sediments or lacustrine deposits.

5.2. Lithostratigraphy

Figure 7 shows a possible scenario for the development and modification of the Slettjökull forefield (Kjær *et al.* submitted.). The lithostratigraphical framework is built up of two separate diamict units: upper till and lower till, overlying outwash sediments: (A) The outwash sediments are thought to have been deposited around year 1000, estimated from the changing positions of easily recognizable tephra bands within the glacier between 1977-1982. Although large channel-structures occur widespread, horizontally bedded sands interbedded with thin gravel sheets and mud-drapes dominate. A tephra marker horizon, originating from an eruption of the Katla volcanic system is also recognized within the deposit. (B) A glacier advance terminating around 1750 resulted in deposition of the lower till unit. This diamict is a grey, massive, extremely firm, matrix-supported actively deposited basal till, generally with a moderate clast-content (Krüger 1994). (C) As the glacier retreated, the ground moraine was exposed and dissected, mainly by fluvial activity. (D and E) A readvance over the already deposited lower till around 1900 generated deposition of the upper till unit. The same glacier advance produced the overridden push-moraine by a temporary ice front stagnation followed by a continued progression. This progression terminated around 1900, which is when the terminal series of end-moraines were being produced. Upper till can be further sub-divided into an upper dark-grey, massive, homogenous, friable and clast-paved diamict and a similar but more deformed unit located closer to the substratum. Also the outwash sediments seem to have been exposed to some deformation in the area of the sorted material/till interface. (F) After 1900, the glacier margin was subjected to continuous frontal retreat. The recession exposed the ground moraine and meltwater streams again dissected the terrain Finally a temporary stagnation in 1989 resulted in the formation of the frontal moraine ridge, seen a few metres beyond the present-day glacier margin.

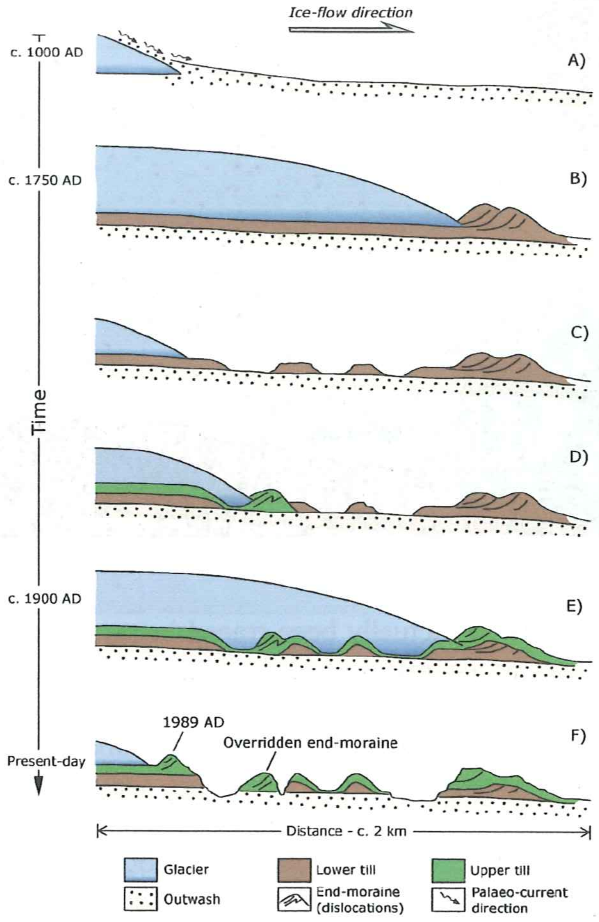

Fig. 7. Lithostratigraphical model of the Slettjökull forefield showing deposition of outwash sediments followed by glacier fluctuations. The lower and upper till units were deposited during advances of Mýrdalsjökull. During retreats the landscape was dissected by fluvial activity (A-F). From Kjær et al. *(submitted).*

5.3. Internal architecture of the glacier forefield

Reconstruction of the relief for the outwash sediments. Figure 8 displays a plan-view over the mapped surface, showing the general outline of the relief and its validity through the distribution of observation points. The surface of the outwash succession covers an area of approximately 1200 m² and slopes gently towards northeast (Fig. 9). A reasonable extrapolation of the contour lines westwards implies the studied surface represents the dextral half of a fan, spreading out beyond the ice margin. Following this reasoning the total area of the fan can be estimated to roughly 2500 m². Most likely the fan is even more extensive, since it seems to extend behind the present-day ice margin for some distance. Although the sur-

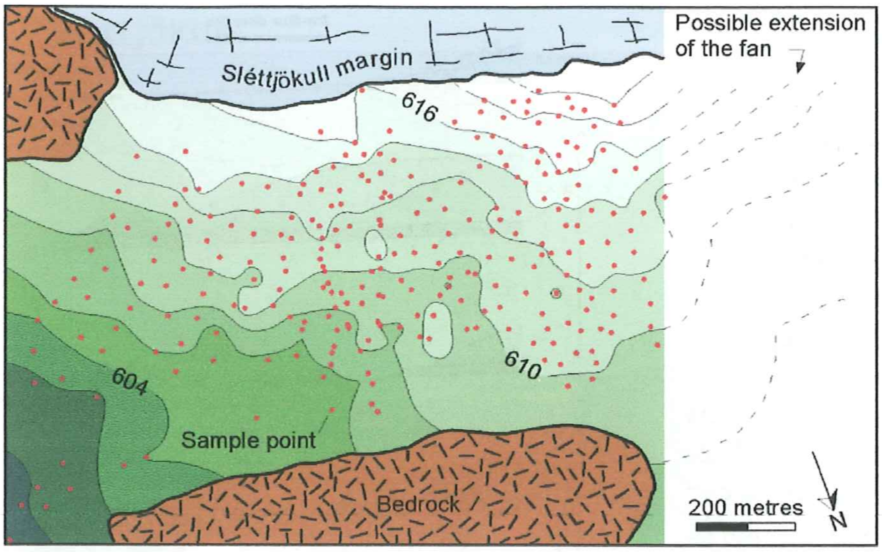

Fig. 8. Plan view over the reconstructed relief of the outwash sediments. Large-scale geomorphological features are displayed as well as the position of sampe points. Furthermore, an extrapolation of the contours is shown to accentuate the fan-shape of the deposit. Contour lines are shown in metres above sea level.

face has not actually been traced beneath the glacier an estimation based on the subglacial topography mapped by Björnsson *et al.* (2000) shows that it probably continues for about 1 km upstream from the present-day ice front. The inclination of the surface seems to increase somewhat beneath the glacier. About 1 km upglacier an over 25 m deep depression in the substratum follows, implying the ice margin was probably not positioned further upslope when the outwash deposit was formed. This because a higher position of the margin means the depression would have been filled before material was transported and deposited further downslope. In addition, a rear location of the ice margin would induce a pattern contradicting to known behaviour of subglacial erosion, since the marginal parts of an ice cap are subject to netdeposition (Benn & Evans 1998).

Taken over a 1.5 km distance from the proximal part to the distal fan-area an altitude difference of 20 m is recorded. Although a well-defined intersection point is not recognized, the inclination is highest in the proximal parts with a 5° dip and decreases to 1° towards more distal areas. Despite the smooth appearance of the fan-surface, a few structures have been identified. A channel-like depression strikes downslope from southwest towards northeast (Fig. 9). It has the shape of a c. 50-100 m wide and several hundred metres long depression less than 1 m deep.

The surface of the outwash fan is considered original and not a result of glacier erosion based

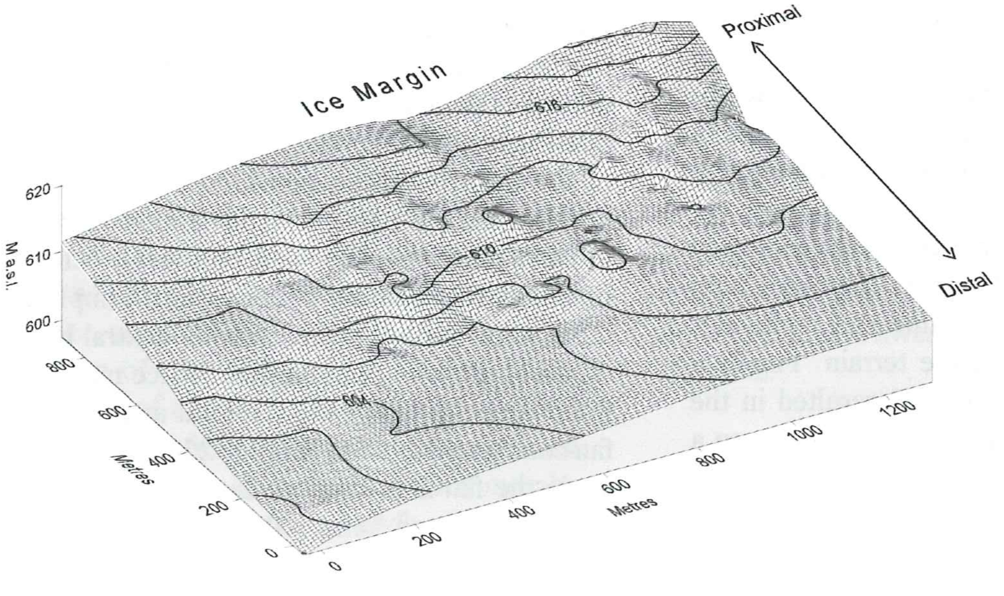

Fig. 9. Three-dimensional model over the mapped relief of the outwash deposit. Note the large-scale channel-structure striking diagonal across the surface. Contour lines are shown in metres above sea level.

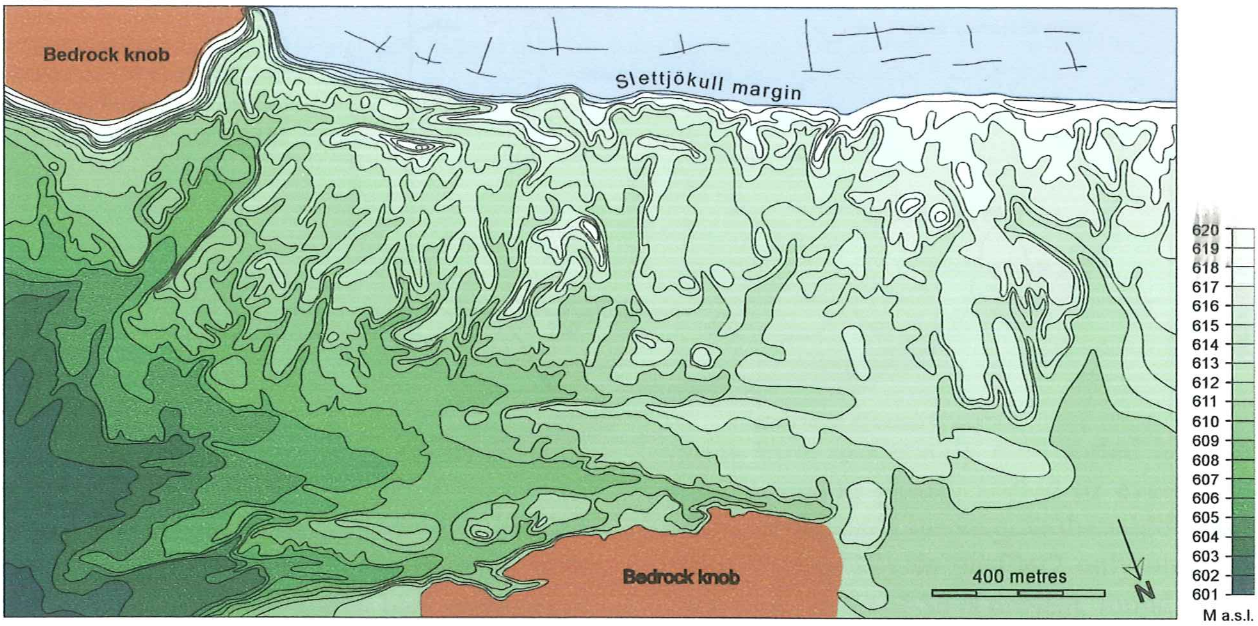

Fig. 10. Plan view over the present-day terrain surface showing landscape dissection. Contour lines are shown in metres above sea level.

on the following line of evidence: Firstly, the surface slopes with an oblique angle from the glacier margin. Accordingly, instead of sloping solely at a right angle to the ice front, as streamlining and glacier erosion would have generated, it has the shape of half a fan with a plano-convex cross-profile. Secondly, the preserved large-scale channel-structure oriented SW-NE agrees with this assumption. If interpreted as a part of a subglacial network, it would have been oriented perpendicular to the glacier margin. Thirdly, on a large scale the till units seem to draped the underlying surface of the outwash fan smoothly. The shearzone between the two units has been measured to c. 10 cm (Kjær 1999), implying only the uppermost part of the surface has been sheared. Thereby the overall shape of the fan has maintained intact. Collectively, the surface of the outwash sediments can be concluded to be the original morphological expression.

Present-day topography. Figure 10 shows the present-day terrain, corresponding to the area above the fan. Also this surface slopes gently towards northeast, although it is not as smooth as the underlying surface. In the eastern part of the domain the terrain is heavily dissected, with a clearly marked difference in altitude between deep incised gullies cutting through the terrain and the highest parts of the remaining ground moraine. Steep walls, up to 4 m high, are exposed along the sides of the gullies. A large number of these former channels are positioned perpendicular to the ice front, generating an elongated nature of the terrain-face dominated by ridges and depressions. Westwards, parallel with the glacier margin, the landscape is only dissected in its most proximal parts, while more distal-lying areas are much smoother.

The highest elevation of the forefield, 619 m a.s.l, is measured closest to the western part of the ice front, while the lowest elevation, 600 m a.s.l, is located further downstream at the eastern side of the study area. Thereby, a difference in altitude of 19 m is present over a 1.5 km distance including the proximal to the distal part of the mapped surface. The inclination ranges from 6° closest to the ice front to 1° for the most distal parts of the study area (Fig. 10).

Comparison between the two surfaces. Figure 11 represents a transect from the ice margin and downslope towards northeast, showing the correspondence of the present-day terrain and the relief of the outwash deposit. The present-day terrain largely follows the underlying surface of outwash sediments, although more undulating and dissected. As seen, the sorted material has been eroded at some places, e.g. 200 metres and 800 metres downstream from the ice front. Similar zones

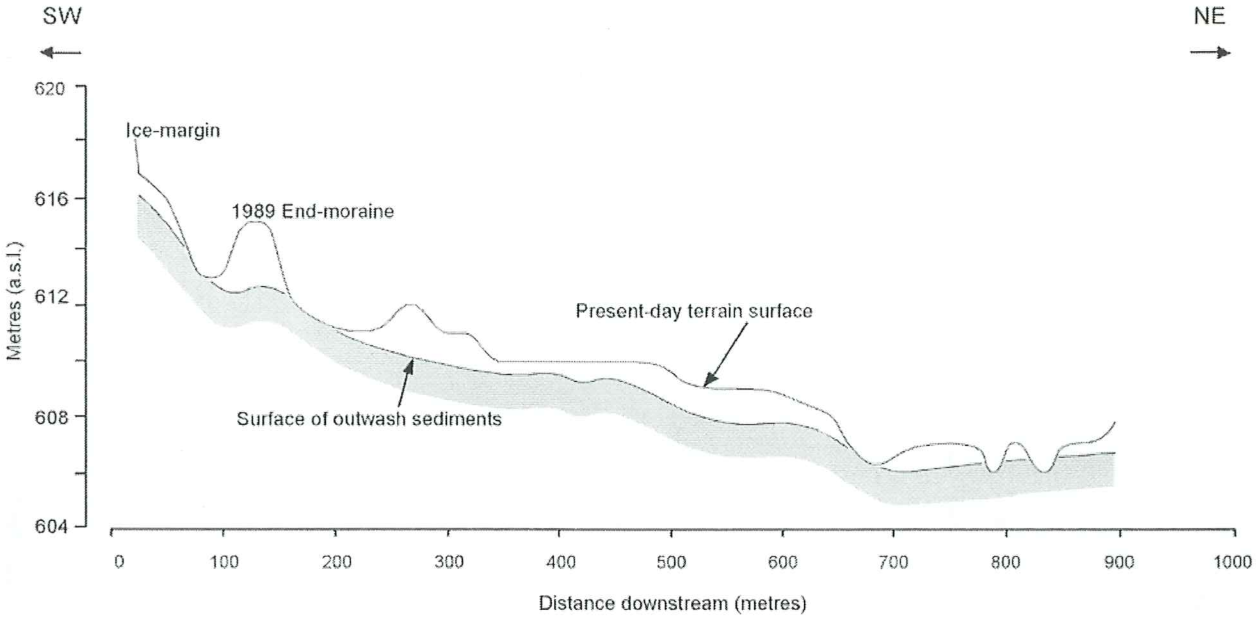

Fig. 11. Comparison between the present-day terrain surface and the relief of the recorded outwash succession. Note the close correspondence between the reliefs of the two surfaces.

where erosion has exposed outwash sediments are scattered in the landscape. Generally though, the two surfaces parallel separated by the 20 cm to a few metres thick ground moraine.

5.4. Sediment description and interpretation

The recorded outwash deposit is buried under an up to 2 metres thick cover of ground moraine, including up to two lithostratigrapical units. The depth and mode of the basal contact to the bedrock underlying the deposit has not yet been described, but Kjær (1999) estimated the thickness of the outwash sediments to approximately 5-20 m. This does, however, not necessarily signify the thickness of the outwash succession, since other fluvial sediments most probable underlie the deposit.

Figure 12 demonstrates the mean grainsize pattern and the variation of the sorting coefficient from the most proximal part of the forefield to about 1 km downslope. As shown, no downstream fining-trend seems to be present. The material is consistently poorly sorted (coefficient 1-2) and the measured average grainsize is medium sand, ranging from very coarse sand to fine sand. The lack of sorting may partly be a result of the employed sampling technique, where bulk-samples generally containing a few thin beds of different grainsize fractions were analysed.

*Boulders (*Bl*) and gravels (*G*)*

Description. Gravel-sized material commonly forms centimetre-thick, discontinuous lines of scarcely scattered particles interbedded in thicker sand beds. Thin, clast-supported beds of this type (*Bl/Gm*) can be seen in the lowermost parts of the recorded succession (Fig. 13). *Gm*, massive or crudely bedded gravel is the dominant gravel facies within the sorted sediments, present not only as coarse boulder-containing beds at the bottom parts of the logs, but also as slightly finer grained clast-supported layers and lenses further up in the deposit interbedded in thicker sand beds. The lateral distribution of gravel beds rarely exceed 5 m and they are typically no more than 10-20 cm thick, often a few millimetres. An example of a discontinuous bed of massive gravel is found in profile 1 at approximately 0.5 m, best developed on the southeastern side (Fig. 14). Horizontally bedded gravel (*Gh*) and plane cross-bedded gravel (*Gp*) are rare, but have been recognized at two sites: a 30 cm thick erosive bed of *Gh* can be seen in the lower part of log 7 and a 15 cm thick layer of *Gp* is shown in the lower middle part of log 8. They both

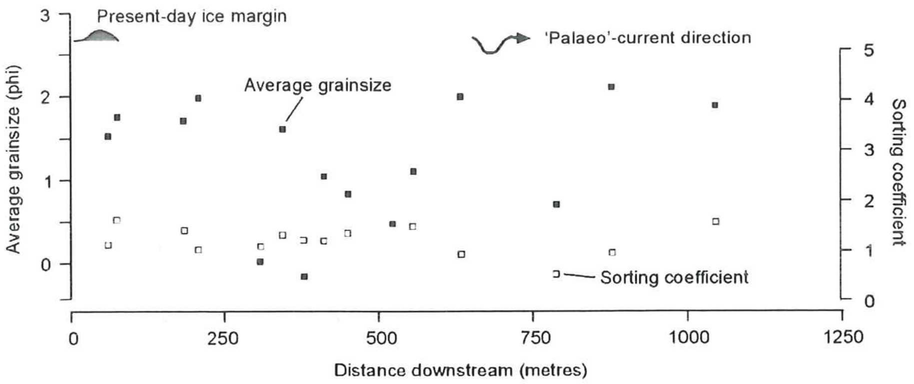

Fig. 12. Grainsize and sorting diagram of outwash sediments taken along two transects from the proximal to the distal parts of the deposit.

display only limited internal structures and poor sorting.

Interpretation. Massive or crudely bedded gravel (*Gm*) may deposit in association with the formation of longitudinal bars up to a few metres in dimension (Miall 1977). Alternatively, they form when flash floods passing through incised channels erode the sides and base leaving a coarse, massive, gravely lag (Blair & McPherson 1994). Small debris flows deposited from viscous, laminar or turbulent flows can also result in the formation of massive clast-supported gravel beds as suggested by Miall (1996). *Gh*, horizontally bedded gravel, may represent infilling of flat, shallow channels. Plane cross-bedded gravel (*Gp*) most commonly develops from migration of 2-D dunes. It can also form beneath standing waves during subcritical flow conditions as described by Rust & Gostin (1981).

Sands (S)

Description. Sand facies predominate the entire outwash deposit. Typically they comprise thin beds, up to 20 cm thick, of heterogeneous, poorly sorted material, dominated by horizontally bedded sand (*Sh*) and low-angled cross-bedded sand (*Sl*). Percentages of fines tend to be consistently low throughout the reach of the deposit, generally not exceeding 5%. Fining-upward successions are common and occasional reverse graded beds have been recognized, particularly within the two most frequently occurring facies — *Sh* and *Sl*. Horizontally bedded sands are usually seen as erosive centimetre-thick normal graded beds which together form thicker beds of a dimension up to approximately 30 cm. The sorting varies from moderately well-sorted beds to more common poorly sorted or even very poorly sorted beds seen e.g. in the middle part of log 5 (Fig. 13). In profile 2 only one thin continuous layer of *Sh* is present, found in the upper part of the profile, while profile 1 contains several well-developed horizontally bedded layers underlying the till cover (Fig. 14 and 15). Low-angled cross-bedded sands resemble horizontally bedded sands, except that they dip slightly cutting each other at low angles (<10%). Individual beds are generally not more than 5 cm thick. They often overly each other, forming beds up to 0.5 metre thick. A good example can be seen in profile 1 between 1-2 m (Fig. 14). Structure-less massive sand, *Sm*, is not as common as *Sh* and *Sl*, but does occur locally and is most clearly seen in profile 1. Two illustrative examples can be found at 1.7 m and 2.0 m in the northwestern part of the profile. The massive facies typically contain 5-10 cm thick beds of poorly sorted heterogeneous silty-gravely-sand often with lenses or crude beddings of gravel. *Sp*, plane cross-bedded sand, occurs most frequently in log 7 and 8. The beds are between 10-30 cm thick with a lateral distribution of a few metres and with foresets dips of 2-28° mainly towards NW, but also towards both W and NE. One site of trough cross-bedded sand (*St*) has been recognized, situated immediately below the till cover of log 7 (Fig. 13). This 20 cm thick bed, displaying an indistinct internal structure of trough cross-bedding, contains poorly sorted sand with thin interbedded gravel horizons. Ripple cross-laminated sand (*Sr*) is rare, although seen at one location in profile 2 underlying the tephra horizon. The bed is a few centimetres thick and partly deformed where cross-cut by a water escape structure. *Sd*, deformed sand beds, are found where post depositional penetration of complex muddy water escape structures (*WES*) have occurred. The entire lower part of profile 2 is disturbed by such mud-layers, obstructing the recognition of any primary structures in the sand. Another bed of deformed sand is found in association with a large water escape structure at the southeastern side of profile 1. Slightly sheared and deformed sediments can also be seen locally immediately below the till cover (log 1 and 2)

Interpretation. Horizontally bedded sand (*Sh*) typically develops under upper stage flow conditions at high water water velocities, at the transition from subcritical to supercritical flows (Miall 1996). Sedimentation on plane beds under the lower flow regime may also occur, resulting in the formation of coarse to very coarse horizontally bedded sand layers (Benn & Evans 1998). Most probable, both flow regimes have been present during the plane bed formation, mainly associated with deposition of sheetflows and deposition within narrow channel systems. Laminae present within the horizontally bedded facies record minor fluctuations in flow velocity or sediment supply (Miall 1978). The erosive and slightly dipping sand facies (*Sl*) often found in association with horizontal beddings may represent either plane beds developed on originally dipping surfaces or cross-beds from dune/ antidune formation typical for increasing flow conditions (Miall 1977; Rust 1978). The erosive nature of these facies imply they may have been deposited within relatively wide and shallow streams where the flow speed was high enough to erode underlying layers. Planar cross-bedded sand (*Sp*) originates from the migration of transverse, two-dimensional dunes under lower flow regime conditions, while trough cross-bedded sand (*St*) is deposited during slightly higher flow velocities from the migration of 3-D dunes. The formation of antidunes migrating upstream during the transition to supercritical flow conditions may also form cross-beddings. Ripple cross-laminated sand (*Sr*) develops from migration and vertical accretion of current ripples, the form depending on the balance between suspension sedimentation and downcurrent migration (Miall 1996). An interpretation of the origin and development of water escape structures associated with deformed sand beds (*Sd*) is beyond the aim of this paper. For further details on such structures see van der Meer *et al.* (1999).

Fines (Silts and clays) (F)

Description. Silts and clays are not as common as the other grainsize fractions within the deposit, although they can be seen in all logs and both profiles. Fines are generally present as thin, yellowish, massive or crudely bedded mud-drapes, typically a few millimetres up to c. 1 cm thick. No beds exceeding a few centimetres exist. The lateral distribution varies from less than 1 m up to tens of metres, as seen in profile 1 and 2 (Fig. 14 and 15). Typically, the mud-drapes are oriented nearly horizontally following the path of underlying facies or dip downstream at low angles (<10°).

Interpretation. As discussed for Kötlujökull the mud-drapes are suggested to represent the final settling of suspension load during a waning flood event. For an interpretation of implications related to the the lateral persistence of the mud-drapes, see p. 25.

Tephra horizons (Grm)

Description. The lithofacies *Grm* (massive or crudely bedded granules) comprise 0.3-0.5 m thick horizons of porous, blackish tephra. Where well-developed the tephra horizons can be subdivided into three separate beds; a bed of sharp-edged tephra, a bed of more rounded tephra mixed with sand and a separating ash-layer. The sharp-edged, fresh-looking tephra horizons comprise some clusters and crude clast-supported interbeddings of coarser components (e.g. Log 3, Fig. 13). This part of the tephra stratigraphy generally do not exceed 0.2 m in thickness. The horizons of slightly rounded, finer tephra grains mixed with dense sand particles have a thickness of 0.1-0.2 m. A horizon of this type can be seen in profile 2 underlying coarser, more fresh-looking tephra (Fig. 15). An illustrative example of a thin bed

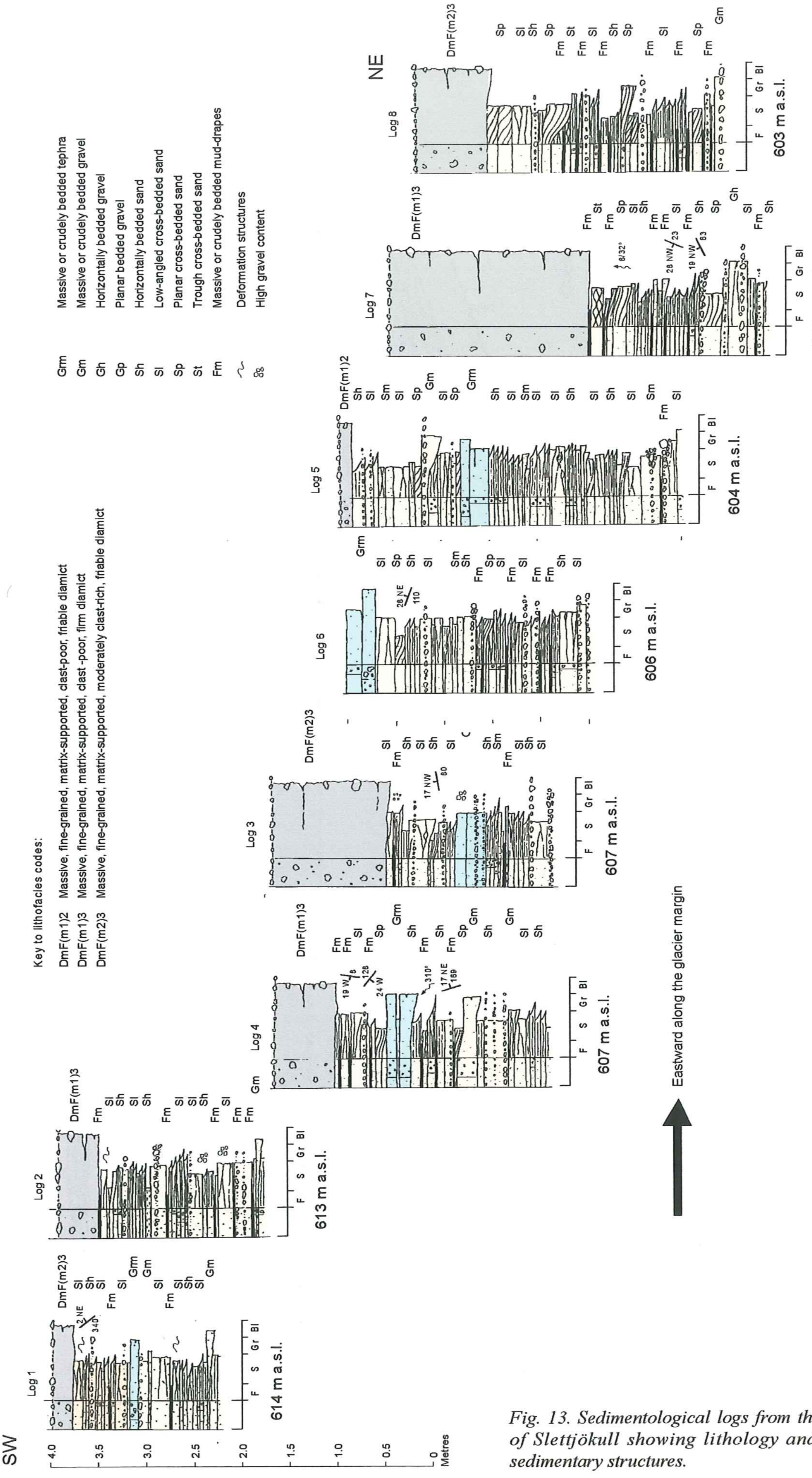

Fig. 13. Sedimentological logs from the forefield of Slettjökull showing lithology and primary sedimentary structures.

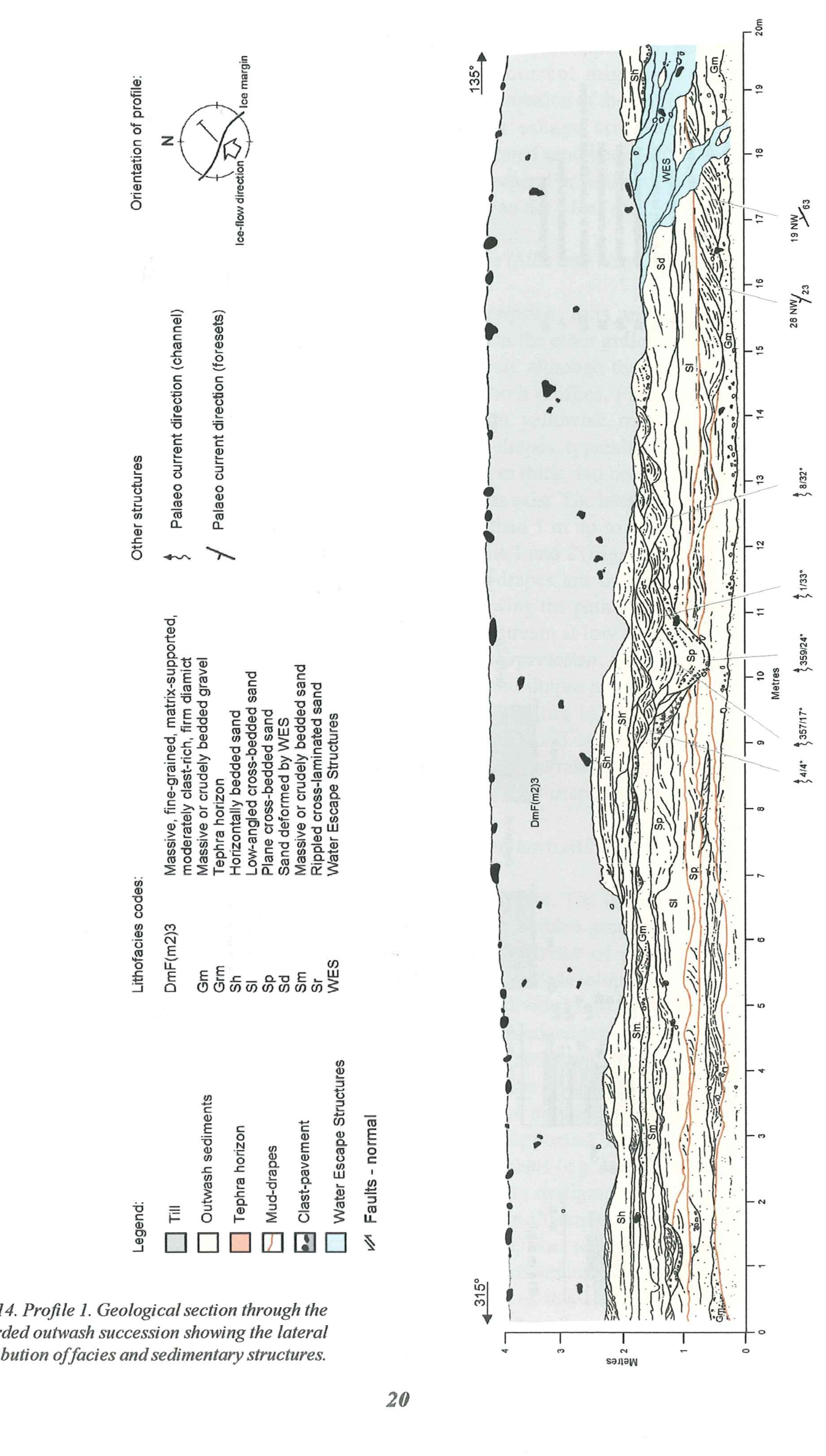

Fig. 14. Profile 1. Geological section through the recorded outwash succession showing the lateral distribution of facies and sedimentary structures.

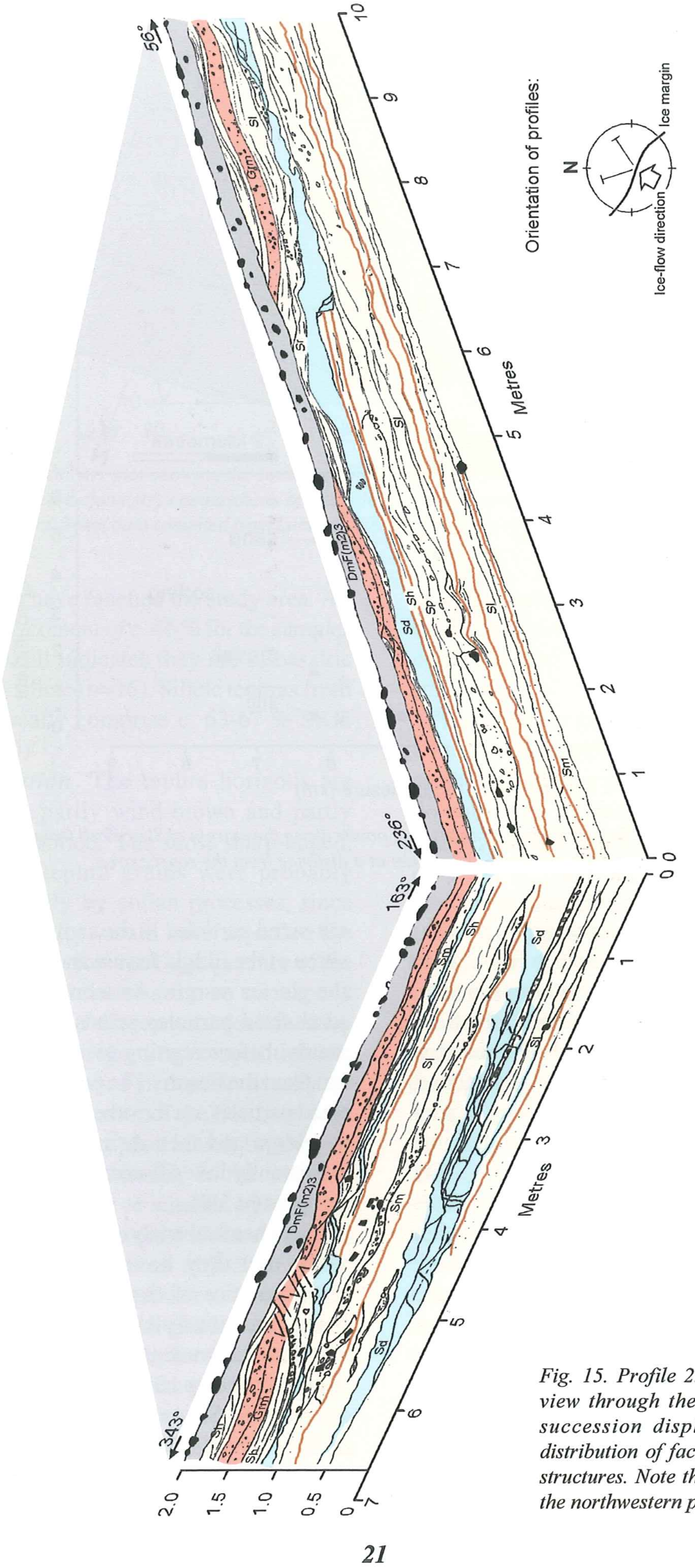

Fig. 15. Profile 2. Three-dimensional view through the recorded outwash succession displaying the spatial distribution of facies and sedimentary structures. Note the fault-structures at the northwestern part of the profile.

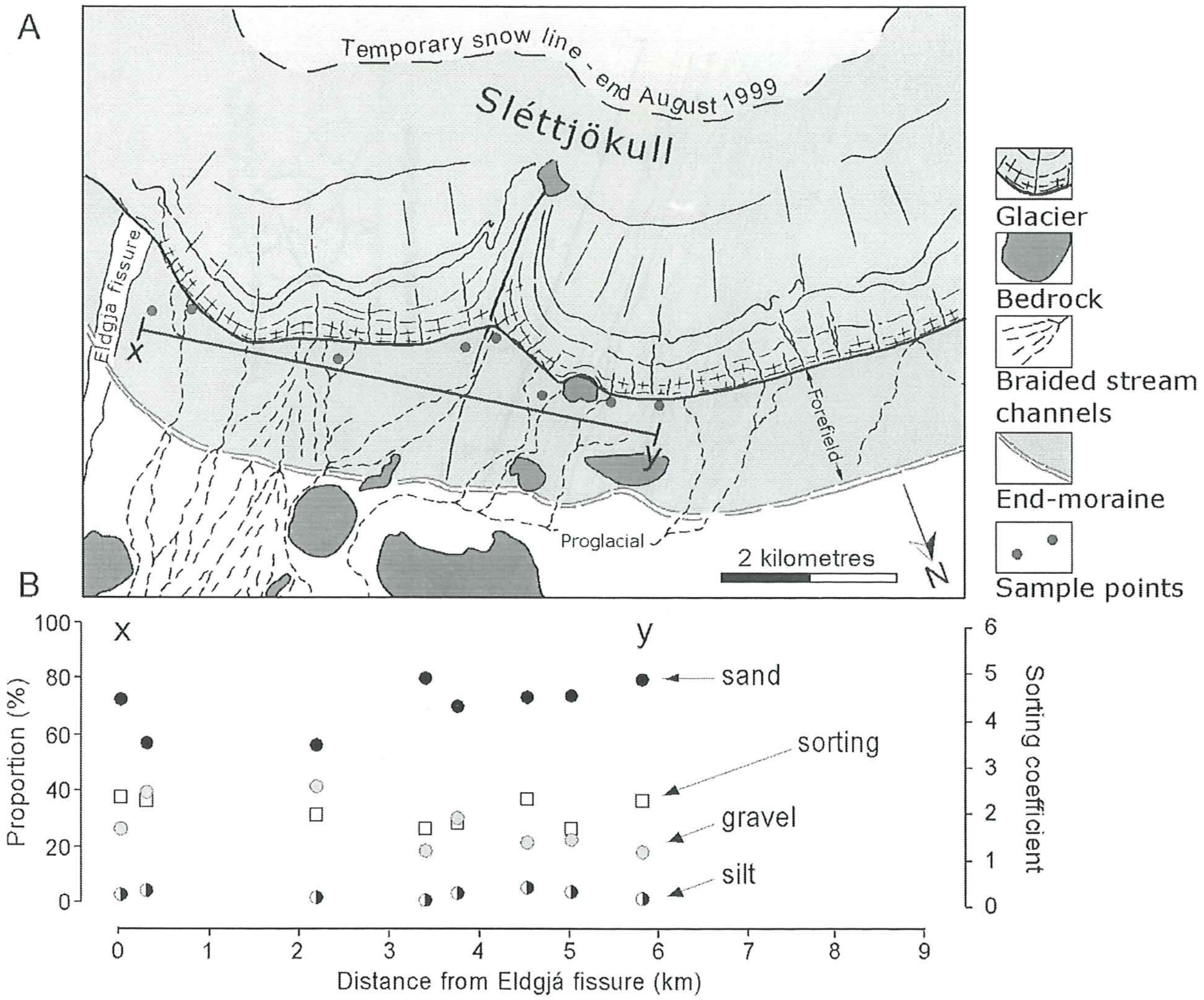

Fig. 16. Tephra samples A) The distribution of measuring points along the margin of Slettjökull from the Eldgjá fissure and westwards B) Tephra grainsize and sorting diagram at a distance from the source area.

of fine-grained light-coloured ash separating two tephra horizons can be seen in log 4. Apart from above mentioned sites also log 1, 6 and 7 contain tephra horizons. Generally, the basal contact to underlying sand-sediment is conformable. Tephra horizons largely seem to follow the inclination of underlying layers, chiefly oriented in horizontal plains, but dips of 3-6° have been recorded (Krüger 1994). Beds draping the underlying surface are laterally persistent with a uniform thickness, often traceable for at least tens of metres or the scale of the exposures. The sorting of the sediment varies from poorly sorted (coefficient 1-2) to very poorly sorted (coefficient 2-4). The average grainsize is between coarse sand to granules and show no preferred trend spatially. Figure 16 shows, apart from the sorting coefficient, the proportion of gravel-, sand- and silt-sized particles in the samples from the position of the Eldgjá fissure and westwards along the glacier margin. As seen, the proportion of sand-sized particles seems to decrease westwards, before starting to increase around 3.5 km from the fissure. The percentages of gravel-sized particles, on the other hand, increase close to Eldgjá and then decrease after 3.5 km. A persistently low silt-content is measured in all samples (< 5%).

Geochemical analyses of the tephra horizons show that they have the typical chemical characteristics of the Katla volcanic system, being transitional alkali basalts with a high iron and titanium content (Larsen 2000). Figure 17 displays a comparison of the tephra horizons sampled at Slettjökull and other eruptions within and outside the Katla volcanic system. All are of known chemical composition,

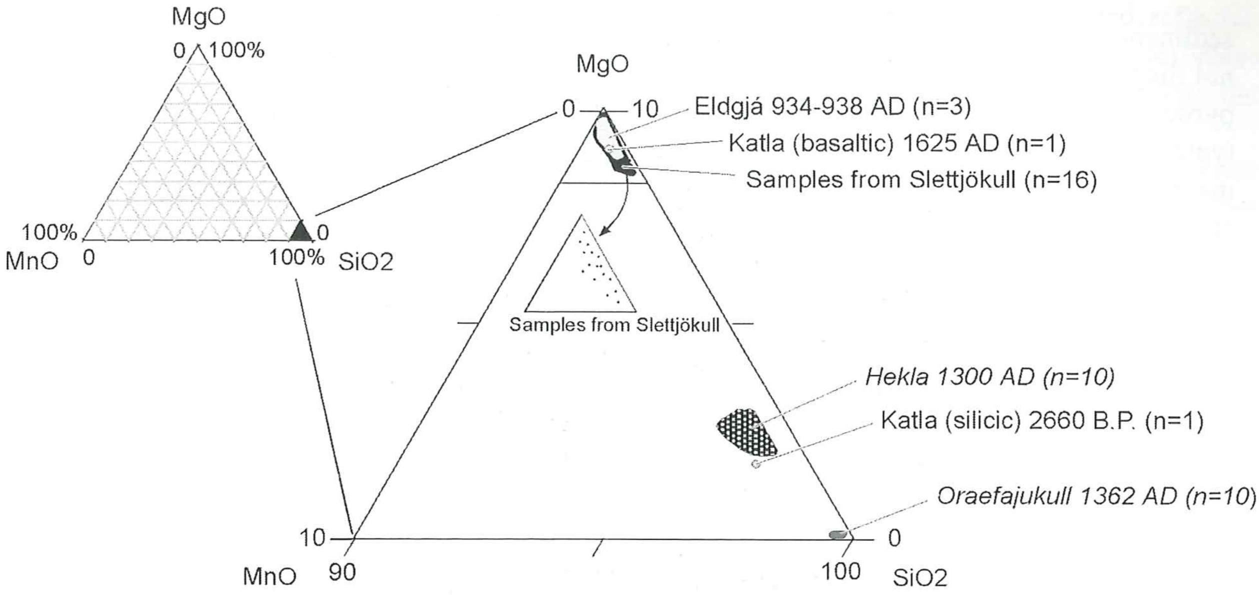

Fig. 17. Tephra chemistry plot showing the content of SiO2, MgO and MnO for the analysed samples from Slettjökull compared with known chemistry compositions of possible sources. Eruptions from outside the Katla volcanic system are written in italics. Some data compiled from Larsen (2000) and http://www.geo.ed.ac.uk/tephraexe/ice_geoc1 (2002).

recognized to have reached the study area. An average SiO2-content of c. 46 % for the samples from Slettjökull indicates they are of basaltic type and not silicic (n=16). Silicic tephras from the area typically comprise c. 63-67 % SiO2 (Larsen 2000).

Interpretation. The tephra horizons are thought to be partly wind-blown and partly fluvially transported. The most sharp-edged, fresh-looking tephra grains were probably deposited directly by eolian processes, since any fluvial activity would have modified the particles given the low rock-competence of the material. These horizons seem to correspond to the pyroclastic fall deposits described by Lajoie (1984), both regarding composition and sedimentary structures. Fall deposits usually are poorly stratified, as most of the horizons seen at Slettjökull, but may also inhibit bedding or grading due to discontinuity in the volcanic activity. The horizons of smaller and slightly rounded tephra clasts mixed with sand particles most probable have been object to short-distance fluvial resedimentation. They might have been deposited on the glacier snout or on the glacier forefield, thereby incorporated in the rest of the outwash material and subjected to re-deposition. These horizons resemble the deposits categorised by Lajoie (1984) as pyroclastic flow deposits and by Larsen (2000) as water-transported vocaniclastic debris. They described units characterized by massive, poorly sorted sediments, lacking primary structures.

Based on the geochemistry shown in figure 17 volcanos outside the Katla volcanic system can be excluded as possible sources, since they do not match the samples collected along the margin of Slettjökull. Also the silicic Katla eruption of 2660 B.P. can be ruled out for similar reasons. However, basaltic layers from individual eruptions within the Katla volcanic system are difficult to distinguish from each other based on major element chemistry alone. To distinguish between the Eldgjá and Katla eruption it is therefore necessary to look on the stratigraphy of the tephra horizons. Most Katla tephra layers show distinct bedding due to shifting wind strength and wind directions during the deposition. The studied horizons though seem to be mainly massive, although divided into separate layers of slightly different grainsize and composition. The Eldgjá tephra was previously thought to be a product of three eruptions (Larsen 1996) and well-developed horizons might contain as much as 15 separate beds reflecting different stages of eruption of separate chemical composition and average grainsize. This division into separate horizons is an indicator of an Eldgjá origin for the studied sediments, since Katla stratigraphical units do not display a similar structure. Moreover, the pyroclastic flow deposit found at Slettjökull is typical for the Eldgjá eruption, recognized at many sites overlying or intercalating the tephra stratigraphy. Finally, the coarseness of the tephra (generally 0.5-2 cm) suggests that it originates from a near-by site, Eldgjá being the closest - the Katla volcano located 20 m to the southeast. During comparisons in field it was noted that the tephra clasts found within the forefield closely resemble fresh tephra from the Eldgjá site. Furthermore, the maximum clast-size appeared to increase towards the fissure.

I argue that if the Eldgjá fissure is the source area for the tephra horizons it should be possible to see some kind of pattern at a distance from the eruption site. Walker (1971) concluded that size, composition and thickness of the tephra deposit should vary with distance from the vent. Generally, the sorting improves with distance and the bed thickness as well as the average grainsize decreases. However, fine-grained deposits can also form near the vent if the eruption is weak, as the Eldgjá eruption was, and variations in sorting and grainsize are not always detectable (Larsen 1996). Close to the eruption site, the variations are not systematic, which might be the explanation for the unclear pattern seen in the samples taken along the margin of Slettjökull. No samples were collected further than 5-6 km from the Eldgjá fissure, considered to be fairly close to the vent. The pattern seen in figure 16, with variable gravel/sand-content westwards might represent different pulses of eruption material. The measured tephra horizons are not thought to be of original thickness, measured to 3-4 m on the other side of the marginal moraine ridges beyond the glacier forefield (Larsen 2000). Erosion by and fluvial activity have probably contributed to decrease the thickness of the horizons.

Lateral distribution of facies

Representative examples of the lateral distribution of facies can be seen in the recorded sections – profile 1 and 2 (Fig. 14 and 15) The two profiles display mainly planar-bedded horizons spreading horizontally or dipping at low angles (< 10°). The lateral persistence of individual beds range from a few metres up to tens of metres.

In the middle part of profile 1, a series of large concave structures can be seen overlying each other mainly vertically, but also laterally (Fig. 14). These erosive features are typically between 0.5-1 m wide and up to 70 cm deep with the largest concave structure in the bottom and smaller towards the top. The structures are interpreted as fossil channels gradually infilled with sediments and prograding vertically, cutting down into each other (Miall 1996). Situated in the lower southeastern part of the profile another series of concave structures has been recorded, interpreted as a channel prograding laterally towards northwest. It seems to have prograded upstream over at least a 5 m distance, probably even longer. A close examination implies a continuation of the structure all through the length of the profile, eroded in the middle part by overlying layers. Similar structures of approximately the same dimensions were identified at many other sites in the area.

In profile 2, a structure located in the northwestern part of the profile shows normal displacement of the uppermost beds along two or possibly three concave rotational slidings (Fig. 15). These normal faults might represent collapse-structures, formed when a lump of ice incorporated in the sediments disintegrated by melting.

Measurements imply the palaeo-current directions within most larger channels were approximately towards north. Variations seen in the flow directions at profile 1 and 2 can be attributed to migrating streams.

5.5. Interpretation of depositional environment

Interpretation of lithofacies, other sedimentological data and an architectural reconstruction of above mentioned outwash succession can be synthesized to identify the depositional processes of an alluvial fan. In the literature, contradicting views are held regarding the identification of alluvial fans, which have lead to confusion in the terminology among contemporary scientists. However, Blair & McPherson (1994) convincingly re-established both a distinct set of characteristics and the importance of identifying alluvial fans. They suggest that on basis of morphology, hydraulics, sedimentary processes and resultant facies alluvial fans are distinguishable from all other sedimentary environments, including rivers.

The most distinctive feature of an alluvial fan is its morphology, typically with a semiconical shape, a restricted radial length (< 10 km), a plano-convex cross-profile and slope values in the range of 1°-25°. As above described, the Slettjökull outwash succession contain all these characteristics, with a radii of 1-1.5 km and an inclination ranging from 1°-5°.

The existence of an alluvial fan system is further supported by recognized facies: the vertically alternating planar bedded horizons of sand and fine gravel, combined with low-angled cross-bedded sand facies and lenticles of gravel found at Slettjökull are typical for sheetflow events on alluvial fans (Blair & McPherson 1994). These structures could reflect deposition under supercritical flow conditions with a high flow attenuation rate and high deposition rate characteristic for high slope values. Inclinations over 1.5° generally favour supercritical flows over subcritical flows, more commonly associated with rivers and resulting bar deposition.

The limited radius of the studied alluvial fan is a net effect of a high sedimentation rate close to the point of confinement. This process is favoured by rapid expansion and resultant flow attenuation occurring at the apex of the fan or at the intersection point, i.e. at the point of confinement. A swift drop in velocity, competency and capacity of the flow is generated by such a flow expansion, followed by rapid sediment deposition. Changing hydraulic conditions, also related to the swift flow expansion and depth/velocity variations characteristic of supercritical flows, causes alternating sand and gravel transportation and deposition. The sediment content of these flows range from low to hyperconcentrated, reflected at Slettjökull in a fluctuating sorting coefficient and different degrees of structures within the sediments.

Drainage-basin feeder channels, associated with alluvial fans in general, tend to extend out to the fan as incised channels where flash floods can be transported across the upper part of the fan to more distal locations prior to their expansion into sheetflows. During such events, the structures interpreted as prograding channels seen in profile 1 (Fig. 15) might have developed. The channel-structure striking diagonal across the fan in figure 10 is likely to be a remnant of an incised channel, cutting down into the sediment either at the end of the fan development or after it was completed. The laterally persistent mud-drapes found within the outwash fan represent periods of complete sedimentation stop, i.e. they represent former fan surfaces that have been subaerially exposed.

Following the reasoning from section 5.4 concerning the volcanic origin of the input material, it is reasonable to conclude that the fan was fed by tephra lying on the glacier surface, i.e. it was supraglacially fed. The fine-grained appearance of the fan and the thin horizons of alternating sand- and gravel-size agree with this assumption, since subglacially fed fans generally are much coarser and consist of thick, stacked beds (e.g. Maizels 1993). After comparisons with previously described fans and planes (e.g. Boothroyd & Ashley 1975; Boulton 1986; Blair & McPherson 1994) the outwash succession at Slettjökull was classified as a Hochsander fan, closely resembling the fans described by Heim (1992) and Krüger (1994, 1997). For a description of the distinct characteristics of these fans, see section 6.

Chronology/age of the outwash sediments. It is concluded at section 5.4 that the Eldgjá event around 1000 AD provided with the material that constitutes the outwash fan. Accordingly, the fan must have begun to form between 934-938 AD, the time of the main phase of eruption. Moreover, an upper boundary for the time of development can be estimated from the deposition of the overlying sedimentary unit, lower till. This unit was deposited during a readvance of Slettjökull during the Little Ice Age maximum when all the Icelandic glaciers expanded, implying the entire fan was formed prior to c. 1750.

6. Discussion

Comparison between depositional environments at Slettjökull and Kötlujökull. It is reaonable to use the fan at Kötlujökull as a modern analogue for the fossil outwash succession at Slettjökull, since the two landforms closely resemble each other sedimentologically, structurally and morphologically. Hence, both deposits can be classified as alluvial fans of the Hochsander type. Apart from a similar construction of mainly planar-bedded sands and gravels, both fans are predominated by poorly sorted material with a mean of medium sand and no clear fining trend from the apex to the distal parts. However, a wider range of facies and structures can be seen at the more extensive fossil fan compared with its minor modern analogue. Large-scale prograding channel-structures have only been identified at Slettjökull. Perhaps, some of these structures can be attributed to the difference in scale between the fans. A larger drainage area and supply of material probably generated more voluminous flow masses that collected in drainage basins, before being transported on to the glacier forefield in incised channels. When these channels, sometimes extending to distal parts of the fan, prograded upstream the concave structures, seen in profile 1, may have developed (Fig. 14).

As the fan at Kötlujökull is used as a facies model, the depositional processes active during the landform development should be similar in both cases. Accordingly, the processes observed in the field during the formation of the modern fan are indicative of how the depositional environment appeared when the Slettjökull fan was formed. As described above, sheetflow deposition and accompanying antidune migration combined with deposition within a shallow braided network dominated.

Despite both being interpreted as Hochsanders, some conditions during the development of the fans seem to have differed, such as the structure of the glacier margin. While the fan at Kötlujökull formed within a dead ice environment in front of a steep, advancing glacier margin, the fan at Slettjökull was formed in front of a continuous ice margin. Furthermore, the material originates from different sources. At the northern margin of Myrdalsjökull the Eldgjá-eruption provided huge quantities of air-born material directly on the ice surface, expressed as a thick cover of tephra. At Kötlujökull, on the other hand, the material was chiefly derived from thrust-planes and debris-bands exposed on the ice surface. Thus, it can be concluded that the mode of the source material is not the main controlling factor of the final fan-structure. Instead, the amount of material available on the ice surface and the mode of transport on to the forefield seems to have a higher ranking.

Sedimentological model. Figure 18 outline the course of events leading to the formation of the buried fan at Slettjökull. The ice margin line is positioned c. 1 km behind the present-day location of the ice front, following the reasoning outlined in section 5.3.

(A) Starting with the 10th century Eldgjá fire, air-born tephra spread to the west, coming to rest both at the glacier snout and on the glacier forefield. Huge quantities of material must have been made available, since a 3-4 metres thick horizon of air-born tephra has survived fluvial erosion outside the glacier forefield north of the study area (Larsen 2000). The high annual precipitation over Slettjökull contributed to a rapid cleaning of the glacier surface and subsequent accumulation beyond the glacier snout. All known volcanic eruptions of the Katla volcanic system have begun in the springtime (Larsen 2000), indicating the downwash of volcanic material to the forefield may have been enhanced by snowmelt. If the tephra had not been transported off the ice surface rapidly it would have generated differentiated ice melting resulting in the formation of an irregular ice topography, more similar to the situation at Kötlujökull in the less mature stages (Kjær & Krüger 2001).

(B) Subsequent to the initial deposition on the glacier surface, the material must have been

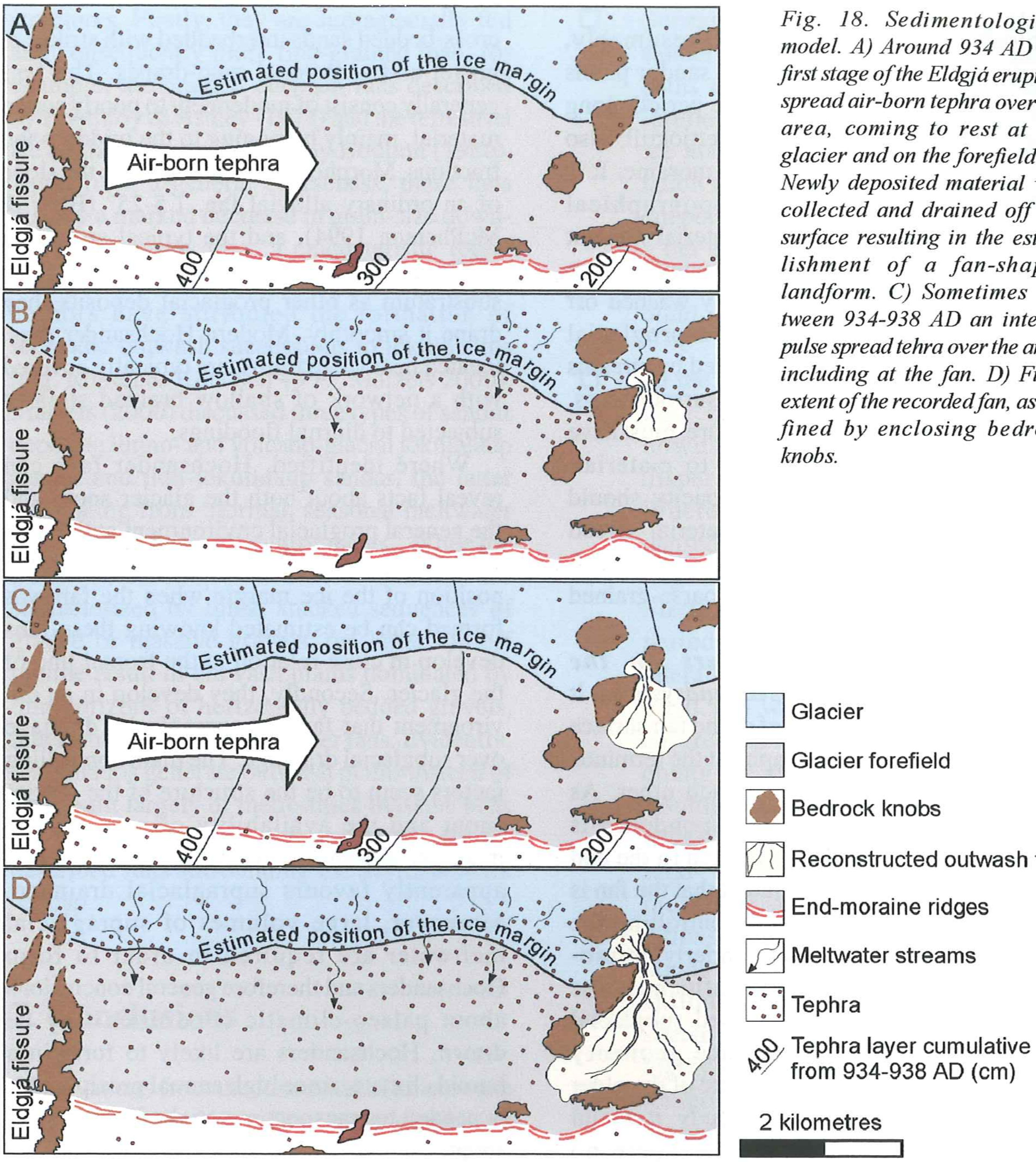

Fig. 18. Sedimentological model. A) Around 934 AD the first stage of the Eldgjá eruption spread air-born tephra over the area, coming to rest at the glacier and on the forefield. B) Newly deposited material was collected and drained off the surface resulting in the establishment of a fan-shaped landform. C) Sometimes between 934-938 AD an intense pulse spread tehra over the area, including at the fan. D) Final extent of the recorded fan, as defined by enclosing bedrock knobs.

collected in some drainage paths. Perhaps the topographical highs suspected below the present-day ice surface worked as confinements, facilitating canalisation of sediments and, hence, prevented a uniform downwash of the volcanic material. Alternatively, the drainage routes were controlled by crevasses in the ice. Either way, material was transported off the glacier and deposited immediately beyond the ice front as a fan with, at this early stage, a short radial length and a steep slope.

(C) Post-dating the initiation of the fan generation a new, more intense pulse of tephra spread over the area, leaving a thick cover of fresh material on the glacier and its forefield, including the newly deposited outwash fan. An up to one metre thick bed of air-born tephra has survived complete distinction by fluvial erosion, preserved within the fan succession. This implies the most intense pulses of the eruption spread huge quantities of material over the area.

(D) The final shape of the fan seems to have been controlled and limited by the surrounding topography, being deposited in a depression enclosed by bedrock knobs. Presumably, similar fans and more extensive sandur plains were developed during the same period along other parts of the margin of Slettjökull, also buried under a cover of ground moraine. It is suggested that where no topographical restrictions were present, the material was not collected in drainage paths. Instead, large quantities of tephra were rapidly washed off the surface, forming extensive proglacial landforms. While the fans were fed by streams restricted to drainage paths, the surroundings, especially close to the Eldgjá fissure, must have had almost unlimited access to material. Consequently, the transport capacity should have been enhanced and the material spread widely across the forefield. Accordingly, outwash plains, probably more coarse-grained than the fans, could be formed.

Influence of Hochsanders on the architecture of superimposed landsystems. It is striking how well the relief of the fan surface and the present-day topography at the terminus region of Slettjökull mirrors each other. As shown in figure 11 the correspondence is significant from the glacier margin to the end of the study area. It is concluded that the fan is the morphostratigraphic unit controlling the surface topography, i.e. the underlying proglacial landsystem strongly influences the architecture of the superimposed subglacial landsystems. Thus, the surface geometry reflects the nature and architecture of the older glacier landscape. As a future study, it would be interesting to map an area where no topographical controls are suspected to determine how such an area differs from that of the studied fan.

Significance of Hochsander fans in the proglacial landsystem. The presence of Hochsanders has implications on the outline of the glacial environment and the internal architecture of the proglacial landsystem (Heim 1992; Krüger 1994, 1997). Evidently, Hochsanders can be distinguished from other alluvial fans in the sedimentary record based on a distinct set of sedimentological characteristics. Diagnostic criteria for recognising Hochsanders in the field involve their construction of essentially planar-bedded sands and low-angled cross-bedded sands interbedded with strikes of gravel and occasional mud-drapes. The fans generally consist of moderately to poorly sorted material, mainly belonging to the middle sand fractions. Morphologically, they have the slope of an ordinary alluvial fan, 1.5-25° (Blair & McPherson 1994), and the typical spreading angle up to 180°, but instead of eroding the substratum as other proglacial deposits they drape it smoothly. Modern Hochsander fans, located near ice margins, are typically covered with a network of shallow braided streams subjected to diurnal floodings.

Where identified, Hochsander fans can reveal facts about both the glacier snout and the general proglacial environment at the time of development. Firstly, the approximate position of the ice margin when the fan was formed can be estimated knowing these fans develop in close relation to the frontal line of the glacier. Secondly, they develop in an environment that favours supraglacial drainage over subglacial drainage. The main controlling factors seem to be the structure of the glacier snout and the availability of supraglacial material. A steep ice front covered in debris apparently favours supraglacial drainage. Moreover, large volumes of supraglacial meltwater are required in order to form Hochsanders and therefore general conclusions about palaeo-climatic conditions may be drawn. Hochsanders are likely to form in a humid climate, since high annual precipitation is needed to transport material off the glacier snout.

It is important to clarify the unique characters of Hochsanders in order to avoid confusions with similar landforms in future studies. Like most southern Icelandic outwash successions the studied fans have been subject to widespread volcanism and a cold, humid climate. Still, they do not resemble any of the classical fans or plains described in the literature, neither in Iceland (e.g. Maizels 1993; Russel & Knudsen 1999) nor in other formerly glaciated northern European lowland-areas (e.g. Landvik & Mangerud 1985). They distinguish concerning material sources, depositional processes and environments together with resulting facies and sedimentary structures. Firstly, they are supraglacially fed and consequently more fine-grained than, for example, the braided outwash fans described by Boothroy & Ashley (1973) and the terrestrial ice contact fans as defined by Boulton (1986). Apart from a general coarseness, these fans display a marked decrease in grain-size downstream from the apex, a characteristic found neither at Slettjökull nor at Kötlujökull. Various authors have attributed the formation of Icelandic outwash successions to jökulhlaups (e.g. Russel & Knudsen 1999; Maizels 2000). Maizels (2000) discussed three types of sandur deposits; limno- and volcano-glacial jökulhlaup sandar and non-jökulhlaup sandar, the latter originating from 'normal, seasonal meltwater flows in braided river environments'. While the both jökulhlaup-associated sandar are characterized by thick, stacked sequences of graded or massive gravels, the latter run-off regime result in outwash plains dominated by thin horizons of horizontally bedded gravels, much coarser than Hochsander fans. Evidently, jökulhlaups generate outwash plains instead of fans, built largely of metre-thick massive beds with hardly any resemblance of the above-described fans surrounding the Mýrdalsjökull ice cap.

7. Conclusions

Observations from the formation of an outwash succession at the Kötlujökull outlet glacier and the reconstruction of a buried deposit in front of Slettjökull, allows the following conclusions:

☐ Both the modern- and the fossil deposits are concluded to be alluvial fans of the Hochsander type.

☐ The fan at Slettjökull was formed as a consequence of the 934-938 AD Eldgjá eruption releasing large quantities of tephra. The Kötlujökull fan developed during the 1980s in association with a glacier advance when the frontal slope was steep and covered in debris.

☐ Supraglacial material feeding Hochsander fans was collected in drainage paths and transported on to the glacier forefield, where it accumulated near the ice margin. The daily rate of sedimentation was extremely high, averaging 2.5 cm per day at Kötlujökull. Accordingly, a fan extending a few hundred square-metres with a thickness of 2-3 m could build-up within a few years time.

☐ At the fan' apex sediment either spread out or was transported further downstream in incised channels, dispersing at the intersection point. Where well developed, migration of incised channels lead to the formation of large-scale channel-structures, as seen at Slettjökull. During the most active periods of accumulation networks of laterally migrating braided streamlets, 0.1-0.5 m wide and up to 0.5 m deep, covered the fan surface. Due to a rapidly changing stream transport capacity resulting from short-term variations in water influx, thin beds of alternating sand- and gravel-size were deposited, indicative of supercritical flow conditions. During floodings in the afternoons sheetflows and accompanying antidune formation dominated over stream deposition. Where the flows were highly concentrated with material they temporarily transformed into hyperconcentrated flows. It is proposed that during waning floods successively finer material accumulated, completed by slow deposition of the finest particles from suspension, draping underlying layers.

☐ Hochsanders have all the characteristics of an alluvial fan, with a semiconical shape, a plano-convex cross-profile, a slope ranging from 1-5° and a radial length of 1-1.5 km. Compared with outwash plains, often covering hundreds of square-kilometres, they must be considered minor. They can be distinguished from other alluvial fans based on their distinct set of sedimentary structures, characteristic fine-grained appearance and non-erosive basal contact. The material is generally poorly sorted with a mean of medium sand. Planar-bedded sands and low-angled cross-bedded sands interbedded with thin gravel beds and occasional mud-drapes dominate the fans, although some massive and cross-bedded facies may occur.

☐ Since Hochsanders develop near glacier margins, their identification can be used for estimating the approximate position of the ice front at the time of formation. Furthermore, they develop in environments that favour supraglacial drainage over subglacial drainage. A humid climate and a debris-covered glacier snout seem to be key factors for the formation of Hochsanders.

☐ Finally, it is concluded that the present-day topography of Slettjökull is fully controlled by the underlying fan, i.e. the morphology of the Hochsander fan strongly influences the architecture of the succeeding subglacial landsystem.

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References

Benn, D. I. & Evans, D. A. J., 1998: *Glaciers & Glaciation.* Arnold, London. 734 pp.

Björnsson, H., Pálsson, F. & Gudmundsson, M. T., 2000: Surface and bedrock topography of the Mýrdalsjækull ice cap, Iceland: The Katla caldera, eruption sites and routes of jökulhlaups. *Jökull 49*, 29-46.

Blair, T. C. & McPherson, J. G., 1994: Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *Journal of Sedimentary Research 3*, 450-489.

Boothroyd, J. C. & Ashley, G. M., 1975: Processes, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska. In: Jopling, A. V. & McDonald, B. C. (eds.) *Glaciofluvial and Glaciolacustrine Sedimentation.* SEPM Special Publication 23, 193-222.

Boothroyd, J. C. & Nummerdal, D., 1978: Proglacial braided outwash: a model for humid alluvial-fan deposits. In: Miall, A.D. (ed.) *Fluvial Sedimentology.* Canadian Society of Petroleum Geologists, Memoir 5, 641-668.

Boulton, G. S., 1986: Push-moraines and glacier-contact fans in marine and terrestrial environments. *Sedimentology 33*, 677-698.

Brayshaw, A. C., 1984: Characteristics and origin of cluster bedforms in coarse-grained alluvial channels. In Koster, E. H. & Steel, R. J. (eds.) *Sedimentology of Gravels and Conglomerates*,. Canadian Society of Petroleum Geologists Memoir 10, 77-85.

Clague, J. J., 1975: Sedimentology and paleohydrology of Late Wisconsinan outwash, Rocky Mountain Trench, Southeastern British Colombia. In: Clague, J. J. (ed.) *Glaciofluvial and glaciolacustrine sedimentation 23*, 223-237.

Cutler, P. M., Colgan, P. M. & Mickelson, D. M., 2002: Sedimentologic evidence for outburst floods from the Laurentide ice sheet margin in Wisconsin, USA: implications for tunnel-channel formation. *Quarternary International 90 (1)*, 23-40.

Folk, R. L. & Ward, W. C., 1957: Brazos River Bar: A study in the significance of grain size parametres. *Journal of Sedimentary Petrology 27*, 3-26.

Gripp, K., 1975: Hochsander-Satzmoräne-Endmoränenvertreter. *Zeitschrift für Geomorphologie, Neue Folge 19*, 490-496.

Heim, D., 1983: Glaziare Entwasserung und Sanderbildung am Kötlujökull, Südisland. *Polarforschung 53*, 21-36.

Heim, D., 1992: Sandergenese und Gletcherentwässerung am Kötlujökull (Höfdabrekkujökull), Südisland. *Polarforschung 62 (2/3)*, 95-128.

Jakobsson, S. P., 1979: Petrology of recent basalts of the Eastern Volcanic Zone, Iceland. Acta Naturalia Islandica 26, 1-103.

Jonsson, J., 1982: Notes on the Katla volcanoglacial debris flows. *Jökull 32*, 61-69.

Kjær, K. H., 1999: Mode of subglacial transport deduced from till properties, Mýrdalsjökull, Iceland. *Sedimentary Geology 128*, 271-292.

Kjær, K. H. & Krüger, J., 2001: The final phase of dead-ice moraine development: processes and sediment architecture, Kötlujökull, Iceland. *Sedimentology 48*, 935-952.

Kjær, K. H., Krüger, J. & van der Meer, J. J. M., submitted: What causes till thickness to change over distance? An Icelandic perspective. *Journal of Quaternary Science.*

Krüger, J., 1994: *Glacial processes, sediments, landforms, and stratigraphy in the terminus region of Myrdalsjökull, Iceland: Two interdisciplinary case studies.* C. A. Reitzels forlag, København, 233 pp.

Krüger, J., 1997: Development of minor outwash fans at Kötlujökull, Iceland. *Quarternary Science Reviews 16*, 649-659.

Krüger, J. & Kjær, K. H., 2000: De-icing progression of ice-cored moraines in a humid, subpolar climate, Kötlujökull, Iceland. *The Holocene 10; 6*, 737-747.

Krüger, J., Kjær, K. H. & van der Meer, J. J. M., in press: From push moraine to single-crested dump moraine during a sustained glacier advance. *Norwegian Journal of Geography.*

Lajoie, J., 1984: Volcaniclastic Rocks. In: Walker, R. G. (ed.) *Facies models*. Geological Association of Canada, Toronto.

Landvik, J. Y. & Mangerud, J., 1985: A Pleistocene sandur in western Norway: facies relationships and sedimentological characteristics. *Boreas 14*, 161-174.

Larsen, G., 1996: Tephrochronology and tephra layers from the time of Norse settlement of Iceland. In. Rádstefnurit, V. & Grímsdóttir, G. Á. (eds.) *Landnám á Íslandi.* Societas Scientiarum Islandica, Reykjavik, 81-106.

Larsen, G., 2000: Holocene eruptions within the Katla volcanic system, south Iceland: Characteristic and environmental impact, *Jökull 49*, 1-28.

Miall, A. D., 1977: A review of the braided river depositional environment. *Earth Science Reviews 13*, 1-62.

Miall, A. D., 1978: *Fluvial Sedimentology.* Canadian Society of Petroleum Geologists Memoir 5, 582 pp.

Miall, A. D., 1996: *The geology of fluvial deposits.* Springer-Verlag, Heidelberg. 582 pp.

Maizels, J., 1993: Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics. *Sedimentary Geology 85*, 299-325.

Maizels, J., 1997: Jökulhlaup deposits in proglacial areas. *Quaternary Science Reviews 16; 7*, 793-819.

Roberts, M. J., Russel, A. J., Tweed, F. S. & Knudsen, O., 2001: Controlls on englacial sediment deposition during the November 1996 jökulhlaup, Skeidarárjökull, Iceland. *Earth Surface Processes and Landforms 26*, 935-952.

Russel, A. J. & Knudsen, O., 1999: An ice-contact rhythmite (turbidite) succession deposited during the November 1996 catastrophic outburst flood (jökulhlaup), Skeidarárjökull, Iceland. *Sedimentary Geology 127*, 1-10.

Russel, A. J., Knight, P. G. & Van Dijk, T. A. G. P., 2001: Glacier surging as a control on the development of proglacial, fluvial landforms and deposits, Skeidarárjökull, Iceland. *Global and Planetary Change 28*, 163-174.

Rust, B. R., 1978: Depositional models for braided alluvium. In: Miall, A. D. (ed.) *Fluvial Sedimentology*. Canadian Society of Petroleum Geologists, Memoir 5, 605-625.

Rust, B. R. & Gostin, V. A., 1981: Fossil transverse ribs in Holocene alluvial fan deposits, Depot Creek, South Australia. *Journal of Sedimentary Petrology 51*, 441-444.

Smith, G., 1754: Dreadful storm in Cumberland. *Gentleman's Magazine 24*, 464-467.

Stanistreet, I. G. & McCarty, T. S., 1993: The Okavango Fan and the classification of subaerial fan systems. *Sedimentary Geology 85*, 115-133.

van der Meer, J. J. M., Krüger, J. & Kjær, K. H., 1999: Subglacial water-escape structures and till structures, Slettjökull, Iceland. *Journal of Quarternary Science 14; 3*, 191-205.

Walker, G. P. L., 1971: Grain-size characteristics of pyroclastic deposits. *Journal of Geology 79*, 696-714.

Zielinski, & Gozdzik, 2001: Palaeoenvironmental interpretation of a Pleistocene alluvial succession in central Poland: sedimentary facies analysis as a tool for palaeoclimatic inferences. *Boreas 30; 3*, 240-253.

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ELEMENT SAMPLES	SiO2 %	Al2O3 %	Fe2O3 %	MgO %	CaO %	Na2O %	K2O %	TiO2 %	P2O5 %	MnO %
LS 1	45.75	13.27	16.3	4.24	8.85	2.05	0.66	4.58	0.55	0.17
LS 2	45.55	13.11	16.81	5.14	10.07	2.62	0.71	4.4	0.42	0.19
LS 3	46.37	13.21	16.78	5.07	10.22	2.7	0.65	4.43	0.53	0.19
LS 4	46.11	13.19	16.61	4.94	9.92	2.72	0.81	4.47	0.5	0.2
LS 5	45.86	13.05	16.85	5.07	10.19	2.67	0.76	4.46	0.47	0.19
LS-6	48.55	12.36	16.14	4.89	9.55	2.73	0.6	4.37	0.37	0.19
LS 7	45.46	13.2	16.74	5.19	10.35	2.58	0.64	4.45	0.44	0.19
LS 8	45.8	13.16	16.74	5.29	10.53	2.65	0.63	4.41	0.43	0.19
LS 9	45.66	13.23	16.99	5.22	10.41	2.57	0.63	4.45	0.51	0.19
LS 10	45.22	13.2	17.08	5.22	10.46	2.55	0.6	4.4	0.41	0.19
RE LS 10	45.33	13.26	16.91	5.3	10.49	2.54	0.56	4.42	0.42	0.19
LS 11	45.61	13.09	16.69	5.29	10.47	2.5	0.59	4.41	0.52	0.19
LS 12	46.34	13.3	16.72	5.1	10.17	2.67	0.63	4.48	0.47	0.2
LS 13	45.61	13.24	16.72	5.35	10.62	2.56	0.55	4.38	0.44	0.19
LS 14	45.42	13.29	16.95	5.33	10.54	2.5	0.6	4.39	0.45	0.19
LS 15	45.39	13.24	16.87	5.12	10.19	2.64	0.67	4.42	0.51	0.19
LS 16	45.76	13.36	17.12	5.25	10.43	2.59	0.64	4.46	0.44	0.19
STANDARD SO-17/CSB	61.29	14.24	5.81	2.33	4.65	4.1	1.4	0.65	0.96	0.52

ELEMENT SAMPLES	Cr2O3 %	Ba ppm	Ni ppm	Sr ppm	Zr ppm	Y ppm	Nb ppm	Sc ppm	LOI %
LS 1	0.005	170	51	433	205	36	48	32	3.5
LS 2	0.006	155	68	395	191	34	14	31	0.8
LS 3	0.004	171	47	414	203	37	< 10	31	< .1
LS 4	0.004	178	65	411	218	39	12	31	0.5
LS 5	0.004	166	41	411	207	36	< 10	30	0.3
LS-6	< .001	172	< 20	396	203	35	34	29	0.6
LS 7	0.008	160	92	405	188	35	< 10	32	0.6
LS 8	0.008	157	63	407	197	35	< 10	33	< .1
LS 9	0.007	155	72	406	197	35	< 10	32	< .1
LS 10	0.011	153	74	402	190	33	< 10	32	0.2
RE LS 10	0.012	154	104	404	187	34	< 10	33	0.3
LS 11	0.007	156	102	408	194	34	< 10	32	0.3
LS 12	0.007	172	76	421	212	37	< 10	32	< .1
LS 13	0.006	153	82	405	193	34	< 10	33	0.1
LS 14	0.01	152	86	402	186	33	< 10	33	0.2
LS 15	0.013	164	92	406	202	34	< 10	32	0.3
LS 16	0.011	160	94	410	198	33	< 10	33	< .1
STANDARD SO-17/CSB	0.458	399	32	298	359	27	24	23	3.4

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