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Sedimentation in a volcanically dammed valley, Brúarjökull, northeast Iceland

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Abstract

Sedimentation in upper Jökuldalur, northeast Iceland reveals a complex deglaciation history for the area. Subglacial eruption of an en-echelon ridge of pillow lavas and tuffs dammed the valley. The retreat of Brúarjökull to within the volcanic dam allowed a proglacial lake to form. Extensive retreat between surges of Brúarjökull may have resulted in the lake infilling and draining several times. The present infill reflects progressive glacier retreat, punctuated by stillstands and deposition of discrete wedges of coarse grained, ice-contact subaqueous fans. The valley infilled with sediment to within 10 m of the uppermost shoreline before progressive lowering of the outlet drained the lake. Breaching of the volcanic dam has since led to the incision of up to 85 m of sediment, deep into the underlying bedrock to create a spectacular gorge. This study documents how proglacial sedimentation can be controlled by glacier surge behaviour and the pattern of quiescent phase retreat. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

The nature of sedimentation into ice-dammed and proglacial lakes is becoming increasingly well understood. Studies of both modern glacial lakes and of lake deposits from the Quaternary sedimentary record are providing a clear picture of how these lakes respond to changing sediment input regimes, and climate and glacier fluctuations (e.g. Benn, 1996; Syverson, 1998; Krainer and Spieler, 1999). This paper presents details of proglacial lacustrine and deltaic sedimentation in an unusual situation in the highland interior of central Iceland. Damming of a narrow glacial valley by subglacial volcanism created a basin which was occupied by a proglacial lake during deglaciation. Glacier surging then acted as a primary control on the timing of sediment input into the lake basin.

The existence of a former glacial lake in southern Jökuldalur (Fig. 1) was proposed previously by Hannesson (1958), who described a thick infill of lake sediments, and suggested that they formed by damming of the valley by the Kárahnúkar volcano. The implications of this explanation have never been studied in detail. The aim of this paper is to describe the sediments infilling Jökuldalur south of Kárahnúkar, and relate them to the deglacial history of northeast Iceland, in particular the surge history of Brúarjökull.

A picture of the deglacial history of Iceland is beginning to emerge (Ingólfsson, 1991; Gudmundsson, 1997). However, at present, more is known about the early stages of deglaciation around the coast than about later stages in the central highlands (e.g. Norðdahl, 1983, 1990, 1991; Ingólfsson, 1987, 1991; Pétursson, 1991; Ingólfsson and Norðdahl, 1994; Sæmundsson, 1994, 1995; Ingólfsson et al., 1995; Richardson, 1998). Uncertainty still exists regarding the rate and timing of early Holocene deglaciation, and of Neoglacial readvances. Deglaciation north of Hofsjökull (Fig. 1) was studied by Kaldal (1978) and Víkingsson (1978), and the central highlands are thought to have been mostly ice free between 8 and 7 ka BP (Kaldal and Víkingsson, 1990). The eastern highlands are also thought to have been largely ice free by the early Holocene, although a broad ice lobe with an outline similar to that of the present day Brúarjökull is thought to have repeatedly surged northwards during this period (Aðalsteinsson, 1987; Kaldal and Víkingsson, 1990).

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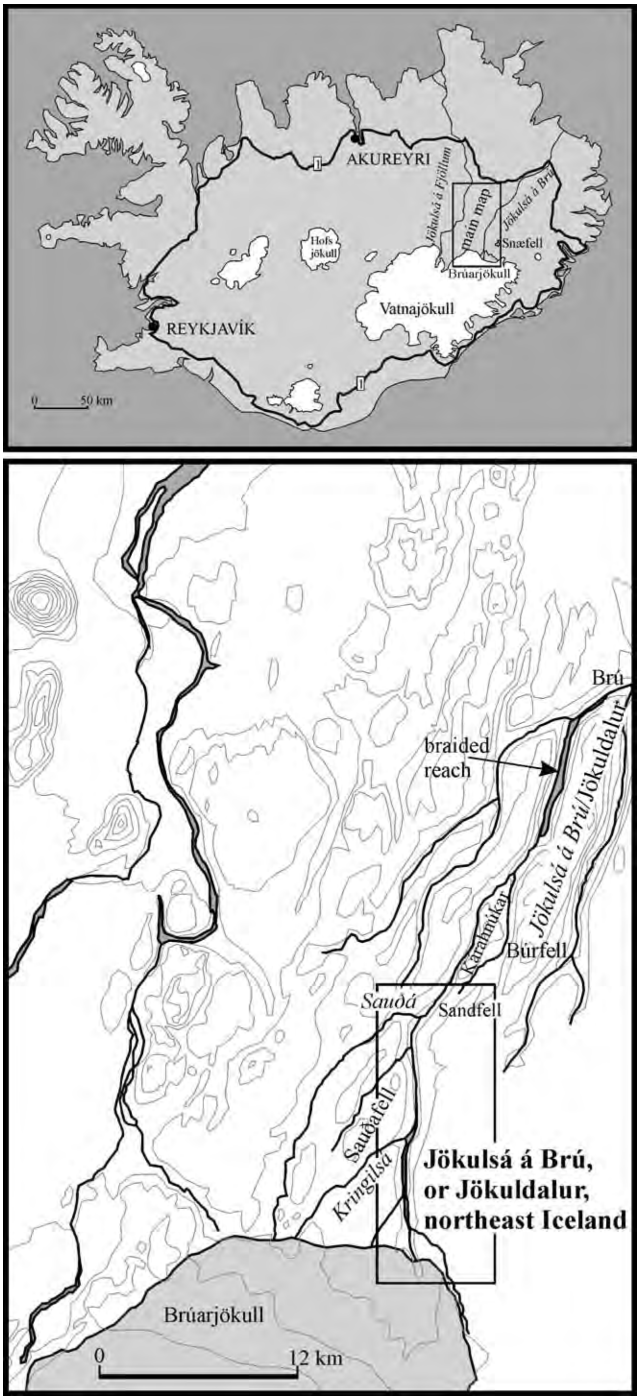

Fig. 1. Location of Jökulsá á Brú in northeast Iceland. Upper map shows location of main diagram in Iceland.

2. Methods

Geomorphological mapping of the area was undertaken using aerial photographs at a scale of 1:10 000 and verified in the field. This recorded the number and location of terraces, and the location of coarse-grained sediment bodies in the valley infill which stand out due to their more resistant nature. Details of the sedimentary infill were recorded on stratigraphic logs, which were correlated across the field area by surveying specific units using an electronic distance measurer (EDM). Sedimentary information recorded included details of grain-size, sorting, rounding, sedimentary structures, packing, and depositional geometry.

3. Formation of the Jökuldalur lake

The Kárahnúkar formation is a distinctive unit of volcanic rocks which erupted into Jökuldalur at some time during the Weichselian (Fig. 2). The volcanic unit forms a 10 km long en-echelon ridge, running NNE–SSW (Fig. 2). At its widest it is approximately 1 km wide and up to 200 m thick. The formation is composed of pillow lavas and tuffs, and the eruption which produced them was therefore subglacial (Walker, 1965). The eruption is distinctive in that it was constrained within Jökuldalur, and the Kárahnúkar formation infilled the valley completely for several kilometres. The nature of the infilling can be seen in cross-profile, based on borehole data, from Lambafell to Desjarárdrög, through Kárahnúkar, which shows the unconformable nature of the valley infill, and the presence of a sediment unit underlying the volcanic rocks (Guðmundsson et al., 1999; Fig. 3). The pre-eruption profile of the valley is thought to have been U-shaped. The post-eruption long profile of the valley had a pronounced over-deepening south of Kárahnúkar (Fig. 4). Proglacial lake formation and glaciolacustrine and deltaic sedimentation would have begun once Brúarjökull had retreated beyond the Kárahnúkar volcanic dam.

4. Sedimentary infill of upper Jökuldalur

The character of the sedimentary infill of Jökuldalur undergoes a distinctive change upstream of the volcanic dam. North of Kárahnúkar the Jökulsá á Brú is a 600 m wide braided channel in a broad, U-shaped valley (Fig. 1). Where the Jökulsá á Brú is diverted alongside the Kárahnúkar formation the river is in a gorge with steep rock walls up to 200 m deep (Fig. 5A). The gorge continues upstream of Kárahnúkar but is cut through both sediments and bedrock, and there are a number of well-developed terrace surfaces (Fig. 5B). A notable feature of these terraces are thick successions of fine-grained sediments dominating the sedimentary infill, although closer examination reveals discrete packages of coarser sediment within the finer material. Further south, near Kringilsá, the valley widens again and a braided channel develops. The total thickness of sediments upstream of the volcanic dam is 80–85 m, thinning to 45 m near Lindur, and 10–15 m near

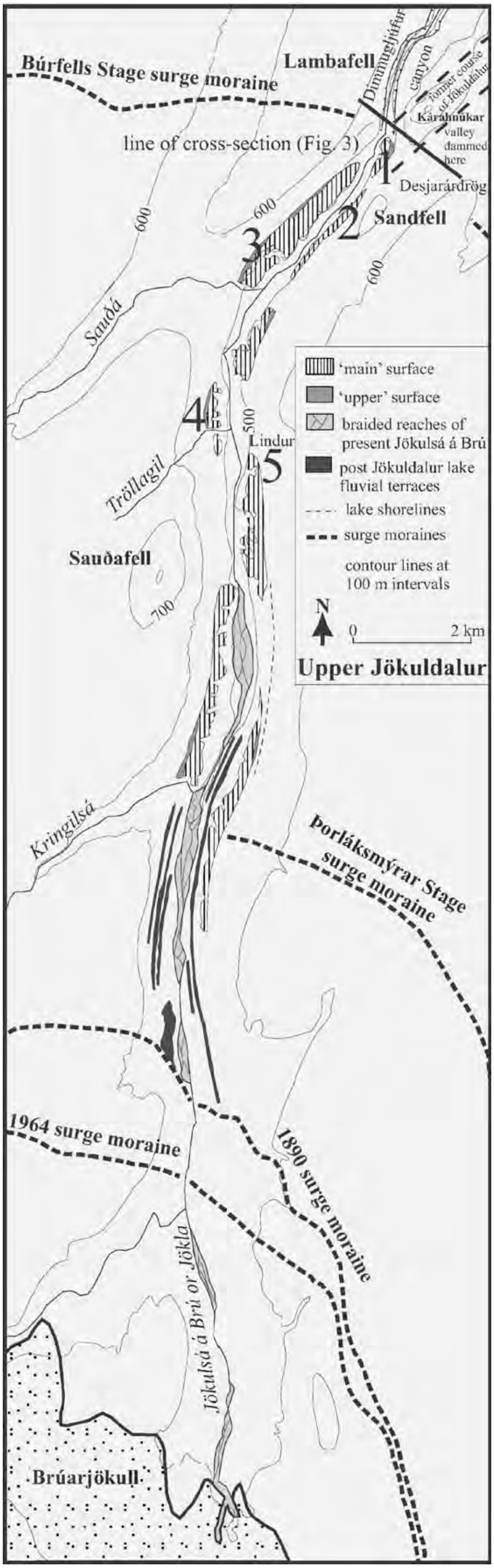

Fig. 2. Geomorphological map of Jökuldalur from Brúarjökull to Kárahnúkar.

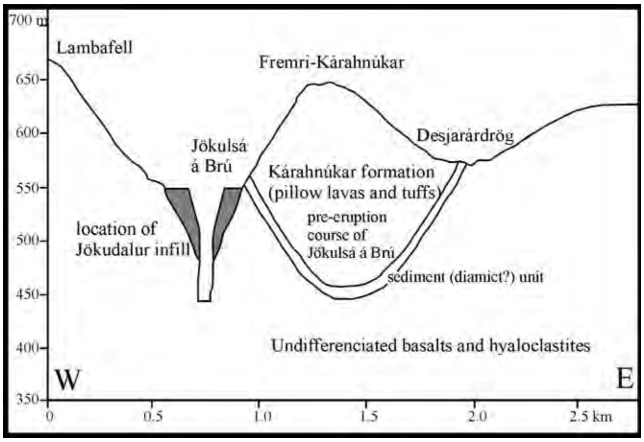

Fig. 3. Cross-section through northern Jökuldalur, from Desjará to Lambafell. Note 'U-shaped' profile of the old course of the Jökulsá á Brú underlying the Kárahnúkar formation, and the steep-sided nature of the gorge occupied by the present day river. Modified from Guðmundsson et al. (1999).

Kringilsá. The stratigraphy of the infill reveals a number of phases in the infilling of upper Jökuldalur (Fig. 4). Each of the main sediment units associated with the infill of Jökuldalur are outlined below.

4.1. Coarse-grained sediment wedges

The sedimentary infill of Jökuldalur contains large volumes of fine-grained sediment (see below) but distinctive packages of coarse-grained sediment also occur along the length of the valley. When viewed in section, the large-scale structure of the coarse-grained units is in the form of a steep sided 'wedge' (Fig. 6). Typically, the glacier-proximal side is very steep, usually almost vertical and the glacier distal side is less steep, at angles ranging between 10° and 40°. The large-scale bedding in the coarse-grained wedges is invariably parallel to the distal slope of the sediment body.

Individual coarse-grained wedges are up to 15 m high and have similar or slightly greater proximal to distal widths. The across-valley width is more difficult to determine due to the incision of the valley fill. Most of the coarse-grained wedges only outcrop on one side of the valley. Some outcrop on both sides of the valley, giving a possible width of 200 m. The frequency of the coarse-grained wedges decreases to the south, with the greatest density occurring near Kárahnúkar. The coarse-grained wedges occur at the base of the section, usually immediately above the bedrock.

The sedimentology of the coarse-grained wedges is generally similar along the length of the Jökuldalur infill. The dominant facies is a matrix-supported gravel which occurs in steeply dipping beds (Fig. 7). Individual units range in thickness from 1.5 to 10 m. The thickest unit occurs as a steep-sided lobe with an erosive, channeled base. The matrix-supported gravel is

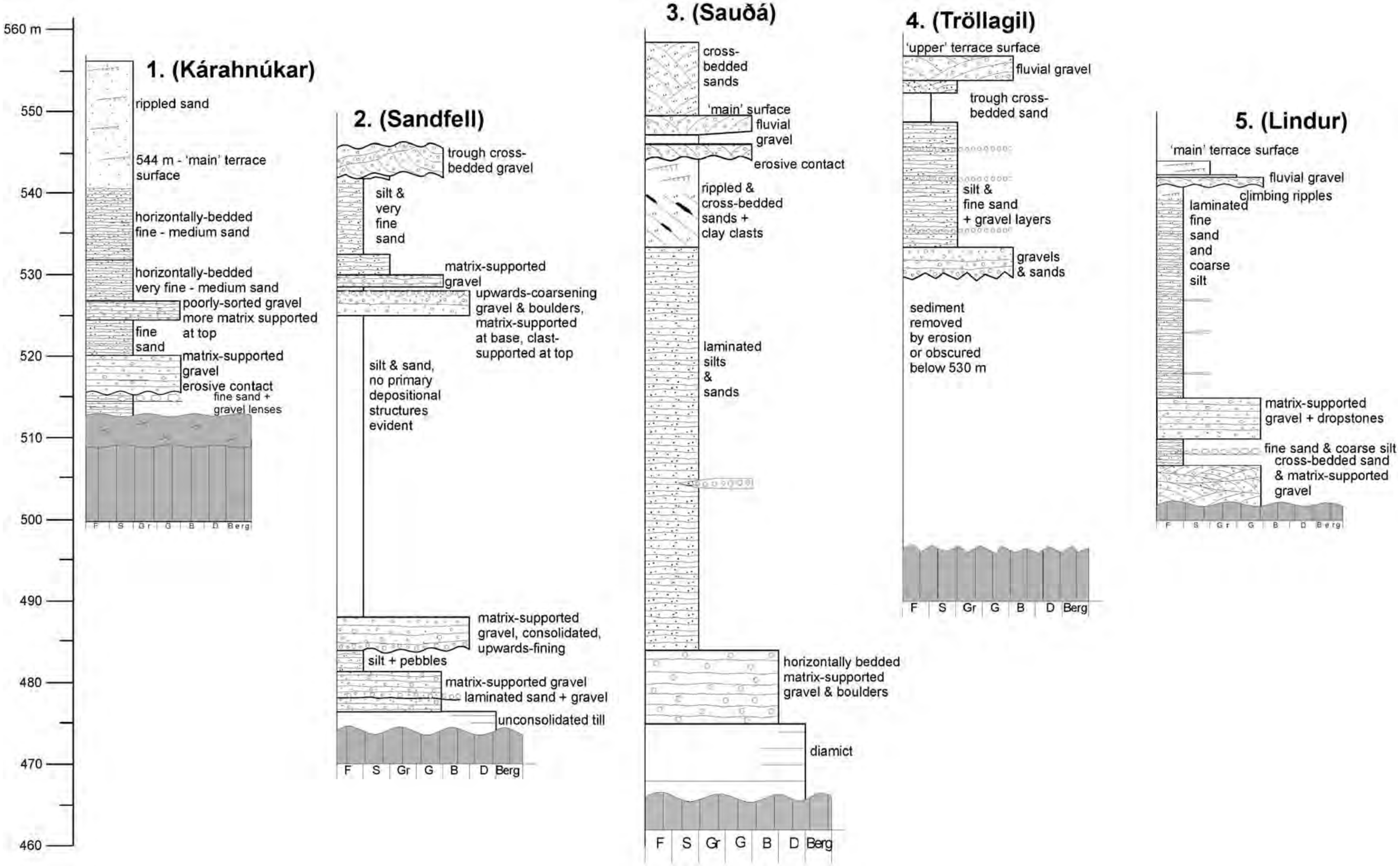

Fig. 4. General stratigraphy of the Jökuldalur sedimentary infill. Location of logs is shown in Fig. 2. Note the presence of an overdeepened bedrock base, the main and upper terrace surfaces, and the widespread occurrence of a fluvial unit below the main terrace surface. Scale is in metres. 'Berg' on the horizontal scale indicates bedrock.

Fig. 5. (A) View northwards from col between Kárahnúkar and Sandfell showing the Dimmugljúfur gorge. This was the location of the lake overflow. The length of the gorge indicates that catastrophic collapse was unlikely. Instead, the incision was due to headward retreat of a waterfall up the canyon, towards the viewpoint. (B) View southwards from col between Kárahnúkar and Sandfell showing the northern part of the Jökuldalur infill. Note the bedrock base to the sediment infill, with a pronounced overdeepening to the north, and the depth of incision below the sediment infill. The large terrace surface is the 'main' surface, often referred to locally as 'the airstrip'. The upper surface is very narrow and lies above the main surface on the sides of the valley.

characterised by poor sorting, and the matrix is usually composed of a polymodal mixture of silt and fine sand, medium to coarse sand and fine pebble gravel. Clasts of all sizes are present. The thickest units are invariably the coarsest, and contain clasts of up to small boulder size. Medium to large cobbles are dominant. Most units are composed entirely of well-rounded clasts. A minority of units also contain angular clasts. Higher densities of larger clasts in some locations leads to clustering, and a more clast-supported structure. In all locations pseudo-imbrication is common, and clasts are predominantly aligned with their *a*-axis parallel to the orientation of the large-scale bedding. Very steeply dipping 'upright' clasts are also common. Individual units are massive, or inversely graded. The only internal structure evident is indistinct horizontal bedding, usually at the base of units.

Within an individual coarse-grained wedge there are usually 3–4 matrix-supported gravel units, separated by sand dominated units. Interbedding with very fine sand is dominant in the north, and sand is the dominant sediment type in the wedges south of Lindur. The very fine sand is laminated, and is identical to that which occurs in thick sequences in the rest of the succession (Fig. 4). These very fine sand units are described in a later section.

Cross-bedded sand units are common in coarse-grained wedges between Lindur and Kringilsá. The sands either occur in association with matrix-supported gravel units at the base of the succession, or with only minor gravels throughout the succession and especially in the upper parts (Fig. 4). The architecture of the cross-bedded sand units is characterised by low-angle bedding

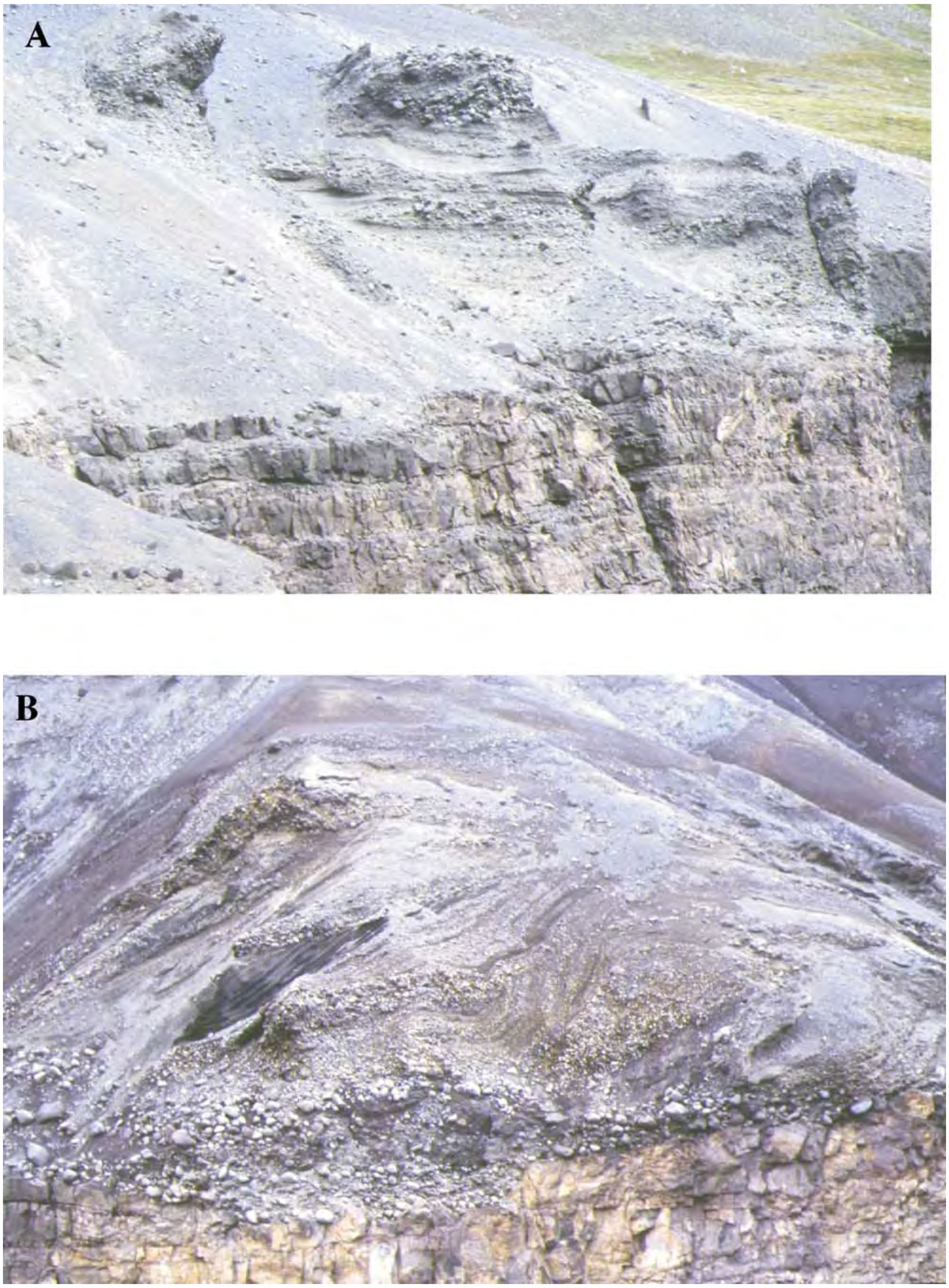

Fig. 6. Views of coarse-grained wedges of sediment at the base of the Jökuldalur infill. In both examples note the interlayering of massive boulder units and bedded sand units. (A) Looking across from base of Sandfell to northern end of 'the airstrip'. The coarse wedge here is approximately 15 m high. Palaeoflow was from left to right. (B) View from west side of valley to near the base of Fremri-Kárahnúkur. The total thickness of sediments in the coarse-grained wedge here is approximately 30 m. Palaeoflow was from right to left.

dipping to the north. Subsequent folding and stepped normal faulting, with downthrow of 0.1–0.2 m is generally perpendicular to the large-scale bedding, leading to progressive lowering of units into the deeper parts of the former lake basin.

Sand-dominated units are characteristically medium to coarse-grained, with numerous pebbles, and pebble layers. Individual units are thin, never exceeding 1 m. Most units are 0.3–0.5 m thick. The dominant depositional structures are climbing ripples and planar and trough cross-bedding. Climbing ripples are predominantly Type B ripples (Fig. 8), with minor draped lamination (Type S ripples) (Jopling and Walker, 1968; Gustavson et al., 1975). Cross-bedding either occurs as packages of large-scale planar-bedded foresets, or as trough cross-bedded units up to 1 m thick. Convoluted

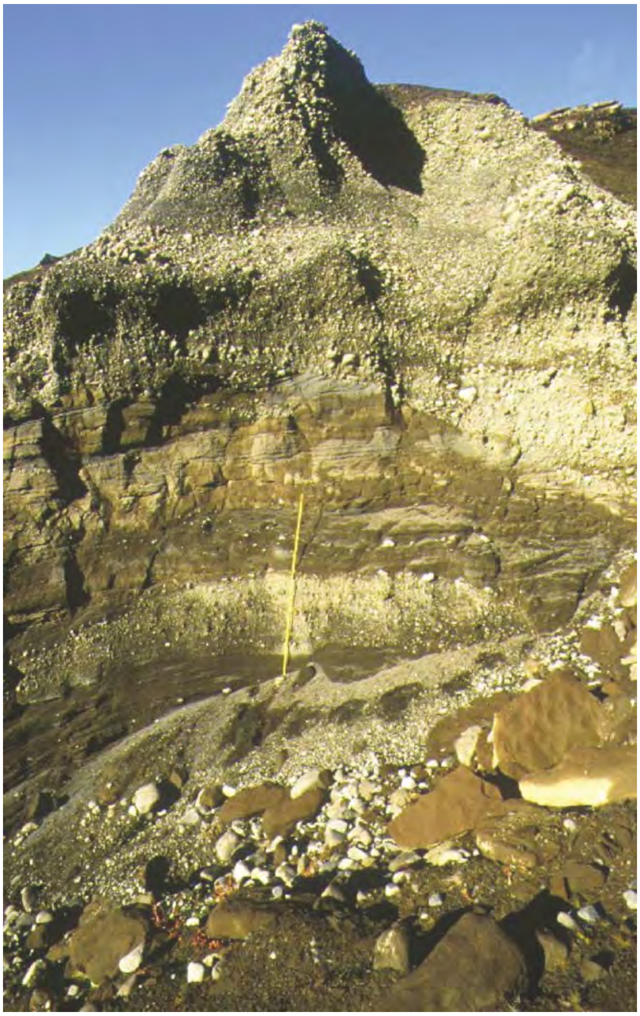

Fig. 7. Details of mass-flow units from the northern part of the Jökuldalur infill, showing two mass-flow units; a thin main unit, separated from the upper unit by a sequence of cross-bedded and laminated sands. The upper unit is at least 6 m thick and has a channelised base which erodes into the underlying sand unit. This unit is characterised by massive, rounded, matrix-supported gravel. Measuring stick is 3 m long. Palaeoflow was towards the viewer.

bedding occurs in a number of locations. Massive sand units also occur. Palaeoflow directions indicated by ripple structures and cross-bedding are consistently to the north, down valley.

4.2. Other coarse-grained sediment units

Within the upper part of the succession, where the cross-bedded sand is not interbedded with matrix-supported gravel, thin gravel layers occur within the sand units. The gravel layers are typically 0.1–0.4 m thick and most commonly dominated by clast-supported pebbles, but matrix-supported units also occur. Larger clasts at the base of some gravel units are associated with deformation of the underlying sands (Fig. 9A).

Fig. 8. Detail of climbing ripple unit observed at Lindur.

Gravels also occur as lenses, surrounded by finer material. The largest gravel lens was 6.7 m wide and 1.5 m high (Fig. 9B). Most observed lenses were 1.2–1.3 m wide and 0.3–0.5 m high (Fig. 9B). The infill of gravel lenses typically comprises poorly sorted, rounded pebbles and small cobbles. Most examples are massive, although horizontal bedding was observed in some cases. Sediments in the uppermost unit at the Kofalækur section near the Þorláksmýrar Stage moraine (Figs. 2 and 4) had folded, almost vertical bedding and vertical clastic dykes cutting through horizontally bedded sediment.

4.3. Interpretation

The massive, matrix-supported gravels are interpreted as mass-flow deposits (Nemec and Steel, 1984; Nemec, 1990). The steep-sided margins of many of the deposits suggests deposition as steep-sided lobes, and implies a high degree of internal cohesion. The presence of vertically orientated clasts, clast clustering and pseudo-imbrication indicates that the flows were partly

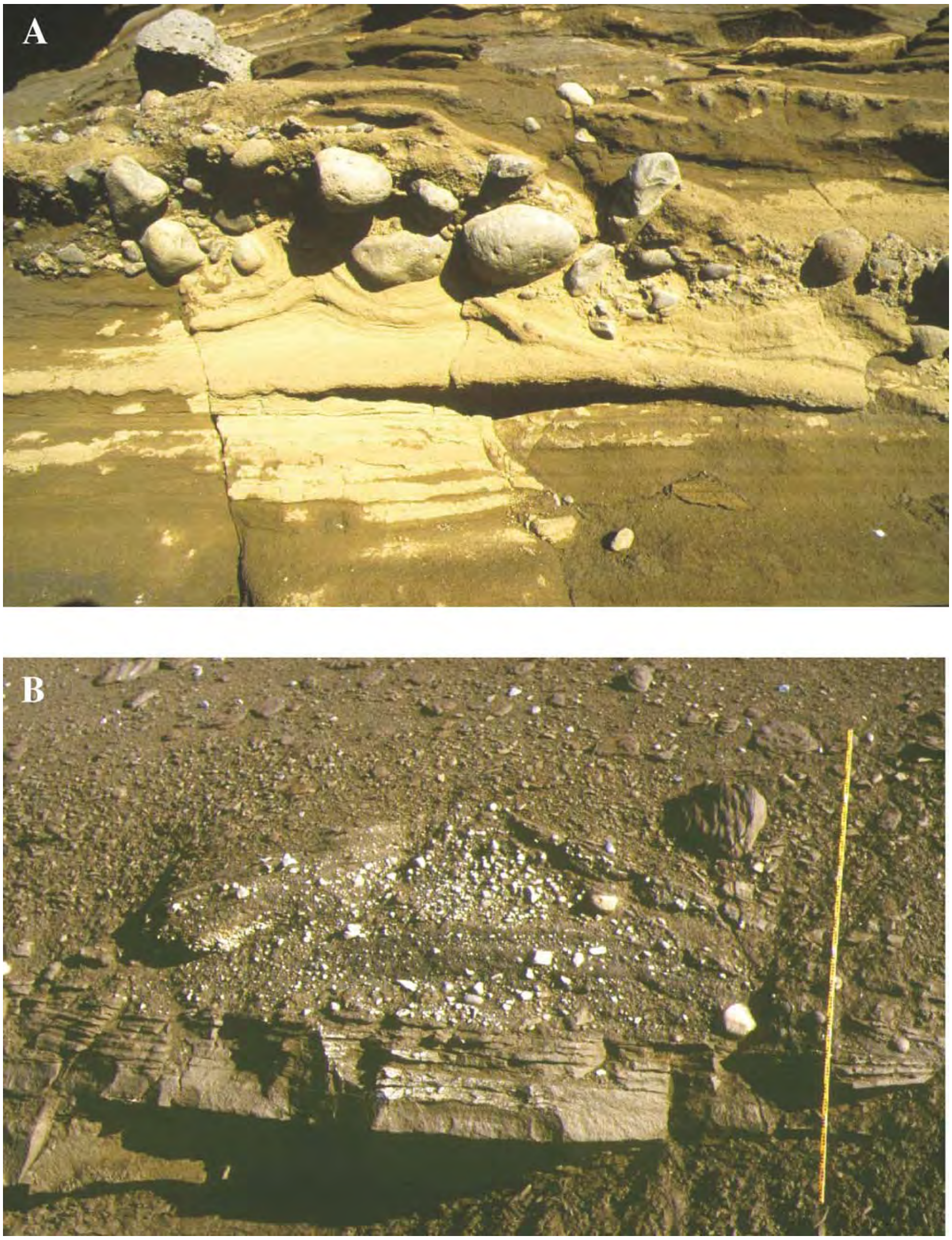

Fig. 9. Details of iceberg dump and drop structures. (A) Deformed bedding underneath a cluster of dropstones on the west side of Jökuldalur, north of Kringilsá. Largest clast has a visible long axis of 20 cm. (B) Symmetrical dump structure similar to those described by Thomas and Connell (1985) observed at Lindur. The feature is 6.7 m wide and 1.5 m high and the measuring stick is 3 m long.

turbulent but the overall character indicates a sediment-rich flow analogous to the 'cohesionless debris flow' of Nemec and Steel (1984) and Nemec (1990). Within individual coarse-grained wedges, the presence of several flow units of limited extent argues for repeated flows utilising separate, localised flow pathways. The rounded nature of the material in the mass-flow deposits indicates fluvial transport prior to deposition on the fan. Given the location of the mass-flow deposits on an ice-contact subaqueous fan (below) an esker source seems most reasonable, indicating a tunnel mouth depositional setting for the material in each coarse-grained wedge.

Cross-bedded sand units are interpreted as representing deltaic deposition under lower energy (compared to the mass-flow deposits), turbulent flow conditions. The large-scale, low-angle architecture of the sand units reflects low-angle foreset deposition. Planar and trough cross-bedded sands indicate the passage of large sandy bedforms, with both straight and crescentic crests (Allen, 1984). The presence of pebbles within most of the cross-stratified sand units indicates that relatively coarse material was being carried in suspension. Massive sand units indicate rapid settling out from suspension (Ashley et al., 1982). Rippled sand units indicate rapid migration and accumulation of sand-sized material under turbid conditions (Type B ripples) and accumulation of finer material from suspension (Type S ripples) (Jopling and Walker, 1968; Ashley et al., 1982). A similar origin is also proposed for the rippled sands that occur near the top of the succession in many locations.

Deformation of bedding within the sandy units is thought to be a consequence of post-depositional sediment remobilisation (Nemec, 1990; Lønne, 1997). Poorly sorted lenses of laterally discontinous gravel, and deformation of sand-sized sediment by large clasts are both attributed to deposition of ice-rafted material (Thomas and Connell, 1985; Lønne, 1995). The overall depositional character of the sand-dominated coarse-grained wedges, and of the cross-bedded sands in the mass-flow dominated units indicates turbid underflows on low-angle fan slopes (Smith and Ashley, 1985; Ashley, 1995) .

Based on their morphology and internal sedimentology, the coarse-grained sediment wedges are thought to represent discrete packages of deltaic sediments with the steeper, proximal side representing the ice-contact face. These structures are therefore ice-contact subaqueous fans according to the definition of Lønne (1995). This interpretation is based on the absence of a sub-aerial delta top-set component. The absence of delta top-sets in conjunction with their location at the base of the sedimentary succession indicates high water depths compared to the sediment source.

The moraine-like ridges exposed in cross section between Kringilsá and Lindur are thought to form in an identical manner to the model for ice-contact submarine (and subaqueous) fans presented by Lønne (1995) due to their morphological similarity. However, the ice-contact subaqueous fans to the north have much steeper ice-contact slopes than fans to the south, and generally contain the coarsest sediments found in the valley. These differences between fans to the north and south along Jökuldalur are thought to reflect both changing patterns of sedimentation during the retreat of Brúarjökull, and changes in the rate of glacier recession (Powell, 1990). The steeper, coarse-grained wedges to the north are interpreted to record rapid deposition of very coarse, steep-sided sediment units, in conjunction with stable tunnels under a thick ice margin. Continued ice-sheet thinning is then thought to lead to a period of more rapid, but staggered retreat and consequently, the deposition of widely spaced subaqueous fans. This depositional model contrasts with models such as that of Rust and Romanelli (1975) where steady retreat leads to overlapping 'subaqueous outwash fans'.

4.4. Sand-dominated units

The 'fine' component of the sediment infill is highly variable. Fine-grained units are distinguished from the coarse-grained wedges based on a number of features. The morphology of fine units is characterised by laterally extensive horizontal, or sub-horizontal lamination which occurs over, and inbetween the coarse-grained wedges. Draping, and downslope settling and compaction of the laminated units against the valley side is common (Fig. 10). In other locations folding around coarse-grained units occurs. The grain-size of 'fine' units

Fig. 10. Laminated sand unit in section on north side of valley north of Kringilsá. Sagging of entire unit to the right (east) is interpreted as representing drape over the valley sides. This drape is accentuated by numerous normal faults with downthrow of 1–5 cm.

varies between coarse silt and fine sand. Medium to coarse sand occurs locally.

North of Sauðá a 15 m thick succession of large-scale (5–10 m) trough cross-beds and horizontally bedded and rippled sand occurs (Fig. 11). Individual units of horizontally bedded sand are up to 1 m thick. Silt layers are common, and frequently drape underlying rippled units. Rippled units are predominantly Type B climbing ripples although Type A ripples also occur (Jopling and Walker, 1968). This unit coarsens up-succession, and thin pebble layers occur near the top.

4.5. Interpretation

Laminated sand and silt units are interpreted as representing a low-angle delta-slope environment (Gustavson et al., 1975). Sedimentation in this setting is thought to be from turbid underflow currents with relatively high sediment volumes (Gustavson et al., 1975; Lønne, 1997). Deposition of a thick succession of fine sand by large-scale three-dimensional dunes is indicated by the trough cross-bedded units observed north of Sauðá. This same succession grades into a sequence of units indicating rapid aggradation by deposition of Type B climbing ripples (Ashley et al., 1982) separated by quiescent phases with deposition of silt drapes from suspension. There is no evidence for seasonality in these successions.

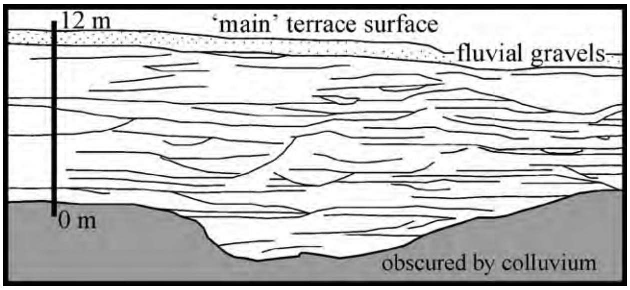

Fig. 11. Sketch of large-scale architecture of horizontal fine sand units near Sauðá, at the south end of 'the airstrip' surface. Silt layers are common in this section. Note the overall horizontal nature of the succession. However, trough cross-bedding was observed in the lower part of the succession, and wide, shallow channels occur throughout the sequence. The succession lies below the main surface, and the uppermost 1–1.5 m comprise fluvial gravels.

4.6. Fine-grained sediments

The most extensive fine-grained units consist of alternating couplets of coarse silt and very fine sand (Fig. 12). These couplets were measured in detail at Tröllagil (Fig. 2). The exposed thickness of the measured section was 11.04 m. Eighty-three couplets, each consisting of a coarse silt layer and a very fine sand layer were counted. Couplet grain size varied little throughout the succession, but layer thickness was highly variable (Fig. 13A). The very fine sand layers are generally much thicker. Sand layers are 20–30 cm thick for the first 19 couplets, and then generally less than 10 cm thick until couplet 66. Sand layers thicken, and generally exceed 10 cm for couplets 67–83. The average thickness of the silt layer was 1.0 cm, and the sand layer averaged 12.0 cm thickness. Therefore, on average, silt layers were only 8.4% as thick as sand layers. Variations in thickness of silt layers compared to sand layers are shown in Fig. 13B. Most of the variations in Fig. 13B

Fig. 12. View of laminated silt and very fine sand couplet succession at Tröllagil which was measured in detail. Total thickness of fine-grained sediments was measured at 11 m. Figure for scale is circled.

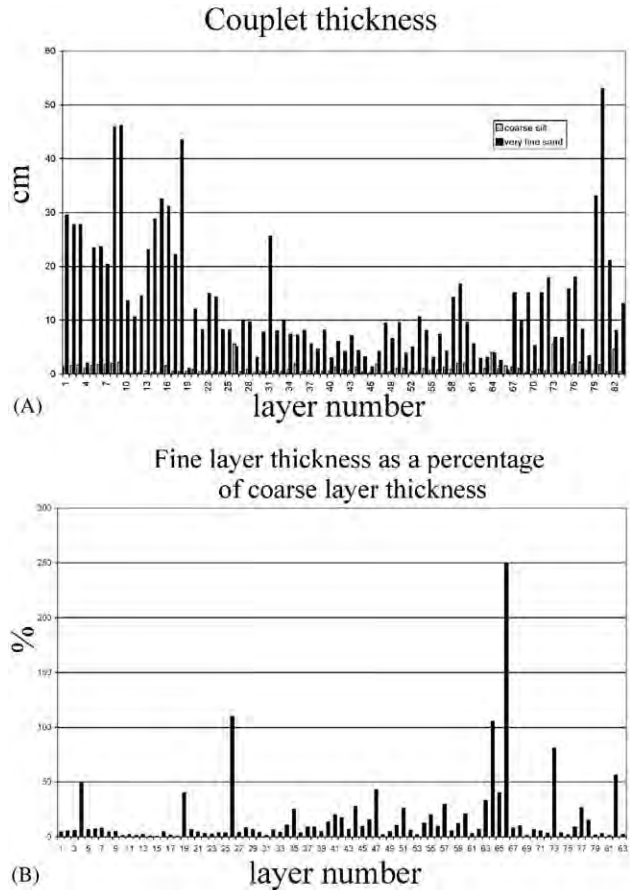

Fig. 13. Details of measured couplets at Tröllagil section. (A) Comparison of thickness of coarse silt and very fine sand component for each couplet. (B) Graph indicating fine layer thickness as a percentage of the coarse layer thickness for each couplet. Trends are discussed in the text.

are caused by variations in the thickness of the sand layer rather than the silt layer. Silt layers have a relatively constant thickness throughout the succession.

The coarse silt layers are massive. In the upper part of the succession seven of the silt layers had sub-0.2 mm fine sand layers within them. The thickest silt layers had diffuse lower contacts and sharp upper contacts. The nature of the lower contact was more difficult to determine in the thinnest layers but the upper contact was always sharp. A sub-0.2 mm layer of fine sand was observed immediately above the coarse silt in a number of cases. Silt layers appeared rippled in some locations, although the ripples appeared to be drapes over bedforms in the underlying sand layer.

The very fine sand units contained a variety of structures. Most of the layers were massive, but, horizontal lamination also occurred. Climbing ripples were observed in some of the thickest layers. Wavelengths of 17, 20 and 25 cm were observed, with amplitudes of 1–2 cm. Sub-1 mm coarse silt layers ran through some of the very fine sand units. Couplet 10 included a stringer of pebbles. Couplets 9, 20, 30, 35 and 74 contained 1–2 cm thick layers of fine sand.

4.7. Interpretation

Distal depositional settings are indicated by the silt and very fine sand couplet-dominated units. However, there is a striking absence of clay within these units. The absence of the clay is accounted for in two ways. Firstly, clay is not a major component of the sediment load of the present day Jökulsá á Brú, draining Brúarjökull (Pálsson and Vigfússon, 1996). Most of the suspended load at present is silt and fine sand. Over the period 1970–1995, clay formed an average of 13% of the summer sediment load, and 37% of (a greatly reduced) winter sediment load (Pálsson and Vigfússon, 1996). There is no reason to suppose that it would have been any different in the past as the glacier is eroding the same bedrock at present as in the past. Secondly, it seems that the most distal sedimentation, where settling from suspension is of equal or greater importance than deposition from underflows (Ashley, 1975) did not occur over wide areas within the Jökuldalur lake.

The very fine sand component of the couplet succession is therefore interpreted as having been deposited by strong turbid underflows, that carried large volumes of suspended sediment (Ashley, 1975; Gustavson, 1975; Gilbert and Shaw, 1981). Silt layers are interpreted to represent deposition from suspension during periods when underflow activity had temporarily ceased. Occasional layers of fine sand in the silt layers are interpreted as the product of an interval of turbid flow reactivation during a phase of otherwise passive sedimentation (Shaw et al., 1978). The most likely origin in Jökuldalur is winter storms as jökulhlaups are rare (approximately 1 in 100 years) in Jökulsá á Brú, and also likely to have a much greater sedimentary impact.

The regularity of the couplet succession, in addition to the sedimentary features discussed above all suggest that the couplets are annual. A deposition period of 83 years is therefore indicated by the measured section.

4.8. Diamictons

Underlying the lake sediments which form the main infill is an unlithified and poorly consolidated diamicton unit. The unit is only exposed locally, and does not underlie all of the sediments. In the Sandfell area the unit extends laterally for 100 m. The entire unit is highly sheared and fissile. The matrix of the diamicton consists of sand, and there are numerous dispersed pebbles and cobbles distributed throughout the unit. Clasts are striated and are sub-angular to sub-rounded.

The diamicton is interpreted as a subglacial till and overlies striated bedrock. The shearing and striated clasts indicate subglacial transport occurred.

4.9. Fluvial sediments

The thick laminated sand and silt succession is truncated by a sharp, laterally extensive erosion surface (Figs. 5A and B and 14). Overlying the erosion surface is a unit which varies in thickness between 1 and 4 m and forms the top unit of the 'main' surface. The unit above the erosion surface is nested into the laminated sediments, and is consequently stratigraphically younger. This stratigraphic relationship is shown in Fig. 4. These sediments are best exposed in the Lindur area where they comprise well sorted, clast-supported, imbricated gravel with rounded clasts. The unit is massive and ungraded. The clast-supported, imbricated nature of these gravels indicates that they were fluvially transported. The laterally extensive, horizontal nature of the unit suggests they were deposited in a river rather than a deltaic environment. There is no relationship between these sediments and the deltaic sediments which occur much lower in the succession. South of Lindur, lower terraces also occur. These terraces have well developed bar and channel patterns on the surface. A section in one of the lower terraces reveals fluvial sediments, similar to those described above, but coarser, and with more internal structure such as accretion surfaces and discontinuous sand layers. The fluvial sediments in this section were divided into two units by a 1.6 m thick soil layer containing at least five tephra layers.

Fig. 14. Detail of fluvial sediments which occur immediately below the 'main' surface at all locations. Section is into a test pit; uppermost layer is soil. The thickness of the fluvial unit is 4 m at this location. The laminated fine sand which underlies the fluvial sediments is separated by an extensive erosion surface.

4.10. Lake shorelines above the upper surface

Shorelines associated with the Jökuldalur lake are not well developed above the main and upper terrace surfaces. The best developed shorelines are at the southern end of the lake, south of Lindur, at an altitude of ca. 560 m above sea level. A section into the shoreline surface reveals a unit of fine-grained diamict with pebbles of up to 5 cm diameter. The diamict was uniform across the exposure, and was compact and sheared. The unit is interpreted as a till and indicates that the shoreline feature it underlies is erosional rather than depositional. This observation also indicates that the lake never completely infilled with sediment.

4.11. Interpretation of the sedimentary infill: summary

The sedimentary evidence presented above records a history of progressive infill of the Jökuldalur volcanically dammed lake. The presence of a glacier in the valley prior to formation of the lake is indicated by the basal diamicts. Coarse-grained sediment wedges record ice-contact subaqueous deposition, and their distribution along the valley indicates progressive, and then more rapid retreat of the glacier. The infill becomes progressively finer up-succession, reflecting the retreat of the glacier. Thick units of fine-grained couplets indicate the most distal depositional settings. The nesting of a fluvial unit into the lacustrine deposits indicates that there was a period of sub-aerial deposition prior to the complete incision of the Dimmuglúfur gorge (see below).

5. Incision

The bedrock dam was at least 7.5 km long and catastrophic collapse and drainage is unlikely. It is probable that the dam was eroded progressively, both by lowering of the lake overflow outlet, and by incision and erosion of the distal end of the volcanic dam. The presence of terraces of lake sediment above the 'upper' surface provide evidence that there was progressive lowering of the outlet. The presence of the pronounced erosion surface at the top of the lacustrine sediments, which is directly overlain by fluvial sediments indicates that the basin had stopped ponding a lake, and was occupied by an active fluvial system prior to incision of the gorge. The presence of the deep incision with no terraces through both the lake sediments and up to 100 m of bedrock suggest that there was also a period of rapid incision. The most viable mechanism for this is progressive backcutting of the gorge through the volcanic dam, until the lake was breached. This mechanism requires the retreat of a 200 m high waterfall over a distance of 7.5 km. As it is clear that the lake had already drained through progressive downcutting of the outlet and had completely infilled, it is apparent that this final period of incision was not in association with a catastrophic flood.

South of Kringilsá there is a sequence of fluvial terraces which extend from near the 1890 surge limit into the southern reaches of the Jökuldalur lake, all at lower heights than the 'main' surface. The terraces all terminate where Jökuldalur narrows north of Lindur. These terraces are thought to be related to development of sandur surfaces at a later period. The presence of at least two fluvial units, separated by a thick soil layer indicates that there was a considerable time interval between the development of the sandur surfaces. Analysis of the tephra contained within the soil is currently underway as part of an ongoing project reconstructing the later, fluvial history of Jökuldalur.

6. Discussion

Jökuldalur contains a record of diverse processes and depositional environments in a relatively confined area. The primary affect of subglacial volcanism (the Kárahnúkar formation) was to dam Jökuldalur which ultimately led to the redirection of the Jökulsá á Brú and the incision of a much deeper and steeper gorge than would otherwise exist. Sedimentation during deglaciation reflects this sequence of events and provides detail of glacier behaviour at this time. However, although most of the sediments in Jökuldalur are associated with retreat of Brúarjökull, fragments of underlying till, interpreted as a subglacial till and therefore deposited earlier are preserved in some locations. The removal of the till from most of the base of the valley suggests considerable scour prior to the lake history.

Volcanic damming created a large accomodation space for sedimentation during deglaciation. Most of the exposed sediments are subaqueous fan or lacustrine in origin. Subaqueous fan sediments, primarily coarse-grained mass-flow deposits, but also cross-stratified gravels and thinly bedded sands and fine gravels, occur throughout the length of the lake, but are most common in the lower part of the succession. The coarse-grained wedges do not form a continuous unit, but rather, occur as distinct sediment bodies surrounded by finer-grained sediment. This relationship suggests retreat of the ice front altering the position of glaciodeltaic sediment input over time (Fig. 15).

A thick, extensive succession of laminated silt and sand indicates periods of more passive, glaciolacustrine sedimentation in all locations. Alternating couplets of coarse silt and fine sand are interpreted as varves. The difference in thickness between the coarse and fine component of the varves indicates that deposition by sediment-rich turbid flows with only minor deposition from suspension. Temporal variations in

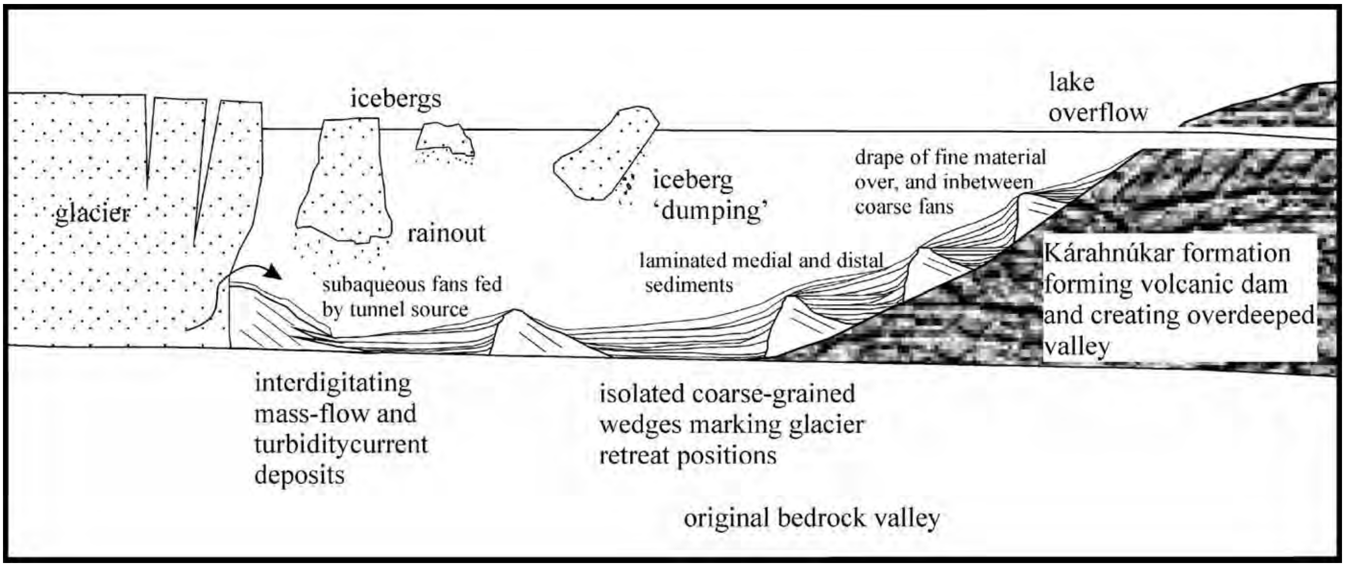

Fig. 15. Conceptual model showing how the coarse- and fine-grained sediments of the Jökuldalur infill are related, and how both are controlled by the nature and timing of glacier retreat. Diagram is not to scale.

sedimentation style are primarily related to changes in glacier position.

Fig. 2 shows the location of the Jökuldalur lake in relation to mapped moraines, interpreted as surge moraines, of Brúarjökull (Aðalsteinsson, 1987, 1991). It is striking that the northern limit of the valley infill corresponds to the location of the Búrfells stage surge moraine. There is strong circumstantial evidence to suggest that there is a relationship between the infilling of the Jökuldalur lake, and the surging of Brúarjökull. Surges of Brúarjökull typically involve 8–10 km of advance (Thorarinsson, 1969; Knudsen, 1995), the longest advances of any present day terrestrial surging glacier. Even if sedimentation into Jökuldalur had begun prior to the Búrfells Stage, it would have been overridden during the surge. There is no evidence from within the main valley infill to suggest the Jökuldalur lake sediments have been overridden. The sediments seen in the present valley were therefore deposited immediately after the Búrfells Stage. Indeed, the only sediments in upper Jökuldalur thought to predate lake infilling are the basal tills and even these are only preserved locally.

It is therefore possible that the Jökuldalur lake existed twice, once before the Búrfells Stage surge, and once after. Removal of the sediments from the first lake is most likely to have occurred during the surge. Evacuation of up to 300 m of sediment in a 20 km long valley has been described for Breiðamerkurjökull during the Little Ice Age (Björnsson, 1996). The Breiðamerkurjökull situation is directly analogous to that in Jökuldalur. Both involve removal of large volumes of sediment from overdeepened valleys during periods of glacier surging. Removal of sediment in Jökuldalur would have been facilitated by the relatively shallow pre-incision topography of the valley. Large-scale removal of the Jökuldalur infill is impossible at the present as the river is so deeply incised below the sediments. Retreat from the Búrfells Stage moraine would then allow development of the lake sediments examined in this study.

The southern limit of the lake sediments corresponds approximately to the Þorláksmýrar Stage surge moraine (Todtmann, 1960; Aðalsteinsson, 1991). Sedimentation into the Jökuldalur lake therefore appears to have been constrained between a surge cycle of Brúarjökull. Given that Brúarjökull surges approximately every 100 years (Thorarinsson, 1964, 1969) it seems likely from the above discussion that the deltaic and lacustrine infill of Jökuldalur was deposited in approximately 100 years. The measurement of 83 annual layers gives a minimum deposition time which is compatible with this reasoning.

The suggestion that the Jökuldalur lake infilled quickly can be tested by comparison with the present-day sediment load. The volume of lacustrine sediment in the Jökuldalur basin prior to incision was at least $660 \times 10^6\,\mathrm{m}^3$. The total volume is likely to be greater as the southern limit of the lake is unknown. Assuming a 100 year sedimentation period gives an average sediment accumulation rate of $6.6 \times 10^6\,\mathrm{m}^3\,\mathrm{a}^{-1}$. The present day sediment load of Jökulsá á Brú is the highest of any river in Iceland at approximately $5.7 \times 10^6\,\mathrm{m}^3\,\mathrm{a}^{-1}$ (Pálsson and Vigfússon, 1996) which would fill an equivalent volume lake in 116 years. Therefore, both the timing and style of sedimentation support formation and infill of the Jökuldalur lake within a single surge cycle of Brúarjökull.

7. Wider implications

This study is significant in that it documents a relationship between surge behaviour, quiescent phase retreat and glaciolacustrine sedimentation. The events outlined here could occur in any location where proglacial lakes are capable of surviving for long periods of time. The most suitable settings would therefore be where proglacial lakes are confined by bedrock rather than moraine ridges.

It is widely recognised that large lakes in glaciated areas tend to preserve sedimentary successions associated with deglaciation rather than advance (Ashley, 1995). Rapid deglaciation by calving into deep lakes or the sea is also common (Benn and Evans, 1998). However, rapid retreat, and continuous glaciolacustrine sedimentation, following a surge is less well documented. The distinguishing characteristic of the retreat in Jökuldalur is that it appears to have begun slowly, and then proceeded more rapidly later on. This pattern may be related to the nature of glacier retreat from a surge maximum which is slower immediately after a surge as the ice margin is thicker and then increases later on as the ice margin thins. It is this pattern of retreat, recorded by the development of coarse-grained subaqueous fans which is significant in Jökuldalur. The sediments themselves, and their arrangement into overlapping morphosequences, are similar to those described for other large proglacial lakes (Ashley, 1995).

8. Conclusions

1. Sedimentation into southern Jökuldalur, northeast Iceland reveals a complex sequence of events during the deglaciation of the last ice-sheet in this region. A subglacial eruption dammed the valley. Glacial sediments are preserved above and below the volcanic formation. During deglaciation, Brúarjökull was a surging glacier, and it is possible that the Jökuldalur lake may have existed more than once. Once the ice

retreated past the volcanic dam for the final time, deposition into the Jökuldalur lake formed the sediments exposed at the present time.
2. Progressive infill, and retreat of the glacier are recorded in the sedimentary infill of the lake basin.
3. The cessation of infilling, and the beginning of incision is indicated by the presence of a well-developed erosion surface and overlying fluvial sediments at the top of the succession. Meanwhile, progressive upstream erosion of the volcanic dam ultimately led to complete breaching of the dam, and incision through the entire sedimentary succession deep into bedrock. Fluvial terraces in the southern part of the lake represent post-lake sandur development in the valley.
4. This study documents how the surge behaviour of a glacier can act as a control on the timing of sediment inputs into the proglacial environment. The location and sedimentary characteristics of the subaqueous fans documented here were directly controlled by the rate of glacier retreat following the Búrfells Stage surge.

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