Reviewed research article

Geomorphological and sedimentological records of glacial events in the northern part of the marginal zone of Tungnaárjökull, Iceland, since the Little Ice Age

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Abstract — *We present geomorphological mapping of glacilacustrine and glacifluvial landforms and lithofacies analysis of deposits in the northern part of the marginal zone of Tungnaárjökull as it retreated from its Little Ice Age (LIA) maximum. This is the first time that this type of study has been conducted in the marginal zone of Tungnaárjökull. Landforms identified included preserved shorelines, small wave-cut platforms, fossil deltas and a kame terrace, all associated with ice-dammed lakes. Lake, delta and kame depositional environments were interpreted on the basis of sedimentological analysis. Ice-dammed lakes developed in the northern part of the forefield as a result of Tungnaárjökull damming the outflow of meltwater between its snout and the Jökulgrindur volcanic ridge. Based on historical maps and aerial photographs the damming of meltwater was probably associated with the 1945 surge.*

INTRODUCTION

Tungnaárjökull is one of several outlet glaciers draining the western part of the Vatnajökull ice cap in SE Iceland (Figure 1A). It is located between 64°15' and 64°24' north latitude, between Skaftárjökull in the south and Sylgjujökull in the north (Figure 1B). The marginal zone of Tungnaárjökull covers the area between its maximum extent during the Little Ice Age (LIA) and its current edge. The indicated marginal zone is about 25 km long and ranges in width from approximately 1.2 km in the northern part to 2.5 km in the central and southern parts of its forefield (Molewski, 2005; Evans *et al.*, 2009). Beyond it are extensive outwash plains of various ages. The topography of the volcanic bedrock and forefield of Tungnaárjökull fundamentally determine the spread and dynamics of the glacier snout (Andrzejewski and Molewski, 2000; Andrzejewski, 2002; Evans *et al.*, 2009). A pattern of parallel, Upper Pleistocene northeast–southwest volcanic ridges are visible both in the relief of the forefield of the glacier and in the morphology of its surface (Figure 1B and 1C). In the northern part of the Tungnaárjökull forefield, at a distance of approximately 1.5 km from its snout and running parallel to this margin, is the Jökulgrindur volcanic ridge of maximum height about 940 m a.s.l. (above sea level), limiting the westward spreading of the glacier's snout. In the central and southern parts of the glacier's forefield, the volcanic ridges are oblique or perpendicular to its snout which has a significant influence on the local dynamics of ice masses and the distribution of meltwaters on the forefield, creating the diverse glacial, glacifluvial and glacilacustrine landforms of Tungnaárjökull's marginal zone (Andrzejewski, 2002; Evans *et al.*, 2009).

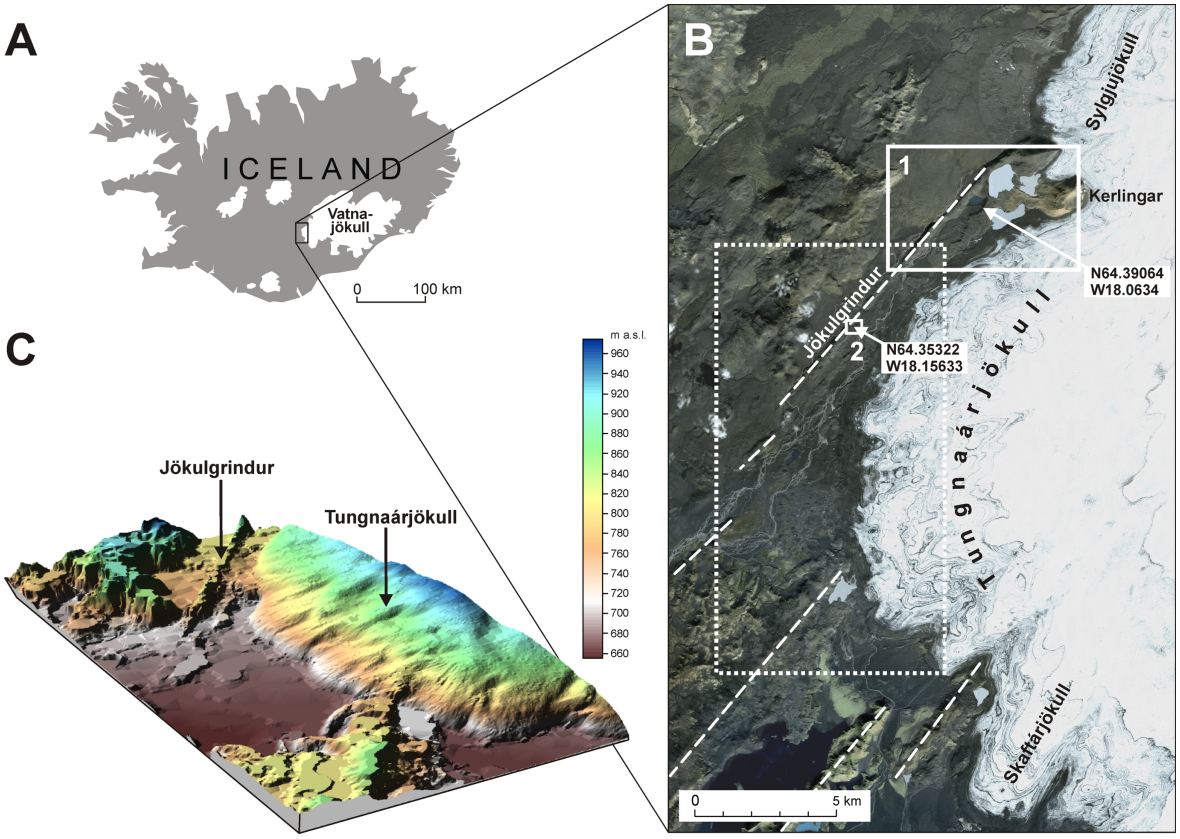

Figure 1. Location of Tungnaárjökull (A) and close up (B) of study areas (1 and 2) on the glacier forefield. Broken lines indicated axes of volcanic ridges and dotted lines mark the boundary of area presented in a 3D model (C) of the snout and forefield of Tungnaárjökull (Data from Loftmyndir ehf.). – *Kort af rannsóknarsvæðinu við jaðar Tungnaárjökuls. Þrívíddarkortið (C) er byggt á gögnum frá Loftmyndum ehf.*

Since the end of the LIA, Tungnaárjökull's dynamics have been dominated by long periods of retreat interrupted by glacier surges. The glacier has been receding since the late 19th century, a pattern interrupted by surges during the years of 1915–1920, 1945 and 1994–1995 (Thorarinsson, 1964; Freysteinsson, 1968; Andrzejewski, 2002). Geomorphological and sedimentological records of these surges in the marginal zone of Tungnaárjökull are represented by a series of landforms associated with successive advances and recessions of the glacier snout (Andrzejewski, 2002; Andrzejewski *et al.*, 2005; Molewski *et al.*, 2005; Evans *et al.*, 2009). Periodic contact of the Tungnaárjökull snout with the Jökulgrindur ridge obstructed the outflow of its meltwaters and caused the formation of ice-dammed lakes. Such events took place when the glacier reached its maximum extent at the end of the LIA and during the surges of 1915–1920 and 1945. The changing hydrodynamic conditions at the contact of the lakes with the glacier snout are expressed in a diverse complex of landforms and deposits, including lake shorelines, delta fans and kame terraces. A study aimed at reconstructing the processes that shaped these landforms

set against the dynamics of Tungnaárjökull was undertaken by the authors during several research expeditions to the forefield of the glacier between 1995 and 2005 (e.g. Molewski, 2005). The main objective of the expeditions was to create a geomorphological map of the entire forefield of Tungnaárjökull. Due to limited time and accessibility, individual landforms and sediments were identified and studied to different degrees. The geomorphological study resulted in the first identification of the morphogenesis of the analysed area. Previous research on the glacial geomorphology of the forefield of Tungnaárjökull includes work by Andrzejewski and Molewski (1999, 2000) in the central and southern parts of the marginal zone of the glacier which focused upon the tectonics of glacial and glacifluvial deposits resulting from glacial surges. Later work by Andrzejewski (2002) identified five morphogenetically different areas within the forefield of Tungnaárjökull which he related to the glacier's varied dynamics, which are mainly conditioned by the topography of the underlying volcanic bedrock. A geomorphological map of the forefield of Tungnaárjökull was published by Molewski (2005) and Evans *et al.* (2009). Evans *et al.* (2009) also described the diagnostic qualities of landforms and deposits associated with glacier surges.

The objective of this study is to reconstruct palaeogeomorphological events in the northern part of the marginal zone of Tungnaárjökull since the end of the LIA, based on geomorphological mapping and sedimentological analysis, as well as published historical maps and aerial photographs of the region (Freysteinsson, 1972; Thorarinsson and Sigvaldason, 1972). The research presented here focuses upon two key areas: one located in the northern part of the forefield; and the other, a smaller area including a part of the Jökulgrindur bedrock ridge and adjacent glacigenic sediments (Figure 1B).

METHODS

Geomorphological field mapping of the Tungnaárjökull forefield was carried out at a scale of 1:30,000 using aerial photographs from 1986 and 1995. The geographical position of the sites examined in the field were determined using a standard GPS receiver and calibrated aerial photographs. The geometric levelling of landforms was conducted using a clinometer.

Sedimentological and lithofacies analysis of the glacilacustrine and glacifluvial sediments was carried out upon exposed natural sections through these deposits. Particular emphasis was placed on recording sediment type and the range of sedimentary structures present, as well as the nature of bedding and lithological contacts, enabling a series of lithofacies to be established. The lithofacies code used in general follows that proposed by Miall (1978). The orientation of ripple cross-lamination, low-angle cross-stratification and inclined stratification surfaces was recorded using a compass clinometer to provide a record of palaeocurrent directions active during the deposition of the glacigenic sequence.

In order to establish the most common transition between pairs of adjacent lithofacies and to detect the deterministic and random components of that succession (i.e. the transition probability), Markov chain analysis (e.g. Miall, 1973; Gradziński *et al.*, 1986) were conducted on the longest lithofacies sequence, i.e. from the kame terrace. Markov chain analysis is a technique which can be used to determine the probability of one state transitioning into another in contexts where it is assumed that states are 'memoryless', i.e. that the probability of the subsequent state depends only on the present state and not on any preceding state or sequence of states. Because the statistical reliability of any resultant transition probabilities depends on the abundance of any given facies in the profile, z-tests were used to evaluate the statistical significance of the probability of individual transitions. The critical z-statistic value for 0.05 reliability is 1.64. It is assumed that transitions for which Z exceeds this value are preferred by the mechanisms of sedimentation processes; that is to say that sedimentation processes result in transitions between layers which are to some extent predictable or regular. These transitions are used in the construction of so-called "transition diagrams" (Gradziński *et al.*, 1986).

Average grain sizes of various deposits were largely recorded in the field using a comparison grain-size visual estimation chart. However, 10 bulk samples collected from the deposits within the kame

terraces were selected for more detailed laboratory-based grain-size analysis. Sandy sediments and sand fractions in silty-clay samples were analysed using the sieve method. Fractions finer than 0.1 mm were measured using a laser grain-size analyser. Based on these methods the deposits were classified by grain-size using nomenclature and fractional categories from the Polish Geological Institute (Wydawnictwo Geologiczne, 1977) which subdivides the sediments into five main categories: clay <0.01 mm; silt 0.01–0.1 mm; sand 0.1–2.0 mm; gravel 2.0–100.0 mm; and boulders 100.0–1000.0 mm.

For selected deposits, average deposition velocity was estimated in cm/s according to Koster's (1978) formula $V=49D^{0.381}$, where the variable is the median grain size (D_{50}) in cm. Maximum Particle Sizes (MPS) were also determined as an indicator of flow rate competence for large-grain deposits. MPS is determined in the field based on measurement of the intermediate axis (b) of the ten largest grains originating from a monogenetic lithosome or lithofacies, or based on the cumulative grain-size curve with MPS fraction size being determined as that of the 95th percentile (D_{95}). The estimated palaeocurrent competence is calculated using Koster's (1978) formula.

THE NORTHERN STUDY AREA

The northern study area is located in the northernmost part of Tungnaárjökull's marginal zone in the vicinity of the volcanic cone of Kerlingar (1,286 m a.s.l.) (Figure 1B), which separates Tungnaárjökull from Sylgjujökull. The area is bordered to the southeast by the glacier snout and to the northwest by the volcanic ridge of Jökulgrindur (Figure 2). The present glacier margin lies parallel to Jökulgrindur at a distance of 1.2 to 1.5 km to the southeast of this bedrock ridge. The area extends from northeast to southwest over about 3.5 km and comprises two distinct structural morphological levels. The higher level ranges between 300 to 950 m across at an altitude of 860 to 900 m a.s.l. The lower morphological level is between 250 and 800 m wide, at an altitude of 800 to 840 m a.s.l. and extends to the foot of Jökulgrindur.

The higher morphological level consists mainly of bedrock covered with subglacial traction till and mass flow deposits of variable thickness (0.5–1.5 m) in the form of a very poorly sorted sand–gravel–boulder diamicton. Its morphology is currently characterised by dry (abandoned), proglacial meltwater channels and flutings. In the northern part of this higher morphological level there is a complex of ice-marginal and proglacial lakes which are fed by glacial meltwater and drained by a river flowing towards the southwest along the glacier's snout (Figure 2A). Water levels in these lakes are at different altitudes ranging from approximately 850 to 895 m a.s.l.

The lower morphological level is dominated by a series of variably developed outwash levels (Figure 2B). The surfaces of the outwash levels descend to an altitude of about 845 m a.s.l. in the north, down to about 820 m a.s.l. in the southern part. The lowest parts of the lower morphological level are represented by the bottom of the former ice-dammed lake. A remnant of this lake is preserved by a small, isolated (no outflow) groundwater-supplied lake which possesses a small coastal bench cut into its southern side. The average water level of the lake is approximately 840 m a.s.l. (Figure 2A).

A diverse set of dead and stagnating ice forms are present in the central part of the northern study area, at the contact with the higher morphological level, along with several preserved delta fans (Figure 2), whereas end moraines characterise its southern part, on the glacier-facing slope of the Jökulgrindur. To the northwest, at the lower morphological level, an elongated end-moraine rampart is undercut by erosion.

Ice-dammed lake shorelines and glacilacustrine deposits

One characteristic feature of the slopes of the upper morphological level, deltas and glacier-facing slope of Jökulgrindur is the traces of ancient shorelines of the ice-dammed lake (Figure 3A). The former shorelines are marked by small wave-cut platforms of up to 2 m wide which gently slope in the direction of the lake. The highest shoreline is situated 37 m above the bottom of the lower morphological level, i.e. up to 877 m a.s.l. Differences in the spacing between the palaeoshorelines (0.5 to 1.5 m) are interpreted as recording the variation in the rate of lowering of the former ice-dammed lake.

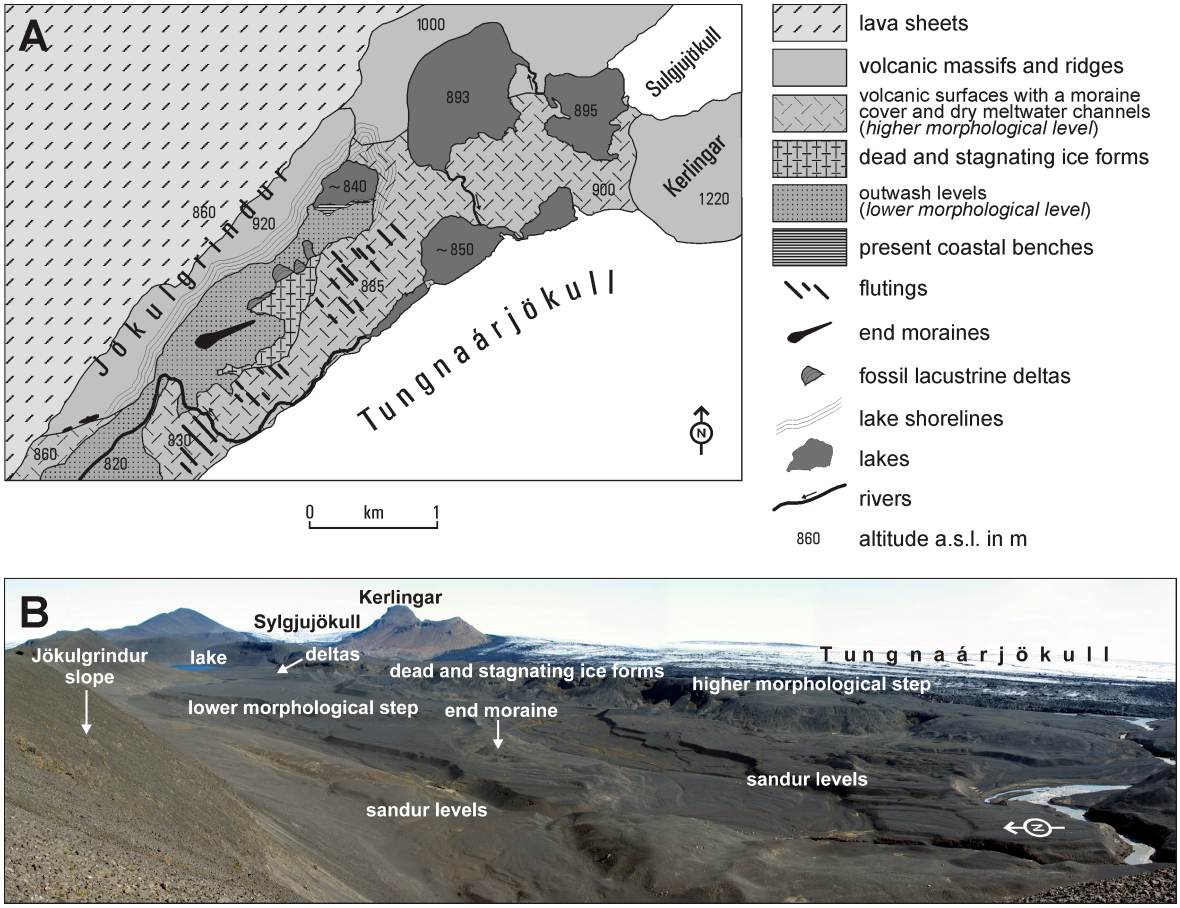

Figure 2. The northern study area. A: Geomorphological sketch; B: Panoramic view. – *Jarðfræðikort og yfirlitsmynd af nyrðra rannsóknasvæðinu, vestan Kerlinga.*

The sedimentary sequence deposited within the ice-dammed lake was examined in a 2.5 m deep excavation dug into the flat upper surface of a bench marking a former palaeoshoreline approximately 3 m above the present lake level (Figure 3A). The base of the sedimentary sequence is marked by a layer of massive, matrix-poor, coarse gravel (Gm), showing the characteristics of a boulder pavement (Figure 3B). The gravel is overlain by a c. 0.95 m thick sequence of fine-grained, horizontally bedded silty sands (Sh, SFh), which contains a c. 10 cm think bed of silt (Fw) of wavy lamination. Between 0.9 and 1.55 m depth, the sequence is represented by gravel–sand–silt lithofacies (GSi, SGi, Si, SFi) characterised by a well-developed inclined stratification which dips at c. 30° towards 310° to 330° and is overlain by a c. 20 cm thick layer of horizontally stratified coarse gravel and sand (GSh) (Figure 3B) and an erosive base which can be clearly seen to truncate the inclined stratification within the underlying sediments. The gravels are overlain by a several-cm-thick layer of massive to horizontally laminated silt (Fh, Fm) which coarsens upwards. The upper 60 to 70 cm of the sequence is composed of interbedded sand and silt (Sl, Fl) which possess a low-angle (c. 10°) cross-stratification recording a palaeoflow direction towards 290°. The top of the sedimentary sequence is truncated by a marked erosional surface.

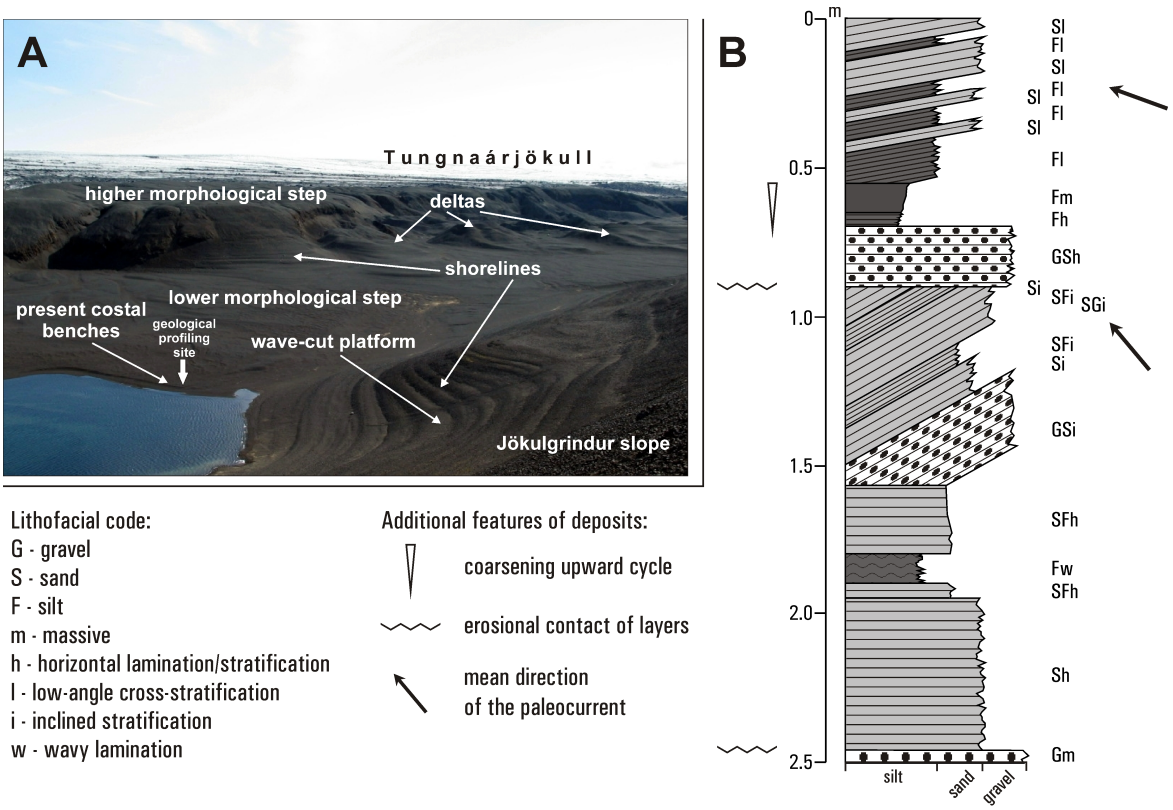

Figure 3. Structure of the ice-dammed lake's bottom. A: Morphology of the central part of the northern study area; B: Lithofacies profile. – *Yfirlitsmynd og setlagasnið af fyrrum jökulstífluðu lónstæði á nyrðra rannsóknarsvæðinu, við Jökulgrindur.*

The sand-dominated lower part of the sequence exposed in the excavation is interpreted as being waterlain and deposited in a high-energy (upper flow regime) environment. The overlying finer grained silts and silty sands are consistent with deposition having occurred in a low-energy environment possibly within standing or very slow moving water within the lake (glacilacustrine). In contrast, the overlying c. 0.5 m thick sequence of gravel, sand and silt represents the development of a relatively higher energy environment within the lake. The inclined surfaces (stratification) which characterise this part of the sequence are interpreted as foresets which record the northwesterly progradation of a small fan or apron into the lake. The top of this fan/apron was subsequently truncated by the erosive base of the overlying gravel. This coarse-grained lithofacies may record the establishing of high-energy, shallow water conditions within the lake. In contrast, the fine-grained sediments at the top of the sequence mark a return to a much lower energy environment, with deposition of these cross-stratified sands and silts possibly having occurred at the distal edge of a subaqueous fan/apron. Changes in grain size within the deposits of the fan/apron probably result from a deepening of the lake and a shift in the pattern of deposition. The cross-stratification records a palaeoflow direction towards the west-northwest (Figure 3B).

Erosion and truncation of the top of this sequence probably occurred during the development of the palaeoshoreline. Apart from the lower part of the sequence, these sediments probably record deposition close to the shore of a shallow proglacial lake.

Glacilacustrine deltas

A number of deltas have been identified within the lower morphologic level in the northern part of the forefield of Tungnaárjökull (cf. Andrzejewski *et al.*, 2005). They occur adjacent to the sloping edge of this higher morphological level on the north-western edge of a complex area of stagnating and dead ice landforms (kettle holes) (see Figures 2 and 3A). The delta examined during this present study is an approximately 80 m long, fan-shaped landform which at its culmination rises 12 m above the surface of the surrounding outwash plain (Figure 4). The delta slopes downwards in a north-westerly direction at an angle of about 15°. On its glacier side, the delta currently ends with a 30°, 17 m high slope. The steep slope of a fan facing the glacier is interpreted as being an ice-contact slope. This interpretation is supported by the presence of dead-ice landforms on the up-ice side of this proposed former ice marginal position. The gentle "down-ice" slope of the delta has been locally modified by the development of ten distinct palaeoshorelines which record the subsequent phased lowering and eventual disappearance of the lake. The upper 3.1 m of the sedimentary sequence is exposed in the central part of the delta (Figures 4 and 5).

The sedimentary sequence is dominated by sands, sands and gravels, and gravels (Si, SGi, GSi, Gi) with a well-developed inclined (c. 25°) stratification recording a palaeoflow direction toward 295° to 345° (Figure 5A). The lower part of the exposed sequence can be divided into two units composed of rhythmically bedded (average bed thickness c. 20 cm) sand and gravel. A prominent erosion surface located at a depth of c. 1 m separates the upper of these units from an overlying 10 cm thick layer of horizontally bedded/laminated sand and gravel (GSh) (Figure 5B). The gravel is overlain by an overall upward-coarsening sequence of sand and gravel (Figure 5A) characterised by a well-developed inclined stratification recording a palaeoflow direction towards the northwest.

The exposed sedimentary sequence is interpreted as recoding deposition on the steep underwater slope of a small delta as a result of the gravitational fall of sediment grains (foreset). The increase in gravel upward through the sequence, including the occurrence of rhythmically stratified sandy gravels (Si/Gi), is interpreted as recording the variability of the hydrodynamic conditions related to the ice ablation rate. Lithofacies comprising horizontally stratified gravels and sands (GSh) in the upper part of the sequence topsets (Zieliński, 2014) were deposited probably on the subaerially exposed upper surface of the delta/alluvial fan (Figure 5C). The overlying gravel–sand sediments which are characterised by a well-developed inclined stratification are interpreted as having been deposited on the delta slope, and as

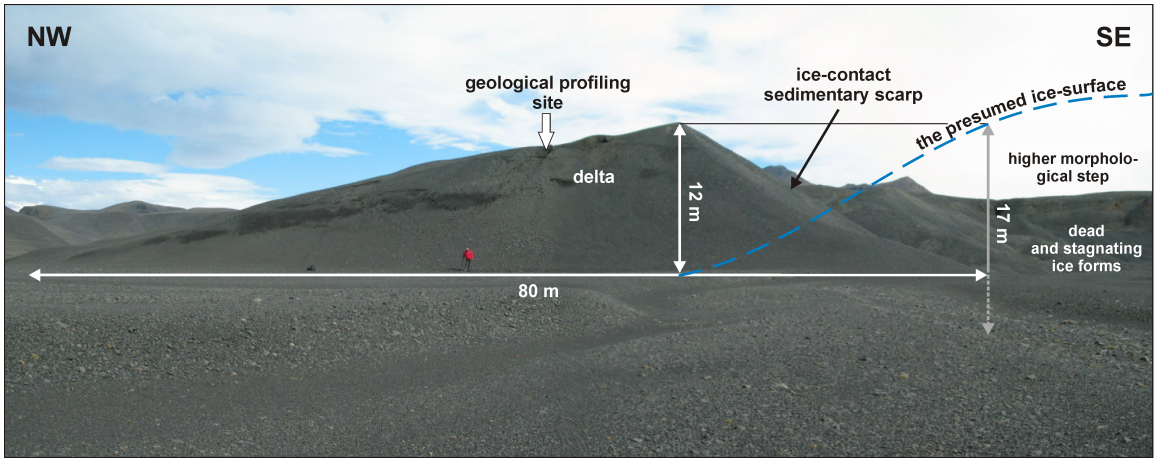

Figure 4. Longitudinal cross-section of the studied lake delta. – *Snið yfir aurkeilu við lónstæðið á 3. og 5. mynd.*

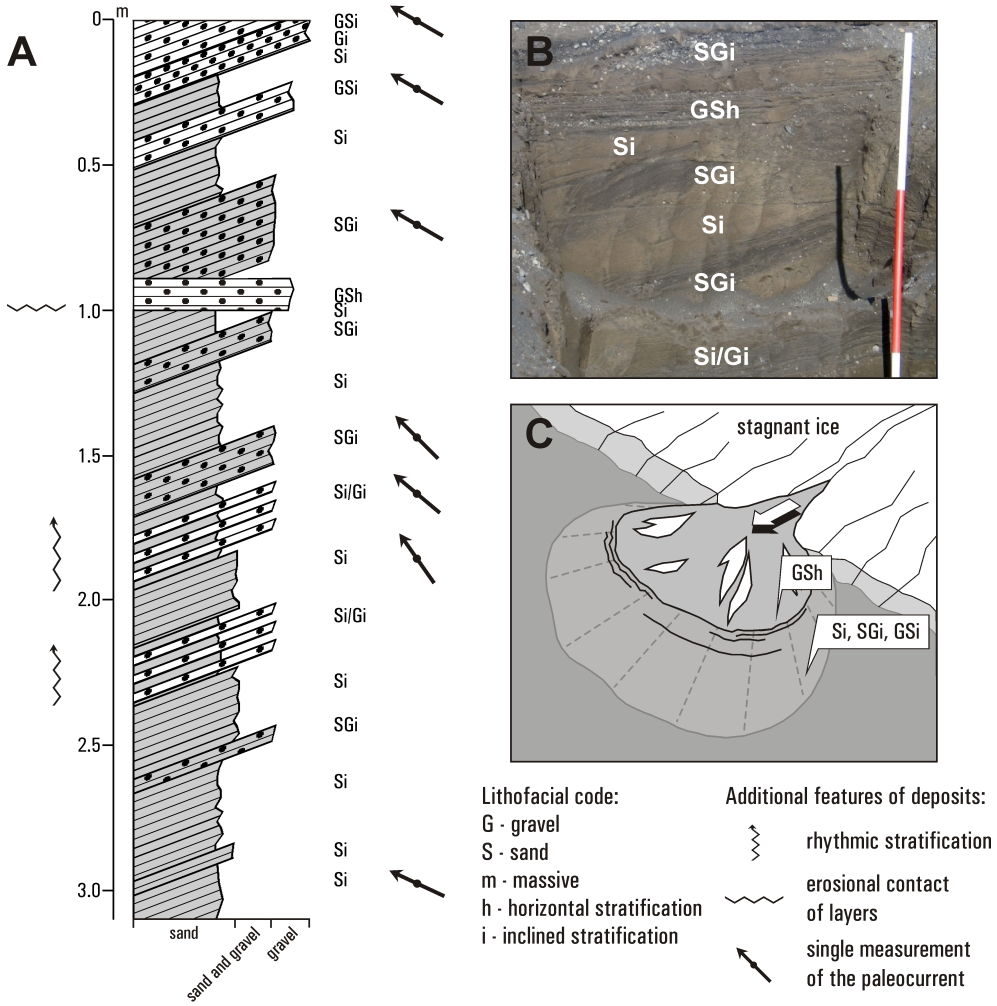

Figure 5. Geological structure of the upper part of the studied delta slope, modified from Andrzejewski *et al.*, (2005). A: Lithofacial profile. B: Delta deposits from about 0.8 to 1.8 m; C: Model of the fan delta. – *Þversnið (A) og ljósmynd (B) af setlögunum í aurkeilunni í lónstæðinu, ásamt líkani (C) af myndun hennar.*

recording a marked shift or change in depositional environments, possibly associated with a deepening of the lake. They may have resulted from periodic damming of the water's outflow from the lake caused by the advance of the glacier in the south-western part of the study area (Figure 10B). In this area the glacier adjoined the Jökulgrindur ridge. The top of these deposits was eroded during a subsequent stage of lowering of the water level within the lake.

The proximal part of the delta deposits were deposited on stagnating glacier ice. After the draining of the ice-dammed lake and degradation of the glacier snout, a steep ice-contact sedimentary scarp was formed.

The delta is classified as a steep slope delta, also known as a Gilbert-type delta. Such deltas develop in the edge zones of lakes of considerable depth and steeply sloping bottom, typical of, among oth-

ers, ice-marginal lakes. The deltas in the forefield of Tungnaárjökull clearly record the development of an ice-marginal glacilacustrine environment with a large supply of material in conditions of hyperpycnal flow (Boggs, 1995), corresponding to a situation in which the density of the water in the lake is lower than that of glacial meltwaters. Such conditions are conducive to the formation of fan deltas (Hjulström, 1952; Holmes, 1965), which develop where an alluvial fan enters a water body (Nemec and Steel, 1988). The fossil sediment record of such a fan is probably represented by the gravel and sand facies of horizontal stratification observed in the profile (Figure 5A).

THE SOUTHERN STUDY AREA

The southern study area, located approximately four kilometres southwest of the northern area (Figures 1B and 6) and c. 900 m SE of the present glacier margin, is characterized by a complex of diverse landforms and ice-contact sediments, mainly in the form of ice-cored moraines (Figure 7A, B, C).

The focus of study in this area was an irregular fragment (200 m long, 130 m wide) of a kame terrace, whose surface lies at an elevation of approximately 775 m a.s.l., adjacent to the Jökulgrindur bedrock ridge, which reaches approximately 800 m a.s.l. (Figure 6). The terrace's relative height is approximately 12 m. A pronounced shoreline of an ice-dammed lake lies approximately 15 m above the kame terrace, at an altitude of 790 m a.s.l. along the glacier-facing slope of Jökulgrindur (Figure 7D). A small hill of 50 by 100 m, about 100 m south of the terrace, is interpreted as being cut off from the kame terrace, by glacifluvial erosion (Figure 7C). The slopes of the kame terraces are undergoing intense denudation. Lithofacial analysis were conducted on the northern slope of both terraces (profiles A and B, Figure 6).

Kame terrace deposits

Sediments exposed within the two kame terrace profiles (A and B on Figures 6 and 7) were divided into 6 discrete lithofacies, namely A1, A2 and A3 in profile A (Figure 8A) (Molewski *et al.*, 2005) and B1, B2, B3 in profile B (Figure 8B).

The silty sands of unit A1 (Figure 8A) are 5.6 m thick and lie directly on buried "dead" glacial ice (Figure 9A). This silty lithofacies is characterised by a horizontal or wavy lamination developed on a range of scales and differing extent. They include secondary

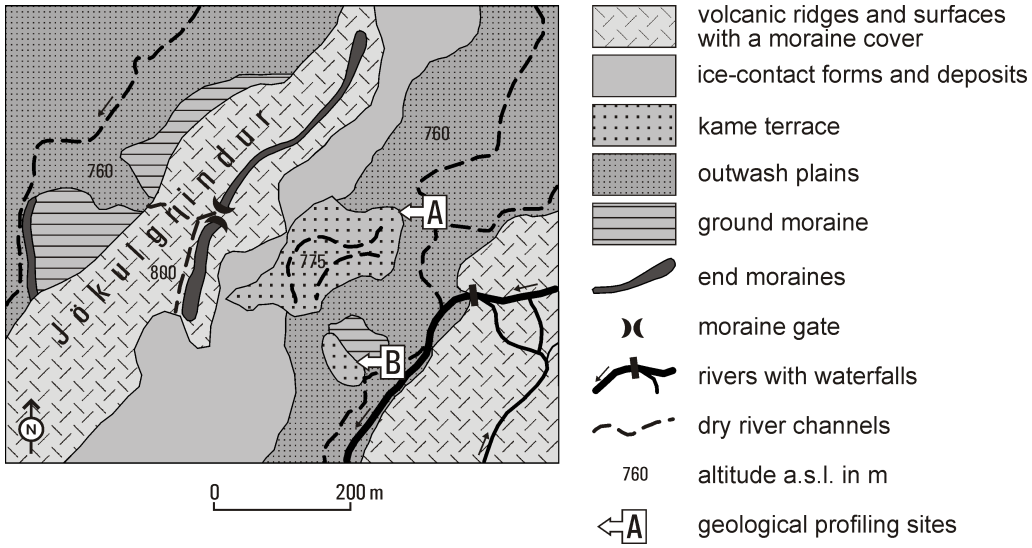

Figure 6. Geomorphological sketch of the southern study area (Molewski *et al.*, 2005, modified). – *Landmótunarkort af syðra rannsóknarsvæðinu. Snið í sethjalla eru merkt A og B.*

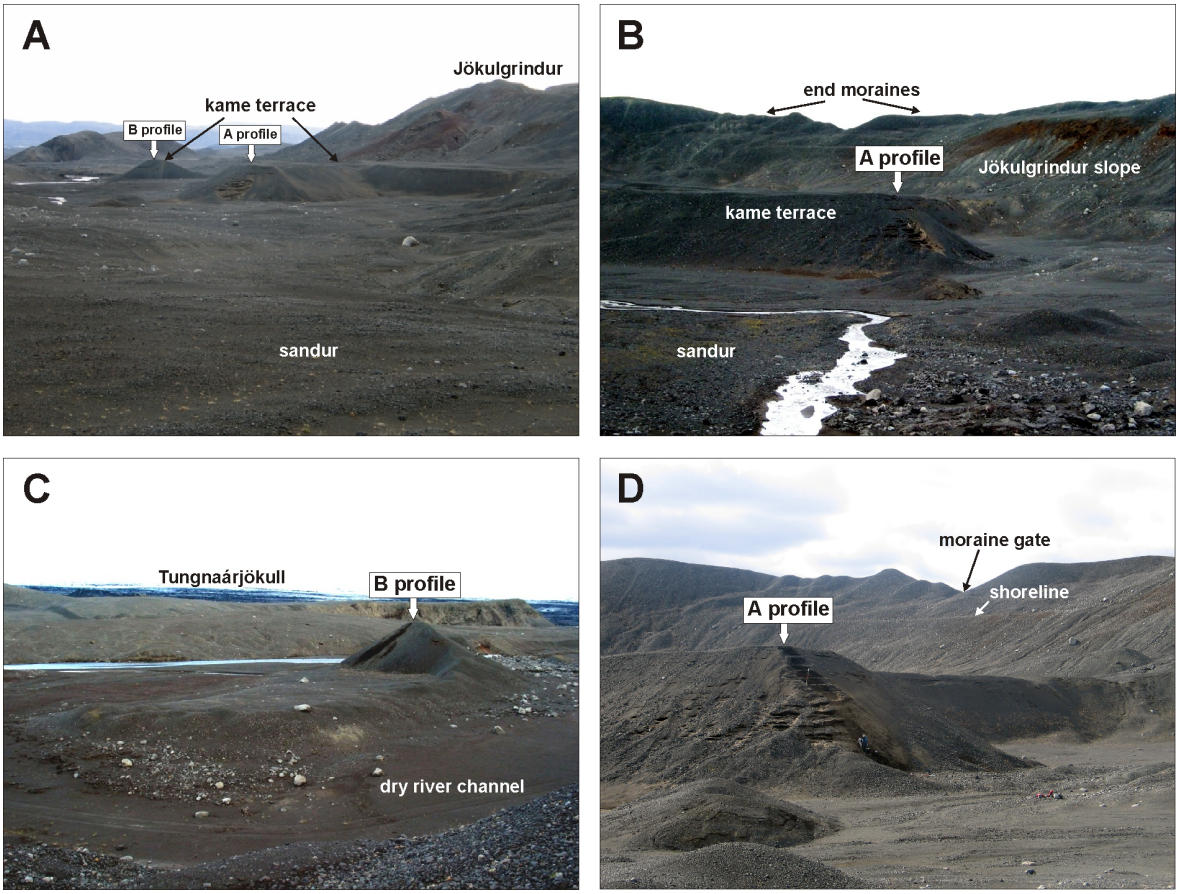

Figure 7. Morphology of the southern study area (profiles A and B, see Figure 8). – *Setlög og landform á syðra rannsóknarsvæðinu, við sethjallasnið A og B.*

lithofacies of ripple cross-lamination and climbing ripple cross-lamination which record a south-west to south-southwest palaeoflow direction. Macroscopically, part of the silty-sandy lithofacies are rhythmically laminated (horizontal and wavy lamination) comprising alternating silty and silty-sandy laminae of thickness 1 to 30 mm. In this unit, the cyclical nature of sedimentation was also observed. Each of the cycles is of varied coarseness, and can be subdivided into mainly silty (Fh, Fw) and silty-sandy (FSh, FSr, FSrc,) or less commonly sandy-silty (SFm, SFh) sections. Individual cycles have varying thickness, ranging from 25 to 90 cm. Their silt parts are usually more thick. These cycles are confirmed by the Markov chain analysis of the probability of occurrence of lithofacies. In unit A1 the greatest probability of transition (6.08, 4.40, 4.24) is between silty lithofacies and silty-sandy or sandy-silty. An alternating fine–coarsening upward sequence is observed in the silty deposits of the upper part of unit A1 (the last three cycles) whereas the bottom of the unit contains silty and silty-sandy sediments with wavy lamination, including a cobble 15-cm in diameter.

The characteristics of unit A1 indicate sediment deposition in standing water (Fh, Fw, FSh, FSw) with episodes of lower flow regime conditions (FSrc, FSr). The deposition velocities of the currents, estimated on the basis of the Koster formula (1978), range from

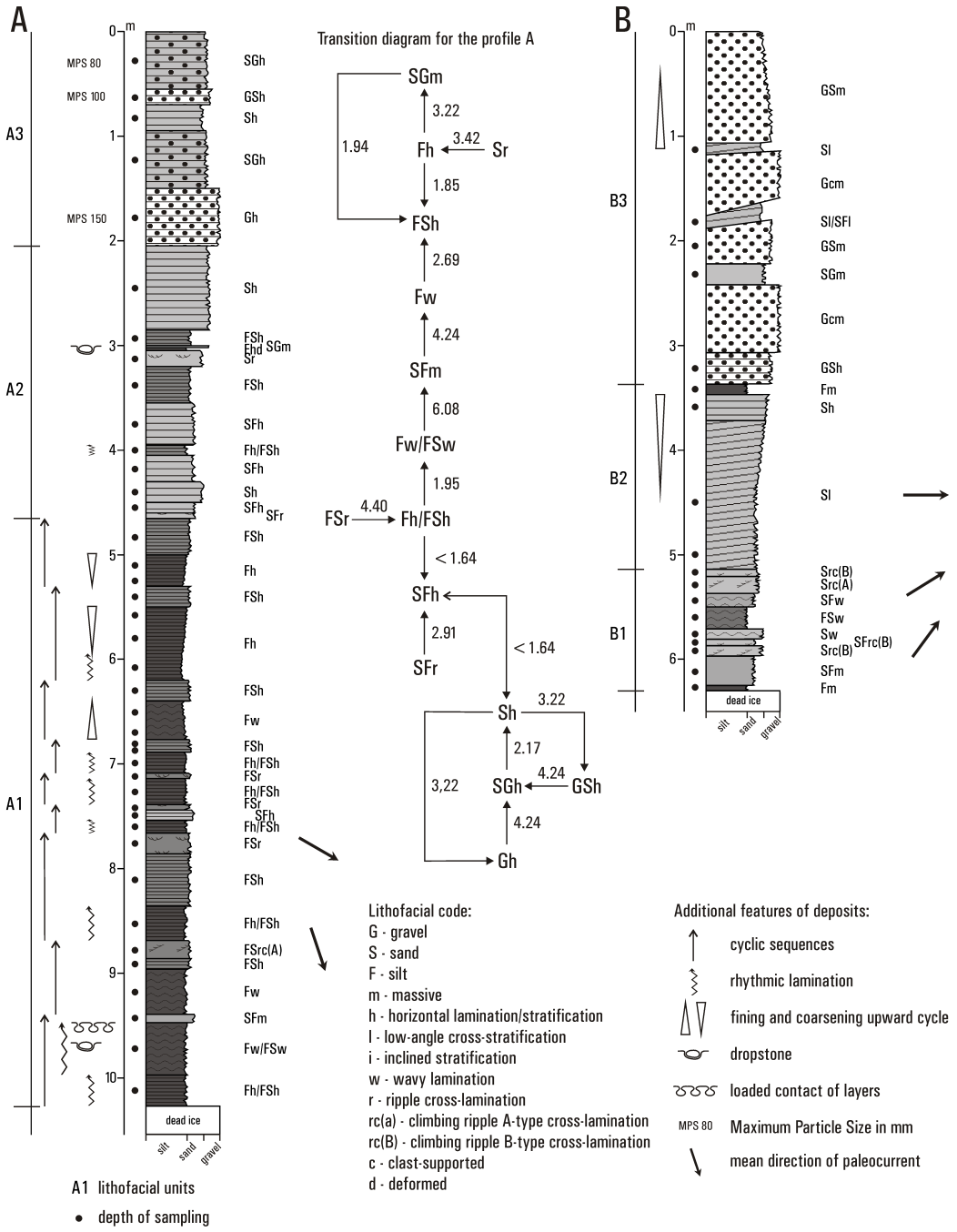

Figure 8. Geological structure of the kame terrace (Molewski *et al.*, 2005, modified). A: and B: Lithofacial profiles; probability analysis of facies transition based on the Markov method (e.g. Miall, 1973; Gradziński *et al.*, 1986). – *Setlagasnið í sethjalla A og B við Jökulgrindur.*

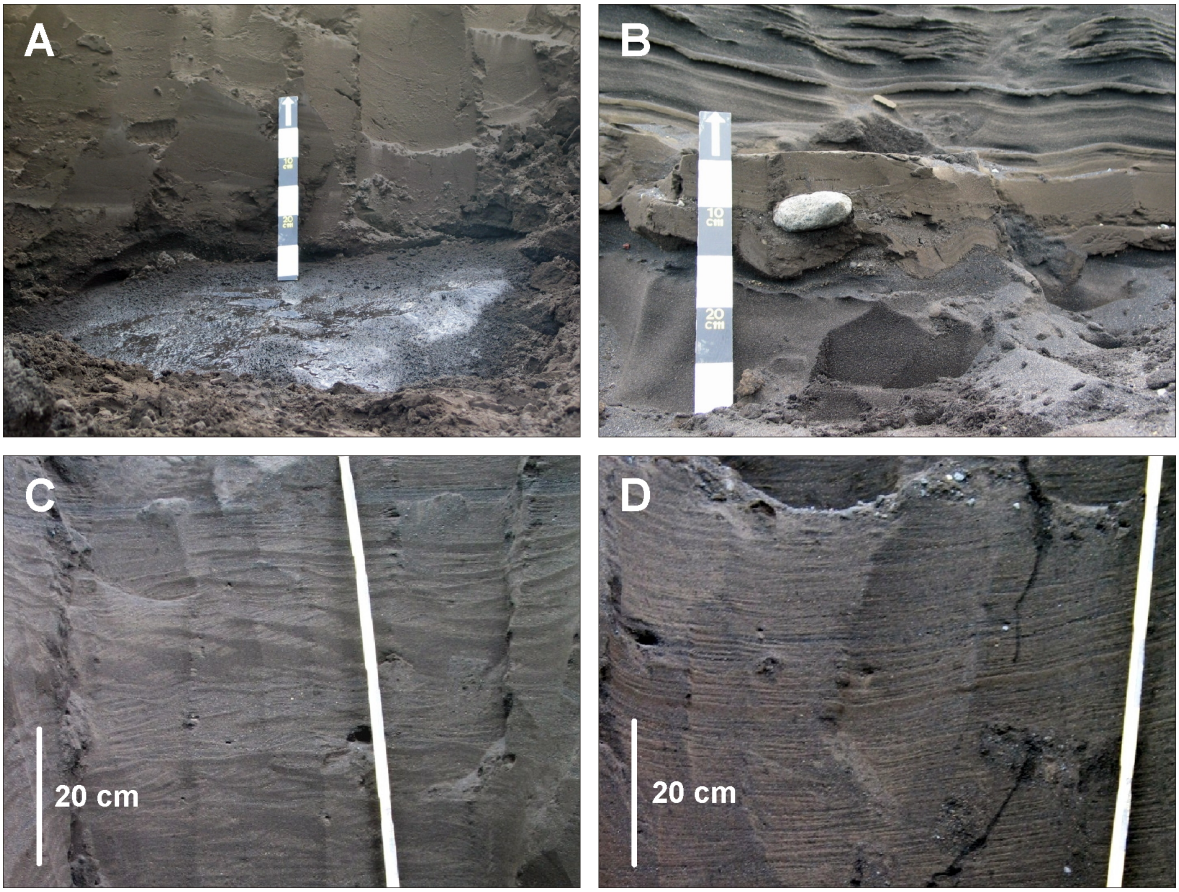

Figure 9. Deposits of the kame terrace. A: Dead glacial ice in the bottom of profile A. B: Cobble in silt deposits at a depth of about 3 m in profile A. C: Rippled, cross-laminated sands in profile B. D: Low-angle cross-stratification sands in profile B. – *Setlög í sethjöllunum á 7. og 8. mynd. A) Dauðís í botni sniðs A. B) Fallsteinn í siltlögum í sniði A. C) Gáróttur og skáhallandi sandur í sniði B. D) Vægt skáhallandi sandlög í sniði B.*

4.9 to 9.2 cm/s. The deposition of the unit's sediments was probably influenced by hyperpycnal flows (Boogs, 1995). The cyclic sets of varying scales which were recognised in the sediment are evidence of short- and long-term changes in the material supply and sedimentation conditions in the water body, associated with the ice ablation rate. The silty deposits were accumulated in a period of little ablation in low temperatures and a lack of rainfall. The silty-sandy deposits were accumulated in a period of increased ablation and relatively high temperature and rainfall conditions. The changeability of ablation rate followed a daily, annual or seasonal cycle. The low lithofacial variation of the analysed sediment proves stable deposition conditions. The silt fraction advantage indicates the dominance of accumulation from suspension. The presence of single cobbles of diameters ranging from 10 to 15 cm in the sediments may be interpreted as the result of iceberg melting (dropstones), is shown by the deformed lamination below the cobble and draped lamination on top of the clast.

Lithofacies A2 is 2.6 m thick and comprises a homogeneous sequence of horizontally stratified sand, sandy-silt and silty-sand (Sh, SFh, FSh) (Figure 8A).

At a depth of approximately 3.2 m from the top of the profile, lithofacies A2 contains a layer of ripple cross-laminated medium- and fine-grained sand. Immediately overlying the sand is a several-cm-thick layer of horizontally laminated silt which contains a large (7-cm diameter) cobble which distorts the lamination (Figure 9B). Overlying the silts is a 2 cm thick layer of massive sand and fine gravel (SGm).

Sediments of unit A2 are interpreted as having been deposited in standing or low-flow water conditions. Their character, however, indicates a higher energy sedimentary environment than the underlying A1 lithofacies. The estimated deposition velocities of the currents responsible for the deposition of lithofacies A2 sediments range from 7.6 to 12.8 cm/s (Koster, 1978). An increase in the grain diameter of the sand fraction in the top of the unit indicates an increase in flow energy. The domination of sand, as well as the presence of ripple cross-lamination, indicates transportation of the material in bottom and fractional suspension. The layer of ripple cross-laminated medium- and fine-grained sand (Sr) is interpreted as episodes of lower flow regime conditions. The layer of silt (Fhd), which contains a cobble of approximately 7 cm diameter, interpreted as a dropstone (Figure 9B), was deposited in an environment of standing water. A thin layer of SGm lithofacies proves the episodic growth of current energy with the participation of traction.

Unit A3 is 2.05 m thick (Figure 8A) and comprises horizontally stratified gravel, sandy-gravel, and sand (Gh, SGh, Sh). The base of the unit, between 2.0 to 1.5 m depth, is marked by 0.5 m thick gravel, which is in turn overlain by a sand dominated sequence (fine to coarse sand) containing occasional sandy-gravel beds. The MPS in the gravel and sandy-gravel layers ranges from 80 to 150 mm.

Unit A3 was accumulated under the conditions of an upper flow regime and high-energy current. Under these conditions, sand and gravel grains are thought to have been transported in traction and bottom suspension (saltation). The average water flow (deposition velocities) rate, estimated on the basis of average grain diameter, is from 30 to 40 cm/s (Koster, 1978). To determine the energy of the depositional environment, the flow competence indicator (MPS) was also used. This was calculated on the basis of the ninety-fifth percentile (D_{95}) and field measurements of the average axis (b) of the ten largest grains from the monogenetic facies Gh, GSh and SGh. The current velocity values calculated from D_{95} range from 0.7 to 0.8 m/s, while those based on field measurements range from 1.1 to 1.4 m/s.

The lowest unit of profile B, (B1) has a thickness of 1.2 m on top of dead glacial ice (Figure 8B). Unit B1 consists of sandy-silty lithofacies of massive structure and wavy laminating or climbing ripples (Figure 9C). The sediments of unit B1 were deposited in an environment of standing water (Fm, SFm, FSw, SFw, Sw) or under low-energy flow conditions (Src, SFrc).

Unit B2 has a thickness of 1.75 m and consists mainly of fine-medium-coarse grained sand. The lower 1.4 m of the unit has a well-developed low-angle cross stratification (layers dip 10°, with dip direction of approximately 100°) which records a palaeoflow direction towards the east (Figure 9D). The upper part of lithofacies B2 comprises a 25 cm thick layer of horizontally bedded sand (Sh) capped by a 10 cm thick bed of massive silt (Fm). The upper part of unit B2 defines a coarsening upward cycle.

The thick series of sediment with low-angle cross stratification (Sl) and horizontal stratification (Sh) at the top, is interpreted as being deposits of an alluvial fan. The massive silt which caps Unit B2 can be interpreted as having been deposited in an environment of standing water in the channel.

Unit B3 (3.35 m thick), consists mainly of gravelly sand inclined layers of deposits with boulders of massive structure and clast-supported (Gcm, GSm SGm), secondary horizontal or low-angle cross stratification (GSh, Sl, SFl). At the top of this unit's sediments there is a fining upward cycle. The maximum diameter of the grains in the gravel–boulder layers range from 100 to 140 mm.

The gravel-rich GSh lithofacies was accumulated under upper flow regime and high-energy current conditions. The mainly inclined layers of the sediment of unit B3 (Figure 8B) were probably the result of a debris flow (e.g. Zieliński, 2014), attested by the massive structure of the deposits, formed as several thick series of boulder–gravel–sand diamicton, and the low

roundness of the gravel and boulders. The sandy deposits separating them (Sl, SFl) may be interpreted as the effect of sheetflows separating the subsequent episodes of debris flow (Nemec *et al.*, 1980; Zieliński and Van Loon, 1996). This flow occurred at the snout of the melting glacier, probably after the ice-dammed lake had drained away.

The sediments building the kame terrace represent two different sedimentary environments, i.e. glacilacustrine (units A1, A2 and B1) and glacifluvial (units A3 and B2, B3). The sediments in profile A represent a deeper part of the water body, while sediments in profile B represent its shore zone. These probably indicate differences in the height of the occurrence of the dead ice layer in the analysed profile. Both studied profiles have a similar altitude. The top of the dead ice in profile B, located further away from Jökulgrindur, is approximately 4 metres higher than in profile A. After a slow draining of the lake, meltwaters probably flowed along the glacier snout, between the snout and Jökulgrindur. This is attested by a dry channel running in a south-westerly direction on the surface of the kame terrace.

RECONSTRUCTION OF GLACIAL EVENTS

The geomorphological and sedimentological research clearly supports the existence of ice-dammed lakes of various sizes in the northern part of the marginal zone of the Tungnaárjökull, formed by the damming of the outflow of meltwaters during successive glacier advances. Combining this study with published, archival cartographic material and aerial photographs (Freysteinsson, 1972; Thorarinsson and Sigvaldason, 1972) we were able to reconstruct a probable sequence of glacial events in the northern part of the marginal zone of Tungnaárjökull since the end of the LIA.

As evident from previous studies (e.g. Eythorsson, 1963; Thorarinsson, 1964) and research by the authors (Andrzejewski and Molewski, 2000; Andrzejewski, 2002), Tungnaárjökull reached its maximum extent in the late nineteenth century, i.e. 1880–1890 (Freysteinsson, 1968) (Figure 10A). This maximum limit is clearly constrained by a series of arcuate end-moraine in the central part of Tungnaárjökull's marginal zone (e.g. Andrzejewski, 2002). In the northern part of its forefield, end moraines are located in different parts of the Jökulgrindur ridge and its vicinity. In the research areas the end moraines are situated on the glacier-facing slope of the ridge, in its culmination or on its western side (Figures 2A and 6). In the southern part of the northern study area the snout of the glacier blocked the meltwater flow in a south-westerly direction between Jökulgrindur and the glacier resulting in the development of a large ice-dammed lake (Figure 10A). The length of time during which this lake existed is, however, unknown. It is known that the water must have drained prior to 1939 because the topographic map from that period (see Freysteinsson, 1972, p. 83) shows a lake whose size is similar to that existing today (Figure 2A).

Tungnaárjökull advanced at least twice during the first half of the twentieth century, in the years 1915–1920 and in 1945 (Thorarinsson, 1964; Freysteinsson, 1968). Earlier studies have shown that these advances were probably surges (e.g. Andrzejewski and Molewski, 1999; Evans *et al.*, 2009). The 1945 advance was documented in the northern part of the glacier's marginal zone, based on aerial photographs (see Thorarinsson and Sigvaldason, 1972, p. 18). Their map indicates that the glacier blocked meltwater flow, resulting in the formation of an elongate, NE–SW-trending lake between the Jökulgrindur bedrock ridge and the margin of Tungnaárjökull (Figure 10B). It cannot, however, be concluded whether a similar situation occurred during the advance of 1915–1920, because of the lack of aerial photography. It is likely that the deltas/ice-contact fans developed during the 1945 advance and represent points at which meltwater flowing off the glacier entered the lake. Its gradual disappearance is indicated by clear traces of ancient shorelines, expressed in the form of a series of small wave-cut platforms (Figures 2A and 3A). Since traces of shorelines on the slope of Jökulgrindur lie approximately 15 m above the delta, it can be assumed that the level of the lake, probably associated with the LIA, was at least that high. The small end moraine ridges on the glacier-facing slope of Jökulgrindur are also probably associated with the LIA

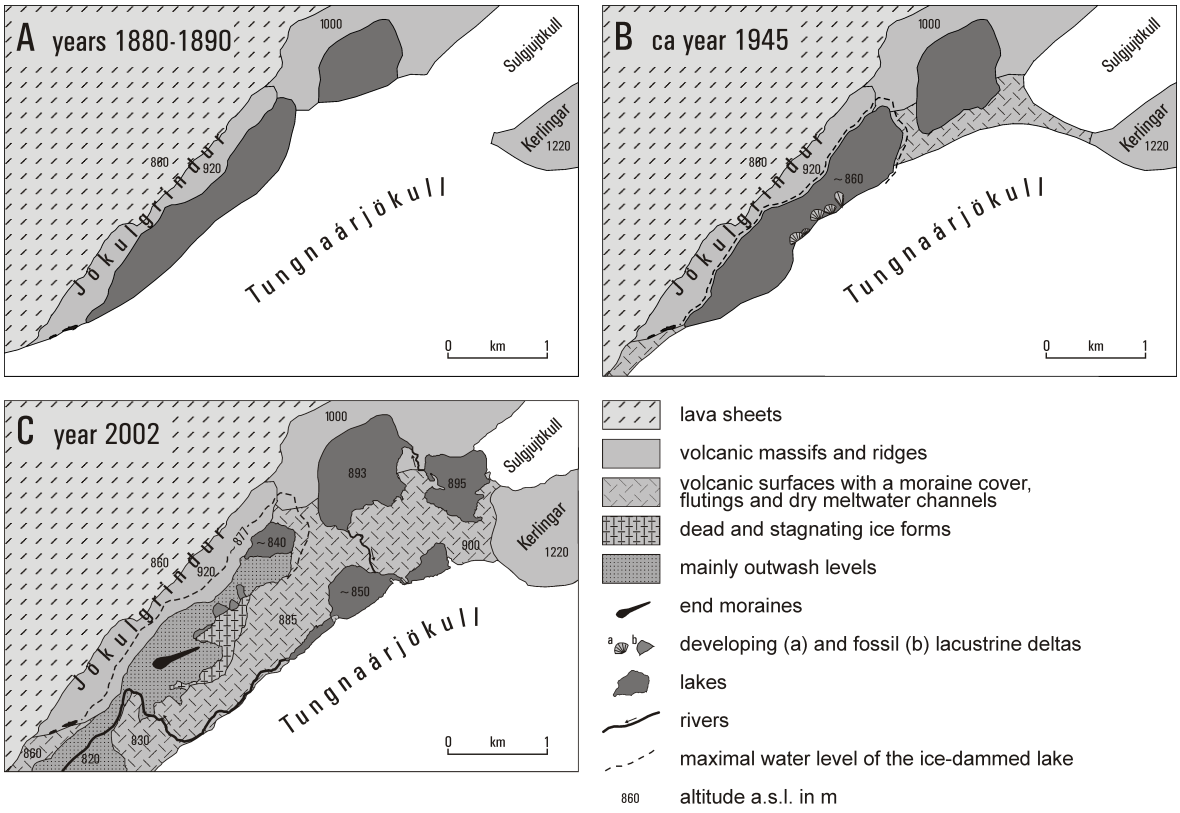

Figure 10. Reconstruction of range changes in Tungnaárjökull's snout and ice-dammed lake since the end of the Little Ice Age (Andrzejewski *et al.*, 2005, modified). A: Probable reach of the glacier and the proglacial lake at the end of the LIA. B: Reconstruction of the extent of the glacier and the ice-dammed lake in the phase of the delta development associated with the glacier's advance ca. 1945. C: The present-day state on the basis of aerial photographs of 2002. – *Endurgerð af stærð Tungnaárjökuls ásamt þróun jökullóna og landslags frá lokum litlu ísaldar til ársins 2002.*

(Figure 10A). Except for the fragment of eroded end moraine at approximately 840 m a.s.l. (Figure 10C) there are no glacial landforms in the bottom of the lake. The end moraine corresponds with the proximal parts of the deltas and indicates the reach of the glacier snout during the 1945 surge.

The basic changes in water level in the ice-dammed lake were probably associated with the damming and release of its drainage to the south-west (Figure 10B). These changes were less affected by the scale of glacial ablation.

Deposition of the kame terrace sediment most likely took place during the recession of the glacier after having crossed Jökulgrindur during the LIA. The crossing is attested by marginal landforms situated on the western side of the ridge (Figure 6). But we cannot rule out the development of the terrace during the later advances of the glacier (Evans *et al.*, 2009). There is no doubt, however, that in this area there was a partial obstruction of meltwater flow between the glacier and Jökulgrindur and the formation of a local through-flow ice-dammed lake (Figure 11A). Small ice-bergs

floated in the ice-dammed lake, as attested by dropstone structures in the glacilacustrine sediments. The lake was feed by meltwaters, which probably formed small fan deltas. After the lake disappeared, meltwaters formed small alluvial fans on the terrace surface (Figure 11B). These waters flowed out between the glacier and Jökulgrindur in a south-westerly direction. A debris flow formed on the melting glacier snout. After degradation of the glacier snout the meltwater flow on the terrace surface disappeared and a lower flow system formed (Figure 11C). Since the kame terrace was partially destroyed (Figure 11D) by the subsequent glacifluvial flow, the size of the lake cannot be inferred from its present size.

The spatial relationships of the studied forms and the range of the moraine deposits in the study area suggest that the original width of the lake and terrace was about 250 m. The trace of the lake shoreline preserved on Jökulgrindur's slopes indicates that its depth was at least a dozen metres.

CONCLUSIONS

The geomorphological and sedimentological studies, as well as the analysis of cartographic and remote sensing materials, have resulted in a reconstruction of the main stages of the formation of relief and depositional environments in the northern part of Tungnaárjökull's marginal zone between the end of the LIA and modern times. It has been shown that the volcanic substrate of the glacier forefield had a major impact on the landforms and sediments in this part of the marginal zone. Its main element is a system of parallel Upper Pleistocene volcanic ridges oriented northeast-southwest. The ridge of Jökulgrindur runs parallel to the northern part of Tungnaárjökull's snout, which blocked the outflow of glacier meltwaters during its subsequent advances.

The damming of meltwater outflow caused the occurrence of ice-dammed lakes in the northern part of the marginal zone of Tungnaárjökull. The preserved lake shorelines and small wave-cut platform, fossil delta and kame terrace are evidence of their existence.

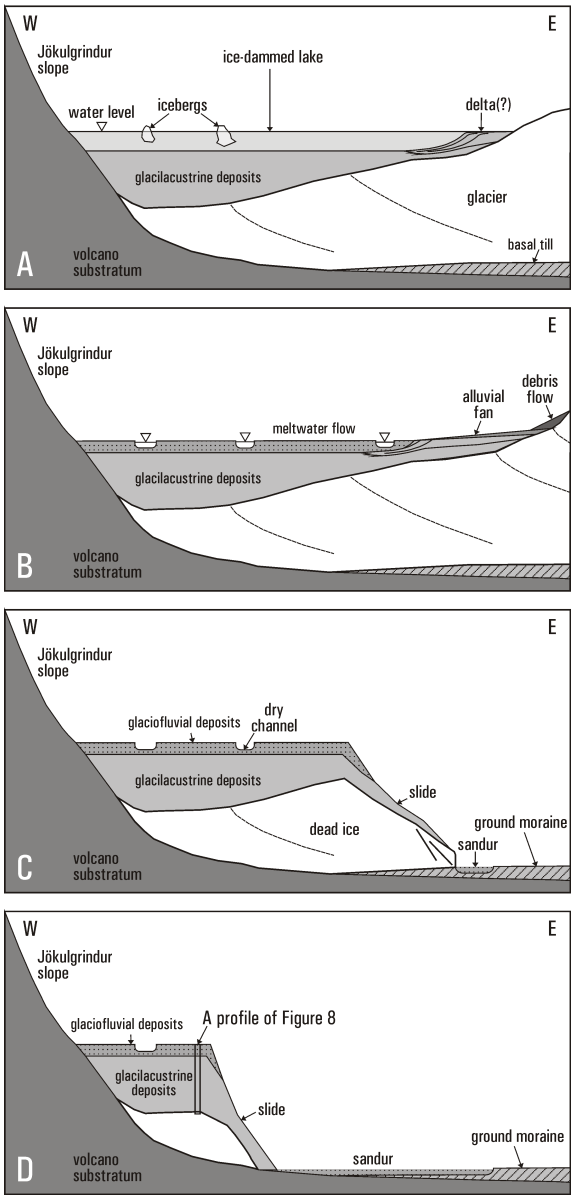

Figure 11. Model of the kame terrace, modified from Molewski *et al.* (2005). A: Ice-dammed lake phase; B: Meltwater flow phase; C: Erosion of the kame terrace and degradation of dead glacial ice; D: Preserved kame terrace. – *Líkan af þróun jökullónsins við norðvesturjaðar Tungnaárjökuls.*

The lake shorelines and wave-cut platform document the varied rates at which the water levels dropped, until the complete disappearance of the lakes. The disappearance of the ice-dammed lake in the northernmost part of the glacier forefield (the northern study area) is documented by the fine-grained nature of the deposits, which probably represent its shore zone. Sedimentological studies of one of the deltas which formed within an ice-dammed lake, in contact with the stagnating glacier snout, showed that it developed as a result of the deposition of sediments in an ice-dammed lake in conditions of hyperpycnal supply.

Sedimentological studies of the preserved fragments of the kame terrace in the southern study area show that it was formed in variable depositional conditions, initially in an ice-dammed lake, and subsequently in conditions of meltwater flow in a southwesterly direction.

The earliest stage of the formation of relief and depositional environments in the northern part of Tungnaárjökull was associated with the maximum extent of the glacier snout at the end of the nineteenth century. Its record includes glacial forms and sediments on the ridge and western side of Jökulgrindur. The ice-dammed lake which developed due to the blocking of the meltwater outflow probably drained before 1939.

The next development of this zone was associated with the surge of 1945, when an ice-dammed lake formed. An ice-dammed lake may also have appeared during a surge in the years 1915–1920. In the opinion of the authors, the preserved glacilacustrine forms and deposits are associated with the surge of the glacier in 1945, at which time the glacier in part reached Jökulgrindur. These forms and deposits are dated similarly by Evans *et al.* (2009).

The last stage in the development of Tungnaárjökull's forefield is connected with its recession following the 1945 and 1994–1995 surges and a small advance in the northern part of the marginal zone which caused a slight redistribution of the proglacial drainage at the immediate forefield of the glacier and the creation of small, episodic lakes.

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ÁGRIP

Birtar eru niðurstöður kortlagningar setlaga og landforma við norðurjaðar Tungnaárjökuls sem mynduðust í og við jökullón frá lokum litlu ísaldar. Þetta er fyrsta rannsókn af þessu tagi við jaðar Tungnaárjökuls. Landmótunarumhverfi voru túlkuð á grunni setlagagreininga. Strandlínur, lítil brimþrep, gamlar árkeilur og sethjallar tengjast gömlum jökullónum. Jökullónin mynduðust við norðvesturjaðar Tungnaárjökuls er hann stíflaði útfallið við Jökulgrindur. Gömul kort og loftmyndir benda til að myndun lónanna megi rekja til framhlaups jökulsins 1945.

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