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Surging glacier landsystem of Tungnaárjökull, Iceland

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Abstract

A 1:30,000 scale map of the snout and proglacial landscape of the surging Icelandic glacier Tungnaárjökull, based upon aerial photography from 1995, immediately after a surge, allows an assessment of the spatial variability in landform-sediment imprints of catastrophic glacier advance across upland bedrock ridges. The ice-margin parallel alignment of the bedrock ridges locally strongly directs proglacial meltwater drainage and initiates strong compression in the ice during surging, resulting in the development of prominent ice-cored hummocky moraine composed of glacifluvial sediment. Diagnostic surge landforms elsewhere on the foreland include thrust block and push moraines, overridden ice-cored thrust block moraines, crevasse squeeze ridges, long flutings, hummocky moraine and ice-cored, pitted outwash.

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1. Introduction

Tungnaárjökull is a 17 km wide glacier lobe of the western margin of Vatnajökull, Iceland, located between latitudes $64°$ 15′ and $64°$ 24′ N. The detailed morphology of the glacier snout comprises minor lobations produced by the flow of ice over a series of parallel volcanic bedrock ridges that are aligned NE-SW. The continuation of the bedrock ridges beneath the ice is manifest by positive relief lineaments on the glacier surface. In the south the minor lobes of the glacier snout have been able to expand into the valleys between bedrock ridges because flow direction has been from the north-east. In contrast, the glacier margin to the north has repeatedly run up against the major bedrock ridge called Jökulgrindur, and therefore its advance has been restricted and has only over-topped the ridge through a small number of cols. The volcanic summit of Kerlingar causes the margin of Vatnajökull to bifurcate, separating, to the north, Tungnaárjökull from Sylgjujökull to the south. During historical advances the two glaciers have isolated Kerlingar to form a nunatak. Because Jökulgrindur disappears beneath the ice to the north of Kerlingar, the snout of Sylgjujökull was able to advance unrestricted onto the flatter lava fields of Innri-Tungnaárbotnar in a similar fashion to the southern minor lobes of Tungnaárjökull. The proglacial meltwater from both glaciers drains NE-SW along the margins of Jökulgrindur and eventually into the river Tungnaá, with the exception of the drainage from the southernmost lobes. During historical advances these lobes drained down the Langisfjor and Skaftá valleys but the present proglacial rivers feed entirely into the Skaftá valley due to the blockage of the Langisfjor valley by a large moraine and ice-contact fan assemblage. The influence of bedrock topography on the distribution of glacial landforms and sediments prompted Andrzejewski (2002) to sub-divide the glacier foreland into domains characterized by distinctive landform assemblages, the details of which are comparable with this map.

Like a number of glaciers in Iceland, Tungnaárjökull is subject to cyclic surging behaviour and any ice-marginal responses to historical climate change appear to have been overwhelmed by surges. Therefore, the landforms and sediments around its margin provide us with an ideal opportunity to assess process-form relationships in glacial geomorphology through the landsystems approach (Andrzejewski, 2002). More specifically we can test the utility of the surging glacier landsystem (Evans et al., 1999; Evans and Rea, 2003) as a modern analogue for palaeoglaciological reconstructions (Evans and Rea, 1999). The historical oscillations of Tungnaárjökull can be charted back to the late 1800's AD (Figure 1). Annual measurements since 1955 show that the glacier underwent continuous recession until a surge over a maximum distance of 1.2 km in 1994-1995 (Freysteinsson, 1968; Sigurdsson, 1994; Andrzejewski, 2002). The aerial photographs used for this map date from 1995 and show the glacier to be heavily crevassed with a steep snout, typical of a surge phase of activity. Historical records indicate that the glacier surged by 1 km in 1945 and by around 450 m sometime between 1915 and 1920 (Thorarinsson, 1964; Freysteinsson, 1968). Prior to this date it has been assumed that an historical maximum limit dating to around 1880-1890 is demarcated by the outermost of two major end moraines (Andrzejewski, 2002). However, this end moraine contains features that are diagnostic of surge activity and lies just inside an older till veneer that forms a delicate trimline crossing weathered bedrock. This older till demarcates the historical maximum limit of Tungnaárjökull and may record either an older, undocumented surge or the response of the glacier to the cold climate of the "Little Ice Age."

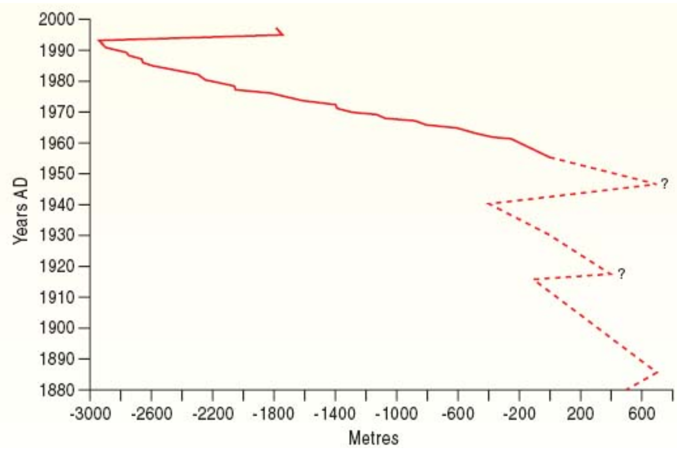


Figure 1. Time-distance diagram of changes of the snout of Tungnaárjökull in the historical period. Solid line represents continuous monitoring and broken line is based upon historical documentation of activity (after Andrzejewski (2002) and based on Thorarinsson (1964), Freysteinsson (1968) and Sigurdsson (1994)).

2. Mapping the snout and foreland of Tungnaárjökull

The base data for glacier surface features and proglacial topography for the 1:30,000 map were compiled on a coloured ink film overlay from aerial photographs dating from 1995 and supplied by Landmælingar Islands. The contours were extracted digitally from a digital terrain model (DTM), generated from orthophotographs, using an LH Systems Digital Photogrammetric workstation. The map overlay containing the base data was manually digitised on a large format CalComp tablet digitiser using MapData vector digitising software. The digitised vector files for the base data were converted from MapData format into ArcInfo "generate" format for importing into Adobe Illustrator, utilizing the Avenza MAPublisher plug-in software to produce a fully editable and structured map file. The contours were created digitally from the digital orthophograph as Adobe Illustrator "eps" files and geo-referenced utilizing Avenza MAPublisher in combination with ESRI ArcView as a means to automatically join and check the geo-referenced contour files. Final design and production was undertaken in Adobe Illustrator, mainly to take advantage of a proven route used in previous maps from an Illustrator file to a digital proof, platemaking and lithographic printing. The raster image used for the glacier surface was created by manipulating the individual monochrome orthophotograph (tif format) in Adobe Photoshop to create the colourised image and saving as a compressed file (jpg format). Interpretations of surface materials and landforms were made by a combined approach involving stereoscopic mapping directly from the aerial photographs and ground truthing during the summer of 2001.

3. Surficial geology and geomorphology

In addition to extensive bedrock exposures dominated by lava flows there are seven surficial geology map units around the margin of Tungnaárjökull. With the exception of blockfield and residuum, all of these surficial deposits are glacigenic or paraglacial in origin and record historical activity of a glacier that is prone to cyclic surging. Moraines are sub-divided according to their geomorphic, structural and sedimentological characteristics. In the case of ice-cored moraine it is presently impossible to differentiate between controlled moraine ridges and eskers that are emerging through a thinning supraglacial debris cover.

3.1 Blockfield and residuum

The in situ mechanical breakdown of the frost-susceptible bedrock in the map area results in the accumulation of blockfield and residuum on the lower angled slopes of bedrock ridges and extensive lava fields, and is particularly well developed beyond the historical limits of the glacier. The blockfield is typically composed of boulder-rich rubble, locally organized by periglacial processes into patterned ground. Residuum is generally a finer-grained weathering product. It may contain pockets of highly degraded or wind deflated till veneer deposited during more extensive glaciation that predates the historical period.

3.2 Till and moraine

The tills and moraines of the glacier foreland are predominantly coarse-grained diamictons with sandy to gravelly matrices. Although subglacial modification of clasts is manifest in striated and facetted examples, the tills and moraines are composed mostly of sub-rounded to rounded clasts typical of glacifluvial deposits. This reflects a short transport distance for much of the material comprising the moraines, making it likely that during surges the glacier reworks the material from the linear sandur and proglacial outwash fans that fringe the whole of its margin. Tills are typically thin, generally less than 2 m thick, even on push moraines through which rare exposures reveal till draped over folded and thrust sequences of stratified sediments (large thrust masses are classified separately as thrust block moraines). The “till and moraine” classification excludes those moraines that still contain an ice core but does include hummocky moraine produced by complete, or at least advanced, melt-out. Lateral moraines are rare, having developed only below the steep cliffs of bedrock ridges that run obliquely to the glacier snout.

Two major end moraine suites can be identified, each suite comprising several closely spaced and often bifurcating ridges (Figure 2). The outermost moraine suite is considered to date to 1880-1890 (Freysteinsson, 1968; Björnsson, 1979; Andrzejewski, 2002). The innermost suite dates to the 1945 surge (Thorarinsson, 1964), because it lies at the ice margin on 1946 aerial photographs depicting a heavily crevassed surging snout. These two former ice-marginal positions are best developed on the flat foreland named Fremri-Tungnaárbotnar where the snout of Tungnaárjökull flowed as an unrestricted lobe during both advances. The till surfaces that lie inside the two major moraines have been subglacially moulded into flutings. Although subtle in many places, individual flutings can be traced for up to 500 m. Some parts of the fluted terrain also contain crevasse-squeeze ridges (Figure 3) that document the intrusion of subglacial till upwards into extensional crevasses at surge temination. To the north of Fremri-Tungnaárbotnar, glacier advance has been restricted by the Jökulgrindur bedrock ridge and so the two moraine suites are juxtaposed and can be differentiated only by the fact that the more recent forms are largely ice-cored (Figures 4 and 5). In the extreme north of the map area, in the flat foreland area named Innri-Tungnaárbotnar, the dual moraine sequence is clearly developed again. In the south of the map area, the outermost moraine fronts a large ice-contact outwash fan that is heavily pitted by melt-out hollows and water-filled kettle holes. The inner moraine suite is represented by a large thrust block moraine, which fronts a wide arc of ice-cored hummocks. Beyond the dual moraines, the outer limit of the till is demarcated by a thin, discontinuous till cover that forms a trimline cutting across blockfield or residuum. This marks the, previously unrecognised, historical maximum extent of Tungnaárjökull and because this limit contains no glacial depositional landforms indicative of surging it could document the response by the glacier to the “Little Ice Age” cold climate phase immediately prior to the surge of 1880-1890 or an earlier advance.

3.3 Thrust block moraine

Glacitectonically thrust and folded masses of proglacial sediment or thrust block moraines occur at two locations along the glacier margin, having been constructed during the

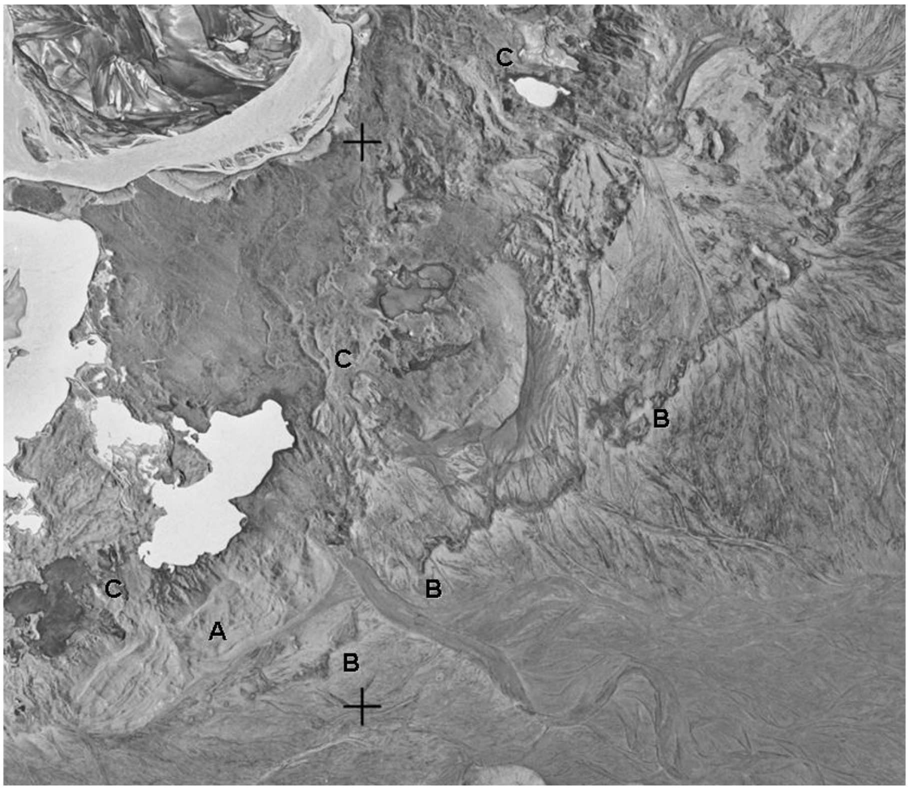


Figure 2. Orthophotograph extract of the complex suite of landforms associated with the dual moraine ridges deposited by the southern lobe of Tungnaárjökull. During the 1945 surge, an arc of thrust block moraines (A) was constructed in a collapsing sandur fan and now fronts a large expanse of ice-cored moraine. This suggests that the 1945 surge disturbed an older melting, outwash-covered ice mass dating to the 1880-1890 surge. The limit of this older surge is marked by the ice-contact face of a sandur fan that lies beyond the thrust moraine arc (B). Ice flow- parallel and sinuous controlled ridges behind the thrust block moraines mark the locations of eskers in the melting glacier ice (C). These eskers mark the locations of englacial drainage systems that, during the 1945 surge, fed sediment into the apices of sandur fans developing behind and between the incised remnants of the 1880-1890 ice-contact fans.

1995 surge. Most examples comprise folded and thrust sequences of outwash sands and gravels (Andrzejewski, 2002) but some exposures reveal that slabs of glacial ice are sandwiched between the sediments. A large thrust block moraine also occurs in the historical moraines to the south of the map area where it constitutes part of the inner moraine suite and fronts a wide arc of ice-cored hummocks. The occurrence of glacier ice slabs within some recent thrust block moraines at the ice margin suggests that some older low amplitude hummocky moraine could have originated as thrust blocks but was later modified by melt-out.

Figure 3. Aerial photograph extract showing crevasse-squeeze ridges and fluted till on Innri-Tungnaárbotnar.

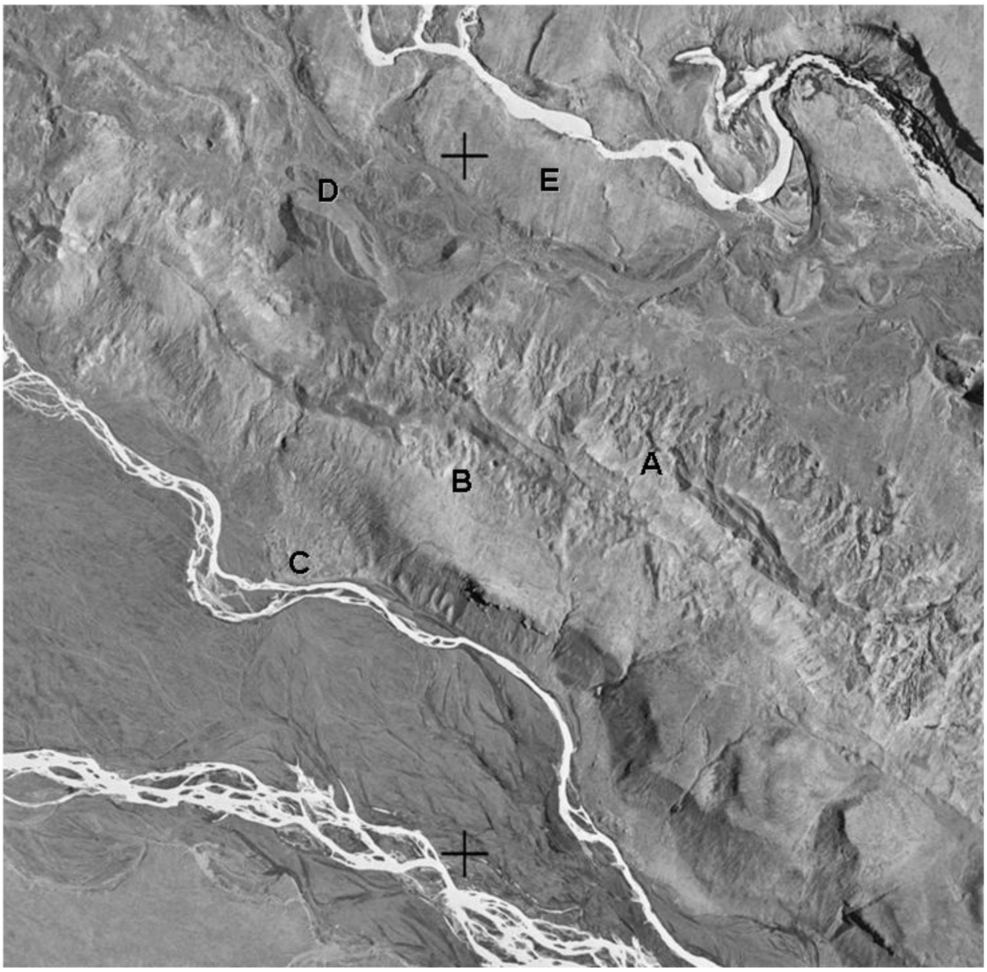


Figure 4. Orthophotograph extract of the dual moraines on the Jökulgrindur bedrock ridge. The controlled ridges of the 1945 ice-cored hummocky moraine are clearly defined on the east slopes of Jökulgrindur (A). The more subdued undulatory till cover of the 1880-1890 surge lies on the summit of the bedrock ridge and passes downslope into some poorly preserved controlled ridges (B). The earlier surge over-topped low cols on Jökulgrindur, depositing hummocky moraine that still retains an ice core, in the valley floor to the west (C). Also visible are kame terraces and lake shorelines, produced by water that was temporarily dammed between the receding glacier and Jökulgrindur (D), and flutings and eskers on the bedrock knolls between the present day linear sandur (E).

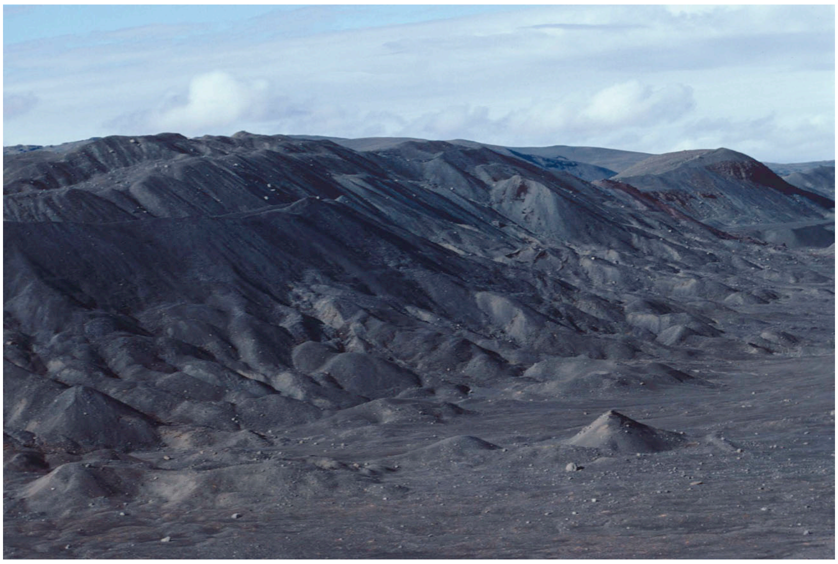
3.4 Ice-cored moraine

Large expanses of ice-cored hummocky moraine occur in linear strips along the former glacier margins (Figures 5 and 6). They are located either on bedrock slopes or at the former lobate margins of Tungnaárjökull where it flowed over sandur fans and produced thrust moraine arcs. Both depositional settings would have been areas where glacier ice was undergoing compressive flow, thereby transporting debris through englacial pathways and stacking debris-rich ice sequences at the ice margin. The ice deformation associated with these processes can be observed at the present day snout wherever ice has been forced to flow over large bedrock obstacles. Additionally, the glacier initiates proglacial thrusting of outwash sediment (see thrust block moraine) interbedded or thrust-stacked with buried glacier ice masses. Development of ice-cored moraine from thrust masses of outwash and glacier ice explains several examples that lie immediately distal to large, often water-filled, depressions on the sandur plain; each ice-cored moraine mass and associated depression represent hill-hole pairs. Exposures in the ice-cored moraine along the east slope of the Jökulgrindur ridge reveal thick slabs of glacier ice, the melting of which is creating extensive retrogressive flows, kettle hole production and tensional cracking/scarp initiation. The ice exposures reveal that up to 90%

(a)

(b)

Figure 5. Continued on next page.



(c)

Figure 5. Views of the 1945 surge moraine on the bedrock ridge Jökulgrindur. The moraine is ice-cored and therefore has developed into hummocky topography displaying controlled ridges due to differential melt-out: a) chaotic hummocky moraine draped on the summit of the bedrock ridge where ice melt-out is more advanced. The 1945 surge flowed from left to right and breached the low col in the middle distance, resulting in the deposition of ice-cored hummocky moraine in the valley floor to the right; b) the outer limit of the 1945 moraine viewed across the more subdued undulatory till cover that has developed through the melt-out of hummocky moraine deposited during the 1880-1890 advance/surge. The 1945 moraine here comprises thrust stacked slabs of glacier ice and outwash, explaining the linearity and numerous controlled ridges aligned transverse to former glacier flow; c) the ice-cored 1945 hummocky moraine, showing the strong transverse linearity produced by ice-marginal thrusting and debris band melt-out in addition to ice flow-parallel controlled, largely sinuous, ridges interpreted as eskers or ice-walled channel fills. Ice flow was away from viewer.

of the ice-cored moraine relief is a product of buried ice thickness and advanced stages of melt-out will produce a low amplitude hummocky moraine surface similar to that mapped elsewhere as "till and moraine."

Significant features of the ice-cored moraine are linear ridges aligned either parallel or transverse to former glacier flow. The transverse ridges are either controlled moraines, produced by the supraglacial melt out of debris bands during early stages of degradation, or the crests of remnant thrust slices in what were formerly thrust moraines composed of stacked slabs of outwash and glacier ice but no longer retain the morphology of thrust block moraines. Linear ridges aligned parallel to former ice flow are more sinuous in plan form and often comprise complexes of anastomosing ridges. In some locations the ridges can be traced onto adjacent glacifluvial surfaces as eskers. These characteristics strongly suggest that the sinuous, ice flow-parallel ridges are eskers emerging through the supraglacial debris cover as the ice-cored moraine degrades. However, there are considerably more of these ridges in the ice-cored moraine than there are eskers on the adjacent foreland and therefore it is possible that some are supraglacial ice-walled channel fills produced by meltwater flowing from buried glacier ice down

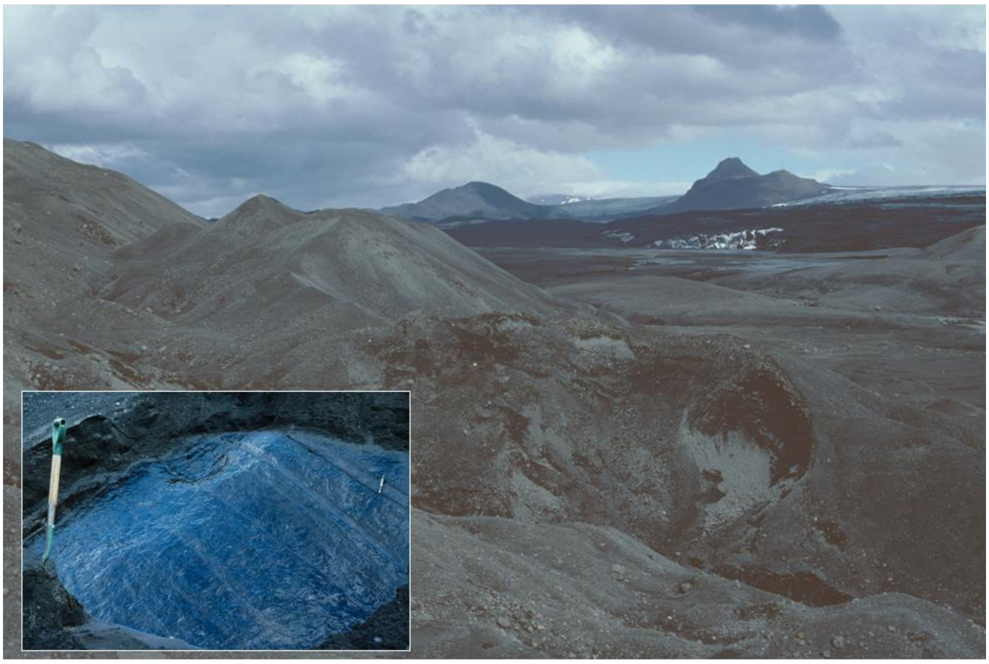


Figure 6. Evidence of glacier ice in the 1945 surge hummocky moraine. The main photograph shows the locations of several ice exposures in the moraine where retrogressive flows have been initiated by sediment saturation due to ice melting. The inset photograph shows the detail of one ice exposure after cleaning and clearly depicts folia and debris bands.

slope towards the glacier margin after it had receded and left part of the debris-covered snout isolated on local bedrock highs.

In one small area on Jökulfitjar, an arc of ice-cored moraine is fluted (Schomacker et al., 2006) and the flutings continue from the surface of the moraine onto the surrounding fluted till surface (Figure 7). This demonstrates that the ice-cored moraine was deposited during an ice advance predating formation of the flutings. The flutings are associated with the 1945 surge, so the overridden ice-cored moraine arc most likely demarcates the limit of the 1915-1920 surge, which was less extensive than the 1880-1890 and 1945 surges. The large volume of glacier ice in the ice-cored hummocky moraine of the 1945 surge is likely the result of the proglacial thrusting of the alluvium-buried snout from the 1915-1920 surge.

3.5 Glacifluvial deposits

The majority of the glacial outwash sands and gravels in the map area occur in two major types of landform (Figures 2 and 4): a) *linear sandar*, one deposited in a narrow corridor by meltwater that was forced to flow between the glacier snout and the Jökulgrindur bedrock ridge and a less significant example deposited along the western side

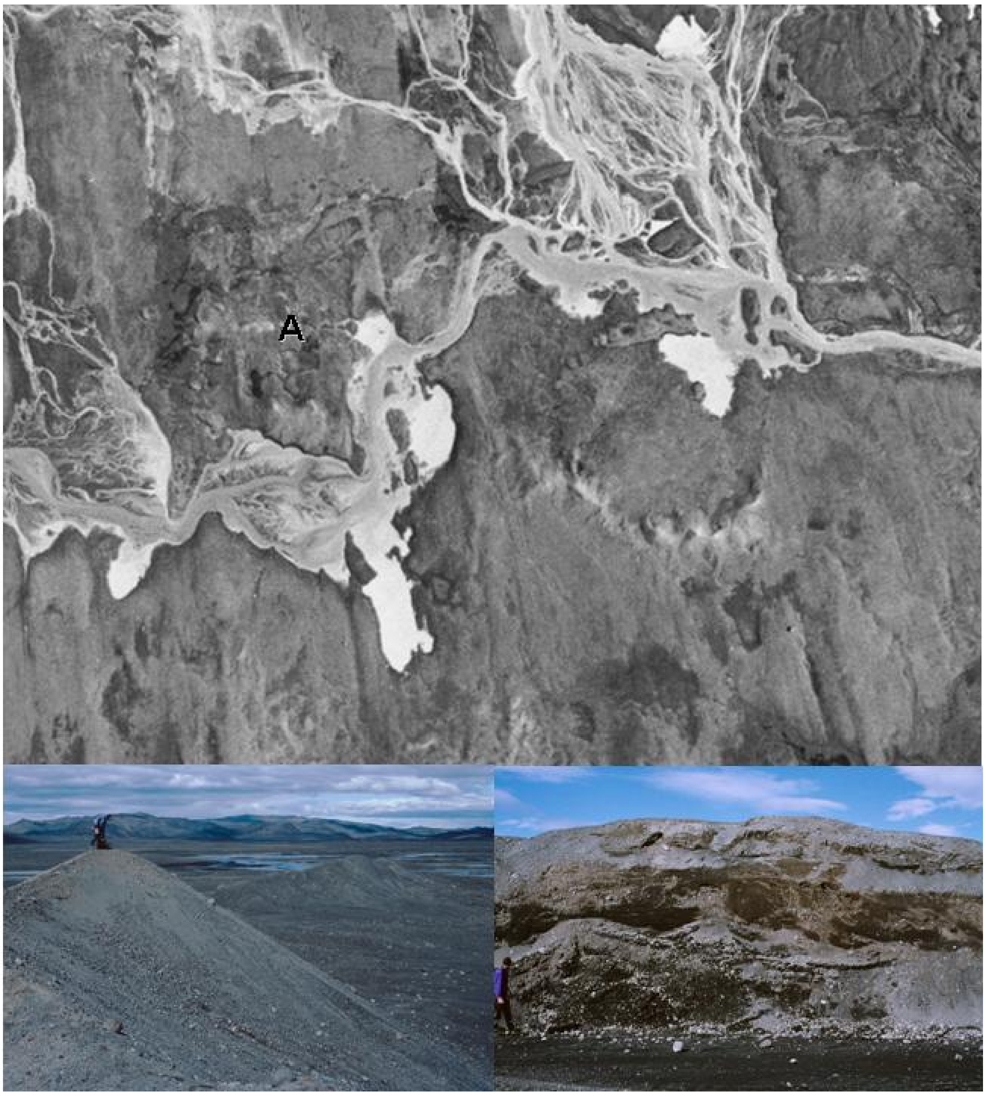


Figure 7. The arc of fluted ice-cored moraine on Jökulfitjar (A). Left inset photograph shows the considerable relief of the feature at its highest point and right inset photograph shows glacitectonic structures developed in the stratified gravels that make up most of the moraine. The continuation of the flutings, which date to the 1945 surge, from the surface of the moraine onto the surrounding fluted till surface demonstrates that the ice-cored moraine was likely constructed during the 1915-1920 surge, which was less extensive than the 1880-1890 and 1945 surges.

of Jökulgrindur by meltwater draining from the ice margin at Innri-Tungnaárbotnar and supplemented by meltwater from the glacier margin when it occupied the top of Jökulgrindur; and b) *coalescent proglacial outwash fans*, with pitted and/or collapsed ice-contact surfaces, which have been prograded into wide valleys that trend NE-SW away from the southern margin of the glacier snout. Other smaller accumulations of glacifluvial sediment include extensive kame terraces that were deposited between the glacier and the lower slopes of Jökulgrindur during ice recession (Figure 8), ribbon sandar that have drained small discharges from the glacier over the fluted till surfaces, and numerous eskers.

Figure 8. Kame terraces, ice-dammed lake shorelines and exposures through glacilacustrine sediments that accumulated between the receding glacier margin and the Jökulgrindur ridge following the 1945 surge.

The pitted surfaces of the sandur fans in the south, because they are relatively small and dispersed, are likely the products of ice block melt-out. Such features are common on jokulhlaup-fed sandar in Iceland where ice blocks are rolled across the outwash surface and partially buried during high discharge events (Fay, 2002). The more extensive collapse features on the surfaces of the sandur fans are indicative of the melt-out of much larger ice bodies, possibly a former glacier snout partially buried by outwash (Evans et al., 1999; Evans and Rea, 2003; Evans et al., 2007; Schomacker and Kjær, 2007, Figure 2). In the south of the map area, the occurrence of a thrust block moraine developed in a collapsing sandur fan and fronting a large expanse of ice-cored moraine suggests that glacier advance has disturbed an older melting, outwash-covered ice mass. Eskers occur as small anabranched complexes, spaced approximately every 800 m across the main sandar, documenting the long-term location of the main subglacial/englacial drainage pathways in the glacier.

3.6 Glacilacustrine deposits

Glacial lake sediments, including numerous lake shorelines, are particularly well developed where ice has advanced into and receded from upland areas, temporarily damming up proglacial lakes (Figures 8 and 9). This is evident in the small valleys that drain eastwards from the uplands of Tungnaárfjöll but is most spectacular in the north where two large lakes were trapped between the receding glacier margin and the slopes of Jökulgrindur (Figure 9). The formation of ice-dammed lakes throughout the map area has led to the cutting of lake spillways across bedrock cols and in some instances the deposition of glacifluvial valley fills in upland catchments not directly fed by glacial meltwater.

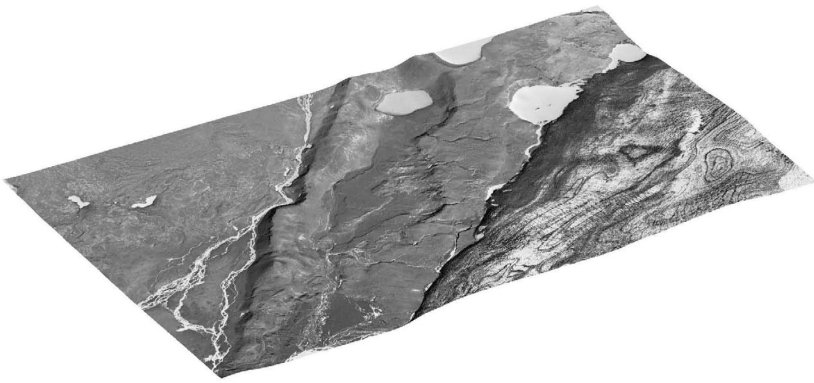
Figure 9. Ice-dammed lake shorelines on the east slopes of Jökulgrindur and documenting the damming of a large lake between the bedrock ridge and the glacier snout during the 1945 surge. The floor of the depression has been extensively blanketed by glacifluvial outwash since lake drainage.

3.7 Scree and paraglacially modified sediments

Extensive screes blanket the steeper slopes of the bedrock ridges around the glacier snout. The screes have accumulated rapidly due to the vigorous mechanical weathering of the highly frost-susceptible bedrock. Some slopes also contain paraglacially re-worked glacial sediments temporarily stored in debris flow fans at the base of gullies that dissect fragmented moraines. Slope and fluvial processes have reworked older tills on the lower relief terrain in the west of the map area. A linear strip of scree and paraglacially modified glacial sediment occurs along the western base of the conspicuous bedrock ridge named Jökulgrindur. This has accumulated just beyond the limit of the historical advances of Tungnaárjökull and a similar strip of paraglacial modification will most likely develop along the eastern side of Jökulgrindur as the extensive ice-cored moraine in that area degrades.

3.8 Surging glacier landsystem

Landform-sediment assemblages on the forelands of contemporary surging glaciers like Tungnaárjökull (Figure 10) provide powerful diagnostic criteria for the recognition of surge imprints on the landscape. The surging glacier landsystem compiled by Evans et al. (1999), Evans and Rea (2003) and Evans et al. (2007) recognizes three overlapping geomorphic zones (Sharp, 1985b), including an outer zone (A) of thrust block and push moraines (Sharp, 1985b; Croot, 1988; Benediktsson et al., 2008), grading up-flow into patchy hummocky moraine (zone B), and then into flutings, crevasse-squeeze ridges (Sharp, 1985a) and zig-zag (concertina) eskers (Knudsen, 1995) with areas of pitted, channelled and/or hummocky outwash and occasional overridden thrust and push moraines (zone C). Cyclic surging by a single glacier snout will often result in the overprinting of one surge event signature by another, and this is particularly significant in the production of hummocky moraine because it is facilitated by the pre-existence of stagnating ice from earlier surges.



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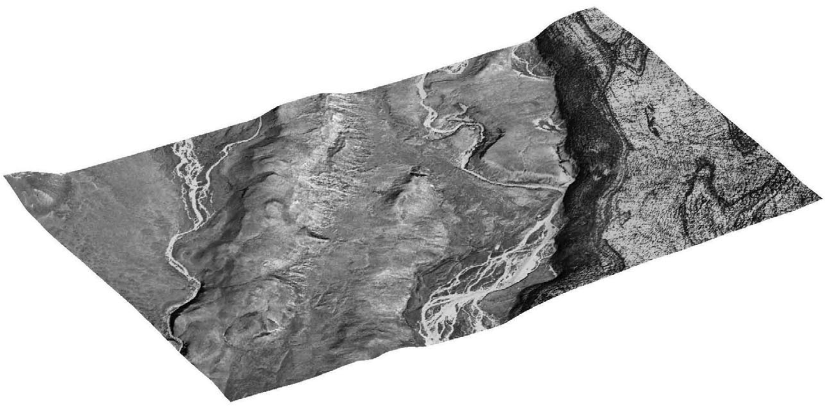
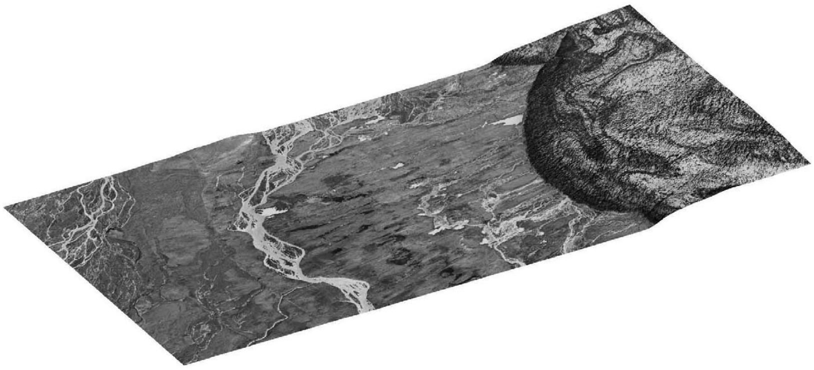


(b)

Figure 10. Continued on next page.



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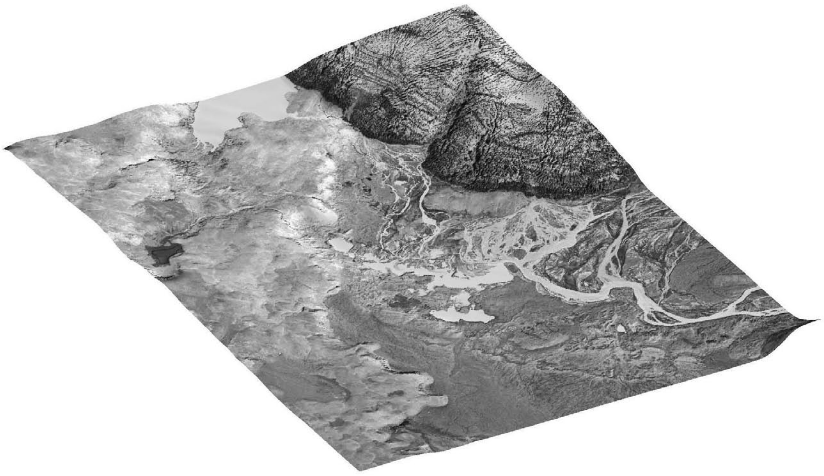

(d)

Figure 10. Digital elevation models with orthophotograph drapes, showing the glacier snout and its foreland, and the spatial distribution of the landform-sediment associations and their relationships to the bedrock topography: a) northern part of the map, showing the depressions containing remnant proglacial lakes and abandoned lake shorelines located between the glacier snout and the Jökulgrindur bedrock ridge. Surge moraines and kame terraces have been deposited up against the ice-proximal side of the ridge; b) north-central part of the map, showing the surge moraines and kame terraces on the ice-proximal side of the Jökulgrindur bedrock ridge and fluted till surfaces between the ribbon sandar that have been channelled between the ridge and glacier snout; c) south-central part of the map, showing the 1890 and 1945 surge moraines and associated fluted terrain produced by the advance of the lobate margin of Tungnaárjökull. Also visible in the area of deranged drainage near the snout is the arc of fluted ice-cored moraine which was likely constructed during the 1915-1920 surge; d) southern part of the map, showing the complex suite of landforms deposited in the corridor of low terrain between bedrock uplands by the southernmost lobe of Tungnaárjökull . The 1890 surge limit is marked by the ice-contact face of a sandur fan. This lies beyond a thrust moraine arc that was constructed in a collapsing sandur fan during the 1945 surge. A large expanse of ice-cored moraine behind the 1945 limit contains sinuous controlled ridges that mark the locations of eskers in the melting glacier ice.

Although local topographic constraints have resulted in some minor differences, the landform-sediment assemblages on the Tungnaárjökull foreland conform to the surging glacier landsystems model (Figure 10). The outer zone (A) of thrust block moraines, hill-hole pairs and push moraines can be identified along the former margins of the 1880-1890, 1945 and 1995 surges, although the high glacier ice-content of the weakly consolidated pre-surge sediments has resulted in the development of ice-cored hummocks throughout most of the thrust masses. The intermediate zone (B) of hummocky moraine located on the down-glacier sides of topographic depressions and often draped on the ice-proximal slopes of the thrust block and push moraines is particularly well developed on the Tungnaárjökull foreland. This reflects the nature of the pre-surge deposits, which were typically glacifluvial outwash draped over buried glacier ice from previous surges. Due to the restrictions placed on sandur development by the proximity of the Jökulgrindur bedrock ridge to the receding glacier snout, the burying of glacier ice by outwash was more widespread that on most other surging glacier forelands. The 1915-1920 surge limit is demarcated on Jökulfitjar by an arc of faintly fluted ice-cored hummocks. The inner zone (C), comprising long, low amplitude flutings produced by subsole deformation during the surge and crevasse-squeeze ridges produced at surge termination, is also well developed throughout the whole foreland despite the fact that proglacial outwash has extensively dissected and reworked it. Zig-zag or concertina eskers are rare, being evident only on Fremri-Tungnaárbotnar. Intrazonal landforms of surging include ice-cored, collapsed outwash, which are located in areas where proglacial outwash fans and streams were prograded over portions of the stagnant snout. This is concentrated in the south of the map area where additional evidence of older ice-cored outwash, which has been proglacally thrust during subsequent surging, occurs as ice-cored hummocks.

Acknowledgements

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