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Glacial landsystems of Satujökull, Iceland: A modern analogue for glacial landsystem overprinting by mountain icecaps

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A R T I C L E I N F O

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A B S T R A C T

Mapping of the surficial geology and geomorphology of the Satujökull foreland of the northern Hofsjökull ice cap in central Iceland provides a clear signature of glacial landsystem overprinting as a result of complex glacier behaviour during the historical period. Landsystem 1 comprises a wide arc of ice-cored moraine and controlled ridges lying outside fluted and drumlinized terrain, and is indicative of polythermal conditions. This landform assemblage commonly marks the historical Little Ice Age maximum limit on the forelands of upland icefields in the arid interior of Iceland and is therefore a record of climatically driven glacier advance. Landsystem 2 contains most of the diagnostic criteria for the surging glacier landsystem and records two separate surges by the western margin of Satujökull in the period since the attainment of the Little Ice Age maximum advance. The occurrence of Landsystem 2 is significant because Satujökull has not been previously regarded as a surging glacier, even though other outlets of Hofsjökull are prone to surging. Landsystem overprinting, especially in response to changing thermal regimes and/or glacier dynamics, and particularly by different flow units in the same glacier, is rarely reported but is crucial to the critical application of modern landsystem analogues to Quaternary palaeoglaciological reconstruction.

1. Introduction

The mapping of sediment-landform associations emerging at the margins of receding Icelandic glacier snouts has facilitated an improved understanding of process-form relationships in glacial geomorphology, specifically through the appreciation of spatial and temporal evolution of historically deglaciated forelands and the compilation of glacial landsystem models (e.g. Price, 1969; Sharp, 1985b; Krüger, 1987, 1994; Evans and Rea, 1999, 2003; Andrzejewski, 2002; Evans and Twigg, 2002; Evans et al., 2006a, b, 2007, 2009a, b; Kjær et al., 2008). These landsystem models have been instrumental in refining palaeoglaciological reconstructions (e.g. Eyles, 1983; Evans et al., 1999, 2006c; Johnson and Hansel, 1999) but there is an increasing need to provide modern analogues for the spatial and temporal changes that have been observed in landsystem imprints in Late Pleistocene glaciated terrains.

These spatial and temporal changes become apparent through intensive landsystem mapping, and have been used in palaeo-ice sheet reconstructions as indicators of basal thermal regime change and concomitant switches in ice dynamics. For example in the southern Laurentide Ice Sheet, Colgan et al. (2003) have documented a sequential change from frozen bed to active temperate and then to surging conditions during ice sheet recession, based upon the occurrence of three characteristic landsystems: *Landsystem A* (fluted till plains and low-relief push moraines) records active temperate ice recession; *Landsystem B* (drumlinized zone grading into moderate- to high-relief moraines and ice-walled lake plains) represents a polythermal ice sheet margin in which sliding and deforming bed processes gave way to a marginal frozen toe zone; and *Landsystem C*, which comprises the diagnostic landforms and sediments of surging activity. This change in ice sheet marginal dynamics during recession is communicated also in a conceptual model of spatial and temporal variations in glacial landform development presented by Mooers (1990) based on evidence from central Minnesota and relating to the operation of the Rainy and Superior lobes of the southern Laurentide Ice Sheet. The dynamics of the Rainy Lobe varied little during ice recession and the geomorphology records the operation of three zones: 1) a debris-covered ice zone fed by englacial thrusting and stacking of debris-rich ice; 2) a basal freeze-on zone; and 3) a thawed bed zone. In contrast, the Superior Lobe landforms record pronounced changes in ice dynamics during recession, with a frozen toe zone operating during the glacial maximum but disappearing during recession. Similar landsystem changes have been used to reconstruct changing thermal regimes and ice dynamics in the southwest Laurentide Ice Sheet in Alberta, Canada by Evans et al. (2006c, 2008) and Evans (2009a). They identify arcuate zones of hummocky moraine lying between sequences of recessional push moraines and relate this pattern of landsystem assemblages to operation of a glacier margin that oscillated between polythermal and active temperate conditions during early deglaciation. Later surging activity is identified

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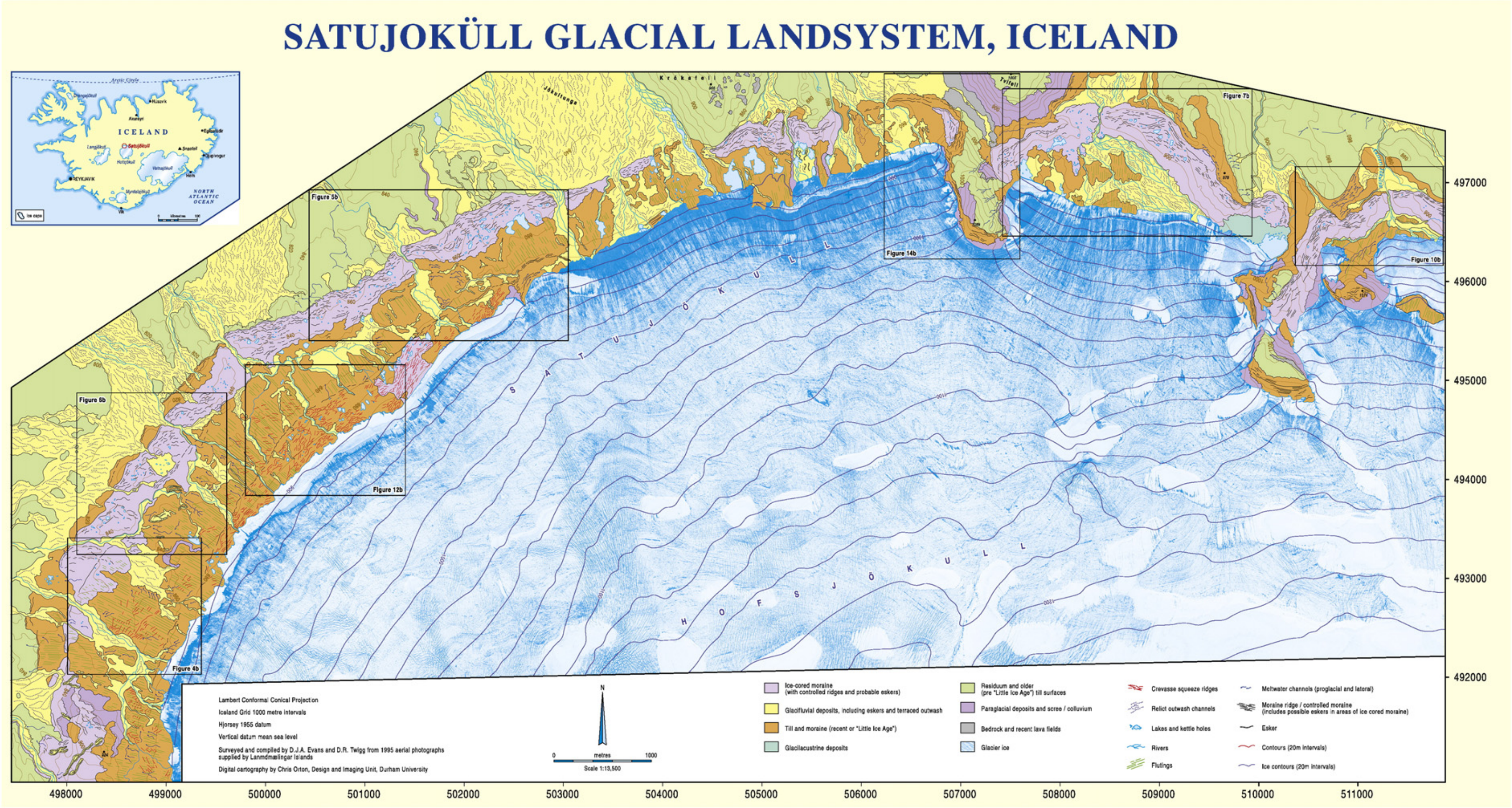

Fig. 1. Glacial geomorphology and surficial geology map of the Satujökull foreland (from Evans et al., 2010; reproduced with permission of the Journal of Maps). A large format version of this map can be viewed and downloaded from Evans et al. (2010) in the Journal of Maps. When printed at A0 paper size the scale is 1:13,500.

also in this region, based upon the clear development of the surging glacier landsystem (Evans et al., 1999, Evans et al., 2008).

Spatial and temporal landsystem changes have been clearly demonstrated also for mountain icefields. For example, Benn et al. (2003) relate different types of mountain landsystem signature to the coupling of the debris transfer processes between glacier snout and foreland. Large accumulations of sediment in ice-contact fans/ramps and latero-frontal moraine loops reflect the restriction of debris transfer away from a glacier snout and the development of a sediment sink in a "decoupled" system. In contrast, "coupled" snouts and forelands are reflected by landsystems comprising proglacial sandar with outwash heads or ice-contact faces. Benn et al. (2003) provide an example of spatial and temporal change from coupled to uncoupled systems through the Late Pleistocene to Holocene deglaciation of the Ben Ohau Range in South Island, New Zealand, where the gradual increase in the interruption of debris transfer through glacial systems was coincident with glaciers becoming more restricted to steep-sided and confined valleys. In addition to these inset sequences of landsystems, overprinted landsystems, or geomorphic palimpsests are also increasingly being recognized in mountain icefields. For example, in the British Younger Dryas landform record, phases of active ice marginal recession and/or incremental stagnation are evident in landforms that have been subglacially streamlined by later glacier readvance (Wilson and Evans, 2000; Golledge, 2007). Hence, it is becoming increasingly evident that large scale mapping of glacial geomorphology and landsystem characterization can provide proxy data for high resolution palaeoglaciological models that, in turn, can be used as valid input into palaeoclimatic reconstruction, providing that it is informed and constrained by modern analogues.

The utility of modern glacial landsystem analogues, and hence their validity in palaeoglaciology, is enhanced by the continued compilation and extension of the range of representative examples from different environmental and physiographic settings (see Evans, 2003a and Benn and Evans, 2010 for a review of the glacial landsystems knowledge base). Additionally, it is understood that glacier thermal regime will reflect, in addition to glacier morphology, the climate of the environment in which a glacier is located. It is therefore highly likely that landsystem imprint will spatially reflect temporal climate change. Even non-climatic drivers such as surging should also be recognizable within the landsystem imprint. A small number of local scale mapping projects on modern glacier forelands have highlighted changes in glacier dynamics over shorter timescales. Because of their recent age, these landsystem signatures can be reconciled with historical documentation of glacier activity and glaciological process observation, and thereby provide invaluable modern analogues for spatial and temporal glacial landsystem change. The case study of the Breiðamerkurjökull foreland (Evans and Twigg, 2002) serves as a good illustration, because it contains evidence of intermittent surging by the eastern margin of the glacier, manifest in the development of thrust moraines, crevasse-squeeze ridges and long flutings, superimposed on and inset within the geomorphology of the more dominant active temperate landsystem. Surges at this site have been recorded both in historical documentation and modern process observation, although the magnitude of these surges is often small and therefore the geomorphic imprint is subtle (Boulton, 1986; Evans and Twigg, 2002). Therefore, the landsystems approach not only provides modern analogues for palaeoglaciological reconstruction but also has the potential to facilitate the recognition of changing glacier behaviour in the landscape record. The important corollary is that spatial variability in glacial geomorphological features records temporal patterns of not only glacioclimatic relationships, such as mass balance, but also thermal regime change and internal instabilities or surges.

As part of the extension of the range of modern glacial landsystem analogues, this paper reports the mapping and interpretation of the glacial geomorphology of the foreland of the northern margin of the plateau ice cap Hofsjökull, locally named Satujökull, in west-central Iceland. Previous research on the glacial landsystem signatures of plateau icefields and ice caps in the temperate maritime North Atlantic region has been restricted to Øksfjordjökelen in north Norway (Rea et al., 1998; Evans et al., 2002; Rea and Evans 2007) and Þorisjökull and Tungnafellsjökull in Iceland (Rea and Evans, 2003; Evans and Twigg, 2004; Evans et al., 2006a; Evans, 2010). The Icelandic plateau icefield forelands are significant in that they contain a landform signature indicative of polythermal conditions at the Little Ice Age maximum. This includes an extensive temperate subglacial bedform signature of long flutings terminating at a wide belt of ice-cored moraine containing "controlled" debris ridges melting out from englacial debris-rich folia (controlled moraine *sensu* Evans, 2009a). Preliminary aerial photograph analysis of the foreland of Satujökull revealed a similar polythermal landform signature but it was also evident that later surges had superimposed surge-type landforms over part of the foreland. Given that northern Hofsjökull had never been identified as a surging margin, it was evident that the Satujökull foreland could provide important new information on the extent and occurrence of glacier surging in Iceland as well as serve as an important modern analogue for spatial and temporal landsystem change.

Satujökull is composed of three flow units/lobes, the largest of which makes up the western half of the ice margin; two smaller lobations in the eastern margin have been created by two mountain ridges that rise above the snout surface and became nunataks during

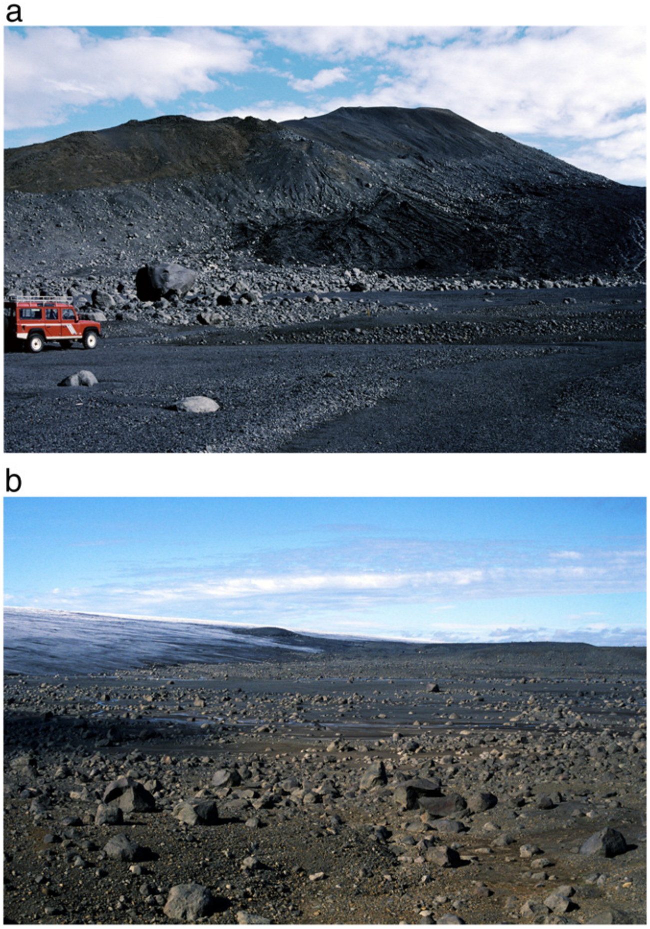

Fig. 2. Examples of paraglacially and fluvially modified landforms and sediments: a) Little Ice Age lateral moraine undergoing paraglacial reworking on the slopes of a nunatak at the eastern end of the western margin of Satujökull. Buried glacier ice is apparent in the darker, water saturated material at the foot of the slope. The boulder-covered surface in the middleground is a heavily fluvially reworked end moraine; b) fluted till surface and frontal moraine locally reworked into outwash.

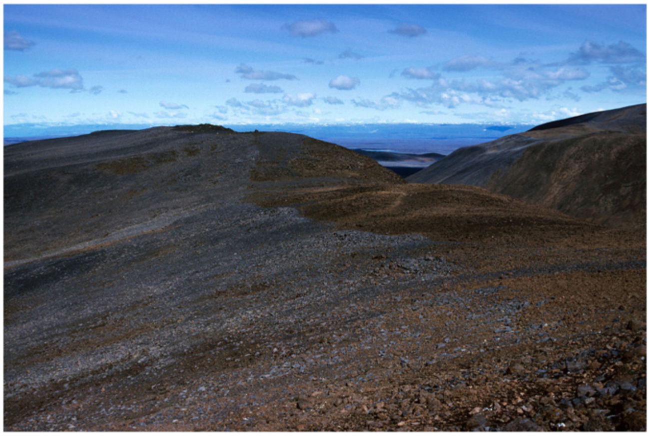

Fig. 3. Trimline marking the contact between a till veneer on the lower slopes and residuum on the summit of a bedrock ridge on the eastern side of the foreland of the central lobe.

the Little Ice Age. The different flow units/lobes are from hereon referred to as the western margin and central and eastern lobes. The whole glacier margin is fronted by a narrow, recently deglaciated foreland containing an overprinted landsystem signature that records two very different types of glacier behaviour; advance and recession of polythermal ice, superimposed in the area covered by the western margin by two surges. The landform-sediment assemblage is therefore a valuable modern analogue for superimposed landsystems in the Quaternary record. This paper presents the field evidence for landsystem overprinting through geomorphology and surficial geology mapping at a scale of 1:13,500, based on 1995 aerial photographs and field survey around the margin of Satujökull, with the aim to provide a modern analogue for landsystem superimposition or overprinting, specifically at the margins of upland or plateau icefields.

2. Methods

The mapping of the spatial distribution of surficial geology units and landforms around the margin of Satujökull was facilitated by the

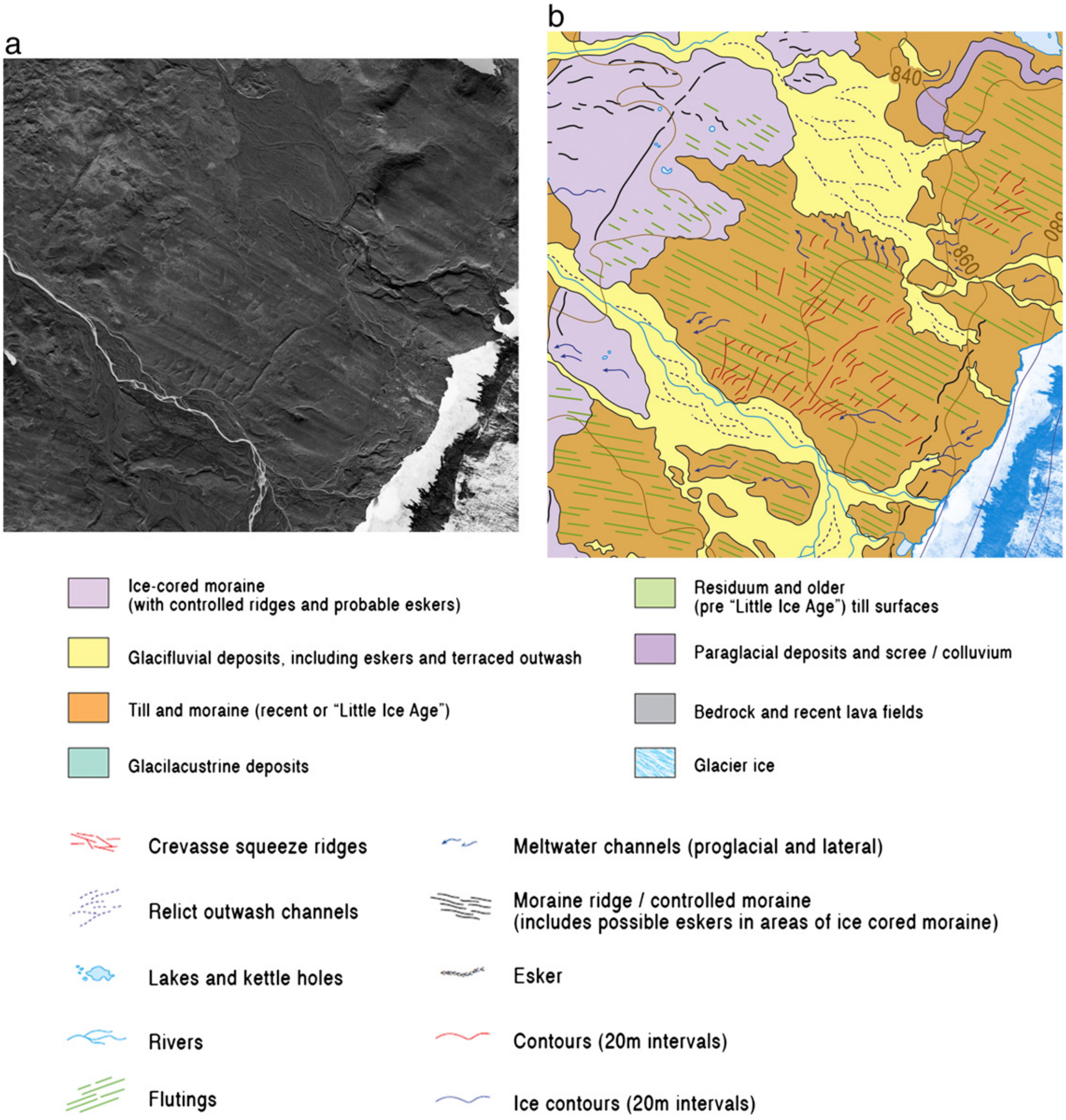

Fig. 4. Aerial photograph extract (a) and associated map extract (b) from the westernmost foreland, showing fluted and drumlinised till surfaces which contain crevasse-squeeze ridges and extend out to ice-cored moraine. The outermost flutings appear fragmented due to their construction over the proximal edge of the ice-cored moraine. The extent of the snout readvance that produced the flutings and crevasse-squeeze ridges is marked by a continuous moraine ridge running through the area of ice-cored moraine. The legend relates to the other enlarged map extracts in Figs. 5–7, 10, 12 and 14.

compilation of an orthophotograph constructed from 1995 aerial photographs originally taken by Landmaelingar Islands. Interpretations of surface materials and landforms were made by a combined approach involving stereoscopic mapping directly from the aerial photographs and ground survey in 2004 of local landform morphology and internal composition. These interpretations and subsequent map classifications of landform and sediment type are based upon known process-form relationships in recently deglaciated terrains, especially those in Iceland (cf.; Krüger, 1987, 1993, 1994, 1995, 1996; Evans and Rea, 1999, 2003; Evans and Twigg, 2000, 2002, 2004; Krüger and Kjær, 2000; Spedding and Evans, 2002; Kjær and Krüger, 2001; Andrzejewski, 2002; Evans, 2003b, 2005, 2009a, b, 2010; Evans and Hiemstra, 2005; Schomacker et al., 2006; Evans et al., 2006a, b, c, 2007, 2009a, b; Schomacker and Kjær, 2007; Benediktsson et al., 2008; Kjær et al., 2008; Bennett et al., 2010). The photogrammetric and cartographic procedures adopted in the compilation of the glacial geomorphology map and its component landsystem imprints (Fig. 1) have been described in detail by Evans et al. (2010), where a large format version of Fig. 1 can be downloaded at A0 size to produce a map scale of 1:13,500. In summary, the orthorectified image was constructed through the use of GPS measured ground control stations which served as tie points on aerial photographs. The roving GPS was tied in to a continuously running GPS station at base camp, which was in turn tied in to the Icelandic GPS network through the nearest survey pillar.

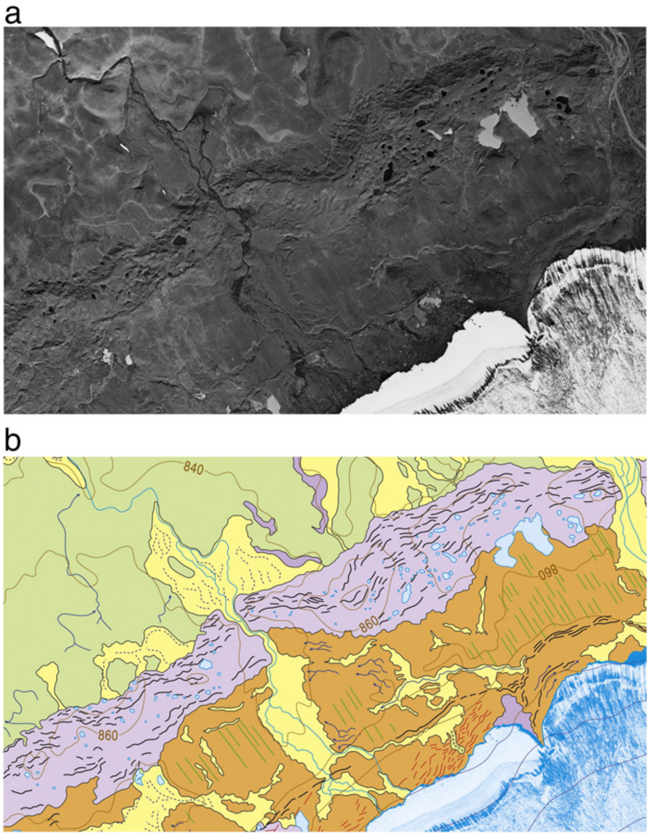

Fig. 5. Aerial photograph extract (a) and associated map extract (b) from the central part of the western margin foreland, showing the different types of moraine. In this area, ice-cored hummocky moraine with localized controlled ridges forms a continuous arcuate belt up to 300 m wide and 30 m high. Low amplitude push moraines ("innermost push moraine assemblage") form the outer limit of a zone of densely spaced crevasse-squeeze ridges adjacent to the modern glacier margin. The "outermost push moraine assemblage" is discontinuous in this area due to its development over a heavily de-iced section of the ice-cored moraine arc. Also illustrated in this map extract are small glacifluvial channels eroded into till surfaces during the early stages of proglacial drainage development. Meltwater channels are also visible in the residuum of the upland terrain beyond the historical moraine limits, documenting proglacial drainage during the Little Ice Age. The later establishment of proglacial drainage is manifest in linear sandar or glacifluvial "corridors", which locally dissect the ice-cored moraine arc.

3. Sediment-landform associations at Satujökull

There are six surficial geology map units around the margin of Satujökull (Fig. 1), the sedimentary and geomorphic characteristics of which are not unlike those previously described on similar maps

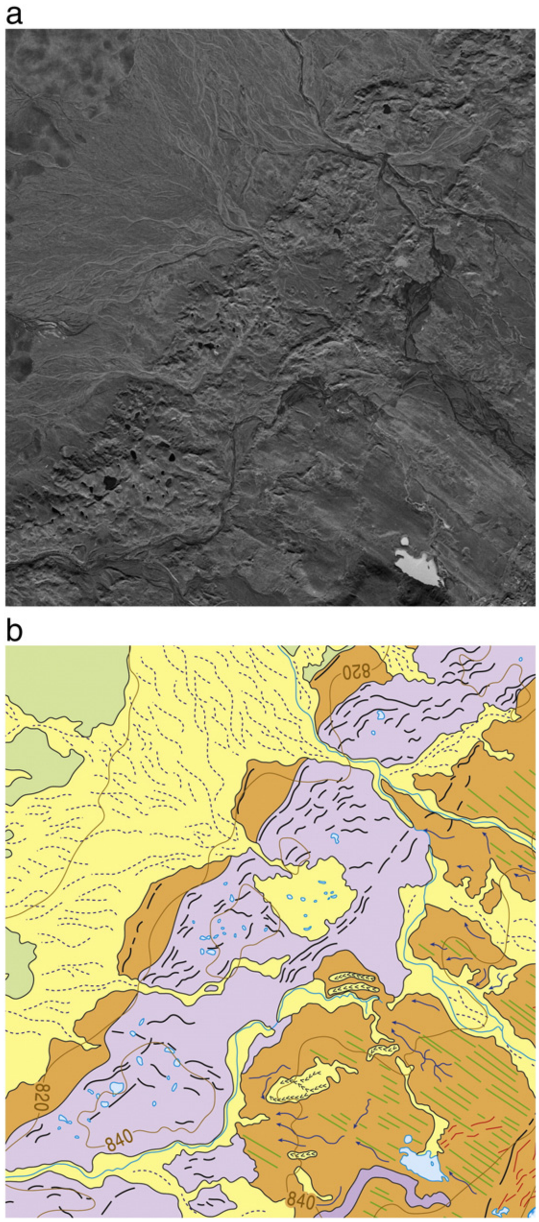

Fig. 6. Aerial photograph extract (a) and associated map extract (b) from the western part of the western margin foreland, showing the various characteristics of the ice-cored moraine arc at its widest point. The ice-cored moraine in this area is up to 500 m wide and 30 m high, but unlike the stretch in the central part of the western foreland it is fronted by a subdued single ridged moraine with minor kettle holes and till veneer rather than a steep ice-cored slope. Also evident is a substantial area of kettled outwash in the centre of the ice-cored moraine arc, which appears to be linked to the later development of the continuous "outermost push moraine assemblage" and flutings on the proximal slopes of the ice-cored moraine. The most extensive eskers also occur in this area. Both sets of push moraine assemblage are visible in this extract; the "innermost" assemblage is visible with its well developed crevasse-squeeze ridges at lower right.

of the forelands of Icelandic glaciers (Evans and Twigg, 2000, 2002, 2004; Evans et al., 2006a, b, c, 2007, 2009a, b; Evans, 2009b; Bennett et al., 2010). Unrelated to the historical glacial landsystems of Satujökull are the mapping units of bedrock and residuum. The bedrock is of volcanic origin and includes localized valley bottom lava flow landforms such as leveed lava flow tracks and extrusion vents, but is predominant on upland ridges or tuya-like hills, some of which are emerging from the downwasting glacier snout and therefore effectively creating lobation of the eastern glacier margin. The summits of the uplands are covered in blockfield or residuum, the latter often containing heavily weathered pre-Little Ice Age till, although uplands that have more recently emerged from the ice are commonly draped, especially on their lower slopes, by Little Ice Age moraines and till or paraglacially reworked glacigenic sediments (Fig. 2). Blockfield and residuum are formed by the in situ mechanical breakdown of the frost-susceptible bedrock and older glacigenic deposits, with blockfield being typically a boulder-rich rubble and residuum being a finer-grained weathering product; both have been locally organized by periglacial processes into patterned ground. In places the residuum may contain pockets, or even extensive spreads, of highly degraded and wind deflated till veneer deposited during a period of more extensive glaciation that pre-dates the historical period. Till veneer also occurs locally in association with ice-cored moraine most likely dating to the Little Ice Age (Fig. 3).

3.1. Till and moraine and ice-cored moraine

The tills and moraines of the glacier foreland date to the historical period or the "Little Ice Age" *sensu lato* (cf. Matthews and Briffa, 2005; Kirkbride and Dugmore, 2008), although no absolute dates are available from these landforms. They are predominantly coarse-grained, often boulder-rich diamictons with sandy to gravelly matrices and contain numerous clasts which display subglacial modification in the form of striae and facets. Nonetheless, localized pockets of sub-rounded to rounded clasts, typical of glacifluvial deposits, occur within the till and moraine surficial unit due to localized accumulations of glacially transported material that only lies a short distance from its source of origin, likely in outwash tracts. Conversely, some outwash tracts have partially reworked till surfaces to produce "avenues" of degraded till in which predominantly the larger boulders remain in situ (Fig. 2b). In the absence of moraines, tills are largely less than 3 m thick over much of the foreland. Till surfaces are commonly characterized by flutings or small drumlins, whose predominantly low amplitude gives rise to a discontinuous appearance on aerial photographs, or crevasse squeeze ridges (Fig. 4). Moraines are classified according to their geomorphic characteristics, being either ice-cored hummocky moraine with localized controlled ridges or low amplitude (<5 m high) push moraines (Fig. 5). Lateral moraines are rare but occur below the steep cliffs of bedrock ridges that are emerging from the receding glacier snout (Fig. 2).

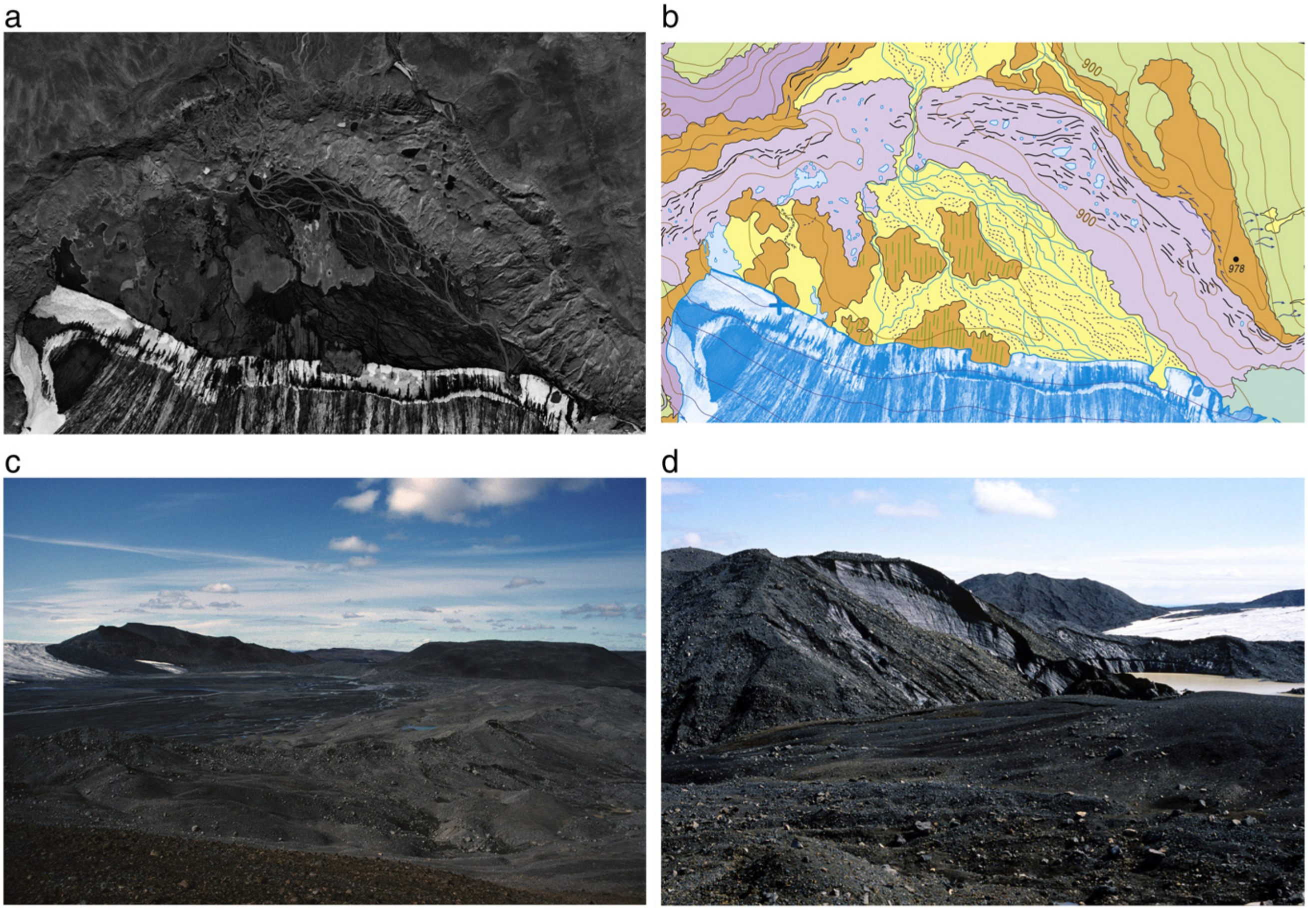

Fig. 7. Glacial landforms on the foreland of the central lobe: a) aerial photograph extract and b) associated map extract covering the central lobe foreland, showing the high amphitheatre–like appearance of the ice-cored moraine belt, which is continuous with debris-rich ice at the modern glacier margin. Also visible are the lateral meltwater channels, meltwater cols and till veneer, which all constitute the outermost part of the ice-cored moraine belt on Tvifell. Note also that the foreland inside the ice-cored moraine arc contains no other moraine assemblages but only a fluted till surface that has been reduced to remnant "islands" due to glacifluvial reworking by a sandur whose lateral development is restricted by the ice-cored moraine arc; c) ground view over the ice-cored moraine arc towards the inner zone of fluted till "islands" separated by outwash channels. Note the retrogressive flow slides and water-filled depressions on the ice-cored moraine crest; d) exposure through debris-covered glacier snout where it is continuous with the ice-cored moraine belt on the foreland of the eastern lobe.

The ice-cored moraine comprises an arcuate belt between 150 and 500 m wide and up to 30 m high and stretches around the whole foreland, draping localized bedrock ridges and punctuated only where the major outwash streams have eroded gaps up to 100 m wide (Figs. 5, 6). The ice-cored moraine belt is continuous with debris-rich ice at the margins of the central and eastern lobes (Fig. 7), thereby revealing the origin of the landform by controlled moraine development (*sensu* Evans, 2009a). Melting ice cores are manifest in occasional glacier ice exposures, water-filled depressions perched well above the local water table, collapse hollows bordered by tensional faults and widespread retrogressive debris flow activity and associated gullying (Fig. 8). The most subdued relief in the ice-cored moraine belt occurs in a narrow distal zone and a wider proximal zone, giving the belt an asymmetrical cross-profile (Figs. 6, 7 & 9). This likely reflects the volume of buried ice, and as a corollary the former pattern of englacial debris-rich ice folia in the snout when it stood at this moraine; this interpretation implies a former polythermal regime for the snout, because large volumes of englacial debris lying down-flow of temperate subglacial bedforms indicates the former operation of a frozen toe zone down ice of a warm-based zone (cf. Boulton, 1970; Hooke, 1973a, b; Hambrey et al., 1999; Evans, 2009a). Due to the ongoing melt-out process in this moraine belt, it is presently impossible to differentiate between controlled moraine ridges (*sensu* Evans, 2009a) and potential eskers that are emerging through a thinning supraglacial debris cover, although there is a striking similarity between the linear ridges in this moraine belt and similar moraine belts on the foreland of Tungnaarjökull (Evans et al., 2009b), where ridge origin may be inferred by alignment. Ridges lying transverse to former glacier flow are either controlled moraines, produced by the supraglacial melt out of debris bands, or the crests of remnant thrust slices in what were formerly thrust moraines composed of stacked slabs of outwash and glacier ice. Ridges lying parallel to former ice flow are often more sinuous in plan form and comprise complexes of anastomosing ridges and are therefore interpreted as eskers emerging through the supraglacial debris cover. An area of low amplitude terrain of ice-cored till occurs in the central part of the western margin where it remains connected to the glacier snout and contains a dense network of crevasse-squeeze ridges.

The ice-cored moraine belt constitutes the outermost limit of the historical glacial landforms on the central part of the western foreland, but elsewhere the Little Ice Age limit is marked by a subdued single- or dual-ridged push moraine with minor kettle holes (Fig. 6). These ridges either form continuations of the ice-cored moraine belt, specifically on the east side of Jokultunga and in the valley to the west of Tvifell (Fig. 1), or lie beyond the ice-cored moraine, as is the case in the valley on the east side of Tvifell (Fig. 7). In the westernmost part of the foreland, the terrain lying between these outer push moraines and the ice-cored moraine is fluted. Beyond the ice-cored moraine arc on the foreland of the central and eastern lobes, a zone of till veneer (Fig. 3), incised down to underlying bedrock by lateral meltwater channels, appears to be associated both spatially and temporally with the outer push moraines and flutings (Figs. 7, 10).

Two prominent push moraine assemblages, comprising predominantly one, but up to three, individual ridges in each assemblage, occur on the foreland of the western snout margin. The outermost assemblage is most conspicuous in the western part of the map area (Fig. 6) but becomes discontinuous due to ice melt-out in an easterly direction (Fig. 5), because it lies on the proximal lower slopes of the ice-cored moraine arc. In the far west it forms the distal limit of a fluting field, wherein the outermost flutings have been constructed over ice-cored topography and therefore appear fragmented on the aerial photographs (Fig. 4). This indicates that the ice-cored moraine arc was partially over-run by a readvance of the western margin before complete melt-out of buried ice. Crevasse-squeeze ridges also occur in association with the flutings (Fig. 4).

The innermost push moraine assemblage lies up to 450 m from the snout and contains glacitectonically deformed outwash (Fig. 11). The moraine encloses small areas of low amplitude ice-cored hummocky moraine and widespread crevasse-squeeze ridges and flutings (Fig. 12).

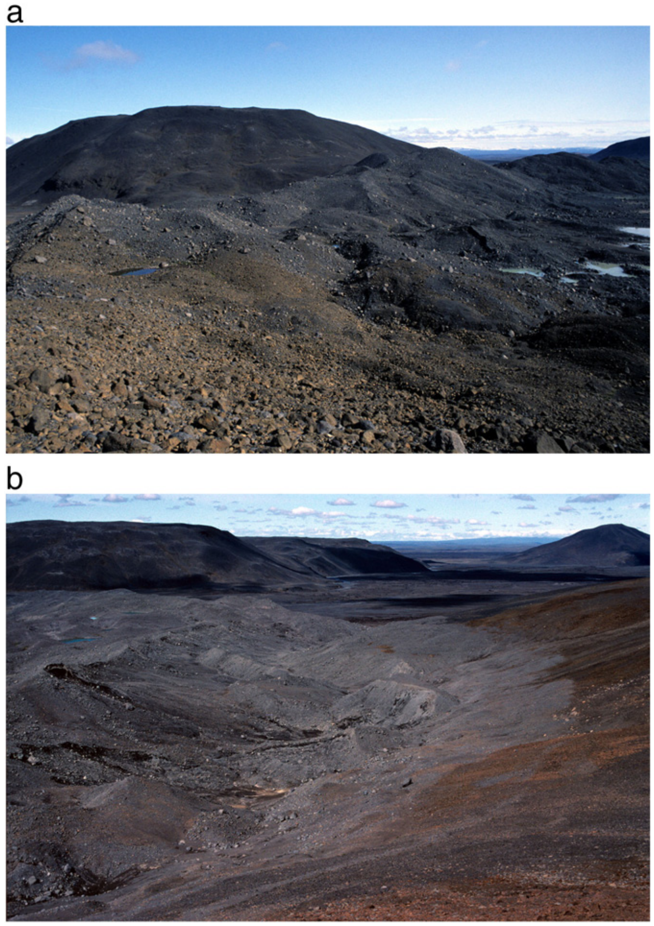

Fig. 8. Ground views of the ice-cored moraine belt, showing evidence of melting ice cores such as occasional glacier ice exposures, water-filled depressions perched well above the local water table, collapse hollows bordered by tensional faults (a) and widespread retrogressive debris flow activity and associated gullying (b).

Fig. 9. Arcuate section of the ice-cored moraine belt located between upland ridges on the eastern side of the central lobe foreland. This view shows the narrow strip of subdued, pitted relief that occurs in some parts of the distal zone of the ice-cored moraine belt, where melt-out beneath a veneer of supraglacial debris is at an advanced stage or complete.

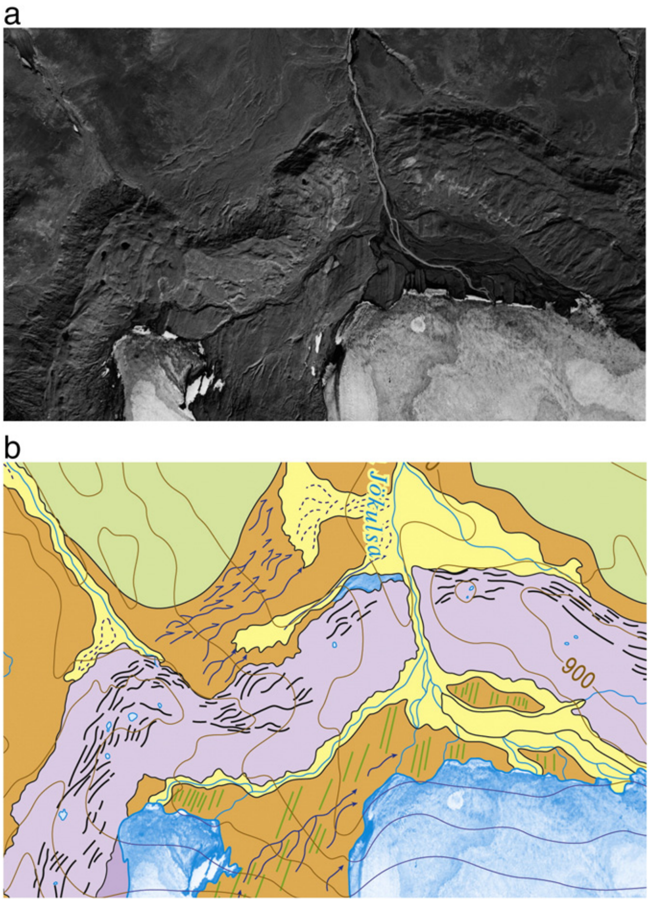

Fig. 10. Aerial photograph extract (a) and associated map extract (b) from the foreland of the eastern lobe, showing the ice-cored moraine belt continuing into debris-covered glacier ice at both ends of the moraine arc. Like the foreland of the central lobe, this foreland does not contain any moraines inside the ice-cored moraine belt, only fluted till. This extract also includes the best examples of lateral meltwater channels cut into till veneer at the maximum Little Ice Age limit.

Although crevasse-squeeze ridges also occur beyond this innermost push moraine, they are more subdued and spatially very restricted. Inside the push moraine assemblage the crevasse-squeeze ridges comprise cross-cutting diamicton ridges that can be traced from the more recently deglaciated part of the foreland into debris ridges on the glacier snout. It is their occurrence within the snout, where they can be traced into annealed crevasses (Fig. 13), that justifies a genetic classification of crevasse-squeeze ridges, similar to the modern

Fig. 11. Section through a push moraine ridge in the "innermost push moraine assemblage", showing glacitectonically deformed stratified sands and gravels.

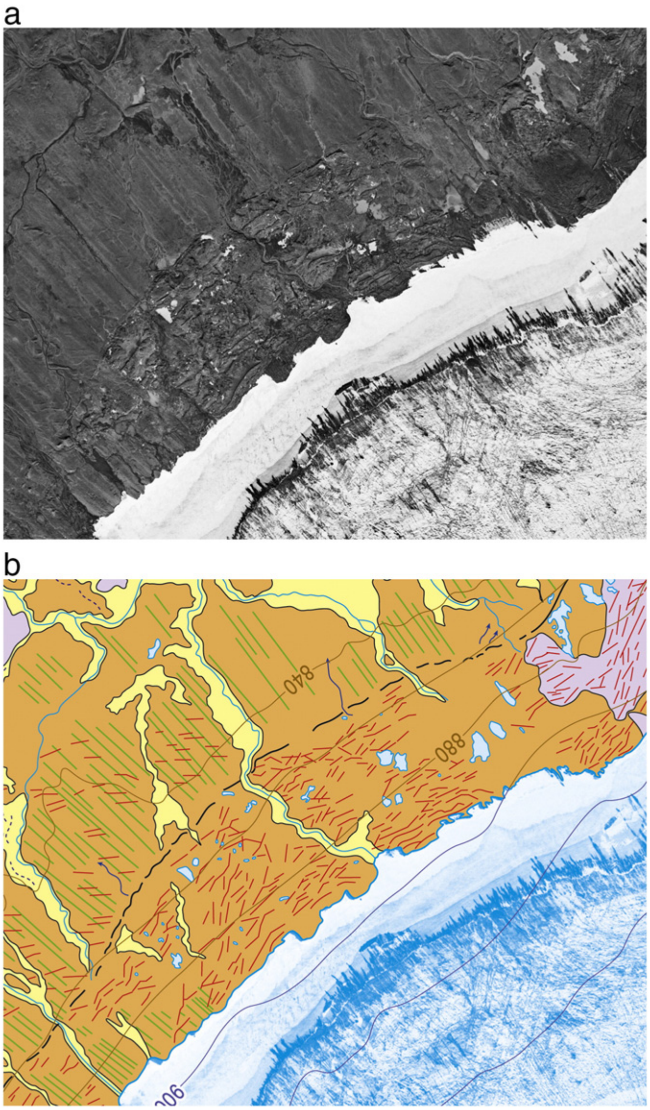

Fig. 12. Aerial photograph extract (a) and associated map extract (b) from the central foreland of the western margin, showing the "innermost push moraine assemblage" enclosing an area of low amplitude ice-cored hummocky moraine and widespread crevasse-squeeze ridges and flutings. Note the greater density and sharper relief of the crevasse-squeeze ridges and the large number of kettle holes inside the moraine assemblage.

Fig. 13. Debris ridge melting out from a vertical debris dyke in the glacier snout. These ridges can be traced into annealed crevasse traces on the ice and into the cross-cutting diamicton ridges on the most recently deglaciated part of the foreland. This spatial relationship justifies the interpretation of the cross-cutting diamicton ridges as crevasse-squeeze ridges.

analogues that are firmly established at Bruarjökull and Eyjabakkajökull on the Vatnajökull ice cap (Sharp, 1985a, b; Evans and Rea, 1999, 2003; Evans et al., 2007).

The foreland of the central and eastern lobes of Satujökull does not contain any push moraines inside the ice-cored moraine arc, but instead displays only a fluted till surface that terminates at the lower, subdued proximal slopes of the ice-cored terrain (Figs. 7, 10). However, some discontinuous lateral moraines have been constructed around the lower slopes of the former nunataks.

3.2. Glacifluvial deposits and landforms

Sand and gravel glacifluvial outwash in the map area is contained within linear sandar that are constrained by bedrock highlands and ice-cored moraine in the glacier foreland. Meltwater has produced "corridors" of outwash in incisions through the fluted and drumlinized till surfaces. In places these corridors have expanded through the erosion and reduction of the till surfaces to remnant "islands" in the glacifluvial deposits (Fig. 7). Beyond the ice-cored moraine arc the outwash systems are less restricted and consequently comprise sandur fans lying between mountain ridges.

Glacifluvial erosion is manifest in a variety of channel features. Numerous small meltwater channels occur on fluted till surfaces (e.g. Fig. 5) where they document the early stages of proglacial drainage before the main linear sandur "corridors" became established. Elsewhere, meltwater channels document ice advance and recession in upland terrain. For example, when the glacier margin occupied the outermost historical moraine on the flanks of upland surfaces, outwash was locally forced through cols, resulting in the cutting of proglacial meltwater channels through upland residuum (Fig. 5). An

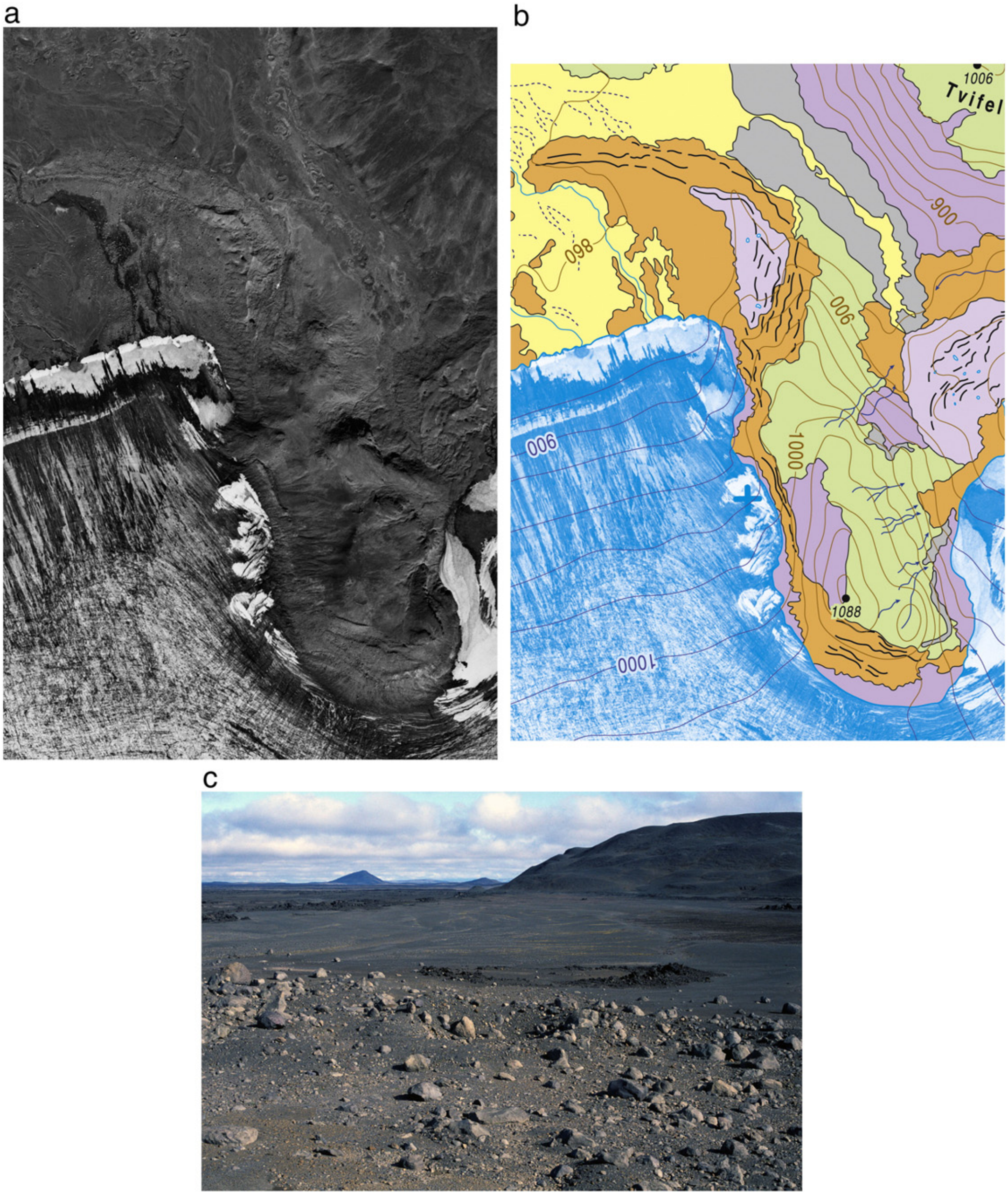

Fig. 14. Aerial photograph extract (a) and associated map extract (b) from the eastern side of the western margin, showing the Little Ice Age latero-frontal moraine arc, which is only partially ice-cored due, at lower elevations, to its fluvial reworking by proglacial streams. Note also the complex of proglacial meltwater channels on the eastern face of the former nunatak, which were incised by meltwater draining from the eastern margin of the central lobe when it occupied the summit ridge. This meltwater was then diverted into the narrow valley below Tvifell, which contains fluvially modified leveed lava flow tracks and extrusion vents shown in (c).

interesting complex of proglacial meltwater channels occurs on the eastern face of the former nunatak separating the central and eastern glacier lobes (Fig. 14). These features were incised by meltwater draining from the eastern margin of the central lobe when it occupied the summit ridge, and the drainage route presumably continued along and/or into the lower elevation margin of the eastern lobe and then into the narrow valley on the southwest slope of Tvifell. This valley contains a linear assemblage of lava flow forms such as leveed lava flow tracks and extrusion vents, which have been locally fluvially modified and interspersed with ribbons of glacifluvial outwash; similar fluvial reworking characterizes the proximal side of the Little Ice Age latero-frontal moraine down valley (Fig. 15), where a wide sandur fan also emanates from the narrow valley despite the fact that ice-cored moraine and no meltwater portal exists at the valley head. These features in combination attest to sustained meltwater discharges through the bedrock-floored valley due to the concentration of drainage along the margin of the eastern lobe for a short period when the central lobe advanced onto the mountain summit ridge. Finally, lateral meltwater channels record the recession of glacier ice from upland surfaces (Figs. 7, 10), indicating that glacier margins may have been predominantly cold-based at the time, because water drained off the ice surface to the margin rather than penetrate to the bed (Dyke, 1993; Ó Cofaigh et al., 2003).

Small quantities of glacifluvial sediments on the foreland are contained in eskers, which are widely spaced and of low (<3 m) amplitude. The longest esker ridge (ca. 450 m) occurs in the southwest corner of the map area, where it has emerged with several other eskers from low amplitude ice-cored moraine due to de-icing. Elsewhere in the ice-cored moraine belt, an esker origin for ice-flow parallel controlled ridges (see section 3.1) can only be confirmed once de-icing is more advanced. Eskers predominantly occur as single ridges, occasionally in parallel clusters up to three or four in number, on the fluted and drumlinized till surfaces. Eskers are rarely ice flow parallel but often curve towards the lowest topography in the breaches through the ice-cored moraine belt. This suggests that the ice-cored moraine formed a barrier to the coupled subglacial and groundwater drainage system at the time of esker formation so that meltwater flowed towards the topographic lows represented by breaches in the moraine belt. In a few locations, controlled ridges or possible eskers in the ice-cored moraine appear to align with eskers on the lower elevation fluted terrain. This confirms the observations of Boulton et al. (2007a, b) that the positions of glacial drainage networks remain stable through time.

A significant area of kettled outwash occurs in the centre of the ice-cored moraine arc on the western foreland (Fig. 6). Because it has no clear linkage to any of the sandar and is instead entirely enclosed by, and overlies, ice-cored moraine, it must have developed as an ice-contact outwash fan at the portal of a glacial drainage network. Its proximal margin lies against the "outermost push moraine assemblage", suggesting that it prograded from the ice margin when the push moraine was being constructed on the proximal slopes of the ice-cored moraine arc.

Fig. 15. View along the heavily fluvially modified latero-frontal moraine on the east side of the central lobe, showing the scatter of boulders left by the winnowing of finer-grained materials by the meltwater discharged down the valley at the base of Tvifell (see route depicted on Fig. 14).

3.3. Glacilacustrine deposits

A small area of glacilacustrine deposits occurs in the eastern part of the map area where a large hollow has been produced by the melt-out of a buried portion of the central lobe (Fig. 16). The hollow occurs on the proximal slope of the ice-cored moraine arc and is isolated by the rising slopes of the moraine, the glacier snout and a till covered bedrock ridge. Due to this isolation, the hollow has been partially filled with water during ice melting, giving rise to numerous collapse pits on the surface of the glacilacustrine deposits. A lake spillway has been excavated between the ice-cored moraine and the till-covered bedrock ridge. When operating, this fed glacifluvial sediment to a small outwash fan to the north and provided the water for the excavation of a bedrock gorge at the northern end of the sandur. Both the sandur and bedrock gorge are now dry due to the reduced volume of lake water.

3.4. Scree and paraglacially modified deposits

Screes occur on the steeper slopes of the bedrock ridges around and above the glacier snout and accumulate rapidly in such settings due to the vigorous mechanical weathering of the highly frost-susceptible bedrock. Similarly, some slopes that have been recently deglaciated also contain paraglacially re-worked glacial sediments temporarily stored in debris flow fans (Fig. 2a). This includes small areas of steeper terrain on deglaciated upland surfaces that were fully submerged and fluted during the Little Ice Age.

4. Glacial landsystems at Satujökull

Landform-sediment assemblages on the foreland of Satujökull represent three overprinted signatures of glacier advance relating to two different landsystems or styles of glacial deposition (Fig. 17). The outermost and older Landsystem 1 contains the wide ice-cored moraine arc with its localized distal zone of push moraines and till veneer and lateral meltwater channels. The foreland of the central and eastern lobes shows that this moraine arc is associated with a fluted and drumlinized till surface with localized eskers. A later readvance of the western margin has superimposed Landsystem 2a (surge 1, Fig. 17), comprising the outer push moraine assemblage, a fluted and drumlinized surface and crevasse-squeeze ridges, over the distal slopes of the ice-cored moraine. The most recent readvance of the western margin is documented by Landsystem 2b (surge 2, Fig. 17), comprising the inner push moraine assemblage, dense crevasse-squeeze networks, low relief ice-cored moraine and flutings. Landsystem 2 also contains localized eskers.

Landsystem 1 contains evidence of both large scale sub-marginal debris entrainment in the form of a wide belt of ice-cored or controlled moraine (Evans, 2009a) and up-ice subglacial deformation manifest in fluted till (Benn, 1994). Exposures through the ice-cored moraine reveal that it is derived from the melting of debris-rich basal ice facies, which in the absence of overdeepenings on the foreland indicate the operation of intensive sub-marginal freeze-on of meltwater and debris rather than other mechanisms such as supercooling (Roberts et al., 2002; Larson et al., 2006). The construction of such a large ice-cored moraine belt suggests occupation by an ice margin for a substantial period, during which the thin subglacial sediments would have been concentrated englacially at the ice margin

Fig. 16. Ground view over the large ice-cored hollow filled with collapsing glacilacustrine deposits in the eastern part of the central lobe foreland. Note the shorelines marking the former water levels.

by freeze-on at the boundary between warm and cold based ice in a polythermal snout (Hambrey et al., 1999; Evans, 2009a). Moreover, the altitude of Satujökull would have been conducive to cold-based marginal conditions during the Little Ice Age. The occurrence of the localized distal zone of push moraines, till veneer and lateral meltwater channels indicates that some parts of the snout, especially the far western margin and the central and eastern lobes were cold based but did not contain large volumes of refrozen debris during the peak of the Little Ice Age advance.

Landsystem 2 contains most of the diagnostic criteria for former surge activity, including crevasse-squeeze ridges, long flutings and localized, low relief ice-cored moraine, all lying inside a prominent end moraine or the "outermost push moraine assemblage" (cf. Sharp, 1985a, b; Evans and Rea, 1999, 2003). Landsystem 2a documents the oldest surge, which reached the proximal slopes of the ice-cored moraine arc of Landsystem 1 in the western foreland but not the forelands of the central and eastern lobes. The surge resulted in localized streamlining of Landsystem 1 ice-cored moraine to produce features similar to the ice-cored drumlins reported by Evans and Rea (1999, 2003) and Schomacker et al. (2006) at Bruarjökull. The significant area of kettled outwash in the centre of the ice-cored moraine arc on the western foreland (Fig. 6) constitutes further diagnostic criteria for glacier surging (Evans and Rea, 1999, 2003), especially as it is temporally and spatially related to the construction of the "outermost push moraine assemblage" during the oldest surge. This ice-contact fan records the progradation of a substantial volume of glacifluvial sediment over pre-existing ice-cored moraine during the high discharges associated with the oldest surge.

Continued de-icing of the Landsystem 1 moraine arc is gradually making the surge limit, marked by the outer push moraine assemblage, appear fragmented. Landsystem 2b records the most recent surge by the western margin, an event that superimposed one surge signature over another in a similar fashion to the landform assemblages on the Bruarjökull foreland (Evans et al., 2007; Kjær et al., 2008).

The occurrence of Landsystem 2 is significant in itself because Satujökull has not been previously regarded as a surging glacier, even though other outlets of Hofsjökull, for example Múlajökull and Þjorsarjökull, are prone to surging (Björnsson et al., 2003). Landsystem overprinting, especially in response to changing thermal regimes and/or glacier dynamics, and particularly by different flow units in the same glacier, is rarely reported (e.g. Krüger, 1994; Glasser and Hambrey, 2001; Evans and Twigg, 2002; Evans, 2009a) but is crucial to the critical application of modern landsystem analogues to Quaternary palaeoglaciological reconstruction (e.g. Colgan et al., 2003; Winguth et al., 2004; Evans, 2009a).

5. Conclusion

The surficial geology and geomorphology of the Satujökull foreland provide a clear signature of complex glacier behaviour in the historical period, which is manifest in landsystem overprinting.

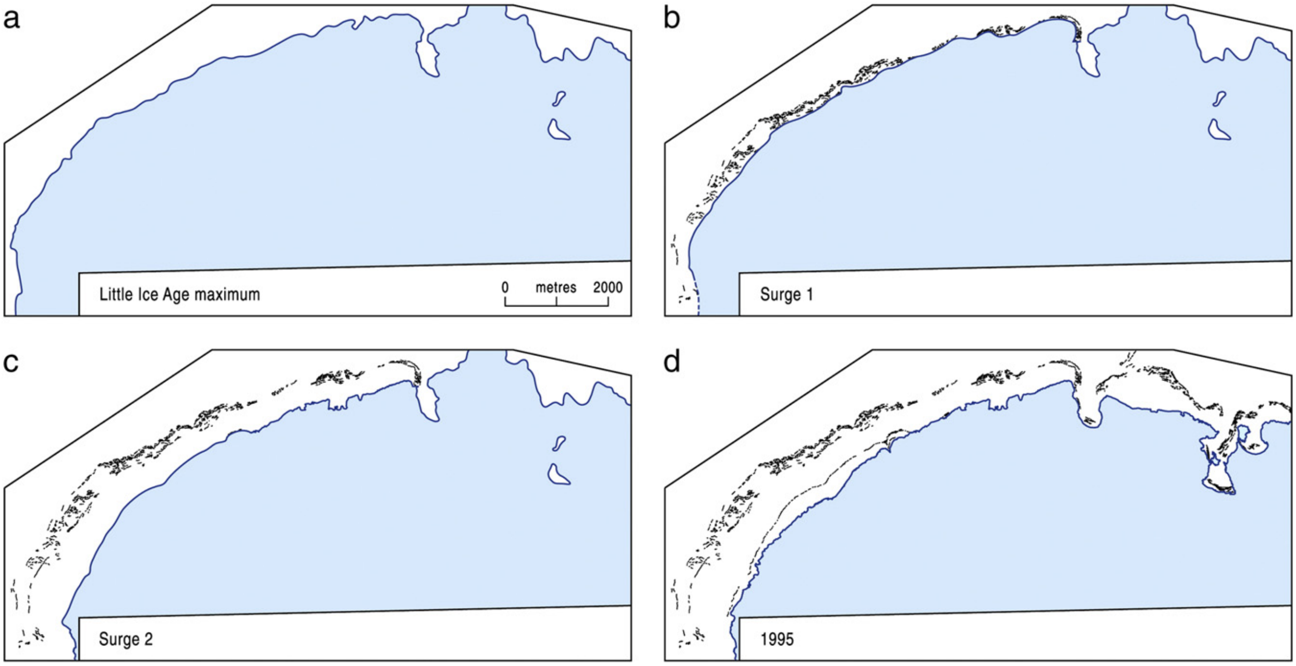

Fig. 17. Maps showing the interpreted sequence of glacial events during the historical period on the Satujökull foreland: a) the extent of ice during the Little Ice Age maximum; b) the extent of the first surge by the western margin; c) the extent of the second surge by the western margin; d) the ice margin in 1995 when the most recent aerial photographs were taken. Note that because the surging events only affected the western margin, the recession of the central and eastern lobes is not depicted in panels b) and c), but it is assumed that climate warming since the Little Ice Age has resulted in gradual downwasting of these ice lobes.

Two landsystems have been created as a result of an initial glacier advance in response to Little Ice Age climate cooling followed by two surge events. Landsystem 1 records climatically driven glacier advance and contains a wide arc of ice-cored moraine with well developed controlled ridges lying outside fluted and drumlinized terrain. These features are characteristic of Little Ice Age maximum limits on a number of glacier forelands in the interior uplands of Iceland, where environmental factors create polythermal conditions in glacier snouts (Evans, 2010). Landsystem 2 contains most of the diagnostic criteria for the surging glacier landsystem and records two separate surges by the western margin in the period since the attainment of the Little Ice Age maximum advance. The occurrence of Landsystem 2 constitutes clear evidence that Satujökull, similar to other outlets of the Hofsjökull ice cap, is prone to surging activity. This demonstrates that the landsystem approach is an effective way of assessing the occurrence of recent surges of glacier snouts for which there is no documented history of activity, and hence can be employed in the spatial analysis of factors that control surging (cf. Jiskoot et al., 2000). Additionally, the landsystem overprinting exemplified by the Satujökull foreland attests to changing thermal regimes and/or glacier dynamics in different flow units of the same glacier, thereby providing a modern analogue for similar spatial and temporal switches in glacier behaviour in Pleistocene landform-sediment assemblages.

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