Evolution of a debris-charged glacier landsystem, Kvíárjökull, Iceland

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Abstract

A time-series of 1:12,500 scale maps of the snout and foreland of the Icelandic glacier Kvíárjökull provides a spatial and temporal assessment of landform evolution from a debris-charged glacier snout over a 58 year period between 1945 and 2003. In addition to providing a valuable record of glacier recession over a period of recent global warming, the maps enable the elaboration of existing conceptual models of the debris-charged glacier landsystem based on measurable process-form relationships. Features were identified using a combination of DEM visualization, morphometric analysis, stereoscopic viewing of aerial photographs and field verification. The maps contain twelve colour coded surficial geology units displayed as polygons and various geomorphological features represented by a combination of lines and points. The spatial and temporal evolution of the landforms on the glacier foreland indicate that the snout of Kvíárjökull has been undergoing active retreat and incremental stagnation over the study period. The maps serve as excellent modern landsystem analogues for palaeoglaciological reconstructions in similar climatic and topographic settings.

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1. Introduction

The concepts of landsystems and process-form models in glacial geomorphology are increasingly being developed and improved through the use of contemporary analogues, wherein ongoing process-form relationships can be unequivocally demonstrated (e.g. Boulton and Eyles, 1979; Krüger, 1987; Owen and Derbyshire, 1989; Evans and Rea, 1999; 2003; Kirkbride, 2000; Evans et al., 1999b; 2006b; 2007; 2009a;b; Evans, 2003a; 2009a;b; Kjær and Krüger, 2001; Lyså and Lønne, 2001; Andrzejewski, 2002; Evans and Twigg, 2002; 2004; Schomacker and Kjær, 2007; Benediktsson et al., 2008). The recent accelerated recession of glacier snouts around the world, punctuated by occasional readvances and accumulation season oscillations, has facilitated more systematic and quantitative analyses of glacial geomorphic processes on the forelands of glaciers with varying dynamics and morphologies. The time-series of maps of Kvíárjökull (Figure 1) presented in this paper provide a multi-temporal record of glacier retreat by utilizing a long aerial photograph archive commencing in 1945 (Figure 2). They also constitute the most recent additions to the map archive of Icelandic glacier snouts and forelands, produced as part of a long term surveying and landsystems research programme (Evans and Twigg, 2000; 2002; 2004; Evans et al., 2006a;b; 2007; Evans, 2009a;b). These maps provide a sequential record of glacier retreat following the Little Ice Age maximum and illustrate the development of characteristic landform assemblages of a debris-charged glacier (Spedding and Evans, 2002; Evans, 2005). Consequently, they will serve as a spatially and temporally quantified landsystem model for use in palaeoglaciogical reconstructions in moderate relief terrain.


Figure 1. Location map of Kvíárjokull, Iceland.

Kvíárjökull, located at $63°55'$N and $16°30'$W, is a temperate outlet glacier of the Öræfajökull icecap and occupies a deep incision or short trough in the southern margin of the Öræfi volcano in southeast Iceland (Figure 1). Below the equilibrium line the glacier is fed by an extensive icefall and terminates as a low-angled piedmont tongue. A high debris turnover by the glacier (Eyles, 1979; 1983) is indicated by the size of its latero-
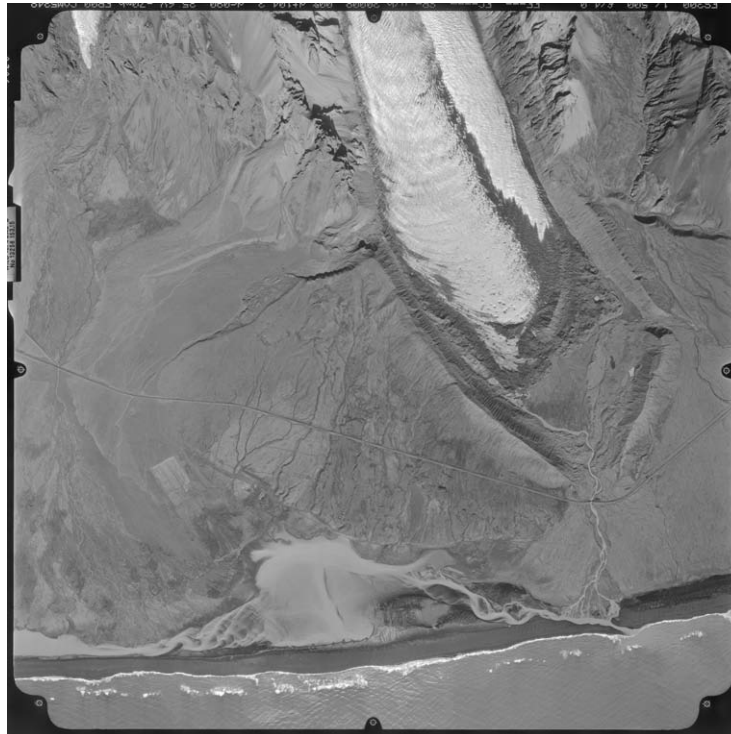
(a)

(b)

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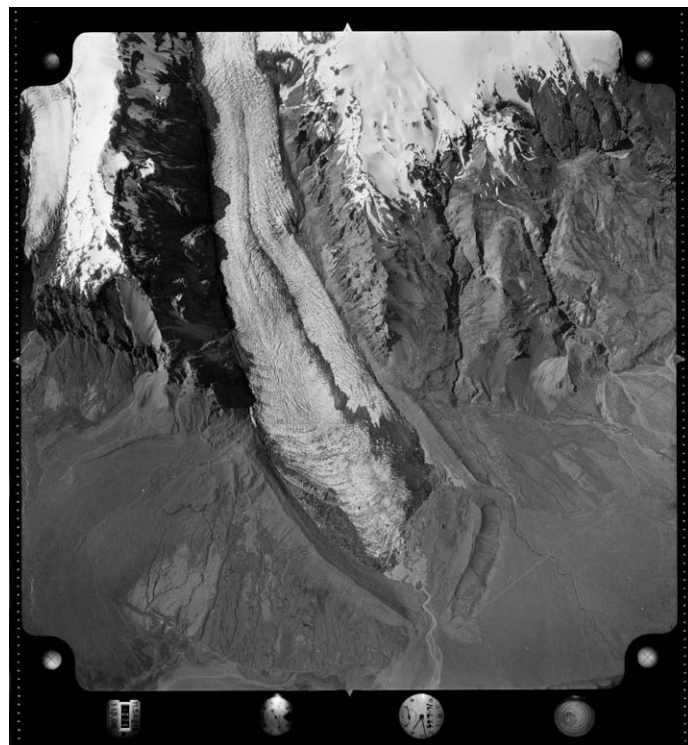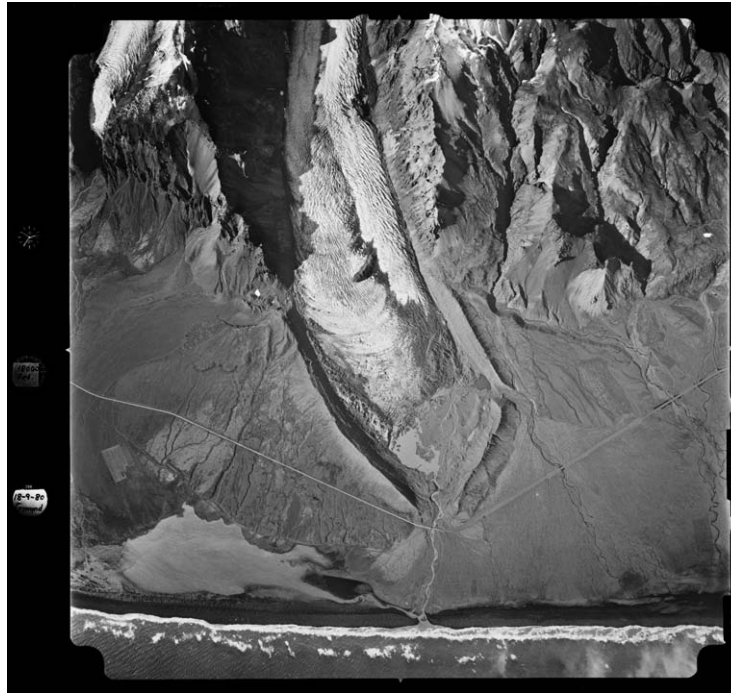
(c)

(d)

(e)

Figure 2. Thumbnail images of aerial photographs from each of the 5 years used in the construction of the maps of Kvíárjökull. a) 1945; b) 1964; c) 1980; d) 1998 and e) 2003.

frontal moraine ridges, which reach a height of 150 m and are the largest in Iceland, being referred to as 'an enormous amphitheatre' by Thórarinsson (1956). Because of their prominence in the landscape they have been named Kvíármýrarkambur (south lateral) and Kumbsmýrarkambur (north lateral). These moraines are thought to have formed over the first period of icecap expansion that occurred within the Neoglacial at around 3200 B.P. (Thórarinsson, 1956; Gudmundsson, 1997; Spedding and Evans, 2002). Along the length of the ice fall, over which the glacier descends from its ice cap down to the coastal plain, steep volcanic rock walls up to 600 m high feed extraglacial debris to the margins of the glacier, and at its terminus the glacier overlies a 50 m deep overdeepening (Spedding and Evans, 2002). The unique topography and high turnover associated with the wet maritime climate combine to produce complex debris transport pathways that differentiate it from a 'glaciated valley landsystem' (Spedding and Evans, 2002; Swift et al., 2006). Although it is a piedmont glacier, Kvíárjökull differs from other Icelandic south coast active, temperate glacier snouts in that its lateral spread has been restricted during the Neoglacial by the latero-frontal moraine and it contains relatively large volumes of debris-rich basal ice and englacial debris septa, which have led to the historical development of complexes of ice-cored ("controlled"; Evans, 2009a) and hummocky moraine and pitted outwash fans and kame terraces inside the latero-frontal moraine "amphitheatre" or loop. The high debris content is a product of: a) the large volume of debris transported through the glacier system by rockfall and along passive

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debris pathways (Eyles, 1979); b) the entrainment of material through thrusting and longitudinal flow compression (ogive formation) at the base of the icefall; c) regelation and folding/thrusting of water-worked debris from englacial channel fills; and d) localized supercooling (Spedding and Evans, 2002; Swift et al., 2006).

The potential operation of supercooling at Kvíárjökull is a matter of some debate (cf. Roberts et al., 2002; Spedding and Evans, 2002; Swift et al., 2006), one that is crucial to the identification of supercooled snouts in the palaeoglaciological record. For example, Larson et al. (2006) have identified a Pleistocene landsystem imprint at Lake Michigan that they regard as indicative of former supercooling. It features stratified diamictons, interpreted as melt-out tills derived from thick sequences of debris-laden, stratified basal ice, in a landform assemblage of hummocky terrain and kettle holes lying on the distal or adverse slope of an overdeepening. The equifinality problems associated with this interpretation have been discussed at length by Evans (2009a), but progress in palaeoglaciological reconstruction relies on an increasing number of modern landsystem exemplars; improving knowledge of the debris entrainment processes at Kvíárjökull coupled with maps that document the evolution of its proglacial landform-sediment assemblage are therefore invaluable to glacial geomorphology.

2. Methods

2.1 Data acquisition

The aerial photograph dataset used for mapping was obtained from Landmælingar Íslands and Loftmyndir ehf (Figure 2; Table 1). All photographs were scanned to a high resolution (15 μm) on a photogrammetric scanner. Twelve ground control points were collected around the glacier foreland in summer 2006 using differential GPS. These were generally large stable boulders deposited on the outer slopes of the latero-frontal moraine rampart and pre-date 1945, thereby avoiding the need for secondary ground control (e.g. Fox and Cziferszky, 2008).

Photograph[a]	Nominal Scale	Camera calibration	Ground resolution (cm)
1945 2 BW	1:50000	Only focal length + flying height	73
1964 2 BW	1:50000	Complete	90
1980 2 BW	1:50000	No fiducials	68
1998 2 BW	1:30000	Complete	82
2003 2 RGB	1:25000	Complete	51

Table 1. Aerial photograph specifications. [a]BW and RGB indicate panchromatic and colour photography respectively.

Year	DEM Resolution (m)	Number of GCPs	RMSE (m)	DEM coverage
1945	3.6	3	7.74	Complete
1964	4.5	8	1.03	Complete
1980	3.4	6	0.96	Top left corner missing
1998	4.1	11	0.71	Complete
2003	2.6	7	0.39	Complete

Table 2. DEM specifications.

2.2   Data processing

Digital photogrammetric processing of the aerial photographs was conducted in Leica Photogrammetry Suite 9.1 (LPS). LPS uses the bundle block adjustment, using least squares estimation, to establish the relationship between the positions of a set of photographs and a ground coordinate system, based on the interior and exterior parameters input into the software and the location of ground control points. Each set of photographs was processed as for a metric camera with the exception of 1945 and 1980 for which incomplete camera calibration information required processing for a non-metric camera. The projection used was UTM, with the spheroid WGS 84 for zone 28N. The selection of strategy parameters was based on a visual inspection of digital elevation models (DEMs) output using different strategy parameters.

Five DEMs were generated from the historical aerial photography with ground resolutions ranging from 2.5 to 4.5 m, depending on the resolution of the aerial photographs (Table 2), and based on a 5x5 correlation window in the stereo matching process. For example, the size of one pixel in real space in the 2003 photographs is 51 cm. The maximum DEM resolution that can be achieved using a 5x5 pixel window is 5 times this value at 2.55. Whilst a finer resolution DEM could have been generated using a smaller window size (e.g. 3x3), this would have resulted in greater matching errors, because there is an increased likelihood that 9 pixels will be mismatched on two images using a 3x3 window compared to 25 pixels being wrongly matched using a 5x5 window. Therefore DEM resolution is sacrificed for the sake of better DEM quality. Orthophotos were generated by resampling the aerial photographs using the DEMs at the resolution of the original photographs.

2.3   Geomorphological mapping

Overlays of the surficial geology and geomorphological features were digitally drawn in ArcMap using the generated orthophotos. This was accomplished by a combination of stereoscopic viewing and interpretation of aerial photographs, scrutinizing different visualizations of the DEMs, and field mapping. The UTM grid (WGS84, 28N) is com-

patible with the system currently used on Icelandic maps produced by Landmælingar Íslands. Contour plots at 10 m intervals that accompanied the extraction of the DEMs were smoothed in ArcMap using a smoothing algorithm. The cartographic design was based on previous maps produced by Evans and Twigg (2000) and Evans et al. (2006a;b; 2007; 2009a;b).

DEM extraction resulted in an inevitable reduction in resolution from that of the aerial photographs. Therefore only larger features such as moraine complexes, large moraine ridges, eskers and outwash fans could be identified in the DEMs. The identification of these within the DEMs was aided by well known visualization techniques: relief shading, slope gradient and aspect (Smith and Clark, 2005) (Figure 3). Smaller features were identified in the high resolution orthophotos, aided by stereoscopic viewing of the aerial photographs. The evolution of many features was apparent in the time series of aerial photographs enabling the origin of many features to be confidently identified. Furthermore morphometric analysis based on a temporal sequence enabled the identification of ice-cored features within the foreland and the ice marginal oscillations responsible for linearity in hummocky moraine belts. Smaller linear features such as crevasse fills, push moraine ridges, kame terraces, ice cliffs and eskers all have a similar morphology but have been differentiated to a high level of confidence due to: a) the high ground resolution of the aerial photographs of between 0.5 and 0.9 m; and b) the verification of features in the field over the period 1992-2008.

3.   Glacial geomorphology and surficial geology

In addition to bedrock surfaces (blue/grey) that dominate in the area of the cliffs that bound the glacier on the western edge of the maps, twelve surficial geology units are recognized. These can be grouped according to their location and age: 1) supraglacial debris occurs only on the glacier surface; 2) the category of "till" includes deposits laid down by glacier ice but these have mostly been emplaced by a variety of supraglacial processes and therefore most areas of this map unit are more appropriately described as "supraglacial morainic till" (Boulton and Eyles, 1979). Small areas of this till cover, too small to map at this scale, will have been post-depositionally reworked by paraglacial processes. Till is sub-divided according to its age relative to the recent "Little Ice Age" (LIA); recession from the LIA limit started at around 1905AD but the LIA till is draped over moraines of older, Neoglacial age (Evans et al., 1999a). Therefore we recognize four sub-divisions of till at Kvíárjökull: a) ice-cored moraine; b) post-LIA till, lying inside the latero-frontal moraine loop; c) LIA till, lying over the older deposits that comprise the latero-frontal moraine loop; and d) pre-LIA till, lying outside the latero-frontal moraine loop and including the latero-frontal moraine remnants that extend beyond the LIA limit; 3) glacifluvial deposits are contained within proglacial sandar and ice-marginal
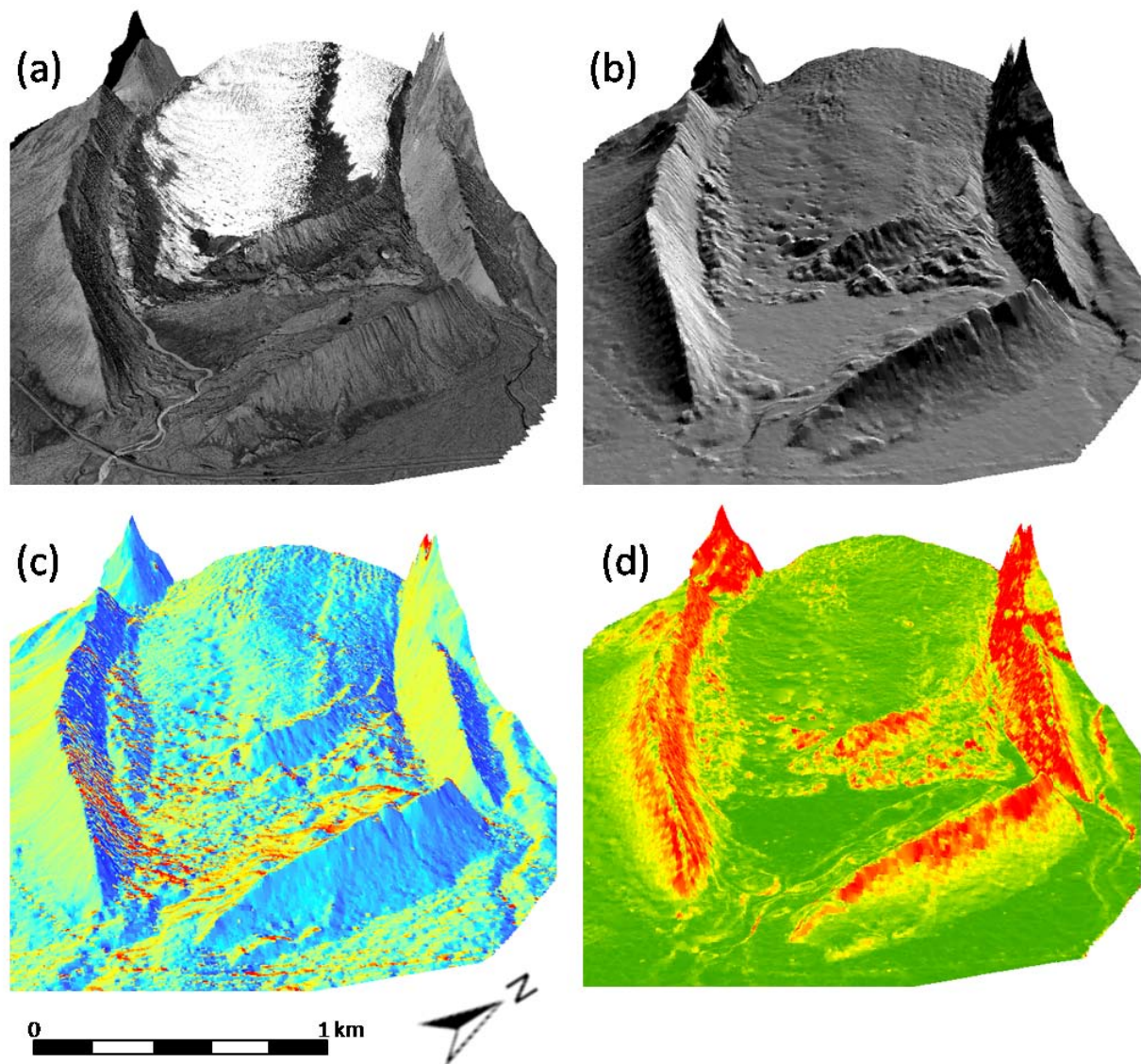
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Figure 3. Visualisations of the 1998 DEM. a) overlaid with orthophoto; b) relief shaded; c) aspect; and d) slope gradient.

kame terraces; 4) glacilacustrine deposits relate to short-lived proglacial lakes on the proximal foreland; 5) non glacial materials include paraglacial deposits or reworked glacigenic sediment, scree accumulating below bedrock cliffs and blockfield and residuum. Additionally, fresh debris flow deposits are recognized within the paraglacial category because of their extensive development on the latero-frontal moraine; 6) ancient jokulhlaup fans occur outside the latero-frontal moraine loop. Geomorphological features relevant to each of the surficial geology units are mapped using symbols and these are described below in association with the surficial units in which they occur.
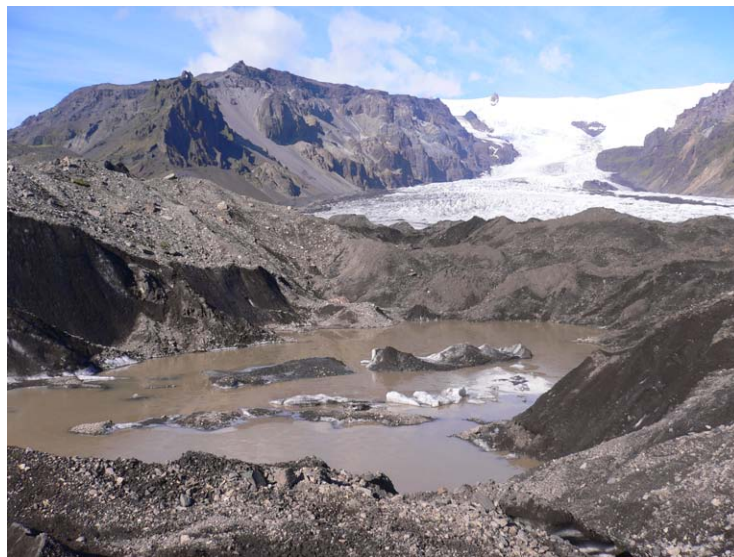
3.1   Supraglacial debris cover

A characteristic feature of Kvíárjökull is its supraglacial debris cover, a feature that prompted Eyles (1979; 1983) to propose the glacier as an exemplar of the glaciated valley landsystem (cf. Spedding and Evans, 2002). It forms a thin veneer on the glacier snout and is concentrated in a single medial moraine, separating north and south ice flow units, and at the edge of the glacier within margin-parallel/arcuate, up-ice descending, debris-rich foliae that are melting out to form 'controlled moraine' (Figure 4a; Evans, 2009a). The medial moraine characteristically widens as it approaches the glacier margin due to the increasing rate of ice ablation and concomitant lateral spreading of the debris as it melts out.

Nearer to the margin, the supraglacial debris cover represents the initial stage in the development of ice-cored moraine, referred to by Clayton (1964) as the "young phase", and at Kvíárjökull is related to active ice and transport of debris to the glacier surface along rising debris-rich folia (Spedding and Evans, 2002; Swift et al., 2006). The concentration of debris-rich ice around the snout has been related to the potential occurrence of supercooling in the overdeepening (Roberts et al., 2002), but Spedding and Evans (2002) and Swift et al. (2006) have used subglacial and fluvial clast form characteristics to demonstrate that other processes, such as englacial drainage and ogive formation at the base of the icefall, are likely more significant as debris transfer processes. The medial moraine on Kvíárjökull is fed by rockfall from a bedrock outcrop in the icefall and hence its debris can be differentiated from that melting out from the rising folia on the northern part of the glacier surface due to its red colouration and angular clast forms. A rockfall origin is also likely for the rising debris-rich folia on the south lateral margin of the glacier, because of the mono-lithological content and clast angularity; in contrast to the medial moraine, this debris has been entirely incorporated into englacial positions as ogives after its initial delivery to the glacier surface, which most likely took place on the heavily crevassed part of the snout and/or above the equilibrium line.

Nearer the frontal margin of the glacier snout, the supraglacial debris cover becomes increasingly dissected by ice-walled channels, which are occasionally continuous with englacial eskers. This suggests that the roofs of englacial and/or subglacial tunnels are collapsing or tunnel fills are being exposed as the snout thins. Together with the widening of moulins on the southern flow unit of the glacier, this is indicative of the more advanced stage of glacier downwasting, leading ultimately to "glacier karst" (Figure 4b; Clayton, 1964). However, this does not indicate glacier stagnation, as the moulins have been a conspicuous feature on the south flow unit of the snout since 1945 and therefore likely relate to a stable glacial meltwater drainage system fed by geothermal activity in the Öræfi caldera. Nonetheless, a proglacial lake has fluctuated in size between 1980 and 2003 and more recently the ponded water has started to flood the thinning snout and occupy the enlarged moulins to produce a supraglacial extension of the lake (Fi-
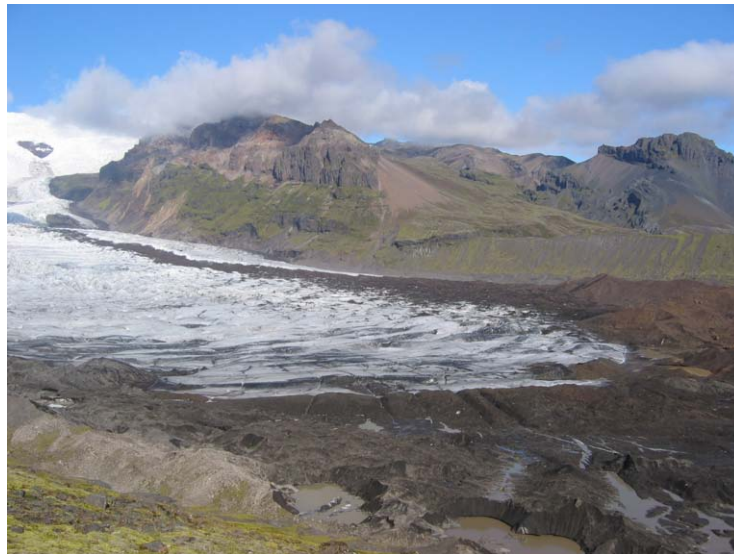
(a)

(b)

Figure 4. The supraglacial debris cover of Kvíárjökull in 2007: a) viewed across the southern flow unit, showing arcuate bands of debris-rich foliae which feather out towards the centre of the snout. Each band contains a distinct clast lithology representative of a rockfall origin in the area of the icefall. Increasing ablation towards the snout has resulted in the development of controlled moraine ridges in the middle ground. These are being consumed by the expansion of glacier karst and supraglacial lake water visible on the bottom right. Also visible in the distance is the red coloured debris of the medial moraine, which has protected the underlying ice from ablation to produce a significantly higher area on the snout; b) localized ponding, indicative of the more advanced stages of glacier downwasting and the development of glacier karst. Interbedded stratified sediments and mass flow diamictons accumulate in such hollows throughout the period of snout melting.

gure 5). The lake will most likely expand in area and depth as the overdeepening is uncovered by glacier thinning and recession (cf. Kirkbride, 2000).
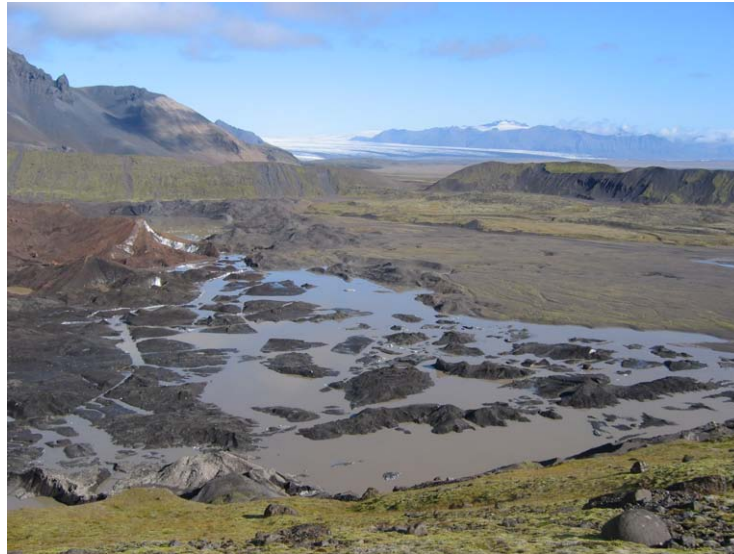
Figure 5. View northwards across the ice-marginal zone of Kvíárjökull in 2007, showing the recent development of a proglacial/supraglacial lake behind the outwash head (foreground) and controlled/hummocky moraine (middle distance). The role of the medial moraine in protecting the snout from ablation is also illustrated by the red coloured debris draping the ice cliff in the middle distance. Note also the pitted surface of the sandur fan, the channelled outwash and linear hummocky moraine in the right middle distance and beyond the latero-frontal moraine loop with its extensive debris flow scars and gullying (paraglacial deposits).

3.2   Ice-cored moraine (till)

Another characteristic feature of Kvíárjökull is its latero-frontal band of ridges or mounds with a relief greater than the adjacent supraglacial debris cover and underlain by buried glacier ice or containing remnant ice cores (Figure 6; Evans, 2009a). This is a product of differential melting and localized thickening of supraglacial debris cover by topographic reversal (cf. Kjær and Krüger, 2001) as well as the advanced development of glacier karst features such as ice walled lakes and collapsed englacial tunnels (Clayton, 1964). This landform/surficial unit is not necessarily completely detached from the glacier-snout, as is suggested to be necessary by Lukas et al. (2007) for it to be classified as "ice-cored moraine"; it is impossible to define the boundary of active snout ice, which is likely to continue locally into the ice-cored ridges and even below the pitted outwash on the foreland (Evans, 2009a).

Several features are indicative of the ice disintegration (backwasting and downwasting) and associated sediment reworking that occurs in ice-cored moraine at the mature stage of development (Kjær and Krüger, 2001). Boulder ridges are linear clusters of boulders that typically occur along the base of ice-cored slopes due to gravitational sorting of debris triggered by ice melt out (Kjær and Krüger, 2001). Sink holes with concentric tension cracks on their inner slopes are small depressions in the debris cover which indicate the collapse of underlying ice (Figure 6b). Meltwater filled depressions in the ice-cored moraine are indicative of more substantial ice cores and are mapped using

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the symbol for lakes (blue polygon with dark blue outline). They are often bounded by ice cliffs (black line with hollow triangle) exposed by slope collapse, fluvial erosion or mass-movements induced by heavy rainfall (Krüger and Kjær, 2000). Other features include eskers and controlled ridges, which are identifiable by their clast forms (higher proportions of water-worked and subglacial material) as well as their linearity amongst high relief hummocks and sink holes. Further linearity has been imparted on ice-cored moraine where it has been pushed by recent ice-marginal oscillations (Evans, 2009a, Figure 6a, c). Former englacial tunnels are also visible as elongate, sinuous sink holes.

(a)

(b)

(c)

Figure 6. Ice-cored moraine (till) at the northern margin of Kvíárjökull in 2009: a) overview of ice-cored moraine showing linearity in arcuate hummocky ridges, which record ice-marginal pushing of the buried snout ice; b) localized ponding and exposure of buried glacier ice at the locality identified by the "E" in Figure 6a. Note the tension cracks surrounding sink holes in the foreground, indicative of melt-out of deeply buried glacier ice; c) exposure through the ice-cored moraine belt in 2000, showing the compressional folding in the crudely stratified sediments at the distal margin of the feature where ice-cored ridges have been bulldozed into fully de-iced hummocks.

Since 1945 the latero-frontal arc of ice-cored moraine has migrated up valley with the receding snout, indicating that the production of debris-rich basal ice is an ongoing process. Moreover, evidence of glacier pushing of the ice-cored moraine (Spedding and Evans, 2002; Evans, 2009a) reveals that Kvíárjökull is undergoing active recession, similar to other Icelandic temperate glacier lobes where the bulldozing of marginal sediments, often annually, is common (Price, 1970; Boulton, 1986; Krüger, 1993; 1995; 1996; Evans and Twigg, 2002; Evans, 2003b; 2005; Evans and Hiemstra, 2005). The proglacial pushing of partially de-iced controlled moraine at Kvíárjökull (Figure 6a) demonstrates that the glacier is coupled to the regional climate. This glacier-climate linkage is possible because the debris cover at the snout is confined to the outer 100 m and therefore does not dampen the mass balance signal from the accumulation zone. Therefore the ice-cored moraine and hummocky moraine (see below) of the foreland is a product of "incremental stagnation" (Eyles, 1979; 1983). More specifically, the ice-cored moraine on the 1945 and 1964 maps is gradually replaced by post LIA hummocky moraine (see below) in the 1998 and 2003 maps, demonstrating a clear process-form relationship.

3.3 Post-Little Ice Age till

Recession of the glacier snout from the base of the latero-frontal moraine rampart has produced a gently undulating terrain comprising moraine complexes of margin-parallel

linear mounds or hummock chains, often containing high concentrations of water-worked clasts (Figure 7). These landforms have been formed by a combination of the melt out of 'controlled moraine' and the ice-marginal bulldozing of ice-cored moraine and pro-glacial outwash sediments during active retreat between 1964 and 1980. Prior to this time the moraine surfaces were characterized by features indicative of ice core melt-out (see above section and 1945 map). In some areas the post-LIA moraines still contain shallow sink holes and turbid lakes that record the final stage of ice-melt out (Kjær and Krüger, 2001). In the outer foreland, moraine complexes are extensively dissected by channels infilled with terraced glacifluvial deposits or ribbon sandur (Figure 7a) and are locally overrun by paraglacial sediments in the form of debris flow fans at the base of the proximal slopes of the latero-frontal moraines. Although paraglacial reworking has been intensive on the proximal slopes of the latero-frontal moraine loop, a number of inset lateral and frontal moraines have survived on the more shallow slopes surrounding the eastern end of the foreland (Figure 7b). Intensive clast form analysis undertaken by Spedding and Evans (2002) has demonstrated that the latero-frontal moraines contain significant quantities of subglacially and fluvially derived material, which increase down moraine in a fashion similar to lateral moraines in mountain terrains where materials indicative of extraglacial transport pathways are gradually diluted by those modified in the subglacial zone and those reworked from proglacial outwash (Matthews and Petch, 1982; Evans, 1999). Additionally, Spedding and Evans (2002) cite the ubiquitous evidence for englacial drainage pathways as a further transport pathway capable of clast modification. Therefore, the striking size and volume of the moraines is not indicative of abnormally high extraglacial debris provision from the steep rockwalls above the icefall (cf. Eyles, 1979; 1983).

3.4 Little Ice Age and pre-Little Ice Age till

A 'Little Ice Age' status for the bouldery materials covering the latero-frontal moraine loop is based on observations by Thórarinsson (1956) that the glacier last filled its foreland and overtopped these ridges during the LIA. Recession from the summit of the moraine loop began around 1905 AD (Evans et al., 1999a). Therefore, during the LIA the glacier deposited a mantle of till on the latero-frontal moraine loop and early recession from its summit is recorded by inset moraine ridges (Figure 8). It is recognized, however, that the latero-frontal moraines are composite features built up over the Neoglacial (Thórarinsson, 1956) and that much of the underlying material and perhaps surficial deposits on the outer moraine slopes dates to pre-LIA times. Moroever, smaller latero-frontal moraine remnants extend from the distal slopes of Kvíármýrarkambur and Kumbsmýrarkambur and are blanketed by Öræfi 1362 tephra, clearly dating them to pre-LIA times (Gudmundsson, 1997). Sections through the proximal slopes of the latero-frontal moraine loop reveal crudely to well stratified boulder to gravelly diamic-

(a)

(b)

Figure 7. Post Little Ice Age till and landforms in 1992: a) view over the linear hummocky moraine ridges on the south side of the foreland, showing spreads of ribbon sandar between moraines; b) view over linear hummocky moraine on north side of foreland, showing more complex forms likely produced by ice-marginal pushing of ice-cored moraine (cf. Figure 6a for more recent example) and the inset sequences of lateral moraines on the paraglacially gullied inner face of Kvíármýrarkambur.

tons, indicative of moraine construction by the mass flowage of glacigenic materials fed by the glacier margin. As noted in the previous section, the down-moraine increase in subglacially and fluvially modified clasts indicates that Kvíárjökull deposited the debris on the latero-frontal moraine loop after transporting it from subglacial and englacial positions, a process likely responsible for the excavation of the overdeepening. Alternatively or additionally, the glacier reworked a large outwash fan that existed on the coastal lowland prior to Neoglacial expansion (cf. Boulton, 1986; Evans and Twigg, 2002; Evans, 2003b).

(a)

(b)

Figure 8. Little Ice Age and older sediments and landforms: a) view along the summit of Kvíármýrarkambur in 2007, showing thin spread of LIA maximum boulders locally thickening to produce a small push moraine. This has been draped over the bulk of the latero-frontal moraine rampart deposited during earlier stages of ice advance in the Neoglacial; b) view along the summit of Kumbsmýrarkambur in 1992, showing the inset sequence of LIA moraine draping the older lateral moraine. Note the location of the ice margin in this view, when the uppermost of a flight of inset kame terraces depicted in Figure 10 were being constructed.

3.5   Glacifluvial deposits

Glacifluvial deposits are contained in either proglacial outwash fans (Figure 9) or kame terraces (Figure 10). Older outwash fans dating to pre-LIA or LIA time are mapped as jokulhlaup outwash and lie outside the latero-frontal moraine loop, with their apexes located at breaches in the loop, immediately below the bedrock cliffs on the north and

south sides of the glacier. Meltwater discharge from these breaches had ceased by 1945 but it was responsible for the incision of the outwash fans during early post-LIA glacier recession, as documented by moraine/valley train associations in the breaches. In the narrow lowland area between the easternmost part of the latero-frontal moraine loop and the coast, a proglacial sandur fan has been constantly occupied and reworked by meltwater since at least 1945. Since Kvíárjökull has receded inside the moraine loop, glacifluvial deposits have been concentrated in kame terraces and a small proglacial outwash fan. The latter occupies the expanding foreland and narrows due to the restricted nature of the contemporary breach in the moraine loop to the east. This fan appears partially flooded at its distal end in 1964 and 1980 when buried glacier ice started to melt out in significant volume.

Figure 9. A 2007 view over the proglacial outwash fan that has been deposited over the glacier snout. Note the outwash head or ice-contact slope at the margin of the overdeepening now filled with lake water. Surface pitting along the fan surface attests to the melt-out of snout ice.

The sequence of maps charts the evolution of the proglacial and lateral glacifluvial assemblages and depicts the influence of ice melt and changing sediment delivery on their form. In 1945 meltwater drained from the centre of the snout terminus, creating a small outwash fan in a corridor through the ice-cored moraine on the foreland. By 1965 the apex of the fan had shifted northwards and by 1980 further drainage was coming from the northern margin of the glacier via the expanding lakes produced by melt-out of buried ice in the ice-cored moraine belt. Consequently, the proglacial fan surface descended in altitude from north to south and ran parallel to the frontal margin of the glacier. Each of these phases is associated with the development of kettle holes and the production of pitted sandur due to the progradation of sands and gravels over the glacier snout and over the remains of reworked ice-cored moraine tracts. By 1998 the fan apex had again shifted southwards to the centre of the snout and kettle holes were fewer in number all over the fan surface, probably due to increased sediment flux and glacifluvial deposition. A further shift in the meltwater efflux point by 2003 shows that drainage was predominantly from two expanding proglacial/supraglacial lakes at the northern and southern glacier margins, likely precursors to a future large proglacial lake situated

in the overdeepening. The outwash fan as a consequence is now elevated above the lakes and is therefore relict. Its abandonment has once again led to the development of a pitted surface due to the melt-out of buried glacier ice. Eskers and fragmented water-filled channels emerging on the adjacent glacier surface in 2003 (Figure 11), all converge on the outwash fan apex, revealing the englacial drainage network that formerly fed the fan.

Unlike ice-contact outwash fans reported at other Iceland glacier snouts, which typically display pitted surfaces at their apexes, the Kvíárjökull proglacial fan has always, with the exception of 1998, contained pits along its entire length, attesting to the burial of an extensive area of glacier snout due to progradation of glacifluvial sediment into the overdeepening (Figure 9). This is best illustrated in the 2003 map where the distal,

(a)

(b)

(c)

Figure 10. Kame terraces along the northern margin of Kvíárjökull: a) view from ice-cored hummocky moraine in 2009, showing accordant surfaces of terrace remnants in the distance which give the impression of continuous benches; b) view across older terraces (left) towards freshly deposited features at the ice margin, showing the importance of ongoing incision and tunnelling of buried ice and concomitant collapse of overlying gravel bench; c) exposure of buried glacier ice in the kame terraces being deposited in 1992 (appearing at left in Figure 9b) at a time when marginal meltwater began to disappear sub-marginally through englacial tunnels. The collapse of ice tunnel roofs leads to the deposition of ice-walled channel fills or supraglacial trough fills, which are locally attached to kame terraces. This process also leads to the juxtaposition of eskers and kames.

Figure 11. Supraglacial esker emerging from the downwasting glacier snout in 1998. The tops of these features were beginning to emerge on the glacier surface in 1992.

eastern as well as the western, ice-contact margins of the sandur fan have collapsed to form linear extensions of the southern proglacial/supraglacial lake (Figure 4b).

Since 1945 glacifluvial sediment has accumulated between the proximal slope of the latero-frontal moraine loop and the northern margin of the glacier in a series of kame terraces that have partially buried the thinning snout (Figure 10). The large volume of

glacier ice beneath these features is evidenced by extensive faulting and collapse. Older features have been almost totally fragmented by ice melt-out and consequently their former horizontal surface is only apparent in the accordance of the remnant surfaces (Figure 10a). The kame terraces are locally draped by mounds and ridges of red-coloured, angular medial moraine debris dumped directly from the glacier snout on to the accumulating glacifluvial landforms.

Smaller areas of glacifluvial deposits occur in ribbon sandar between moraine ridges in the post-LIA till units (Figure 7a). This network of ribbon sandur and channels was well developed by 1964 and largely relict by 1980, attesting to the melt-out, fluvial reworking and gradual stabilization of ice-cored moraine between 1945 and 1980.

Glacifluvial deposits are also contained within eskers, which at Kvíárjökull occur as discontinuous sinuous gravelly ridges that can be traced from englacial and supraglacial positions to the ice-cored moraine around the glacier margin (Figure 11). The emergence, and in most cases in the ice-cored moraine the disappearance, of these eskers through the sequence of maps indicates that they relate to englacial drainage networks (cf. Spedding and Evans, 2002) whose traces become fragmented by the progression of ice core melt-out. If englacial tunnel drainage is widespread in the snout, as envisaged by Spedding and Evans (2002) based on observations on emerging landforms and clast form data, the relict outwash fan that overlies an extensive part of snout ice in the overdeepening should continue to collapse and gradually expose eskers in a similar fashion to the sandar and esker systems at Breiðamerkurjökull (Price, 1969; Evans and Twigg, 2002).

3.6   Glacilacustrine deposits

Substantial proglacial lakes have developed intermittently on the foreland of Kvíárjökull, specifically in 1964, 1980 and 2003, where the downwasting snout has locally been flooded before proglacial outwash aggrades and fills up the accommodation space provided by the overdeepening (Figure 2). On the deglaciated forelands of southern Iceland such lakes typically occupy the ice-proximal depressions formed by the abandonment of ice-contact outwash fans or outwash heads (e.g. Howarth and Price, 1969; Evans and Twigg, 2002). At Kvíárjökull additional lakes are produced within tracts of downwasting ice-cored moraine, where the lake water is at least partially supraglacial in nature (Figure 5). This is best illustrated at the northern margin of the snout where until at least 1964 a narrow lake occupied the depression between ice-cored moraine and lateral moraine. This had disappeared by 1998, a time when no lakes appeared anywhere on the foreland, but a substantial lake was developing in the ice-cored moraine at the northern snout margin by 2003 (Figure 6a). The ephemeral nature of the proglacial/supraglacial

lakes at Kvíárjökull, together with their development in a confined foreland that is largely ice-cored and repeatedly reworked by melt-out and meltwater streams, results in the very restricted accumulation of glacilacustrine deposits. The reworking of these deposits is well illustrated in the maps by their changing areal extent over time. Nonetheless, the maps allow us to predict that glacilacustrine deposits will interdigitate with glacifluvial and mass movement deposits in a complex sequence of folded and faulted sediments in a hummocky terrain once the foreland at Kvíárjökull has undergone complete melt-out.

3.7 Non-glacial materials (paraglacial deposits, scree and residuum)

Scree and residuum occur in small areas at the bases of the bedrock buttresses that form the northeastern and southeastern boundaries of Kvíárjökull. Although residuum is predominantly the product of weathered bedrock, some highly weathered and wind-deflated glacially transported material may be present. Paraglacial deposits comprising colluvially re-worked glacial sediments occur extensively on both the proximal and distal slopes of the latero-frontal moraine loop, with the degree and intensity of reworking increasing through time, especially as distal slopes become more extensive due to glacier downwasting. Paraglacial deposits are dominated by debris flow features such as channels and levees and lobate fans or cones (Figures 7b, 12). Due to the increasing importance of paraglacial slope processes around the foreland, fresh debris flow deposits are identified as a separate surficial unit in the 2003 map.

Figure 12. Debris flow lobe and source gully on the inner slopes of Kvíármýrarkambur.

4. Synopsis

The frequency of aerial photography of many Icelandic glacier snouts and forelands has facilitated time series mapping of landform-sediment assemblages indicative of specific glacial landsystems (Price, 1969; Evans and Twigg, 2002; Evans et al., 2007; 2009a;b; Benediktsson et al., 2008). These modern process-form analogues are also long term cryospheric monitoring programmes that serve as powerful diagnostic criteria for palaeoglaciological reconstructions in an arena of geomorphology that is traditionally heavily reliant on ergodic principles. Our maps of Kvíárjökull record the evolving patterns of landform and sediment associations relating to the recession of a debris-charged glacier snout lying above an overdeepening. Although it is now recognized that Kvíárjökull is not an appropriate exemplar of the glaciated valley landsystem due to its piedmont tongue morphology and the dominance of actively over passively transported debris (cf. Eyles, 1983; Spedding and Evans, 2002; Evans, 2005; Swift et al., 2006), it nonetheless has much in common with the moderate debris/high ice flux end of the glaciated valley landsystem continuum identified by Benn et al. (2003), in which debris cover does not buffer glacier responses to short timescale (annual-decadal) climatic signals and strong coupling between glacier and proglacial meltstreams leads to the development of an outwash head.

The maps of Kvíárjökull presented in this paper illustrate how complex transport pathways in a temperate, debris-charged piedmont glacier are manifest in the landform record over a sustained period of glacial retreat and moraine formation. They also document the evolution of a glacier foreland characterized by an overdeepening, which has become increasingly effective as a depositional sink for ice-marginal glacifluvial sediments. Additionally, the enclosure of the glacier foreland by the latero-frontal moraine loop has resulted in the aggradation of glacifluvial outwash on the immediate foreland and the concomitant burying of the downwasting glacier snout. Continued melt-out of the buried snout ice is manifest in extensive pitting of the proglacial sandur surface and the expansion of proglacial lake water which links up with supraglacial lakes developing from expanding glacier karst.

The changing ice-marginal dynamics and glacier-topography interactions charted in our maps since 1945, allow the sub-division of the foreland of Kvíárjökull into three zones. Zone A comprises the latero-frontal moraine loop, which accumulated as a sequence of ice-contact, debris flow-dominated fans during a sustained period or periods of positive mass balance (Matthews and Briffa, 2005, Little Ice Age Type Events; LIATE's,). The moraine loop summit was abandoned by the receding glacier margin at the turn of the 20th Century, at which point depositional processes on the ice-proximal slopes were dominated by paraglacial reworking, interrupted by latero-frontal push and dump moraine construction. The latter form an inset sequence of ridges documenting active recession, but moraine continuity has been progressively destroyed by

paraglacial processes. Kame terraces also developed along the northern and southern margins of the glacier but their positioning on the steep proximal faces of the latero-frontal moraine loop has resulted in significant downslope failure in addition to disaggregation by ice melt-out. Kame terraces are unusual features for a temperate piedmont tongue or lobe and exist at Kvíárjökull only because of the lateral boundary formed by the older moraine loop. This large topographic boundary has forced meltwater streams to follow the ice margin, where they often disappear and continue sub-marginally or englacially before reappearing nearer the snout. Since 1998 the streams have failed to reappear along the margin, probably feeding instead into the proglacial/supraglacial lakes developing in the overdeepening.

Zone B is the outer part of the foreland, inside the lower proximal slopes of the eastern end of the latero-frontal moraine loop, where post-LIA moraines comprise discontinuous chains of elongate hummocks separated by pitted glacifluvial channels. These landforms constitute evidence of ice-marginal oscillations, and therefore the only indications likely to survive complete deglaciation that Kvíárjökull is an active temperate snout. This moraine is an assemblage of bulldozed, ice-cored ridges that have locally been channelized by marginal, submarginal and supra-marginal meltwater to produce margin-parallel ribbon sandar. Ridge size reflects the former englacial debris concentration as well as the duration of snout stillstand. No subglacial tills have been observed at Kvíárjökull, a reflection of the predominantly supraglacial and proglacial nature of moraine construction in ice-contact glacifluvial material.

Zone C covers the ice-marginal zone and proglacial sandur fan and is characterized by widespread collapse due to the melt-out of buried glacier ice. This comprises areas of controlled moraine with their signatures of ice-marginal pushing, kame terrace and ice-contact sandur fan. The landform-sediment assemblage that is gradually evolving in this zone will, upon complete deglaciation, be characterized by predominantly chaotic hummocky terrain and heavily kettled surfaces lying on the down-ice or adverse slope of an overdeepening. It is the location of the overdeepening that is conditioning the nature of landform development. Localized linear pockets of sediment with specific grain size and clast form characteristics will mark the former locations of englacial debris concentrations such as eskers, rockfall concentrations and debris-rich foliae. Larger englacial and subglacial meltwater networks may form sinuous ridges (eskers and moulin fills) once they emerge from beneath the melting snout and controlled moraine (cf. Evans and Twigg, 2002). Changes between 1998 and 2003 document the recent expansion of the area of supraglacial ponding and indicate that the glacier snout is beginning to downwaste into the overdeepening. Additionally, the pitting on the downstream end of the proglacial sandur fan is indicative of future collapse of the surface. The pitting of the sandur surface appears to have been interrupted in the 1998 map, when the distal outwash prograded into the proglacial lake visible in 1980. The mid 1990's was a period when Kvíárjökull, like some other south coast snouts, readvanced in response to sustained changes in the North Atlantic Oscillation (Bradwell et al., 2006; Sigurdsson, 2005)

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resulting in the bulldozing and freshening of the linearity of the ice-marginal controlled moraine (Spedding and Evans, 2002; Evans, 2009a). The reduction in areal extent of pitting on the proglacial sandur between the 1980 and 1998 maps was most likely a result of the same readvance, whereby meltwater and glacifluvial sediment was temporarily delivered to the fan apex again after a period of decoupling due to snout thinning below the outwash head.

Acknowledgements

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