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- Rapid reduction in active glacier length during retreat
- Thrusting of detached active section over the stagnant lower section
- Structural response allows rapid reequilibration to changes in mass balance

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Structural evolution triggers a dynamic reduction in active glacier length during rapid retreat: Evidence from Falljökull, SE Iceland

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Abstract Over the past two decades Iceland's glaciers have been undergoing a phase of accelerated retreat set against a backdrop of warmer summers and milder winters. This paper demonstrates how the dynamics of a steep outlet glacier in maritime SE Iceland have changed as it adjusts to recent significant changes in mass balance. Geomorphological evidence from Falljökull, a high-mass turnover temperate glacier, clearly shows that between 1990 and 2004 the ice front was undergoing active retreat resulting in seasonal oscillations of its margin. However, in 2004–2006 this glacier crossed an important dynamic threshold and effectively reduced its active length by abandoning its lower reaches to passive retreat processes. A combination of ice surface structural measurements with radar, lidar, and differential Global Navigation Satellite Systems data are used to show that the upper active section of Falljökull is still flowing forward but has become detached from and is being thrust over its stagnant lower section. The reduction in the active length of Falljökull over the last several years has allowed it to rapidly reequilibrate to regional snowline rise in SE Iceland over the past two decades. It is possible that other steep, mountain glaciers around the world may respond in a similar way to significant changes in their mass balance, rapidly adjusting their active length in response to recent atmospheric warming.

1. Introduction

Retreating glacier margins are often considered to behave in two ways: (i) "active retreat" where the margin oscillates on an annual cycle, as retreat due to summer melt is offset by forward motion resulting in a small readvance during the cold winter months [e.g., *Krüger*, 1995; *Evans and Twigg*, 2002; *Benn and Evans*, 2010] and (ii) "passive retreat" where the glacier margin is no longer moving forward and simply stagnates, retreating by in situ melting or "downwasting" [e.g., *Schomacker et al.*, 2014]. Annual recessional moraines occur in front of many Icelandic glaciers including Skálafellsjökull [*Sharp*, 1984], Mýrdalsjökull [*Krüger*, 1995], Lambatungnajökull [*Bradwell*, 2004], Breiðamerkurjökull, and Fjallsjökull [*Price*, 1970; *Evans and Twigg*, 2002]. The magnitude of the oscillations exhibited by an actively retreating margin are strongly dependent on the glacier's mass balance, which is partially controlled by climatic factors, such as temperature and precipitation (snow fall), averaged over time [*Ahlmann*, 1940; *Björnsson and Pálsson*, 2008]. Owing to their maritime North Atlantic setting, high-mass turnover and steep gradients, southern Iceland's glaciers are particularly sensitive to climatic fluctuations on annual to decadal timescales [*Jóhannesson and Sigurðsson*, 1998; *Sigurðsson et al.*, 2007], making them an ideal natural laboratory for the study of glacier response during the current period of climate change.

This paper presents the results of a multidisciplinary study at Falljökull, SE Iceland, (Figure 1a) and shows that this glacier does not fit the simple two-end-member model of retreat. Continuous differential Global Navigation Satellite Systems (GNSS) monitoring of glacier surface velocity over a 12 month period, Ground Penetrating Radar (GPR) and terrestrial light detection and ranging (lidar) surveys, coupled with detailed structural glaciological studies and geomorphological analysis of recent glacial landforms are used to show that Falljökull has undergone an evolving, structurally complex history of retreat which reflect changes in its dynamics. The study, which builds upon the previous work of *Bradwell et al.* [2013] and *Phillips et al.* [2013] allows this retreat history to be divided into three stages, each corresponding to changes in glaciological response as it retreated from a well-constrained position at the end of a significant ice front advance between 1970 and 1990 [*Sigurðsson et al.*, 2007; *Bradwell et al.*, 2013]. A structural glaciological model is proposed by which Falljökull and potentially other Alpine-type glaciers with steep gradients can rapidly adapt to negative changes in their mass balance by reducing their active length.

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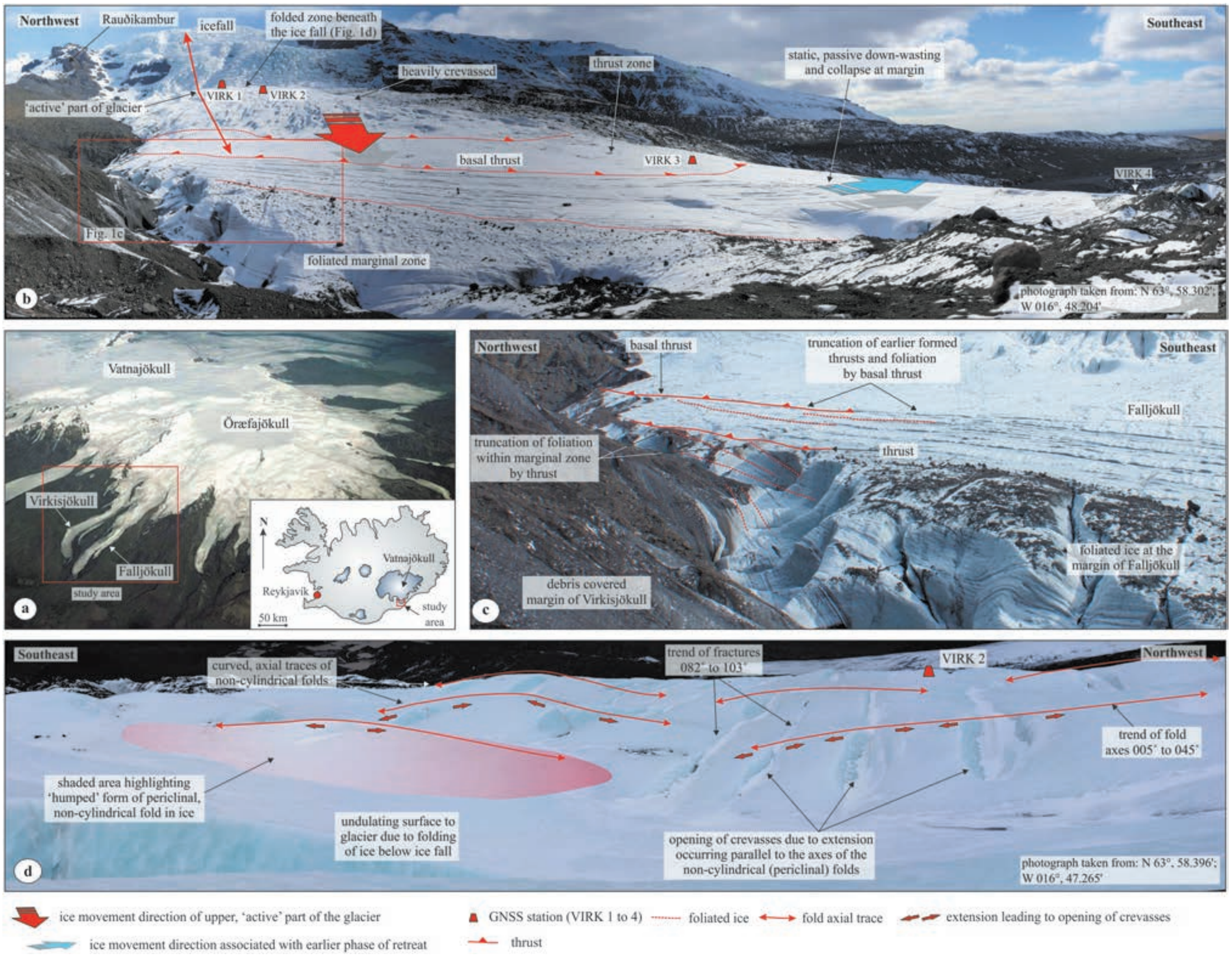

Figure 1. (a) Oblique air photograph of Öræfajökull showing the location of the twin outlet glaciers Virkisjökull and Falljökull (image from LineLeak.com). Inset—Simplified map of Iceland showing the location of the study area on the southern side of the Vatnajökull ice cap. (b) Photograph of Falljökull showing the main glaciological deformation structures, ice movement directions in the upper and lower parts of the glacier, and the location of four GNSS stations (VIRK 1 to 4). (c) Photograph of the northwestern margin of Falljökull showing the basal thrust cutting earlier formed thrusts and zone of steeply inclined foliated ice. (d) Photograph showing the undulating surface of the glacier immediately below the icefall reflecting the periclinal folding of the ice.

2. Location of Study Area and Glaciological Setting

Falljökull in SE Iceland forms the southern arm of the twin outlet glacier Virkisjökull-Falljökull which drains the southwestern flank of the Öræfajökull ice-capped stratovolcano—the southernmost accumulation center within the much larger Vatnajökull ice cap (Figure 1a). These steep glaciers descend from their combined source area at over 1500 m above sea level (asl), to below 150 m asl within just 2 to 3 km, via steep icefalls which feed ice to the lower part of the glaciers (Figure 1b). At higher altitudes (above 600 m asl) the two arms of the twin outlet glacier are separated by a prominent bedrock ridge known as the Rauðikambur which provides the principle source for a wide supraglacial debris band, or medial moraine marking the boundary between the glaciers when they merge down valley. In the eighteenth and nineteenth centuries the terminal zone of the glaciers extended ~2 km down valley beyond their present positions [*Danish General Staff*, 1904; *Guðmundsson*, 1997]. However, in the period since 1932 both Virkisjökull and Falljökull have undergone over 1200 m of retreat punctuated by one major advance of approximately 180 m which took place between 1970 and 1990 [*Sigurðsson*, 1998; *Bradwell et al.*, 2013]. The present study focuses on the

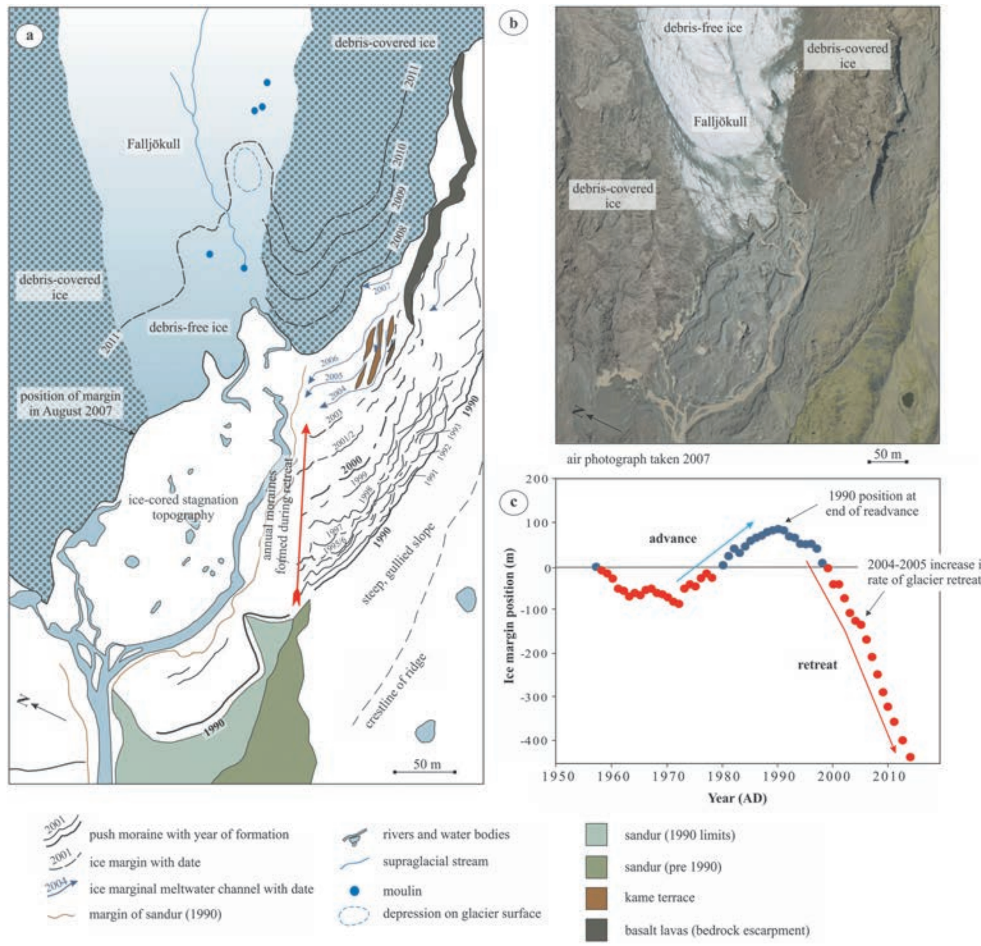

Figure 2. (a) Geomorphological map of the forefield of Virkisjökull and Falljökull constructed using upon air photographs taken in 2007 and showing the annual recessional moraines, meltwater channels, and area of ice-cored stagnation topography formed during the retreat of this twin outlet glacier [after *Bradwell et al.*, 2013]. Also shown is the position of the ice margin between 2007 and 2011. (b) Graph showing the variation in ice margin position at Falljökull between 1960 and 2013.

evolution of Falljökull as it retreated from this 1990 readvance limit with a suite of newly acquired data demonstrating that this glacier has now crossed a "threshold" and is undergoing rapid structurally complex retreat in response to recent ablation and mass balance changes.

3. Methodology

The continuing evolution of Falljökull over the past two decades is recorded in the glacigenic landforms (recessional moraines, eskers, and meltwater channels) preserved within its foreland and deformation structures (thrusts, faults, and foliations) present within the glacier itself. Understanding this complex record has required a multidisciplinary approach using the following methods.

3.1. Geomorphological Analysis

Geomorphological analysis of the glacigenic landforms within the foreland of Falljökull was made using vertical aerial photographs, supplemented by field photographs and field survey (Figure 2). High-resolution (ground sampling distance = 0.2 m) digital scans of seven vertical analogue aerial photographs (National Land Survey of Iceland) taken between 1945 and 2007 were georectifed and imported into ArcGIS 9.3, with the most recent (2007) digital color image (Natural Environment Research Council (NERC) Airborne Research Survey Facility) being used for on-screen geomorphological mapping. Positional ground control data were collected in the field using a geodetic-grade Leica ViVa dGPS during 2010 and 2011 with an accuracy of

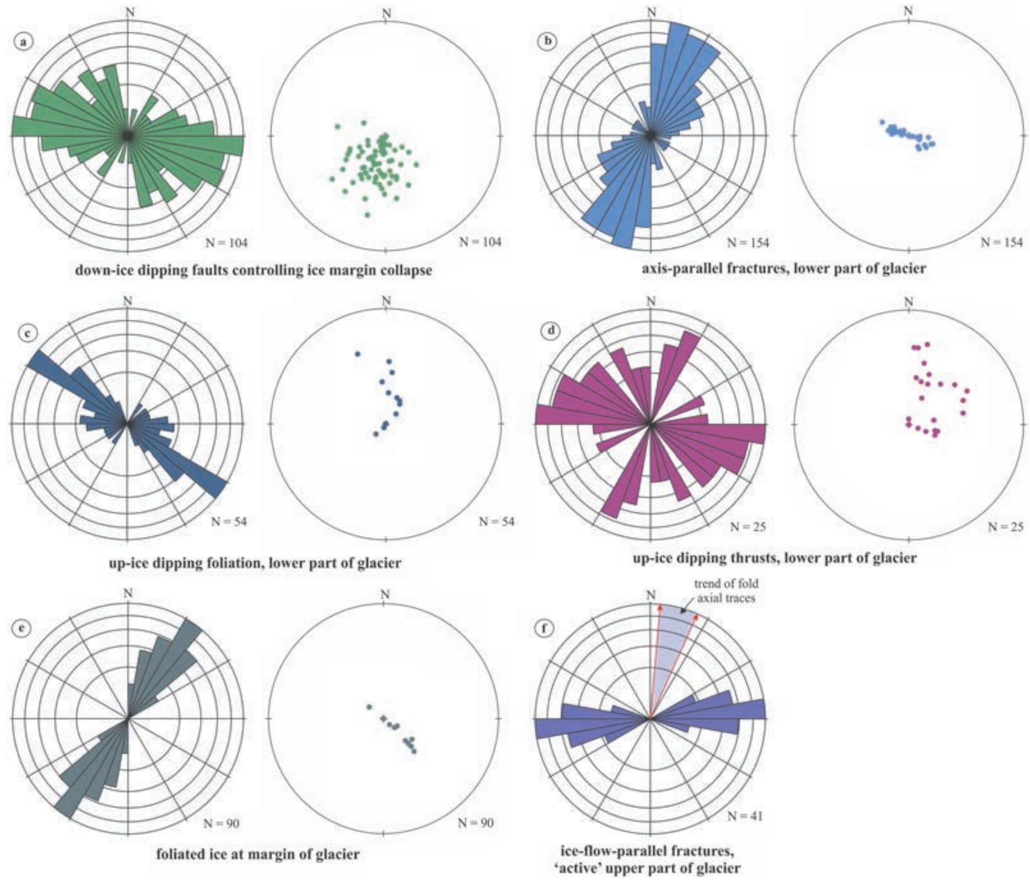

Figure 3. Structural data plotted on a series of rose diagrams (strike) and lower hemisphere stereographic plots (dip and dip azimuth): (a) Down-ice dipping faults; (b) axis-parallel fractures, lower part of the glacier; (c) up-ice dipping foliation, lower part of glacier; (d) up-ice dipping thrusts, lower part of the glacier; (e) foliation at western margin of Falljökull; and (f) trend of ice flow-parallel fractures and fold axes in active upper part of the glacier.

0.03 m in x and y and 0.05 m in z. The recessional moraines were surveyed in the field to derive ridge height (±0.1 m), width (±0.5 m), and spacing (±1 m). Where possible, three transects of ridge morphology and spacing were measured. Ice front measurements since 1990 (made by the Icelandic Glaciological Society [*Sigurðsson*, 1998]) were cross referenced with field mapping to ascertain the formation frequency of the moraines. In addition, field photographs taken from the same location over a period of 18 years (1996–2014), supported by aerial photographs, were used to determine the exact ice margin position with respect to moraines formed between 1990 and the present day.

3.2. Structural Glaciology

A structural glaciology study of the large-scale pattern of deformation within Falljökull carried out in April 2012 and April 2013 involved detailed surface mapping along a series of traverses across the glacier recording the orientation (dip, strike, and dip azimuth), sense and amount of offset (where applicable), and interrelationships between the various sets of faults, fractures, and foliations. The orientations of the planar structures were measured using a compass clinometer (corrected for magnetic deviation) with the data displayed on a series of lower hemisphere stereographic projections and rose diagrams (Figure 3). The trends of the axial traces of mesoscale to large-scale folds developed within the upper part of the glacier were also recorded. The subsurface structural characteristics of the glacier were examined in a number of 5 to 15 m high ice cliff sections located along south/southeast margin of Falljökull. Particular emphasis was placed upon determining the interrelationships between the various generations of structures allowing a detailed relative chronology of ice deformation to be established.

3.3. GPR Survey

A GPR survey to investigate glacier thickness and internal structure was conducted in April 2012 and April 2013, using a PulseEKKO™ Pro system with 50 and 100 MHz antennae. Survey lines covered 5 km of surface travel and were completed both parallel and perpendicular to ice flow. Antennae were aligned perpendicular to the survey direction and were towed manually across the glacier surface at 0.25 and 0.5 m intervals. Raw GPR data were processed in EKKO View Deluxe [*Sensors and Software*, 2003]. Processing consisted of applying a dewow filter, band-pass filtering, 2-D migration, and topographic correction. A radar wave velocity of 0.156 m ns^{-1}, previously calculated for Falljökull [*Murray et al*., 2000], was used for processing and interpretation of the profiles. Profiles were imported into GOCAD™ to allow viewing and interrogation of multiple profiles together with lidar surfaces in a 3-D environment.

3.4. Terrestrial Lidar Survey

Two terrestrial lidar surveys were carried out in September 2011 and September 2012. The first was conducted to obtain a surface model, and a derived surface fracture map, for the clean ice glacier margin (reported in *Phillips et al*. [2013]). The second survey used multiple instrument setups at a series of locations on and around the glacier to build a surface model for the whole ablation area below the icefall. Data sets were captured using a Riegl VZ-1000 system and accurately referenced to a common coordinate system. A high-resolution digital camera mounted on the scanner allowed for the capture of colored point clouds (ASCII format data comprising *x*, *y*, *z*, intensity, and red-green-blue color values). These data were oriented using the relative differential Global Navigation Satellite Systems (GNSS) positions of both the scanner and the back sights and, once processed, a Virtual Outcrop Model of the glacier and glacial margin were produced. The RiScanPro package was used to align individual scans and check for errors in orientation. Surface 3-D digital elevation models (DEMs) were created using Surfer and I-Site Studio.

3.5. Continuous GNSS Monitoring

Four Leica GS10 single-frequency GNSS units attached to large metal tripods were deployed on Falljökull in April 2012 to investigate ice surface velocity. A Leica GR10 dual-frequency GNSS unit was setup as a permanently recording base station, on stable ground away from the ice, in order to accurately monitor the rate of glacial movement. The data (downloaded April 2013) were processed in Leica Geo-Office, with positional change and glacier surface flow velocities calculated using Microsoft Excel and Surfer. The feet of each tripod were attached to 300 mm screws that enabled it to melt into the ice and then remain secured in place; this resulted in an initial "settling in" period of 10–15 days while the unit established a secure "locked-in" position. The first 6 months of data are "noisy" compared to the remaining data due to a malfunction of the GNSS base station (after 28 days). Consequently, the positional data relied on the accuracy of postprocessing using the Continually Operating RINEX Stations (CORSs) maintained by the Icelandic Meteorological Office. RINEX stands for Receiver Independent Exchange Format and is an interchange format for raw satellite navigation system data that allow the user to postprocess the received data to produce a more accurate result. Using this approach, the positional accuracy of the GS10 units was improved after 6 months when CORS data were obtained from two stations located with baseline lengths much closer to Falljökull. The Icelandic RINEX stations used in this study are KVSK, EYVI, GFUM, and HOFN.

4. History of Retreat at Falljökull

The detailed analysis of the glacial landforms and deformation structures present within Falljökull have revealed that the dynamics of this glacier have changed significantly over the past two decades as it has adjusted to major changes in mass balance [*Sigurðsson et al*., 2007; *Bradwell et al*., 2013; *Phillips et al*., 2013]. These changes have occurred as Falljökull retreated from the well-constrained 1990 readvance limit marked by a prominent push moraine. For ease of description this retreat history has been divided into three stages, the evidence for which is described below.

4.1. Stage 1—Active Retreat During the Period 1990 to 2004

The geomorphological record preserved on the foreland of Falljökull shows that prior to 2004 the glacier margin was undergoing active retreat (Figures 2a and 2b), with oscillations due to minor (yearly) winter-spring readvances leading to the development of a series of annual recessional moraines [*Sigurðsson et al*., 2007;

Bradwell et al., 2013]. A detailed account of this landform record has previously been published by *Bradwell et al.* [2013] and is therefore only summarized here.

Measurements of ice margin positions have been made annually in Iceland since the 1930s [*Jóhannesson and Sigurðsson*, 1998], providing a detailed baseline against which to chart glacier retreat of Falljökull from the 1990 push moraine (Figure 2c). Geomorphological mapping has revealed that the size of the annual recessional moraines formed between 1990 and 2003 gradually decreases, while their spacing generally increases. This relationship strongly suggests an increased summer melt rate between these years, accompanied by a decrease in the magnitude of the winter/spring readvance [*Krüger*, 1995; *Evans and Twigg*, 2002; *Bradwell et al.*, 2013]. Yearly ice front measurements, supported by the spacing between annual moraines, show that the average retreat rate between 1990 and 2004 was around 14 m yr^{-1} [*Bradwell et al.*, 2013], coinciding with a 15 year period of increasing summer temperatures [*Sigurðsson*, 1998, 2005]. Measurements show a marked, twofold, increase in the average rate of ice front retreat since 2004, which has remained high over the past 7 years at approximately 35 m yr^{-1} (Figure 2c) despite summer temperatures having not increased significantly over this period.

Since 2005 the geomorphological record has been dominated by deposition of proglacial outwash sediments and fans cut by a series of meltwater channels (Figures 2a and 2b). Importantly, no annual moraines have formed since 2004, consistent with the glacier margin no longer advancing during the winter-spring. Consequently, it is concluded that at some point during the period 2004–2006 Falljökull crossed a threshold which led to a change from active retreat, with a seasonally oscillating ice margin, to passive downwasting and stagnant ice margin collapse [*Bradwell et al.*, 2013; *Phillips et al.*, 2013].

This change from active to passive retreat appears to have coincided with a marked decline, or the switching off of an overpressurized subglacial drainage system. Field observations made at the front of Falljökull record that prior to 2005, overpressurized englacial and/or subglacial meltwater formed a series of artesian upwellings or fountains along the glacier margin during the spring/summer. However, since this time such features have been absent, consistent with a fall in hydrostatic pressure. Overpressurized subglacial drainage systems are thought to facilitate basal sliding and thereby the forward motion of glaciers [*Hubbard et al.*, 1995; *Clarke*, 2005; *Schoof*, 2010; *Sundal et al.*, 2011]. Consequently, a switching off or marked decline in pressure of the subglacial drainage system at Falljökull may have contributed to a reduction in its forward motion and the cessation of active retreat.

4.2. Stage 2—Passive Downwasting and Ice Margin Collapse, 2005 to Recent

Since 2005 the geomorphology around the margins of Falljökull has become dominated by an area of ice-cored stagnation topography (Figure 2a), comprising buried ice mantled by a relatively thin (1–3 m thick), pitted veneer of sand and gravel outwash, and glaciolacustrine deposits (Figure 2b). Linear chains of sink holes mark the position of collapsing englacial drainage channels within the buried ice which is up to 40 m thick. These channels, along with surface drainage, feed meltwater to a proglacial lake which periodically develops in front of the glacier, as well as the proglacial river system which drains the catchment. Similar dead-ice environments are forming at the retreating margins of a number of Icelandic glaciers, including Kötlujökull [*Kjær and Krüger*, 2001], Bruarjökull [*Kjaer et al.*, 2008], and Eyjabakkajökull [*Schomacker et al.*, 2014].

The clean, debris-free ice at the margin of Falljökull dips gently southward beneath the mantle of glacial outwash. Work by *Phillips et al.* [2013] has shown that the collapse of the margin of Falljökull takes the form of a multiple rotational failure which is progressively propagating up-ice over time. Collapse is controlled by several large, moderately to steeply (40° to 90°) down ice (S-SW) dipping normal (extensional) faults (Figures 3a and 4). The faults are marked by zones of locally intense brittle fracturing orthogonal (E-W trending; Figure 3a) to the former ice flow direction (S/SW). As the fault-bound blocks of ice slip down-slope they rotate leading to localized compression and the formation of down-faulted graben-like structures observed on the glacier surface [*Phillips et al.*, 2013]. Between September 2012 and April 2013, continued movement on one of the down-ice dipping normal faults has led to the glacier surface being vertically offset by approximately 4 to 5 m (Figure 4a), clearly showing that fault-controlled ice margin collapse can have a profound effect on the rate of surface lowering. From Figure 4a it is clear that a number of englacial meltwater channels are preferentially developed within this fault zone. Furthermore, ablation of the surface

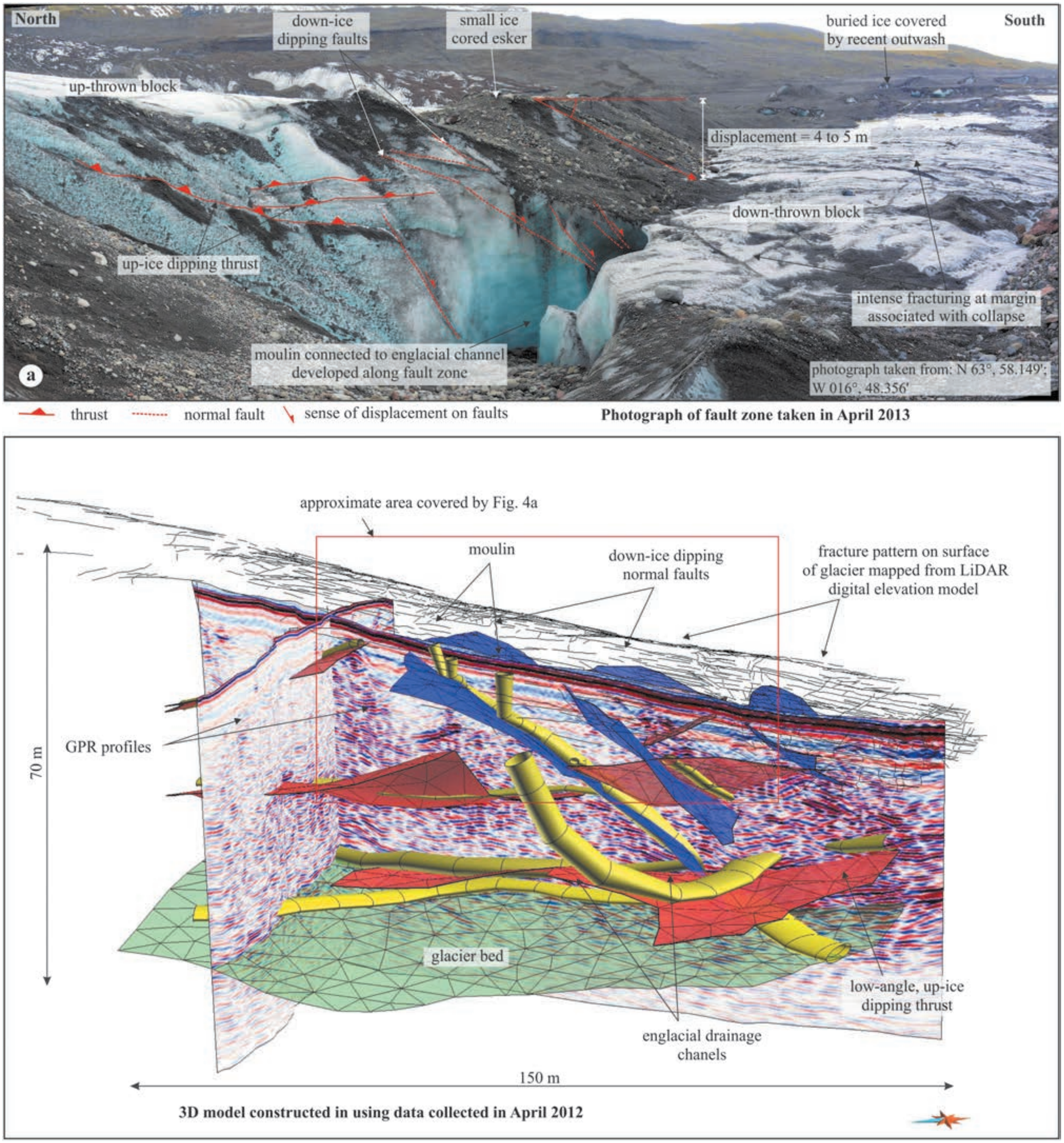

Figure 4. (a) Photograph showing the offset across a large, down-ice dipping normal fault controlling the collapse of the glacier margin (see text for details) and (b) 3-D model of collapsing margin of Falljökull constructed using GPR profiles and surface observations. The prominent down-ice dipping fault is the same structure shown in Figure 4a and shows that this fault extends through the ice to the glacier bed. Also shown is the proposed relationship between the englacial drainage channels and the down-ice dipping faults and up-ice dipping thrusts.

of the glacier has revealed a small ice-cored esker preserved within the immediate hanging wall of the fault, marking the position of a former channel which was aligned parallel to the strike of this brittle structure. Moulins also occur along this large fault with surface observations indicating that they are linked to active englacial drainage channels. A GPR survey of the marginal zone of the glacier in April 2012 combined with surface observations of the fault zone made in April 2012 and 2013 has allowed a detailed 3-D model of this

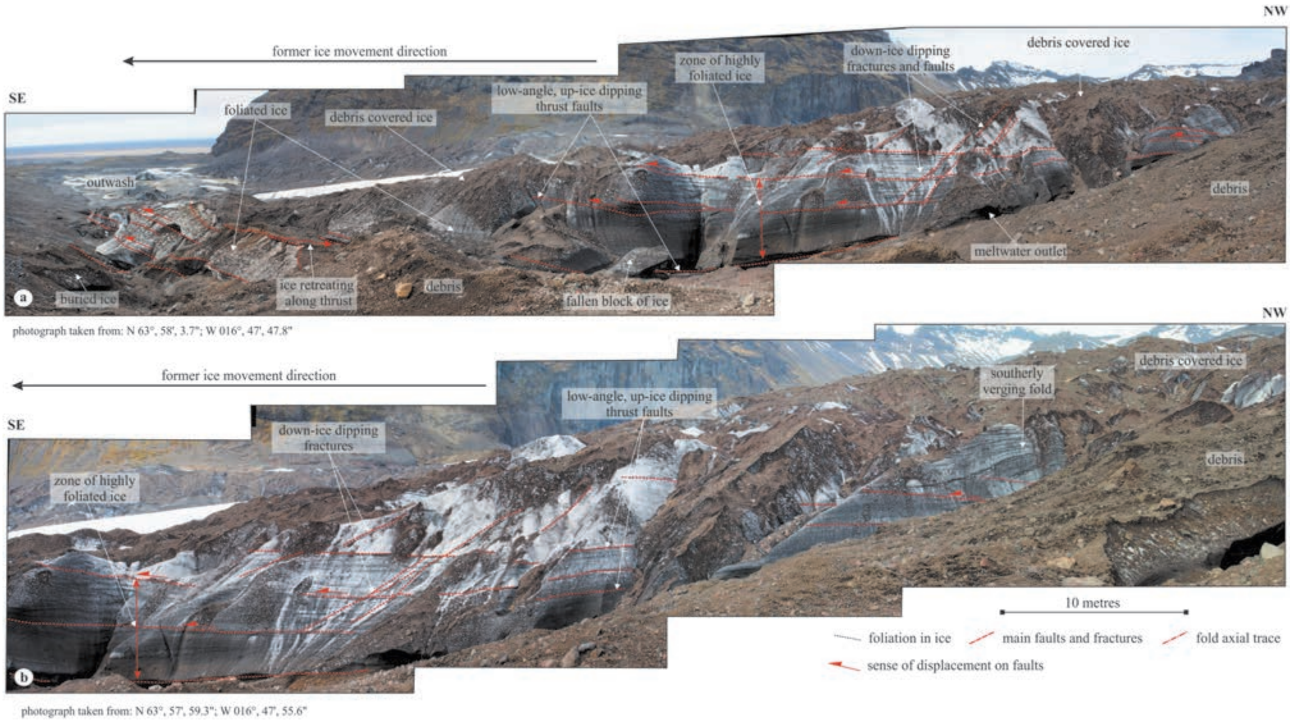

Figure 5. Ice cliff section along the eastern margin of Falljökull showing the low-angle southerly directed thrusting of the zones of foliated ice developed near to the base of the glacier. Also note the presence of an asymmetrical southerly verging fold developed within the hanging wall of one of the thrusts (Figure 5b).

fault system to be constructed. This model, shown in Figure 4b, also shows the proposed relationship(s) between the englacial drainage channels and the down-ice dipping normal faults and the relationship of these faults to a number of up-ice dipping thrusts (see below). The preferential development of englacial meltwater channels along these faults would have led to further weakening the ice by thermal erosion, accelerating collapse of the glacier margin [*Gully and Benn*, 2007; *Phillips et al*., 2013].

Up ice from the collapsing margin, englacial deformation structures associated with the S to SW down-valley forward motion of Falljökull are being progressively revealed both on its surface, due to continued ablation, as well as in a series of ice cliffs (Figure 5) along its southern and eastern flanks [*Phillips et al*., 2013]. These structures include subvertical to very steeply dipping NE-SW trending, fractures (Figure 3b) parallel to the axis of the glacier and zones of foliated basal ice (Figures 3c and 5), the latter brought to the surface by southerly directed, low-angle, up-ice dipping thrusts (Figures 1b, 3d, and 5). Rare S to SW verging, asymmetrical folds are also present within the hanging walls of the thrusts (Figure 5b) with thrusting leading to the glacitectonic thickening of the glacier. However, in the lower part of Falljökull, the thrusts are now inactive and being exploited by englacial drainage channels which have locally deposited lenses of cross-bedded, graded sands and gravels along these low-angle structures [*Phillips et al*., 2013]. On the GPR sections these sediment-lined thrusts can be traced beneath the glacier surface where they are linked to a prominent detachment located at the ice bed interface (see Figure 6). Adjacent to the margin of the glacier, the thrusts are offset by listric, down-ice dipping normal faults (Figure 4b) with rotation of the collapsing fault blocks leading to back rotation and steepening of these up-ice dipping faults [*Phillips et al*., 2013]. At the margin between Falljökull and Virkisjökull (marked by a prominent gorge) the foliated basal ice of both glaciers has been forced upward and is now steeply inclined and dips away from this contact (Figures 1b, 1c, and 3e).

4.3. Stage 3—Continued Movement and Overthrusting in the Upper Part of the Glacier

Time-lapse photography (three images per day over 2 years; see the British Geological Survey (BGS)-NERC Iceland Glacier Observatory project website http://www.bgs.ac.uk/research/glacierMonitoring/home.html?src=sfb) of the icefall, using a fixed camera located adjacent to the icefall, shows that the upper part of the glacier is still moving forward as ice from the summit area of Öræfajökull flows down the mountain flank.

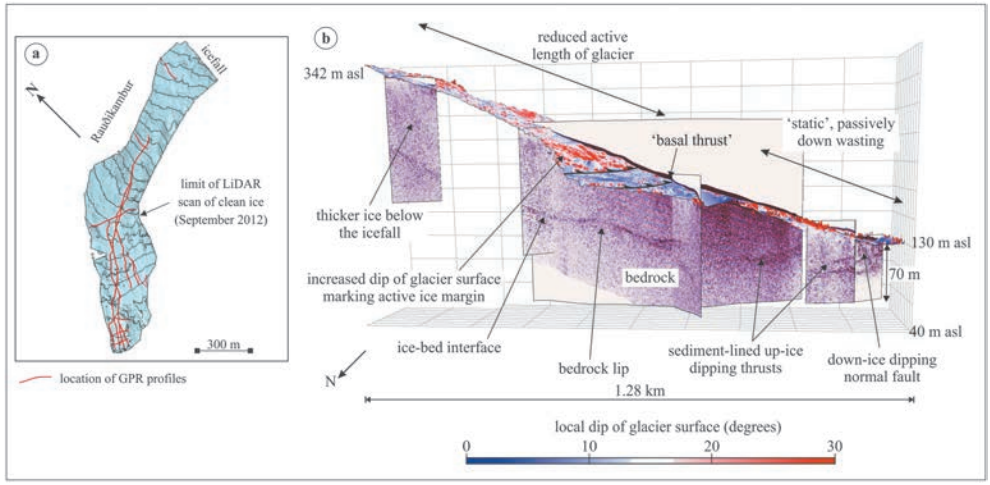

Figure 6. Three-dimensional model of Falljökull constructed using GPR profiles (× 2 vertical exaggeration) and terrestrial lidar digital elevation model (DEM) of the surface of the glacier. The glacier surface has been colored up for dip of slope in order to show the marked break at the currently active margin (40 m asl = meters above sea level).

Consequently, unlike the lower part of the glacier which is stagnating, the upper reaches of Falljökull remain active. However, the key question is how the glacier is accommodating this continued forward motion while its lower section undergoes stagnation and collapse. To address this question four GNSS stations (VIRK 1 to 4) were located along the central axis of Falljökull to monitor the variation in ice surface velocity down the length of the glacier (Figure 7a) and identify the point at which forward motion ceases. The first 12 months of ice surface velocity data are shown in Figure 7b and clearly show a deceleration in ice velocity immediately below a marked topographic bulge in the glacier surface (Figure 1b). The lower most station, VIRK 4 (Figure 7a), located within the zone of collapse (Stage 2) adjacent to the margin of Falljökull confirms that this part of the glacier is essentially stationary with an average velocity of 3 m yr^{-1} (Figure 7b and Table 1). This relatively small amount of forward movement can be easily accommodated by displacement on the major normal faults during collapse of the ice front in this area (for example, see Figure 4a).

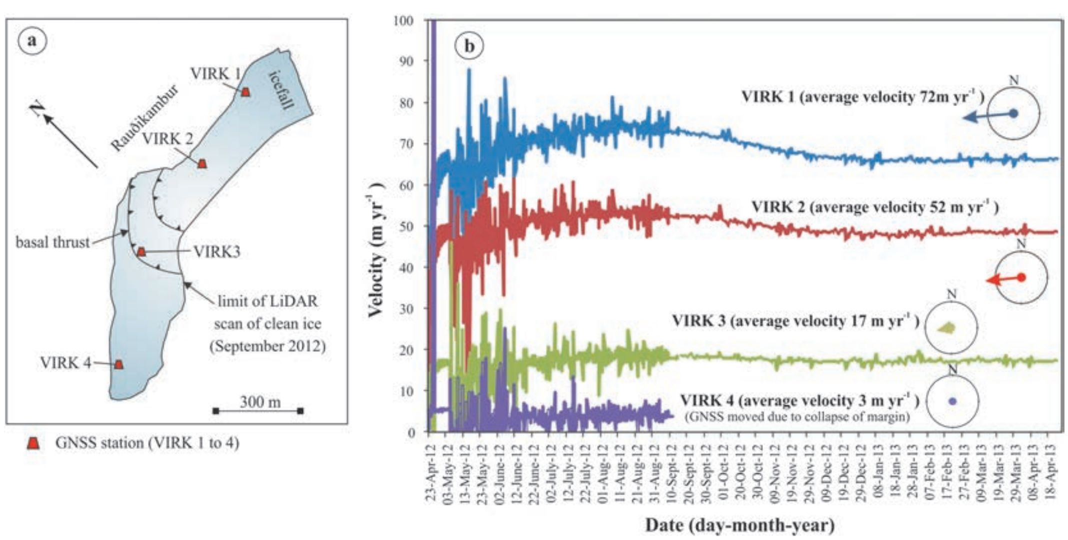

Figure 7. Graph showing the variation in ice surface velocity between April 2012 and April 2013. Insets show the ice movement vector at each of the four GNSS stations located along the axis of Falljökull (see Figure 1b) with the length of the arrow reflecting ice surface velocity.

Table 1. Observed Surface Velocities Obtained From the Four GNSS Station Located Along the Axis of Falljökull and Theoretical Surface Velocities Due To Ice Deformation and Basal Motion

GNSS Station	Observed Mean Surface Velocity	Theoretical Surface Velocity Due To Ice Deformation	Theoretical Velocity Due To Movement at the Ice Bed and/or Fault Planes
VIRK 1	72 m yr^{-1}	15 m yr^{-1}	57 m yr^{-1}
VIRK 2	52 m yr^{-1}	32 m yr^{-1}	20 m yr^{-1}
VIRK 3	17 m yr^{-1}	5 m yr^{-1}	12 m yr^{-1}
VIRK 4	3 m yr^{-1}	0.0 m yr^{-1}	3.0 m yr^{-1}[a]

[a]Movement along the fault planes.

The upper GNSS station (VIRK 1; Figure 7a) is located on an undulating ice surface immediately below the icefall at a starting elevation of 324 m asl. GNSS readings over 12 months show that the glacier in this area is flowing at approximately 72 m yr^{-1} toward the west (Figure 7b and Table 1). Below the icefall the GPR data show that the glacier is much thicker (approximately 140 m thick; Figure 6b) and that the bed is overdeepened, probably due to increased bedrock erosion. Wave-like undulations on the glacier surface in this area are the crests of NNE-SSW trending periclinal folds (Figures 1d and 3f), with compression resulting in folding orthogonal to the westerly ice movement direction determined from GNSS station VIRK 1. Folding would have resulted in the observed thickening of the ice as it accommodates forward motion of the glacier descending the steep icefall. The amplitude of the folds decreases and their wavelength increases in a down-ice direction, consistent with the most intense folding occurring immediately below the icefall and progressively dying out down ice as the ice flows away from this compressional zone. The crests of the anticlines (folds) are cut by open, ice flow parallel, E-W trending crevasses (Figures 1d and 3f). The trend of these crevasses is orthogonal to the axial trace of the anticlines; the open fractures close as they are traced into the hollows (4 to 5 m deep) which mark the adjacent synclines. This relationship is consistent with crevasses opening in relation to extension occurring parallel to the axes of the anticlines (see Figure 1d) as these folds progressively develop and "dome" upward.

GNSS station VIRK 2 is located on top of a large topographic bulge in the glacier surface (Figures 1b and 7a) at a starting elevation of 275 m asl. Data from this station record forward ice movement of approximately 52 m yr^{-1} toward the west (Figure 7b and Table 1). This glacier bulge is dissected by E-W trending, open crevasses (Figures 1b and 3f), the down-ice terminations of which are marked by water-filled, boat-shaped hollows formed by a line of artesian meltwater springs issuing onto the glacier surface; the latter indicating that a pressurized meltwater system is active within the upper part of Falljökull.

Farther down ice, at an elevation of 200 m asl, data from GNSS station VIRK 3 (Figures 1b and 7a) record ice velocities of only 17 m yr^{-1} (Figure 7b and Table 1). Velocity curves from the upper three GNSS stations all record an increase in forward motion during the spring/summer (Figure 7b), accelerating in May, to a maximum in August, and gradually decelerating during September and into October. This phenomenon has been recognized at other glaciers where it has been equated with increased spring-summer meltwater production where the meltwater reaches the impermeable ice bed interface leading to increased basal sliding [*Hubbard et al*., 1995; *Clarke*, 2005; *Schoof*, 2010]. However, the magnitude of this spring-summer "speed-up" at Falljökull decreases significantly immediately below the crest of the bulge in the glacier surface (compare the overall trend of the curves for VIRK 1, VIRK 2, and VIRK 3 on Figure 7b). This suggests that the bulk of the forward motion of Falljökull, driven by ice descending the icefall, is currently being accommodated within a relatively small section of the glacier located between the icefall and the base of the topographic bulge, a distance of approximately 850 m.

A marked change in the trend of the ice flow-parallel fractures, from NNE-SSW in the lower reaches of Falljökull to approximately E-W in its upper section (compare Figures 3b and 3f), denotes a marked difference in the structural configuration of the glacier in these areas. This fundamental change in structural architecture corresponds to the change from the area of "active ice" which is still moving forward in the upper part of the glacier and the relatively static, passively downwasting lower section. Analysis of the deformation structures exposed on the surface of Falljökull has revealed that the boundary between these two structural "domains" coincides with a prominent up-ice dipping thrust which crops out immediately below station VIRK 3 and can be traced laterally across the entire width of the glacier (Figure 1b). This detachment can be seen to truncate both the foliated ice at the margin of Falljökull, as well as older (earlier "advance phase") thrusts

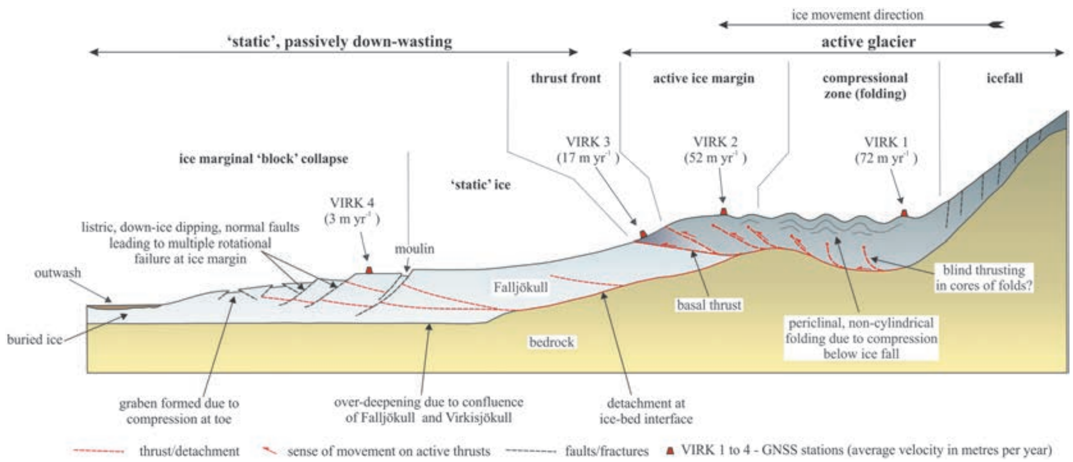

Figure 8. Schematic structural cross section through Falljökull (not to scale) showing the main deformation structures controlling collapse of the glacier margin and thrusting and folding accommodating continued active forward motion of the upper part of the glacier as it overrides stagnating (downwasting) lower part of the glacier. Also shown are the positions of the four GNSS stations and average ice velocity calculated at these locations highlighting the marked decrease in forward motion observed between the active upper section of the Falljökull and the passively downwasting lower part of the glacier.

(Figure 1c), and is therefore younger (postdates) than these structures, which were formed during the earlier southerly advance of the glacier. The "basal thrust" can be projected beneath the glacier surface where it is thought to merge with the main detachment at the ice bed interface, propagating from a bedrock lip marking the edge of the overdeepening beneath the icefall. The clean ice-ice contact formed by this basal thrust (see Figures 1b and 1c) is less clearly defined on the GPR profiles than the sediment-lined thrusts observed in the lower part of the glacier (see Figure 6b). The geometry and relative age of this basal thrust are consistent with its displacement being responsible for accommodating at least part of the continued forward motion of the upper part of Falljökull. Moreover, this basal thrust effectively forms the boundary between the active upper section of the glacier and its "stagnant" lower reaches (Figure 8). The observed reduction in ice surface velocity (deceleration) at VIRK 3 located immediately above the basal thrust may be due to frictional drag as the active ice overrides the immobile ice in its footwall. This would force the faster flowing ice in the hanging wall of the basal thrust upward forming the observed topographic bulge in the glacier surface (Figures 6 and 8). Where the glacier becomes unconfined by the bedrock valley topography it is able to spread laterally resulting in the opening of ice flow-parallel crevasses (Figure 1b). Consequently, this area of Falljökull is thought to represent its new active margin, above which the glacier is moving forward ($>50\,\mathrm{m\,yr^{-1}}$) and under compression, leading to thrusting of the "dynamic" upper section over the lower stagnant portion of the glacier.

5. Model for the Structural Evolution of Active Glacier Length in Response to Rapid Retreat

This work shows that Falljökull has evolved structurally over the past two decades and that these changes have occurred in response to a significant reduction in its annual net mass balance resulting predominantly from warmer summers [*Guðmundsson*, 2000; *Jóhannesson et al*., 2013]. Between 1990 and 2000, in a decade of comparatively cooler (or average temperature) summers, the glacier was highly dynamic and undergoing active retreat (Stage 1) as it pulled back from the 1990 push moraine. Systematic changes in the size and spacing of the resultant annual moraines, however, clearly shows that there was a reduction in the magnitude of the winter-spring readvances over time, reflecting a decrease in annual net mass balance [*Bradwell et al*., 2013]. Eventually, during the period 2004 to 2006, active retreat ceased and Falljökull's ice front crossed an important threshold entering a phase of passive downwasting and fault-controlled ice margin collapse (Stage 2), a process which continues to the present day. In fact, annual measurements of the position of the ice front indicate that since 2007 the rate of frontal retreat has accelerated and Falljökull is retreating at a faster rate than in any 5 year period since measurements began in 1932 (see Figure 2c) [*Bradwell et al*., 2013].

Although the margin of Falljökull has ceased moving and is now undergoing stagnation, field and photographic evidences clearly show that the icefall remains active, feeding ice from the accumulation zone on Öraefajökull to the lower reaches of the glacier. To accommodate this continued forward motion, the upper section of the glacier below the icefall is undergoing intense deformation (folding and thrusting) and, as a result, is being thrust over the lower, immobile section of Falljökull which has become dynamically detached and is undergoing stagnation (Stage 3). Consequently, Falljökull does not fit the simple two-end-member model of either "active" or "passive" retreat reported in the literature. Instead, it is suggested that this glacier is currently undergoing both active and passive retreat in different zones along its length as it rapidly adjusts to changes in mass balance. The occurrence of both active and passive (inactive) sections at different elevations within Falljökull is apparently similar to the situation in many surging glaciers where large masses of static or very slowly moving ice occur in the lower reaches, while at higher elevations the glacier remains active. During a surge event ice is rapidly transferred from the "reservoir area" to the "receiving area" effectively reactivating the inactive/static lower part of the glacier as this "surge wave" moves down ice [e.g., *Kamb et al*., 1985; *Murray et al*., 1998; *Frappé and Clarke*, 2007; *Benn and Evans*, 2010]. However, in contrast to a surging glacier where the active upper section remains structurally connected to its inactive lower reaches, at Falljökull the passively downwasting lower section has become glacitectonically detached and is being overridden by the active upper part of the glacier with the boundary between the two areas being formed by a prominent thrust zone (Figures 1b and 8).

A conceptual model of the overall structure of Falljökull is shown in Figure 8 and highlights the differences in deformation style between the static passively downwasting lower section of the glacier, and the upper active part of the glacier system. As the active section is thrust westward during the overriding process, it is emerging from the confines of the valley, allowing the ice to spread laterally, leading to crevassing of the advancing margin. The basal thrust, on which the upper section of the glacier is overriding, propagated upward through the ice from the bedrock lip at the margin of an overdeepened area immediately below the icefall (Figure 8). The movement of the glacier as it flows through the overdeepened zone (see Figure 8) may, at least in part, have provided the driving force behind thrust propagation and upward displacement of the ice within the hanging wall of the thrust. The end result of thrusting within the upper part of Falljökull is that the active length of the glacier has been reduced.

The conclusion that the basal thrust represents the glacitectonic boundary separating the active upper section of Falljökull from its passively downwasting lower reaches has been tested by calculating the theoretical surface velocity along the axis of the glacier (Figure 9) [see *Cuffey and Paterson*, 2010]. This method states that theoretical surface velocities due to ice deformation (u_s) can be estimated, according to the shallow ice approximation, using the equation

$$u_s = \frac{2A}{n+1} (\rho g \tan \alpha)^n H^{n+1}$$

where A = 75 MPa^{-3}, n = 3, ρ is the density of ice (917 kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), α is the ice surface slope, and H is the ice thickness [*Cuffey and Paterson*, 2010]. The approach does not account for valley side drag or longitudinal stresses. However, it does provide an approximate indication of where surface velocity contrasts may be expected, due to changes in ice thickness and surface slope (Figure 9). Interestingly, the main change in theoretical surface velocity at Falljökull occurs at the location where several prominent thrusts are observed on the glacier surface (Figures 1b and 1c), decreasing from over 32 m yr^{-1} on top of the bulge in the ice surface in the vicinity of GNSS station VIRK 2 (Figure 9), to less than 1 m yr^{-1} below the basal thrust. Consequently, the theoretical approximation is consistent with the proposed conceptual model in which the active upper section of the glacier is being thrust over the immobile lower section (Figure 8).

Comparing these theoretical values, due to ice deformation, with the measured surface velocities from the GNSS stations located along the central axis of Falljökull (see Table 1) allows an estimation of motion at the ice bed and along fault planes (Table 1). The values at VIRK 1 to 3 provide an estimate of the basal motion that may be transferred into the low-angle, up-ice dipping thrusts as the glacier overrides its inactive lower reaches. The approximately 3 m yr^{-1} surface motion at the glacier snout (VIRK 4) is likely to be almost entirely a result of horizontal displacement of the downthrown block along a full depth normal fault at that location (Figure 4).

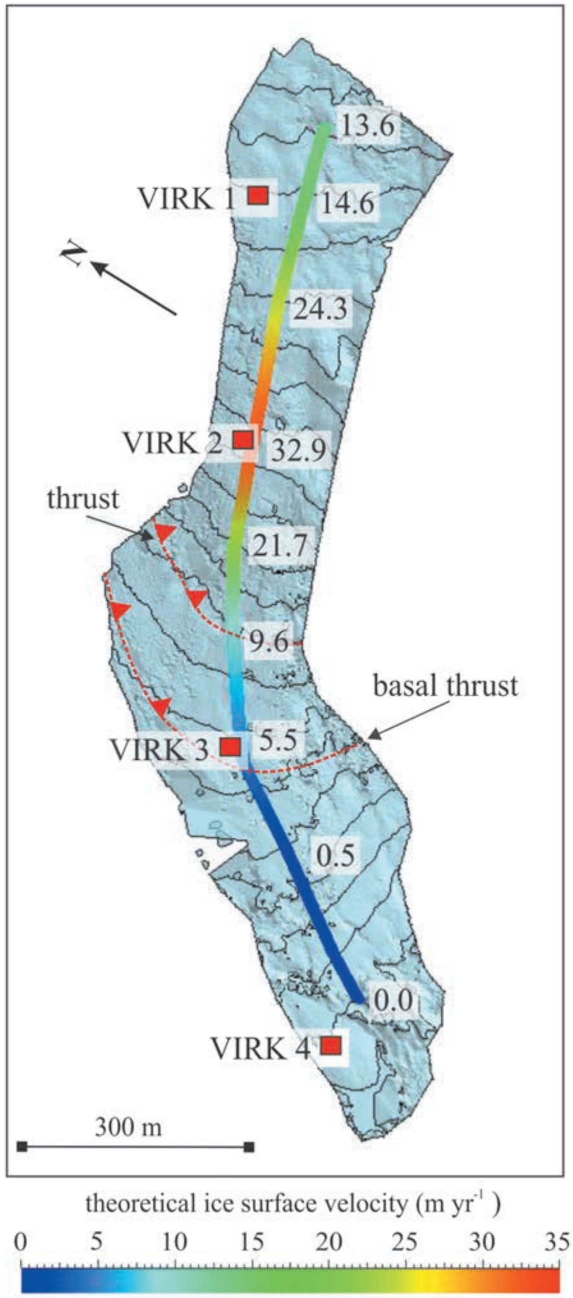

Figure 9. Variation in theoretical surface velocity due to ice deformation (m yr^{-1}) along the axis of the clean ice (see Table 1 and text for details). Velocities were calculated using a glacier surface that was smoothed to a horizontal resolution that exceeds the ice thickness. Ice surface contours at 10 m intervals.

The dynamic threshold responsible for this fundamental structural change within Falljökull was probably crossed in 2004–2006; coinciding with the cessation of annual push moraine formation and onset of stagnation of its margin [*Bradwell et al.*, 2013]. It is likely that it took 1 or 2 years for the stresses which led to overthrusting to build up within the glacier. Consequently, in a period of probably less than 5 years Falljökull has significantly reduced its active length by approximately 700 m (see Figures 6 and 8). The overriding active margin, marked by the prominent surface bulge in the ice, is now 700 m up glacier from the exposed clean ice margin (and 1300 m up glacier from the buried ice margin) and at an elevation 100 m higher than the glacier terminus. This structural process which led to this reduction in the active length of Falljökull probably occurred as a function of the steep hypsometry and high mass turnover of the glacier which provided the driving force for the upper active section of Falljökull to structurally detach and override its stagnant lower reaches. In the future, if the active upper section of the glacier continues to advance it may result in the lower part of Falljökull being composed of an upper "active carapace" of ice overriding a lower, immobile/stagnant basal zone. The key factor controlling the continued forward movement of the upper section of the glacier is its connection, via the icefall, to the ice cap on Öræfajökull. If in the future the icefall becomes too highly attenuated (thin) or is breached, and Falljökull becomes isolated from its source area, then thrusting of active glacier ice over stagnant ice will cease.

The structural process described here provides a previously unrecognized mechanism by which land-terminating glaciers can efficiently and rapidly adjust their length in response to a sustained period of negative mass balance. It is likely that similar steep, high-mass turnover glaciers around the world (e.g., Alpine glaciers in Europe, New Zealand, and the Himalayas) are capable of responding in a similar way to a significant reduction in total accumulation [*Quincey et al.*, 2009; *Quincey and Glasser*, 2009]. For example, work by *Quincey et al.* [2009] on the quantification of glacier velocities in the Everest region between 1992 and 2002 using satellite radar interferometry and feature tracking has shown that forward motion in 12 of the 20 glaciers studied is largely confined to their upper reaches. These steep, high-altitude glaciers (e.g., Khumbu and Ngozumpa glaciers) comprise an active upper section where the ice shows some evidence of flow and a much longer, lower section which is undergoing widespread stagnation and in situ decay [*Quincey et al*., 2009]. Although a structural control on the reduction in active glacier length has yet to be demonstrated for the Himalayan glaciers, *Quincey et al*. [2009] suggest that catchment topography plays an important role in controlling glacier flow regimes, with steep glaciers fed by high-altitude accumulation areas showing the most extensive sections of active ice.

The proposed structural process leading to reduction in active length of glaciers also has implications for studies investigating links between glacier size and climate change [*Hooker and Fitzharris*, 1999; *Andreassen et al*., 2005; *Paul et al*., 2007; *Haeberli et al*., 2007] and demonstrates that in many cases glacier length alone does not reflect the full glaciological response of an ice mass to a warming climate. Active glacier length, as defined by its velocity profile and structural architecture, may be a more appropriate measure of glaciological response in high-mass turnover, steep glaciers. The present study suggests that structurally controlled length changes may provide a mechanism by which these glaciers can rapidly adjust to periods of pronounced climate change over a short-term (decadal) timescale.

6. Conclusions

A multidisciplinary study of Falljökull, a steep, high-mass turnover temperate glacier in maritime SE Iceland, has shown that the pattern of retreat and structural configuration of this glacier have changed markedly over the past two decades in response to a significant reduction in its mass balance resulting from recent warming. During this period Falljökull crossed a threshold which led to abandonment of the lower part of the glacier, now undergoing stagnation, while the upper section has become glaciologically detached and started to override the lower stagnant section. The structural model proposed for this glacier highlights the differences in deformation style between the active part of the glacier system and the static passively downwasting lower section. This rapid structural response, which can take place in a period of only a few years, probably occurred as a function of the steep hypsometry and high mass turnover of the glacier. Consequently, it is possible that similar steep, high-mass turnover glaciers around the world may be responding in a similar way to significant changes in their mass balance, rapidly adjusting their active length in response to periods of pronounced climate warming over short (decadal) timescales.

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