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Going against the flow: Testing the hypothesis of pulsed axial glacier flow

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ABSTRACT: Hypothesised lobe-like flow of a temperate glacier in southeast Iceland, proposed from an analysis of ice surface crevassing patterns, is appraised from both empirical and theoretical perspectives. The hypothesis comprises the migration of individual lobes (or 'pulses') of ice through the glacier body, with central lobes migrating more rapidly along a narrow, central, 'axial flow corridor'. Our alternative hypothesis is that crevasse patterns at this glacier reflect simple surface ice responses to stresses caused by flow over uneven bed topography. To substantiate our rejection of the lobe-like, pulsed axial flow hypothesis, we provide: (a) evidence for a prominent transverse foliation that exhibits no evidence of shear of the required magnitude to support the hypothesis; and (b) an analysis of ice surface displacement, obtained by feature tracking, that shows a uniform flow field throughout the glacier tongue. We argue that caution needs to be exercised when interpreting glacier flow solely from crevasse patterns and observations of minor displacements along near-surface fractures and other features. © 2018 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: glaciology; glacier flow; crevasses; foliation; thrusting; Iceland

Introduction

Phillips *et al.* (2017) propose that fracture (i.e. crevasse) patterns at Kvíárjökull (Figure 1), a temperate glacier in southeast Iceland, indicate that flow since *c.* 1940 has proceeded as a series of independently moving lobes or 'pulses' of ice (Figure 1(b)) originating in the upper glacier tongue. These authors have used 'marked changes' in crevasse patterns to divide the glacier surface into 27 domains, which are claimed to be individual pulses of ice separated by shear zones. Perceived 'cross-cutting' relationships between domains, and the elongate nature of the central domains, is inferred to show that lobes within a narrow central corridor (or axis) 'bypass' packages of slow-flowing or stationary marginal ice (Figure 1 (b)). The conclusion – that flow can occur in discrete lobes that migrate independently through the glacier body – profoundly contradicts widely demonstrated patterns of glacier flow (Hooke, 1998; Cuffey and Patterson, 2010).

The work presented by Philips *et al.* (2017) sets a new standard for glacier fracture mapping. In addition, it is essential for the development of glaciological theory that, as in all fields of science, new methods are trialled that seek to challenge received wisdom. It is also essential that all new theories and methods are subject to rigorous testing, and that those found wanting are dismissed, or highlighted as deserving of further work. We set out to test the pulsed axial flow hypothesis of Phillips *et al.* (2017) because crevasse patterns are more commonly interpreted to reflect local tensile stresses caused by undulations at the glacier bed (see Discussion). In addition, Swift *et al.* (2006) have previously documented the presence of a glacier-wide, transverse, ogive-origin foliation at Kvíárjökull. This foliation is largely overlooked by Phillips *et al.* (2017), yet could provide strong supporting evidence for their theory if it can be shown that independently migrating lobes of ice have caused the foliation to be sufficiently offset.

Study area and methods

Kvíárjökull (Figure 1(a)) is a valley glacier fed by the Oræfajökull icecap via a steep icefall located *c.* 6 km from the glacier terminus. For this study, horizontal displacement of ice in the icefall and tongue was obtained by analysis of high-resolution (3 m) PlanetScope imagery (Planet Team, 2017) using a normalised cross-correlation algorithm that tracks movement of surface features (Kääb and Vollmer, 2000; Heid and Kääb, 2012). A limited structural survey (restricted to mapping open crevasse areas and notable examples of transverse foliation) was undertaken from an aerial photograph acquired in 2009 (shown in Figure 1(b) and (c)), and mapped features were observed in the field in August 2007 and 2012. Band-ogives (Goodsell *et al.*, 2002) are clearly visible in aerial and satellite images from the 1940s onwards (Phillips *et al.*, 2017 and Figure 1(a)), and thrusting along ogive-origin foliae has previously been observed in ice approaching the glacier terminus (Swift *et al.*, 2006). These thrusts were argued by Swift *et al.*, (2006) to originate from reactivation of shear along dark-ogive

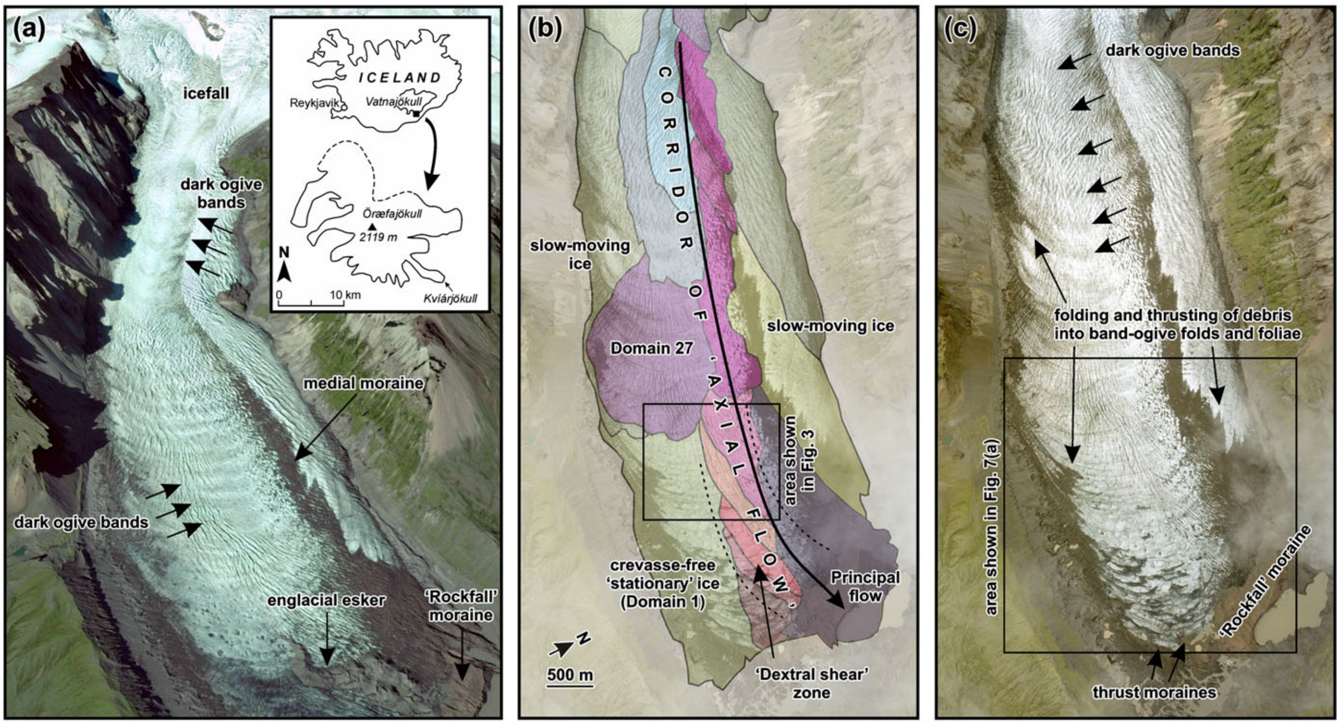

Figure 1. (a) Oblique view of Kvíárjökull, December 2012 (copyright Google Earth). Annotated features are discussed in the text. (b) Domains mapped by Phillips *et al.* (2017), superimposed onto an August 2009 aerial image. Annotations highlight an 'axial flow' corridor of more elongate lobes, and deflection of flow toward the true-left by dextral shear near the terminus, as proposed by Phillips *et al.* (2017). (c) Annotated aerial image showing a heavily crevassed ice surface, and highlighting dark ogive banding and prominent transverse englacial foliation. The dark ogive banding first appears immediately below the ice fall, see (a). The thrusts and the lighter-coloured 'rockfall' moraine are discussed in the text. [Colour figure can be viewed at wileyonlinelibrary.com]

bands that contain a higher density of foliae (Goodsell *et al.*, 2002) by a change in deviatoric stress that occurs as ice nears the adverse slope of the terminal overdeepening.

Phillips *et al.* (2017) describe the mapped domains (Figure 1 (b)) as a series of radially crevassed, teardrop-shaped regions of ice centred around ice-surface topographic highs, and interpret these to be a chronosequence of discrete lobes of ice produced in the upper tongue. The central lobes are more elongate and said to 'clearly cross-cut and truncate the relatively earlier developed teardrop-shaped (i.e. less elongate) lobes at the ice margins' (p. 14). Particular attention is given to Domain 27, a marginal domain (Figure 1(b)) that displays a rounded 'teardrop' shape and radial crevasse pattern. This domain is immediately upglacier of Domain 1 (Figure 1(b)), which has relatively low relief and an absence of surface crevassing. Small displacements on steeply dipping, closed fractures in Domain 27 lead Phillips *et al.* (2017) to conclude that Domain 27 is a discrete lobe that has overthrust slower moving ice in Domain 1. Small displacements (10s of centimetres) along crevasses are also used to conclude that a longitudinal crevasse zone adjacent to Domain 1 is a 'dextral shear zone' (see Figure 1(b)), marking a deflection of the active ice flow corridor to the true-left (i.e. to the northern part of the frontal margin).

Results

Measured displacement of glacier ice (Figure 2) is highest along a broad central zone, with maximum displacements occurring in the steep topography of the icefall, and decreases towards the glacier tongue and margins. Displacements therefore demonstrate a broadly uniform flow field that is characterised by 'plug-flow' across *c.* 60% of the glacier width (Figure 2(c)), with the majority of shear being restricted to ice at the lateral margins. Rapid changes in displacement that are perpendicular to flow, which might indicate longitudinal shear, are not apparent (Figure 2(c)), meaning no discrete central (or 'axial') flow corridor is observed. Mapped flowlines (Figure 2(b)) indicate that flow near the terminus instead bends slightly to the true-right (i.e. the southern region of the terminus), and show no evidence of dextral shear. Rather, the northern region appears almost to be stagnant (see Discussion). A small area (10s of m wide) of low displacement near the terminus (Figure 2(a)) possibly reflects localised mass loss caused by subglacial water flow, or resistance provided by a subglacial landform, such as an esker deposit. Debris-covered ice at the extreme lateral margins near the terminus Figure 2(a) also exhibits low displacements.

Two prominent ice structures visible from aerial and satellite imagery (and in the field) are present along the length of the glacier tongue. The first is an arcuate transverse englacial foliation that originates from band-ogive foliation, which first appears below the icefall (Figure 1(a)). The second is a medial moraine that originates from a bedrock outcrop within the icefall (Figure 1(a)) and extends to the terminus. Band-ogive foliation continues to be visible along the tongue and is traceable across the glacier width (Figure 1, 3). Incorporation of debris into foliae associated with band-ogive formation (see Goodsell *et al.*, 2002) is demonstrated by the concertina-style margins of the medial moraine structure and lateral edges of the glacier (Figure 1(c)). Bands become less clear in the lower tongue and terminus, but many distinct, occasionally debris-rich ogive-parallel foliae remain (Figure 3). The reduced visibility of ogive bands in the lower tongue may be due to surface ablation, which diffuses sediment across the glacier surface, and removes upper layers of ice containing snow-filled crevasses that contribute to the lighter appearance of the 'winter' bands (Swift, 2015).

Both medial moraine and transverse, ogive-origin structures originate upglacier of the area identified by Phillips *et al.* (2017) as being a possible source of the lobes. Phillips *et al.* (2017) observed minor displacements of ogive-related banding

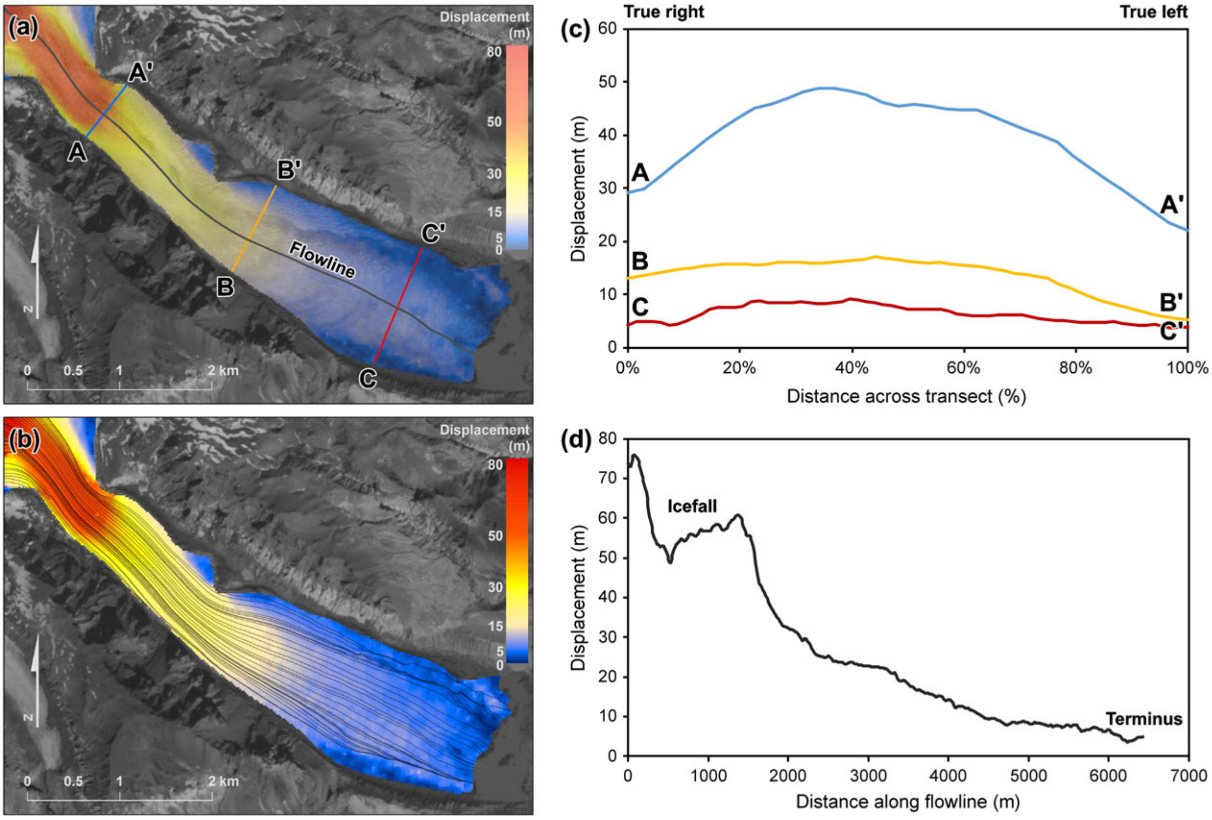

Figure 2. Ice flow mapped from measured displacement of surface features between 8 August and 1 September 2017 from PlanetScope imagery (see text). (a) Semi-transparent overlay showing horizontal displacement (see colour bar, inset). (b) Flow lines of ice through the tongue, overlaid onto horizontal displacement as in (a). (c) Displacement values for profiles A to C across the glacier tongue (see (a)). True-right and true-left are indicated for an observer facing down-flow. (d) Displacement values along a near-centreline flowline profile (see (a)). [Colour figure can be viewed at wileyonlinelibrary.com]

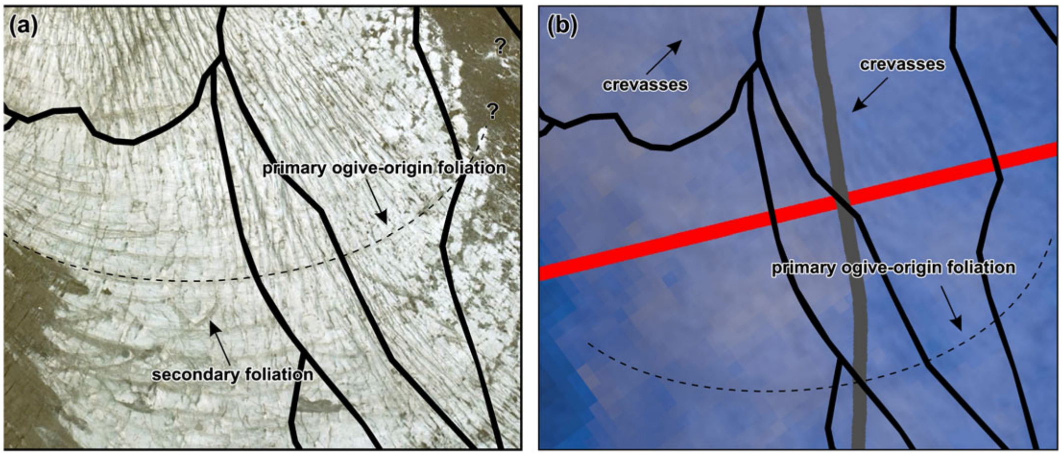

Figure 3. (a) Close view of an area shown in Figure 1(b), showing intact ogive-origin transverse foliation, even when crossing the boundaries between lobes (heavy black lines) mapped by Phillips *et al.* (2017). (b) The same area from Figure 2(a), showing displacement of transverse foliae between 2009 and 2017 in a manner consistent with glacier flow, but no substantive change in the patterns and locations of surface crevassing. The domains identified by Phillips *et al.* (2017) are shown again for reference, and the heavy red and grey lines are the displacement profiles shown in Figure 2(a) and plotted in Figure 2(c). [Colour figure can be viewed at wileyonlinelibrary.com]

along surface fractures, but only on the order of 10s of centimetres. Substantial offset of such features was not observed in the field and is not evident from aerial imagery, even where such features intersect the boundaries of domains that are interpreted by Philips *et al.* (2017) to be independently moving lobes (Figure 3). The more debris-rich features appear to reflect the emergence of marginal and basal sediment, the latter identified by the presence of faceted and striated clasts (Benn, 2004), that has been incorporated into band-ogive foliae by folding and thrusting (Figure 1(c)), as observed in 2002 by Swift *et al.* (2006). A notably large thrust observed in 2002 was again observed in 2007, when it could be traced from the southern glacier margin (Figure 4(b) and (c)) to its meeting point with the medial moraine, while a series of emergent thrust moraines were observed behind (Figure 4(a)). A large englacial esker (Figure 5) that has emerged since *c.* 2010 (see also Phillips *et al.*, 2017) does demonstrate an offset morphology, but, rather than shearing, this may instead indicate shortening (giving rise to a concertina morphology; Figure 1(a)) that is consistent with compressional flow near the terminus.

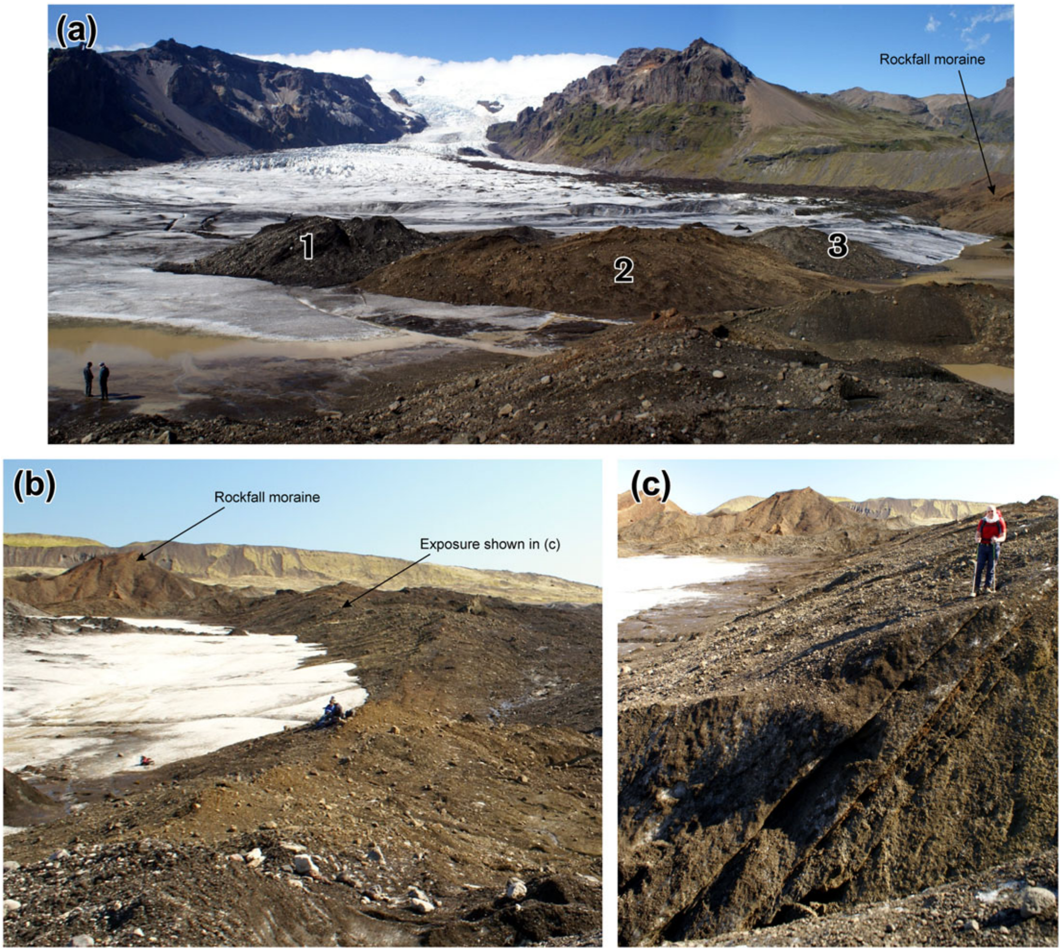

Figure 4. Thrusts photographed in 2007 at the margin of Domain 1, which is a relatively low relief area described by Phillips *et al.* (2017) as slow-moving or stagnant ice. (a) Small moraines (labelled 1 to 3), forming from several separate thrust planes, viewed from the crest of the large thrust moraine shown in (b). (b) View along the crest of a large thrust moraine from the southern edge of the glacier tongue toward the 'rockfall' moraine (mapped in Figure 1(c)). (c) Exposed thrust within the thrust moraine shown in (b), showing steep upglacier dipping debris laminae. [Colour figure can be viewed at wileyonlinelibrary.com]

Discussion

Crevasse patterns and glacier flow

Crevasses are tensional fractures that form at 90° to the direction of maximum tension (Nye, 1952; Hambrey and Müller, 1978; Huddleston, 2015). They are typically a shallow surface phenomenon because the confining pressure imposed by surrounding ice sets a maximum depth limit that in temperate ice is about 25 to 30 m (Nye, 1957; Hambrey and Müller, 1978). (Water-filled crevasses can exceed this, but do not occur on Kvíárjökull.) Crevasses form relatively quickly under a specific local stress regime, and may close similarly rapidly as flow transports them into a new stress regime. The minimum extensional strain required for crevasse formation varies greatly, meaning the absence of crevassing does not necessarily indicate slow or stagnant flow (Hambrey and Müller, 1978; Cuffey and Patterson, 2010). Closed fractures are sometimes observed deep within the interior of glaciers, but the origin of these is debated, and most documented examples are transverse features originating in areas of very rapidly extending ice flow, such as icefalls (Hambrey and Müller, 1978; Goodsell *et al.*, 2002).

Their relatively shallow depth means crevasses have limited significance for glacier flow (Huddleston, 2015). Instead, horizontal stress coupling in ice below the depth limit for crevassing transmits internal forces over distances of several ice thicknesses, meaning glacier flow proceeds in the manner of a stiff fluid in which flow is dictated by the creep properties of ice. This precludes sharp longitudinal velocity gradients, and causes the drag exerted by bedrock at the glacier sides to restrain the flow at the glacier centre. Rapid shear is concentrated in thinner ice near the lateral margins and almost absent in thick ice near the glacier centre, as shown by field measurements of longitudinal velocity (Figure 6) (Raymond, 1971). This general pattern is reinforced by patterns of basal water pressure that promote high rates of basal slip beneath thick ice in the centre. Studies show that slip accounts for typically greater than 65% (and frequently 80 to 90%) of ice surface velocity across more than half the width of the glacier (Cuffey and Paterson, 2010). Flow within this central region is therefore nearly uniform (i.e. 'plug flow').

Longitudinal flow of ice in discrete, fast-moving, corridors or streams (but not 'lobes') is known to occur only in ice sheet systems. Such systems are sufficiently large to accommodate 'shear margins' 5 to 10 km wide (Joughin *et al.*, 2004) that separate fast moving ice-stream ice from adjacent, slow moving ice. Similar longitudinal separation of flow within outlet and valley glacier systems, such as would be needed to produce a central corridor of fast-moving ice, lacks precedent or physical plausibility. Distinct flow units are commonly observed in compound glacier tongues formed by the confluence of ice from two or more tributaries or accumulation basins, the boundaries between which may show considerable shear arising from longitudinal and vertical extension necessary to accommodate adjustment of unit width according to flux differences from the input basins (Jennings *et al.*, 2014). However, there is no

Figure 5. An englacial channel fill (or esker) in 2012 looking due E, i.e. in the approximate direction of ice flow. The esker is also visible in Figure 1(a). The 'concertina' morphology is most probably the result of compressive, active ice flow in the terminus region. [Colour figure can be viewed at wileyonlinelibrary.com]

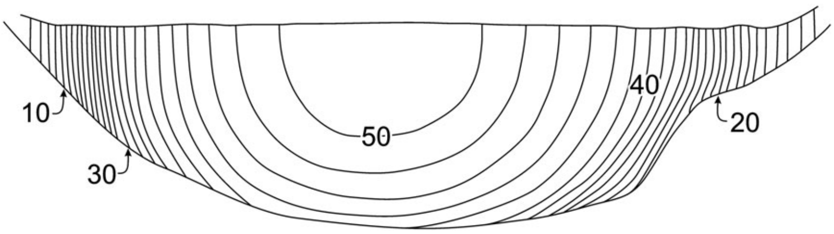

Figure 6. Contours of longitudinal velocity in a transverse section of Athabasca Glacier inferred from measurements in boreholes, redrawn from Raymond (1971). The glacier is *c.* 1 km wide, which is approximately the width of Kvíárjökull. Values are in metres per year. 'Plug flow' occurs across about half the glacier width due to high rates of basal slip.

evidence that longitudinal shear at unit boundaries enables input flux differences to be accommodated by independent flow of adjacent units. Rather, as in all glaciers, flow in the tongue proceeds 'en masse'.

Complex crevasse patterns may occur as a result of the uneven character of glacial valleys and beds (Hambrey and Lawson, 2000; Cuffey and Patterson, 2010; Huddleston, 2015). Notably, longitudinal undulations in glacier beds give rise to alternating regions of transverse and longitudinal crevassing arising from longitudinal flow extension on areas of steeper bed and transverse extension due to flow compression on areas of less steep or negative bed slope, respectively (Nye, 1952). Thus, short wavelength bed undulations will cause crevasse formation under rapidly alternating stress regimes, and therefore to contrasting crevasse patterns being 'overprinted'. Further, longitudinal and radial (or splaying) patterns are common at glacier termini where a widening valley enables ice flow to splay out laterally (Hambrey *et al*., 2005), or where ice flows past a valley constriction or promontory, or where it negotiates subglacial ridges or hills (Cuffey and Paterson, 2010).

Interpretation of flow at Kvíárjökull

Phillips *et al*. (2017) reject simple dynamic reasons for crevasse formation at Kvíárjökull and favour explanations based on ice flow history (see Field Site and Methods). Minor observed displacements on faults and fractures are used to support the hypothesis of independently migrating lobes, and to support the existence of a dextral shear zone in the main axial flow corridor on approaching the terminus. Longitudinal shear fractures are, however, rare in glaciers (Hudleston, 2015) and observed displacements on such features are typically very modest (up to 1 m, e.g. Hambrey, 1994). The majority of such features appear to be formerly open crevasses and do not indicate displacements on faults of any great depth (Cuffey and Patterson, 2010; Hudleston, 2015). Considerable strike-slip displacements are typically observed only on transverse, upglacier-dipping planes (i.e. thrusts) in situations where variations in deviatoric stresses are imposed by changes in bed gradient or thermal regime (Hambrey and Müller, 1978) (see below). Except in unusual cases (Hambrey *et al*., 2005), thrusting appears to require pre-existing, glacier-wide, weaknesses in the body of the ice that have the correct orientation (Moore *et al*., 2010, 2011; Huddleston, 2015), such as ogive-origin foliae (Swift *et al*., 2006).

A simpler interpretation of flow at Kvíárjökull is that lobe-like highs and crevasse patterns reflect flow over uneven subglacial topography. Importantly, a series of highs and ridges in the bed of Kvíárjökull are shown in bed data (Figure 7(b)) published by Magnússon *et al*. (2012), which has been derived from point radio-echo soundings of ice thickness. The valley constrictions noted by Phillips *et al*. (2017) also probably play a role, but only in the immediate vicinity of those features. In the terminal area that includes Domains 27 and 1, rather than a discrete lobe centred on one high, orientations of radial and longitudinal crevasses that form a contiguous field indicate flow

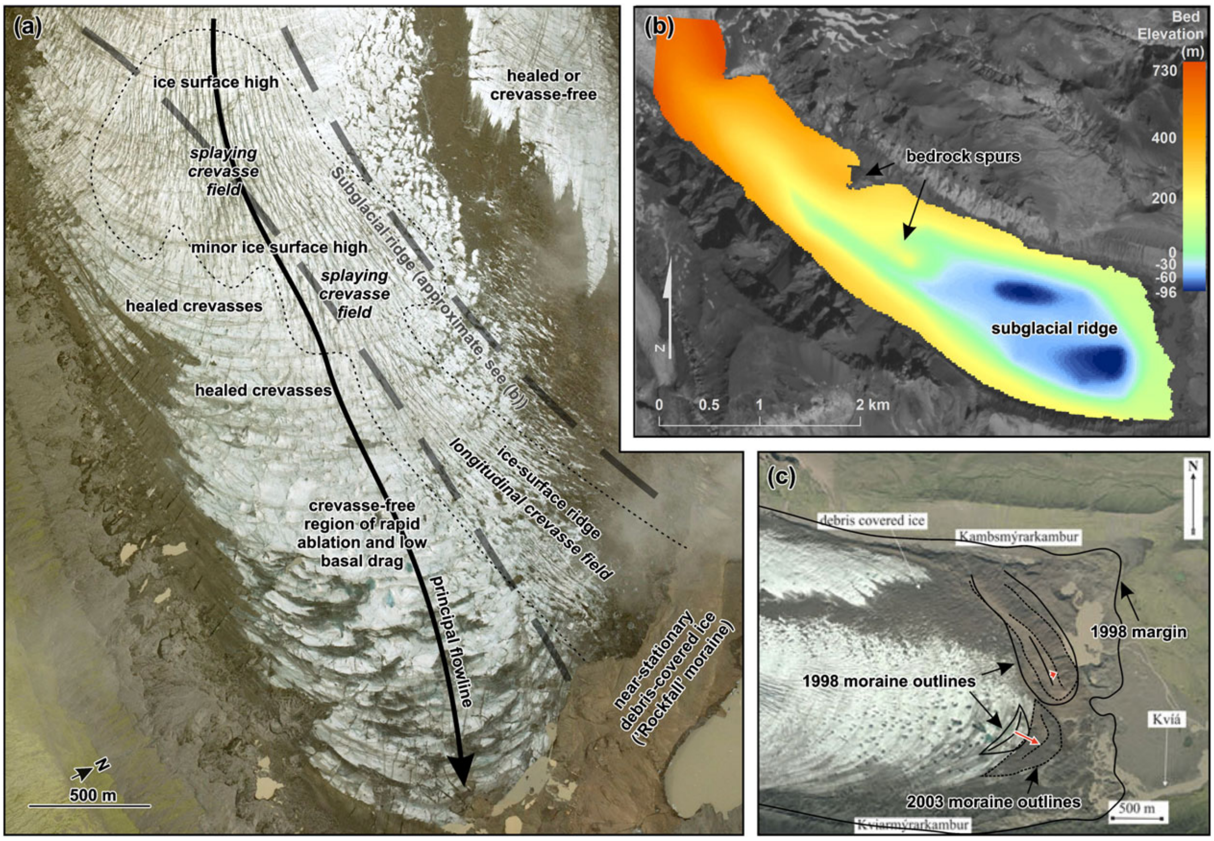

Figure 7. (a) Interpreted crevasse and flow patterns near the terminus. The thin dashed line defines an area of open crevassing, with active crevassing annotated in italicised text. Thick semi-transparent dashed lines indicate the approximate location of the subglacial ridge shown in (b). Arcuate development of transverse foliae indicates that the central flowline (black arrow) is directed through the crevasse-free area toward the true-right, in agreement with feature-tracking (Figure 2(b)). (b) Bed topography of the tongue and terminus region (Magnússon *et al.*, 2012). (c) Mapped displacement of prominent surface debris accumulations between 1998 and 2003. Displacement of the 'rockfall' moraine (see Figure 1(a)) is *c*. 100 m, whereas displacement of the emergent thrust moraine crest in the crevasse-free area is 300 to 500 m. The background to (c) has been obtained from Phillips *et al.* (2017). [Colour figure can be viewed at wileyonlinelibrary.com]

deflection by possibly several subglacial highs (Figure 7(a)), before flow continues into Domain 1 where these crevasses close. These highs correlate with the upglacier termination of a diagonally oriented subglacial ridge mapped by Magnússon *et al.* (2012) (Figure 7(b)). The change in longitudinal crevasse orientation north of Domain 1, as ice approaches the terminus, reflects quasi-transverse extension of ice that overrides the ridge (Figure 7(a) and (b)). Displacement in this region (Figure 2) indicates broadly uniform flow similar to that of other glaciers (Figure 6) and does not provide evidence of longitudinal shear or lobe-like flow.

Displacement measurements (Figure 2(b)) also show that the central flowline of ice in the glacier tongue is not deflected to the true-left when approaching the terminus and that Domain 1 is not slow-moving or stagnant ice. Rather, the central flowline runs through Domain 27 into Domain 1, and ice meeting the subglacial ridge appears to slow and extend transversely. This general pattern is supported by patterns of deformation shown by ogive bands and ogive-origin foliae (see below), and displacements of prominent ice-surface debris accumulations (Figure 7(c)). An absence of crevasses and the low elevation of Domain 1 likely reflect high surface ablation rates and reduced basal drag in this location on account of flow entering a deep, terminal subglacial basin (Magnússon *et al.*, 2012; Figure 7(b)). An advance of the northern frontal margin at a time of no clear change in the position of the southern frontal margin is noted by Phillips *et al.* (2017) as further evidence that active ice flow is deflected to the true-left. However, such an advance could also have resulted from thermal insulation of the ice margin by large terminal debris accumulations that are not present in the southern region. Further, 2017 imagery confirms the continued presence near the ice-front of the 'rockfall' moraine (Figure 2).

Coherent glacier-wide, transverse ogive-origin banding is also present throughout the region of proposed lobe-like and axial flow (Figure 1(c)). Band-ogives are an arcuate glacier-wide foliation phenomenon commonly observed in glacier tongues where ice has navigated a steep icefall. Band-ogive formation reflects the compression of ice flow at the base of an icefall to produce an annual pair of lighter 'winter' and darker 'summer' bands comprising transverse foliae that dip steeply upglacier (Swift, 2015). Individual foliae are produced by the healing, rotation and shortening of crevasses formed within the icefall and by shearing at the base of the ice fall, a process that has been observed to entrain basal ice and debris, with folia in darker 'summer' bands appearing denser and more sediment-rich (Goodsell *et al.*, 2002). Drag imposed by the valley bed and sides (see above; Figure 6) causes ogive folia to rotate from being initially sub-vertical to being semi bed-parallel, and bands to become increasingly arcuate, with distance down-flow. Bands therefore form a series repeating arches that are convex in the direction of glacier flow and closely spaced near the ice margins and widely spaced near the centre of flow (see Figure 8 and caption).

At Kvíárjökull, the integrity of ogive-origin foliation throughout the lower tongue and terminal region indicates an absence of internal longitudinal shear of the magnitude required to support the presence of discrete ice lobes and therefore support the pulsed axial flow hypothesis. It is also clear that, near the terminus, the deformation patterns shown by dark ogive

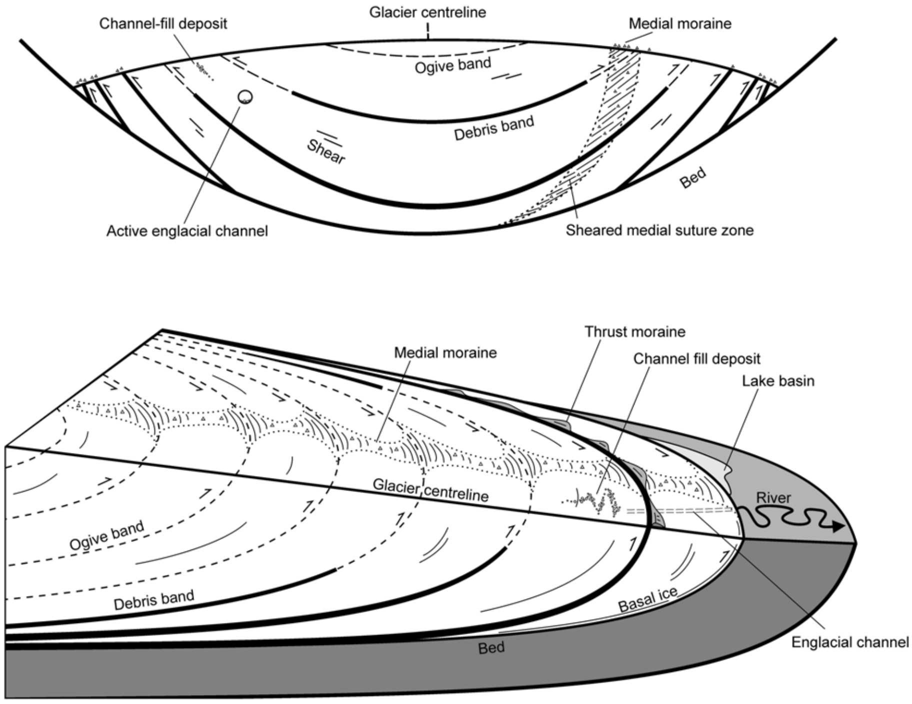

Figure 8. Generalised model of structure in the ablation area of a glacier undergoing longitudinal flow compression due to proximity of a terminal adverse slope, showing (a) transverse and (b) longitudinal sections through the tongue and terminus. Diagram (b) is adapted from Swift *et al.* (2006). Melt in the ablation area causes ice flow to be directed towards the frontal and lateral margins and the glacier surface (Hooke, 1998). Shear (indicated by arrows) takes place along favourably oriented ogive-origin foliae. Higher rates of shear occur along dark-ogive bands, causing entrainment of basal ice and sediment exposed in debris bands and thrust moraines at the glacier surface. Horizontal velocity patterns (cf. Figure 2) mean foliae and thrusts are closely spaced and almost vertical at the glacier margins (Phillips *et al.*, 2017, Figure 9(c)), and near the centreline are widely spaced and dip gently upglacier. A medial moraine structure formed by the suture of two separate flow units higher up the glacier is also folded into ogive foliation and subjected to subsequent shear. Deposits within abandoned englacial channels (Figure 6) that span terminal overdeepening (cf. Fountain and Walder, 1998; Cook and Swift, 2012) are exhumed by ablation and appear shortened or concertinaed by compressive flow. [Colour figure can be viewed at wileyonlinelibrary.com]

banding and related transverse foliae show that active flow is directed towards the southern part of the frontal margin, an observation supported by feature tracking (Figure 2). This means the crevasse-free ice surface in Domain 1 does not indicate stagnation, but likely indicates rapid ablation. Further, it is this flow pattern, rather than strike-slip at the edge of Domain 1, that likely explains the *c.* 260 m movement of the ice-cored esker between 2010 and 2014 (see Phillips *et al.*, 2017). Further evidence of this general flow pattern and the integrity of the ogive-origin foliation throughout the lower tongue and terminal region is provided by observations of thrusting close to the terminus that apparently occurs along ogive-origin foliae (Swift *et al.*, 2006) (Figures 4 and 8).

Surging as an analogue and links to surge mechanisms

Phillips *et al.* (2017) speculate that the pulses of flow required to produce individual lobes are the result of a surge-type phenomenon linked to the temporary storage of ice behind subglacial bedrock highs beneath the upper tongue. Flowers *et al.* (2011) have indeed proposed a surge mechanism linked to the presence of a subglacial basin (i.e. overdeepening), but observations at surging glaciers demonstrate that surging in temperate ice leads to even greater plug-like flow because it is associated with uniformly high basal water pressures that produce widespread, rapid basal slip (Kamb *et al.*, 1985). Surging ice has not – to our knowledge – been observed to flow in a corridor past non-surging or stagnant adjacent ice. Surging can produce certain lobe-like flow phenomena, specifically ‘loop’ or ‘tear-drop’ moraines (Post and LaChapelle, 1971), but these occur only where surging ice from one glacier displaces or strongly shears the ice of another glacier at a tributary–trunk junction. The images we present indicate no evidence of such lobe-like structures at Kvíárjökull. Nonetheless, it is possible that decadal scale changes in velocity at Kvíárjökull do occur, and that they may indeed be linked to the presence of subglacial basins that influence subglacial hydrological and sediment transfer processes (Turrin and Forster, 2014).

Conclusion

The motivation for the study by Phillips *et al.* (2017) appears to be the assumption that crevasse patterns at Kvíárjökull are inconsistent with traditional views of glacier flow. As a result, Phillips *et al.* (2017) advance an explanation based on ice flow history. However, the analysis and interpretation presented by Phillips *et al.* (2017) is inconsistent with our observations in two main respects.

First, crucial aspects of crevasse formation and glacier flow are not given adequate consideration. Crevasses form in response to near-surface stress in their immediate locality and close as glacier flow causes ice to move from one stress regime to another, while traces of shallow crevasse may be removed entirely by surface ablation. Crevasses cannot therefore be used to identify, unequivocally, discrete areas or packages of ice flow originating decades apart, or areas of historically stagnant ice. Moreover, flow of ice in discrete corridors or streams appears to occur only in much larger ice sheet systems and lacks physical plausibility at the valley glacier scale. Second, unequivocal evidence of shear of suitable magnitude at the boundaries of the proposed lobes is lacking. Even more importantly, the existence of such lobes is incompatible with glacier-wide transverse ogive-origin foliae and thrusts observed in the glacier tongue.

A simpler explanation for the crevasse patterns at Kvíárjökull is the uneven nature of the glacier bed, which is indicated by published bed data. This explanation is supported by the unchanging nature and positions of crevasse patterns between 2009 (ARSF aerial photograph) and 2017 (PlanetScope imagery). Longer-term changes in crevasse patterns may nevertheless occur as a result of glacier thinning and thickening, and it is probable that subtle changes in patterns identified by Phillips *et al*. (2017) since 1940 reflect changes in mass balance that have affected ice thickness and velocity. In the absence of other evidence, these explanations are far more likely than those that invoke surge behaviour or, even, changes in the morphology of the bed.

Crevasse patterns should primarily be interpreted in view of valley and bed morphology, which determines local patterns of stress in surface ice, but in addition caution needs to be exercised when interpreting glacier surface structures because their behaviour cannot be extrapolated to ice behaviour at depth. For example, horizontal and vertical displacements along faults probably represent local movements on open crevasses or their traces in the context of the very different behaviour of surface ice. Such ice is not subject to large confining pressures or the transverse stress couplings that dictate the behaviour of ice within the body of the glacier below. In light of this, the 'sense of shear' that may be demonstrated by small displacements observed on such near-surface features must be considered insufficient to support broader theories of ice flow.

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