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Structural evolution during a surge in the Paulabreen glacier system, Svalbard

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Abstract

We assess the evolution of glaciological structures during the 2003–05 surge in the Paulabreen glacier system, Svalbard. Glaciological structures on the glacier surface were mapped using aerial photographs captured in the early stages of the surge (2003) and 5 years after surge termination (2011). Three-dimensional measurements of glaciological structures were collected at the tidewater front in 2013. These datasets document the physical changes during (1) the late quiescent phase; (2) the early phase of the surge as the surge front propagated down Skobreen and advanced into Paulabreen and (3) the final stages of the surge following the surge front reaching the glacier terminus. Crevasse patterns and clusters of arcuate shear planes record zones of compressive and extensional flow associated with the downglacier progression of the surge front. The transfer of surging ice from Skobreen into Paulabreen caused lateral displacement of the medial moraines to the northeast. At the ice front, this movement tilted glaciological structures in the same direction. Structures at the southwest margin record strike–slip faulting and the elevation of debris into the ice in a zone of compression and transpression. We summarise these observations in a schematic reconstruction of structural evolution during the surge.

Introduction

Polythermal glacier surges in Svalbard are characterised by dynamic and cyclical switches between a decades-long quiescent phase of low velocities and terminus recession and a years-long active phase, during which ice flow velocities can increase to 10–1000 times typical quiescent phase values (Dowdeswell and others, 1991; Hagen and others, 1993; Murray and others, 2003). Increased flow velocities in the surge active phase are usually accompanied by the transfer of mass to lower elevations, often resulting in frontal advance (Murray and others, 2003; Sund and others, 2009, 2014; Kristensen and Benn, 2012). Glacier geometry and internal structural properties can change rapidly during surge active phases (Raymond and others, 1987; Sharp and others, 1988; Lawson and others, 1994; Murray and others, 2012; Małecki and others, 2013; King and others, 2016). Investigation of glaciological structures such as crevasses, shear planes, foliation and medial moraines have increased understanding of cumulative deformation and variable stress and strain regimes experienced during different phases of the surge cycle (e.g. Sharp and others, 1988; Hodgkins and Dowdeswell, 1994; Lawson and others, 1994, 2000; Lawson, 1996, 1997; Hambrey and Dowdeswell, 1997; Fleming and others, 2013; Hudleston, 2015; King and others, 2016; Sevestre and others, 2018; Hambrey and Clarke, 2019; Young and others, 2022).

Ice deformation during the quiescent and active phases of surges can lead to a complex array of glaciological structures and detailed structural mapping can help to establish a chronology of structural development (e.g. Lawson and others, 1994, 2000; Hambrey and Dowdeswell, 1997; King and others, 2016; Hambrey and Clarke, 2019). Kinematic structures associated with ductile deformation, such as medial moraines and longitudinal foliation, are largely a passive consequence of ice flow and develop during the quiescent phase. Brittle deformation dominates the active phase, when strain rates can be an order of magnitude higher than during quiescence, forming dynamic/constructive structures such as thrust-faults and crevasses (Sharp and others, 1988; Lawson and others, 1994, 2000; Hambrey and others, 1996; Lawson, 1996, 1997; Hambrey and Dowdeswell, 1997; King and others, 2016; Hambrey and Clarke, 2019). The evolution of active phase structures is typically closely linked to either (1) downglacier propagation of a surge front, where structures such as longitudinal crevasses (where extension is normal to ice flow) and shear planes form in a zone of longitudinal compression at or below the surging ice, and structures such as transverse crevasses (where extension is parallel to ice flow) form above the surge front (e.g. Hambrey and others, 1996; Lawson, 1996; Hambrey and Dowdeswell, 1997; Kristensen and Benn, 2012; King and others, 2016); or (2) up-glacier expansion of crevasse fields where surges initiate at the front of tidewater glaciers (e.g. Hodgkins and Dowdeswell, 1994; Sund and others, 2014; Flink and others, 2015; Sevestre and others, 2018).

We aim to investigate the genesis of glaciological structures in the Paulabreen glacier system and constrain their evolution during the most recent surge by (1) mapping 2-D surface structures interpreted from aerial photographs captured during the early stages of surging and after the surge terminated; and (2) mapping and measuring 3-D structures exposed in the tidewater front since surge termination. We present a conceptual model for the structural evolution of the glacier system during the final stages of its recent surge cycle.

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Paulabreen glacier system surge history

The glacier system is located in southern Spitsbergen at the head of Rindersbukta, a 12 km-long-tributary fjord of Van Mijenfjorden (Fig. 1). Three main contiguous glaciers comprise the glacier system at present: the main tidewater terminus Paulabreen is flanked by Bakaninbreen (to the northeast) and Skobreen (to the southwest). Bakaninbreen and Paulabreen are trunk glaciers separated by a medial moraine extending from Siggerudfjella. Skobreen is a tributary glacier separated from Paulabreen by a frontal moraine loop (Sund, 2006; Kristensen and Benn, 2012).

The Paulabreen glacier system has one of the longest and best recorded surge histories of any glacier system in Svalbard (Lovell and others, 2018). The largest surge occurred in AD ~1300, when the combined glacier system advanced to the boundary between inner and outer Van Mijenfjorden (Hald and others, 2001; Ottesen and others, 2008; Kristensen and others, 2009a; Larsen and others, 2018). The surge moraines of Torellmorenen, Damesmorenen and Crednermorenen were deposited at this time (Kristensen and others, 2009a, 2009b; Larsen and others, 2018) and a short-lived proglacial lake was dammed in the area now occupied by the shallow lagoon Braganzavågen (Lyså and others, 2018). At the mouth of Rindersbukta, three submarine moraines with associated debris-flow lobes on their distal flanks (M1–3 in Fig. 1) record three additional surge maximum positions (Ottesen and others, 2008; Larsen and others, 2018). The innermost moraine/debris-flow lobe (M1) is coincident with the AD 1898 frontal position of the glacier system as mapped by Kjellström (1901), indicating a surge during the Little Ice Age (Ottesen and others, 2008; Larsen and others, 2018). M2 and M3 are undated but can be very broadly constrained to between AD ~1300 and AD 1898 (Larsen and others, 2018; Lovell and others, 2018).

The glacier system underwent sustained frontal retreat of ~10 km to the head of Rindersbukta throughout the 20th century (Ottesen and others, 2008; Benn and others, 2009; Larsen and others, 2018). A renewed phase of quasi-independent surge activity began in 1985 with the development of a surge front in the upper part of Bakaninbreen (Dowdeswell and others, 1991; Hambrey and others, 1996; Murray and others, 1998). The surge front propagated downglacier as a ramp up to 60 m high and at rates of 1.0–1.8 km a^{-1}, before becoming less steep and slowing considerably in the later years of the surge (Murray and others, 1998). The surge terminated in 1995 when the surge front was still ~1.8 km from the tidewater terminus (Murray and others, 1998, 2000; Smith and others, 2002). The surge did not propagate laterally across the medial moraine into Paulabreen (Benn and others, 2009). Independently, the uppermost parts of Skobreen were in the initial stages of a surge active phase in 1990 (Sund, 2006). By summer 2003, the entire Skobreen tributary was surging and the frontal moraine loop had begun to advance into Paulabreen (Sund, 2006; Benn and others, 2009; Kristensen and Benn, 2012) (Figs 2a, b). A surge front and associated longitudinal crevasses could be identified close behind the moraine loop and transverse crevassing and ice-drawdown was widespread in the upper reaches of the glacier (Sund, 2006; Benn and others, 2009; Kristensen and Benn,

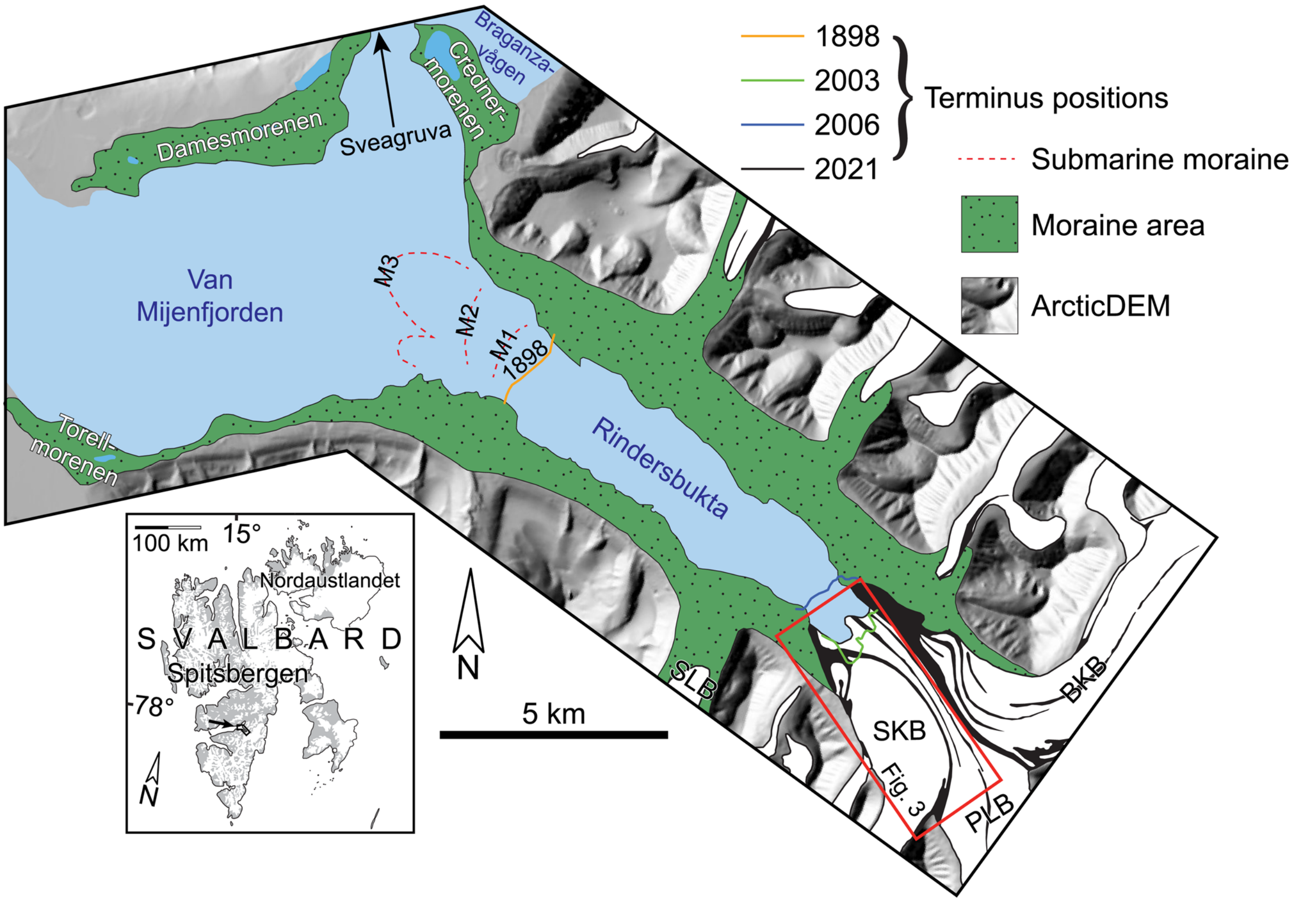

Fig. 1. Map of inner Van Mijenfjorden and Rindersbukta showing the glaciers Bakaninbreen (BKB), Paulabreen (PLB) and Skobreen (SKB) comprising the Paulabreen glacier system. Scheelebreen (SLB) is also a surge-type glacier. The main moraine systems in the fjord and the location of the settlement Sveagruva are labelled. Glaciers are mapped from a Sentinel-2 image (captured on 9 August 2021). The 2003 and 2006 terminus positions are mapped from an ASTER image (captured on 24 July 2003) and Landsat ETM + image (captured on 26 July 2006), respectively. Satellite images were acquired from EarthExplorer (earthexplorer.usgs.gov). The 1898 terminus position is from Ottesen and others (2008). Submarine moraines (M1–3) are from Larsen and others (2018) and their age has been broadly constrained to between AD ~1300 and AD 1898. The background is an ArcticDEM image (https://www.pgc.umn.edu/data/arcticdem/). Inset map shows location of the study area (in black and arrowed) within Svalbard.

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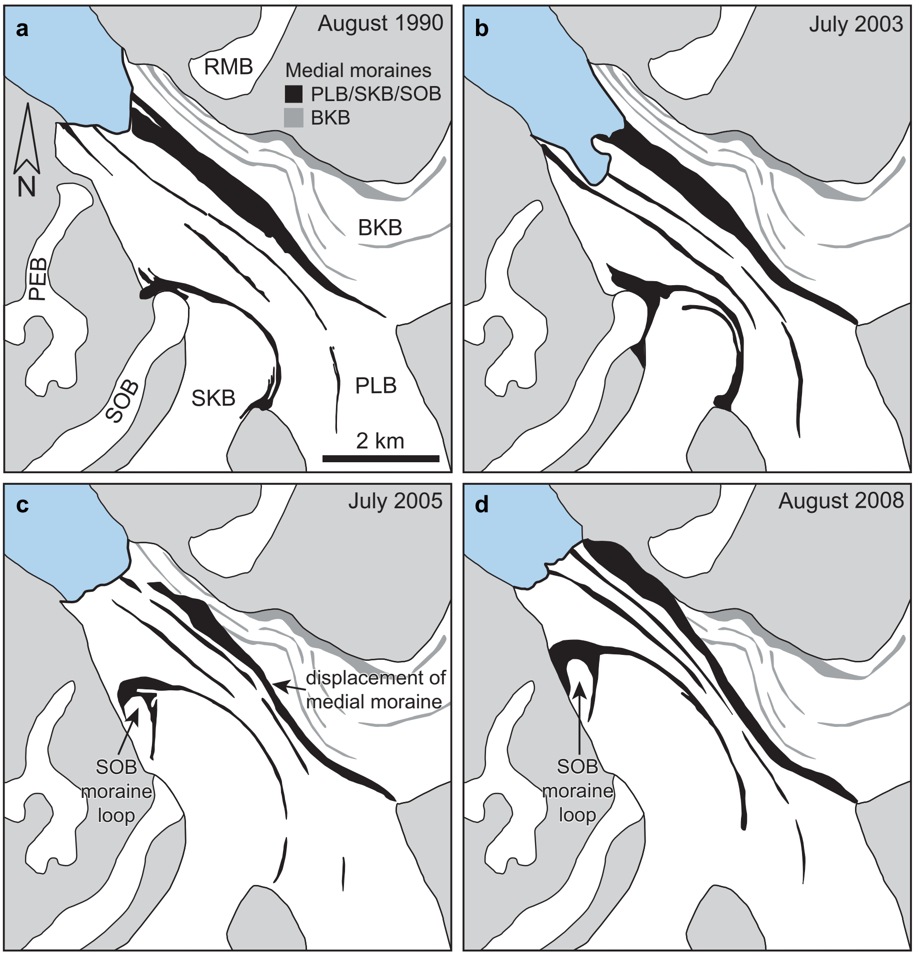

Fig. 2. Progressive displacement of medial moraines and advance of the tidewater front during the Skobreen–Paulabreen surge. BKB, Bakaninbreen; PLB, Paulabreen; SKB, Skobreen; SOB, Sokkbreen; PEB, Peisbreen; RMB, Ragna-Mariebreen. Adapted from Kristensen and Benn (2012).

2012). The Skobreen moraine loop continued to advance from 2003 to 2005 as the surge front propagated into Paulabreen, recording a total displacement of ~1.4 km (Benn and others, 2009; Kristensen and Benn, 2012) (Figs 2c, d). The surge front reached the Paulabreen tidewater terminus by April 2005 and the terminus advanced at ~4.8 m d^{-1} between April and August 2005. The terminus had advanced ~1.4 km by surge termination in winter 2005/06 (Benn and others, 2009; Kristensen and Benn, 2012).

The surge activated the lower part of Paulabreen across its entire width. Remote-sensing analysis shows that the medial moraine separating Paulabreen and Bakaninbreen was progressively displaced sideways and, as a result, Bakaninbreen is now land-terminating (Benn and others, 2009; Kristensen and Benn, 2012) (Fig. 2). Both the Bakaninbreen (1985–95) and Skobreen–Paulabreen (2003–05) surges failed to propagate laterally across the medial moraine between Bakaninbreen and Paulabreen, which Benn and others (2009) attributed to the presence of a persistent subglacial conduit below the medial moraine. Time-lapse footage of the advancing southwest margin of the Skobreen–Paulabreen surge in 2005 demonstrates plug-like flow, deformation of the lateral proglacial moraine area and the incorporation of large volumes of debris into the ice (Kristensen and Benn, 2012). Since 2006, the tidewater terminus has receded ~1 km, exposing the glaciological structures in the ice cliff investigated in this study.

Methods

Two-dimensional glaciological structures exposed on the glacier surface were digitised from georeferenced vertical colour aerial photographs at a maximum resolution of 1:5000. The aerial photographs were captured on 8 August 2003 (as Skobreen began to surge into Paulabreen) and 7 July 2011 (~5 years following surge termination). The 2003 photographs were collected by the UK Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) and acquired from the NERC Earth Observation Data Centre. The 2011 photographs were collected by the Norwegian Polar Institute and acquired from the TopoSvalbard online archive (toposvalbard.npolar.no). Structures were identified and categorised according to their inferred sequential development using standard structural geological notation and following the examples of previous structural glaciology studies (e.g. Lawson and others, 1994; Hambrey and Dowdeswell, 1997; Hambrey and others, 2005; Hudleston, 2015; Lovell and others, 2015a; King and others, 2016; Hambrey and Clarke, 2019; Jennings and Hambrey, 2021). Fieldwork in April 2013 focused on the identification of planar glaciological structures exposed in the ~1.5 km-long Paulabreen tidewater ice cliff following surge termination. Vertical cross sections were recorded from a photomosaic of the ice cliff. Three-dimensional orientation measurements (strike and dip) of foliation and englacial debris-rich structures (debris layers) were collected using a compass clinometer. Measurements of linear structure (dip and dip direction) were collected from sheared debris laminae, or mineral stretching lineations, within the debris layers (Fleming and others, 2013). Structural data were corrected for magnetic deviation and plotted as equal-area stereographic projections using Stereo32 software (Röller and Trepmann, 2008).

Results

Glaciological structures

The five sets of glaciological structures identified on the glacier surface in the 2003 and 2011 aerial photographs are medial

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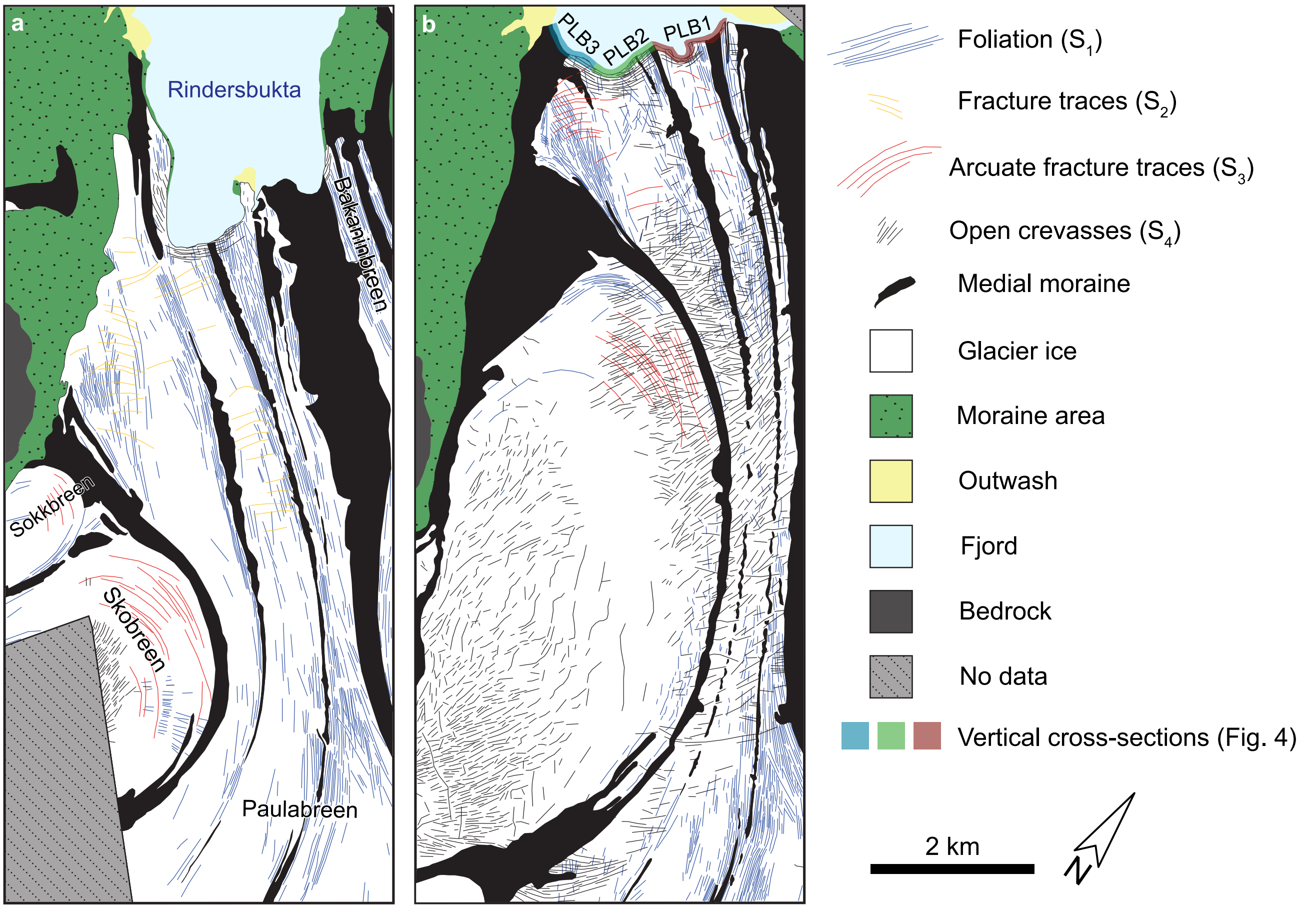

Fig. 3. Maps of 2-D surface structures exposed at the front of the Paulabreen glacier system in (a) August 2003 (early surge phase) and (b) July 2011 (5 years after surge termination). See Figure 1 for location of mapped area.

moraines, foliation (S_1), fracture traces (S_2), arcuate fracture traces (S_3) and open crevasses (S_4) (Fig. 3). Primary stratification (S_0) is not visible in the lower reaches of the glacier system covered by Figure 3 but is seen higher up on TopoSvalbard aerial photographs, and we include this within the overall structural sequence for completeness (Table 1). Medial moraines, foliation (S_1) and fractures were also identified in the ice cliff in 2013, together with englacial debris-rich structures (debris layers) (Figs 4–6). The structures are first described here, before their distribution, morphology and structural properties as observed on the glacier surface and in the ice cliff are outlined.

The large medial moraines observed on the glacier surface (Fig. 3) can also be identified in the ice cliff (Figs 4, 5a, 6c). The medial moraines are characterised by kilometres-long, tens-of-metres-wide surface debris drapes with a positive topographic expression (Fig. 3) emanating from thin, near-vertical or inclined debris layers (Figs 4, 5a, 6c). Medial moraines typically

Table 1. Summary of principal glaciological structures in the Paulabreen glacier system in inferred sequence of formation.

Notation	Structure	Interpretation
S_0	Primary stratification	Original layering formed by firnification processes in the accumulation area.
S_1	Foliation	Formed by deformation and folding of primary stratification (S_0) through simple shear in association with glacier flow.
S_2	Fracture traces	Healed crevasses.
S_3	Arcuate fracture traces	Shear planes developed in a zone of longitudinal compression.
S_4	Open crevasses	Crevasses formed in zones of longitudinal compression and extension.

form (1) through the merger of supraglacial lateral moraines at the confluence of two flow-units or (2) as buried debris layers that have been tightly folded meltout in a glacier's lower reaches (Eyles and Rogerson, 1978a; Hambrey and others, 1999; Hambrey and Glasser, 2003; Hudleston, 2015). The latter process occurs in conjunction with the formation of strongly developed longitudinal foliation (S_1) (Hambrey and others, 1999). Most of the medial moraines observed in the lower reaches of the glacier system separate major flow-units/tributaries and can be traced to supraglacial lateral moraines (Figs 2 and 3). In a few cases, smaller discontinuous medial moraines in close association with longitudinal foliation may be debris-bearing S_1 structures that have melted out at the surface (e.g. Hambrey and others, 1999, 2005).

Foliation (S_1) is observed on the glacier surface (Fig. 3) and in the ice cliff (Fig. 5b). The surface expression of foliation forms linear stripes oriented with the direction of ice flow (Fig. 3), termed longitudinal foliation (e.g. Hambrey and Clarke, 2019). In the ice cliff, foliation can be identified as alternating layers of bubble-rich and clear (bubble-poor) ice (Fig. 5b) (Lawson and others, 1994). Foliation is considered a secondary structure originating from primary stratification (S_0) that has subsequently been deformed and folded. Longitudinal foliation is the result of high degrees of simple shear relating to glacier flow, creating structures aligned parallel to glacier flow with isoclinal folds reflecting differing flow velocities within the ice (Jennings and Hambrey, 2021).

Two generations of fractures can be identified on the glacier surface: fracture traces (S_2) and arcuate fracture traces (S_3). Fracture traces (S_2) are in general short, straight features and are likely to be relict extensional crevasses that have healed (e.g. Hambrey and Dowdeswell, 1997; Goodsell and others, 2005; King and others, 2016). Arcuate fracture traces (S_3) are typically

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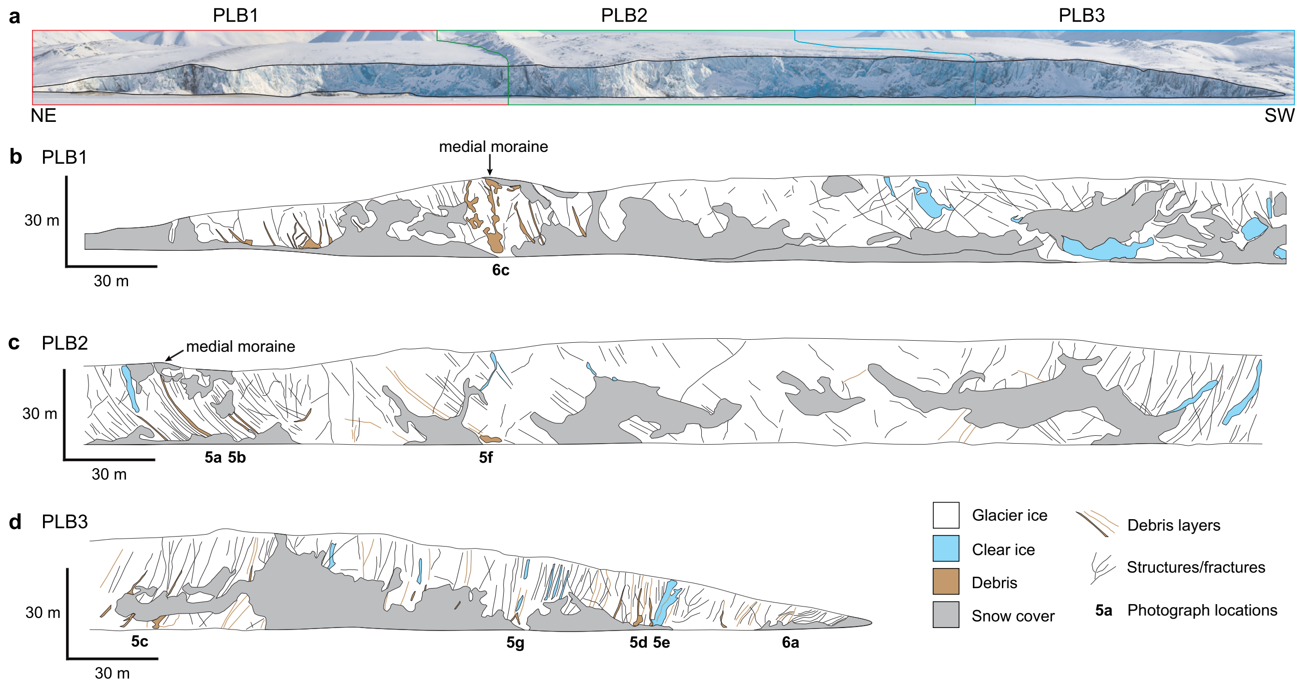

Fig. 4. Vertical cross sections of the tidewater glacier front. (a) Photomosaic of the glacier front in April 2013. (b) PLB1 section. (c) PLB2 section. (d) PLB3 section. See Figure 3b for locations of the cross sections.

longer and have a curved morphology (Fig. 3). Such features are commonly interpreted to be shear planes or thrust-faults formed in zones of longitudinal compression (e.g. Hambrey and others, 1999; Appleby and others, 2010; Roberson and Hubbard, 2010; Lovell and others, 2015a). Fracture traces are also seen in the ice cliff, where they crosscut foliated ice, other fracture traces and debris layers, and in general display one or two dominant orientations (Fig. 4). We are unable to distinguish the fractures observed in section as separate structural elements, but it is likely both healed crevasses (S_2) and shear planes (S_3) are represented.

Open crevasses (S_4) are observed on the glacier surface. Crevasses typically form transverse to ice flow (45° either side of flow perpendicular) in zones of extension and longitudinal to ice flow (45° either side of flow parallel) in zones of compression (Lawson and others, 2000; Rea and Evans, 2011; Kristensen and Benn, 2012).

Debris layers observed in the ice cliff are thin near-vertical or dipping debris-rich structures extending tens-of-metres from the visible base of the section (Figs 4, 5). Debris layers in PLB1 and PLB2 often display tangential geometries (Fig. 5a) and steepen towards the top. Larger areas of debris are common towards the base of debris layers, which typically taper out towards their upper limits. Debris within the layers varies from sorted sands and gravels (Fig. 5c) to poorly sorted diamicton ranging from silts to pebble and cobble-sized clasts (Fig. 5g). Where debris layers consist of fine material, sheared debris laminae/mineral stretching lineations can be identified (Fig. 5g) (e.g. Fleming and others, 2013). Debris layers exposed in section in surge-type glaciers are typically inferred to have formed at a glacier bed experiencing very large stress gradients by (1) squeezing into basal crevasses, (2) hydrofracturing or (3) thrust-style displacement of pre-existing planar weaknesses (e.g. shear planes, crevasse traces) (e.g. Glasser and others, 1998; Woodward and others, 2002; Rea and Evans, 2011; Lovell and others, 2015b).

Structures on the glacier surface

In 2003, the Bakaninbreen and Paulabreen medial moraines were relatively straight and continuous, tracing the overall flow configuration of the glacier (Fig. 3a). The medial moraine loop separating Skobreen and Paulabreen had begun to advance into Paulabreen as ice surged out of Skobreen (Figs 2b, 3a). By 2011, the Bakaninbreen and Paulabreen medial moraines had been laterally displaced ~500 m to the northeast and the Skobreen moraine loop extended a similar distance laterally into Paulabreen and up to ~1.8 km downglacier (Fig. 3b).

The orientation and morphology of longitudinal foliation (S_1) exposed on the glacier surface appears generally unaltered between 2003 and 2011, but both lateral and downglacier displacement is evident. Longitudinal foliation was densely clustered around the Bakaninbreen–Paulabreen and Paulabreen medial moraines in 2003 and extended to the glacier front (Fig. 3a). In 2011 the longitudinal foliation was largely unaltered in Paulabreen above the heavily crevassed zone. Closer to the glacier front, longitudinal foliation was displaced laterally to the northeast together with the medial moraines.

Fracture traces (S_2), interpreted as healed crevasses, were found in the central and southwest parts of Paulabreen in 2003 (Fig. 3a). Arcuate fracture traces (S_3), interpreted as shear planes, were concentrated up-glacier of the Skobreen moraine loop, closely associated with arcuate topographic 'waves' in the ice surface (Kristensen and Benn, 2012). By 2011, the arcuate fracture traces (S_3) within Skobreen were displaced as the moraine loop advanced into Paulabreen but were otherwise relatively unaltered in morphology and distribution. The lower part of the glacier system was heavily crevassed and only a small area of arcuate fracture traces (S_3) concentrated at the southwest margin was visible (Fig 3b). We suggest these are shear planes (S_3) rather than healed crevasses (S_2) because of their location in a zone of compression at the lateral glacier margin. However, some of the shear planes are likely to have reactivated the healed crevasses that were present in this area in 2003 (e.g. Hambrey and Müller, 1978; Goodsell and others, 2005; Appleby and others, 2010; Rea and Evans, 2011).

Open crevasses (S_4) were confined to two zones in 2003: transverse crevasses associated with the tidewater front and short longitudinal crevasses in the centre of Skobreen (Fig. 3a) (Kristensen and Benn, 2012). By 2011 most of the lower section of Skobreen and Paulabreen was crevassed. The Skobreen crevasse pattern was

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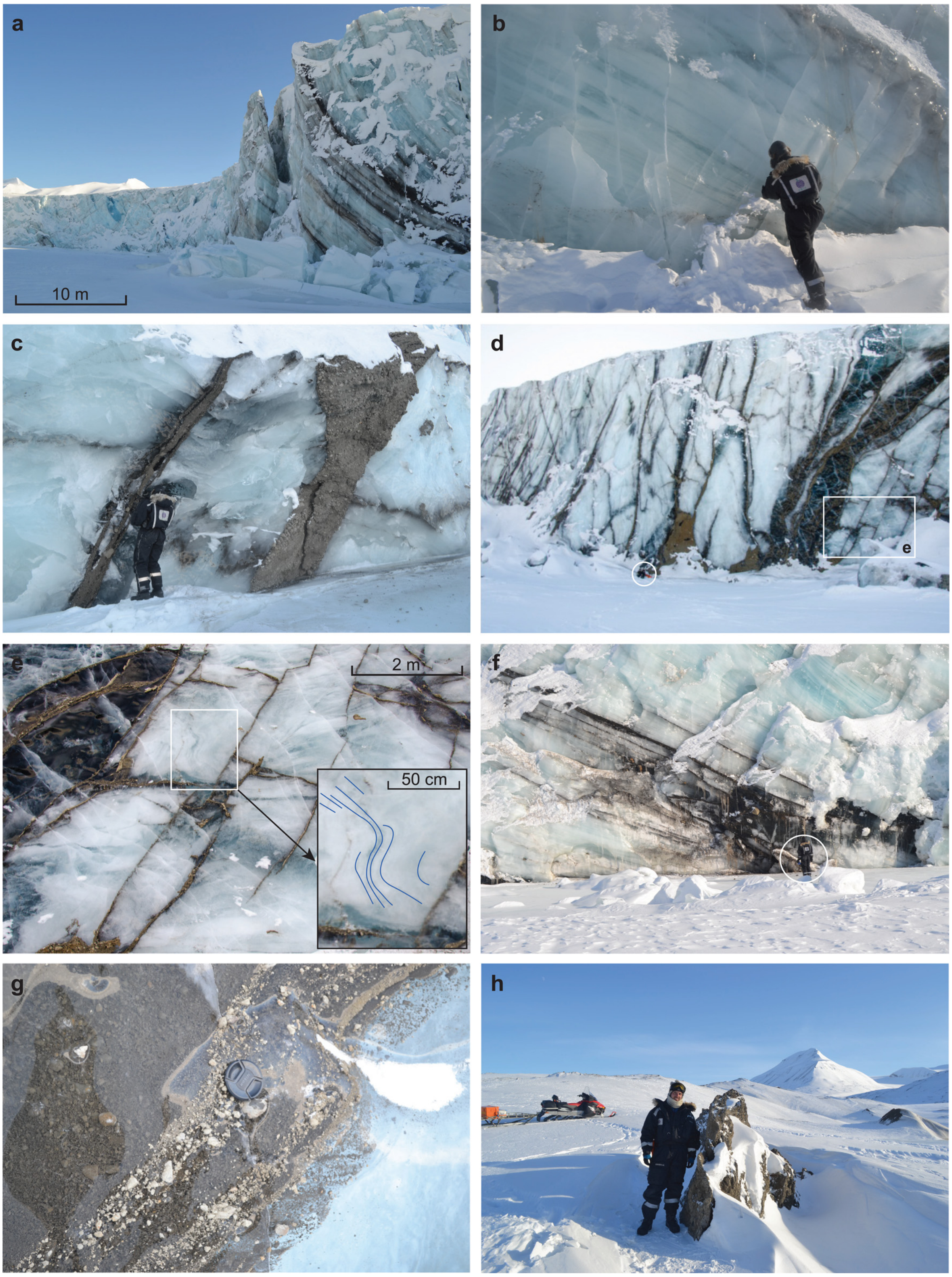

Fig. 5. Glaciological structures and debris exposed at the tidewater front in April 2013. (a) Inclined debris layers feeding a medial moraine in PLB2 section. The layers display a tangential geometry suggesting simple shear with the highest magnitude at the base. (b) Highly deformed foliation displaying isoclinal folds with axial planes dipping to the right. (c) Sorted sands and gravels within debris layers. (d) Debris layers and fractures within PLB3 section. Person encircled for scale. (e) Localised chaotic folding of foliation (see annotations on zoomed-in inset) that is heavily fractured and truncated by debris layers. See (d) for location. (f) Rotated isoclinal fold within debris layers. (g) Sheared debris laminae (mineral stretching lineations) within a debris layer. (h) Near-vertical debris ridge emerging from the ice at southwest glacier margin. See Figure 4 for photograph locations.

dominated by short longitudinal crevasses aligned with the main axis of ice flow to the north. At the moraine loop, the Skobreen crevasse orientation remained similar, transverse to ice flow within the Paulabreen main trunk (Fig. 3b). Crevasses in the central section of Paulabreen were generally aligned transverse to ice flow, indicative of mode 1 fracturing (Benn and others, 2007; Rea and Evans, 2011). The densest crevassing in Paulabreen in 2011 was close to the downglacier limit of the Skobreen moraine loop, ~2 km from the tidewater front. Many crevasses in this zone were aligned ~45° from perpendicular to ice flow with two dominant orientations, forming conjugate fracture sets (e.g. Lawson and others, 1994; Rea and Evans, 2011). Aside from transverse crevasses at the tidewater front, the lowermost ~2 km of Paulabreen was largely crevasse-free in 2011.

Structures in the ice cliff

A ~1.5 km-long section of the tidewater front of Paulabreen was investigated in 2013, extending from close to where the Bakaninbreen–Paulabreen medial moraine intersects the glacier front (towards the northeast lateral margin) to the point where the southwest margin of Paulabreen meets the lateral proglacial moraine area (Fig. 4a). The ice cliff comprises the central and southwest parts of the glacier system, as Bakaninbreen is currently land terminating. The ice cliff is divided into three sections for ease of reporting: PLB1 (towards the Bakaninbreen–Paulabreen medial moraine), PLB2 (central section) and PLB3 (southwest margin) (Figs 3, 4). The left-hand (northeast) part of PLB1 contains several dipping debris layers with tangential geometries (Fig. 5a) and the easternmost of the large medial moraines within Paulabreen (Figs 4b, 6c). The right-hand (southwest) part of PLB1 contains a series of fractures and areas of clear (bubble-poor) ice.

PLB2 contains several debris layers (e.g. Fig. 5f) and areas of clear ice. The second large Paulabreen medial moraine is exposed here. Its cross section reveals the relationship between foliation, debris layers and the medial moraine (Figs 6c, d). The surrounding foliation is tightly folded but dips consistently to the southwest. Thin debris layers are observed with a similar orientation, which thicken towards the medial moraine. The trace of the medial moraine can clearly be seen and consists of a zone of debris of varying thickness (10–50 cm), also dipping to the southwest. The foliation and debris layers are truncated by the medial moraine.

Debris layers are particularly well exposed in PLB3, often in close association with areas of clear ice (e.g. Figs 5d, e). Here they display evidence for polyphase deformation. For example, Figures 6a and b show flow-parallel debris layers cut by a subparallel debris layer that follows a strike–slip fault.

Structures in the tidewater front typically strike subparallel to parallel to the main axis of ice flow in Paulabreen (Fig. 7). However, significant spatial variation in dip orientation is seen depending on the position along the ice cliff. In PLB1, foliation is typically oriented subparallel to the glacier margins and displays a strong preferred orientation striking northwest/southeast and dipping steeply to the southwest (131/34). A second sub-vertical orientation is observed in the foliation trending north–south, dipping subvertically to the west (359/80) (Fig. 7b-ii). Foliation is tightly folded and a number of isoclinal folds are recognised, with horizontal axes orientated parallel to the strike of the foliation (mean vector 132/03) (Fig. 7b-iii). Debris layers display a similar orientation to the foliation, trending northwest–southeast and dipping steeply to the east-northeast (mean orientation 128/43). As with the foliation, a second sub-vertical orientation is observed trending north–south and dipping subvertically to the west (004/76) (Fig. 7b-i).

Structures in PLB2 are typically also oriented subparallel to the glacier margins, but dip directions vary considerably (Fig. 7c). Two distinct clusters are observed in the foliation data. In the southwest part of the section, the foliation follows a similar pattern to that seen in PLB3, striking north-east-north/

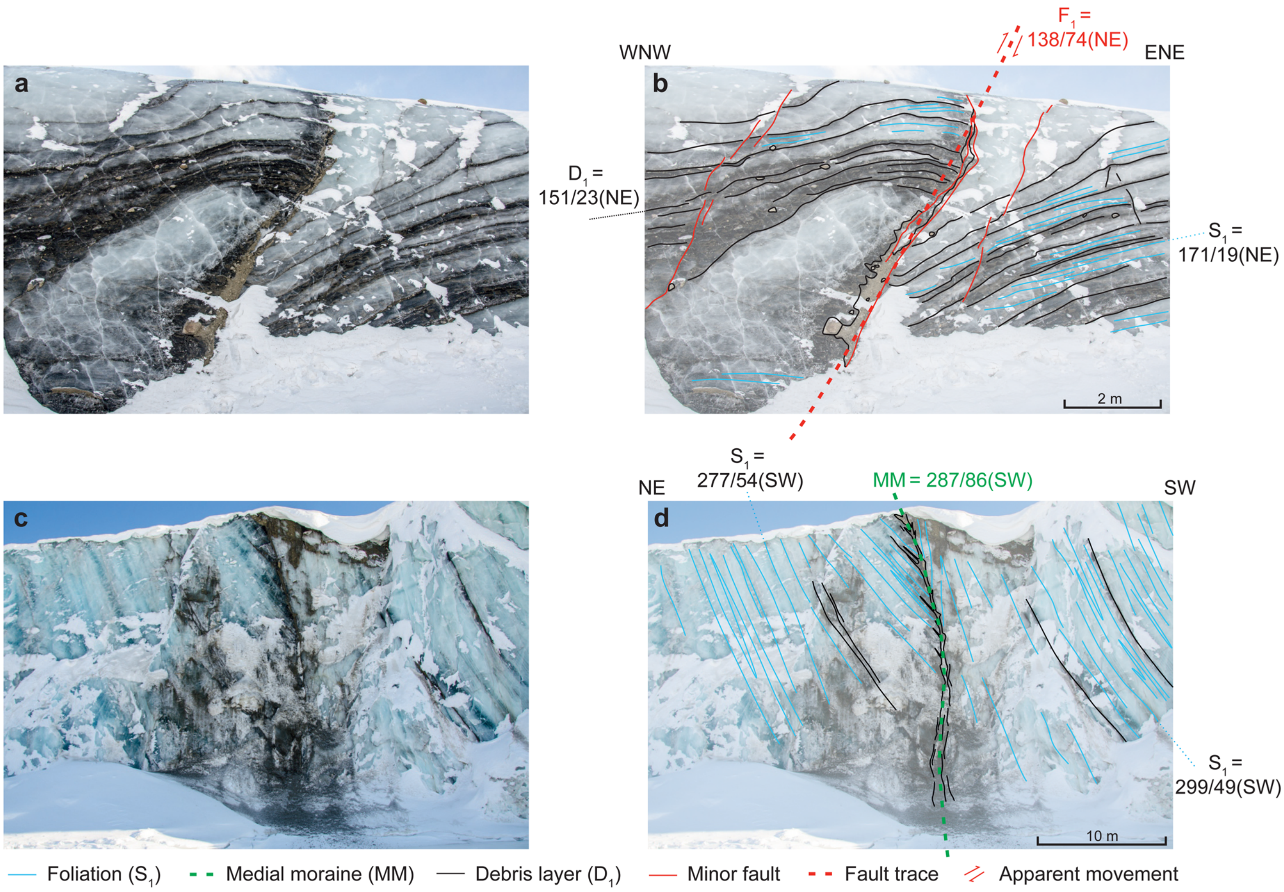

Fig. 6. Interpretations of glaciological structures. (a) Debris-rich strike–slip fault in PLB3 close to the southwest end of the ice cliff. (b) Interpretation of (a) showing the displacement of debris layers (D_1) and foliation (S_1). Orientation suggests strike–slip movement with minor dip slip causing the apparent thrusting. (c) Section view of the medial moraine in PLB1. (d) Interpretation of (c) showing tightly folded foliation and debris layers truncated against the medial moraine (MM). See Figure 4 for photograph locations.

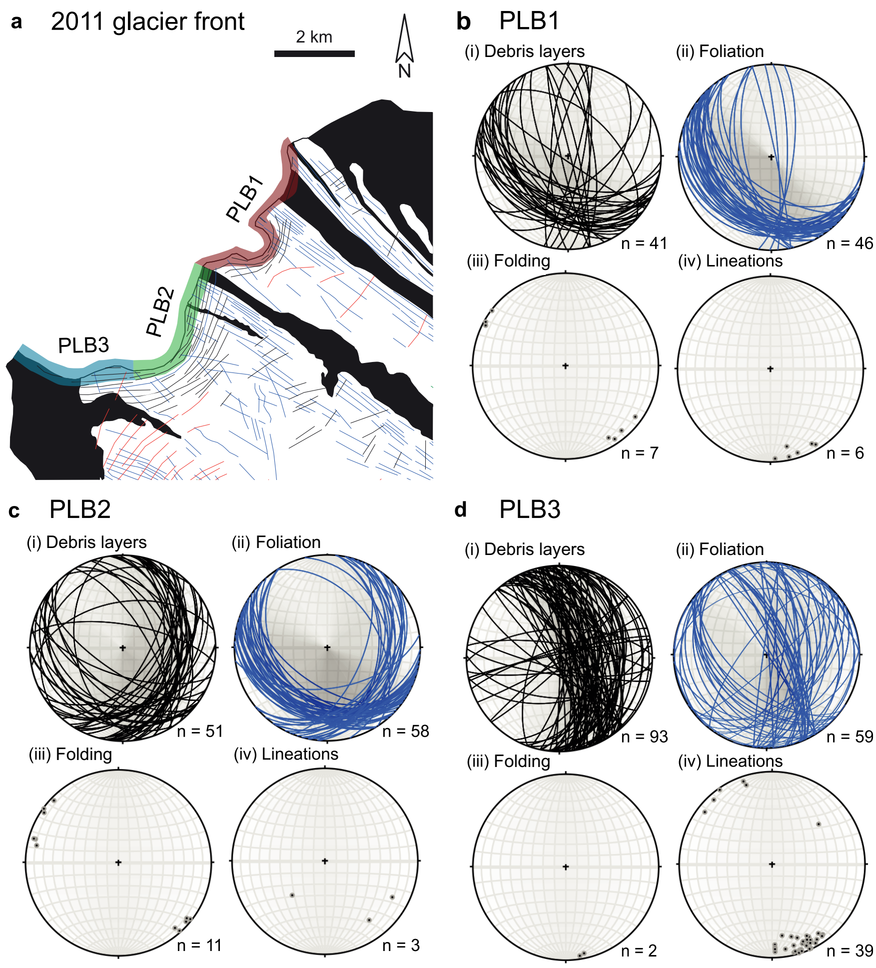

Fig. 7. Three-dimensional data of glaciological structures exposed in the Paulabreen tidewater front. Data are plotted on lower-hemisphere equal-area stereographic projections. Planes (debris layers and foliation) are plotted as great circles. Fold axes and mineral stretching lineations are plotted as points. Legend for structures in (a) is the same as Figure 3.

south-west-south and dipping to the east-southeast (020/35). In the northeast part of the section foliation strikes west-northwest/east-southeast, dipping to the south-west-south (111/33) (Fig. 7c-ii). Foliation in PLB2 is also tightly folded, with axes orientated parallel to the strike of the foliation (mean vector 302/03) (Fig. 7c-iii). Debris layers in PLB2 show similar bipartite clustering with one cluster from the southwest part of the section striking north–south, dipping moderately to the east (304/40), while those from the northeast part strike northwest–southeast, dipping to the southwest (120/39) (Fig. 7c-i). Stretching lineations are typically sub-horizontal, trending southeast (120/39), although a steeply dipping lineation was recognised (48/224) (Fig. 7c-iv), which could represent thrust-style displacement along a debris layer (e.g. Rea and Evans, 2011; Lovell and others, 2015b).

Structures in PLB3 are generally oriented subparallel to the glacier margins (Fig. 7d). Foliation is oriented subparallel to the glacier margins but is variable. Most of the foliation trends northwest/southeast (338/75), dipping steeply to the northeast. However, a second sub-vertical orientation is observed trending northwest–southeast, dipping moderately to the southwest (135/47) (Fig. 7d-ii). Foliation is tightly folded and a number of folds are recognised. These have horizontal axes orientated parallel to the strike of the foliation (mean vector 135/01) (Fig. 7d-iii). Debris layers are less variable and mostly strike north-northwest–south-southeast, dipping steeply to the east-northeast (mean orientation 349/53) (Fig. 7d-i). Stretching lineations within the debris layers are sub-horizontal (163/08) (Fig. 7d-iv).

These structural data reveal that foliation and debris layers predominantly strike subparallel to glacier flow, which is also indicated by foliation on the glacier surface (Figs 3, 7a). However, measurements at the ice front reveal distinct variations in dip, contrary to what might be expected. At the lateral margin (PLB3), structures predominantly dip to the northeast (Figs 4, 7d). However, the orientation quickly changes along the ice front in a northeast direction and from the medial moraine in PLB2 onwards, structures dip to the southwest (Figs 4, 7b, c). Furthermore, structures display distinct tangential bases (Fig. 5a), suggesting simple shear to the north with increasing intensity towards the base.

Discussion

Glaciological structures exposed on the glacier surface in 2003 and 2011 and in the ice cliff in 2013 are a product of the recent surge history of the glacier system. We combine these data with observations by Kristensen and Benn (2012) to reconstruct the impact of surging on the structure of the glacier system since 1995, capturing the period immediately following the Bakaninbreen surge termination in 1995 through to the late stages of the Skobreen/Paulabreen surge in 2005 (Fig. 8).

Late quiescent phase structural evolution

Figure 8a is a simplification of the configuration of the glacier system following the 1995 Bakaninbreen surge, which terminated when the surge front was still ∼2 km up-glacier from the tidewater terminus (Murray and others, 1998, 2000; Smith and others, 2002). The tidewater front was shared evenly between the two main flow-units of Bakaninbreen and Paulabreen. The medial moraine between the two was relatively straight and oriented parallel to the main axis of glacier flow, aside from a slight bulge into

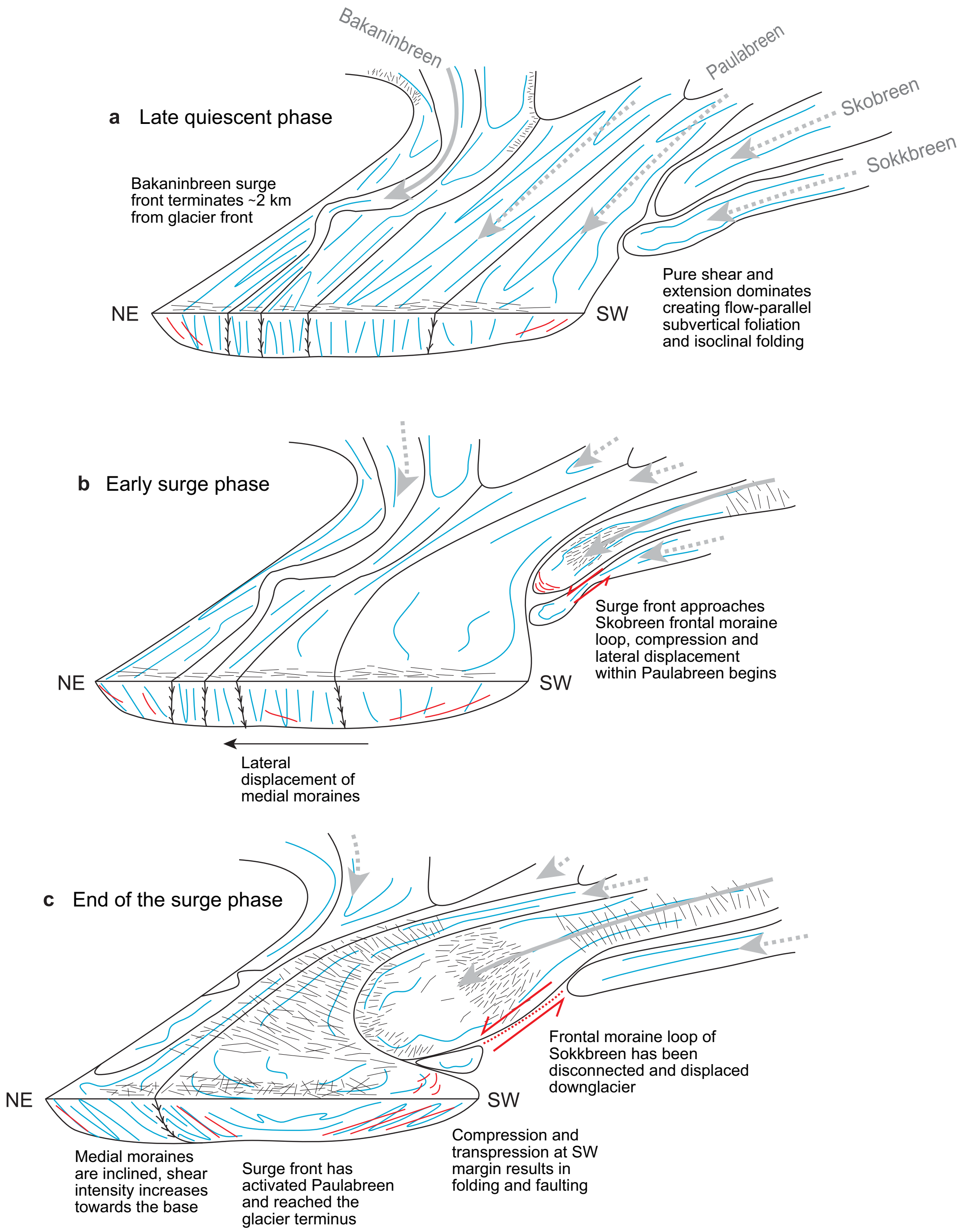

Fig. 8. Schematic reconstruction of structural evolution during the 2003–05 Skobreen/Paulabreen surge. (a) The Paulabreen glacier system following termination of the Bakaninbreen surge in 1995. (b) Early surge phase in summer 2003. (c) End of the surge phase in spring 2006. Grey arrows = glacier flow (solid lines indicate surging ice, dashed lines indicate non-surging ice); blue lines = foliation (S_1); red lines = faults/shear planes (S_3); thin black lines = crevasses (S_4); thick black lines = medial moraines and glacier margins.

Paulabreen, close to the medial moraine's inception point, associated with the passage of the Bakaninbreen surge front in this area from ~1987 onwards (Murray and others, 1998). Foliation (S_1) in Paulabreen was well-developed and orientated parallel to glacier flow, as were the medial moraines, which we assume were near-vertical (e.g. Eyles and Rogerson, 1978b). Fracture traces and any debris layers were subparallel to flow, reflecting simple shear at the base and margins. The Skobreen and Sokkbreen (and further downglacier, Peisbreen, not shown in Fig. 8a) moraine loops extended into Paulabreen but were not actively impeding flow. Oblique aerial photographs from 1936 show these tributaries had uncrevassed surfaces and moraine loops with a similar morphology to that in 1995, indicating that this was a relatively stable glacier configuration during the quiescent phase (Sund, 2006). Marginal crevassing in the uppermost basins of Skobreen (not shown in Fig. 8a) suggests the glacier was in the initial stages of the surge active phase at this time (Sund, 2006).

Early surge phase

Figure 8b depicts the arrival of the surge front at the Skobreen moraine loop in summer 2003, which had begun to advance into Paulabreen. Longitudinal crevasses in the centre of Skobreen reflect compressive flow at the surge front, creating topographic waves on the ice surface close to the moraine loop

(Kristensen and Benn, 2012). Arcuate fracture traces (S_3) inside the moraine loop are interpreted as shear planes formed in the compressive zone downglacier of the surge front. The extension of the Skobreen moraine loop into Paulabreen by ∼300 m caused southwest–northeast compression and initiated lateral migration of ice to the northeast, evidenced by small displacements of the Paulabreen and Bakaninbreen–Paulabreen medial moraines (Fig. 2b). The displacement began to reorientate the structures in the PLB1 and PLB2 sections of the ice front towards the northeast (dipping to the southwest) from their original orientation subparallel to flow through simple shear (Fig. 7). The absence of crevasses (S_4) in the main trunk of Paulabreen indicates that, although the surge had begun to affect the overall structure, it had not yet activated the ice in Paulabreen (Kristensen and Benn, 2012).

End of the surge phase

Figure 8c shows the glacier system at the end of the surge, which terminated by spring 2006 (Kristensen and Benn, 2012). Paulabreen dominated the entire tidewater front at this time, which had advanced ∼1.4 km. Kristensen and Benn (2012) showed that the surge reached the southwest margin of Paulabreen first in April 2005, initiating frontal advance in this area, before extending to the entire front by July 2005. The terminus stopped advancing sometime between December 2005 and February 2006 (Benn and others, 2009). Transverse crevassing (S_4) indicates an extensional flow regime dominated in the lower part of Paulabreen and at the front of Skobreen, where crevasses were oriented perpendicular to the main axis of ice flow in Paulabreen. The frontal zone of Paulabreen was chaotically crevassed, but the area immediately up-glacier remained relatively crevasse-free, suggesting ice moved by plug flow at the surge front (Kristensen and Benn, 2012). The Skobreen frontal moraine loop extended a further ∼200 m laterally into Paulabreen and ∼1.8 km downglacier. The Sokkbreen moraine loop was displaced downglacier a similar distance and was now disconnected from Sokkbreen. The Paulabreen and Bakaninbreen–Paulabreen medial moraines were compressed and displaced laterally by up to 500 m and the tidewater front of Bakaninbreen was squeezed out completely. The lateral compression of Paulabreen rotated structures to the northeast via simple shear in PLB1 and PLB2 (Fig. 7). The reorientation is particularly visible where the two Paulabreen medial moraines are exposed in the ice cliff (Fig. 4). Foliation (S_1) in PLB3 at the southwest margin remained subparallel to glacier flow, dipping steeply to the northeast (Fig. 7).

Most englacial debris layers are likely to have formed during the surge as saturated subglacial sediment was elevated into the glacier front via squeezing into crevasses, hydrofracturing and thrust-style displacement (Rea and Evans, 2011; Lovell and others, 2015b). Debris layers are best exposed at the southwest margin, where the glacier partly advanced onto the moraine area. The Kristensen and Benn (2012) time-lapse footage shows large volumes of debris in the surging ice in this area and active proglacial deformation of the moraine surface. Mineral stretching lineations on debris layers in PLB3 provide some evidence for shear subparallel to glacier flow (e.g. Fig. 7d-iv) and large-scale faulting is visible in the ice cliff (e.g. strike–slip fault in Fig. 6a). Together with the presence of shear planes (S_3) on the glacier surface in this area (Fig. 3b), these observations are consistent with a zone of intense compression and transpression (strike–slip deformation that deviates from simple shear because of a component of shortening orthogonal to the deformation zone; Dewey and others, 1998) at the southwest margin (Kristensen and Benn, 2012).

Near-vertical debris ridges were observed to be melting out at the southwest glacier margin in spring 2013 (Fig. 5h), which will likely form a geometrical ridge network in the lateral proglacial moraine area (e.g. Glasser and others, 1998; Evans and Rea, 1999; Lovell and others, 2015b, 2018; Farnsworth and others, 2016). The geomorphic imprint of the latest surge is also likely to be recorded on the fjord floor (e.g. Ottesen and others, 2008; Flink and others, 2015).

Conclusions

The 2003–05 glacier surge in the Paulabreen glacier system initiated in the Skobreen tributary and propagated downglacier into the lower part of Paulabreen. Glaciological structures exposed on the glacier surface and in the ice cliff allow the structural evolution of the surge to be reconstructed from the late quiescent phase through to the end of the surge phase. The structure of the late quiescent phase is recorded by relatively straight medial moraines and foliation aligned subparallel to glacier flow in Skobreen and Paulabreen. The early surge phase is characterised by the propagation of the surge front from the upper zone of Skobreen to its shared moraine loop with Paulabreen. In summer 2003, the zone of compression associated with the arrival of the surge front at the moraine loop was recorded by longitudinal crevassing immediately up-glacier from arcuate shear planes and topographic ‘waves’ on the glacier surface. The extension of the moraine loop into Paulabreen initiated lateral displacement of medial moraines towards the northeast and the associated rotation of foliation and debris layers. By summer 2005, the surge front had propagated to the tidewater terminus and activated the lower part of Paulabreen, initiating frontal advance and widespread extensional crevassing. At surge termination by spring 2006, medial moraines and frontal moraine loops had been displaced both laterally and downglacier and the terminus had advanced ∼1.4 km. The lateral displacement further rotated foliation and englacial debris layers to the northeast via simple shear in the central part of Paulabreen and closed off Bakaninbreen from the tidewater front. Simple shear was greatest at the base of the ice cliff, resulting in tangential geometries of the structures where dip shallows towards the base. The southwest margin experienced intense compression and transpression as surging ice advanced at the lateral margin, evidenced by shearing, strike–slip faulting and the elevation of debris into the ice.

These observations demonstrate that surges leave a clear imprint on the 3-D structure of glaciers, in addition to the more obvious surface changes, which can still be identified in ice cliffs several years after surge termination. Our work provides additional insight into the evolution of structures as surges propagate through glaciers. The study also demonstrates the potential for deciphering complex glacier flow dynamics through detailed structural glaciological investigations. Such work could be particularly useful at glaciers where the surge history is unclear or unknown.

Data. The data presented in this study are available from the corresponding author, HL, upon reasonable request.

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