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A structural glaciological map of Austre Brøggerbreen, northwest Svalbard.

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Abstract

Structural glaciological maps can be used to study the structural evolution and past dynamics of glaciers. The map described here documents the glacier-wide structural characteristics of Austre Brøggerbreen, a *c*. 12 km^2 predominantly cold-based valley glacier in northwest Svalbard. The structural map reveals that the glacier is dominated by deep-penetrating fractures that are now relict (crevasse traces). These structures indicate that, despite being relatively inactive at present, the glacier was once much more dynamic, presumably during its last advance in the Neoglacial (*c*. 1900 AD). Contemporary glacier structures (i.e. those that are actively forming) include primary stratification, longitudinal foliation and rare surface fracturing (crevasses and water-healed crevasses). Relict fracture sets become increasingly re-orientated and folded down-glacier as a result of ductile flow. Individual flow units show large differences in the evolution of structures, indicating that the flow units have been subject to different flow histories and dynamics. The map will also be useful for future change-detection studies on this rapidly receding glacier.

Keywords: Structural glaciology; Austre Brøggerbreen; Svalbard; Arctic; ice dynamics.

1. Introduction

Maritime Arctic glaciers are known to be particularly susceptible to climate change (e.g. Hambrey et al., 2005; Lovell et al., 2015), with many glaciers in Svalbard receding and thinning substantially since their Neoglacial maxima (*c*. 1900 AD). As climatic warming is most pronounced in the polar regions, it is necessary to understand how Arctic glaciers will respond to ongoing climate change. This is especially important as, at present, the ice caps and glaciers outside the major ice sheets are currently the main contributors to sea-level rise (e.g. Meier, 1984; Warrick et al., 1996; Hagen et al., 2003; Meier et al., 2007; Radić and Hock, 2011; Jacob et al., 2012). Understanding how glacier flow characteristics change in response to climate is of considerable importance for assessing the future implications for Arctic ice masses. One method for deducing changes in the dynamics of a glacier is to map and interpret its structural characteristics (see Hambrey and Lawson, 2000). The upwards-migration of equilibrium lines and pronounced surface-lowering of glaciers in Svalbard have revealed the internal structure of many ice masses in unprecedented detail. Recent structural glaciological research in Svalbard has primarily focused on structural controls on entrainment and transport of debris in polythermal and cold-based glaciers (Bennett et al., 1996; Hambrey et al., 1996, 1999, 2005; Boulton et al., 1999; Hambrey and Glasser, 2003; Hubbard et al., 2004; Lovell et al., 2015). The map described in this paper documents the glacier-wide structural characteristics of Austre Brøggerbreen, a cold-based valley glacier in Svalbard. This mapping approach allows the structural evolution and past dynamics of the glacier to be inferred, which then can be applied to other maritime Arctic glaciers that are also undergoing substantial recession and thinning.

2. Study site

Austre Brøggerbreen is a valley glacier located at *c*. 79º 55’ N in northwest Spitsbergen, the largest island in the Norwegian high-Arctic archipelago of Svalbard

(Figure 1). The glacier is primarily composed of cold ice that is below the pressure melting point (Hagen and Sætrang, 1991), and comprises multiple accumulation basins that coalesce into a comparatively short tongue. In the 1990s it had an area of *c*. 12 km^2 (Hagen et al., 1993; Etzelmüller and Sollid, 1996), and the subglacial topography of the glacier has been reconstructed from borehole measurements and radio-echo soundings (Hagen and Sætrang, 1991). Austre Brøggerbreen has been recorded as having a maximum ice thickness in the accumulation area of *c*. 110 m (Björnsson et al., 1996); however, substantial ablation and surface lowering over the past two decades has greatly reduced this. The glacier is also relatively inactive, with flow velocities ranging from 0.5 to 3.0 m a^{-1} (Hagen and Liestøl, 1990; Hagen et al., 1993). Like many glaciers in Svalbard, Austre Brøggerbreen has receded substantially from its Neoglacial maximum, and thinned to reveal the internal structure of the glacier in remarkable detail. The structure of Austre Brøggerbreen has been captured in high-resolution aerial photography towards the end of an ablation season (in 2004) that stripped most of the glacier of its snow and superimposed ice cover.

3. Methods and software

Detailed structural mapping of Austre Brøggerbreen was undertaken on-screen using ESRI ArcMap 10.1 Geographical Information System software using UK Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) aerial imagery. As part of a NERC ARSF campaign, aerial photographs were acquired of Austre Brøggerbreen in northwest Svalbard on 25th July 2004 using a calibrated RC-10 aerial camera system. The photographs were taken at an elevation of 3800 m above sea level, yielding 1:25 000-scale images. The images were scanned at a resolution of 10 µm (2540 dpi) giving a sea-level pixel spacing of *c*. 25 cm on the ground. The high level of detail in these images is ideal for mapping glacier surface structures. The photographs were processed in BAE Systems' SOCET SET digital photogrammetry suite. Camera calibration data enabled lens geometry errors to be modelled and removed. Ground control points, which link the two-dimensional image space to three-dimensional ground space, were extracted on stable land surfaces from a 2 m resolution light detection and ranging (lidar) digital elevation model (DEM) that was collected by the ARSF in 2005. This method is described in more detail in James et al. (2006; 2012). Finally, the lidar DEM was down-sampled to 20 m resolution and used to orthorectify the images. The outcome of this process is a single, high-resolution georectified image of Austre Brøggerbreen with the planimetric correctness of a map (Wolf and Dewitt, 2000). Matching these photographs to ground control point measurements yielded an average planimetric root mean square (RMS) error of 1.27 m, which provides a good estimate of the horizontal accuracy of the resulting orthophoto.

Structural and surface-feature mapping included digitising the outline of the glacier, areas of supraglacial debris and snow cover, transverse structures (primary stratification), longitudinal structures (foliation), fractures and fracture traces. The criteria used to identify these features were outlined by Goodsell et al. (2005) and adapted for this study as shown in Table 1. These structures were verified by field observations in 2013.

4. Description of glaciological structures

A range of ductile and brittle structures is observed on Austre Brøggerbreen. These structures are described sequentially from the upper reaches of the glacier to the terminus using structural geological notation, e.g. S_0, S_1, S_2, S_3, S_4 and S_5, that represent the order in which they form (summarised for each flow unit in Table 2).

4.1. Flow units

Austre Brøggerbreen is formed of six major flow units (with Flow Units 2 and 5 further divided into 3 and 2 sub-flow-units, respectively), each of which originates in its own sub-accumulation basin or becomes separated by flow around nunataks. Flow units are identified as wide bands of transverse structures, commonly becoming increasingly arcuate or re-orientated down-glacier, separated by narrow zones of strongly folded or longitudinal structures at their boundaries. Each flow unit has different characteristics, reflecting the morphology of their corresponding sub-accumulation basin and structural history (e.g. Jennings et al., 2014).

4.2. Primary stratification (S_0)

Primary stratification (S_0) comprises continuous but irregularly folded arcuate structures, primarily confined to the upper reaches of the glacier (Figure 2). Alternating layers of snow and superimposed ice formed during initial snowpack development become preserved as different ice facies during firnification and metamorphism to glacier ice. As ice flows from the glacier's broad accumulation area into a comparatively narrow tongue, the initially horizontal layers become increasingly folded by lateral compression and longitudinal extension, forming large-scale asymmetric folds around flow-parallel fold axes (Hambrey and Glasser, 2003). Parasitic folds are common on larger-scale fold limbs, with the strongest folding occurring at flow-unit boundaries.

4.3. Crevasses (S_1)

Crevasses are open fractures that generally develop perpendicular to the direction of maximum tensile stress. Crevasses on Austre Brøggerbreen are confined to the relatively steep upper reaches of the accumulation area where they open transverse to the direction of ice flow (Nye, 1952).

4.4. Water-healed crevasses (S_2)

Comparatively broad blue-coloured sub-linear transverse features observed primarily in the upper reaches of Flow Units 2a and 6 are interpreted as water-healed crevasses (S_2) (Figure 2). Open fractures high in the accumulation area fill with supraglacial meltwater, slush and snow, subsequently refreezing and healing the fracture as a blue scar. Such water-healed crevasses become increasingly arcuate down-glacier as a result of ductile flow, especially in the middle reaches of flow units. Water-healed crevasses eventually melt-out in the upper reaches of Flow Unit 2a and the middle reaches of Flow Unit 6, indicating that the open crevasses (S_1), from which they formed, do not penetrate to depths of more than a few tens of metres.

4.5. Crevasse traces (S_3)

Thin linear traces that commonly become increasingly arcuate down-glacier are interpreted as crevasse traces. Such traces are characterised by clear ice layers a few centimetres wide, with crystals orientated normal to the fracture. Like open crevasses, crevasse traces form perpendicular to the direction of maximum tensile stress, and commonly form on other glaciers as continuations of open crevasses. However, crevasse traces also form as independent structures that are analogous to tensional veins in rocks (Hambrey and Lawson, 2000). All flow units in Austre Brøggerbreen are dominated by relict suites of fractures that become increasingly folded and re-orientated down-glacier as a result of ductile flow. The high ratio of crevasse traces to open crevasses present on Austre Brøggerbreen suggests that the majority of crevasse traces form as independent structures and not from the closure of open crevasses (see Jennings et al., 2014). Despite undergoing substantial ablation, crevasse traces are present all the way to the glacier terminus, suggesting that, in contrast to water-healed crevasses (S_2), the initial fractures forming S_3 must have been relatively deep (e.g. Hambrey and Müller, 1978; Jennings et al., 2014).

4.6. Longitudinal foliation (transposed) (S_4)

Longitudinal structures are primarily found in the glacier tongue (Figure 2). They are most discernible at the margins of the glacier and at flow-unit boundaries, and are interpreted as transposed longitudinal foliation (S_4). Transverse primary stratification (S_0) becomes increasingly folded and re-orientated by ductile flow, eventually becoming transposed into longitudinal foliation (S_4). This primarily occurs in areas dominated by simple shear and extending flow, such as at flow unit boundaries (Hambrey, 1977; Hambrey and Lawson, 2000; Hambrey and Glasser, 2003).

4.7. Longitudinal foliation (axial planar) (S_4)

A second form of longitudinal structure, observed primarily at the boundary between Flow Units 1 and 2a on Austre Brøggerbreen, is axial planar foliation (S_4) that intersects folded primary stratification (S_0). Geometrically, this structure is similar to the slaty cleavage observed in low-grade metamorphic rocks. Unlike transposed longitudinal foliation, axial planar foliation does not appear to be derived from a pre-existing layering. However, the exact mechanism of formation is unknown (Hambrey and Lawson, 2000). It has been suggested that axial planar foliation formation preferentially forms in areas where cumulative strain values are lower, allowing primary stratification (S_0) to be preserved comparatively far down-glacier (Jennings et al., 2014).

4.8. Fracture-derived longitudinal foliation (S_5)

In two cases on Austre Brøggerbreen (Flow Units 4 and 5b), reorientation of initially transverse crevasse traces into a longitudinal orientation has developed a fracture-derived longitudinal foliation (S_5). This is most discernible at flow-unit boundaries where higher rates of simple shear are inferred.

5. Discussion

The structure of Austre Brøggerbreen is dominated by fractures that originate high in the glacier's accumulation area, indicating that the glacier was substantially more dynamic during Neoglacial time than at present. Contemporary structures include folded primary stratification and (subsequently) associated longitudinal foliation, with the majority of fractures being relict structures that formed when ice-flow velocities were sufficiently high to initiate widespread ice fracturing. Limited contemporary fracturing high in the accumulation area produces open crevasses, which subsequently heal as they become infilled by meltwater, slush and snow. However, water-healed crevasses melt-out down-glacier suggesting that the initial fractures were relatively shallow. In contrast, the presence of crevasse traces across the entire surface of Austre Brøggerbreen, despite undergoing substantial ablation and surface-lowering, suggests that these fractures penetrate to much greater depths than currently forming fractures, possibly even reaching the bed (see Hambrey and Müller, 1978; Jennings et al., 2014). The depth to which crevasse traces penetrate also suggests that their formation must have taken place when the glacier had a substantially more dynamic flow regime. The low flow-velocity of Austre Brøggerbreen makes it unlikely that deeply penetrating crevasse traces are currently forming and no evidence of this was seen during fieldwork in 2013. Re-orientation and folding of crevasse traces occurs as fractures are passively transported down-glacier and undergo ductile deformation as a result of ice creep. Ductile modification of passively transported crevasse traces varies between each flow unit, and may be used to infer contrasting flow conditions in different sectors of the glacier. Transverse crevasse traces in discrete flow units undergo a unique deformation history that reflects the characteristics of the flow unit. This is especially evident in Flow Units 2a, 4 and 5b, where initially transverse fracture sets undergo different flow histories when transported down-glacier. In Flow Unit 4, transverse crevasse traces become increasingly arcuate down-glacier, indicating that flow is fastest in the centre of the flow unit, whereas there is increased simple shear occurring at the flow-unit boundaries. However, this is not the case in Flow Units 2a and 5b, where crevasse traces remain as comparatively linear structures but are rotated into different orientations. In Flow Unit 2a crevasse traces become rotated in a clockwise direction, whereas in Flow Unit 5b the crevasse traces are rotated anticlockwise. This suggests that flow within each flow unit is non-uniform, but is fastest on the true left and true right of Flow Units 2a and 5b respectively.

6. Conclusions

Detailed structural mapping of Austre Brøggerbreen has revealed the distribution and evolution of ice structures, enabling the past dynamics of an Arctic valley glacier to be inferred. Despite being slow-moving and almost stagnant at present, the structure of Austre Brøggerbreen is dominated by fractures, mostly now represented as crevasse traces, suggesting that the glacier was substantially more dynamic during Neoglacial time than at present. The persistence of fractures through the ablation zone to the glacier's terminus, despite undergoing substantial surface-lowering, indicates that those crevasses penetrated to great depths, possibly reaching the glacier bed. Contemporary structures that are actively forming on Austre Brøggerbreen include primary stratification, longitudinal foliation and scarce spatially-restricted surface-fracturing (crevasses and water-healed crevasses). Relict transverse fracture sets become increasingly re-orientated and folded down-glacier as a result of ductile flow. Structures contained in discrete flow units evolve differently, reflecting the unique nature of the flow dynamics of each individual flow unit. For two flow units (4 and 5b), initially transverse fracture sets become sufficiently re-orientated by ductile flow to develop a fracture-derived longitudinal foliation that has not previously been observed on other glaciers.

7. Software

Manipulation of aerial imagery was carried out using BAE Systems' SOCET SET digital photogrammetry suite. Initial map production was undertaken using ESRI ArcMap 10.1 Geographical Information System software, with further map/figure manipulation conducted in Inkscape version 0.91.

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Figure 1. Location map: (A) the location of Svalbard in relation to continental Europe; (B) the location of Brøggerhalvøya in northwest Spitsbergen, the largest island in the Norwegian high-Arctic archipelago of Svalbard; (C) the location of Austre Brøggerbreen (highlighted red) on Brøggerhalvøya; note the location of the nearby research settlement of Ny-Ålesund is shown.

Figure 2. Aerial photographs of some major structural features found in Austre Brøggerbreen: (A) primary stratification (S_0), parallel and continuous layering running approximately from left to right of the image; (B) water-healed crevasses (S_2), comparatively thick dark blue arcuate features; (C) longitudinal foliation (S_4), thin long linear traces running from the bottom to the top of the image; (D) flow unit map of Austre Brøggerbreen showing the different flow units along with the location of image A-C.

Table 1. Summary of structures from aerial imagery, including the sequential notation and spatial distribution on Austre Brøggerbreen.

Structure	Sequential notation	Identification on aerial imagery	Location
Primary stratification	S_0	Continuous transverse layers initially parallel to the equilibrium line; increasingly folded down-glacier	Ubiquitous in the upper accumulation area
Crevasses	S_1	Open fractures, up to a few metres wide, evident as straight white (snow-filled) or dark lines (non-snow-filled)	Confined to the steep upper reaches of the accumulation area
Water-healed crevasses	S_2	Thick dark blue lines, up to a few metres wide. Initially transverse and linear but becoming increasingly arcuate down-glacier	Found in the upper reaches of Flow Units 2a and 6
Crevasse traces	S_3	Thin dark lines; initially linear and transverse to flow, but becoming increasingly arcuate or rotated down-glacier	Ubiquitous
Longitudinal foliation (transposed)	S_4	Long linear traces orientated parallel to ice flow	Well developed at flow-unit boundaries
Longitudinal foliation (axial planar)	S_4	Long linear traces orientated parallel to ice flow intersecting primary stratification (S_0)	Found at the boundary between Flow Units 1 and 2a
Fracture derived longitudinal foliation	S_5	Long linear traces orientated parallel to ice flow originating from re-orientation of crevasse traces (S_3)	Found in Flow Units 4 and 5b

Table 2. Summary of the sequential structural evolution of each flow unit. Key located below main table (colours are related to the colours that represent each structure on the map).

Order of formation	Flow Unit 1	Flow Unit 2			Flow Unit 3	Flow Unit 4	Flow Unit 5		Flow Unit 6
		A	B	C			A	B	
1									
2									
3									
4									
5									

Key	
	Primary stratification
	Water-healed crevasses
	Longitudinal foliation
	First, second and third generation crevasse traces respectively