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2

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21 **A structural glaciological map of Austre Brøggerbreen, northwest Svalbard.**

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24

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30 **Abstract**

31 Structural glaciological maps can be used to study the structural evolution and past
32 dynamics of glaciers. The map described here documents the glacier-wide structural
33 characteristics of Austre Brøggerbreen, a c. 12 km² predominantly cold-based valley
34 glacier in northwest Svalbard. The structural map reveals that the glacier is
35 dominated by deep-penetrating fractures that are now relict (crevasse traces). These
36 structures indicate that, despite being relatively inactive at present, the glacier was
37 once much more dynamic, presumably during its last advance in the Neoglacial (c.
38 1900 AD). Contemporary glacier structures (i.e. those that are actively forming)
39 include primary stratification, longitudinal foliation and rare surface fracturing
40 (crevasses and water-healed crevasses). Relict fracture sets become increasingly
41 re-orientated and folded down-glacier as a result of ductile flow. Individual flow units
42 show large differences in the evolution of structures, indicating that the flow units
43 have been subject to different flow histories and dynamics. The map will also be
44 useful for future change-detection studies on this rapidly receding glacier.

45
46 **Keywords:** Structural glaciology; Austre Brøggerbreen; Svalbard; Arctic; ice
47 dynamics.

48 49 **1. Introduction**

50 Maritime Arctic glaciers are known to be particularly susceptible to climate change
51 (e.g. Hambrey et al., 2005; Lovell et al., 2015), with many glaciers in Svalbard
52 receding and thinning substantially since their Neoglacial maxima (c. 1900 AD). As

53 climatic warming is most pronounced in the polar regions, it is necessary to
54 understand how Arctic glaciers will respond to ongoing climate change. This is
55 especially important as, at present, the ice caps and glaciers outside the major ice
56 sheets are currently the main contributors to sea-level rise (e.g. Meier, 1984; Warrick
57 et al., 1996; Hagen et al., 2003; Meier et al., 2007; Radić and Hock, 2011; Jacob et
58 al., 2012). Understanding how glacier flow characteristics change in response to
59 climate is of considerable importance for assessing the future implications for Arctic
60 ice masses. One method for deducing changes in the dynamics of a glacier is to
61 map and interpret its structural characteristics (see Hambrey and Lawson, 2000).
62 The upwards-migration of equilibrium lines and pronounced surface-lowering of
63 glaciers in Svalbard have revealed the internal structure of many ice masses in
64 unprecedented detail. Recent structural glaciological research in Svalbard has
65 primarily focused on structural controls on entrainment and transport of debris in
66 polythermal and cold-based glaciers (Bennett et al., 1996; Hambrey et al., 1996,
67 1999, 2005; Boulton et al., 1999; Hambrey and Glasser, 2003; Hubbard et al., 2004;
68 Lovell et al., 2015). The map described in this paper documents the glacier-wide
69 structural characteristics of Austre Brøggerbreen, a cold-based valley glacier in
70 Svalbard. This mapping approach allows the structural evolution and past dynamics
71 of the glacier to be inferred, which then can be applied to other maritime Arctic
72 glaciers that are also undergoing substantial recession and thinning.

73

74 **2. Study site**

75 Austre Brøggerbreen is a valley glacier located at c. 79° 55' N in northwest
76 Spitsbergen, the largest island in the Norwegian high-Arctic archipelago of Svalbard

77 (Figure 1). The glacier is primarily composed of cold ice that is below the pressure
78 melting point (Hagen and Sætrang, 1991), and comprises multiple accumulation
79 basins that coalesce into a comparatively short tongue. In the 1990s it had an area
80 of c. 12 km² (Hagen et al., 1993; Etzelmüller and Sollid, 1996), and the subglacial
81 topography of the glacier has been reconstructed from borehole measurements and
82 radio-echo soundings (Hagen and Sætrang, 1991). Austre Brøggerbreen has been
83 recorded as having a maximum ice thickness in the accumulation area of c. 110 m
84 (Björnsson et al., 1996); however, substantial ablation and surface lowering over the
85 past two decades has greatly reduced this. The glacier is also relatively inactive, with
86 flow velocities ranging from 0.5 to 3.0 m a⁻¹ (Hagen and Liestøl, 1990; Hagen et al.,
87 1993). Like many glaciers in Svalbard, Austre Brøggerbreen has receded
88 substantially from its Neoglacial maximum, and thinned to reveal the internal
89 structure of the glacier in remarkable detail. The structure of Austre Brøggerbreen
90 has been captured in high-resolution aerial photography towards the end of an
91 ablation season (in 2004) that stripped most of the glacier of its snow and
92 superimposed ice cover.

93

94 **3. Methods and software**

95 Detailed structural mapping of Austre Brøggerbreen was undertaken on-screen
96 using ESRI ArcMap 10.1 Geographical Information System software using UK
97 Natural Environment Research Council (NERC) Airborne Research and Survey
98 Facility (ARSF) aerial imagery. As part of a NERC ARSF campaign, aerial
99 photographs were acquired of Austre Brøggerbreen in northwest Svalbard on 25th
100 July 2004 using a calibrated RC-10 aerial camera system. The photographs were

101 taken at an elevation of 3800 m above sea level, yielding 1:25 000-scale images.
102 The images were scanned at a resolution of 10 μm (2540 dpi) giving a sea-level pixel
103 spacing of c. 25 cm on the ground. The high level of detail in these images is ideal
104 for mapping glacier surface structures. The photographs were processed in BAE
105 Systems' SOCET SET digital photogrammetry suite. Camera calibration data
106 enabled lens geometry errors to be modelled and removed. Ground control points,
107 which link the two-dimensional image space to three-dimensional ground space,
108 were extracted on stable land surfaces from a 2 m resolution light detection and
109 ranging (lidar) digital elevation model (DEM) that was collected by the ARSF in 2005.
110 This method is described in more detail in James et al. (2006; 2012). Finally, the
111 lidar DEM was down-sampled to 20 m resolution and used to orthorectify the
112 images. The outcome of this process is a single, high-resolution georectified image
113 of Austre Brøggerbreen with the planimetric correctness of a map (Wolf and Dewitt,
114 2000). Matching these photographs to ground control point measurements yielded
115 an average planimetric root mean square (RMS) error of 1.27 m, which provides a
116 good estimate of the horizontal accuracy of the resulting orthophoto.

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

123

124 **4. Description of glaciological structures**

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

129

130 **4.1. Flow units**

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

140

141 **4.2. Primary stratification (S_0)**

142 Primary stratification (S_0) comprises continuous but irregularly folded arcuate
143 structures, primarily confined to the upper reaches of the glacier (Figure 2).

144 Alternating layers of snow and superimposed ice formed during initial
145 snowpack development become preserved as different ice facies during
146 firnification and metamorphism to glacier ice. As ice flows from the glacier's
147 broad accumulation area into a comparatively narrow tongue, the initially
148 horizontal layers become increasingly folded by lateral compression and

149 longitudinal extension, forming large-scale asymmetric folds around flow-
150 parallel fold axes (Hambrey and Glasser, 2003). Parasitic folds are common
151 on larger-scale fold limbs, with the strongest folding occurring at flow-unit
152 boundaries.

153

154 **4.3. *Crevasses (S₁)***

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

159

160 **4.4. *Water-healed crevasses (S₂)***

161 Comparatively broad blue-coloured sub-linear transverse features observed
162 primarily in the upper reaches of Flow Units 2a and 6 are interpreted as water-
163 healed crevasses (S₂) (Figure 2). Open fractures high in the accumulation
164 area fill with supraglacial meltwater, slush and snow, subsequently refreezing
165 and healing the fracture as a blue scar. Such water-healed crevasses become
166 increasingly arcuate down-glacier as a result of ductile flow, especially in the
167 middle reaches of flow units. Water-healed crevasses eventually melt-out in
168 the upper reaches of Flow Unit 2a and the middle reaches of Flow Unit 6,
169 indicating that the open crevasses (S₁), from which they formed, do not
170 penetrate to depths of more than a few tens of metres.

171

172 **4.5. *Crevasse traces (S₃)***

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

190

191 **4.6. Longitudinal foliation (transposed) (S_4)**

192 Longitudinal structures are primarily found in the glacier tongue (Figure 2).
193 They are most discernible at the margins of the glacier and at flow-unit
194 boundaries, and are interpreted as transposed longitudinal foliation (S_4).
195 Transverse primary stratification (S_0) becomes increasingly folded and re-
196 orientated by ductile flow, eventually becoming transposed into longitudinal
197 foliation (S_4). This primarily occurs in areas dominated by simple shear and

198 extending flow, such as at flow unit boundaries (Hambrey, 1977; Hambrey
199 and Lawson, 2000; Hambrey and Glasser, 2003).

200

201 **4.7. Longitudinal foliation (axial planar) (S_4)**

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

212

213 **4.8. Fracture-derived longitudinal foliation (S_5)**

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

219

220 **5. Discussion**

221 The structure of Austre Brøggerbreen is dominated by fractures that originate high in
222 the glacier's accumulation area, indicating that the glacier was substantially more
223 dynamic during Neoglacial time than at present. Contemporary structures include
224 folded primary stratification and (subsequently) associated longitudinal foliation, with
225 the majority of fractures being relict structures that formed when ice-flow velocities
226 were sufficiently high to initiate widespread ice fracturing. Limited contemporary
227 fracturing high in the accumulation area produces open crevasses, which
228 subsequently heal as they become infilled by meltwater, slush and snow. However,
229 water-healed crevasses melt-out down-glacier suggesting that the initial fractures
230 were relatively shallow. In contrast, the presence of crevasse traces across the
231 entire surface of Austre Brøggerbreen, despite undergoing substantial ablation and
232 surface-lowering, suggests that these fractures penetrate to much greater depths
233 than currently forming fractures, possibly even reaching the bed (see Hambrey and
234 Müller, 1978; Jennings et al., 2014). The depth to which crevasse traces penetrate
235 also suggests that their formation must have taken place when the glacier had a
236 substantially more dynamic flow regime. The low flow-velocity of Austre
237 Brøggerbreen makes it unlikely that deeply penetrating crevasse traces are currently
238 forming and no evidence of this was seen during fieldwork in 2013. Re-orientation
239 and folding of crevasse traces occurs as fractures are passively transported down-
240 glacier and undergo ductile deformation as a result of ice creep. Ductile modification
241 of passively transported crevasse traces varies between each flow unit, and may be
242 used to infer contrasting flow conditions in different sectors of the glacier. Transverse
243 crevasse traces in discrete flow units undergo a unique deformation history that
244 reflects the characteristics of the flow unit. This is especially evident in Flow Units 2a,
245 4 and 5b, where initially transverse fracture sets undergo different flow histories

246 when transported down-glacier. In Flow Unit 4, transverse crevasse traces become
247 increasingly arcuate down-glacier, indicating that flow is fastest in the centre of the
248 flow unit, whereas there is increased simple shear occurring at the flow-unit
249 boundaries. However, this is not the case in Flow Units 2a and 5b, where crevasse
250 traces remain as comparatively linear structures but are rotated into different
251 orientations. In Flow Unit 2a crevasse traces become rotated in a clockwise
252 direction, whereas in Flow Unit 5b the crevasse traces are rotated anticlockwise.
253 This suggests that flow within each flow unit is non-uniform, but is fastest on the true
254 left and true right of Flow Units 2a and 5b respectively.

255

256 **6. Conclusions**

257 Detailed structural mapping of Austre Brøggerbreen has revealed the distribution
258 and evolution of ice structures, enabling the past dynamics of an Arctic valley glacier
259 to be inferred. Despite being slow-moving and almost stagnant at present, the
260 structure of Austre Brøggerbreen is dominated by fractures, mostly now represented
261 as crevasse traces, suggesting that the glacier was substantially more dynamic
262 during Neoglacial time than at present. The persistence of fractures through the
263 ablation zone to the glacier's terminus, despite undergoing substantial surface-
264 lowering, indicates that those crevasses penetrated to great depths, possibly
265 reaching the glacier bed. Contemporary structures that are actively forming on
266 Austre Brøggerbreen include primary stratification, longitudinal foliation and scarce
267 spatially-restricted surface-fracturing (crevasses and water-healed crevasses). Relict
268 transverse fracture sets become increasingly re-orientated and folded down-glacier
269 as a result of ductile flow. Structures contained in discrete flow units evolve

270 differently, reflecting the unique nature of the flow dynamics of each individual flow
271 unit. For two flow units (4 and 5b), initially transverse fracture sets become
272 sufficiently re-orientated by ductile flow to develop a fracture-derived longitudinal
273 foliation that has not previously been observed on other glaciers.

274

275 **7. Software**

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

280

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291

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374

375

376

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

382

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

390

391 **Table 1.** Summary of structures from aerial imagery, including the sequential
 392 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

394 **Table 2.** Summary of the sequential structural evolution of each flow unit. Key located below main table (colours are related to the
 395 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							

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