

1 **Marginal fluctuations of a Svalbard surge-type tidewater glacier,**
2 **Blomstrandbreen, since the Little Ice Age: a record of three surges**

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8

Abstract

9 Previous advances and retreats of Blomstrandbreen within the cold period known as the Little
10 Ice Age, between approximately 1400 and 1920, are relatively well documented. The sea
11 floor characteristics associated with these glacier fluctuations, and their importance for the
12 identification of similar surge-type tidewater glaciers, are discussed. We use detailed
13 multibeam-bathymetric data acquired within Nordvågen, the marine area offshore of
14 Blomstrandbreen, to provide a new understanding of the style and pattern of deglaciation
15 around Blomstrandhalvøya since Blomstrandbreen's neoglacial maximum. Glacial landforms
16 on the sea floor of Nordvågen comprise overridden moraines, glacial lineations, terminal
17 moraines and annual recessional moraines. Crevasse-fill ridges, which are often regarded as a
18 characteristic landform of surging tidewater glaciers, are present on only restricted areas of
19 Nordvågen. Significantly, this study shows that large terminal surge moraines and numerous
20 crevasse-fill ridges may not always be well developed in association with glacier surges, with
21 implications for the identification of surges in the geological record. Using historical
22 observations, aerial photographs and satellite imagery of Blomstrandbreen we have correlated
23 former ice-marginal positions with mapped submarine landforms. Three surge events

24 occurred during a pattern of overall retreat, with a spacing of about 50 years between active
25 advance phases; this represents a relatively short quiescent phase for Svalbard glaciers.
26 Average retreat rates of 10-50 m yr⁻¹ are typical of the quiescent phase of the surge cycle
27 whereas surge advances vary from 200 m to over 725 m.

28 **Introduction**

29 Assemblages of submarine landforms, found proximal to modern tidewater glaciers, have
30 been described and interpreted from a number of fjords around Svalbard (e.g. Solheim and
31 Pfirman 1985, Sexton *et al.* 1992, Boulton *et al.* 1996, Ottesen and Dowdeswell 2006, 2009,
32 Ottesen *et al.* 2008, Robinson and Dowdeswell 2011, Flink *et al.* 2015). These submarine
33 sediments and landforms are generally better preserved than terrestrial records because they
34 have not been disturbed subsequently by subaerial erosional processes (Ottesen and
35 Dowdeswell 2006, Ottesen *et al.* 2008) and they are not deeply buried because there is a
36 relatively low sedimentation rate in the waters surrounding Svalbard compared with milder
37 glacimarine settings (Dowdeswell and Dowdeswell 1989, Dowdeswell 1998, Forwick *et al.*
38 2010, Dowdeswell and Vasquez 2013). The landforms provide records of past glacier
39 advance and retreat and indicate the nature of ice-flow dynamics.

40 Glaciers on Svalbard thickened and experienced what was probably their most significant
41 neoglacial advance during the Little Ice Age (LIA), between approximately 1400 and 1920
42 (Werner 1993). The glaciers reached their maximum extent around the beginning of the 20th
43 Century (Liestøl 1988), prior to subsequent retreat following the end of the LIA. This date
44 range has some degree of uncertainty, due partly to the use of lichenometry and the inherent
45 variability of moraine stabilisation and lichen growth rates (Werner, 1990). Historical
46 records, including maps such as that compiled by Isachsen in 1909-10, who led the mapping
47 of land areas on Svalbard between Kongsfjorden and Raudfjorden on behalf of the

48 Norwegian government from 1906 onwards, provide direct evidence of significant glacier
49 advances, including that of Blomstrandbreen (Liestøl 1988). More recently, multibeam
50 bathymetry has been used to identify the extent of LIA advances for a number of tidewater
51 glaciers, such as those terminating in Borebukta, Yoldiabukta (Ottesen and Dowdeswell
52 2006), and Tunabreen (Flink *et al.* 2015) in central Spitsbergen.

53 Lefauconnier (1992) used single-beam depth soundings from the eastern channel off
54 Blomstrandhalvøya (Figs. 1, 2, 3) to identify submarine ridges and thus locate the maximum
55 neoglacial advance position of Blomstrandbreen. Here we present new high-resolution
56 multibeam-bathymetric data covering almost all of Nordvågen that provide a much greater
57 understanding of the style of retreat from the LIA maximum to the 2009 extent of
58 Blomstrandbreen including its detachment from the former peninsula of Blomstrandhalvøya.

59 **Study area**

60 Blomstrandbreen is an approximately 18 km-long tidewater glacier located in northwest
61 Spitsbergen, that drains towards the southwest from Isachsenfonna into Kongsfjorden (Fig.
62 1). Kongsfjorden is approximately 20 km long with five large tidewater glaciers at its head.
63 The fjord widens to about 10 km at its distal part before merging with Krossfjorden.
64 Blomstrandbreen is fed by a number of smaller tributary glaciers, resulting in a total drainage
65 area of approximately 90 km² (Arendt *et al.* 2012; Fig. 1). It is known to be a surge-type
66 glacier, which is relatively common for glaciers on Svalbard (Dowdeswell *et al.* 1991, Liestøl
67 1993, Hagen *et al.* 1993, Jiskoot *et al.* 2000), with documented surges in the 1960s (Liestøl
68 1988, Hagen *et al.* 1993), from 2008 onwards (Mansell *et al.* 2012), and a possible surge
69 between 1911 and 1928. Surging glaciers exhibit cyclical activity with a quiescent phase of
70 stagnation and slow ice flow, and an active phase of increased ice velocities (Meier and Post
71 1969). A surge often causes frontal advances and longitudinal extension that lead to severe

72 crevassing and calving if the terminus ends in fjord waters (Kamb *et al.* 1985, Sharp 1988).
73 After a surge event the glacier returns to a quiescent state until the next surge, which
74 generally occurs decades to centuries later (Meier and Post 1969, Kamb *et al.* 1985). Glacier
75 surges on Svalbard appear to have less frequent surge events than, for example, Alaskan
76 glaciers, but with longer lasting active phases and lower ice velocities (Dowdeswell *et al.*
77 1991).

78 The island of Blomstrandhalvøya in central Kongsfjorden was, as recently as 1992, connected
79 to the mainland of Spitsbergen by Blomstrandbreen (Fig. 2b-e); the Norwegian word halvøya
80 itself translates as ‘peninsula’. It is around 5 km wide, reaches 300 m a.s.l. and consists of
81 resistant crystalline limestone (Svendsen *et al.* 2002). The island is now separated from
82 Blomstrandbreen and Spitsbergen by a 4-km wide bay, referred to as Nordvågen, which
83 consists of two distinct main channels (Figs. 1, 2a). There is a wide, deeper channel on the
84 western side of the island and a narrower, shallower channel on the eastern side; the channels
85 merge together near the 2009 glacier front. The western channel reaches 2.5 km in width and
86 65 m in depth, whilst the eastern channel is approximately 1 km wide and is up to 40 m deep.

87 **Methods**

88 Sea floor mapping of the Nordvågen study area, surrounding northern Blomstrandhalvøya,
89 was conducted by the Norwegian Hydrographic Service. Data were acquired during the
90 summer of 2010 using a Kongsberg Maritime EM 3002D multibeam-bathymetric echo-
91 sounder. The EM 3002D’s shallow depth range makes it ideal for the study area, providing
92 exceptionally high-resolution 1 m grid-cell sizes for the whole 10.5 km² of sea floor
93 surveyed. These data were then processed by removing spurious depth soundings. Water
94 depths within the study area range from 81 m to <2 m.

95 A single-channel seismic line acquired with a Geoacoustics “Geopulse” Boomer system (300
96 J acoustic pulse; 15 m hydrophone; Whittington *et al.* 1997) has also been utilised. Landsat
97 imagery and aerial photography from the Norwegian Polar Institute (NPI) were used to
98 delineate the margin of Blomstrandbreen for all years that cloud-free imagery was available
99 (eleven images were used in this study, ranging from 1966 to 2013), and to correlate
100 submarine landforms with dated ice-marginal positions. Distances of retreat or advance were
101 measured at 250 m intervals along each delineated former ice-front, and average retreat or
102 advance was calculated. Rates of retreat (or advance) were assumed to be linear between each
103 dated ice margin.

104 **Description of submarine features in Nordvågen**

105 The full coverage of multibeam-bathymetric data around Blomstrandhalvøya is illustrated in
106 Figure 1. Submarine landforms in Nordvågen are well preserved, with some evidence of
107 cross-cutting relationships to provide a relative chronology for deposition. The landforms
108 identified are described and interpreted below.

109 *LARGE SUBDUED TRANSVERSE RIDGES: OVERRUN MORAINES*

110 There are a number of large but subdued ridges within Nordvågen, which are orientated
111 approximately perpendicular to the main channel axes and are slightly sinuous in planform
112 (Fig. 2b). Three of these large ridges are identified in the deeper western channel: the most
113 distal (R1, Fig. 2a) is 3.2 km from the 2009 margin and varies from 10 m to 20 m high and is
114 between 70 m and 120 m wide; the next (R2, Fig. 2a) is approximately 3 km from the 2009
115 margin, is 10 m to 15 m high and varies in width from 40 m to 100 m; the most proximal (R3,
116 Fig. 2a) is about 2.2 km from 2009 margin, is 10 m high, around 130 m wide and has a length
117 of only approximately 500 m. Some evidence of the most distal and proximal ridges can be

118 found in the narrow channel between the Breøyane islands and Blomstrandhalvøya, but here
119 the ridges are smaller in size. Only one relatively large but subdued ridge (R4) is visible in
120 the eastern channel (Fig. 2a), at 3.2 km from the 2009 margin, and is around 15 m high and
121 between 100 to 200 m wide; however, the ridge may extend beyond the data coverage.

122 The ridges described above are interpreted as terminal moraines, which have been overridden
123 by glacial advances since their formation. They have, therefore, been modified substantially
124 and could mark the extent of previous surges of Blomstrandbreen in the same way that
125 overridden ridges identified in Borebukta were interpreted to represent the former surge
126 margins of Borebreen (Ottesen and Dowdeswell 2006). These modified ridges probably acted
127 as pinning points for the retreating glacier. The most ice-proximal ridge in the western
128 channel (R3, Fig. 2a), with its more discontinuous appearance, has developed a cupola-like
129 hill form and has also been modified by curvilinear features on its surface, at around 45 m
130 water depth.

131 *LARGE TRANSVERSE RIDGES: TERMINAL MORAINES*

132 The most distal transverse ridges are large and clearly identifiable on both the western and
133 eastern sides of Blomstrandhalvøya, at 3.6 and 3.4 km from the 2009 margin of
134 Blomstrandbreen, respectively (T1, Fig. 2a). The western ridge is approximately 30 m high
135 and 350 m wide; in contrast, the eastern ridge is smaller, with a maximum height of 15 m and
136 is about 250 m wide. The distal ridge in the main western channel adjoins another ridge at the
137 distal end of the narrow channel between Blomstrandhalvøya and the Breøyane islands, with
138 dimensions of approximately 10 m in height, and 200-300 m in width. It is located 3.4 km
139 from the 2009 margin. A lobe of sediment is visible on part of the distal slope of this ridge.
140 The lobe has a length up to 250 m and a maximum width of 300 m. There is no evidence of

141 neoglacial subglacial features on the relatively smooth sea floor on the distal side of these
142 ridges.

143 There is another prominent transverse ridge across Nordvågen further to the east, in addition
144 to the one described above (T2, Fig. 2a). This ridge crosses the western channel, at a distance
145 of 2.3 km from the 2009 margin, reaching up to 15 m high and around 100 m wide. Within
146 the topographically-constrained passage, which splits off the western channel and passes
147 between Blomstrandhalvøya and the Brøøyane islands, this ridge is located 2.2 km from the
148 2009 margin and is smaller and narrower, with maximum dimensions of 10 m high and 50 m
149 wide. In the eastern channel the ridge is 1.8 km from the 2009 margin and has the same
150 dimensions as in the topographically-constrained channel. The most extensive transverse
151 ridges, located on both sides of Blomstrandhalvøya, are interpreted as terminal moraines (Fig.
152 2b), representing the maximum neoglacial extent of Blomstrandbreen. This is further
153 supported by the survey record from Whittington *et al.* (1997; Fig. 3), and by historical
154 records (Liestøl 1988) and NPI aerial photographs, which show lateral moraines on land
155 leading to this maximum extent (Figs. 2a, b). It is interpreted that the glacier extended further
156 offshore in the western channel than the eastern channel. This was probably because the main
157 glacier drainage was into the western channel.

158 The sediment lobe described above is interpreted as a glacial debris flow, representing a
159 slope failure (Ottesen *et al.* 2008) and may be a result of sediment that has been bulldozed in
160 front of the glacier and subsequently been prone to failure and gravitational spreading
161 (Boulton *et al.* 1996, Kristensen *et al.* 2009). The large transverse ridge most proximal to the
162 2009 margin of Blomstrandbreen is correlated, by the associated occurrence of glacial
163 lineations and through the use of NPI 1966 aerial photography, with the glacier's maximum

164 surge extent culminating in 1967-1968 (Lefauconnier 1992) and is thus interpreted as a
165 terminal surge moraine (Figs. 4, 5).

166 *STREAMLINED FEATURES: GLACIAL LINEATIONS*

167 In the deeper western channel of Nordvågen, close to the 2009 margin of Blomstrandbreen
168 and extending 2.5 km to the proximal prominent transverse ridge (Figs. 2a, b), there is
169 evidence for another landform type that has had transverse ridges superimposed upon it. This
170 landform appears in the central part of the bay as small curvilinear groove-ridge features, or
171 lineations, running parallel to the main channel flow (orientated southwestwardly) (Fig. 4a).

172 These features have amplitudes around 2 m to 5 m, widths typically between 20 m and 50 m,
173 and can reach lengths of over 500 m. The curvilinear ice-flow parallel features are all found
174 within the deeper western channel on the proximal side of the moraine associated with the
175 1960s surge (Fig. 2a, b). The superimposition of small transverse ridges over the streamlined
176 landforms (Fig. 4a) suggests that the streamlined landforms are older than the ridges.

177 The description of these landforms leads to their interpretation as glacial lineations, which
178 form as a result of movement of ice on a sedimentary substrate producing low-amplitude
179 streamlined ridges aligned parallel to ice-flow (Boulton 1976, Gordon *et al.* 1992, Clark
180 1993). In addition, glacial lineations are also indicative of actively surging ice flow in the
181 Svalbard archipelago (Ottesen and Dowdeswell 2006, Ottesen *et al.* 2008, Robinson and
182 Dowdeswell 2011). The lineations were produced subglacially, during a period of high
183 velocity, as Blomstrandbreen surged to its 1960s maximum position. The limited spatial
184 distribution of glacial lineations (Fig. 2) could be due to subsequent burial and destruction as
185 the glacier retreated again (Ottesen *et al.* 2008). We suggest that these landforms provide

186 further evidence that Blomstrandbreen drained mainly through the deeper western channel at
187 a relatively high velocity.

188 *SMALL TRANSVERSE RIDGES: RETREAT MORAINES*

189 There are numerous minor sub-parallel transverse ridges identified throughout Nordvågen
190 (Fig. 2, 4). A suite of around 65 small transverse ridges is identified within the western
191 channel (Fig. 4a). These ridges (Fig. 4a, y-y') have more complex morphologies than those
192 described in the shallower channels (Fig. 4b). Away from the fjord sides and topographic
193 highs, the ridges are subdued in comparison with the simple ridges in the eastern channel and
194 frequently bifurcate and coalesce (Fig. 4a). These small ridges range from <0.5 and 6 m in
195 height, are typically 20 m wide, and inter-ridge spacing is highly variable between 10 to 70 m
196 (Figs. 4a, c).

197 From the eastern maximum extent to where the eastern channel converges with the western
198 channel there is a suite of approximately 50 small transverse ridges (Fig. 4b). Similarly, there
199 are around 40 small transverse ridges in the narrow channel between the Breøyane islands
200 and Blomstrandhalvøya (Fig. 2). The transverse ridges are uniform in appearance and
201 frequently form one ridge crest across the whole width of the channels with heights from 1 m
202 to 2.5 m and widths typically between 15 and 20 m (Fig. 4b, y-y'). However, at certain points
203 they join together forming wider and higher ridges with dimensions of up to 4 m in height
204 and 30 m in width. Ridge spacing varies from <5 m to 50 m, but is typically <20 m (Fig. 4b).

205 The small transverse ridges in Nordvågen, between the terminal moraines and the 2009
206 margin of Blomstrandbreen, are interpreted as retreat moraines (Fig. 2b). The retreat
207 moraines formed ice-marginally, at the grounding line of Blomstrandbreen, during numerous
208 small re-advances in the context of the general deglaciation of the bay, similar to features

209 described in Bennett (2001). The ridge spacing of <30 m that occurs in many areas of
210 Nordvågen probably indicates that the features are annual-push retreat moraines formed by
211 small winter re-advances (e.g. Boulton 1986, Bennett 2001, Ottesen and Dowdeswell 2006,
212 Dowdeswell *et al.* 2008), especially in the shallow and narrow channels. In Table 1 we
213 calculate average retreat rates between years when the ice-front position was known; this has
214 been done by dividing the mean distance between two ice-margin positions by the number of
215 years that separate them. The average retreat rate of Blomstrandbreen in the western channel
216 from 1966 to 2009 is 55 m yr⁻¹ (Table 1). However, the bathymetric data reveal that inter-
217 moraine spacing is highly variable, with some sets of moraines being closely spaced (within
218 5m), and some ridges being separated by more than 55 m. In addition, the ridges are
219 morphologically more complex than those in the eastern channel. We suggest that this
220 difference is the result of greater water depths in the western channel. Fewer continuous
221 ridges are present in the deepest parts of the western channel (Fig. 2a, 2c) indicating that the
222 ice margin may have been susceptible to floatation in local depressions during thinning and
223 retreat. The more lobate and bifurcating form of the ridges is somewhat similar to sinuous
224 moraines formed by radially-crevassed ice margins (e.g. Sharp 1984, Bradwell 2004) and it is
225 also seen in annual retreat moraines as water depths increase in front of other surging
226 tidewater glaciers in Svalbard (Ottesen and Dowdeswell 2006; their Fig. 9E). It is unusual for
227 stagnating or slow-moving ice to have a heavily crevassed surface (Fig. 1b) during retreat
228 and, therefore, we interpret this ridge variability to reflect partial lift-off during retreat of the
229 ice margin in local depressions, whereas the ice margin could remain more stable in
230 shallower areas more often forming discontinuous or lobate ridge segments.

231 A few of the transverse ridges appear to be linked together by parallel-to-flow ridges (Fig.
232 4a), forming a pattern similar to the better developed rhombohedral ridges described in
233 several Svalbard fjord and open-marine settings where glaciers have surged across the sea

234 floor (e.g. Solheim and Pfirman 1989, Solheim 1991, Ottesen and Dowdeswell 2006, Ottesen
235 et al. 2008). However, as in the fjord sediments beyond the present terminus of Tunabreen in
236 Isfjorden (Flink *et al.* 2015), these landforms, interpreted as a result of the squeezing of soft
237 basal sediments into bottom crevasses in the early part of quiescence, are relatively poorly
238 developed at Blomstrandbreen.

239 *SMALL DEPRESSIONS AND MINOR SCOURS: ICEBERG PITTING*

240 There is evidence of small-scale morphological features on some of the large and small
241 transverse ridges in their shallowest areas and on their distal sides (Fig. 4d), particularly on
242 the ridges marking Blomstrandbreen's neoglacial maximum. These features comprise
243 numerous depressions (<0.5 m deep) often surrounded by small berms. Depressions have
244 been identified to a maximum water depth of around 45 m on the distal side of the neoglacial
245 maximum moraine in the eastern channel. By contrast, within Nordvågen, they are
246 concentrated in shallower areas, rarely occurring in water depths greater than 25 m.
247 Occasionally, these depressions form small curvilinear troughs up to around 15 m in length.

248 The form and bathymetrically constrained distribution of these depressions is consistent with
249 their interpretation as iceberg-grounding pits (Barrie *et al.* 1992, Dowdeswell *et al.* 1993,
250 Todd and Shaw 2012). These pits are produced when the keel of an iceberg or bergy bit
251 comes into contact with the sea floor before lifting off again as a result of tides, currents or
252 fragmentation. Icebergs can become grounded, melting and rotating to form the pits (Syvitski
253 *et al.* 1996). The location of the depressions only on topographic highs, and their small
254 surrounding berms, further support this interpretation. Iceberg-grounding pits were also noted
255 on the distal slope of the terminal moraine in side-scan sonar data published by Whittington
256 *et al.* (1997). The regular presence of icebergs within Kongsfjorden has been noted
257 previously (Dowdeswell 1989, Dowdeswell and Forsberg 1992). The maximum depth at

258 which iceberg keel ploughmarks are identified within bathymetric data of the sea floor
259 corresponds with the 40 m iceberg keel depths observed by Dowdeswell and Forsberg (1992).
260 The increase to around 45 m depth on ice-distal slopes is attributed to the higher resolution of
261 bathymetric data used within this study. The presence of grounding pits on the distal side of
262 the terminal moraine in the eastern channel demonstrates that these moraines act as a barrier,
263 preventing larger icebergs from drifting into Nordvågen. The icebergs were calved from
264 glaciers at the head of Kongsfjorden (Kronebreen, Kongsbreen, and Conwaybreen; Fig. 1),
265 which have modern tidewater ice cliffs mostly between 10 and 60 m and are intermittently
266 fast-flowing (Sund *et al.* 2011).

267 *IMAGERY*

268 A combination of satellite imagery and aerial photography shows that between 1990 and
269 2007 there was an increase in crevassing on Blomstrandbreen, then, between 2008 and 2009,
270 there was a small advance indicating the initiation of a change in dynamic regime (Sund and
271 Eiken 2010). Landsat imagery reveals that the margin of Blomstrandbreen advanced an
272 average of 33 m between 2006 and 2009 (Table 1). Recent imagery further demonstrates this
273 latest surge, with a further advance from 2009 to 2013, resulting in an average advance of
274 215 m and covering the recently exposed 26 m a.s.l. islet of Tjukholmen (see Fig. 5 for
275 location of Tjukholmen).

276

Discussion

277 *LANDFORM ASSEMBLAGE*

278 The full multibeam-bathymetric dataset around Blomstrandhalvøya and the assemblage of
279 landforms identified are illustrated in Figures 2a and 4. The superimposition of landforms
280 allows relative ages to be determined, with younger elements cross-cutting older features

281 (Ottesen *et al.* 2005, Ottesen and Dowdeswell 2006). A simplified relative age of deposition
282 from oldest to youngest in Nordvågen is: (1) overridden large palaeo-moraines; (2) large
283 terminal moraines; (3) retreat moraines; (4) 1960s surge-related glacial lineations and
284 terminal surge moraine; (5) further retreat moraines (Fig. 2b). This is similar to landform
285 assemblages described elsewhere on Svalbard at the margin of surge-type tidewater glaciers
286 (Ottesen and Dowdeswell 2006, Ottesen *et al.* 2008); however, because Blomstrandbreen is
287 known to have surged recently and relatively frequently (Liestøl 1988, Lefauconnier 1992,
288 Hagen *et al.* 1993, Sund and Eiken 2010, Mansell *et al.* 2012) there is a transition within
289 Nordvågen between pre- and post-surge landforms, with pre-surge landforms being located
290 west of the surge moraine (cf. Fig. 4) and post-surge landforms within its confines.

291 The 1960s surge provides an example of a glacier advance, which would have overridden
292 numerous retreat moraines, producing glacial lineations and a terminal surge moraine by
293 bulldozing sediments in to a ridge (Figs. 2b, 5). These flow-parallel lineations were
294 subsequently cross-cut by younger transverse retreat moraines, as Blomstrandbreen returned
295 to its quiescent phase and retreated again, forming retreat moraines annually. This largely
296 conforms to the previous models for tidewater surging glaciers (Ottesen and Dowdeswell
297 2006, Ottesen *et al.* 2008), but as the 1960s surge did not extend beyond the LIA maximum
298 there is some divergence from these earlier schematic models. We suggest that, because the
299 surge was only short-lived, it did not produce a large moraine ridge at its outer limit or a
300 steep enough slope to generate debris flows on its distal side. Indeed, there is no
301 morphological evidence to differentiate the 1960s terminal surge moraine (marked as surge
302 moraine on Fig. 2b) from a moraine formed during a major stillstand during retreat. The
303 limited distribution of basal crevasse-fill ridges (cf. Fig. 4a), which have been identified as an
304 indicative landform linked to surging glaciers elsewhere in Svalbard (Solheim and Pfirman
305 1985, Boulton *et al.* 1996, Ottesen and Dowdeswell 2006, Ottesen *et al.* 2008), suggests that

306 the ice margin at Blomstrandbreen may have continued to be active even in the early stages
307 of quiescence, in order for transverse-to-flow push ridges to form close to maximum terminus
308 positions. The lack of crevasse-fill ridges and a terminal surge moraine that has no
309 morphological difference from a moraine formed during a large stillstand have implications
310 for how surge-type glaciers are identified in the bathymetric record across Svalbard and in
311 other high-latitude fjords, highlighting that there are potential variations to surge-related
312 landform assemblages and not all individual landforms of the assemblage may be present in
313 all locations (Ottesen and Dowdeswell 2006, Ottesen *et al.* 2008, Flink *et al.* 2015).

314 The subsequent glacier retreat resulted in numerous ice-marginal retreat moraines forming on
315 top of the lineations. The variation in morphology of the retreat moraines implies that some
316 areas of the tidewater glacier calving front were more stable than others, supported by Table
317 1, and demonstrates the nature of the observed unevenness of retreat at the margin (cf.
318 Hanson and Hooke 2000, Nick *et al.* 2010, Sundal *et al.* 2013). Therefore, the submarine
319 landform assemblage of Nordvågen (Fig. 2b) provides an insight into more general glacier
320 dynamics as well as landforms produced during a minor post-LIA surge.

321 *DATING THE RETREAT OF BLOMSTRANDBREEN*

322 The suite of moraines in Nordvågen is well dated through reference to historical records
323 (Liestøl 1988), NPI aerial photographs, and Landsat satellite imagery, which show
324 Blomstrandbreen's margin at several times over the past few centuries. This enables a
325 number of moraines to be linked to specific years of formation (Fig. 5). The retreat of
326 Blomstrandbreen, with the three surge-related re-advances is also shown, is illustrated in
327 Figure 6.

328 By the end of the 17th Century, rudimentary maps from sealing and whaling vessels suggested
329 that Blomstrandhalvøya was an island, clearly separated from the mainland (Liestøl 1988).
330 However, by the mid-18th Century the peninsula was well connected to the north shore of
331 Kongsfjorden (Fig. 5), at a time when many glaciers advanced on Svalbard due to LIA
332 cooling (Werner 1993). Blomstrandbreen's neoglacial maximum extent was earlier than
333 1861 (Liestøl 1988; Fig. 5), which is when detailed scientific observations of the ice margin
334 began, but the actual timing of the neoglacial maximum is unknown. Towards the end of the
335 19th Century the glacier began an initial retreat (Liestøl 1988, Lefauconnier 1992), but this
336 was punctuated briefly by a small re-advance around the beginning of the 20th Century
337 (Lefauconnier 1992), resulting in the 1907 terminus being less extensive than in 1911 (Fig.
338 5). There was an average advance across the terminus of approximately 200 m between 1910
339 and 1928 (Table 1). Gradual retreat occurred until 1956, with an average retreat rate of 55 m
340 yr⁻¹ in the western channel and 41 m yr⁻¹ in the eastern channel (Table 1). By 1956 only a
341 narrow corridor of ice still connected Blomstrandbreen to Blomstrandhalvøya (Fig. 5).

342 Blomstrandbreen's retreat was interrupted between 1960 and 1968 (Liestøl 1988,
343 Lefauconnier 1992) by an advance of between 900 m in the west and 550 m in the east,
344 which has been interpreted as the result of a surge observed in the 1960s (Hagen *et al.* 1993;
345 Figs. 1b, 2b, 5). The glacier then re-entered a quiescent phase and retreated, with an average
346 rate of 49 m yr⁻¹ in the western channel and around 35 m yr⁻¹ for the eastern channel
347 (Lefauconnier 1992) between 1966 and 1986 (Table 1). Between 1986 and 1989 both the
348 western and eastern ice-fronts of the glacier had retreated again leaving a thin corridor of ice,
349 only 240 m wide (Liestøl 1988), connecting the peninsula (Figs. 1b-e, 5). From 1990 to 2006
350 the glacier retreated approximately 1 km (Fig. 6), with an average retreat rate of 65 m yr⁻¹. It
351 has been proposed that this relatively rapid retreat was caused by the grounding-line breaking
352 away from a shallower pinning point on the northern tip of Blomstrandhalvøya and into the

353 deeper water of central Nordvågen (Benn *et al.* 2007, Mansell *et al.* 2012), resulting in the
354 peninsula becoming an island between 1990 and 1994 (Figs. 1d-e, 5).

355 *FREQUENCY OF SURGES AND LENGTH OF QUIESCENT PHASE*

356 The 21st Century surge makes Blomstrandbreen one of only five glaciers confirmed to have
357 had two observed surges on Svalbard, and one of two glaciers (Tunabreen; Flink *et al.* 2015)
358 to most likely have had three surges, resulting in a surge-cycle of approximately 51 years
359 (Table 1). This calculated surge cyclicity is very similar to the estimate of 47 years put
360 forward by Mansell *et al.* (2012) on the basis of glacier surface flow speeds and frontal
361 positions. This is one of the shortest known cycles on the archipelago (Dowdeswell *et al.*
362 1991, Flink *et al.* 2015) and helps explain the suite of landforms, including the overrun
363 moraines, identified within the bay. The relatively high frequency of the surge cycle implies
364 that there have been a number of surge landform assemblages overprinting and modifying
365 earlier sea floor morphologies, including previous surges, within the LIA maximum limit of
366 Blomstrandbreen. In summary, the known surge history of Blomstrandbreen includes a minor
367 surge between 1911 and 1928, a substantial surge in the 1960s and a surge from 2008
368 onwards.

369 The relatively short quiescent phase of the surge cycle at Blomstrandbreen (Fig. 6) is likely to
370 be related indirectly to the mass balance of the glacier. Dowdeswell *et al.* (1995) have shown
371 that, while climate-related changes in mass balance are not triggers of individual surges, such
372 changes may affect the length of time a glacier takes to build up mass in its upper, reservoir
373 area before a new surge can take place. Other factors being equal, and given that most
374 Svalbard glaciers are presently experiencing negative mass balance (e.g. Hagen *et al.* 2003,
375 Nuth *et al.* 2010), a relatively less negative balance would yield a more rapid build-up of
376 accumulation-area mass and a new surge would take place relatively sooner than on a glacier

377 with a very negative mass balance. Indeed, at Scott Turnerbreen in central Spitsbergen, which
378 is in the driest part of the archipelago, increased post-LIA surface melting appears to have
379 prevented the glacier from building up the necessary mass for further surges (Dowdeswell *et*
380 *al.* 1995).

381 *INFLUENCE OF TOPOGRAPHIC HIGHS ON GLACIER DYNAMICS*

382 Many of the transverse ridges on the sea floor of Nordvågen are linked to topographic highs,
383 which are often associated with recently exposed islands. One clear example of how these
384 highs have influenced moraine formation is the shallow water (5 – 15 m deep) surrounding a
385 small islet off the northern tip of Blomstrandhalvøya (Fig. 4). Numerous ridges cross the
386 width of the channels and converge at this shallow spur, where there is a decreased spacing
387 between the ridges (around 30 m) from the deep western channel. In contrast, at the deepest
388 point within the western channel (80 m deep), the ridges bifurcate and coalesce more often
389 and have a wider spacing of >40 m. This is further supported by the maximum distances of
390 retreat and relatively high retreat rates (Table 1) which are recorded from the deeper western
391 channel.

392 The complex morphology of retreat moraines in the deeper parts of Nordvågen is interpreted
393 to represent instability of the ice-front at increased water depths (Benn *et al.* 2007), and on
394 occasion likely detachment from the bed (Dowdeswell *et al.* 2008). Detachment seemingly
395 occurred for a large portion of the grounding line from 1995-1999 (Table 1), most likely
396 driven by the glacier retreating from its pinning point on Blomstrandhalvøya (Fig. 7), which
397 had acted as a stabilising factor.

398 A Boomer profile from Whittington *et al.* (1997) spans the data gap in the eastern channel
399 (Fig. 2a) and reveals evidence of at least 10 further transverse ridges (Fig. 3). Therefore, the

400 850 m wide data gap probably contains a number of ridges not mapped in this study, possibly
401 indicating relatively large stillstands of Blomstrandbreen (Fig. 2a).

402 The 2009 aerial photographs of Nordvågen reveal a number of islands exposed within the bay
403 that were once covered by Blomstrandbreen (Figs. 4, 5). These islands and associated
404 submarine shallows are most likely to consist of or are underlain by glacially-sculpted
405 resistant bedrock. They have had a strong influence on glacial retreat, supporting longer
406 stillstands by acting as pinning points (Benn *et al.* 2007), and promoting the regular linear
407 morphology of the retreat moraines in the shallow and narrow sections of Nordvågen (Figs.
408 2a, 2c, 4). The associated increase in calving rate at greater depths (Brown *et al.* 1982, Pelto
409 and Warren 1991, Van der Veen 1996, Vieli *et al.* 2001) is likely to have produced the
410 complex pattern of ridges found in centre of the bay, indicating a more unstable grounding-
411 line and, at times, the possible decoupling of the glacier from the bed. Luckman *et al.* (2015)
412 report that some recent tidewater glacier fluctuations in Spitsbergen are linked to sub-surface
413 water temperature change (for which we have no data), but Blomstrandbreen appears to
414 respond strongly to water-depth change and dynamic change associated with the surge cycle.

415 **Conclusions**

416 The multibeam-bathymetric data from Nordvågen (Figs. 2, 4) demonstrate an assemblage of
417 submarine landforms that represents the style of retreat for Blomstrandbreen since the LIA.
418 The relatively large moraines in the waters on both the western and eastern flanks of
419 Blomstrandhalvøya provide examples of submarine terminal moraines, marking the LIA
420 maximum extent of Blomstrandbreen and the most extensive neoglacial connection between
421 the island and the mainland. There are very clear and regularly spaced annual-push retreat
422 moraines orientated transverse to flow, representing a gradual retreat of the glacier, especially
423 across the shallow and narrow eastern channel. Blomstrandhalvøya became an island between

424 1990 and 1994, when its connection by glacier ice to the mainland of Spitsbergen was broken
425 (Fig 7).

426 The morphology of the channels, including island areas probably consisting of, or underlain
427 by, resistant bedrock, has clearly affected the pattern of glacial retreat. Shallow areas acted as
428 pinning points which enabled a relatively gradual retreat. Stillstands during retreat are
429 identified by slightly more prominent transverse ridges, having built up material over a
430 number of years. Regularly spaced annual-push retreat moraines, often indicating retreat rates
431 of $<20 \text{ m yr}^{-1}$, are visible in the shallow eastern channel (Fig. 4b). Retreat moraines in the
432 deeper areas have more irregular morphologies and wider inter-ridge spacings, suggesting
433 greater instability of the former ice margin and possible decoupling of the grounding-line
434 from the bed, promoting more rapid retreat at these locations.

435 The complex suite of landforms present within Nordvågen is interpreted to be the result of
436 the relatively frequent surges of Blomstrandbreen (Figs. 4, 5). Unusually for Svalbard fjord
437 records, the submarine landforms at Blomstrandbreen record three recent surges, with a
438 spacing of about 50 years between each of them (Fig. 6); this represents a relatively short
439 quiescent phase between surges (Dowdeswell *et al.* 1991). This is supported by the landforms
440 associated with Blomstrandbreen's documented surge in the 1960s. The surge-type behaviour
441 of Blomstrandbreen, occurring between 1911 and 1928, throughout the 1960s, and from 2007
442 onwards, has resulted in a number of advances and retreats overriding older landforms. The
443 landforms that these surges produced are likely to be a good indication of the landform
444 assemblage that will be produced by other glaciers on Svalbard that have had a minor post-
445 LIA surge within the confines of their LIA maximum. Importantly, these surge moraines may
446 not be morphologically dissimilar from large stillstand moraines and crevasse-fill ridges may
447 also be limited in distribution. This is significant, as previously a prominent terminal surge

448 moraine and the occurrence of large numbers of crevasse-fill ridges have been used as key
449 landforms to identify surging in the marine sedimentary record of tidewater glaciers.

450

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457

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Figure Captions

634

635

636 Figure 1. Satellite map of Kongsfjorden, Svalbard, including the glaciers draining into the fjord and
637 showing the extent of multibeam-bathymetric data coverage (colour shaded) in Nordvågen. The
638 purple line indicates the drainage basin of Blomstrandbreen (Randolph Glacier Inventory: Arendt *et*
639 *al.*, 2012). Landsat imagery data available from the U.S. Geological Survey. Bathymetric contours
640 are from IBCAO v3.0. Inset: Location of the study area on the Svalbard archipelago (IBCAO Version
641 3.0: Jakobsson *et al.* 2012) marked by the red box. (b-e) Glacier margins of Blomstrandbreen showing
642 detachment of the glacier from Blomstrandhalvøya. Images from: (b) 1966; (c) 1976; (d) 1990 and (e)
643 1994. Images (b) and (d) are NPI aerial photographs, whilst (c) and (e) are Landsat TM RGB
644 composites (30 m resolution).

645

646 Figure 2. (a) The extent of sun-illuminated multibeam swath bathymetry showing sea floor
647 morphology in Nordvågen and around Blomstrandhalvøya. Aerial photographs show the adjacent
648 glacier (Blomstrandbreen). Lateral moraines (LM) and western and eastern channels are labelled; Tj
649 denotes the islet of Tjukkkholmen; R1, R2, R3 and R4 indicate the locations of the large but subdued
650 transverse ridges; T1 and T2 indicate the locations of the large transverse ridges; SL denotes a lobe of
651 sediment; the black dashed line is the approximate continuation of the LIA moraine. (b) Landform
652 map of submarine glacial features in Nordvågen derived from multibeam-bathymetric data. Terrestrial
653 lateral moraines (LM), the islet off the northern tip of Blomstrandhalvøya and the surge moraine are
654 labelled; Br denotes the Breøyane islands.

655

656 Figure 3. (a) Boomer seismic profile showing small transverse moraines and a larger, terminal
657 moraine assumed to be from the LIA in the gap between bathymetric datasets. (b) Interpretation of the
658 seismic profile in panel (a). Vertical arrows are small transverse ridges. Profile located on Fig. 2 and
659 adapted from Whittington *et al.* (1997).

660

661 Figure 4. (a) Detailed bathymetric image showing bifurcations and coalescing of small transverse
662 ridges. Landforms interpreted as lineations and rhombohedral ridges are also marked. (b) Detailed
663 bathymetric image of small transverse ridges with regular morphology and spacing. (c) Sea floor
664 depth profiles across transverse ridges (x-x', y-y'). (d) Area with extensive depressions, interpreted as
665 iceberg-grounding pits.

666

667 Figure 5. Glacier margin fluctuations of Blomstrandbreen. Positions of the former ice-front are from a
668 combination of evidence from Liestøl (1988), Landsat imagery, and aerial photographs. Dashed
669 delineations are from Liestøl (1988). The solid lines represent margins with a higher degree of
670 certainty. The retreat of Blomstrandbreen from its LIA maximum is separated into three retreat phases
671 punctuated by three surges. Tj is Tjukholmen.

672

673 Figure 6. Mean distance of the margin of Blomstrandbreen from the LIA maximum in the western
674 channel (black) and the eastern channel (green), using recorded extents at dates presented in Table 1
675 and Figure 5. Rates of retreat and advance have been assumed to be linear between these dates.
676 Colours on graph are the same for the delineations presented in Figure 5. The arrow highlights the
677 1960s surge event.

Top

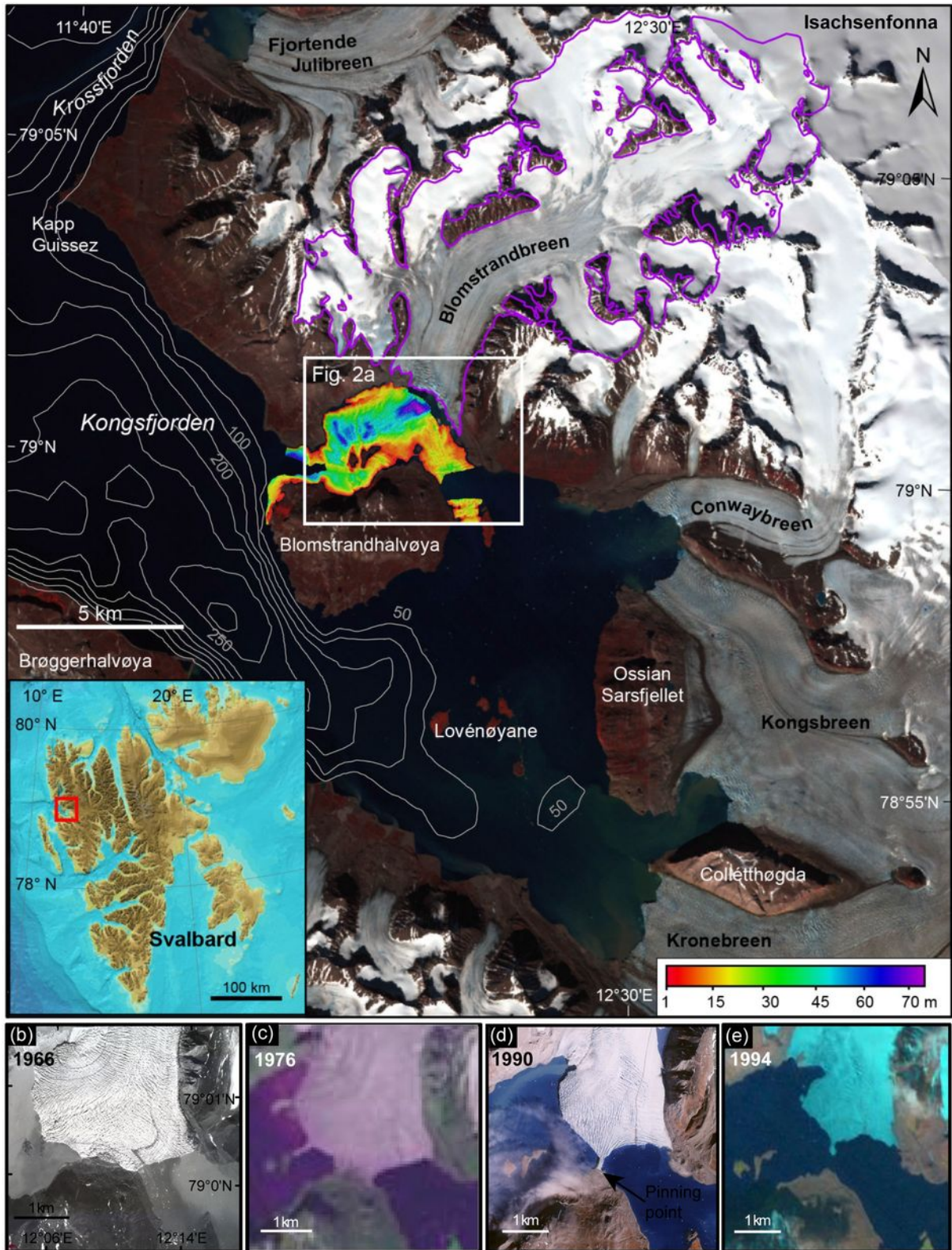


Figure 1. Burton

Top

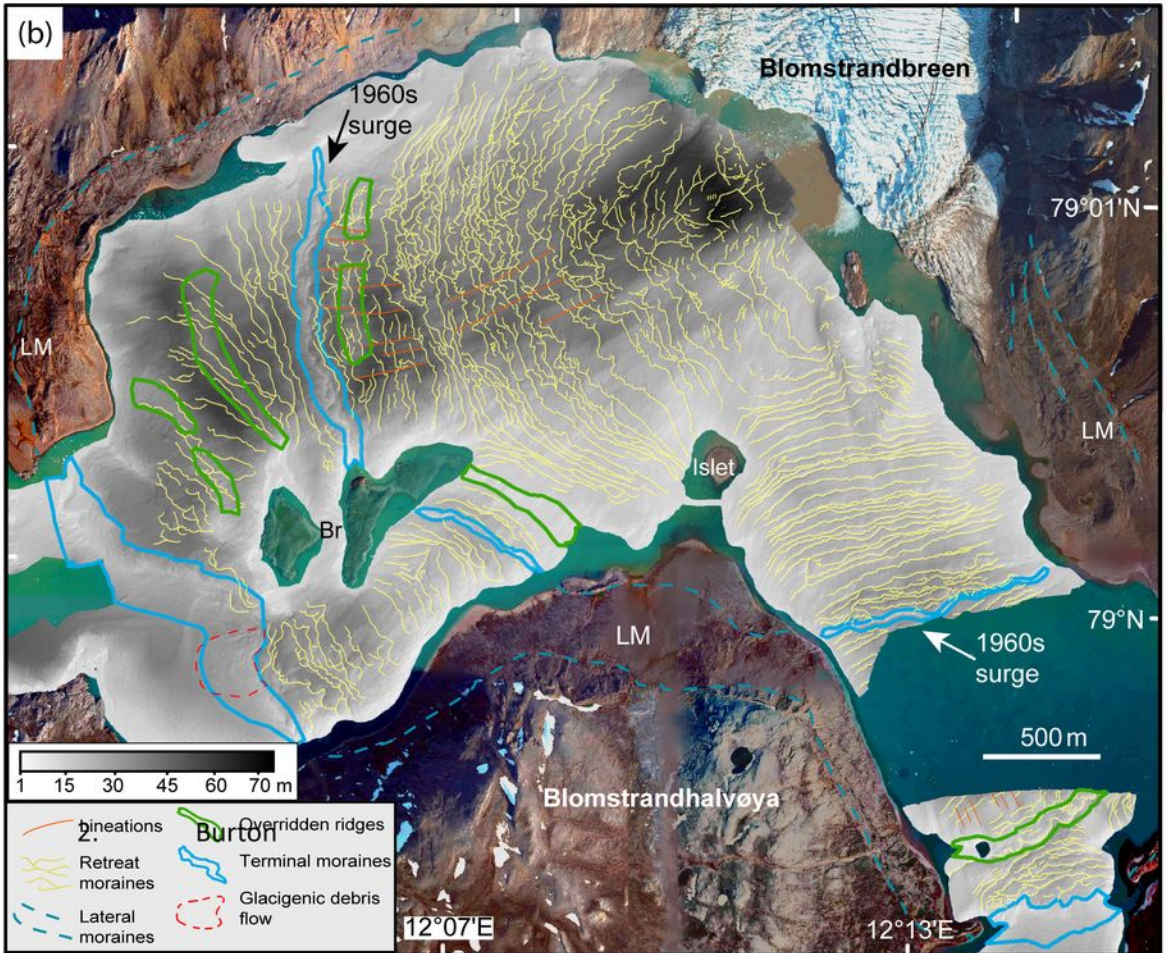
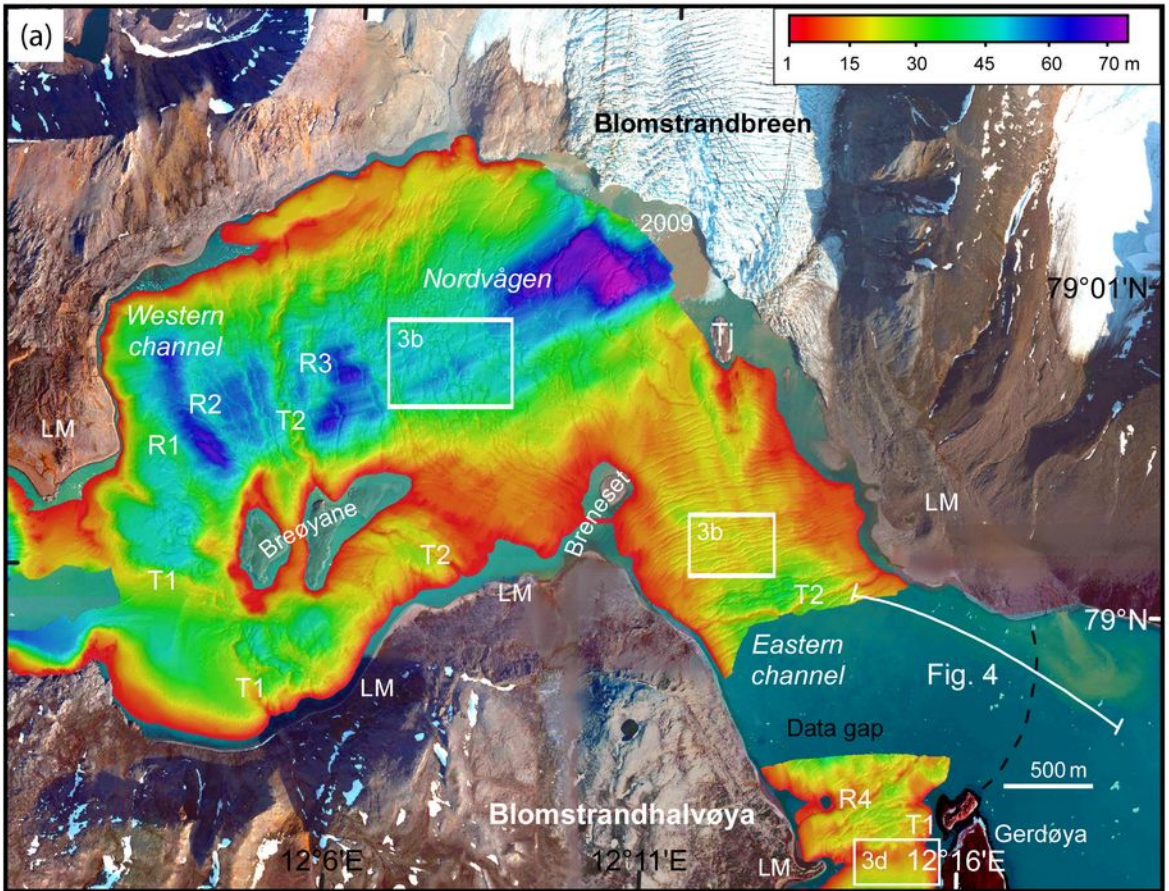


Figure 2.

Burton

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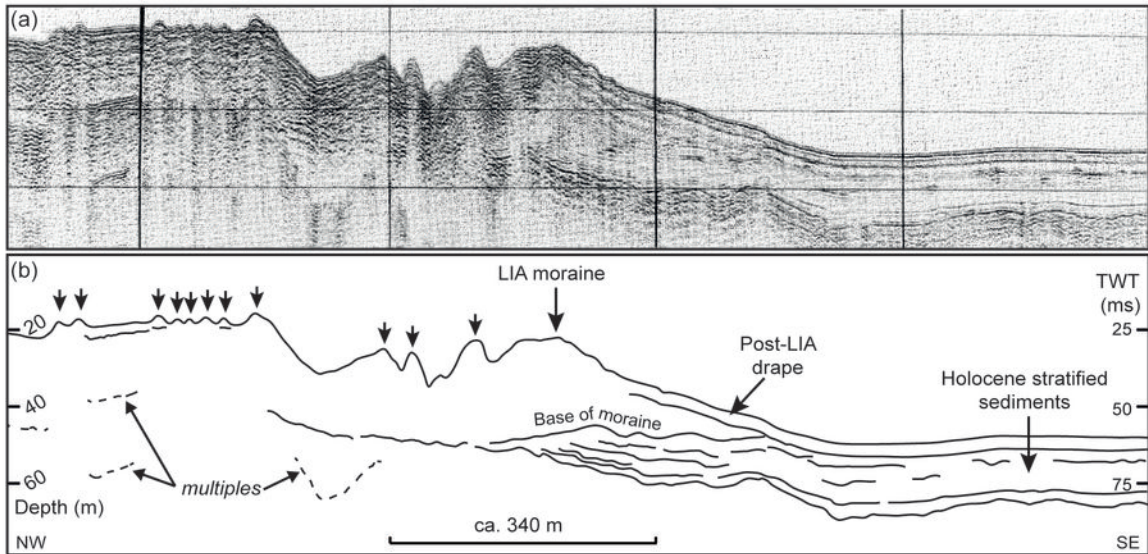


Figure 3.

Burton

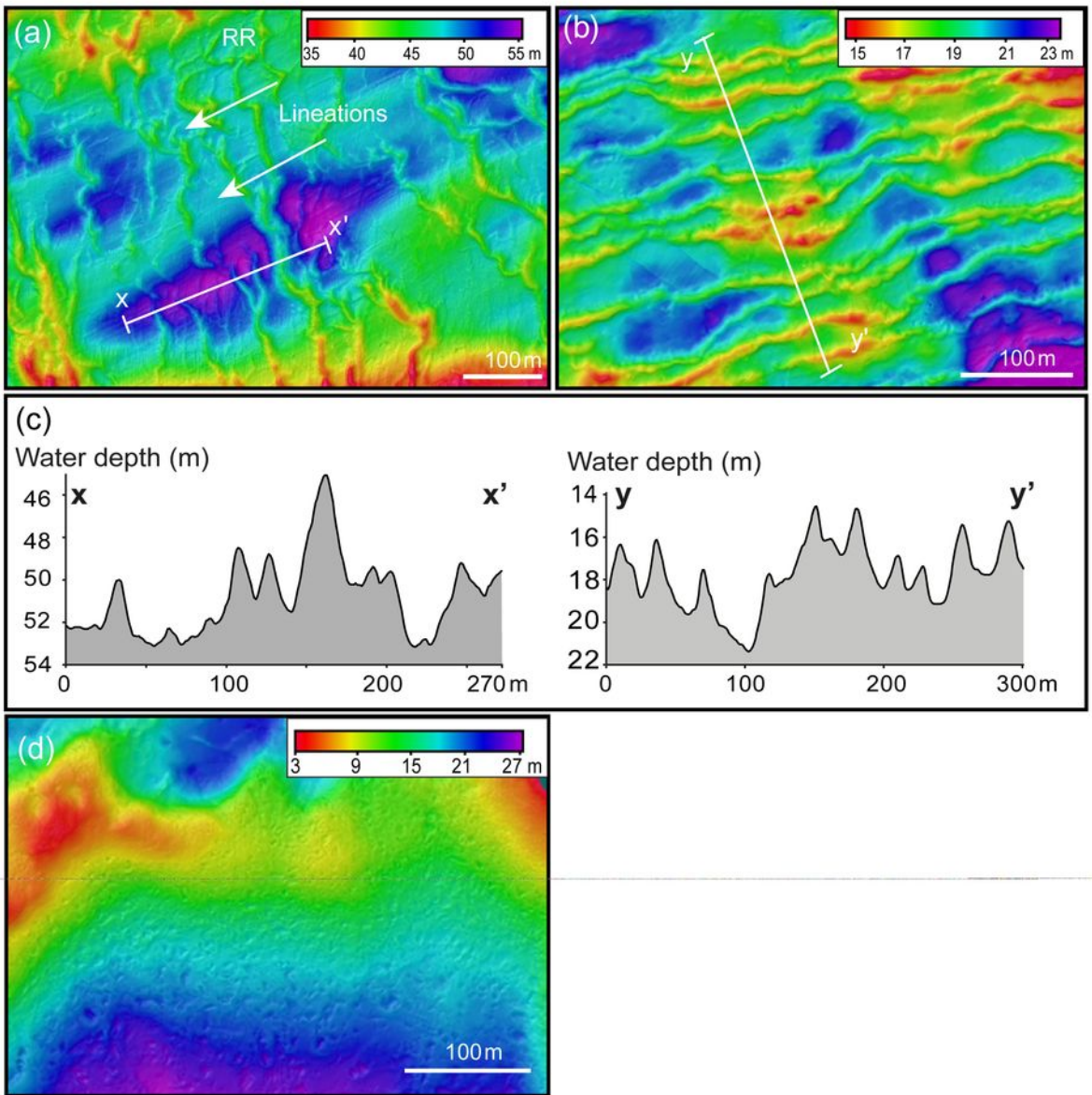


Figure 4. Burton

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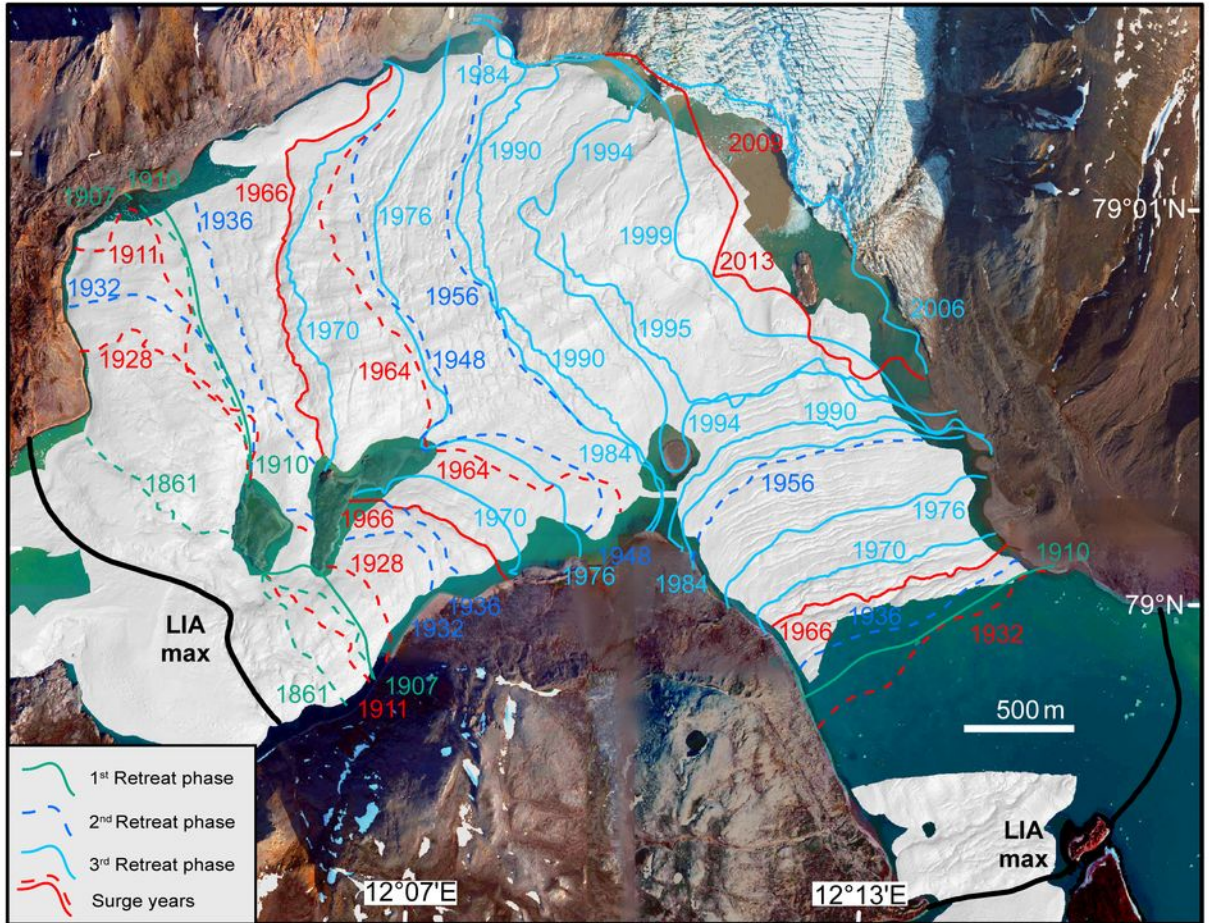


Figure 5. Burton

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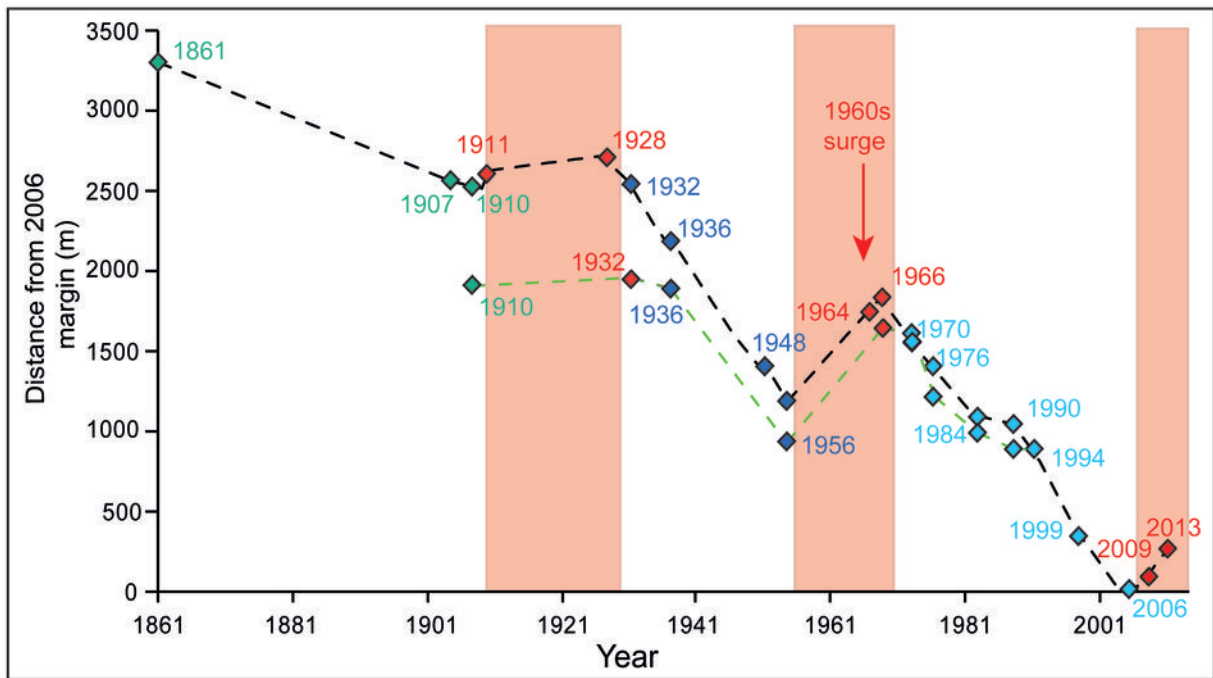


Figure 6.

Burton

Table 1:

TABLE 1: Summary of the retreat or advance between delineations of the former ice-front positions of Blomstrandbreen presented in Figure 5. Measurements have only been made for the eastern channel to where it merges with the western channel. Rate of retreat/advance has been assumed as linear. Negative values represent retreats, whilst positive values represent advances.

Time period	Retreat/advance	Distance (m) from previous delineation			Mean distance from 2006 margin (m)	Rate of retreat/advance (m yr ⁻¹)		
		Max.	Min.	Mean		Max.	Min.	Mean
LIA max. - 1861	Retreat	415	195	311	3054	-	-	-
1861-1907	Retreat	1080	27	502	2552	-23	-1	-11
1907-10	Retreat	125	10	43	2509	-42	-3	-14
1910-11	Advance	290	5	111	2620	+290	+5	+111
1911-28	Advance	545	-335	91	2711	+32	-20	+5
1928-32	Retreat	315	+20	156	2555	-79	+5	-39
1932-36	Retreat	850	75	280	2275	-213	-19	-70
1936-48	Retreat	925	310	684	1591	-116	-39	-86
1948-56	Retreat	620	205	411	1180	-78	-26	-51
1956-64	Advance	610	250	372	1552	+76	+31	+47
1964-66	Advance	630	115	368	1920	+315	+58	+184
1966-70	Retreat	160	35	93	1827	-40	-9	-23
1970-76	Retreat	545	155	345	1482	-91	-26	-58
1976-84	Retreat	655	195	387	1095	-82	-24	-48
1984-90	Retreat	150	+25	55	1040	-25	+4	-9
1990-94	Retreat	375	40	235	805	-94	-10	-59
1994-99	Retreat	540	20	398	407	-135	-5	-100
1999-2006	Retreat	735	60	407	0	-105	-9	-58
2006-09	Advance	135	-70	33	33	+45	-23	+11
2009-13	Advance	555	-80	215	248	+139	-20	+54
Eastern channel*:								
LIA max. - 1910	Retreat	1780	645	1252	1905	-	-	-
1910-32	Advance	175	10	63	1968	+8	+0.5	+3
1932-36	Retreat	295	65	168	1800	-74	-16	-42
1936-56	Retreat	930	710	823	977	-47	-36	-41
1956-66	Advance	750	525	651	1628	+75	+53	+65
1966-70	Retreat	175	50	108	1520	-44	-13	-27
1970-76	Retreat	300	160	240	1280	-50	-27	-40
1976-84	Retreat	405	190	332	948	-51	-24	-42
1984-90	Retreat	120	20	84	864	-20	-3	-14