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

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Abstract

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

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

Introduction

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

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

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

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

Study area

Blomstrandbreen is an approximately 18 km-long tidewater glacier located in northwest Spitsbergen, that drains towards the southwest from Isachsenfonna into Kongsfjorden (Fig. 1). Kongsfjorden is approximately 20 km long with five large tidewater glaciers at its head. The fjord widens to about 10 km at its distal part before merging with Krossfjorden. Blomstrandbreen is fed by a number of smaller tributary glaciers, resulting in a total drainage area of approximately 90 km^2 (Arendt *et al.* 2012; Fig. 1). It is known to be a surge-type glacier, which is relatively common for glaciers on Svalbard (Dowdeswell *et al.* 1991, Liestøl 1993, Hagen *et al.* 1993, Jiskoot *et al.* 2000), with documented surges in the 1960s (Liestøl 1988, Hagen *et al.* 1993), from 2008 onwards (Mansell *et al.* 2012), and a possible surge between 1911 and 1928. Surging glaciers exhibit cyclical activity with a quiescent phase of stagnation and slow ice flow, and an active phase of increased ice velocities (Meier and Post 1969). A surge often causes frontal advances and longitudinal extension that lead to severe crevassing and calving if the terminus ends in fjord waters (Kamb *et al.* 1985, Sharp 1988). After a surge event the glacier returns to a quiescent state until the next surge, which generally occurs decades to centuries later (Meier and Post 1969, Kamb *et al.* 1985). Glacier surges on Svalbard appear to have less frequent surge events than, for example, Alaskan glaciers, but with longer lasting active phases and lower ice velocities (Dowdeswell *et al.* 1991).

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

Methods

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

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

Description of submarine features in Nordvågen

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

LARGE SUBDUED TRANSVERSE RIDGES: OVERRUN MORAINES

There are a number of large but subdued ridges within Nordvågen, which are orientated approximately perpendicular to the main channel axes and are slightly sinuous in planform (Fig. 2b). Three of these large ridges are identified in the deeper western channel: the most distal (R1, Fig. 2a) is 3.2 km from the 2009 margin and varies from 10 m to 20 m high and is between 70 m and 120 m wide; the next (R2, Fig. 2a) is approximately 3 km from the 2009 margin, is 10 m to 15 m high and varies in width from 40 m to 100 m; the most proximal (R3, Fig. 2a) is about 2.2 km from 2009 margin, is 10 m high, around 130 m wide and has a length of only approximately 500 m. Some evidence of the most distal and proximal ridges can be found in the narrow channel between the Breøyane islands and Blomstrandhalvøya, but here the ridges are smaller in size. Only one relatively large but subdued ridge (R4) is visible in the eastern channel (Fig. 2a), at 3.2 km from the 2009 margin, and is around 15 m high and between 100 to 200 m wide; however, the ridge may extend beyond the data coverage.

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

LARGE TRANSVERSE RIDGES: TERMINAL MORAINES

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

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

The sediment lobe described above is interpreted as a glacigenic debris flow, representing a slope failure (Ottesen *et al.* 2008) and may be a result of sediment that has been bulldozed in front of the glacier and subsequently been prone to failure and gravitational spreading (Boulton *et al.* 1996, Kristensen *et al.* 2009). The large transverse ridge most proximal to the 2009 margin of Blomstrandbreen is correlated, by the associated occurrence of glacial lineations and through the use of NPI 1966 aerial photography, with the glacier's maximum surge extent culminating in 1967-1968 (Lefauconnier 1992) and is thus interpreted as a terminal surge moraine (Figs. 4, 5).

STREAMLINED FEATURES: GLACIAL LINEATIONS

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

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

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

SMALL TRANSVERSE RIDGES: RETREAT MORAINES

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

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

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

A few of the transverse ridges appear to be linked together by parallel-to-flow ridges (Fig. 4a), forming a pattern similar to the better developed rhombohedral ridges described in several Svalbard fjord and open-marine settings where glaciers have surged across the sea floor (e.g. Solheim and Pfirman 1989, Solheim 1991, Ottesen and Dowdeswell 2006, Ottesen et al. 2008). However, as in the fjord sediments beyond the present terminus of Tunabreen in Isfjorden (Flink *et al.* 2015), these landforms, interpreted as a result of the squeezing of soft basal sediments into bottom crevasses in the early part of quiescence, are relatively poorly developed at Blomstrandbreen.

SMALL DEPRESSIONS AND MINOR SCOURS: ICEBERG PITTING

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

The form and bathymetrically constrained distribution of these depressions is consistent with their interpretation as iceberg-grounding pits (Barrie *et al.* 1992, Dowdeswell *et al.* 1993, Todd and Shaw 2012). These pits are produced when the keel of an iceberg or bergy bit comes into contact with the sea floor before lifting off again as a result of tides, currents or fragmentation. Icebergs can become grounded, melting and rotating to form the pits (Syvitski *et al.* 1996). The location of the depressions only on topographic highs, and their small surrounding berms, further support this interpretation. Iceberg-grounding pits were also noted on the distal slope of the terminal moraine in side-scan sonar data published by Whittington *et al.* (1997). The regular presence of icebergs within Kongsfjorden has been noted previously (Dowdeswell 1989, Dowdeswell and Forsberg 1992). The maximum depth at which iceberg keel ploughmarks are identified within bathymetric data of the sea floor corresponds with the 40 m iceberg keel depths observed by Dowdeswell and Forsberg (1992). The increase to around 45 m depth on ice-distal slopes is attributed to the higher resolution of bathymetric data used within this study. The presence of grounding pits on the distal side of the terminal moraine in the eastern channel demonstrates that these moraines act as a barrier, preventing larger icebergs from drifting into Nordvågen. The icebergs were calved from glaciers at the head of Kongsfjorden (Kronebreen, Kongsbreen, and Conwaybreen; Fig. 1), which have modern tidewater ice cliffs mostly between 10 and 60 m and are intermittently fast-flowing (Sund *et al.* 2011).

IMAGERY

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

Discussion

LANDFORM ASSEMBLAGE

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

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

The 1960s surge provides an example of a glacier advance, which would have overridden numerous retreat moraines, producing glacial lineations and a terminal surge moraine by bulldozing sediments in to a ridge (Figs. 2b, 5). These flow-parallel lineations were subsequently cross-cut by younger transverse retreat moraines, as Blomstrandbreen returned to its quiescent phase and retreated again, forming retreat moraines annually. This largely conforms to the previous models for tidewater surging glaciers (Ottesen and Dowdeswell 2006, Ottesen *et al.* 2008), but as the 1960s surge did not extend beyond the LIA maximum there is some divergence from these earlier schematic models. We suggest that, because the surge was only short-lived, it did not produce a large moraine ridge at its outer limit or a steep enough slope to generate debris flows on its distal side. Indeed, there is no morphological evidence to differentiate the 1960s terminal surge moraine (marked as surge moraine on Fig. 2b) from a moraine formed during a major stillstand during retreat. The limited distribution of basal crevasse-fill ridges (cf. Fig. 4a), which have been identified as an indicative landform linked to surging glaciers elsewhere in Svalbard (Solheim and Pfirman 1985, Boulton *et al.* 1996, Ottesen and Dowdeswell 2006, Ottesen *et al.* 2008), suggests that the ice margin at Blomstrandbreen may have continued to be active even in the early stages of quiescence, in order for transverse-to-flow push ridges to form close to maximum terminus positions. The lack of crevasse-fill ridges and a terminal surge moraine that has no morphological difference from a moraine formed during a large stillstand have implications for how surge-type glaciers are identified in the bathymetric record across Svalbard and in other high-latitude fjords, highlighting that there are potential variations to surge-related landform assemblages and not all individual landforms of the assemblage may be present in all locations (Ottesen and Dowdeswell 2006, Ottesen *et al*. 2008, Flink *et al*. 2015).

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

DATING THE RETREAT OF BLOMSTRANDBREEN

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

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

Blomstrandbreen's retreat was interrupted between 1960 and 1968 (Liestøl 1988, Lefauconnier 1992) by an advance of between 900 m in the west and 550 m in the east, which has been interpreted as the result of a surge observed in the 1960s (Hagen *et al.* 1993; Figs. 1b, 2b, 5). The glacier then re-entered a quiescent phase and retreated, with an average rate of 49 m yr^{-1} in the western channel and around 35 m yr^{-1} for the eastern channel (Lefauconnier 1992) between 1966 and 1986 (Table 1). Between 1986 and 1989 both the western and eastern ice-fronts of the glacier had retreated again leaving a thin corridor of ice, only 240 m wide (Liestøl 1988), connecting the peninsula (Figs. 1b-e, 5). From 1990 to 2006 the glacier retreated approximately 1 km (Fig. 6), with an average retreat rate of 65 m yr^{-1}. It has been proposed that this relatively rapid retreat was caused by the grounding-line breaking away from a shallower pinning point on the northern tip of Blomstrandhalvøya and into the deeper water of central Nordvågen (Benn *et al.* 2007, Mansell *et al.* 2012), resulting in the peninsula becoming an island between 1990 and 1994 (Figs. 1d-e, 5).

FREQUENCY OF SURGES AND LENGTH OF QUIESCENT PHASE

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

The relatively short quiescent phase of the surge cycle at Blomstrandbreen (Fig. 6) is likely to be related indirectly to the mass balance of the glacier. Dowdeswell *et al.* (1995) have shown that, while climate-related changes in mass balance are not triggers of individual surges, such changes may affect the length of time a glacier takes to build up mass in its upper, reservoir area before a new surge can take place. Other factors being equal, and given that most Svalbard glaciers are presently experiencing negative mass balance (e.g. Hagen *et al*. 2003, Nuth *et al*. 2010), a relatively less negative balance would yield a more rapid build-up of accumulation-area mass and a new surge would take place relatively sooner than on a glacier with a very negative mass balance. Indeed, at Scott Turnerbreen in central Spitsbergen, which is in the driest part of the archipelago, increased post-LIA surface melting appears to have prevented the glacier from building up the necessary mass for further surges (Dowdeswell *et al*. 1995).

INFLUENCE OF TOPOGRAPHIC HIGHS ON GLACIER DYNAMICS

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

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

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

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

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

Conclusions

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

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

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

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

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Figure Captions

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

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

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

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

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

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

Top

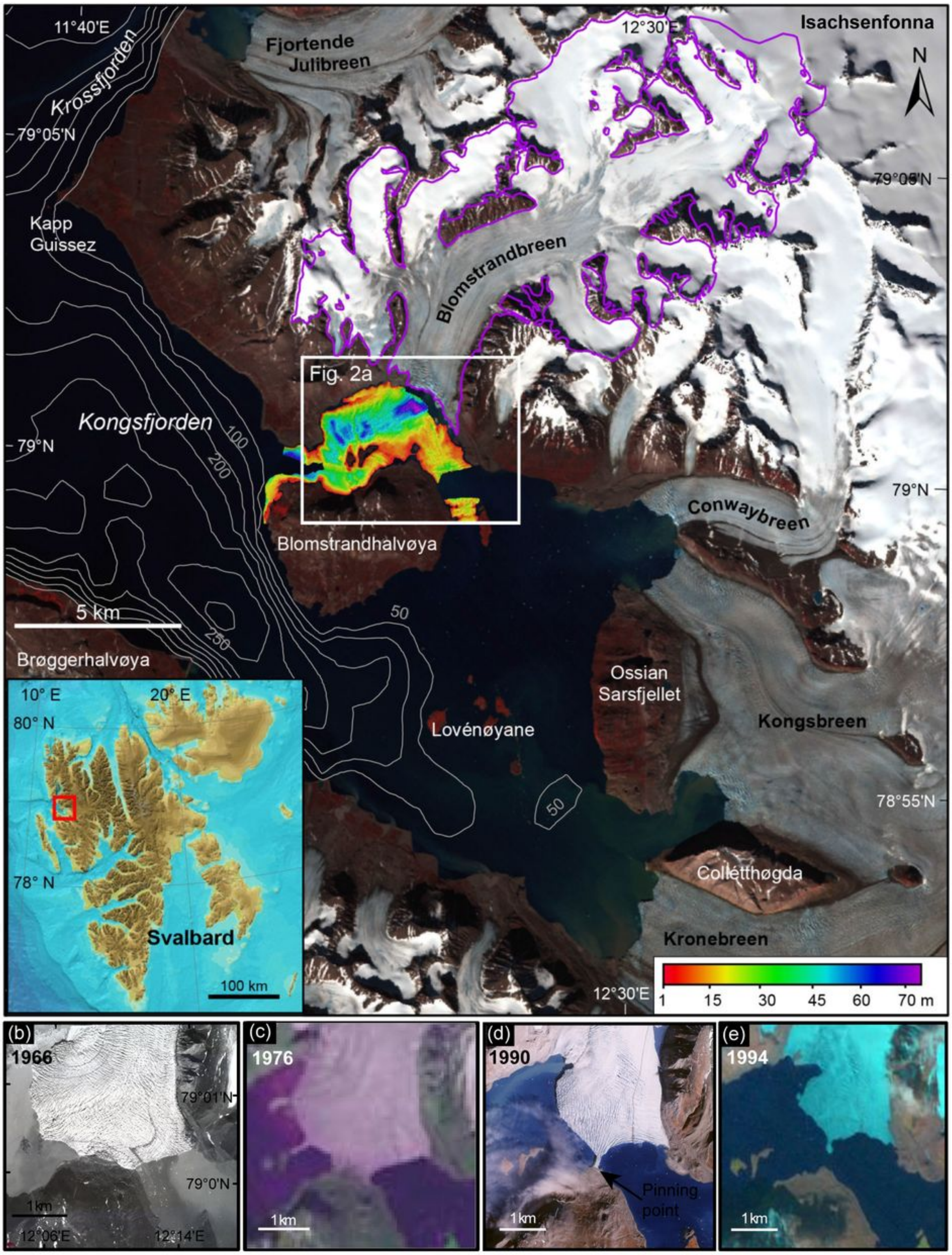

Figure 1. Burton

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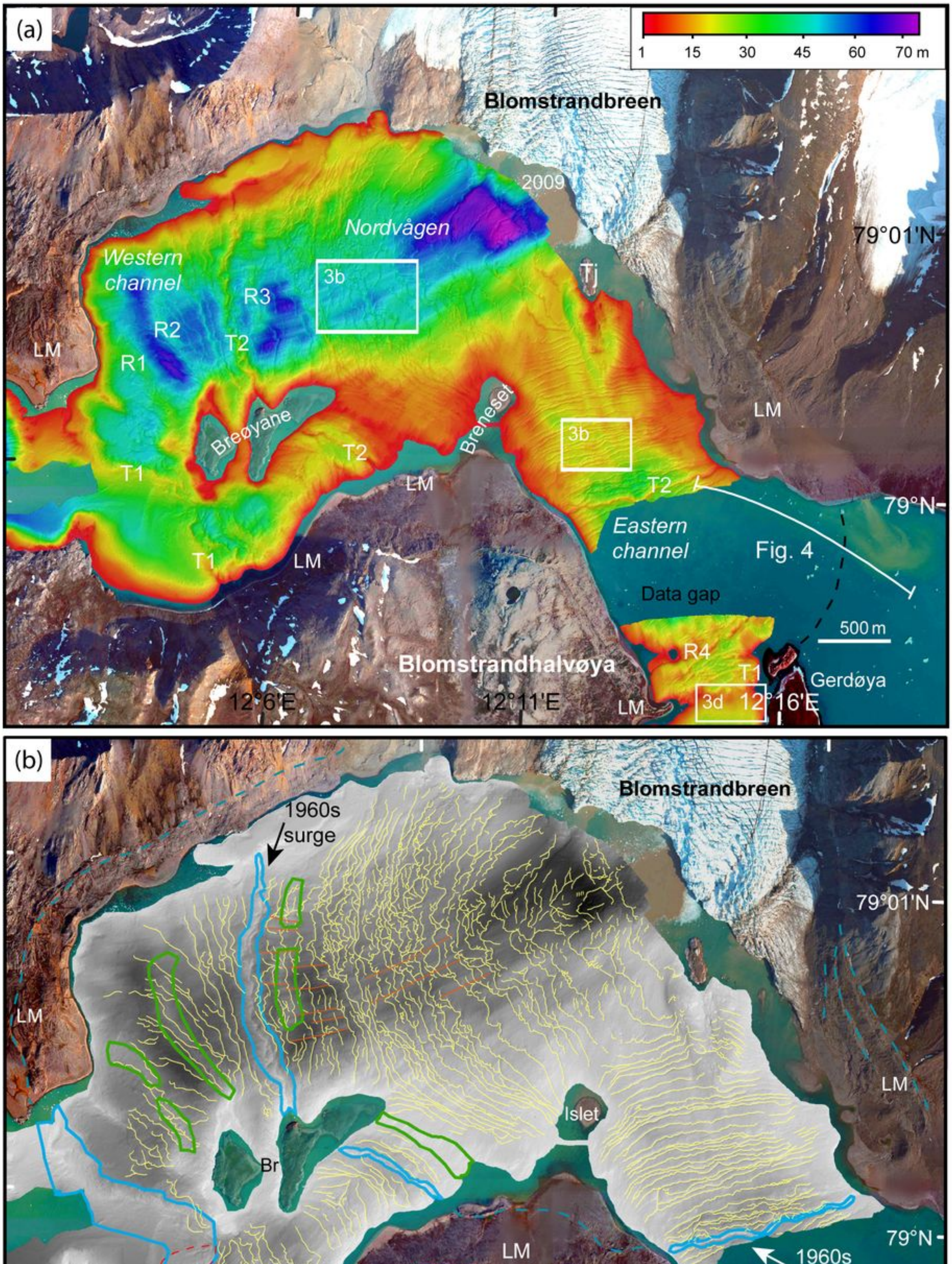

Figure 2. Burton

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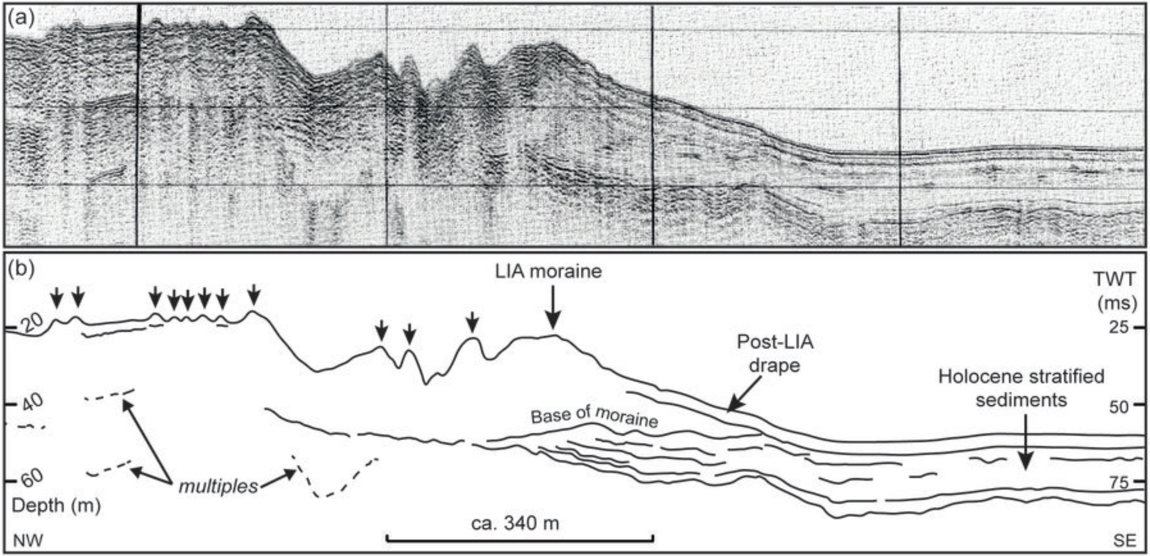

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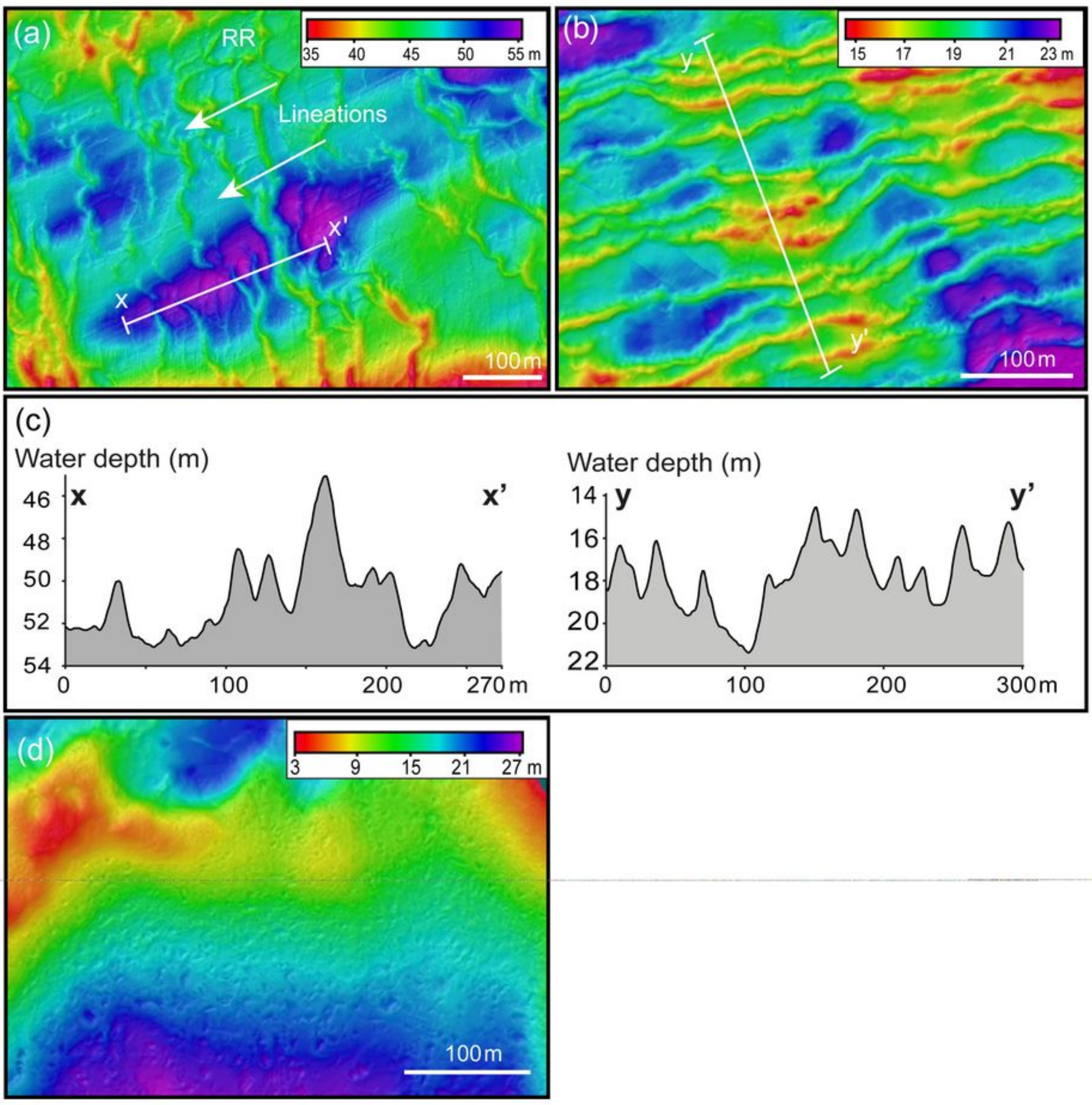

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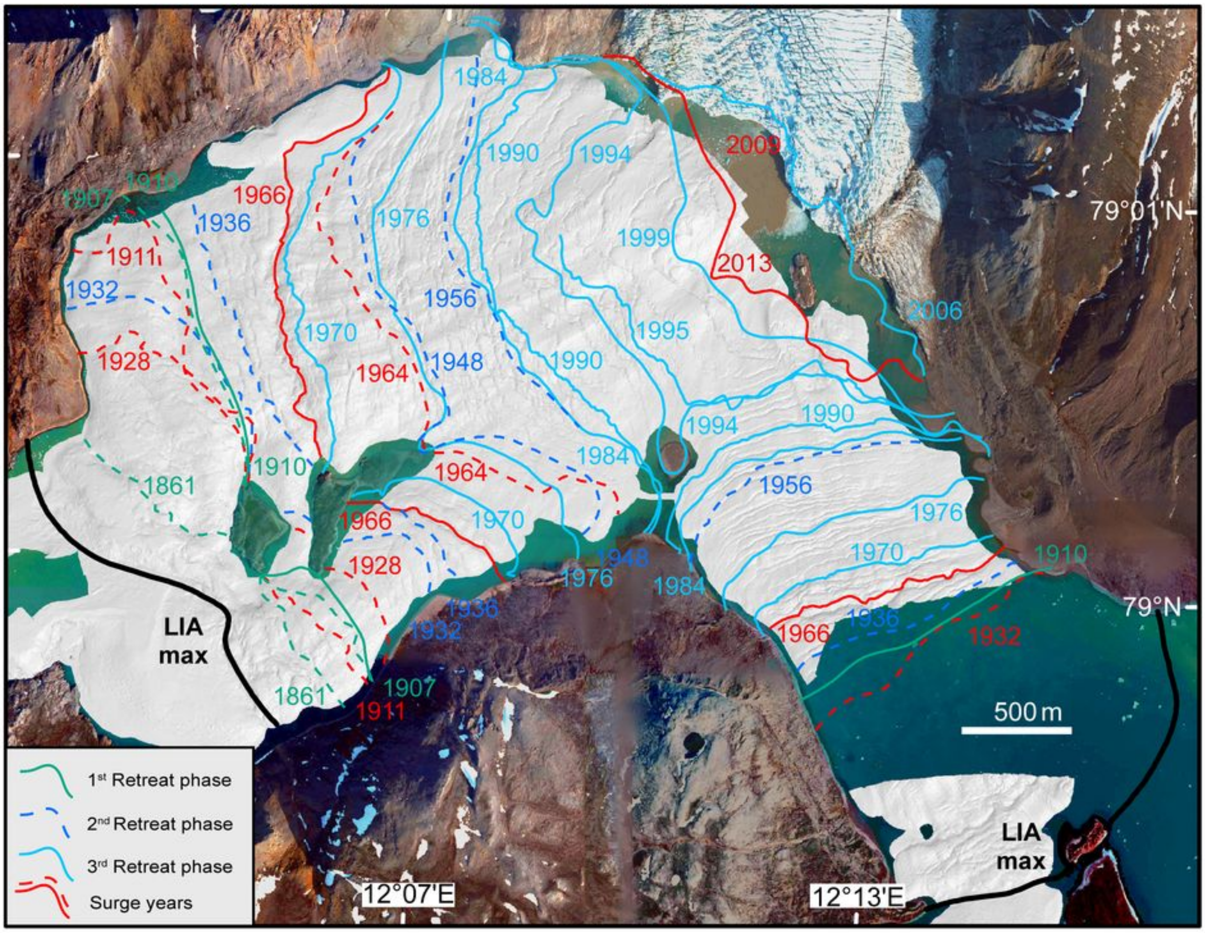

Figure 5. Burton

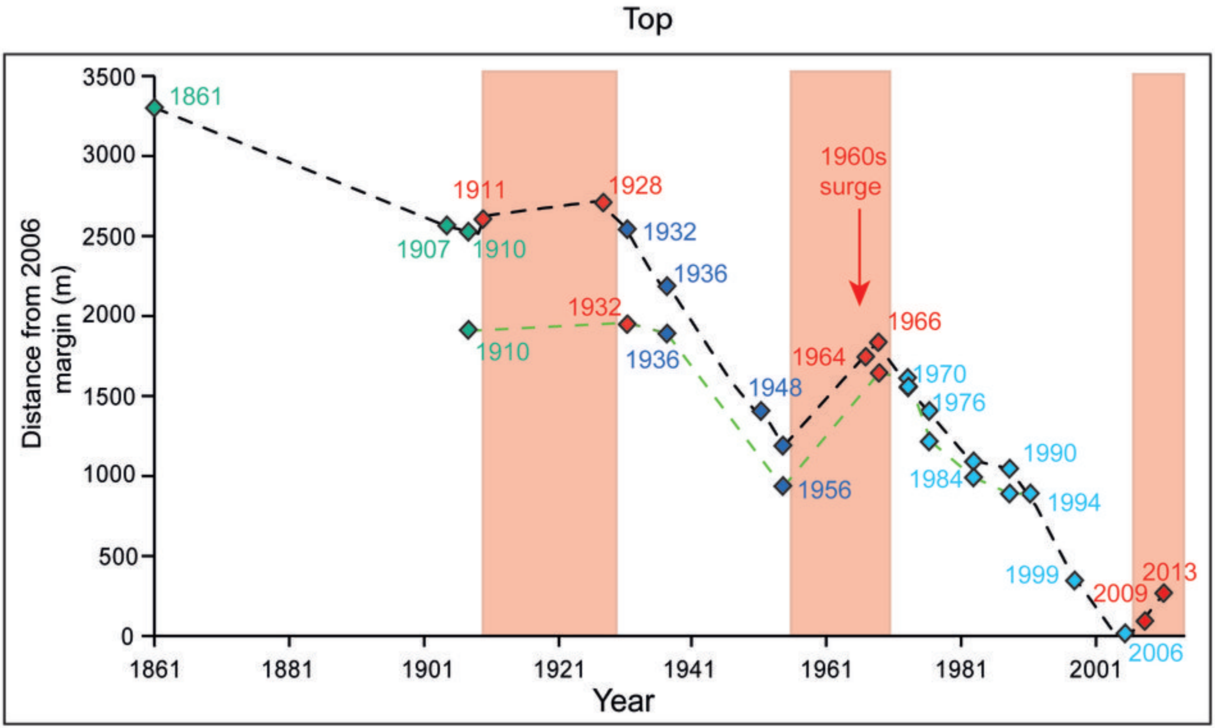

Figure 6. Burton

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