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Geomorphological investigation of multiphase glacitectonic composite ridge systems in Svalbard

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Abstract

Some surge-type glaciers on the High-Arctic archipelago of Svalbard have large glacitectonic composite ridge systems at their terrestrial margins. These have formed by rapid glacier advance into proglacial sediments during the active surge phase, creating multicrested moraine complexes. Such complexes can be formed during single surge advances or multiple surges to successively less-extensive positions. The few existing studies of composite ridge systems have relied on detailed information on internal structure and sedimentology to reconstruct their formation and links to surge processes. However, natural exposures of internal structure are commonly unavailable, and the creation of artificial exposures is often problematic in fragile Arctic environments. To compensate for these issues, we investigate the potential for reconstructing composite ridge system formation based on geomorphological evidence alone, focusing on clear morphostratigraphic relationships between ridges within the moraine complex and relict meltwater channels/outwash fans. Based on mapping at the margins of Finsterwalderbreen (in Van Keulenfjorden) and Grønfjordbreen (in Grønfjorden), we show that relict meltwater channels that breach outer parts of the composite ridge systems are in most cases truncated upstream within the ridge complex by an inner pushed ridge or ridges at their ice-proximal extents. Our interpretation of this relationship is that the entire composite ridge system is unlikely to have formed during the same glacier advance but is instead the product of multiple advances to successively less-extensive positions, whereby younger ridges are emplaced on the ice-proximal side of older ridges. This indicates that the Finsterwalderbreen composite ridge system has been formed by multiple separate advances, consistent with the cyclicity of surges. Being able to identify the frequency and magnitude of former surges is important as it provides insight into the past behaviour of surge-type glaciers and, if absolute dating is possible, allows for the assessment of surge-type glacier response to climate change on decadal to centennial timescales. Although further investigations into the internal structure of these deposits should be sought where possible, our study demonstrates that geomorphology could be an invaluable tool for reconstructing the formation of composite ridge systems.

Keywords: glacitectonic composite ridge system; glacier surge; glacial geomorphology; Svalbard

1. Introduction

Glacitectonic composite ridge systems, also termed push moraine complexes, are large (up to 50 m high), multicrested glacial deposits found in latero-frontal positions at the terrestrial margins of 50 glaciers in Svalbard (Fig. 1; Lovell and Boston, 2017). Many of these glaciers are known to have surged, experiencing cyclical phases of rapid ice flow punctuating extended periods of relative inactivity (Croot, 1988a; Hagen et al., 1993). Composite ridge system formation typically is explained by rapid glacier advance into proglacial sediments that are pushed or stacked into a series of ridges at the glacier margin as stresses are transmitted longitudinally through the forefield (Hagen, 1988; Aber et al., 1989; Etzelmüller et al., 1996; Hart and Watts, 1997; Boulton et al., 1999; Bennett, 2001). The observation that composite ridge systems are often coincident with known surge-type glaciers in Svalbard has led to the suggestion that large composite ridge systems are genetically linked to surge activity (Croot, 1988a; Evans and Rea, 1999). This is supported by observations from the margins of surge-type glaciers in other regions, such as Iceland (e.g., Sharp, 1985; Croot, 1987, 1988b; Andrzejewski, 2002; Bennett et al., 2004; Benediktsson et al., 2008, 2009, 2010, 2015; Schomacker et al., 2014; Ingólfsson et al., 2016) and West Greenland (e.g., Yde et al., 2005; Roberts et al., 2009; Larsen et al., 2010). Such observations also lend support to interpretations that glacitectonised moraine sequences in palaeo settings are related to ice streaming and surge-like activity at the margins of former ice sheets (e.g., Clayton et al., 1985; Evans and Rea, 1999; Evans et al., 1999, 2008; Hart, 1999; Benn and Clapperton, 2000; Kehew et al., 2005; Lovell et al., 2012; Darvill et al., 2017; Gribenski et al., 2016).

The link with surging is strengthened if it can be demonstrated that the formation of composite ridge systems records evidence diagnostic of surge activity, namely (i) rapid glacier advance and (ii) cyclical advances. The internal sedimentological and structural architecture of composite ridge systems provides a key insight into their formation and allows direct links to be made to surge processes (e.g., Hart and Watts, 1997; Boulton et al., 1999; Benediktsson et al., 2008, 2009, 2010, 2015; Kristensen et al., 2009a). These studies have typically made use of natural exposures, often cut by meltwater channels, to significantly advance our understanding of the glacitectonic formation of composite ridge systems caused by rapid terminus advance during surges. This includes (i) spatial variations in deformation styles related to structural evolution during the surge, submarginal and proglacial components of the complex, and sediment composition of the pre-surge foreland (Boulton et al., 1999; Benediktsson et al., 2008, 2009, 2010, 2015); (ii) timing and duration of composite ridge system formation (Benediktsson, 2008, 2010); (iii) glacier-foreland coupling (Benediktsson et al., 2010, 2015); (iv) longitudinal shortening and deformation of pre-surge foreland sediments and the depth of basal detachment planes (Boulton et al., 1999; Benediktsson et al., 2010, 2015); and (v) release of over-pressurised water in front of the advancing margin (Benediktsson et al., 2008, 2010). However, extensive natural exposures through composite ridge systems are not always available or accessible. Alternative approaches to studying composite ridge system formation include using geophysical techniques to interpret internal structure (Bennett et al., 2004; Kristensen et al., 2009a,b; Benediktsson et al., 2010) and lichenometry to determine the relative age of different sections of a composite ridge system (Hart and Watts, 1997). In the latter example, Hart and Watts (1997) demonstrated that, despite the limited availability of internal exposures, four separate zones could be identified within the Finsterwalderbreen composite ridge system in Svalbard based on lichenometry. These zones were equated to four separate successively less-extensive, ridge-building advances consistent with cyclical surges.

A further alternative approach that is yet to be investigated fully is the geomorphology of composite ridge systems. It has been demonstrated that different phases of the surge cycle can be identified from the geomorphological record based on reconstructing former ice-contact faces and therefore ice front positions (Lønne, 2016). Large multicrested composite ridge systems can form during a single surge advance caused by longitudinal transmission of stresses in front of the rapidly advancing margin (e.g., Croot, 1987, 1988b; Hagen, 1988; Boulton et al., 1999; Benediktsson et al., 2010), or they could form from several ridge-building advances to successively less-extensive positions (e.g., Hart and Watts, 1997; Lønne, 2016). Lønne (2016) used detailed geomorphological mapping from aerial photographs to identify the termination of the surge active phase(s) as recorded within the proglacial geomorphology. This was chiefly achieved by differentiating between proglacial moraines (formed in front of an advancing margin) and supraglacial moraines (formed as ice recedes from a maximum position) and by identifying the relationship between meltwater channels and these different parts of the moraine system.

In our study, we build on these previous geomorphological investigations by specifically focusing on composite ridge systems and the potential for exploring their formation based on geomorphological relationships. We identify relict meltwater channels/outwash fans that breach/cut through outer parts of the ridge complexes, but are truncated by an inner ridge or ridges at a position we term the buried fan apex (BFA; Fig. 2). Relict meltwater channels/outwash fans with BFAs are inferred to be younger than, or contemporaneous with, the ridges they breach but older than the truncating ridges. This relationship provides a method for differentiating phases of ridge formation. We investigate the application of this method by assessing the formation of two composite ridge systems in Svalbard based on the crosscutting relationships of meltwater channels and ridges.

2. Svalbard glacier surges and composite ridge systems

Approximately 60% of the land surface on the High-Arctic archipelago of Svalbard is covered by glacier ice (Fig. 1) and a significant proportion of the glaciers have exhibited surge-type behaviour (Hagen et al., 1993; Jiskoot et al., 2000; Sevestre and Benn, 2015; Farnsworth et al., 2016). Surge-type glaciers in Svalbard typically have extended quiescent periods of between ~40 and 150 years during which flow is below balance velocity, allowing mass to accumulate in an upper reservoir area (Dowdeswell et al., 1991; Hagen et al., 1993). This is punctuated by short active phases (~3-10 years) when flow velocities can increase by about 10-1000 times to typical rates of between 0.1 to 16 m d^{-1} (Liestøl, 1969; Dowdeswell et al., 1991). During the active phase the accumulated mass is rapidly transferred downglacier to the glacier front (Murray et al., 2003; Sund et al., 2014). In most cases the terminus advances, with typical total distances of the advance ranging between 0.2 and 20 km (Hagen et al., 1993; Sund, 2006). In terrestrial settings, this can result in the formation of large composite ridge systems, which are distributed widely across Svalbard (Fig. 1; Gripp, 1929; Croot, 1988a; van der Meer, 2004; Lovell and Boston, 2017). The morphology of composite ridge systems in Svalbard ranges from large (~2 km wide, defined as distance from ice-distal to ice-proximal flanks, and 4 km long, defined as distance between lateral extents) complexes with multiple (up to 50) individual ridge crests (e.g., Holmströmbreen; Boulton et al., 1999) to smaller complexes (~200 m wide, ~700 m long) with only 3-4 identifiable ridge crests. The internal composition of the few composite ridge systems investigated includes glacimarine muds at the terrestrial margins of tidewater glaciers (e.g., Boulton et al., 1996; Kristensen et al., 2009a,b), glacilacustrine sediments and outwash sands and gravels (e.g., Hambrey and Huddart, 1995; Hart and Watts, 1997; Kristensen et al., 2009a), subglacial till (e.g., Hambrey and Huddart, 1995), and a combination of the above (e.g., Boulton et al., 1999). Evidence for glacitectonic deformation is common, typically in the form of large-scale folds, thrust faults (e.g., Hart and Watts, 1997; Boulton et al., 1999; Kristensen et al., 2009a) and stacked units (e.g., Hambrey and Huddart, 1995).

This study focuses on two composite ridge systems located at the margins of Finsterwalderbreen (77°31'N, 15°19'E) on the southern side of Van Keulenfjorden and at Grønfjordbreen (77°57'N, 14°19'E) in Grønfjorden (Fig. 1). Finsterwalderbreen is a surge-type glacier, with a last recorded surge during the Little Ice Age (LIA) maximum sometime between 1898 and 1910 (Liestøl, 1969; Nuttall et al., 1997; Nuttall and Hodgkins, 2005). Grønfjordbreen has not been observed to surge, but Croot (1988a) suggested that the western flow unit, Vestre Grønfjordbreen, may have previously surged based on the lobate nature of the medial moraine separating it from Austre Grønfjordbreen. Oblique aerial photographs from 1936 provided by the Norwegian Polar Institute (available at toposvalbard.npolar.no) show that Finsterwalderbreen and Grønfjordbreen were close to the ice-proximal flanks of their composite ridge systems at this time (Fig. 3), from where they have both since receded ~2.5 km.

3. Methods

Geomorphological mapping at Finsterwalderbreen and Grønfjordbreen was conducted in the field and from 1:15,000 scale aerial photographs. Additionally, a LiDAR-derived 1-m digital elevation model (DEM) was used to map Grønfjordbreen. The aerial photographs (2004) and the LiDAR data (2005) were collected by the UK Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) and acquired from the NERC Earth Observation Data Centre. Mapping from the remote sensing data and in the field focused on identifying BFAs (Fig. 2) by investigating the relationship between ridges and relict meltwater channels/outwash fans within the complex. Additional information on ridge morphology and surface characteristics across the complexes from an ice-distal to ice-proximal position was also recorded in the field. Ridge morphology was assessed qualitatively based on the roundness, symmetry, and degree of surface consolidation and stability (e.g., presence and abundance of surface tension cracks, flow scars and subaerial sediment flows). Surface tension cracks indicate collapse of the moraine surface as a result of internal instabilities, such as the degradation of buried ice (e.g., Lukas et al., 2005). Flow scars and subaerial sediment flows within moraine ridges are also indicative of internal instabilities (e.g., Lawson, 1982; Lukas et al., 2005; Schomacker, 2008; Schomacker and Kjær, 2008), often related to melting of buried ice in association with meltwater eroding and destabilising moraine slopes (e.g., Etzelmüller et al., 1996). Surface sediment composition (e.g., grain sizes, degree of sorting) and vegetation/soil cover (e.g., distribution of vegetation cover, types of vegetation observed, soil thickness and distribution) were recorded to provide insight into any apparent differences in the formational processes and/or relative age of ridges across the complex.

4. Composite ridge system geomorphology

4.1. Finsterwalderbreen

The Finsterwalderbreen foreland (Fig. 4A) can be divided into two zones: an outer zone consisting of the composite ridge system (Fig. 5) and an inner zone of hummocky topography, outwash deposits and numerous dead-ice hollows (often containing meltwater ponds). Several outwash fans also extend beyond the ice-distal margins of the composite ridge system, documenting contemporary and relict drainage into Van Keulenfjorden (Figs. 5E and 5F). The latero-frontal composite ridge system covers an area of ~1.5 km^2 and has a maximum height of up to 50 m above the fjord. The complex contains multiple individual ridges separated by linear depressions, typically ranging from ~1 to 10 m in height (i.e., ridge base to ridge crest). The width of the composite ridge system reaches a maximum of ~700 m in the northwest of the complex but is typically 250-300 m, and the number of identifiable individual ridge crests ranges from 4 to 17. The morphology, surface consolidation, surface sediment composition, and vegetation characteristics vary across the complex (Table 1). In the outermost (ice-distal) zone (I in Table 1 and Fig. 6A), individual ridges are rounded, symmetrical, and have a surface composed predominantly of sorted, rounded gravels and occasional large boulders. No surface tension cracks, flow scars or subaerial sediment flows were observed, and large areas of complete vegetation cover and thin soils occur, principally in the depressions between ridges. A transition is observed to a second zone (II in Table 1 and Fig. 6A) consisting of rounded ridge crests with occasional evidence for small flow scars and subaerial sediment flows, a surface composition of sorted gravel and some diamict, with frequent large boulders, and patchy soil and vegetation cover. Moving toward the ice-proximal part of the complex, the ridges become sharper and more asymmetric (typically with a steeper distal slope). Surface tension cracks, flow scars and subaerial sediment flows are more frequently observed. The range in sediment grain sizes on the surfaces of ridges increases (Figs. 5A-C), including coarse gravel, sand, diamict, and frequent large boulders. Vegetation cover is characterised by isolated plants and very thin soil cover (zone III in Table 1 and Fig. 6A). The innermost zone of ridges (IV in Table 1 and Fig. 6A) contains sharp-crested, asymmetric ridges with abundant flow scars and subaerial sediment flows. The ridges in zone IV are composed of coarse gravel, sand, mud, diamict, and frequent large boulders, with very few isolated plants and no identifiable soil cover.

At several places within the Finsterwalderbreen composite ridge system, relict meltwater channels and associated outwash fans emerge from the complex but cannot be traced through to the inner zone of the foreland (Fig. 6A). Several of the relict meltwater channels form narrow gorges through the composite ridge system and contain concentrations of coarse gravel and edge-rounded boulders, with no modern meltwater drainage routed along them (Figs. 5A-D). The channels feed several large relict outwash fans that extend beyond the distal margin of the complex (Figs. 5A and 5D-F). The relict outwash fans are characterised by low gradient surfaces of coarse gravel and display varying degrees of vegetation cover, suggesting a possible variation in length of inactivity. Within the ridge complex, the channels/fans are all truncated by an inner (e.g., located in an ice-proximal position) continuous ridge (Figs. 5A-D), forming BFAs (e.g., Fig. 2). The BFAs are all associated with evidence of material avalanching off the front of the truncating ridge, burying or infilling the channel/fan apices (Fig. 5C).

4.2. Grønfjordbreen

The Grønfjordbreen foreland comprises a frontal composite ridge system covering an area of ~0.8 km^2 and a large lagoon, Bretjørna, which separates the complex from the present-day glacier front (Fig. 4B). The composite ridge system consists of multiple rounded ridges with a maximum height of ~45-50 m above the fjord, with up to 12 individual symmetrical ridge crests identifiable across the widest (~500 m) part of the complex. The outer (ice-distal) part of the complex displays a surface sediment cover of sorted rounded gravels, whilst the inner (ice-proximal) ridges contain a larger proportion of coarse clasts and large boulders on the surface. The boundary between the two zones is very sharp (Figs. 6B, 7A, and 7B). The inner ridges transition into a narrow, lower-relief zone of poorly consolidated hummocky terrain that separates the composite ridge system from Bretjørna. The zone of hummocky terrain contains subaerial sediment flows, small meltwater ponds, and poorly sorted sediments. At the western end of the composite ridge system, the active meltwater channel has exposed the internal composition and structure of the outer ridges, revealing a ~25-30 m thick sequence of deformed sands (Fig. 7C).

Several relict meltwater channels cut through the outer part of the Grønfjordbreen composite ridge system and join relict outwash fans extending to the fjord (Fig. 5B). The channels form deep (~20 m) gorges, and in several cases two or three individual channels coalesce within the complex before exiting as a single channel (e.g., Fig. 8B). Most of these channels cannot be traced all the way through to the hummocky terrain of the inner foreland but are truncated at their ice-proximal extents by ridges within the composite ridge system, forming BFAs (Figs. 5B and 8B).

5. Composite ridge system formation

5.1. Interpretation

The observations of relict meltwater channels/outwash fans that are truncated within the moraine complexes, forming BFAs, can be examined in the context of composite ridge system formation. Two models are considered: formation of the entire complex during a single episode of glacier advance (Fig.8A); or formation of the complex during multiple separate episodes of glacier advance to successively less-extensive positions, whereby younger ridges are emplaced on the ice-proximal side of older parts of the complex (Fig. 8B).

5.1.1. Single advance model

Two possible explanations for the formation of BFAs are consistent with processes of formation during a single episode of rapid ice advance (Fig. 8A): (1) channel abandonment and truncation during the advance caused by (a) seasonal reorganisation of meltwater drainage routes (e.g., Boulton et al., 1999; Lønne, 2016) and/or (b) different phases and styles of glacitectonic deformation (e.g., Boulton et al., 1999; Benediktsson et al., 2010); and (2) channels developing from blowouts of overpressurised water within the moraine complex (e.g., Benediktsson et al., 2008, 2010).

(1a) Glacier surges in Svalbard typically last for at least three years (Dowdeswell et al., 1991; Murray et al., 2003), therefore spanning multiple summer/winter cycles and the associated changes in discharge. The relict meltwater channels within the composite ridge system could therefore represent re-routing of proglacial drainage over several summer/winter seasons (e.g., Lønne, 2016), whereby channels dry up as drainage shuts down in late autumn but are not reoccupied during the subsequent melt season. It is also possible that previously abandoned channels become reoccupied during a later stage of the advance and/or, in the case of those channels that cut through the entire complex, following surge termination (Boulton et al., 1999). (1b) Channels that are truncated within the composite ridge system (e.g., Figs. 5A, 5D, and 7B) could also represent drainage routes that were active during an early stage of composite ridge system formation (e.g., syntectonic drainage, cf. Boulton et al., 1999). The formation of new ridges during a later tectonic phase could lead to channel truncation caused by folding/faulting within the moraine complex, and thus channel abandonment at the BFA. It is also possible that channels abandoned because of drainage reorganisation (1a) could then be truncated owing to deformation during a later stage of composite ridge system formation (1b).

(2) Composite ridge system formation caused by glacitectonic deformation of the foreland is facilitated by, among other controlling factors (e.g., foreland sediment distribution, thickness, grain size, and frozen/unfrozen state), high porewater pressures within foreland sediments (Boulton et al., 1999; Benediktsson et al., 2010). If porewater pressures become too high during the surge, it can cause abrupt blowouts in front of the advancing margin as water escapes upward along hydrofractures within the composite ridge system. Benediktsson et al. (2008, 2010) identified blowout depressions with channels emanating from them in front of and on the foreslope of composite ridge systems in Iceland. The BFAs within the Finsterwalderbreen and Grønfjordbreen complexes possibly formed in a similar manner during a single rapid advance.

Considering the observed variations in ridge morphology, surface sediment composition, degree of consolidation, and vegetation characteristics across the composite ridge systems is also necessary in the context of formation during a single rapid advance. Variations in ridge morphology (e.g., roundness and symmetry of crests) from an ice-distal to ice-proximal position could relate to different distal-proximal structural styles and deformation phases along a continuum (e.g., Benediktsson et al., 2010) across the composite ridge system. For example, at Finsterwalderbreen the outermost rounded ridges could be the surface expression of symmetric, anticlinal folds within the distal part of the moraine complex. The innermost sharp-crested asymmetric ridges could have developed as imbricate thrust slabs in a proximal position (e.g., Boulton et al., 1999; Benediktsson et al., 2010), perhaps reflecting the part of the complex that formed in a submarginal position (Benediktsson et al., 2010, 2015). Such changes in the style of deformation might also explain the observation that subaerial sediment flows within the moraine complex are more abundant in the proximal zone, as oversteepened asymmetrical ridges would be more prone to collapse. Observed variations in surface sediment composition and grain size and sorting (Table 1), from distal to proximal positions, could simply reflect the surface characteristics of the foreland into which Finsterwalderbreen advanced. The changes in ridge asymmetry (e.g., Fig. 7A; Table 1) are also consistent with these parts of the complex forming in a submarginal position (Benediktsson et al., 2010, 2015) and thus being differentiated from the rounded, symmetrical ridges with a surface composition of sorted sediments in the proglacial parts of the complex. The changes in vegetation and lichen size are less easy to explain within the single advance model, however, as they strongly suggest increasing surface age and soil maturity from ice-proximal to ice-distal parts of the complexes.

5.1.2. Multiple advance model

In the multiple advance model, the different zones of the ridge complexes formed at widely separated times. Meltwater channels (syn- and/or post-tectonic drainage) cut through the outer part of the moraine complex formed during a first advance and were truncated by a younger ridge formed during a second, separate advance (i.e., following a period of glacier recession) to a less-extensive position (Fig. 9B). The emplacement of the younger ridge truncates some existing drainage routes through the older ridges, creating BFAs and forcing meltwater to find alternative routes through the moraine complex. This model indicates that where meltwater channels cut through outer parts of the moraine complex, but are demonstrably truncated by inner ridges (e.g., Figs. 5A and 5D), the two parts of the complex are unlikely to have formed during the same advance (Fig. 8B).

A similar geomorphological approach was applied at a number of different surge-type glacier forelands in Svalbard by Lønne (2016) based on the recognition that channels within composite ridge systems identify meltwater runoff points at the glacier front. These runoff points mark the locations where the glacier was in contact with the ice-proximal side of the composite ridge system and therefore the maximum position of the glacier during the surge. We assume that whilst the glacier is in contact with the composite ridge system, the large channels that have cut deep gorges are occupied by meltwater. However, through several years of advance it can be expected that meltwater routes may reorganise and switch between occupation and inactivity on a seasonal basis. Once the surge advance has terminated and the glacier begins to recede from the composite ridge system, some of the large meltwater channels will likely become inactive. Based on a number of such forelands (e.g., Finsterwalderbreen, Grønfjordbreen, Penckbreen, Hessbreen, Abrahamsenbreen; this study and Lønne, 2016), as the glacier recedes meltwater begins to be dammed in the low-lying foreland, forming large lagoons or braided outwash surfaces. Meltwater drainage often occupies new routes around the lateral parts of the abandoned composite ridge system. Thus, meltwater channels cutting through composite ridge systems can become inactive upon frontal downwasting and recession — particularly where the composite ridge system effectively forms a reverse slope. During a subsequent surge advance to a successively less-extensive position, the foreland is bulldozed into a new ridge that forms a geomorphological barrier to these channels, truncating the drainage route (whether already inactive or not) and forming a BFA.

5.1.3. Discussion of single vs. multiple advance models based on composite ridge system geomorphology

The geomorphological evidence of BFAs where relict meltwater channels/outwash fan apices are truncated within composite ridge systems can be interpreted in the context of single and multiple advances. We suggest that the evidence at Finsterwalderbreen and, to a lesser extent, Grønfjordbreen is more consistent with the multiple advance model and consider the reasons for this here in relation to the origin of BFAs.

In the single advance model, BFAs could be formed by blowouts within the moraine complex ahead of an advancing glacier margin and/or the abandonment and incorporation of syntectonic drainage channels during a subsequent phase of deformation. The BFAs at Finsterwalderbreen and Grønfjordbreen are inconsistent with blowouts. The heads of the channels/fans are clearly truncated by depositional ridges, with evidence for avalanching from the frontal slope of the truncating ridge into the channel/fan (Fig. 4C), consistent with fall-sorting of material contained in the avalanche cones forming these blockages. Any blowout structures emerging from underneath existing ridges would exhibit very different features not observed at either site, such as retrogressive flow scars and subaerial sediment flows within the ridges and erosional depressions at their respective points of exit (e.g., Benediktsson et al., 2010). In addition, the deeply incised channels that emanate from the BFAs are inconsistent with a short-lived outburst event. The depositional nature of the truncating ridges implies they were emplaced onto the channel apices, either forcing channel abandonment or truncating an already inactive channel. This emplacement could be caused by a later (i.e., post-channel formation) phase of deformation within the composite ridge system as it is formed during a single advance, such as the development of folds or thrust faults at the channel apex or by a second separate advance following a period of frontal recession. Internal cross sections through the breached and truncating ridges would provide an important insight into whether this is a structural (e.g., fault) or stratigraphic (e.g., separate ridge) boundary. Based strictly on geomorphological relationships and variations in surface cover, we suggest that the BFAs are most likely created by the emplacement of a stratigraphically separate, younger ridge.

The BFAs at Finsterwalderbreen are located at various locations across the composite ridge system. In some cases (e.g., BFAs 3, 4, and 8; Fig. 9), the channel truncations are ~100-200 m from the proximal side of the composite ridge system. The simplest explanation for the channels is that they represent proglacial runoff points at the ice margin (cf. Lønne, 2016). Under the single advance model, these runoff points cannot have been located at the BFA, as the glacier margin did not reach these positions (or at least cannot have reached them all). Therefore, the single advance model requires these channels to have initially extended at least a further ~100-200 m into a complex that was actively deforming (characterised by shortening of the pre-foreland wedge) at this time, where they were fed by drainage from the advancing glacier front. Continued advance of the margin, characterised by further shortening of the pre-foreland wedge (and therefore narrowing of the complex), would then be required in order for the development of folding/faulting that causes channel truncation ~100-200 m beyond (i.e., distal to) the ice front (e.g., at the BFA). In addition, the channels emanating from BFAs typically are deeply incised into the ridges they cut through (e.g., Figs. 5A and 5B), and no evidence exists for ridge collapse or further truncation in distal positions along the channels. This implies that these outer ridges must have been fairly stable at the time when the channels were active, which is difficult to reconcile with a tectonically active composite ridge system within which folding and faulting can occur hundreds of metres from the glacier front, and whereby pushed ridges presumably reach their maximum height at the point of maximum shortening of the pre-foreland wedge (e.g., at the end of composite ridge system formation). Finally, it is difficult to envisage how large outwash fans, such as the one that extends ~500 m from BFA 1 through the outer parts of the complex (Figs. 5A and 9), can develop/be active during a period of advance, and then subsequently be truncated across the full width of the fan by the (presumably relatively rapid) development of an inset ~50-m-high ridge — all during the same period of advance.

In the Finsterwalderbreen examples, we suggest the simplest interpretation of the geomorphological evidence is that BFAs mark former runoff points at the ice margin. Following a period of frontal recession and foreland sediment accumulation, these run-off points have then been truncated by the formation of an inset, younger push ridge emplaced onto the proximal slope of preexisting ridges during a subsequent period of frontal advance. Therefore, in the absence of internal exposures that might provide further insight, we suggest (based on the geomorphological field evidence alone) that the BFAs demarcate the distal flanks of push ridges formed by subsequent ridge-building events. Although the observations at Grønfjordbreen are also consistent with the multiple-advance model, the BFAs could also represent a separate structural phase within the ice-marginal part of the moraine complex and thus be formed during a single advance. We suggest further investigation into the internal moraine structure would help to clarify this, in addition to dating ridges of different inferred ages using a method such as cosmogenic nuclide dating (e.g., Young et al., 2015).

Changes in vegetation characteristics across the ridge complexes, which at Finsterwalderbreen indicate different stages of a vegetation succession, are consistent with the ridges being of different ages and thus formed by multiple separate advances. This is further supported by lichenometric data collected by Hart and Watts (1997). Although it has been suggested that lichenometry perhaps should be treated cautiously as a numerical dating method (cf. Osborn et al., 2015), in this example it provides useful insight into the relative age of the ridges. Under the single advance model, the vegetation succession must have already been present on the foreland before the glacier advanced and was preserved during composite ridge system formation. Based on this, we suggest that the multiple advance model is thus also the most logical interpretation of the vegetation changes across the width of the Finsterwalderbreen composite ridge system.

5.2. Identifying multiple advances within composite ridge systems

Based on the multiple advance model, identifying BFAs that terminate within composite ridge systems (Fig. 6) provides an opportunity to disentangle the number of separate advances responsible for forming the entire complex. At Finsterwalderbreen and Grønfjordbreen, meltwater channels/outwash fans with a BFA breach outer parts of the ridge complex but are truncated by an inner ridge (Figs. 5A, 5D and 7B). However, at Finsterwalderbreen BFAs clearly are not all associated with the same individual ridge or part of the ridge complex. This provides a potential way to identify the number of separate ridges within the ridge complex and, therefore, according to the multiple advance hypothesis, the number of ridge-building events recorded within the complex. The explanation for this is as follows: meltwater channels/outwash fans extend varying distances into the moraine complex. In all cases, the channels/fans breach some parts of the complex, cutting through one or more individual ridge crests and are truncated by an inner ridge, creating a BFA where the ridge crests are complete or continuous (Fig. 9). If the ridge crests associated with individual BFAs are traced laterally across the ridge complex, however, the same ridge or set of ridges responsible for a BFA in one location clearly have been breached by a channel/fan in another part of the ridge complex.

This provides evidence that the ridges are unlikely to all be associated with the same ridge-building event. For example, if the semicontinuous ridge crests that truncate BFA 1 are traced in a northeasterly direction, they are clearly breached by the meltwater channel emanating from BFA 2 (Fig. 9); therefore, the ridge that truncates BFA 1 is not the same ridge that truncates BFA 2, indicating at least two separate ridge-building events. BFA 3 is farther to the east of BFA 2 and is truncated by a zone of ridges that, when traced westward, is clearly breached by the channel originating at BFA 2. The BFA 3 channel in turn cuts entirely through the outer parts of the composite ridge system, within which BFA 4 (to the east of BFA 3) is truncated. This indicates that the ridges truncating BFA 3 did not form at the same time as those truncating BFA 4. If this morphostratigraphic logic is applied methodically across the composite ridge system by tracing the relationships between the identified BFAs and ridge crests (Table 2), four separate zones can be identified, which in the multiple advance model (Fig. 8B) equates to four separate ridge-building events (Fig. 9). This is in agreement with Lønne's (2016) independent study of the Finsterwalderbreen composite ridge system, which determined four ice-contact systems based on remote mapping from aerial photographs of meltwater channels, pond distribution, and identified ridge crests within the complex. Our study complements and supports the Lønne (2016) interpretations by proving additional detailed insight into the geomorphological relationships of the truncated meltwater channels and composite ridge system ridges.

The multiple advance model requires the separate ridge zones to be of different ages. In the absence of numerical dating, the observations of ridge characteristics as relative age indicators at Finsterwalderbreen are consistent with this inference of four separate ridge-building events. First, the transition in ridge morphology from rounded, symmetrical ridges with little or no evidence of slope instabilities in the outermost ice-distal zone to sharp-crested, asymmetric ridges with frequent evidence for flow scars and subaerial sediment flows in the innermost ice-proximal zone may reflect the inferred variation in ages of ridges across the complex, whereby the outermost ridges are the oldest, most stable part of the complex and the innermost ridges are younger, fresher and more unstable. Second, the variations in surface sediment composition across the ridge zones, characterised by an increase in the range of grain sizes from sorted gravel in the outermost part to poorly sorted gravels, sands, muds, and diamict in the innermost part of the complex (Table 1), is consistent with a glacier first advancing into forelands dominated by outwash, forming the outer part of the complex, followed by a period of significant frontal recession during which sediment accumulated in different subenvironments on the foreland (e.g., supra-/subglacial material left behind by the receding glacier including large boulders, outwash gravels, glacilacustrine sediments and buried ice). This mix of material is then bulldozed into a new pushed ridge emplaced on the ice-proximal side of the existing complex during a subsequent advance, creating stratigraphically younger ridge zones composed of a wider range of grain sizes. This is also consistent with the sharp transition in surface sediment composition at Grønfjordbreen between the outer breached ridges (sorted gravel) and the inner truncating ridges (wider range of grain sizes and abundant large boulders; Fig. 7A), although the latter might also represent the submarginal part of the composite ridge system and, thus, separate structural phases during a single advance. Third, the inferred relative age difference of ridges at Finsterwalderbreen is also supported by the observed changes in vegetation and soil cover (Table 1). The transition across the four zones from areas of complete vegetation with patchy soils containing several types of plants through to the innermost ridges being devoid of soil cover and containing only occasional, isolated plants is consistent with several stages along a vegetation succession. This is further supported by lichenometric data collected by Hart and Watts (1997), who independently identified four separate zones within the Finsterwalderbreen composite ridge system based on variations in lichen size and the inferred relative age of ridge zones (Table 1), without reference to the geomorphological relationships we report.

The examples presented here suggest that the identification of multiple ridge-building advances recorded within composite ridge systems is possible. Key geomorphological indicators for this include (i) large, relict meltwater channels that cut through the outer parts of the composite ridge system and feed outwash fans but are truncated upstream within the complex, or cannot be traced through to the inner foreland; (ii) individual ridge crests within the complex that are coincident with the upstream truncation of the meltwater channels; and (iii) individual ridge crests identified in (ii) that can be traced across the entire complex to identify the number of separate former ice front positions and therefore zones within the complex that can be resolved. Differing ridge characteristics (such as morphology, surface sediment composition, soil cover, and vegetation characteristics across the identified separate ridge zones) may also provide an important indication of different relative ages. Further testing of this model through investigations of composite ridge system internal structure and numerical dating of ridges is important, as the more lines of evidence that converge, the more robust will be any such interpretation based on morphostratigraphy (cf. Lukas, 2006). The advantage of the geomorphological approach presented here is that it provides testable criteria for the targeted application of more sophisticated methods, such as selecting the location of a geophysical survey and designing a robust sampling framework for numerical dating (cf.

Lukas, 2006; Boston et al., 2015). In locations where the creation of selected exposures may be granted in protected areas, such working hypotheses are invaluable in the selection of sites for trial pits or trenches. Therefore, the approach presented here is a relatively simple, yet powerful and potentially highly effective geomorphological method for assessing whether composite ridge systems are the result of single or multiple advances.

6. Conclusion

Glacitectonic composite ridge systems are formed by rapid glacier advance into foreland sediments and in Svalbard are intrinsically linked to glacier surges (Croot, 1988a; Lovell and Boston, 2017). Multicrested complexes can be formed by a single rapid advance or by multiple advances to successively-less extensive positions (e.g., Boulton et al., 1999; Lønne, 2016). In this paper, we explore if identifying multiphase composite ridge systems is possible from geomorphology at Finsterwalderbreen and Grønfjordbreen. We analyse the genesis of relict meltwater channels that breach the outer part of the moraine complex and feed relict outwash fans, but are truncated upstream by a ridge or ridges within the complex. We suggest that this geomorphological relationship indicates that the breached and truncating parts of the ridge complex are unlikely to relate to the same glacier advance and therefore is indicative of multiple advances. One of the main advantages of this geomorphological approach is that it provides a hypothesis of composite ridge system formation that can be tested by the targeted application of complementary methods, such as information on internal structure based on sedimentology and geophysical investigation (e.g., Benediktsson et al., 2010) and by absolute dating of ridges inferred to be of different ages (e.g., Young et al., 2015).

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Table 1

Ridge characteristics across the four broad zones (I-IV from ice-distal to ice-proximal) identified within the Finsterwalderbreen composite ridge system (see Fig. 6A for approximate location of zones in the northwest part of the complex; *indicates lichenometric data from Hart and Watts, 1997).

Zone	Morphology	Surface sediment characteristics	Vegetation cover and lichenometric data	Frost-shattered lithologies
I	Rounded ridge crests; 3-8 m relative height; small solifluction lobes on surface; isolated small drained or infilled former meltwater ponds between ridge crests.	Sorted rounded gravels; occasional large (>0.5 m diameter) boulders; small-scale polygons and stripes on surface (periglacial sorting).	Large areas of complete cover; isolated plants; patchy humic and mineral soils (~2 cm-thick) focused in depressions; *Silene acaulis*, *Dryas Octopetala*, *Oxyria digyna*. Mean *Rhizocarpon geographicum* short axis = 49 mm*.	Shale, sandstone, limestone, quartzite, schist.
II	Rounded ridge crests; 5-10 m relative height; small solifluction lobes on surface; some flow scars and subaerial sediment flows; large meltwater ponds between ridges.	Sorted rounded gravels and some diamict; frequent large (>50 cm diameter) boulders; accumulations of larger (20-30 cm) clasts; some small-scale periglacial sorting phenomena.	Patchy cover; patchy, thin (~0.5 cm-thick) soils; *Silene acaulis*, *Dryas Octopetala*. Mean *Rhizocarpon geographicum* short axis = 31 mm*.	Shale, sandstone, limestone, quartzite.
III	Sharp-crested ridges; frequent evidence of flow scars and subaerial sediment flows; large meltwater ponds between ridges.	Coarse gravels, sand and diamict; frequent large boulders; weak periglacial sorting phenomena.	No complete areas; few isolated plants; patchy, thin (~0.5 cm-thick) soils; *Silene acaulis, Oxyria digyna*. Mean *Rhizocarpon geographicum* short axis = 25 mm*.	Shale, sandstone, limestone.
IV	Sharp-crested ridges; up to 15 m relative height; abundant flow scars and subaerial sediment flows; buried ice observed; frequent and abundant meltwater ponds of all sizes.	Poorly sorted gravels, sand, mud and diamict; frequent large boulders.	Very rare isolated plants; no soils. No lichens.	Shale, occasional sandstone.

Table 2

Buried fan apex (BFA) and ridge zone relationships within the Finsterwalderbreen composite ridge system (see Fig. 9 for BFA locations).

BFAs	Breaches	Truncated by
BFA 1	Ridges 1 and 2	Ridge 3
BFA 2	Ridges 1, 2 and 3	Ridge 4
BFA 3	Ridges 1 and 2	Ridge 3
BFA 4	Ridge 1	Ridge 2
BFA 5	Ridges 2 and 3	Ridge 4
BFA 6	Ridges 1, 2 and 3	Ridge 4
BFA 7	Ridges 1 and 2	Ridge 3
BFA 8	Ridges 1 and 2	Ridge 3

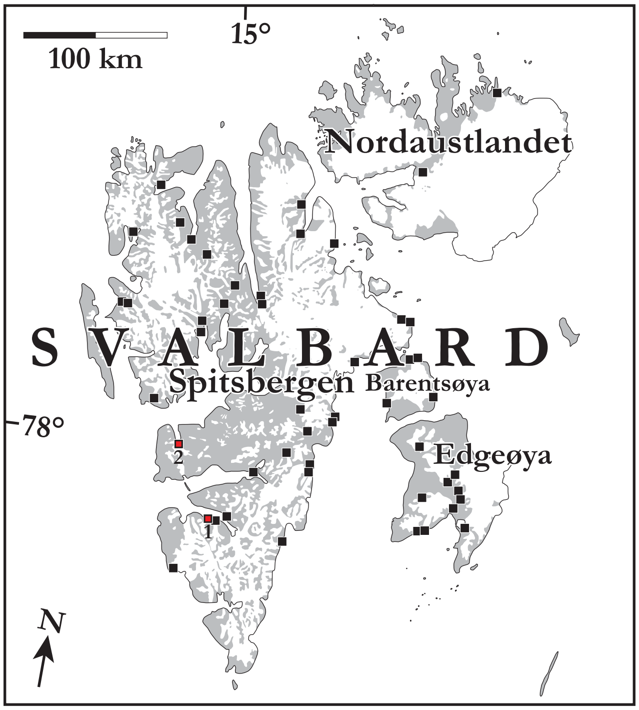

Fig. 1. Location map of Svalbard showing distribution of large composite ridge systems in Svalbard according to Lovell and Boston (2017). Red squares are the study glaciers Finsterwalderbreen (1) and Grønfjordbreen (2).

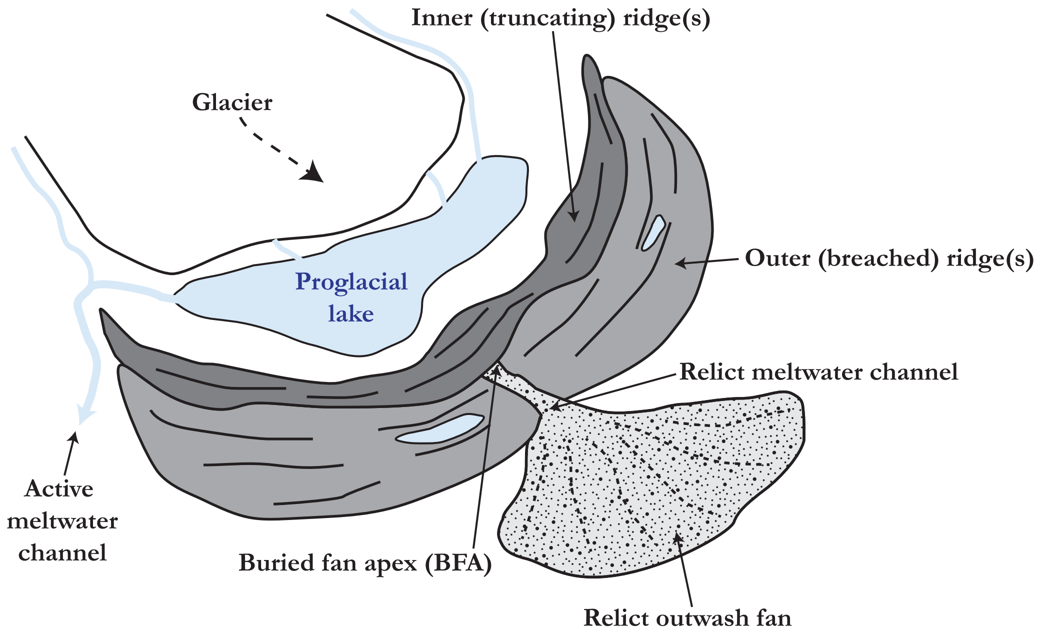

Fig. 2. Schematic illustration of a buried fan apex (BFA) located within a glacitectonic composite ridge system based on the crosscutting geomorphological relationship between relict meltwater channels/outwash fans and ridges within the moraine complex.

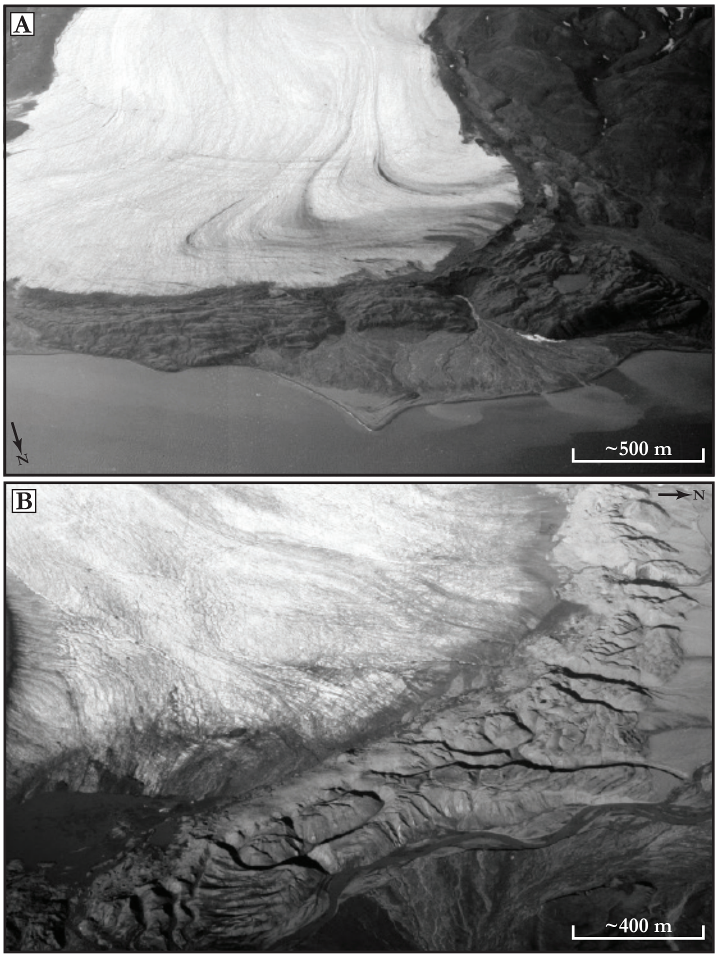

Fig. 3. Oblique aerial photographs from 1936 provided by the Norwegian Polar Institute of (A) Finsterwalderbreen and (B) Grønfjordbreen.

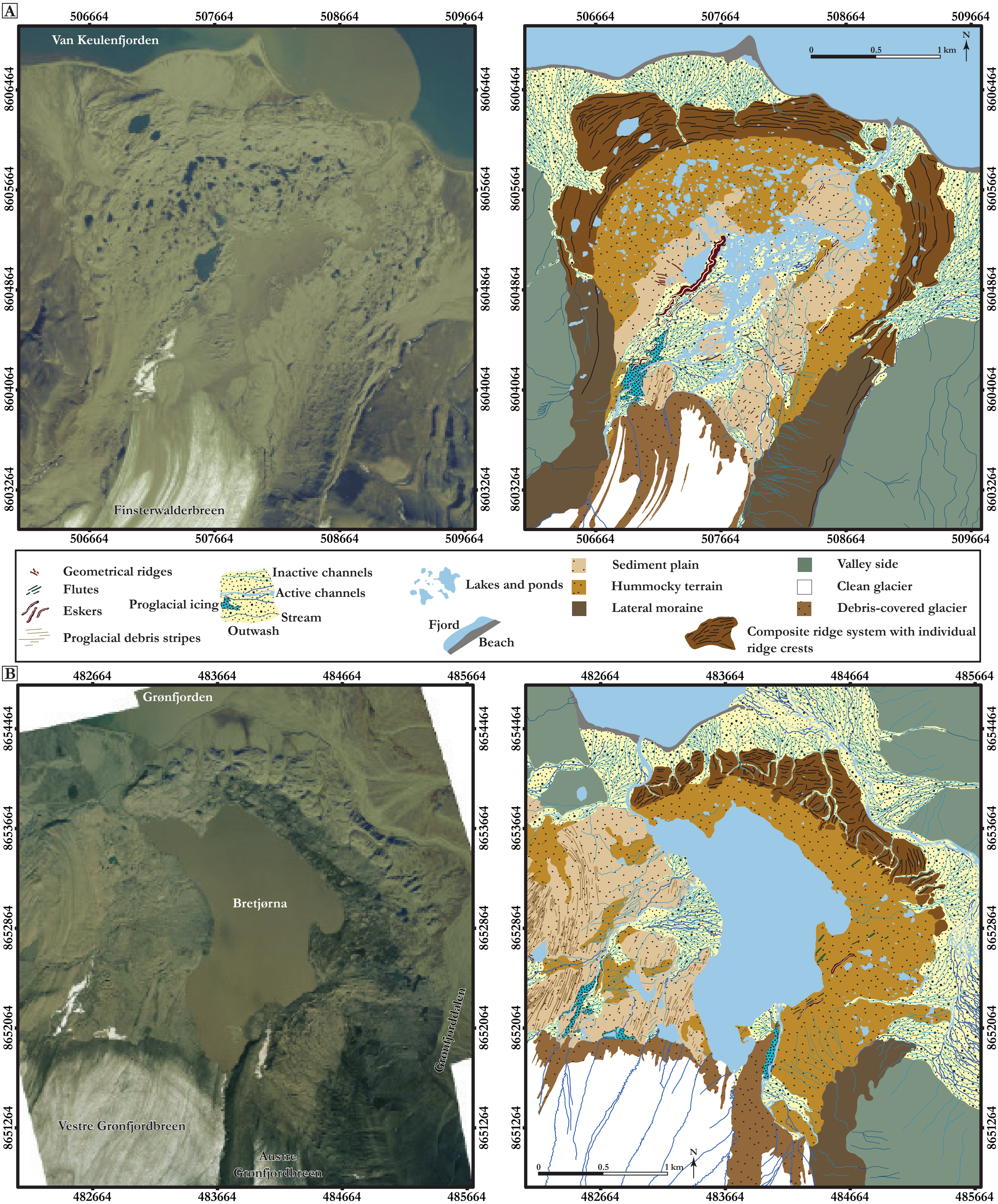

Fig. 4. Aerial photographs and geomorphological maps of (A) Finsterwalderbreen and (B) Grønfjordbreen.

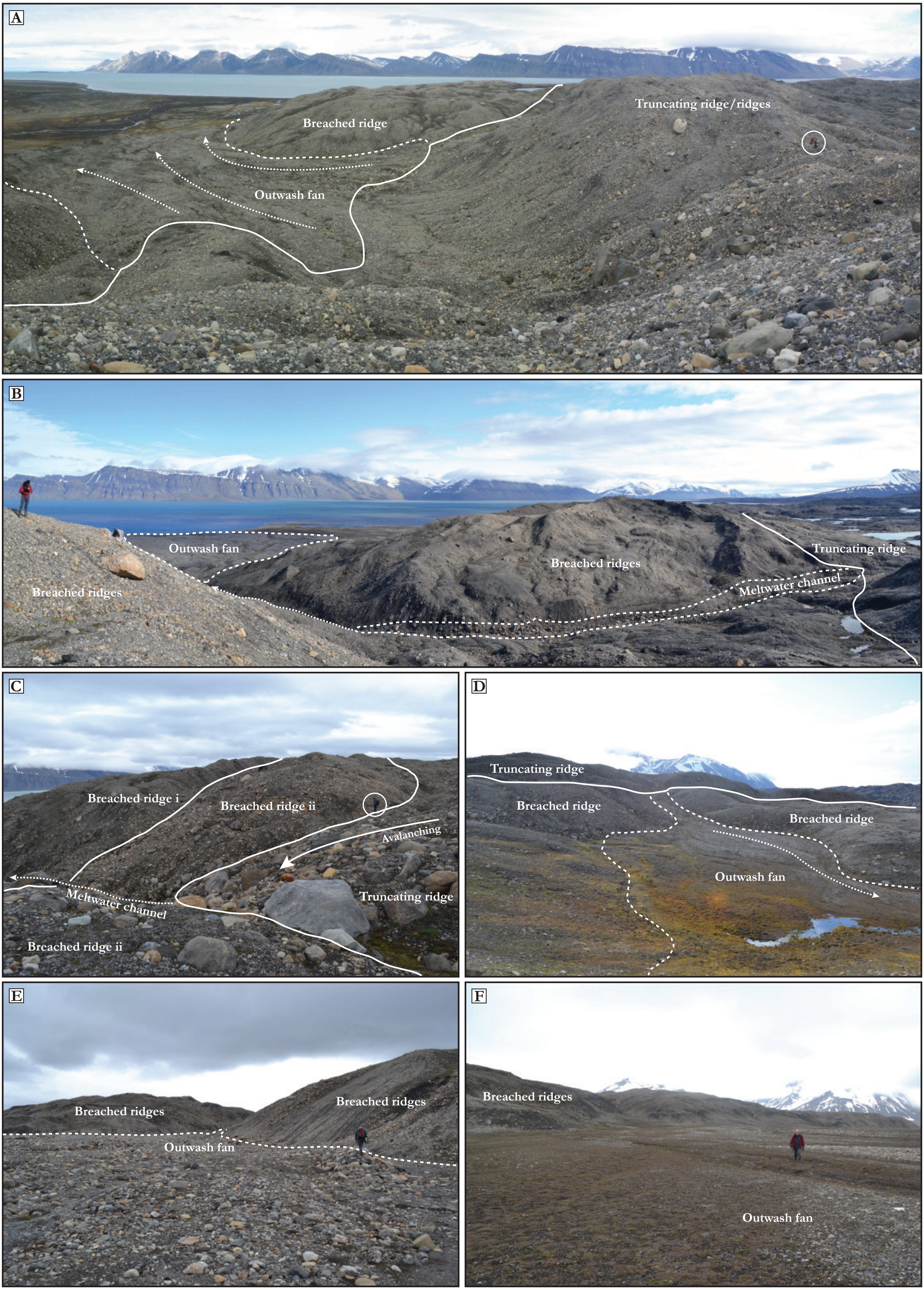
A
Breached ridge
Truncating ridge/ridges
Outwash fan
B
Outwash fan
Breached ridges
Truncating ridge
Meltwater channel
Breached ridges
C
Breached ridge i
Breached ridge ii
Avalanching
Meltwater channel
Truncating ridge
Breached ridge ii
D
Truncating ridge
Breached ridge
Breached ridge
Outwash fan
E
Breached ridges
Breached ridges
Outwash fan
F
Breached ridges
Outwash fan

Fig. 5

Fig. 5. Examples of the relationship between ridges and meltwater channels at Finsterwalderbreen. Solid lines delimit front of truncating ridges, dashed lines delimit meltwater channel/outwash fans, dotted lines show direction of drainage. (A) Outwash fan truncated by an inner ridge on western side of complex. People circled for scale. View direction is to the north. (B) Meltwater channel breaching outer ridge zones and truncated by innermost ridge zone on northern side of complex. View direction is to the east. (C) Meltwater channel breaching two outer ridge zones but truncated by an inner ridge zone on northern side of complex. Person circled for scale. View direction is to the east. (D) Outwash fan breaching outer ridge zone but truncated by an inner ridge zone on eastern side of complex. View direction is to the southwest. (E) and (F) Relict outwash fans on northern side of complex. Note difference in clast sizes and vegetation cover between (E) and (F). View direction in (E) is to the southeast and in (F) is to the southwest.

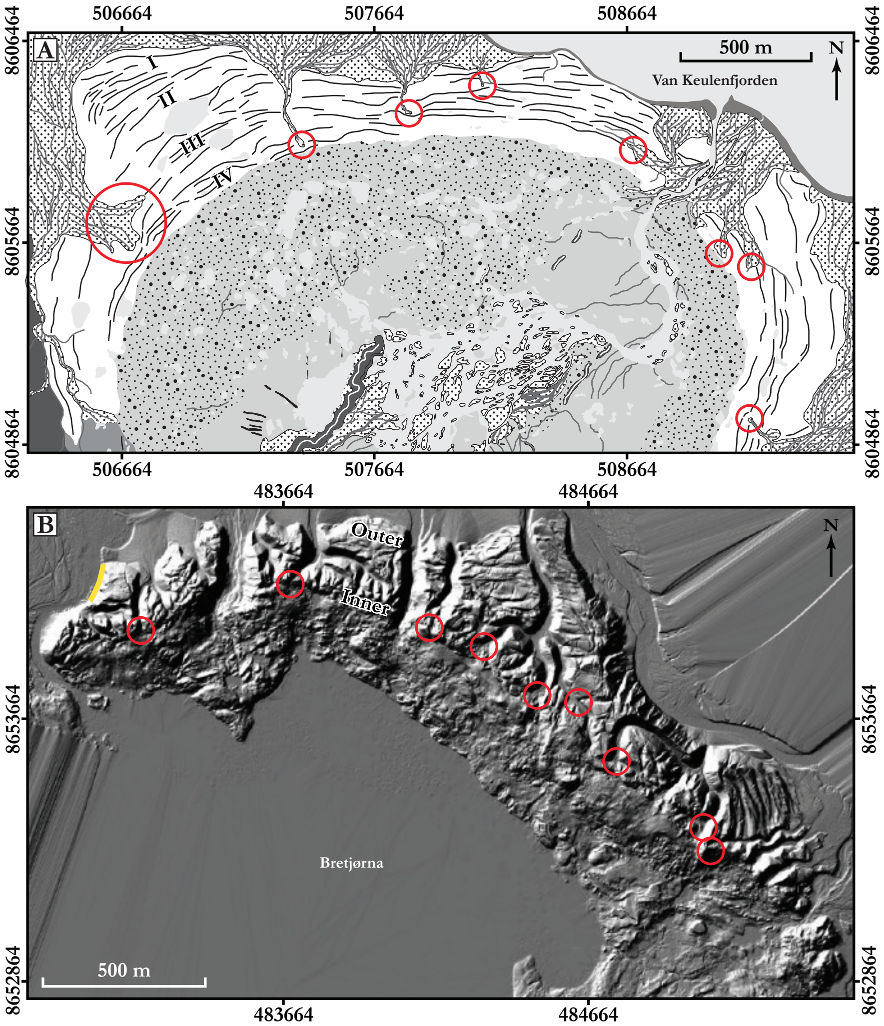

Fig. 6. Examples of channels that are truncated within the composite ridge systems (red circles) of (A) Finsterwalderbreen (annotated on an interpreted geomorphological map) and (B) Grønfjordbreen (annotated on a hill-shaded DEM). Zone I-IV labels in (A) refer to ridge zones in the text and in Table 1. Outer and inner labels in (B) refer to ridge zones in the text and in Fig. 7. Yellow line in (B) shows location of exposure in Fig. 7C.

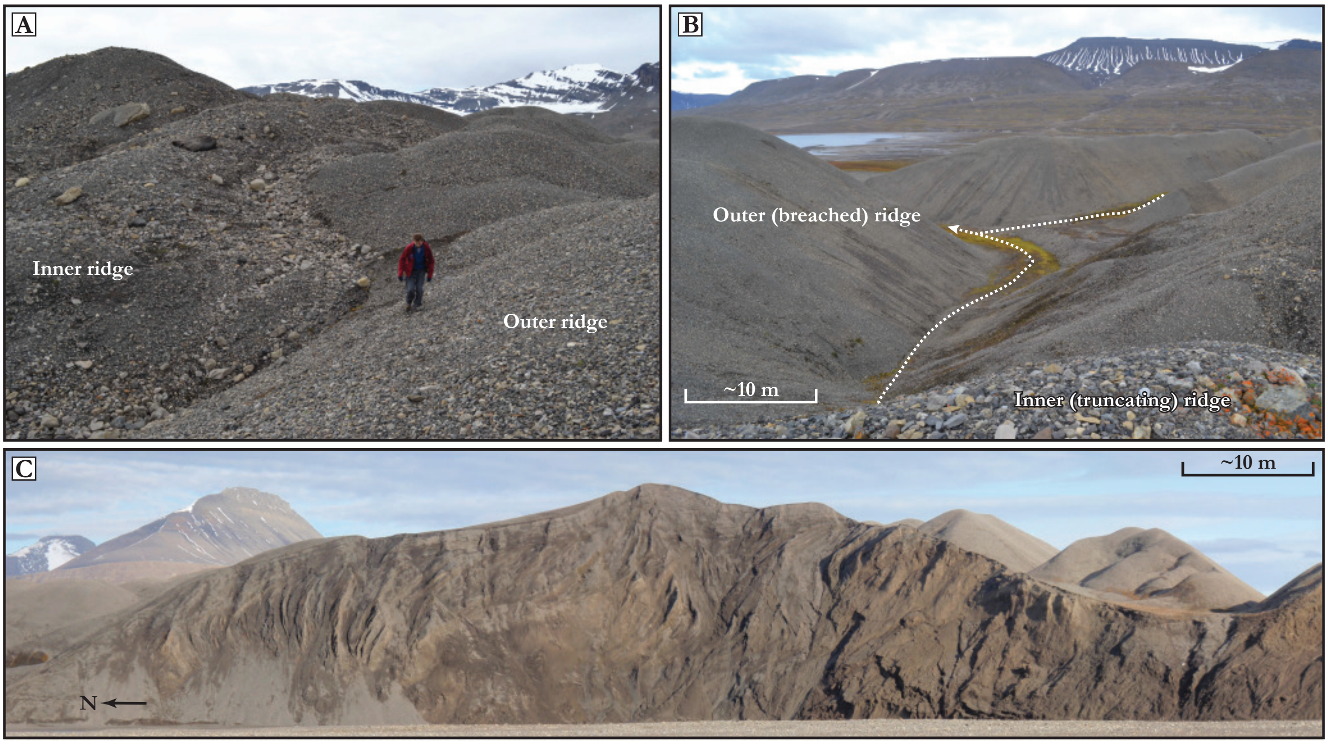

Fig. 7. Examples of the composite ridge system at Grønfjordbreen. (A) Boundary between inner ridge zones (left) and outer ridge zone (right). Note difference in surface sediment compositions. View direction is to the west. (B) Truncated channel (dotted arrow) through outer ridge zone viewed from inner (truncating) ridge. View direction is to the northeast. (C) Exposure of deformed sands in western side of composite ridge system outer zone cut by active meltwater channel. Photomosaic provided by Pierre-Marie Lefeuvre.

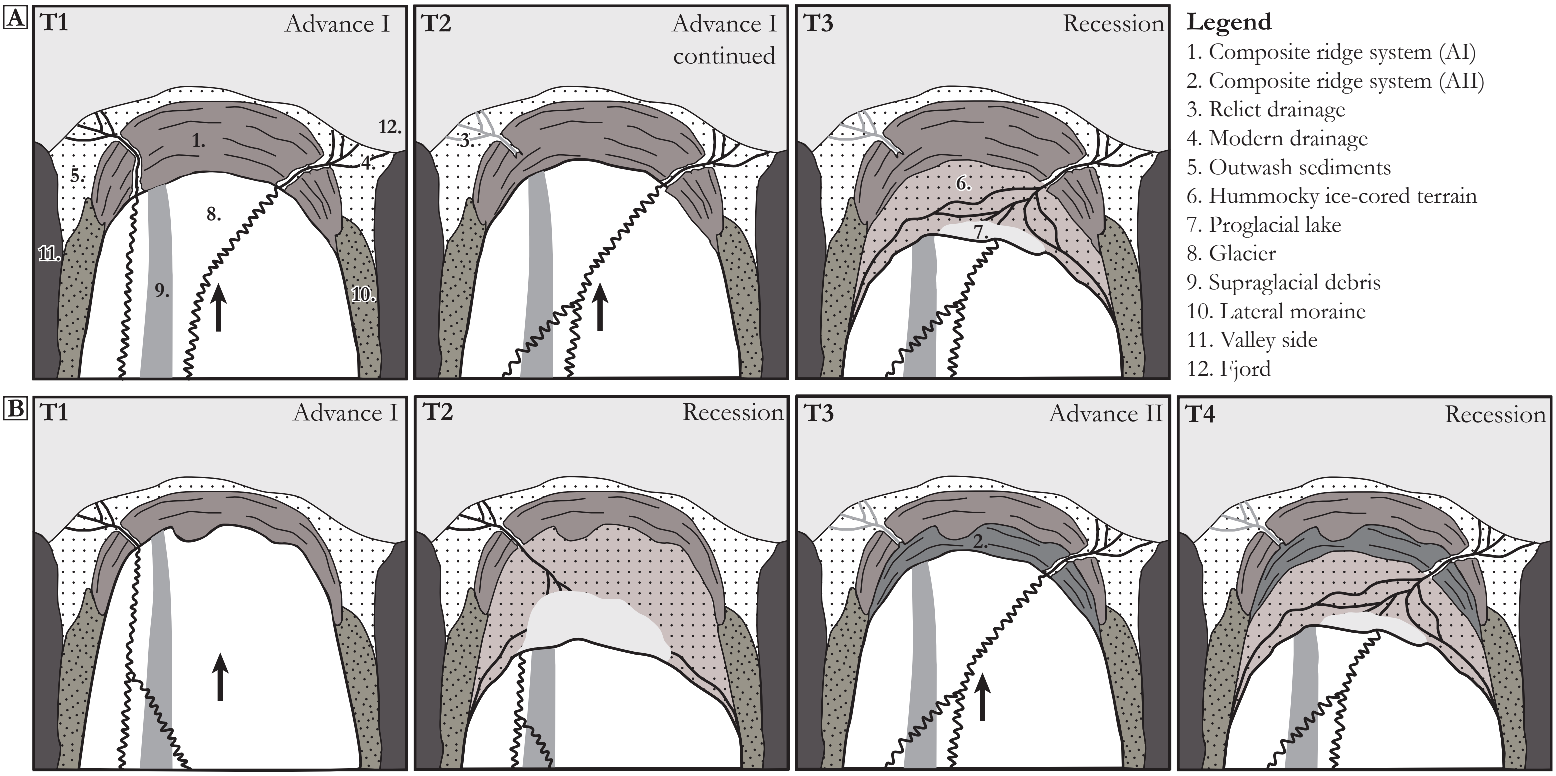

Fig. 8. Conceptual diagrams of how ridge-meltwater channel relationships could be interpreted in the context of composite ridge system formation during (A) a single rapid advance; or (B) multiple separate rapid advances to successively less-extensive positions (T = time-step).

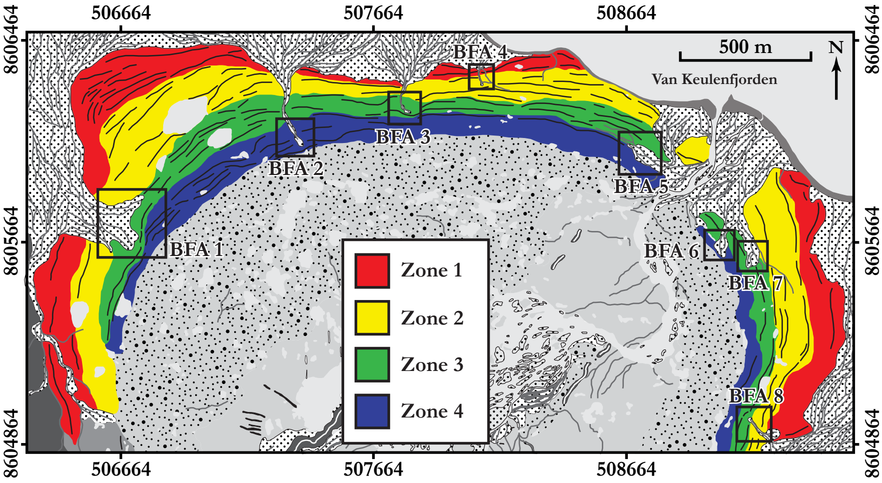

Fig. 9. Buried fan apex (BFA) locations and four identified separate ridge zones within the Finsterwalderbreen composite ridge system based on the multiple advance model. Table 2 summarises the identified BFAs and ridge zone relationships.

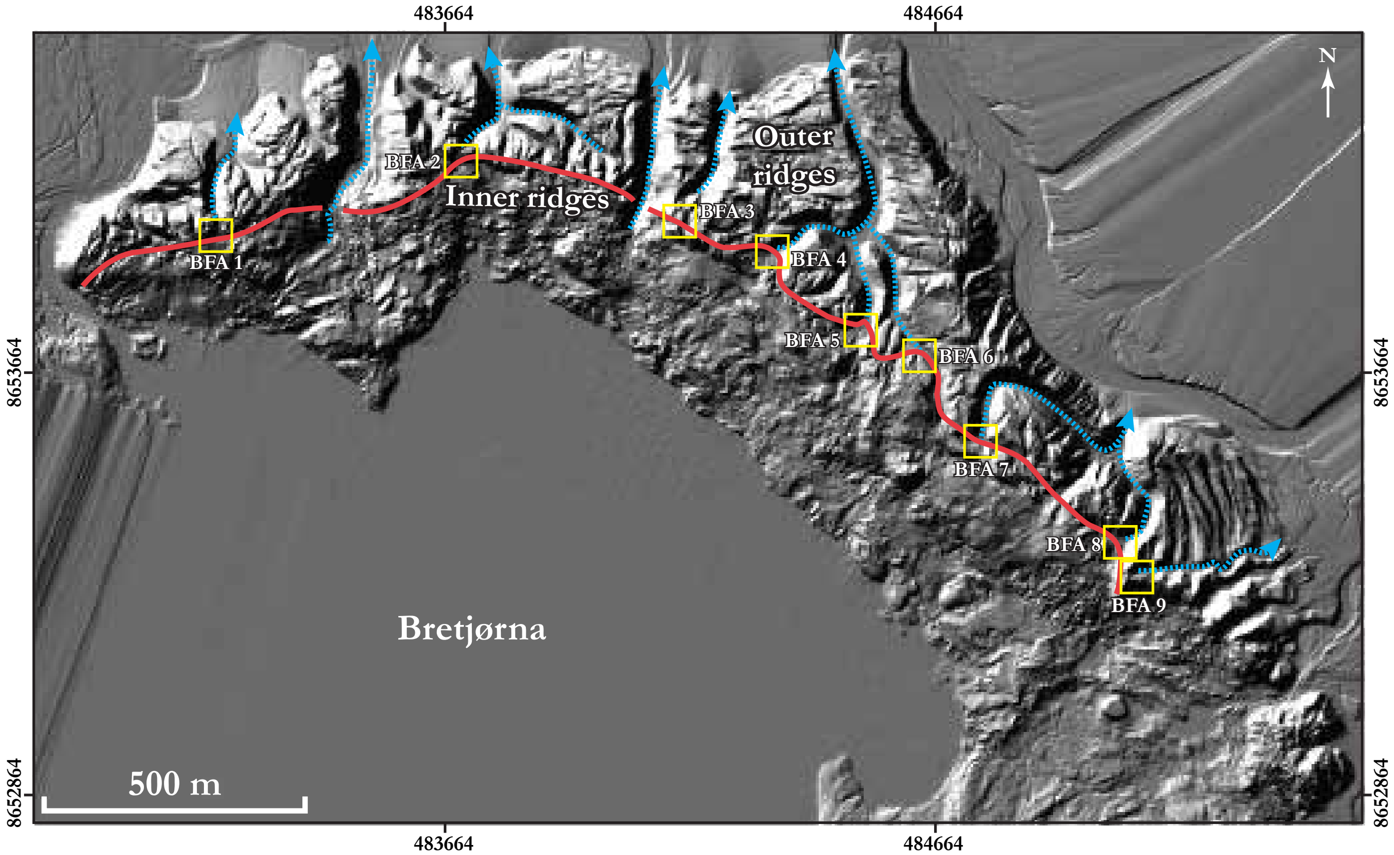

Fig. 10. Hill-shaded DEM showing identified buried fan apex (BFA) locations within the Grønfjordbreen composite ridge system. Blue dotted arrows are relict meltwater channels; solid red line delimits boundary between the outer and inner (truncating) ridge zones.