Glacitectonic composite ridge systems and surge-type glaciers: an updated correlation based on Svalbard, Norway

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ABSTRACT Glacitectonic composite ridge systems are found at the margins of a number of surge-type glaciers globally. On the High-Arctic archipelago of Svalbard, the pioneering work of Croot (1988a) highlighted the coincidence between composite ridge systems and surge-type glaciers on the island of Spitsbergen. These observations have contributed significantly to our understanding of the links between glacier surges and the landforms they produce. We update this work and expand it to the whole archipelago by using the Norwegian Polar Institute's TopoSvalbard aerial photograph archive to identify 50 composite ridge systems. These are found on all four of the largest islands: Spitsbergen, Nordaustlandet, Edgeøya and Barentsøya, and at the margins of both tidewater and land-terminating glaciers. Of the 50 composite ridge systems, 49 are associated with glaciers that have either been documented as surge-type or contain indicative geomorphological evidence of surging in the form of crevasse-squeeze ridge (CSR) networks. This provides further support for the established link between composite ridge systems and surging. Based on the proportion of glaciers that are documented as being of surge-type and those that display indicative evidence of surging (but have not been observed to surge), we conclude that at least 32.6% of all glaciers in Svalbard surge or are likely to have surged. This study contributes to the understanding of the links between glacier surging and specific landforms/landform assemblages (composite ridge systems and CSR networks), which has applications in other modern glacial environments and at the margins of former ice masses in palaeoglaciological settings.

KEY WORDS: composite ridge systems; surge-type glaciers; glacial geomorphology; glacitectonics; crevasse-squeeze ridges; Svalbard

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Introduction

Composite ridge systems are large (up to 100 m high), multi-crested glaciectonic depositional landforms composed of deformed unconsolidated sediment (cf. Aber et al. 1989) found at the margins of both modern glaciers (e.g. von Heuglin, 1872, Garwood and Gregory 1898; Lamplugh 1911; Gripp 1929; Kälin 1971; Croot 1988a, b; Hagen 1988; Evans and England 1991; Huddart and Hambrey 1995; Hart and Watts 1997; Boulton et al. 1996, 1999; van der Meer 2004; Benediktsson et al. 2008, 2009, 2010, 2015; Kristensen et al. 2009a, b; Roberts et al. 2009; Lønne 2016) and former ice sheets (e.g. Clayton et al. 1985; Aber et al. 1989; Hart 1990; van der Wateren 1995; Evans and Rea 1999; Evans et al. 1999, 2008; Benn and Clapperton 2000; Bakker and van der Meer 2003; Kehew et al. 2005; Boston et al. 2010; Darvill et al. 2016; Gribenski et al. 2016). The origin of composite ridge systems is typically attributed to proglacial and/or sub-marginal glaciectonic deformation during periods of sustained glacier/ice lobe advance as stresses are transmitted longitudinally through foreland sediments (e.g. Clayton et al. 1985; Aber et al., 1989; van der Wateren 1995; Etzelmüller et al. 1996; Boulton et al. 1999; Evans and Rea 1999; Benediktsson et al. 2008). These landforms are sometimes referred to as push moraines or push moraine complexes in this context in the literature (e.g. Hart and Watts, 1997; Boulton et al. 1999; van der Meer 2004; Christoffersen et al. 2005), although these terms are problematic as they are also used for a broad range of landforms at various scales and with often quite different morphologies and inferred genetic origins (cf. Bennett, 2001). To avoid possible confusion, we use the term composite ridge system as defined by Aber et al. (1989) throughout this contribution.

Composite ridge systems at modern glacier margins are often coincident with known surge-type glaciers (e.g. Croot 1988a; Huddart and Hambrey 1995; Boulton et al. 1996, 1999; Hart and Watts 1997; Evans and Rea 1999; Benediktsson et al. 2008, 2009, 2015; Kristensen et al. 2009a, b; Roberts et al. 2009). Most of the above studies imply at the very least a direct link between composite ridge systems (including thrust-block moraines) and glacier surging, although alternative, non-surging genetic origins have been suggested in the past for similar

landforms. These alternatives include sustained glacier advance into proglacial permafrost (e.g. Kålin, 1971) and englacial thrusting within polythermal glacier snouts (e.g. Hambrey and Huddart, 1995; Huddart and Hambrey, 1996). The awareness of a link between composite ridge systems and surge-type glaciers stems in part from the pioneering work of Croot (1988a), who identified 29 composite ridge systems in Svalbard, 27 of which were located at the margins of known or inferred (based on the presence of looped moraines; cf. Meier and Post 1969) surge-type glaciers (Fig. 1). Similar correlations have also been recognised in Iceland (e.g. Croot 1988b; Benediktsson et al. 2008, 2009, 2010, 2015; Ingólfsson et al. 2016), West Greenland (e.g. Yde et al. 2005; Roberts et al. 2009; Larsen et al. 2010), the Canadian Arctic (e.g. Copland et al. 2003) and High-Arctic Russia (Grant et al. 2009). As a result, glacetectonic composite ridge systems are recognised as being part of a diagnostic suite of geomorphological indicators, or landsystem, of glacier surging in modern environments (Evans and Rea 1999, 2003). A second key feature of the surging glacier landsystem is crevasse-squeeze ridges (CSRs; Sharp 1985; Evans and Rea 1999, 2003), which have been genetically linked to processes active during surge cycles. CSRs are formed through the injection of deformable sediments into basal crevasses that open in response to enhanced ice velocities in the surge active phase. These subsequently melt out as foreland geometrical ridge networks upon surge termination and glacier stagnation. It is widely accepted that, although individual CSRs are not necessarily diagnostic of surging *per se*, their arrangement in dense networks at glacier margins is. These networks are characterised by multiple ridges oriented oblique and transverse (and occasionally normal) to ice flow (Sharp 1985; Evans and Rea 1999, 2003; Kjær et al. 2008; Rea and Evans 2011; Schomacker et al. 2014; Lovell et al. 2015a; Evans et al. 2016; Farnsworth et al. 2016).

Better understanding of the geomorphology produced by surging, including composite ridge systems and CSR networks, is important in order to help identify previously unrecognised surge-type glaciers in modern environments (e.g. Ottesen and Dowdeswell 2006; Grant et al. 2009; Streuff et al. 2015; Farnsworth et al. 2016). This in turn can improve interpretations of possible surging behaviour of ice lobes at the margins of former ice sheets (e.g. Clayton et al. 1985; Evans and Rea 1999; Evans et al. 1999, 2008; Benn and Clapperton 2000; Kehew et al. 2005; Davies et al. 2009; Evans and Thomson 2010; Boston et al. 2010; Lovell et al. 2012; Darvill et al. 2016; Gribenski et al. 2016).

In this contribution, we aim to investigate the coincidence between composite ridge systems and surge-type glaciers in Svalbard. To achieve this, we revisit and update Croot's (1988a) study of composite ridge systems in Spitsbergen with the benefit of ~30 years of research on surge-type glaciers and surge geomorphology alongside access to high-resolution

aerial photographs of the entire archipelago via the Norwegian Polar Institute (NPI)'s online archive *TopoSvalbard* (toposvalbard.npolar.no). We produce an updated distribution map of composite ridge systems and examine their correlation with both documented surge-type glaciers and glaciers that have not been observed to surge, but contain geomorphological evidence that is indicative of surging in the form of CSR networks (based on Farnsworth et al. (2016)). We use this combined dataset to refine the minimum estimate of the number of glaciers in Svalbard that are likely to be of surge-type. This study contributes a database that we hope will be of use to future research focused on surge geomorphology and surge-type glacier distribution.

Svalbard and glacier surges

Approximately 57% (~34,000 km²) of the total surface area of Svalbard is glacierized (Nuth et al. 2013), comprising >2,000 glaciers ranging from large (~1000 km²) ice cap outlet glaciers to small (<1 km²) cirque glaciers (cf. Hagen et al. 1993; Fig. 1). The latter account for ~56% of all glaciers, but cover only ~1% of the total glacierized area (Hagen et al. 1993). By comparison, ~7% of all glaciers are tidewater- or marine-terminating, but these drain ~68% of the total glacierized area (Błaszczyk et al. 2009; Nuth et al. 2013). Glacier surges are commonly observed in Svalbard. They are characterised by long quiescent phases of ice stagnation and frontal recession lasting ~40-150 years, punctuated by short (~3-10 years) active or surge phases. During the surge phase, ice velocities increase between 10 to 1000 times and the glacier front typically advances several kilometres (Dowdeswell et al. 1991; Hagen et al. 1993; Murray et al. 2003). Previous inventories have documented a total of 280 glaciers (12.8% of all glaciers) as being of surge-type (Croot 1988a; Dowdeswell et al. 1991; Lefauconnier and Hagen 1991; Hamilton 1992; Hagen et al. 1993; Liestøl 1993; Dowdeswell et al. 1999; Jiskoot et al. 2000; Dowdeswell and Benham 2003; Błaszczyk et al. 2009; Sund et al. 2009).

Due to the multi-decadal return periods of glacier surges and the remote nature of the archipelago, many surges are likely to have gone undetected (Dowdeswell et al. 1991; Farnsworth et al. 2016; Lønne 2016), and thus the figure quoted above represents a minimum value for the surge-type glacier total. It is also recognised that some glaciers may have surged in the past (e.g. during the Little Ice Age maximum ~1900 AD) but are no longer in the surge cycle (e.g. Hodgkins et al. 1999; Hansen 2003; Małeckı et al. 2013; Lovell et al. 2015b; Farnsworth et al. 2016). This is largely in response to the strongly negative mass balance experienced by all Svalbard glaciers during the 20th and 21st centuries (James et al. 2012; Nuth

et al. 2013; Małeckı 2016). Several previous studies have attempted to refine the proportion of surge-type glaciers through a variety of approaches, including:

(i) Estimates based on a combination of both observed surges and glaciological and geomorphological evidence for surging (Lefauconnier and Hagen 1991; Hagen et al. 1993).

(ii) Probabilistic (Hamilton and Dowdeswell 1996) and multivariate (Jiskoot et al. 1998) statistical methods that use various parameters including glacier geometry (e.g. length, aspect, slope, presence/number of tributaries), underlying geology, mass-balance measurements and thermal regime of a sub-sample of glaciers.

(iii) The identification of diagnostic geomorphological evidence for surging in the form of CSR networks on glacier forelands (Farnsworth et al. 2016).

These studies provide a wide range of estimates for the likely proportion of surge-type glaciers in Svalbard, from 13% (Jiskoot et al. 1998), >32% (Farnsworth et al. 2016), and 36% (Hamilton and Dowdeswell 1996) to 90% (Lefauconnier and Hagen 1991; Hagen et al. 1993).

Composite ridge system geomorphology

Composite ridge systems vary in size, morphology, internal structure and sediment composition, and location relative to the glacier that was responsible for forming them. There are, however, a number of shared geomorphological characteristics that are linked to the inferred process of formation at the margins of surging glaciers, and these are listed in Table 1. Typically, composite ridge systems can be described as multi-ridged sediment masses located in a proglacial frontal or latero-frontal position (Fig. 2), although they can also be found at lateral glacier margins. Most are no longer in contact with the glacier and are clearly distinguishable from de-icing forelands, which are characterised by hummocky terrain, abundant meltwater pools and outwash deposits. This distinction reflects the difference between composite ridge systems, formed in a proglacial position, and de-icing forelands comprising sub-/supraglacial deposits left-behind by glacier recession during the quiescent phase of the surge cycle (e.g. Lønne 2016). The few studies that have investigated the internal structure of glacitectonic composite ridge systems in Svalbard report stacked and contorted sequences consisting of predominantly sorted and fine-grained sediment, typically with varying compositions of mud, sand and gravel (e.g. Garwood and Gregory 1898; Lamplugh 1911; Gripp 1929; Hambrey and Huddart 1995; Boulton et al. 1996, 1999; Hart and Watts 1997; Kristensen et al. 2009a, b). This variation is found both between different complexes and across a single complex (e.g. Boulton et al. 1996, 1999).

Identifying composite ridge systems from aerial photographs

A systematic assessment of glacier forelands was undertaken using TopoSvalbard aerial photographs in order to identify the location of composite ridge systems using the criteria listed in Table 1. A combination of oblique (captured in 1936) and vertical (captured in 2008-2012) aerial photographs were assessed. In order to reduce the chance of missing any composite ridge systems, the Croot (1988a) composite ridge system and Hagen et al. (1993) push moraine inventories were examined in detail, alongside all glaciers documented as surge-type (Croot, 1988a; Farnsworth et al. 2016; and reference therein) and those likely to have surged based on the presence of CSR networks (Farnsworth et al. 2016).

Composite ridge systems have only been included if they meet most, if not all, of the criteria outlined in Table 1. Complexes were identified from aerial photographs based on:

- Geomorphological characteristics, e.g. a large, often arcuate in planform sediment accumulation with a series of multiple adjacent ridges on the surface aligned perpendicular to glacier flow.
- Location, e.g. in a proglacial frontal/latero-frontal position.
- Their smooth surface texture due to the fine-grained sediment they typically comprise. This allows them to be differentiated from surrounding terrain consisting of a wider range of grain sizes, up to and including large boulders, as commonly found on de-icing forelands (Fig. 2).
- The presence of large meltwater channels incised into the ridges (e.g. Figs 2a, 2b and 2e-h). These typically form deep gorges within the complex that highlight the thickness of the sediment accumulation, especially when compared to meltwater channels in adjacent areas of outwash.

To be more confident of the glacetectonic origin of composite ridge systems, it is desirable to also have information on their internal structure. This is not possible to determine conclusively in this study due to its remote sensing approach. However, based on the shared diagnostic geomorphological characteristics of composite ridge systems (Table 1) displayed both by those identified only from aerial photographs and those also previously subjected to detailed internal investigations (e.g. Garwood and Gregory 1898; Gripp 1929; Hambrey and Huddart 1995; Boulton et al. 1996, 1999; Hart and Watts 1997; Kristensen et al. 2009a, b), we suggest these have a common glacetectonic origin.

A number of push moraines or push moraine complexes reported in the literature have not been included as the geomorphological evidence is not sufficiently compelling, and typically justifications for their classification in the first instance are absent or unclear. This may in part be due to the range of landforms that have come under the broad category of push moraines in the glacial geomorphological literature (cf. Bennett 2001). An example of this is Hagen et al. (1993), which lists 283 glaciers as having push moraines but do not define what criteria this is based on. It is clear that some of these (e.g. Arnesenbreen, Deltabreen, Gandbreen and Seidbreen, to name a few) are composite ridge systems as defined by the criteria in Table 1, but a large number are not. Similarly, several glaciers (e.g. Hessbreen, Renardbreen and Scottbreen) identified by Croot (1988a) also do not meet our geomorphological criteria for composite ridge systems (Table 1). It is possible some of these landforms formed during surges, but their geomorphology as assessed from aerial photographs is not diagnostic of glaciectonic composite ridge systems, and therefore additional information (e.g. direct observations of formation, investigations of internal structure) would be necessary before such a classification could be made.

A further explanation for the misidentification of some composite ridge systems in previous studies is that they share some geomorphological characteristics with landform-sediment assemblages that are genetically very different (i.e. not of a glaciectonic origin). Specifically, both controlled moraines (cf. Evans 2009; Figs 3a and 3b) and fluvially-dissected ice-marginal sediment masses (Figs 3c and 3d) appear to consist of multiple linear ridges, which in some contexts is not dissimilar to composite ridge systems.

Controlled moraines (e.g. Figs 3a and 3b) are supraglacially-deposited ice-cored landform assemblages that have inherited linear surface features from debris-rich structures within the parent ice (cf. Evans 2009). These features are common in the forelands of polythermal glaciers. Debris derived from various sources (e.g. subglacial, rockfall, englacial meltwater channels, proglacial) and incorporated into the ice by several process such as basal freeze-on (e.g. Alley et al. 1997), shear-plane development (e.g. Sletten et al. 2001; Lovell et al. 2015b), apron entrainment (e.g. Evans 1989) and via crevasse/fracture networks (e.g. Rea and Evans 2011), melts out on the surface at the glacier front to form supraglacial debris cover. During glacier recession and frontal thinning, ice beneath thicker debris cover (e.g. at the emergence of a debris-rich structure) is preserved relative to surrounding areas, creating a topographic inversion controlled by the delivery of debris to the surface within structures. This creates ice-cored moraine sequences that display clear linearity reflecting the englacial structures from which the debris is derived, typically preserving the shape of the former glacier

front (e.g. Fig. 3b). In many cases, the surface linearity of controlled moraine can be traced into a lateral (e.g. flow-parallel structure) position (Figs 3a and 3b). Controlled moraine assemblages also typically display evidence for degradation and reworking due to de-icing thermo-erosion processes (e.g. Etzelmüller et al. 1996; Schomacker and Kjær 2008), such as debris flows (e.g. Fig. 3b). By contrast, composite ridge systems are formed proglacially and, although they can incorporate pre-existing buried glacier ice and/or glacier nales located on forelands (e.g. Yde et al. 2005; Roberts et al. 2009), the ice content of the resultant composite ridges would be significantly lower than areas of controlled moraine derived from englacial debris-rich structures. As a result, de-icing indicators are usually absent or minimal in composite ridge systems (e.g. Fig. 2 and Table 1).

Fluvially-dissected moraines or ice-marginal sediment masses (e.g. Figs 3c and 3d) also display linearity and contain meltwater canyons/gorges that are not dissimilar to those seen within composite ridge systems (e.g. Figs 2a and 2g). These areas are typically found towards the lateral margins of glaciers, or occasionally in latero-frontal positions (e.g. Figs 3c and 3d). They are formed where lateral meltwater channels have eroded into an ice-marginal sediment mass, creating an inset sequence of channels that are similarly aligned and therefore give the impression of multiple ridges within a depositional landform (Figs 3c and 3d). However, the channels within fluvially-dissected sediment masses often meander, giving the same form to the ridges as the adjacent channels (e.g. Fig. 3c). In composite ridge systems, although the deep gorges cutting through the systems may meander (e.g. Figs 2a, 2b and 2e-h), the ridges themselves are straight to curvilinear rather than having a sinuous form (Table 1).

Distribution of composite ridge systems and surge-type glaciers in Svalbard

Using the geomorphological criteria outlined in Table 1, 50 composite ridge systems are identified across the Svalbard archipelago (Fig. 1 and Table 2). 19 of these are located at the terrestrial margins of marine-terminating or tidewater glaciers (e.g. Figs 4a and 4c-f) and 31 are at the margins of land-terminating glaciers (e.g. Figs 2a-h and 5b). Of the latter glaciers, nine currently terminate in proglacial lakes (e.g. Figs 2c, 2e and 2g). Of the 50 composite ridge systems, 17 were listed by Croot (1988a; out of a total of 29 identified) and 34 were listed as push moraines by Hagen et al. (1993; out of a total of 283 identified). Our inventory also includes composite ridge systems that have previously been described at Duckwitzbreen and Ulvebreen (Gripp 1929), and Paulabreen (Kristensen et al. 2009a, b), but that did not feature in either the Croot (1988a) or Hagen et al. (1993) studies. We have therefore identified 12

composite ridge systems that, to the best of our knowledge, have not previously been reported. These are: Augnebreen, Austre Kvitisen, BEØ-13 (as named in Farnsworth et al. 2016; located on Edgeøya at 77.8307°N, 22.5578°E), Besselsbreen, Gardebreen, Koristkabreen, Kosterbreen, Kvastbreen, Laubefjellebreen, Mittag-Lefflerbreen, Schweigaardbreen and Winsnesbreen (Fig. 4).

Almost all of the 50 composite ridge systems we have identified are coincident with known or inferred surge-type glaciers. 30 are located at the margins of documented surge-type glaciers (according to Croot (1988a) and Farnsworth et al. (2016, and references therein)) and a further 19 are located on forelands that also contain CSR networks (cf. Farnsworth et al. 2016). Therefore, Schweigaardbreen in Nordaustlandet (Fig. 4f) is the only glacier with a composite ridge system that has not previously been reported or inferred (based on the presence of CSRs) to be of surge-type. In order to assess the identified spatial distribution of composite ridge systems, the Svalbard archipelago is divided into six regions following the approach of Farnsworth et al. (2016): Northwest (NWS), Northeast (NES), Central (CS) and Southern (SS) Spitsbergen; Barentsøya and Edgeøya (BEØ); and Nordaustlandet (NA). The largest number of composite ridge systems (34) are located in Spitsbergen, with 12 in NWS, nine in SS, eight in NES, and five in CS (Fig. 1 and Table 3). Of the other main islands in the archipelago, there are ten composite ridge systems in Edgeøya, four in Barentsøya and two in Nordaustlandet (Fig. 1 and Table 3).

Figure 5 shows the distribution of composite ridge systems, documented surge-type glaciers and CSR networks compared to the total number of glaciers and number of glaciers >1km² (according to Hagen et al. 1993). The reason for including the number of glaciers >1km², which constitute 46.7% of all glaciers in Svalbard (Table 3), is based on the observations that: (i) none of the identified composite ridge systems in this study are coincident with glaciers smaller than this size; and (ii) with very few exceptions (e.g. Sund et al. 2009), almost all documented surge-type glaciers in Svalbard are significantly larger than this (cf. Sevestre and Benn 2015). These data show that glaciers with composite ridge systems constitute 2.3% of all glaciers in Svalbard (and 4.9% of all glaciers >1 km²). This proportion varies regionally, with the highest in BEØ (4.1% of all glaciers in the region) and the lowest in NA (0.9%) (Fig. 5 and Table 3).

As a point of wider interest, the distribution of documented surge-type glaciers by region reveals that SS has the largest proportion at 35.1% of all glaciers in the region, and BEØ the lowest at 4.1% (Fig. 5 and Table 3). If we include those glaciers that have not been documented as surge-type but contain indicative geomorphological evidence for surging in the

form of CSR networks and composite ridge systems, this increases for all regions (Table 3). For Svalbard as a whole, this indicates that at least 32.6% of all glaciers are of surge-type, which is a significant increase on the figure of 12.8% based solely on documented surge-type glaciers (cf. Farnsworth et al. 2016).

Discussion

What does the distribution of composite ridge systems tell us about their formation?

All but one of the identified composite ridge systems in Svalbard are at the margins of glaciers that have either been previously documented as surge-type (30 glaciers) or contain compelling geomorphological evidence for surging in the form of CSR networks (19 glaciers; Table 2). This provides clear support for the suggestion that composite ridge systems in Svalbard are formed by glacier surges (cf. Croot 1988a).

Our investigation reveals that composite ridge systems are distributed across the four largest islands in the archipelago (Fig. 1), but overall are very restricted in number (50, i.e. only 2.3% of all glaciers). This is particularly apparent when compared to the number of documented surge-type glaciers (280, or 12.8% of all glaciers) and glaciers with CSR networks (612, or 28% of all glaciers; Table 3). Furthermore, out of the 711 glaciers that are thought to be of surge-type (32.6% of the total number of glaciers), this means that only 7% have formed (or preserved) composite ridge systems, considerably fewer than those that have CSR networks at their margins (86%), for example. This implies that composite ridge system formation at the margin of a rapidly advancing glacier is dependent on specific conditions, as they clearly do not form (or are not preserved) at all surge-type glaciers. Although a full assessment of these conditions is beyond the scope of this study, previous investigations on composite ridge formation in Svalbard provide some indication of what these are likely to be.

Firstly, the availability of a thick sequence of fine-grained, deformable sediments on the pre-surge foreland is likely to be necessary for composite ridge formation. This is based on investigations of their internal structure, which demonstrate that most are predominantly composed of sorted and fine-grained sediment ranging from muds to gravel. This reflects a range of depositional environments including shallow marine (e.g. Lamplugh, 1911; Boulton et al. 1996; Hart and Watts 1997; Kristensen et al. 2009a, b); glaciallacustrine (e.g. Boulton et al. 1999), and glacialfluvial outwash (e.g. Garwood and Gregory, 1898; Hambrey and Huddart 1995; Hart and Watts 1997; Boulton et al. 1999). High pore water pressures within these sediments, perhaps driven by enhanced meltwater drainage from the glacier during the surge,

is likely to be required in order to minimise resistance in the deforming foreland (Boulton et al. 1999).

Secondly, the role of permafrost and partially-frozen conditions within foreland sediments has been suggested to be important for composite ridge system formation, as this facilitates the transmission of stress through the foreland as the glacier advances (e.g. Etzelmüller et al. 1996; Boulton et al. 1999). Boulton et al. (1999) also suggest that the presence of permafrost serves to extend the zone of high pore water pressures further into the proglacial sediments than if the ground was unfrozen.

Thirdly, it is probably necessary for the glacier margin to be initially stationary in order to allow the development of an ice-contact zone with a sufficiently thick proglacial sediment accumulation. This is then followed by a frontal advance of sustained duration over a distance ranging from 100s to 1000s of metres, during which the well-defined ice-contact zone promotes the transmission of stresses into the sediments (e.g. Boulton et al. 1999).

Finally, in order to preserve composite ridge systems, low compositions of buried glacier ice within the initial foreland sediments and thus within the resultant complex are required. This means that degradation and/or (fluvial) erosion of the composite ridge system over time is much lower compared to supraglacial moraine deposits, as indicated by the typical absence of de-icing evidence.

How can the discrepancies with previous inventories be explained?

Our inventory presents some discrepancies when compared to previous studies, both in terms of the number of composite ridge systems identified and individual classifications. Misidentification of composite ridge systems could result in incorrect conclusions being drawn on both the genetic origin of the moraine system and, based on the correlation between composite ridge systems and surge-type glaciers highlighted in this and other studies, potentially whether a glacier has surged or not. In most cases where we disagree with composite ridge systems or push moraines identified in Croot (1988a) and Hagen et al. (1993), we suggest it is due to the following reasons:

(i) The use of the broad term ‘push moraine’ in Hagen et al. (1993), which can describe a range of landforms at various scales and with quite different morphologies and inferred genetic origins (cf. Bennett, 2001).

(ii) The misidentification of moraine areas that contain or appear to contain multiple linear ridges, but are actually derived from englacial structural control (cf. Evans 2009) and/or ice-marginal fluvial dissection rather than glacitectonic deformation of foreland sediments.

(iii) Moraine systems may have formed proglacially during surges, but do not display the characteristic form that allows them to be identified as composite ridge systems based on geomorphology alone. These might include small single- or double-ridged push moraines that geomorphologically cannot be differentiated from supraglacially-derived ice-cored moraines, and would therefore require additional information (e.g. investigations of internal structure) in order to be classified. Examples of this may include the composite ridge system reported at Hessbreen (Croot 1988a), the push moraine complex at Elisebreen (Christoffersen et al. 2005), and thrust-block moraines at the margins of Kongsvegen (Bennett et al. 1999), none of which meet the geomorphological criteria for composite ridge systems outlined in Table 1.

(iv) Examples where the complex appears to have been formed by a combined glacier tongue that has since split into two separate glaciers during recession. In these examples, the composite ridge systems have been attributed to the glacier that appears to have been the more-dominant flow unit based on supraglacial moraine patterns (e.g. Universitetsmorenen is attributed to Lisbetbreen rather than Universitetsbreen, as previously suggested by Croot (1988a)).

How many glaciers are of surge-type in Svalbard?

Based on our study and Farnsworth et al. (2016), who identified CSR networks using *TopoSvalbard*, we suggest that at least 711 glaciers, or 32.6% of the total population, are of surge-type. This number comprises 280 that have previously been documented as surging glaciers and an additional 431 glaciers that display geomorphology that is indicative of surging. This is a minimum value because:

(i) Not all documented surge-type glaciers have CSR networks (cf. Farnsworth et al. 2016) and/or composite ridge systems at their margins, and thus it is clear that glaciers can surge without producing (or preserving) such landforms. This is likely to particularly be the case for a number of small valley glaciers (~3 km²; e.g. Scott Turnerbreen; Hodgkins et al. 1999), where evidence for past surges or surge-like behaviour may only be preserved englacially and does not appear to survive de-icing (e.g. Lovell et al. 2015b).

(ii) Tidewater glaciers that have undergone unobserved surges may only record geomorphological evidence for this on the seafloor (e.g. Streuff et al. 2015; Flink et al. 2017), and therefore if their forelands have not been the subject of a submarine investigation then evidence indicating surge behaviour may not yet have been found.

These observations suggest that at least one-third of all glaciers in Svalbard surge or have surged, but it is worth noting that over half of the total population of glaciers (~53%) is

smaller than $\sim 1 \text{ km}^2$ (Hagen et al. 1993; Fig. 5). Although glaciers of this size have been reported to surge (e.g. Sund et al. 2009), the vast majority of documented surge-type glaciers, glaciers with CSR networks, and glaciers with composite ridge systems, are larger than this (cf. Sevestre and Benn 2015; Farnsworth et al. 2016). Therefore, if the suggested minimum number of surge-type glaciers (711) is reported as a proportion of only those glaciers larger than 1 km^2 , this value increases to 69.8%.

How useful is the identification of composite ridge systems from remote sensing data?

Identifying composite ridge systems from imagery is possible because they have a characteristic form dependent on the inferred processes of glacitectonic formation at the margin of a rapidly advancing glacier. However, as with any such investigation based solely on remote sensing imagery, it is possible that some composite ridge systems have been misidentified or missed. It is also not possible to investigate the internal structure of composite ridge systems through remote sensing analysis, which would provide further support for their inferred glacitectonic origin. We have tried to reduce these potential issues as much as possible through rigorous application of mapping criteria (Table 1). Based on our investigation, we suggest that the majority of composite ridge systems can be easily identified from aerial photographs, as is also the case for CSR networks (e.g. Farnsworth et al. 2016). Their coincidence with surge-type glaciers indicates that, like CSR networks, composite ridge systems in Svalbard can be linked to glacier surging with some confidence. CSRs are clearly formed more often than composite ridge systems during surges, but their smaller scale ($\sim 1\text{-}2 \text{ m}$ wide, 100s of metres long) means they often can only really be identified from high-resolution imagery (e.g. at least $\sim 1 \text{ m}$ pixel resolution). Composite ridge systems, on the other hand, are large enough ($\sim 300 \text{ m}$ wide, $\sim 1000 \text{ m}$ long) that they could potentially also be identified from medium to high resolution satellite imagery in other surge clusters where aerial photograph coverage is less complete, such as in the Canadian Arctic (e.g. Evans and England 1991; Copland et al. 2003), West Greenland (e.g. Yde et al. 2005; Roberts et al. 2009) and High-Arctic Russia (Grant et al. 2009).

Conclusion

Glacitectonic composite ridge systems are found at the margins of 50 glaciers across the Svalbard archipelago. Of these glaciers, 19 are documented to be of surge-type and a further 30 display indicative geomorphological evidence for surging in the form of crevasse-squeeze

ridge (CSR) networks. This provides support for observations first made by Croot (1988a) that composite ridge systems are uniquely linked to surging in Svalbard. However, out of the 711 glaciers that are thought to be of surge-type (32.6% of all glaciers in Svalbard), only 7% have produced composite ridge systems, which is considerably fewer than those with CSR networks at their margins. This confirms that specific conditions are necessary for the formation and preservation of composite ridge systems, which may include the availability on the pre-surge foreland of a thick sequence of deformable sediments, high pore water pressures within the foreland sediments, and the presence of permafrost.

These observations contribute to our understanding of the links between composite ridge systems and surge-type glaciers, which requires further investigation at other known surge clusters (e.g. the Canadian Arctic, West Greenland and High-Arctic Russia). This work also has the potential to provide additional support for the interpretations of glaciectonic sequences at the margins of former Quaternary ice masses.

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Table 1 Geomorphological criteria for identifying composite ridge systems in Svalbard from aerial photographs and links to inferred processes of formation during surges, including observations in Aber et al. (1989), Croot (1988a), Hart and Watts (1997), Boulton et al. (1999) and Lønne (2016).

Key feature	Description	Interpretation
<i>Multi-ridged sediment accumulation</i>	<ul style="list-style-type: none"> Large, topographic sediment accumulation ranging from ~0.2-2 km-wide (proximal to distal flanks), ~0.7-5 km-long (lateral extents) and ~30-50 m high (relative to adjacent surfaces) (Fig. 2). Often arcuate in planform (e.g. Figs 2f-h). 	<ul style="list-style-type: none"> Significant shortening/compression of the pre-surge foreland by proglacial deformation during glacier advance results in folding and stacking of sediments into defined ridges.
	<ul style="list-style-type: none"> Series of multiple (>3) separate ridges identifiable on surface of sediment accumulation (Fig. 2). 	<ul style="list-style-type: none"> Ridges are the surface expression of glacitectonic deformation (e.g. folding and emplacement of thrust slabs).
	<ul style="list-style-type: none"> Typically located in a proglacial latero-frontal position (Fig. 2), but can be found in lateral positions. 	<ul style="list-style-type: none"> Formed by bulldozing/pushing of proglacial sediments in front of an advancing glacier margin.
	<ul style="list-style-type: none"> Clear elevation difference between sediment accumulation and surface of adjacent extra-/proglacial area (e.g. Figs 2b and 2e). 	<ul style="list-style-type: none"> Adjacent surfaces are at same relative height as pre-surge foreland, therefore lower than post-surge complex.
	<ul style="list-style-type: none"> Clear elevation difference between sediment accumulation and glacier surface (Fig. 2e). 	<ul style="list-style-type: none"> Formation in the proglacial zone means no/little buried ice within the ridges or ice that is continuous with the glacier, meaning ridges and glacier can be separately defined upon frontal recession.
	<ul style="list-style-type: none"> Surface often has a smooth texture (e.g. Figs 2b, 2e and 2f) and in places retains characteristics of the pre-tectonic sediment surface (e.g. channel forms). 	<ul style="list-style-type: none"> Reflects typical sorted and fine-grained sediment composition (e.g. gravel, sand, silt, clay) of the composite ridge system (and therefore pre-surge foreland).
	<ul style="list-style-type: none"> Slope instability indicators (e.g. debris flows) are typically absent or minimal (Fig. 2). 	<ul style="list-style-type: none"> No significant buried glacier ice in complexes due to proglacial formation.
<i>Ridges within system</i>	<ul style="list-style-type: none"> Ridge crest alignment is typically perpendicular to dominant ice flow direction and crestlines are straight to slightly curvilinear (i.e. not sinuous) (e.g. Fig. 2b). 	<ul style="list-style-type: none"> Bulldozing/pushing in front of advancing glacier margin creates ridges oriented transverse to glacier flow direction, but which are not the result of fluvial erosion.
	<ul style="list-style-type: none"> Ridge morphology is typically rounded and, across the whole complex, this creates an undulating surface (e.g. Figs 2a and 2b). Ridges are rarely discrete and sharp-crested. 	<ul style="list-style-type: none"> Ridges are surface expression of glacitectonic deformation (e.g. predominantly folding and emplacement of thrust slabs) of coherent sediment mass.
	<ul style="list-style-type: none"> Individual ridge width (distance between lower breaks-of-slope) and spacing (crest-to-crest) is typically ~10-30 m. Ridge width is typically larger than spacing width (Fig. 2). 	<ul style="list-style-type: none"> Reflects proglacial glacitectonic origin as opposed to ridges derived from englacial debris structures (controlled) or fluvial erosion.
	<ul style="list-style-type: none"> In a latero-frontal and lateral position, the ridges are not a continuation of the lateral moraine (and linearity thereof) (e.g. Fig. 2h). 	<ul style="list-style-type: none"> Reflects proglacial glacitectonic origin as opposed to ridges derived from englacial debris structures (controlled) or fluvial erosion.

<i>Meltwater channels</i>	<ul style="list-style-type: none"> • Deep (up to ~20 m) meltwater channels form often sinuous canyons/gorges cut (typically normal to crestlines) through ridges within the complex (e.g. Figs 2b and 2e-h). 	<ul style="list-style-type: none"> • Channels represent syn-/post-tectonic drainage originating from run-off points at the ice margin and cutting-through the complex.
	<ul style="list-style-type: none"> • Some channels terminate within the complex and are truncated by ridges (e.g. Fig. 2e). 	<ul style="list-style-type: none"> • Truncated channels could be the result of different phases of deformation during composite ridge system formation and/or multiple separate ridge-building advances creating a piggy-backed moraine system.

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727 **Table 2** Glaciers with composite ridge systems in Svalbard

Glacier	Island	Region	Terminus	Composite ridge system Lat./Long.	Documented surge-type ^c	Crevasse-squeeze ridges (CSR)	Photograph year	Key reference(s) for composite ridge system
Abrahamse nbreen ^{ab}	Spitsbergen	NWS	Terrestrial	79.1846°N, 14.5368°E	Yes	Yes	2011	Lønne (2016)
Arnesenbreen ^b	Spitsbergen	SS	Marine	77.8716°N, 18.3228°E	Yes	Yes	2012	
Augnebreenn	Barentsøya	BEØ	Marine	78.5705°N, 21.7948°E	No	Yes	2010	
Austre Kvitisen	Edgeøya	BEØ	Terrestrial	78.0476°N, 21.6969°E	Yes	Yes	2010	
Battyebreenn ^{ab}	Spitsbergen	NWS	Terrestrial	78.9388°N, 15.2315°E	Yes	Yes	2011	
BEØ-13 ^d	Edgeøya	BEØ	Terrestrial	77.8307°N, 22.5578°E	No	Yes	2010	
Besselsbreen	Barentsøya	BEØ	Marine	78.5657°N, 21.4213°E	No	Yes	2011	
Comfortlessbreen ^b	Spitsbergen	NWS	Marine	78.8385°N, 11.9044°E	Yes	Yes	2009	Huddart and Hambrey (1996); King et al. (2016); Lønne (2016)
Deltabreen ^b	Edgeøya	BEØ	Marine	77.5122°N, 22.9913°E	Yes	Yes	2010	
Duckwitzbreen	Barentsøya	BEØ	Marine	78.3142°N, 20.7318°E	Yes	Yes	2010	Gripp (1929)
Edvardbreen ^b	Spitsbergen	SS	Terrestrial	77.9690°N, 17.5754°E	Yes	Yes	2011	Lønne (2016)
Elfenbeinbreen ^{ab}	Spitsbergen	CS	Terrestrial	78.1156°N, 18.1521°E	Yes	No ^e	1936	Gripp (1929)
Erikbreen ^b	Spitsbergen	NWS	Terrestrial (lake)	79.5904°N, 12.6001°E	No	Yes	2011	
Finstervalderbreen ^{ab}	Spitsbergen	SS	Terrestrial	77.5322°N, 15.3265°E	Yes	Yes	2011	Hart and Watts (1997); Lønne (2016)
Gandbreen ^b	Edgeøya	BEØ	Terrestrial (lake)	77.7085°N, 22.7388°E	No	Yes	2010	
Gardebreen	Spitsbergen	NES	Terrestrial	78.5884°N, 19.5157°E	No	Yes	2011	
Grønfjordbreen ^{ab}	Spitsbergen	CS	Terrestrial (lake)	77.9602°N, 14.3292°E	Yes	No	2004	Gripp (1929)
Gullfaksebreen ^{ab}	Spitsbergen	NES	Terrestrial	79.5837°N, 17.5534°E	No	Yes	2010	
Holmströmbreen ^{ab}	Spitsbergen	NWS	Terrestrial (lake)	78.7784°N, 14.5509°E	Yes	Yes	2009	Boulton et al. (1999)
Inglefieldbreen ^{ab}	Spitsbergen	SS	Marine	77.9199°N, 18.2054°E	Yes	Yes	2012	

Karlsbreen ^{ab}	Spitsbergen	NWS	Terrestrial (lake)	79.3827°N, 13.4487°E	Yes	No	2011	
Koristkabreen	Spitsbergen	NES	Marine	78.8472°N, 21.2097°E	No	Yes	2011	
Kosterbreen	Spitsbergen	NES	Marine	79.3019°N, 18.8206°E	Yes	Yes	2010	
Kuhrbreen ^b	Edgeøya	BEØ	Terrestrial	77.5011°N, 21.7686°E	Yes	Yes	2010	Lønne (2016)
Kvastbreen	Spitsbergen	SS	Marine	77.4203°N, 17.5553°E	Yes	Yes	2011	
Laubefjellebreen	Spitsbergen	NES	Marine	78.8495°N, 21.1432°E	No	Yes	2011	
Lisbetbreen ^{nab}	Spitsbergen	NWS	Terrestrial	79.0401°N, 15.4848°E	Yes	Yes	2011	
Mittag-Lefflerbreen	Spitsbergen	NES	Marine	78.9166°N, 16.5029°E	Yes	Yes	2011	
Nathorstbreen ^a	Spitsbergen	SS	Marine	77.5291°N, 16.0599°E	Yes	Yes	2011	Gripp (1929)
Paulabreen	Spitsbergen	SS	Marine	77.8658°N, 16.5484°E	Yes	Yes	2011	Kristensen et al. (2009a,b)
Penckbreen ^{nab}	Spitsbergen	SS	Terrestrial (lake)	77.5223°N, 15.5906°E	Yes	Yes	2011	Hart and Watts (1997); Lønne (2016)
Rabotbreen ^{nab}	Spitsbergen	CS	Terrestrial	78.2711°N, 17.8996°E	No	Yes	2012	
Reymondbreen ^b	Barentsøya	BEØ	Terrestrial	78.4043°N, 22.1578°E	Yes	Yes	2010	
Schweigaa rdbreen	Nordaustlandet	NA	Marine	80.2400°N, 24.7657°E	No	No	2011	
Schwerdtbreen ^b	Edgeøya	BEØ	Terrestrial	77.7295°N, 21.7085°E	No	Yes	2010	
Sefströmbreen ^{nab}	Spitsbergen	NWS	Marine	78.6738°N, 14.7176°E	Yes	Yes	2009	Boulton et al. (1996)
Seidbreen ^b	Edgeøya	BEØ	Terrestrial (lake)	77.7598°N, 22.7149°E	No	Yes	2010	
Skrentbreen ^{n^b}	Edgeøya	BEØ	Terrestrial	77.5073°N, 21.5921°E	Yes	No	2010	Lønne (2016)
Stubendorf fbreen ^b	Spitsbergen	NES	Marine	78.9798°N, 16.4165°E	No	Yes	2011	
Supanbreen ^{n^b}	Spitsbergen	NWS	Terrestrial	79.3008°N, 11.8298°E	Yes	No	2009	
Ulvebreen	Spitsbergen	CS	Marine	78.1978°N, 18.9982°E	Yes	Yes	2012	Gripp (1929)
Usherbreen ^{nab}	Spitsbergen	CS	Terrestrial	78.2640°N, 18.9264°E	Yes	Yes	2012	Hagen (1988); Lønne (2016)
Uvêrsbreen ^{n^b}	Spitsbergen	NWS	Terrestrial	78.8347°N, 12.0841°E	Yes	Yes	2009	Hambrey and Huddart (1995)
Veidebreen ^{n^b}	Edgeøya	BEØ	Terrestrial	77.6639°N, 22.4641°E	No	Yes	2010	

Vestre Edgeøyjøkulen ^b	Edgeøya	BEØ	Terrestrial	77.8460°N, 22.6334°E	No	Yes	2010	
Vestre Torellbreen ^b	Spitsbergen	SS	Marine	77.1977°N, 14.4728°E	No	Yes	2011	
Veteranen ^b	Spitsbergen	NES	Terrestrial	79.3700°N, 17.5745°E	Yes	No	2010	
Vetternbre en ^b	Spitsbergen	NWS	Terrestrial (lake)	78.2767°N, 13.3031°E	No	Yes	2009	
Vonbreen ^{ab}	Spitsbergen	NWS	Terrestrial (lake)	79.2615°N, 13.9393°E	No	Yes	2011	
Winsnesbr een	Nordautlan det	NA	Terrestrial	79.7880°N, 22.1263°E	No	Yes	2011	

^aListed in Croot (1988a). ^bListed in Hagen et al. (1993). ^cAccording to Croot (1988a) and

Farnsworth et al. (2016; and references therein). ^dAs named in Farnsworth et al. (2016). ^eNot

possible to determine due to obscured imagery

Table 3 Number of total glaciers, glaciers >1 km² (both from Hagen et al. (1993)), documented surge-type glaciers (according to Croot (1988a) and Farnsworth et al. (2016; and references therein)), glaciers with crevasse-squeeze ridge (CSR) networks (according to Farnsworth et al., 2016) and glaciers with composite ridge systems as distributed by region (see Fig. 5). NWS = northwest Spitsbergen, NES = northeast Spitsbergen, CS = central Spitsbergen, SS = south Spitsbergen, NA = Nordaustlandet, BEØ = Barentsøya and Edgeøya. Percentages are out of the total glacier population in each region, apart from those marked by * that are calculated relative to the total glacier population in Svalbard

Regions	NWS		NES		CS		SS		NA		BEØ		Svalbard	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
All glaciers	704	32.2 *	201	9.2*	403	18.5 *	316	14.5 *	214	9.8*	345	15.8 *	2183	-
Glaciers >1 km ²	374	53.1	117	58.2	193	47.9	145	45.9	78	36.4	112	32.5	1019	46.7
Surge-type glaciers	78	11.1	23	11.4	43	10.7	111	35.1	11	5.1	14	4.1	280	12.8
CSR networks	225	32.0	71	35.3	60	14.9	199	63.0	3	1.4	54	15.7	612	28.0
Composite ridge systems	12	1.7	8	4.0	5	1.2	9	2.8	2	0.9	14	4.1	50	2.3
Surge-type glaciers plus previously undocumented surges ^a	241	34.2	78	38.8	83	20.6	239	75.6	14	6.5	56	16.2	711	32.6

^aPreviously undocumented surges are glaciers that display indicative surge geomorphology at their margins (CSR networks and composite ridge systems) but have not been observed to surge/documented as surge-type

Fig. 1 Location map of Svalbard showing distribution of composite ridge systems according to Croot (1988a) (white dots) and this study (black squares; listed in Table 2). Regions: NWS = Northwest Spitsbergen; NES = Northeast Spitsbergen; CS = Central Spitsbergen; SS = South Spitsbergen; BEØ = Barentsøya and Edgeøya; NA = Nordaustlandet.

Fig. 2 Examples of composite ridge systems as identified from aerial photographs. (a) Abrahamsenbreen; (b) Battyebreen; (c) Erikbreen; (d) Finsterwalderbreen; (e) Gandbreen; (f) Kuhrbreen (right) and Skrentbreen (left); (g) Penckbreen; (h) Usherbreen. Red arrows indicate generalised flow direction of the glaciers. See online version for figure in colour

Fig. 3 Examples of controlled moraines (cf. Evans, 2009) and fluvially-dissected moraine/ice-marginal sediment masses that could be misidentified as composite ridge systems. Controlled moraines at (a) Andreasbreen (78.6142°N, 12.1783°E) and (b) Greinbreane (77.9195°N, 16.0522°E). Fluvially-dissected moraine/sediment masses at (c) Elnabreen (79.1919°N, 14.0367°E) and (d) Instebreen (77.6566°N, 15.2470°E). Of these, (c) is listed as a composite ridge system in Croot (1988a) and all are listed as push moraines in Hagen et al. (1993). Red arrow indicates generalised flow direction of the glacier. Small back arrows in (b) highlight evidence for de-icing in the form of debris flows. See online version for figure in colour

Fig. 4 Examples of previously unreported composite ridge systems in Svalbard. (a) Augnebreen; (b) Gardebreen; (c) Koristkabreen; (d) Laubefjellebreen; (e) Mittag-Lefflerbreen; (f) Schweigaardbreen. Red arrow indicates generalised flow direction of the glacier. See online version for figure in colour

Fig. 5 Map showing distributions by region and numbers of: all glaciers, glaciers with an area >1 km² (both based on Hagen et al. (1993)), documented surge-type glaciers (according to Croot (1988a) and Farnsworth et al. (2016; and references therein)), glaciers with reported crevasse-squeeze ridge networks (according to Farnsworth et al. (2016)) and glaciers with composite ridge systems (this study). Regions: NWS = Northwest Spitsbergen; NES = Northeast Spitsbergen; CS = Central Spitsbergen; SS = South

806 Spitsbergen; BEØ = Barentsøya and Edgeøya; NA = Nordaustlandet. See online
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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5