Basal processes beneath an Arctic glacier and their geomorphic imprint after a surge, Elisebreen, Svalbard

Poul Christoffersen a,*, Jan A. Piotrowski b, Nicolaj K. Larsen b

a Centre for Glaciology, Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, Ceredigion SY23 3DB, UK
b Department of Earth Sciences, University of Aarhus, C.F. Møllers Allé 120, DK-8000, Aarhus C, Denmark

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Abstract

The foreground of Elisebreen, a retreating valley glacier in West Svalbard, exhibits a well-preserved assemblage of subglacial landforms including ice-flow parallel ridges (flutings), ice-flow oblique ridges (crevasse-fill features), and meandering ridges (infill of basal meltwater conduits). Other landforms are thrust-block moraine, hummocky terrain, and drumlinoid hills. We argue in agreement with geomorphological models that this landform assemblage was generated by ice-flow instability, possibly a surge, which took place in the past when the ice was thicker and the bed warmer. The surge likely occurred due to elevated pore-water pressure in a thin layer of thawed and water-saturated till that separated glacier ice from a frozen substratum. Termination may have been caused by a combination of water drainage and loss of lubricating sediment. Sedimentological investigations indicate that key landforms may be formed by weak till oozing into basal cavities and crevasses, opening in response to accelerated ice flow, and into water conduits abandoned during rearrangement of the basal water system. Today, Elisebreen may no longer have surge potential due to its diminished size. The ability to identify ice-flow instability from geomorphological criteria is important in deglaciated terrain as well as in regions where ice dynamics are adapting to climate change.

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Introduction

Glacier surges are highly dynamic events characterized by an abrupt increase in ice-flow velocity by up to several orders of magnitude. Surges are often considered a recurrent instability of ice flow leading to bimodal glacier motion (Meier and Post, 1969). The highly non-linear behavior of surging glaciers stems from threshold conditions in the control of basal motion. Much research has addressed the role of subglacial water (Kamb, 1987; Engelhardt and Kamb, 1997, 1998; Kavanaugh and Clarke, 2000, 2001) and its lubricating effect on ice flow (Clarke, 1987; Kamb, 1991; Fisher et al., 1999; Tulaczyk et al., 2000). Identification of a single specific surge mechanism has been unsuccessful so far, partly because there are regional differences in surge characteristics (Murray et al., 2003). Surges in Svalbard build up gradually and terminate slowly over several years (Murray et al., 1998). In contrast, surges in Alaska, as seen in the particularly well-documented 1982–1983 surges of Variegated glacier, can build up over a short period of a few months and terminate very abruptly in just a few hours (Kamb et al., 1985). The differences in basal conditions (between polythermal and temperate glaciers) may well explain why surge mechanisms seem different (Murray et al., 2003). The thermal evolution of weak till beds may control Svalbard surges (Murray et al., 2000; Fowler et al., 2001) while subglacial water flow tortuosity (Kamb, 1987) may control Alaskan surges. Release of englacially stored meltwater may be a key factor in both regions (Lingle and Fatland, 2003; Murray et al., 2003).

Although much glaciological insight has been gained by studies in front of glaciers known to have surged (Bennet et
it is still uncertain whether surge mechanisms can be derived from geomorphological studies alone. Geomorphological criteria for identification of surging glaciers have been proposed among others by Evans and Rea (1999) and it is becoming increasingly important to test these criteria. The main objective of this study is to identify ice-flow instability, e.g., surge-related events, for a retreating glacier with unknown surge record. We compare the landform assemblage from the foreground of Elisebreen with hypothesized geomorphological criteria derived from observations of surging glaciers elsewhere and find that ice-flow instability can be inferred when geomorphological criteria are combined with sedimentological data.

Changing dynamics of polythermal glaciers in Svalbard

In the maritime-arctic climate of Svalbard, glaciers need to gain a thickness greater than about 100 m before warm-based conditions can arise (Hambrey et al., 1999; Murray and Porter, 2001). Jiskoot et al. (1998, 2000) estimated that a little over 10% of the glaciers in Svalbard have surge potential and their statistical analysis showed that long glaciers overlying weak sedimentary rocks, such as shale and mudstone, have the highest probability of surging. Murray et al. (2000) suggested that surge propagation in Svalbard could be controlled by the transition between unfrozen and frozen bed. Fowler et al. (2001) therefore proposed thermally controlled surge mechanism for Svalbard glaciers. Investigations of Bakaninbreen showed that surge propagation probably occurred as sliding and deformation of a thin layer of thawed sediment, just centimeters to decimeters thick (Murray et al., 2000; Porter and Murray, 2001). Polythermal valley glaciers terminating on land may have displayed similar characteristics in the past when ice was thicker and the bed warmer (Hansen, 2003). Ice dynamical regime may have subsequently changed due to glacial recession following the end of the Little Ice Age ca. 100 yr ago and the progression of anthropogenic climate warming (Hambrey et al., 2005; ACIA, 2004). Understanding the response of polythermal glaciers to climatic variability is an integral part of assessing freshwater release and contribution to sea-level rise from Svalbard.

Elisebreen and other glaciers in Kaffiøyra

There are six small valley glaciers in Kaffiøyra, a coastal plain in West Svalbard bordered by two major tidewater glaciers, Aavatsmarkbreen to the north and Dahlbreen to the south (Fig. 1). The lengths of these valley glaciers are approximately 2–10 km and they retreat at a rate of 6–26 m yr⁻¹ (Lankauf, 2002). Polythermal valley glaciers have been studied for several decades, among others (Boulton, 1972) by Forman (1989), Grzes and Lankauf (1997), Marciniak and Marszelewski (1991), Olszewski (1977), and Zapolski (1977). To our knowledge, no surge has taken place during this period.

Elisebreen is the largest of the six glaciers in Kaffiøyra (Fig. 2a). A large network of moraine ridges crisscrosses its glacially remoulded foreground (Figs. 2b and c). These landforms and their abundance stand in striking contrast to the
barren foregrounds of the adjacent valley glaciers all of which are smaller in size. Elisebreen is approximately 7 km long and 1.2–1.8 km wide, and its surface area is around 12 km². The margin of Elisebreen is situated about 30–60 m above sea level. Studies of raised beach deposits have shown that the Lateglacial ice retreat was followed by marine transgression up to 48 m above the present sea level (Forman, 1989; Niewiarowski et al., 1993). The coastal plain of Kaffiøyra is thus composed of a succession of marine sediments that in some places have been overridden by glaciers at least once during the Little Ice Age. A prominent push moraine complex marks the maximum advance of Elisebreen about 1.3 km from its present margin. At present, the glacier retreats by about 26 m yr⁻¹ (Lankauf, 2002) and exposes a flat to gently undulating till plain at 30–40 m above sea level.

Geological and geomorphological investigations of the proglacial terrain were performed during two field seasons. The geology of the study area was established from a 70-m-long and 5-m-deep river section in the central till plain (Fig. 2a) as well as from several smaller sections through the terminal moraine. Two radiocarbon datings were done on shell fragments from the marine gravel. The location, size, and orientation of different types of proglacial ridges were mapped with GPS and compass. A series of small pits (>10) were excavated at selected sites in the ridges. Sedimentological and structural descriptions of glacial deposits, beyond what is presented here, are subject of work in progress.

**Geological setting**

Four major sedimentary units were mapped in a river section dissecting a gentle hillock in the central part of the valley. These units include:

- **Formation 1**: Fluvial deposits consisting of poorly sorted, matrix-supported sand and gravel, with occasional lenses of gravelly silt and silt. The lower part of this unit is characterized by a well-developed cross-stratification and scour marks, indicating a high-energy fluvial environment.
- **Formation 2**: Aeolian sand dunes, characterized by well-sorted, medium-grained sand with a regional stratification and a prominent set of foreset bedding. These dunes are interpreted as the result of windblown sediment deposition in a sandplain.
- **Formation 3**: Lake deposits, consisting of fine-grained silt and clay layers with occasional lenses of peat. These deposits are interpreted as periods of lake formation during glacial recessions.
- **Formation 4**: Tillite, consisting of homogeneous, finely lenticular till with occasional pebbles and cobbles. The till is interpreted as the result of glacial erosion and deposition.

The map shows the distribution of these formations across the study area, with Formation 1 predominating in the western part, Formation 2 in the central area, Formation 3 along the eastern boundary, and Formation 4 in the easternmost part of the study area.
glacier foreground (Fig. 3). The lowermost unit (unit 1) overlying the bedrock is a 0.4-m-thick, occasionally laminated, greyish-green clayey silt (19% sand, 67% silt, and 14% clay) with marine shells and shell fragments. It is overlain by an up to 0.5-m-thick well-sorted, well-rounded openwork gravel (unit 2) grading upwards into a clast-supported gravelly sand with abundant fragments of re-deposited mollusc shells (unit 3). The gravelly sand is parallel bedded with individual beds usually decimeters thick. The beds dip in accord with the ground surface of the hillock, giving the appearance of an onion-like structural arrangement. Shell fragments from unit 3 were dated to 10,980 ± 60 14C yr B.P. (Poz-700) and 10,820 ± 65 14Cy r B.P. (Poz-694), which is in the bracket of radiocarbon dates on marine shells from other parts of Kaffiøyra (Niewiarowski et al., 1993). In the topmost 30 cm, this deposit is cryoturbated and contains frost-shattered boulders. The periglacial structures are well preserved and display no signs of glacier-induced deformation despite being over-ridden by ice. The uppermost unit (unit 4) is a stony diamicton with fine-grained matrix (37% coarser than sand, 28% sand, 26% silt, and 9% clay). This unit constitutes a thin drape of glacially re-deposited sediment with erratics from the local bedrock composed of the Precambrian Haeklahook Formation with characteristic tillites, and various tertiary formations consisting of sedimentary rocks as mudstone, siltstone, limestone, and shale (Hjelle, 1993).

We interpret units 1, 2, and 3 as a concession of marine sediments deposited during the Lateglacial/early Holocene transgression. Unit 4 is a layer of basal till, which is the source material of the landform assemblage described below. Texture of this till is largely the same regardless of the landform it occurs in (Fig. 4).

**Landforms**

The foreground of Elisebreen reveals a high concentration of distinctly different landforms. Several hundred small moraine ridges, approximately 0.1–1 m in height and up to 200 m in length, protrude from the ground surface (Figs. 2b and c). The ridges are composed of the same till source (Fig. 4b) and they can be divided into groups based on geomorphic appearance.

**Ice-flow parallel ridges (flutings)**

The most prominent landforms in front of Elisebreen are linear moraine ridges oriented parallel to ice-flow direction. Several hundreds of these closely spaced and easily discernible ridges are distributed throughout the foreground (Figs. 2b and c). They vary in height from just a few centimeters to a little more than 1 m (Figs. 5a, b, c, and e) and in length from a few meters to almost 200 m. The ridges have a relatively constant width/height ratio of about 5, but their lengths vary extensively. Length/width ratios are

![Figure 3. Photograph (a) and drawing (b) of a river cut through proglacial sedimentary succession in front of Elisebreen. A thin drape of till (shaded) covers stratified units of sand and gravel, which overlie a layer of clayey silt. View is towards SE and location is given in Figure 2a. Synthetic log (c) shows the major lithological units (1–4) of this site.]
spread from about 5 to >100 with average around 25. A comparison to landform geometries measured at other glaciers is shown in Figure 6. The ridges have two subforms: they come with or without a boulder on their ice-proximal end. Boulders located in front of the ridges are polished and striated parallel to the ridge orientation (Fig. 5d). There is no direct correlation between boulder size and landform geometry. Most of the boulders are found at the end of ploughing trails (Fig. 5d), which deepen progressively towards the boulders. The ploughing marks are largely filled with till.

The ridges are mainly composed of material from the adjacent, thin till layer, which overlies marine sediments along a subhorizontal contact surface (Figs. 7a–c). The landform relief is therefore given predominantly by variations in till thickness. A string of test pits excavated on two separate sites revealed diapirs or up-thrusts of marine gravel immediately down-ice from the boulders (Fig. 7d), and tongues of till intruded from the sides. Till and marine sediment become progressively mixed down-ice from the boulders (Fig. 7c), but we observed centimeter- to decimeter-large inclusions of marine sediment transported more than 50 m from the boulder site. Till fabric measured on 14 sites in one fluting reveals a strong ridge-parallel orientation (mean S1 = 0.833) and low dip angles evenly distributed either in up-ice or down-ice direction (Fig. 8). Fabric at the transition between till plain and landform is weaker (mean S1-value from 11 sites is 0.760).

The ice-flow parallel ridges with boulders on their proximal ends are interpreted as classic flutings (e.g., Benn
and Evans, 1998, p. 426). The measured clast fabric is consistent with observations of flutings in other field sites (e.g., Rose, 1989; Benn, 1994; Eklund and Hart, 1996). Ice-flow parallel ridges without initiating boulders are also interpreted as flutings, although they contain no evidence of ploughing or thrusting. These flutings (Fig. 5b) are likely formed by sediment infill of basal ice cavities, which may have formed by ice sliding over an irregular surface, e.g., bedrock protrusions. This mechanism is similar to the groove-ploughing theory for production of large glacial lineations by fast ice-stream flow (Clark et al., 2003).

The subglacial conditions from which flutings develop are uncertain. Their elongation ratios exceed values proposed to be indicative of fast ice flow (Stokes and Clark, 2001, 2002), and fast ice flow depends on warm-based conditions (Clarke et al., 1984; Clarke, 1987). Yet, the landform is observed in both warm-based and cold-based environments (Gordon et al., 1992; Evans and Twigg, 2002). Structural data from our field site indicate two separate mechanisms whereby sediment accumulated in the lee of the lodged boulders. These are up-thrusting from below and inflow from the sides. We speculate that while thrusting can occur under any subglacial thermal field, oozing-in from the sides depend on warm-based conditions and high pore-water pressure, which yields low basal shear strength.
Another prominent network of moraine ridges has orientation oblique to ice-flow direction (Figs. 5a and g) with an offset of about 20–30° (Fig. 9). These landforms (Figs. 7a and e) are regularly distributed throughout the proglacial till plain and superimpose the ice-flow parallel landforms described above. The ridges range from 0.3 to 0.6 m in height and from 10 to 50 m in length. They often have slightly undulating crests and lack the perfect linearity typical for flutings. They are nonetheless composed of the same basal till. Formation of the oblique ridges can be observed at present at the retreating ice terminus (Fig. 5f).

Ice-flow oblique ridges are interpreted as crevasse-fill ridges, which have either basal or supraglacial source of debris (Sharp, 1985; Bennett et al., 2000). Here, compositional similarity to the surrounding basal till shows that the former source is most likely. Fracture mechanical analysis demonstrates that basal crevasses can form when basal water pressure is close to the ice overburden pressure (Weertman, 1980; van der Veen, 1998). Pore-water pressure a few bars below the ice overburden pressure was observed during the 1982–1983 surge of Variegated Glacier (Kamb et al., 1985) and similar conditions are found beneath ice streams in Antarctica (Engelhardt and Kamb, 1997, 1998). Crevasse-fill ridges composed of basal sediment may be a diagnostic feature of past surges if they are found in front of surge-type glaciers. Basal crevasses are, however, not easily identified due to their subglacial origin and their closure from compressional stresses arising in the slow-moving quiescent phase. Basal crevasse-fill has nonetheless been interpreted from studies at other localities in Svalbard (Woodward et al., 2002) as well as studies in Canada (Clarke et al., 1984), Alaska (Ensminger et al., 2001), and Iceland (Sharp, 1985).

There is also morphological evidence of till ridges orientated transverse to ice-flow direction in the study area. These ridges are, however, much more subdued and less frequent than the landforms described above. Their height is typically 0.1–0.3 m and their length is generally less than 20 m. We interpret these ridges as a result of melt-out of debris-rich thrust faults (Hambrey et al., 1999). Observations from the glacier terminus show that thrust faults have a gentle dip and tend to strike perpendicular to ice-flow direction due to high compressional stresses arising at the warm/cold thermal transition near the terminus.

Meandering ridges (conduit infill)

This type of ridges is characterized by a meandering shape quite similar to that of an esker (Figs. 5g, 7a, and e). The undulating crests of these ridges are typically less than 0.5 m high. Their lengths range from a few meters to
Figure 7. Sediment structural data from a fluting-meandering ridge-crevasse-fill ridge assemblage. (a) Landform spatial arrangement and cross sections observed in excavated trenches. Numbers refer to fabric measurements shown in Figure 8. View direction in cross sections is down-ice. (b–d) Geological composition seen in cross sections with view direction up-ice. Note the gravel diapir projecting through the till behind the initiating boulder in panel d; (e) landform assemblage viewed down-ice before excavation. The same assemblage is shown in the opposite direction in Figure 5g.

Figure 8. Fabric measurements from locations shown in Figure 7a. Lower hemisphere equal-area projection, 25–40 stones measured on each site. Si eigenvalues indicate fabric strength (Mark, 1973). Symbols denote fabric measurements in fluting (F), meandering ridge (M), and till plain (P).
several tens of meters. Despite similarity to eskers we found no fluvial sediment in these landforms. They are, just like the other ridges described above, composed of basal till that overlies marine gravel along a subhorizontal interface (Fig. 7a). Till fabric measured at 14 locations in one meandering ridge is strong (mean S1 = 0.808; Fig. 8) and uniformly ice-flow parallel, which indicates that it exhibits an active-ice signature similar to the flutings and the flat ground-moraine surface. Meandering ridges are often superposed by the crevasse-fill ridges and located alongside the flutings (Fig. 7).

We interpret this group of ridges as infill of an abandoned water conduit system. Their composition and structure, together with the absence of fluvial sediment, indicate that meltwater became distributed within the till and that pore-water pressure rose to the point where material behavior became fluid-like, i.e., water content above the liquid limit of the sediment (Mitchell, 1993). Till thus started to ooze into the abandoned water conduit system following an instantaneous cessation of water flow and pressure drop in the channel. A similar observation of conduit infill was made in front of an Icelandic glacier that surged in 1991 (Bennett et al., 2000).

Other landforms

A large terminal moraine complex, approximately 20 m high and 50 to >100 m wide (Fig. 10a), marks the maximum extent of Elisebreen. The complex is composed of multiply stacked but internally intact, fossil-bearing marine sediments similar to those exposed in the river section shown in Figure 3. A large ice-cored moraine and hummocky terrain with multiple topographic highs are found immediately up-ice from the thrust moraine (Fig. 10b). The till plain, which is located between the hummocky terrain and the ice margin, features several drumlinoid hills. The drumlinoids, which lack a typical stoss-and-lee-side asymmetry, are about 100 m long, 20 m wide, and 3–5 m high (Fig. 2a). Preservation of original strata in the stacked succession of the terminal moraine complex indicates that glaciotectonic thrusting (also noted by Niewiarowski et al., 1993; Olszewski, 1977) occurred under permafrozen conditions. Given thawed conditions, the clay layer in the marine succession (Fig. 3) would most likely be too weak to remain intact during displacement. The moraine complex may have been deposited around or just after the Little Ice Age when Elisebreen was larger.

Discussion

Surge-related landforms have mainly been explored in front of glaciers with a known surge record. It remains uncertain whether these landforms can be used to infer ice-flow instability for glaciers with no such record. Our observations comply with existing geomorphological cri-
Common to the landform assemblage outlined above is formation by lateral entrainment of soft, deformable till into basal ice cavities, crevasses, and water conduits abandoned in response to a rearrangement of the basal water system, possibly to a linked cavity configuration (Kamb, 1987). It is probable that Elisebreen experienced a surge (or a series of surges) during the Little Ice Age or shortly thereafter, ca. 100 yr ago, when ice was thicker and the bed warmer. The overall smoothness of Elisebreen’s foreground including ice-flow parallel lineaments stands in distinct contrast to other valley glaciers in Kaffiøyra, which have rugged foregrounds mainly composed of chaotically scattered angular debris. Such different appearances of glacier foregrounds may result from different ice-flow regimes with fast flow in the former case (Hart, 1999). In contrast to ice-flow parallel lineaments and conduit infill, which are individually ambiguous indicators of fast ice-motion, crevasse-fill ridges with a subglacial source may act as a more direct piece of evidence of past ice-flow instability as basal crevasses only form when glaciers are close to flotation due to subglacial pore-water pressure close to the ice overburden pressure (Weertman, 1980; van der Veen, 1998).

Historical accounts of surges in Iceland indicate reduced surge potential in response to glacial recession since the early 1900. The same may be the case in Svalbard. A transition from surge to non-surge glacier potential was for instance identified on Midre Loevenbreen, which is a small valley glacier ca. 25 km northeast of Elisebreen (Hansen, 2003; Hambrey et al., 2005). The absence of surges in recent time together with ongoing glacial retreat at a rate of ca. 26 m yr⁻¹ suggests that Elisebreen’s surge potential may no longer exist. The glacier appears to be thinning rather than rebuilding mass and this may be related, at least partly, to the Arctic amplification of global warming. The projected warming of the Arctic is 4–7°C over the next 100 yr with an increase in precipitation falling mainly as rain (ACIA, 2004).

Conclusions

Fast glacier flow is commonly associated with basal lubrication arising from pore-water build-up in fine-grained subglacial sediment (Clarke et al., 1984; Kamb, 1991; Tulaczyk et al., 2000). Bedrock composed of fine-grained sedimentary material is thus likely to generate surge-favorable conditions (Jiskoot et al., 2000). However, with its ~65% of sand and gravel, and ~35% of silt and clay, the Elisebreen till is very different from the fine-grained West Antarctic sub-ice stream tills in which the content of sand and gravel is ~45%, while silt and clay constitute ~55% (Tulaczyk et al., 1998). This indicates that fast glacier flow may also occur from sliding over coarse-grained sediment.

The well-preserved sedimentary structures in the marine deposits underlying the thin till layer support the potential role of subglacial permafrost beneath surging glaciers in Svalbard. It is likely that Elisebreen surged over a thin layer of thawed till while the underlying marine sediments remained largely frozen and thus undisturbed apart from scattered ploughing by boulders that were large enough to penetrate through the till layer. A very thin till layer was also observed beneath Bakaninbreen (Murray and Porter, 2001; Murray et al., 2000), whose surge may have terminated from a drop in water pressure associated with loss of basal meltwater into permafrost discontinuities (Smith et al., 2002). Termination of a surge of Elisebreen may also have been caused by (1) loss of basal lubricant into basal cavities and bottom crevasses opening in response to accelerated ice flow, and (2) drop in subglacial pore-water pressure from collapse of a linked cavity system and a return to a channelized subglacial drainage system (Kamb, 1987).

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