Glacial geomorphology of the terrestrial margins of the tidewater glacier, Nordenskiöldbreen, Svalbard

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Abstract: A 1:4000 map of the terrestrial margins of the foreland of Nordenskiöldbreen, based on a 2013 high-resolution satellite image, depicts a polythermal glacial landsystem containing a record of the landform signatures of individual ice flow units that operate within the glacier snout. A 1:700 map provides a detailed overview of fluted terrain, based on UAV images captured in 2014, and displays multiple sets of flutes that record late stage changes in the ice movement direction. The pattern of landforms lying inside the LIA latero-frontal moraine on the northern side of the fjord comprises a fluted till surface, which in turn grades into ice moulded bedrock. This signature records the recession of a single, wide ice flow unit, which was characterised by limited incorporation of subglacial material and restricted delivery of supraglacial debris. Inside the latero-frontal moraine on the south side of the fjord, a fluted surface is subordinate to a pronounced and large ice-cored moraine complex related to the confluence of five narrower ice flow units, each of which transported significant quantities of englacial and supraglacial debris at their suture zones as a series of longitudinal debris stripes. The suite of foreland landforms is diagnostic of both temperate subglacial and frozen-snout conditions, indicating the operation of a warm polythermal glacier fed by multiple flow units during the Little Ice Age.

Keywords: polythermal glacier, Spitsbergen, geomorphology, remote sensing, UAV, ice-cored moraine

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1. Introduction

Nordenskiöldbreen, an outlet of the Lomonosovfonna plateau, is the largest and only calving glacier in the Billefjorden basin in central Spitsbergen. The glacier flows around nunataks, Terrierfjellet and Ferrierfjellet, and then descends steeply towards Adolfbukta, developing a ~3.5 km wide calving front flanked by south and north terrestrially terminating margins (Figure 1). They have retreated extensively since the end of the Little Ice Age (LIA) (Rachlewicz, Szczuciński, & Ewertowski, 2007), in a manner similar to many other marine- and land-terminating glaciers on Svalbard (e.g. Błaszczyk, Jania, & Kolondra, 2013; Małecki, 2013; Mansell, Luckman, & Murray, 2012; Nuth, Kohler, Aas, Brandt, & Hagen, 2007; Nuth et al., 2013). De Geer (1910, after Slater, 1925) reported a stationary ice margin of Nordenskiöldbreen between 1892 and 1896, located at the maximum historical limit, and a slight retreat (100-200 m) between 1896 and 1908. The map presented in Slater (1925) shows a more rapid retreat of the marine part of the margin between 1908 and 1921, whereas land-based margins were still located close to the maximum historical limit. Between 1896 and 2013, the northern margin of clean glacier surface retreated about 1.4 km in total, whereas the southern margin retreated about 3.5 km. The area covered by glacier around Adolfbukta shrank by about 16 km^2 since the termination of the Little Ice Age. Some 6.7 km^2 of this recession was from the terrestrial margins, areas that are the subject of the mapping here.

Contemporary terrestrial parts of the glacier exhibit very different characteristics. The ice is delivered to the northern margin by only a single, 3.9 – 5.0 km wide flow unit with limited supraglacial debris cover, flowing between Terrierfjellet and DeGeerfjellet. The southern margin is fed by several narrower flow units, including the tributary glacier Gerritbreen, showing a more extensive debris cover. Therefore, Nordenskiöldbreen was targeted for landsystem mapping so as to assess the landform imprints related to the complex dynamics of an outlet glacier with multiple flow units and both tidewater and terrestrial snout characteristics.

Nordenskiöldbreen has been the subject of a number of glaciological (Den Ouden et al., 2010; Hagen, Eiken, Kohler, & Melvold, 2005; Rachlewicz et al., 2007; Van Pelt et al., 2012; van Pelt et al., 2014) and geomorphological (Boulton, 1970, 1976; Kłysz, 1988; Kłysz, Lindner, Marks, & Wysokiński, 1989; Slater, 1925; Stacke, Mida, Lehejček, Tóthová, & Nývlt, 2013; Strzelecki, 2011) studies, including some geomorphological mapping (Karczewski et al., 1990; Kłysz et al., 1989) as well as offshore sedimentological and bathymetric studies (Baeten, Forwick, Vogt, & Vorren, 2010; Plassen, Vorren, & Forwick, 2004; Szczuciński, Zajączkowski, & Scholten, 2009). However, most of the previous work concentrated on the northern margin, and so far no coherent map of glacial geomorphology has been produced for both terrestrial parts of the foreland and hence no comparison has been made between the landform signatures of these two clearly contrasting parts of the snout.

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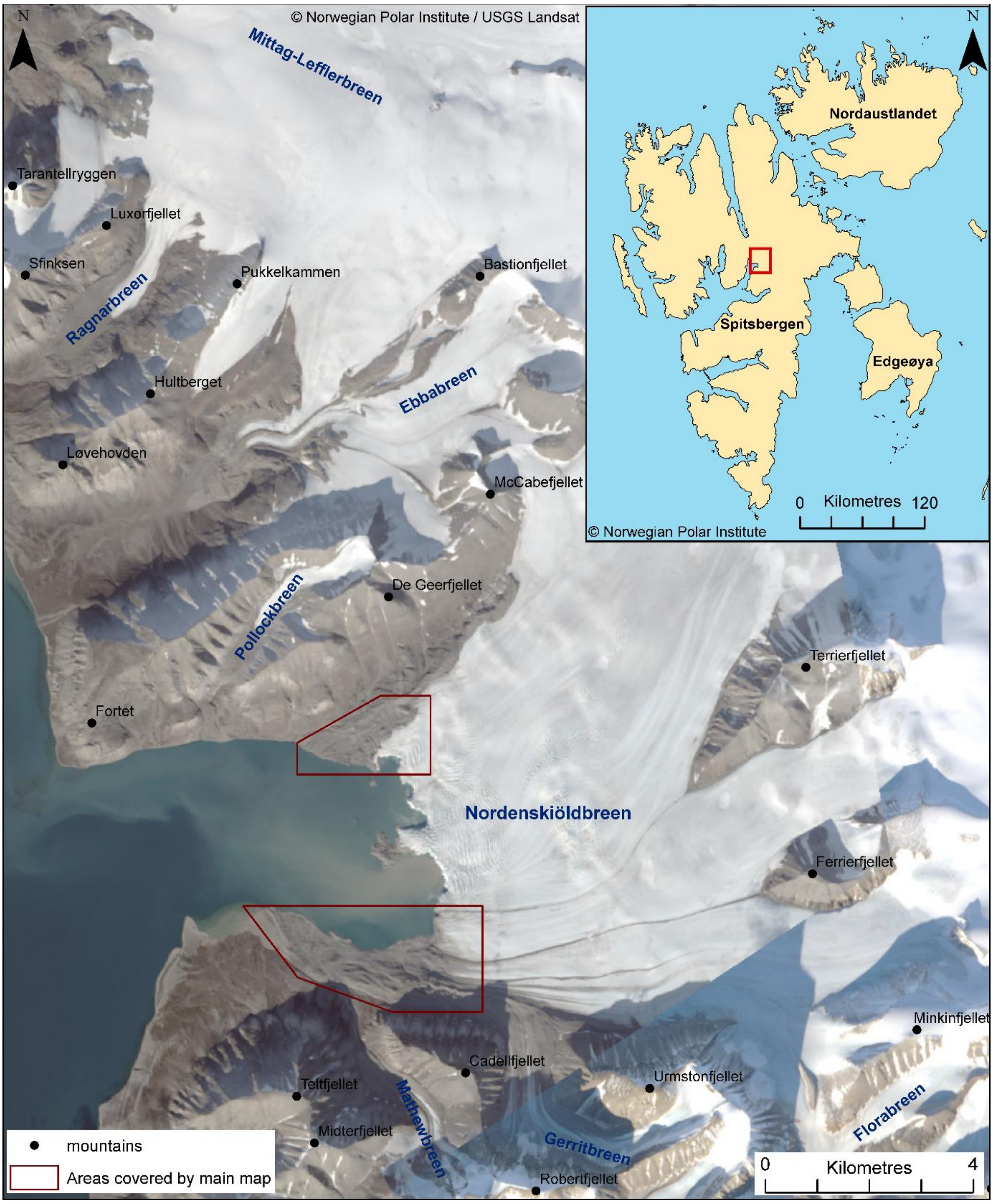

Figure 1. Location of the study area with extent of the main map 1 marked in dark red. Basemap data and background satellite imagery provided by © Norsk Polar Institute (http://www.npolar.no).

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The purpose of producing a detailed map of both terrestrial parts of Nordenskiöldbreen was twofold:

(1) To provide a context for examining the contrasting characteristics of two parts of the same glacial foreland, one of which (the northern snout margin) was influenced by a single flow unit and the other (the southern snout) created by the interaction of several smaller flow units
(2) To compare field surveys carried out between 2005 and 2014 with recently available high-resolution satellite imagery and UAV-derived data in order to chart recent landscape change in rapidly deglaciated terrains.

2. Data, methodology and map production

2.1. Datasets and data processing

A glacial geomorphology map (Main Map 1) has been produced at a scale of 1:4000 based on 2013 high-resolution satellite imagery captured by the WordView-2 satellite of Digital Globe. The obtained scene was a bundle, comprising a panchromatic band (0.5 m Ground Sampled Distance – GSD) and 4 multispectral bands (2.0 m GSD). The image was captured on July 17, 2013 at 6:48 pm, which resulted in low sun elevation (15.5^{o}), an advantage for mapping as low-angle sunlight emphasises landform shapes and facilitates landform interpretation. It was orthorectified using a DEM produced from 2009 aerial photographs and pansharpened to produce a 4-band multispectral image with 0.5 m GSD.

In addition, detailed mapping of complex flutings (Main Map 2) has been conducted based on a second dataset, which was acquired by UAV during aerial surveys conducted in July 2014. The images were taken using a quadcopter equipped with a 14MP camera. Surveys were flown at an altitude of 50 m, resulting in images with 0.02 m GSD. A total of 400 images were collected and subsequently processed in Agisoft Photoscan, utilizing a structure from motion (SfM) approach. Processing followed the workflow proposed by Evans, Ewertowski, and Orton (2015b) and resulted in generation of an orthomosaic (0.02 m GSD) and a digital elevation model (0.04 m GSD), covering about 0.5 km^2 of the sample area of flutings and associated ice-moulded bedrock.

2.2. Map production

Mapping of the glacial geomorphology combined the analysis of satellite imagery with fieldwork-based investigations, which were carried out during scientific expeditions in 2005, 2007, 2013 and 2014. In the case of ambiguous features, historical aerial photographs from 1936, 1960/61, 1990 and 2009 (Norsk Polar Institute) were used to ensure accurate observation and interpretation. Such a combined approach, linking remote sensing data with direct field

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observations, has been successfully applied for the mapping of glacial landforms in various environmental settings (e.g. G. L. Bennett, Evans, Carbonneau, & Twigg, 2010; Boston, 2012; Brown, Evans, & Evans, 2011; Darvill, Stokes, Bentley, & Lovell, 2014; Evans, Ewertowski, & Orton, 2015a; Evans et al., 2015b; Evans, Twigg, Rea, & Shand, 2007; Pearce, Rea, Bradwell, & McDougall, 2014). Geomorphic features were vectorised in ArcGIS and stored in a file geodatabase. Three different feature datasets were generated:

1) General surficial map units (e.g. glacier ice, sea, fluted till surface) were stored as polygons.
2) Individual landforms (debris flows, large channels, moraine ridges, depressions), which were large enough to be represented as polygons in the scale chosen for the final presentation (1:4000), were also stored as polygons.
3) Small features (narrow channels, debris flow tracks, moraine structures), which were too small to be visualised as polygons at 1:4000 scale, were stored as lines.

3. Sediment-landform associations

3.1. Moraines

The three main morphological moraine units are identified on the glacier foreland based on the 1:4000 scale map (Main Map 1). They were divided according to their relief, stability and inferred amount of ice content. The outer and oldest moraine belt marks the LIA-maximum of Nordenskiöldbreen (Kłysz et al., 1989; Rachlewicz et al., 2007; Slater, 1925). Analysis of historical aerial photographs indicates that this external belt has been a stable landscape component since at least 1960. It, most probably, is still ice-cored; however, the amount of dead-ice and thickness of the debris cover are unknown. Morphologically the outer moraine belt takes the form of multiple (north side, Figure 2a) or single (south side, Figure 2b) ridges between 10-30 m high and 60-100 m wide, forming high relief latero-frontal moraine semi-arcs around the northern and southern parts of the glacier snout.

Two other groups of morainic deposits occur only at the southern part of the glacier foreland. Immediately ice proximal to the outer moraine ridge, a zone of hummocks, ponds and depressions occurs (Figure 2c, d), which is classified as a degraded ice-cored moraine with no or low dead-ice content, forming a moraine-mound complex *sensu* Glasser and Hambrey (2003).

Finally, the most significant geomorphological assemblage on the southern part of Nordenskiöldbreen is a large and complicated complex of recent and fully ice-cored moraine (Main Map 1). Morphologically it takes the form of a 600-800 m wide belt consisting of former individual flow units, which are still recognizable due to the occurrence of linear debris patterns or controlled moraine (see below). It shows a strongly asymmetric transverse profile with a gentler slope towards Adolfbukta and a much steeper slope towards the valley side. The elevation of the whole complex increases in the up-glacier direction, reaching 250 m a.s.l. along

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the current glacier margin. Four wide but relatively low-relief ridges observed within the moraine complex are interpreted as overridden ice-cored moraines or traces of former looped moraines associated with individual ice flow units (Main Map 1).

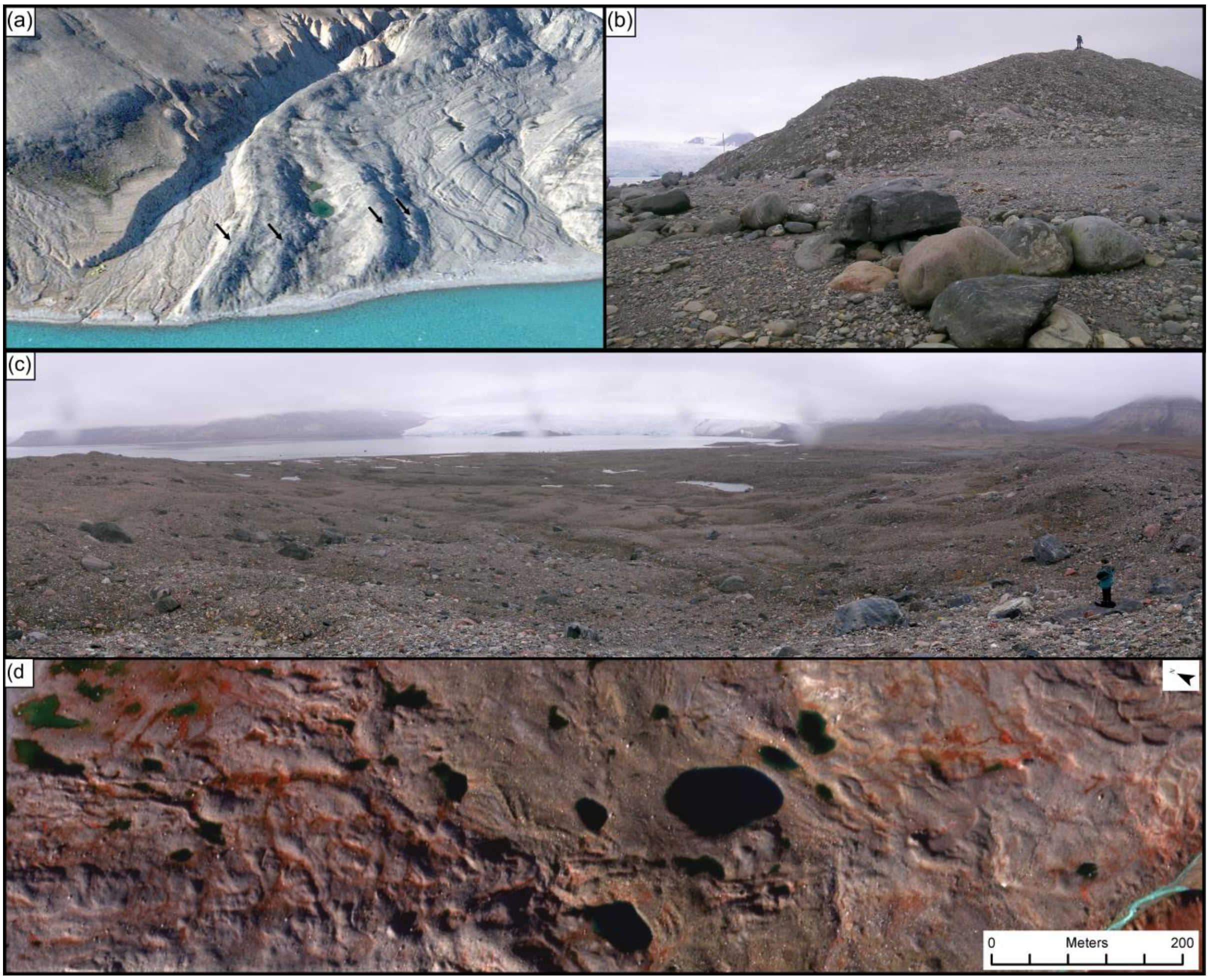

Figure 2. Moraine complex: (a) oblique view depicting multiple ridges of the outer moraine complex at the northern side of the fjord; (b) single ridge at the southern side of the fjord (person for scale); (c) Degraded ice-cored moraine complex on southern foreland - ground-view panorama showing chaotic arrangement of depressions and ponds; (d) Degraded ice-cored moraine complex on southern foreland - satellite imagery showing inactive debris flows, ponds and depressions.

The recent ice-cored moraine complex is a controlled moraine (sensu Evans, 2009), exhibiting clearly visible linear structures on its surface (Figure 3d,e). They are mapped as lineations (inherited glacial structures) and their spatial distribution is dictated by the confluence of three narrow flow units from Nordenskiöldbreen and two other flow units emanating from Gerritbreen (a tributary glacier emerging from a side valley). The lineations are continuations of longitudinal foliations visible on the glacier surface further up valley (see Section 3.5). In

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some places, the groups of lineations formed patterns, which still reflect the shape of the individual flow units (Figure 3d).

Surface fractures and cracks related to dead-ice melting, clearly indicate the presence of ice-cores. They are also spatially associated with large collapsing edges, related to the development of enlarging drainage pathways emerging through the moraine (Figure 3b).

The melting of the recent ice-cored moraine complex is most intensive along its downslope margin, with drainage flowing down the topographic gradient towards the bay. It results in numerous active debris flows, which create a belt of very actively transformed moraines, full of debris flow tracks, lobes and scarps (Figure 3a).

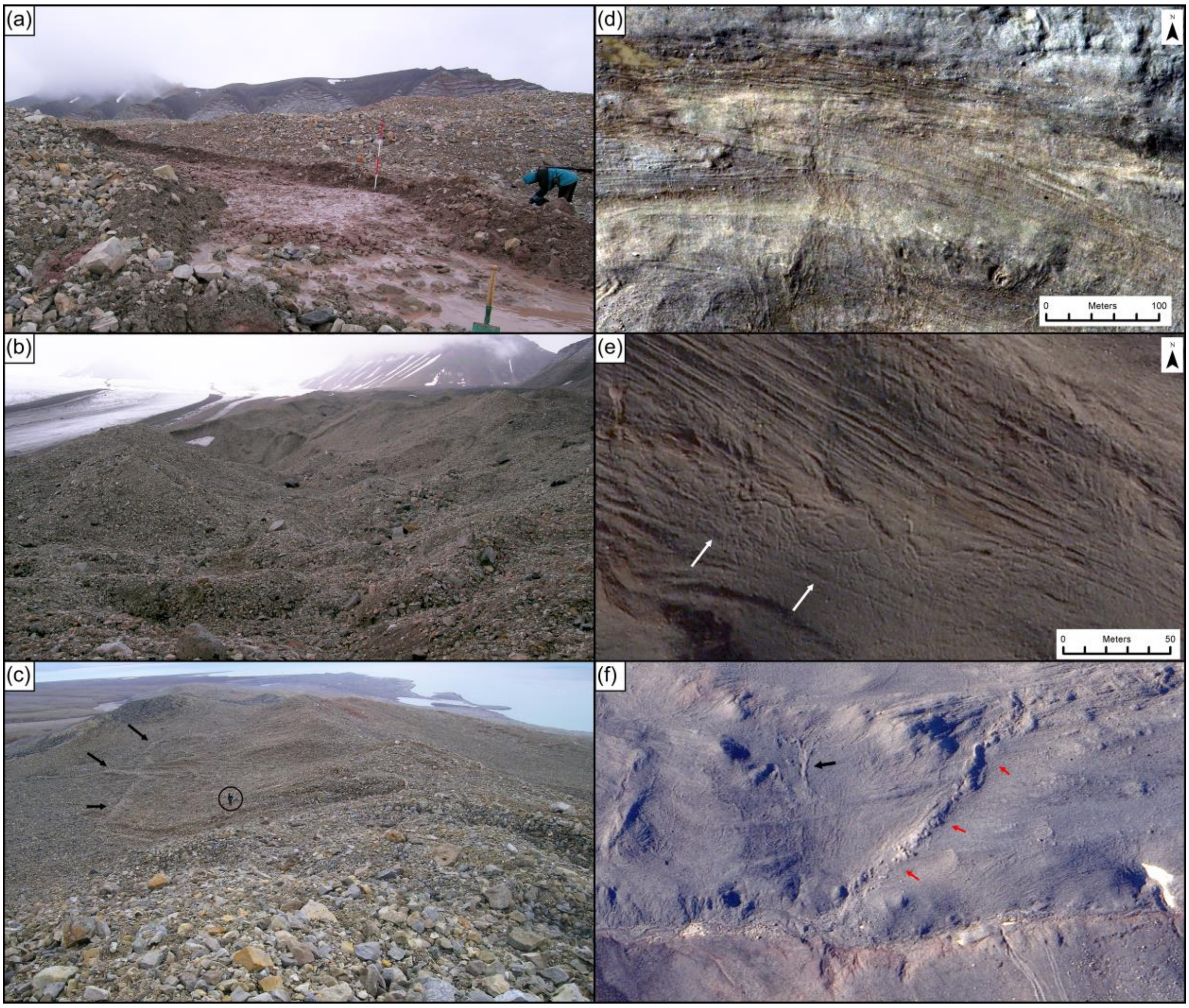

Figure 3. Ice-cored moraine complex on southern foreland: (a) active debris flow degrading inner part of the complex; (b) large depressions surrounded by collapsing edges, related to drainage through the moraine; (c) small dendritic features, with confluences marked by black arrows. Note that these features are more visible from birds-eye view in Figure 3f; Person (for scale) is encircled) (d) Glacially inherited lineations visible on the surface of the ice cored moraine; (e) longitudinal lineations and patterns of dendritic features (marked with

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white arrows); (f) oblique view of dendritic features from Figure 3c (marked by black arrow) and debris-covered esker (marked by red arrows) emerging as surrounding ice melts down.

Two morphological types of complex or geometrical ridge networks (sensu M. R. Bennett, Hambrey, Huddart, & Ghienne, 1996) were also observed in the ice cored-moraine. The first group comprises short, straight to slightly sinusoid, densely spaced features. Their shape resembles crevasses, possibly modified by water flow and filled with sediment. In some places, these crevasse-traces show a distinct dendritic pattern and join together into wider ridges (Figure 3c, f). The general shape of the wider ridges and their location in local depressions suggest that they are possible debris covered eskers, emerging as the dead-ice around the sediment-filled englacial channels melts out (Figure 3f) (cf. Evans, Twigg, Rea, & Orton, 2009).

3.2. Fluted till surface

Subglacial till is draped onto the bedrock and is thin, therefore it does not mask the general shape of the ice-moulded substrate. Fluted surfaces are visible in both the northern and southern part of the foreland, demonstrating that some areas of glacier bed were temperate at the time of fluting construction (Benn, 1994). A lateral transition from controlled, ice-cored moraine complex at the outer fringe of the glacial foreland toward fluted surfaces in the inner parts indicates the general signature of former polythermal conditions (Evans, 2010, 2011; Evans et al., 2015a; Evans, Twigg, & Orton, 2010).

The flutings of Nordenskiöldbreen exhibit some interesting features (Main Map 2). The first group of flutings in the northern part of the foreland are associated with ice-moulded bedrock (Figure 4a). They are straight, long, regular, densely spaced and clearly draped onto the bedrock mounds (Figure 4b). However, the second group overlies the first, and consists of less regular features characterised by a bend or “banana” shape and start at stoss boulders (Main Map 2). Flutings present in the southern part of the foreland are generally less regular and associated with boulders (Figure 4a). A more detailed investigation of fluting formation on this foreland, together with the associated sedimentological data, will be presented elsewhere.

In addition to the flutings, there are a number of short ridges, lying transverse to the fluting orientations, that occur only in the southern part of the foreland (Figure 4e). They might represent proglacial geometrical ridge networks (cf. M. R. Bennett et al., 1996; Evans & Rea, 1999, 2003; Lovell et al., 2015) potentially originating from debris-rich englacial structures. Such debris-rich structures are often linked with surge behaviour (Glasser, Hambrey, Crawford, Bennett, & Huddart, 1998; Lønne, 2006; Roberts, Yde, Knudsen, Long, & Lloyd, 2009) and the main mechanism proposed to be responsible for their origin is squeezing of debris into crevasses (Rea & Evans, 2011); thrust faulting related to longitudinal compression (Glasser, Hambrey, et al., 1998; Lovell et al., 2015); reorientation of vertical crevasses, which facilitates subsequent thrusting (Evans & Rea, 1999; Rea & Evans, 2011); and hydrofracturing (Denis, Buoncristiani, & Guiraud, 2009; Lovell et al., 2015; Roberts et al., 2009). However, no

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surge behaviour has been observed in the historical records for Nordenskiöldbreen, which suggest that potential surge behaviour had to occur prior to 1882.

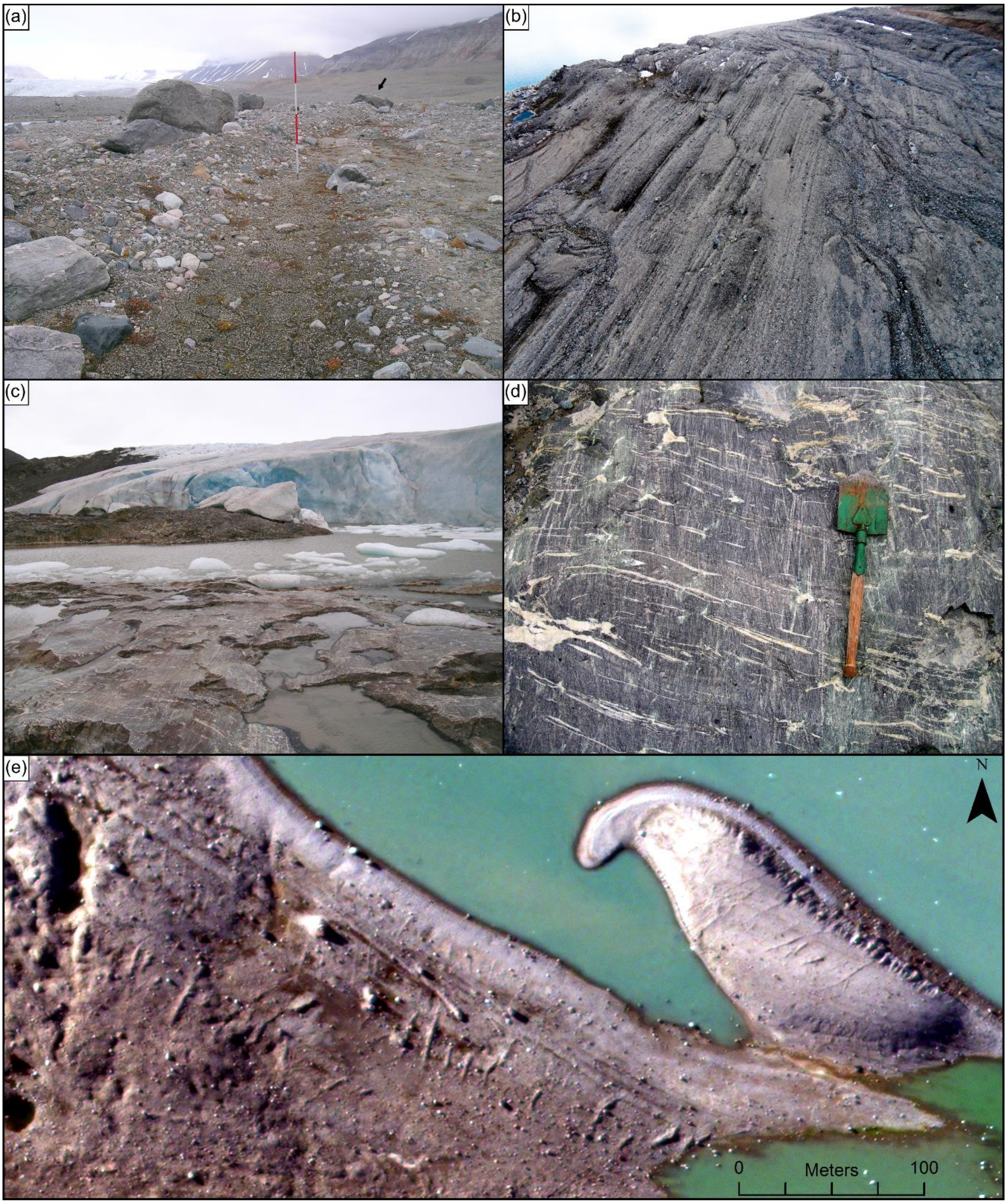

Figure 4. (a) Flute with stoss boulder on southern foreland; (b) UAV-based oblique photograph of fluted surface on north foreland, looking toward SW; (c) ice-moulded bedrock near the margin of the glacier on the north foreland; (d) overprinted striations displaying various orientations on the north foreland; (e) short, transverse ridges visible within southern foreland

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3.3. Ice-moulded bedrock

Outcrops of ice-moulded bedrock comprise a large area of the northern side of the foreland, but are only present in a small area of the southern side, close to the current glacier margin. They are heavily abraded and in places covered with a very thin and sparse layer of glacigenic material (Figure 4c, d). The ice-moulded bedrock takes the form of roches moutonnées with gentle stoss sides and plucked, steep lee sides similar to those identified previously on the forelands of glaciers elsewhere, including Svalbard (cf. Boulton, 1970; Evans, Rea, & Benn, 1998; Glasser, Crawford, Hambrey, Bennett, & Huddart, 1998; Hart, 2006; Hoppe, Schytt, Häggblom, & Österholm, 1969; Lane, Roberts, Rea, Cofaigh, & Vieli, 2015; Österholm, 1978; Roberts & Long, 2005).

3.4. Glacifluvial deposits

Glacifluvial deposits occur in two main locations, either outside or inside the moraine complex. The main water sources for the former location are snow patches and springs located along the sides of De Geerfjellet, combined with the lateral outflow from Nordenskiöldbreen (northern side), and drainage from Mathewbreen and the slopes of Cadellfjellet and Telltfjellet (southern side). These deposits are topographically confined to relatively narrow (30 – 100 m wide) corridors between the moraine complex and valley sides.

Glacifluvial deposits inside the moraine complexes form short ribbons of outwash in corridors wrapped around the ice-moulded bedrock (northern side) or passing through the ice-cored moraine belts and fluted till surfaces (southern side). In both situations, inactive meltwater channels and deposits related to them reflect the migration of ice marginal drainage pathways following the retreating ice margin (Boulton, 1970; Stacke et al., 2013).

3.5. Glacier surface

The map presents the glacier surface in a form of masked satellite imagery, which enables the reader to trace the general pattern of crevasses and other glaciological structures. Longitudinal features, visible on the surface of the glacier at the southern side (Figure 5a,c), resemble longitudinal foliation reported from many glaciers worldwide (e.g. Goodsell, Hambrey, & Glasser, 2005; Hambrey, 1975; Hambrey et al., 2005; Jennings, Hambrey, Glasser, James, & Hubbard, 2015). These structures can be traced downflow into an ice-cored moraine complex, where they are still detectable as linear structures (Figure 5b) on the surface of the moraine.

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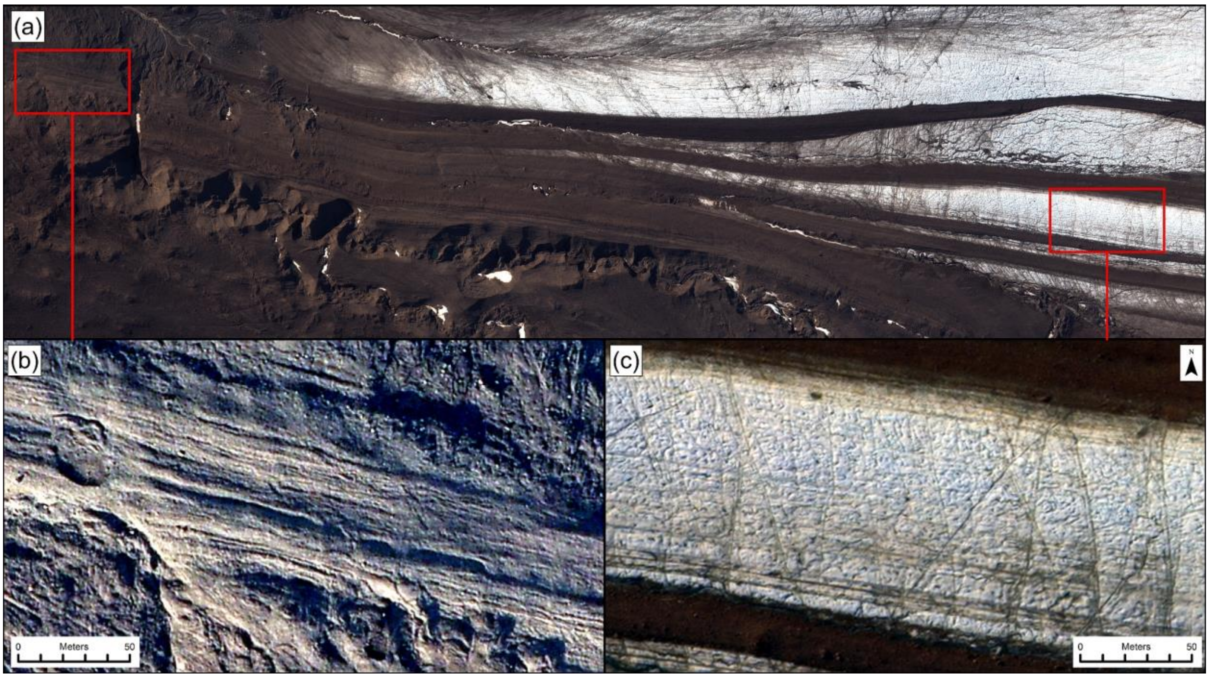

Figure 5. (a) The origin of linear ice flow-parallel landforms (b) as melted out englacial flow stripes, visible on the glacier surface (c) as debris bands.

The glacier margin at the northern part of the foreland is generally poor in debris content, which results in the development of subglacial till sheets that emerge from the current margin (Figure 6c), and which are destroyed by the meltwater relatively quickly. At the southern side, debris coverage is more substantial, which results in the creation of an extensive ice-cored moraine complex (Figure 3, 5a, 6b), however, there are also sections of the margin where debris content is very limited, resulting in the exposure of the till surface (Figure 6a) or bare bedrock as the ice margin retreats (Figure 6d).

4. Glacial landsystem

The identification and characterisation of landform patterns have been successfully used to develop glacial landsystems representative of specific types of glacial process – landform assemblage (e.g. Benn, Kirkbride, Owen, & Brazier, 2003; Evans et al., 2015a, 2015b; Evans & Rea, 2003; Evans & Twigg, 2002; Evans et al., 2009; Glasser & Hambrey, 2003; O'Cofaigh, Evans, & England, 2003). However, in some cases, glacial forelands can contain overprinted landform-sediment assemblages representative of spatial and/or temporal change in glacier dynamics (Evans, 2011; Evans et al., 2010).

The Nordenskiöldbreen foreland contains elements that are common to the polythermal snouts on Svalbard (Evans, Strzelecki, Milledge, & Orton, 2012; Glasser & Hambrey, 2003), especially fluted till surfaces located up-flow from the latero-frontal belt of moraines and moraine-mound complexes. However, the landform assemblage observed at Nordenskiöldbreen is complex and different from the assemblages described for forelands located in a valley setting or a tidewater surging glaciers (cf. M. R. Bennett et al., 1996; M. R. Bennett, Hambrey, Huddart, Glasser, & Crawford, 1999; Boulton et al., 1996; Glasser, Hambrey, et al., 1998; Kristensen, Benn, Hormes, & Ottesen, 2009; Lønne, 2014a, 2014b; Lovell et al., 2015; Ottesen & Dowdeswell, 2006).

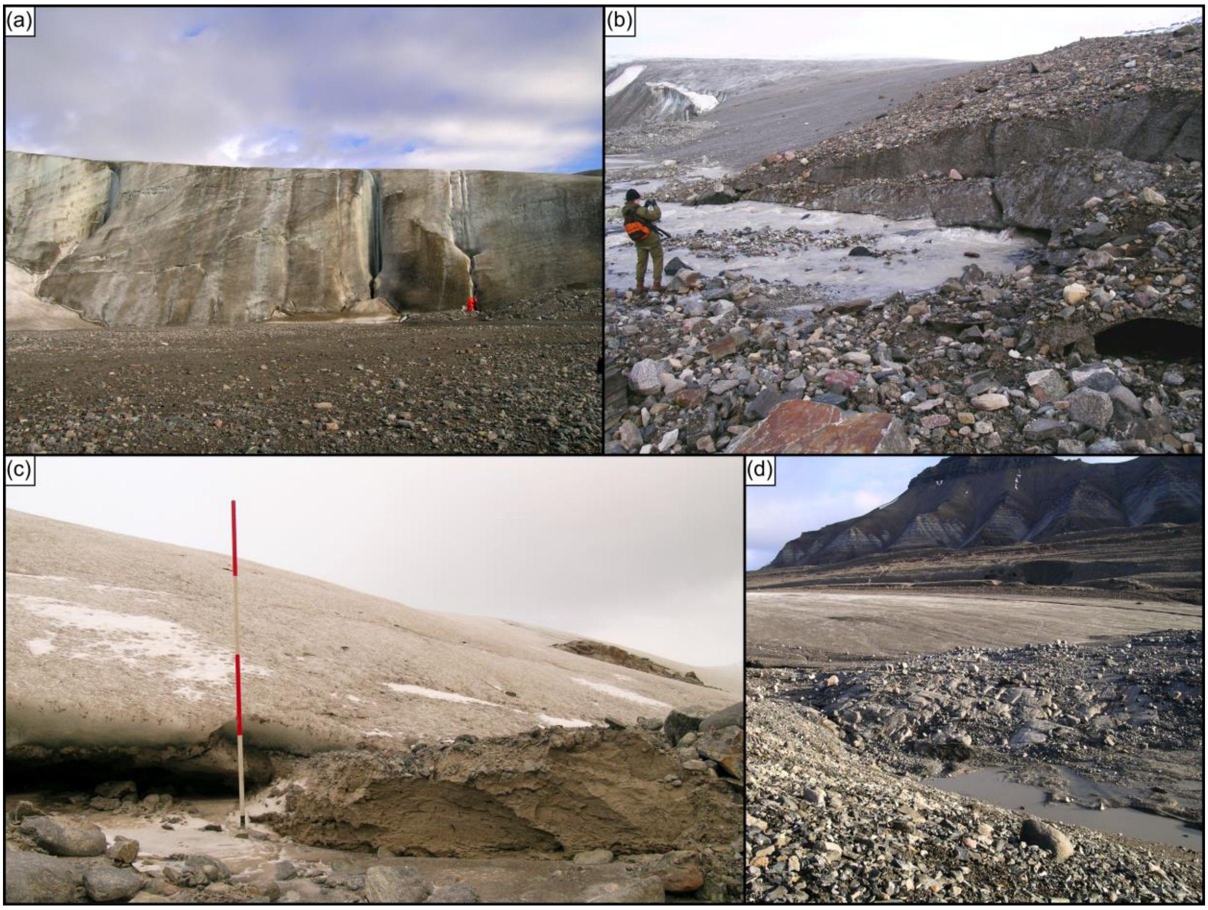

Figure 6. Glacier surface and ice margin: (a) non-active, land-terminating part of the ice-cliff and till plain in front of the cliff on the south foreland; (b) thin debris cover, which constitutes medial moraine, overlying exposed ice; (c) subglacial till emerging as glacier margin retreats from the northern foreland; (d) exposure of bedrock covered by sparse debris, created by retreat of debris-poor section of the glacier on the south foreland.

In detail the northern and southern parts of the terrestrial foreland share only two similar elements: latero-frontal moraines marking the maximum LIA extent and fluted surfaces, which are developed up-valley and generally close to the current fjord margin. Such an assemblage indicates the occurrence of warm-based conditions close to the central axis of the glacier and cold-based ice at the lateral margins (Evans, 2010; Evans et al., 2012; Glasser & Hambrey, 2001, 2003). Other elements of the landsystem are specific to the separate margins on either side of the fiord:

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1) The northern part of the foreland is generally stable, a large part of it is characterized by a thin unit of fluted till and exposed ice-moulded bedrock. The amount of dead-ice is limited (comparing to the southern side), hence transformation of landforms due to dead-ice melting is spatially restricted to very small areas located near the northern lateral glacier margin. The overall volume of sediment on the north foreland is very small in comparison not just to the southern side but also to other glaciers in the surrounding area (Evans et al., 2012; Ewertowski, 2014; Ewertowski, Kasprzak, Szuman, & Tomczyk, 2012; Gonera & Kasprzak, 1989). The cause of the limited debris volume and relatively small number and size of constructional landforms on the north foreland likely relates to the fact that this side of the glacier has been influenced by a wide, single flow unit, which drains the Lomonosovfonna plateau, so the possibility of incorporating supraglacial debris was very limited and restricted only to the fringes of the flow units. Also potentially influential in debris provision is the possibility that the warm-cold based transition zone was spatially and temporally limited, resulting in the creation of only the outer moraine ridge by marginal debris entrainment during the LIA maximum, similar to some other glaciers around Svalbard (Glasser & Hambrey, 2003; Lyså & Lønne, 2001; Sletten, Lyså, & Lønne, 2001). Recession of the glacier since that time has most probably been continuous as no minor recessional moraines have been observed.
2) The southern part of the foreland is more complicated. Fluted till surfaces are restricted to the relatively narrow, 75 - 200 m wide belt along the current fjord margins, and areas of exposed bedrock are limited to the current glacier margin. The most prominent geomorphological feature is the ice-cored moraine complex which was produced by supraglacial and englacial debris transported at the boundary between different flow units. As the landform contains a large amount of dead-ice, the surface processes are more dynamic here than on the northern foreland. The medial moraines visible in older maps are deformed (looped), which may be related to a glacier surge (prior to 1892) or simply differences in flow speed between individual ice-flow units. In general, the volume of subglacial debris is probably of similar magnitude to that on the northern foreland. However, supraglacial debris is present in far larger quantities, which allowed for the creation of distinct ice-cored landforms. Therefore, the geomorphology on the southern foreland is a result of interaction between five narrow ice flow units, which facilitated the delivery of supraglacial, englacial and subglacial debris from nunataks and valley sides and its transportation toward the ice margin along longitudinal flow stripes/foliations (cf. Casassa & Brecher, 1993; Ely & Clark, 2015; Glasser & Gudmundsson, 2012; Hambrey, 1975; Hambrey & Glasser, 2003; Roberson & Hubbard, 2010). One further aspect of the southern foreland is the fact that the five southern ice flow units were squeezed by the two larger northern flow units during the advance of Nordenskiöldbreen, resulting in them advancing relatively further and being compressed and contorted over the site of the present foreland, where they are now melting out.

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5. Conclusions

The geomorphology map of terrestrial parts of the Nordenskiöldbreen foreland on Svalbard depicts two distinct landform-sediment assemblages. The northern foreland records the recession of a single, relatively debris-free, ice flow unit, whereas the southern foreland is characterized by the impacts of multiple, narrow, debris-covered ice flow units that have been compressed and contorted by the northern flow units. The glacial landsystem model that emerges from this study contains elements of a polythermal signal (a fluted surface grading downflow into an ice-cored moraine complex) modified by the superimposition of complex medial and controlled moraine related to numerous individual glacier flow units. Where glacier ice did not incorporate large quantities of debris, the resultant landscape contains less ice-cored morainic topography and hence is stable over decadal time-scales and comprises large areas of thin till cover or debris-free, ice-moulded bedrock. In contrast, when multiple, narrow ice flow units, transporting supraglacial debris at their boundaries, were compressed and distorted, the resultant landscape consists of large ice-cored moraines being actively modified by dead-ice melting and associated debris flows. In both cases, the landform signature demonstrates a continuous recession of the glacier after termination of the LIA, which was not interrupted by surge events.

Software

UAV image processing was performed in Agisoft Photoscan. The processing of satellite images and on-screen vectorization of geomorphic features were carried out using ArcGIS software. The final map layout was produced in ArcGIS.

Acknowledgements

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Main Map 1: Glacial geomorphology of terrestrial foreland of Nordenskiöldbreen, Adolfbukta, Svalbard

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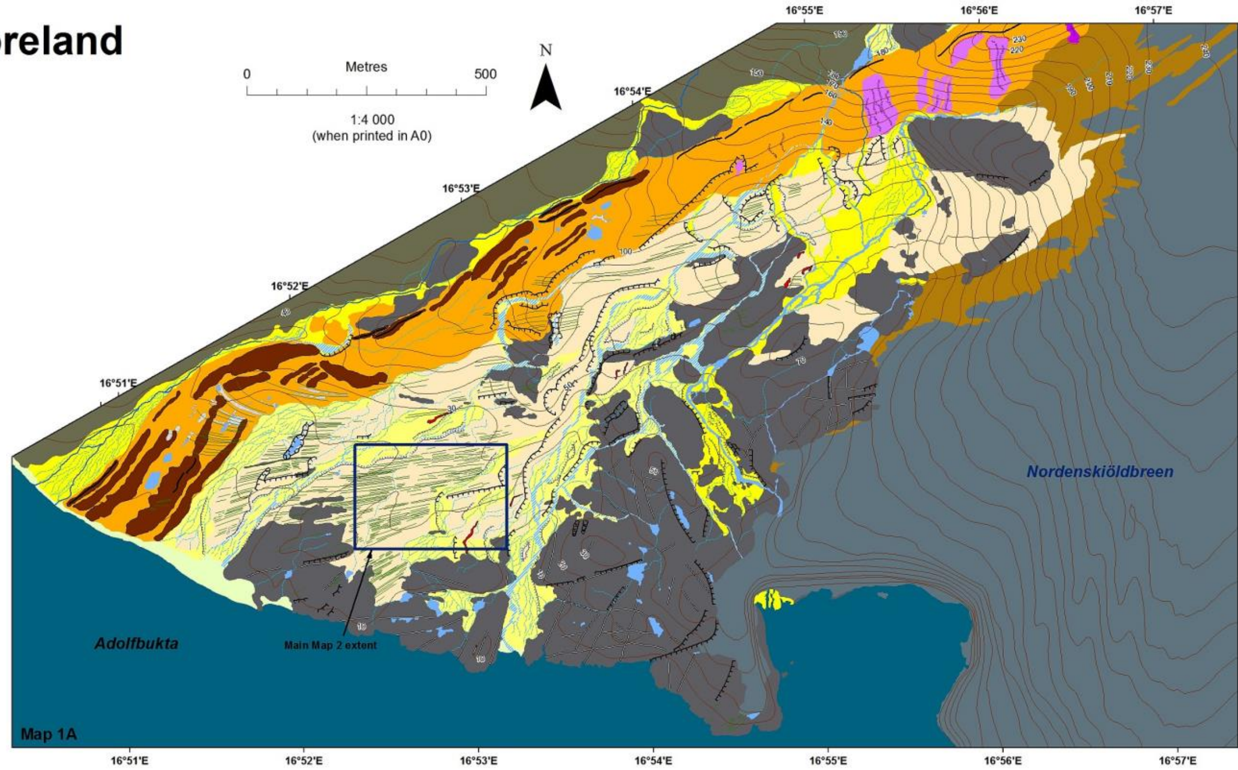
Durham University   UAM   UNIVERSITY of York



Surficial geology map units

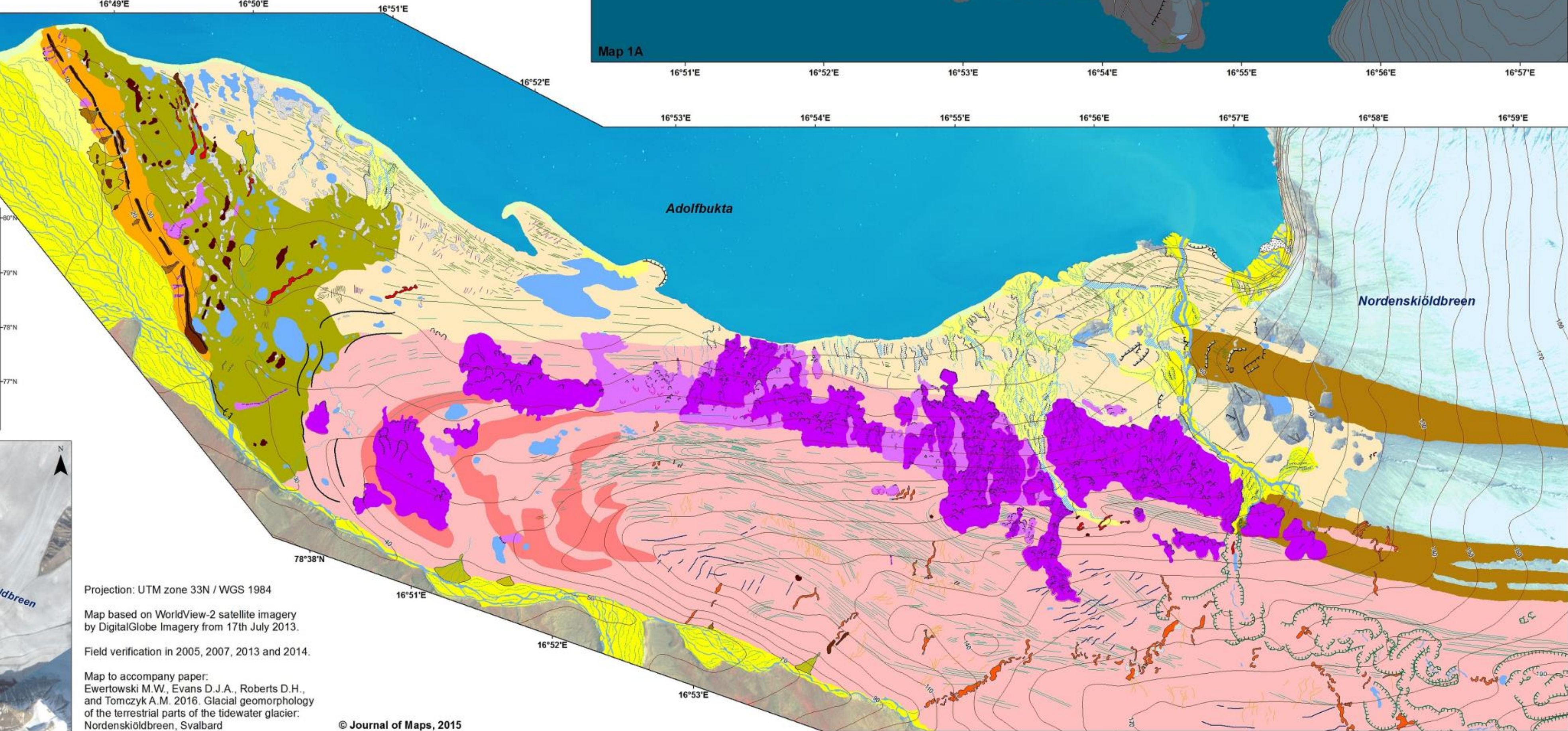
General
- Glacier ice
- Sea
- Valley side bedrock
- Fluted till surface
- Debris covered glacier ice
- Ice-moulded bedrock
- Marine beach

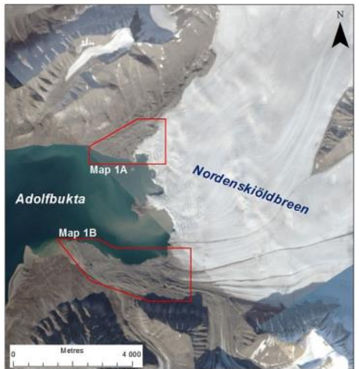
Moraine
- Stable, high-relief moraine (probably still ice-cored)
- Degraded ice-cored moraine (no or low ice content)
- Recent, low-relief ice-cored moraine
- Overridden moraine

Glacifluvial deposits
- Active outwash
- Inactive outwash

Landform and structures
- Moraine ridges and isolated hummocks
- Colluvial fan
- Alluvial fan
- Recent debris flow
  - debris flow scarp
  - debris flow channel
  - debris flow lobe
- Old debris flow
- Inland water (pond and active channel)
- Inactive channels
- Major terrace
- Depression
- Eskers
- Complex ridge networks (possible eskers and crevasse fills)
- Icing

Ice-cored moraine structures
- surface fractures and cracks related to dead-ice melting
- lineations (inherited glacial structures) in ice-cored moraine
- distinct collapsing edges
- moraine crests
- Escarpment
- Bedrock lineament
- Flutings
- Geometrical ridges
- Main Map 2 extent
- 10-meters contour





Projection: UTM zone 33N / WGS 1984

Map based on WorldView-2 satellite imagery by DigitalGlobe Imagery from 17th July 2013.

Field verification in 2005, 2007, 2013 and 2014.

Map to accompany paper:
Ewertowski M.W., Evans D.J.A., Roberts D.H., and Tomczyk A.M. 2016. Glacial geomorphology of the terrestrial parts of the tidewater glacier: Nordenskiöldbreen, Svalbard

Main Map 2: An example of fluted till surface at Northern side of the Nordenskiöldbreen foreland, Adolfbukta, Svalbard

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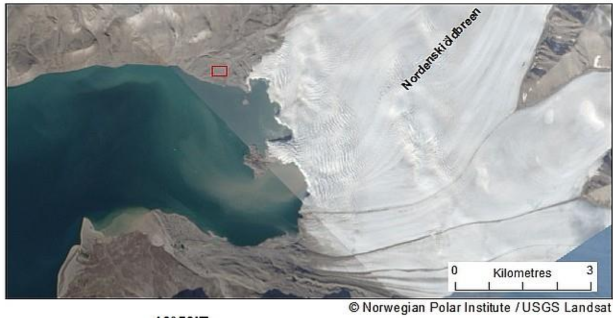

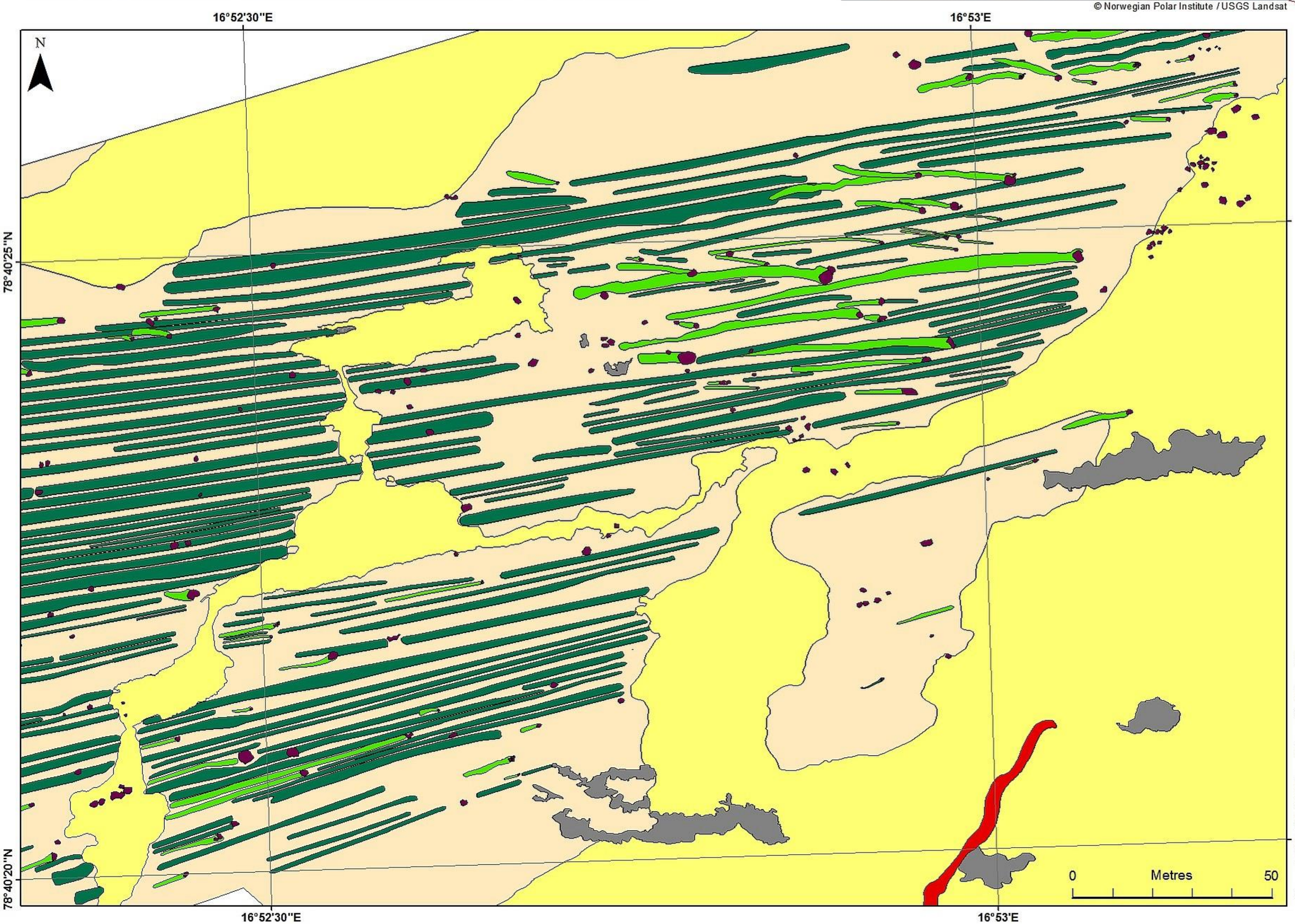

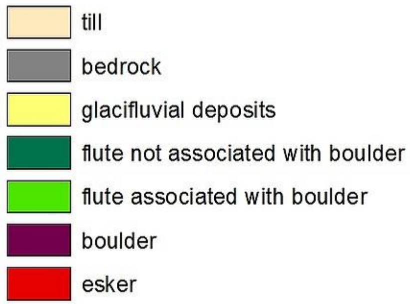

Projection: UTM zone 33N / WGS 1984

Map based on UAV imagery captured at 29th July 2014.

Field verification in 2005, 2007, 2013 and 2014.

Map to accompany paper:
Ewertowski M.W., Evans D.J.A., Roberts D.H., and Tomczyk A.M. 2016. Glacial geomorphology of terrestrial parts of tidewater glacier: Nordenskiöldbreen, Svalbard