Polyphase development and preservation potential of complex eskers

Robert D. Storrar[1*], Marek Ewertowski[2], Aleksandra M. Tomczyk[2], Iestyn D. Barr[3], Stephen J. Livingstone[4], Alastair Ruffell[5], Ben J. Stoker[4,6] and David J. A. Evans[7]

[1]Department of the Natural and Built Environment, Sheffield Hallam University, UK

[2]Faculty of Geographical and Geological Studies, Adam Mickiewicz University, Poland

[3]School of Science and the Environment, Manchester Metropolitan University, UK

[4]Department of Geography, University of Sheffield, UK

[5]School of Natural and Built Environment, Queens University Belfast, UK

[6]Department of Physical Geography and Geoecology, Charles University, Prague, Czech Republic

[7]Department of Geography, Durham University, UK

*Corresponding author: r.storrar@shu.ac.uk

This is a non peer-reviewed EarthArXiv preprint, submitted to *Boreas*

Abstract

Eskers are useful for reconstructing meltwater drainage systems of ice sheets. However, our process understanding of eskers suffers from a disconnect between detailed morpho-sedimentary investigations of abundant large-scale ancient esker systems, and a small number of modern analogues where esker formation has been observed. This paper presents the results of detailed studies into esker systems that have recently emerged at Hørbyebreen, Svalbard, and Breiðamerkurjökull, Iceland. Despite the different glaciological settings (polythermal valley glacier *versus* active temperate piedmont lobe), in both cases a distinctive planform morphology has developed, where eskers are orientated in two dominant directions corresponding to the direction of ice flow and the shape of the ice margin. These two orientations in combination form a cross-cutting and locally rectilinear pattern. The complexity in esker morphology on both glacier forelands is likely a product of polyphase or multi-generational development. The eskers at Hørbyebreen contain substantial ice cores with a high ice:sediment ratio, suggesting that they would be unlikely to survive after ice melt. The Breiðamerkurjökull eskers emerged from terrain characterised by buried ice which has melted out. Our observations lead us to conclude that eskers may reflect a wide range of processes at dynamic ice margins, including significant paraglacial adjustments. Constraints on esker morphology include: topographic setting (e.g. confined valley or broad plain); sediment availability; meltwater availability; position of formation (supraglacial, englacial or subglacial); and ice-marginal dynamics such as channel abandonment, the formation of outwash heads or the burial and/or exhumation of dead ice.

Keywords

Esker, Meltwater drainage, Hørbyebreen, Breiðamerkurjökull, Svalbard, Iceland

Introduction

The nature of glacial meltwater drainage is important for understanding the response of glaciers to changes in meltwater supply, particularly in the case of climatic warming. Meltwater drainage is associated with glacier surging (e.g. Fowler, 1987; Kamb, 1987), temporary accelerations in mountain glaciers (e.g. Hubbard *et al.*, 1995; Nienow *et al.*, 1996; Hubbard & Nienow, 1997; Nienow *et al.*, 1998), seasonal speed-up events at ice sheet-scale outlet glaciers (Zwally *et al.*, 2002; Bartholomew *et al.*, 2012; Cowton *et al.*, 2013), longer-term changes beneath ice streams (e.g. Engelhardt *et al.*, 1990; Stearns *et al.*, 2008; Stokes *et al.*, 2016) and exerts an important control on the stability of ice shelves (Fricker *et al.*, 2016; Bell *et al.*, 2017).

Despite advances in understanding the dynamics of glacial meltwater drainage systems, they remain difficult to study because of the challenging nature of accessing englacial and subglacial channels, either directly through glacio-speleology (e.g. Piccini *et al.*, 2000; Gulley *et al.*, 2014) or indirectly through dye tracing (e.g. Nienow *et al.*, 1998; Willis *et al.*, 2012; Cowton *et al.*, 2013), borehole water pressure observations (e.g. Hubbard *et al.*, 1995; Meierbachtol *et al.*, 2013; Hart *et al.*, 2015), geophysical methods (e.g. Stuart *et al.*, 2003) or numerical modelling (e.g. Fowler, 1987; Hewitt, 2011; Hewitt, 2013; Werder *et al.*, 2013). Hydrological systems have been documented for only a relatively small number of glaciers, principally in the European Alps (e.g. Hubbard & Nienow, 1997), Western Greenland (e.g. Nienow, 2014), Antarctic ice shelves (e.g. Fricker *et al.*, 2016) and Svalbard (e.g. Irvine-Fynn *et al.*, 2011). It is therefore difficult to predict how the meltwater drainage systems of ice masses at a variety of scales will evolve as the climate changes, and how glacier dynamics will change as a result.

An alternative to direct or indirect glaciological observations is the geomorphological record of glacial meltwater drainage. As glaciers retreat, landforms are revealed that contain information about how the glacial drainage system operated. Eskers are a particularly useful landform type in this respect. They are sedimentary infills of glacial meltwater channels, and form in subglacial, englacial and, more rarely, supraglacial positions (Price, 1969; Fitzsimons, 1991; Huddart *et al.*, 1999). Since eskers are effectively the casts of glacial meltwater channels, they have the potential to be used to reconstruct the form and characteristics of the channelized component of palaeo-glacial meltwater drainage systems (e.g. Warren & Ashley, 1994; Brennand, 2000; Storrar *et al.*, 2014a; Burke *et al.*, 2015; Livingstone *et al.*, 2015).

Eskers formed during the deglaciation of northern hemisphere ice sheets between approximately 18 ka BP and 6 ka BP are particularly abundant on the beds of the Laurentide and Cordilleran (Prest *et al.*, 1968; Margold *et al.*, 2013; Storrar *et al.*, 2013), British-Irish (Clark *et al.*, 2018) and Fennoscandian (Stroeven *et al.*, 2016) ice sheets. The wealth of eskers on these palaeo-ice sheet beds means that inferences can be made about meltwater dynamics at the ice sheet scale. This, in turn, may provide insights into the likely response of the Greenland and Antarctic ice sheets to future melting. Thus, a detailed understanding of how to interpret late Quaternary eskers in terms of ice sheet processes is important. Fortunately, eskers are actively forming at modern glaciers, and may serve as analogues for their late Quaternary ice sheet counterparts. They have been observed at glaciers in locations such as Alaska (e.g. Price, 1966; Gustavson & Boothroyd, 1987), Iceland (e.g. Price, 1969; Burke *et al.*, 2008), Svalbard (e.g. Huddart *et al.*, 1999) and even Mars (Gallagher & Balme, 2015). These modern analogues are essential for describing in detail the process-form relationships between eskers and their parent glaciers. In particular, many modern eskers are highly complex in planform, containing multiple branches that converge and diverge (e.g. Price, 1966; Storrar *et al.*, 2015). Although eskers recorded on ice sheet beds are typically simpler in planform (Aylsworth & Shilts, 1989; Brennand, 2000; Storrar *et al.*, 2014b), complex esker systems do form at these scales also (Gorrell & Shaw, 1991; Thomas & Montague, 1997) and are increasingly being recognised with the advent of high-resolution Digital Elevation Models (DEMs) (e.g. Delaney *et al.*, 2018; Figure 1). This paper presents observations of complex eskers actively forming at contrasting glaciers in Svalbard and Iceland, which we use to address two areas of uncertainty with respect to interpreting esker patterns:

1. In what types of channel do eskers form (subglacial, englacial, supraglacial) and does this change spatially and temporally? (e.g. Gustavson & Boothroyd, 1987; Hebrand & Åmark, 1989)

2. Why do eskers sometimes form complex systems with cross-cutting long axes when glaciological theory and associated observations suggest that tunnels largely remain stable (e.g. Boulton et al., 2007a;b)?

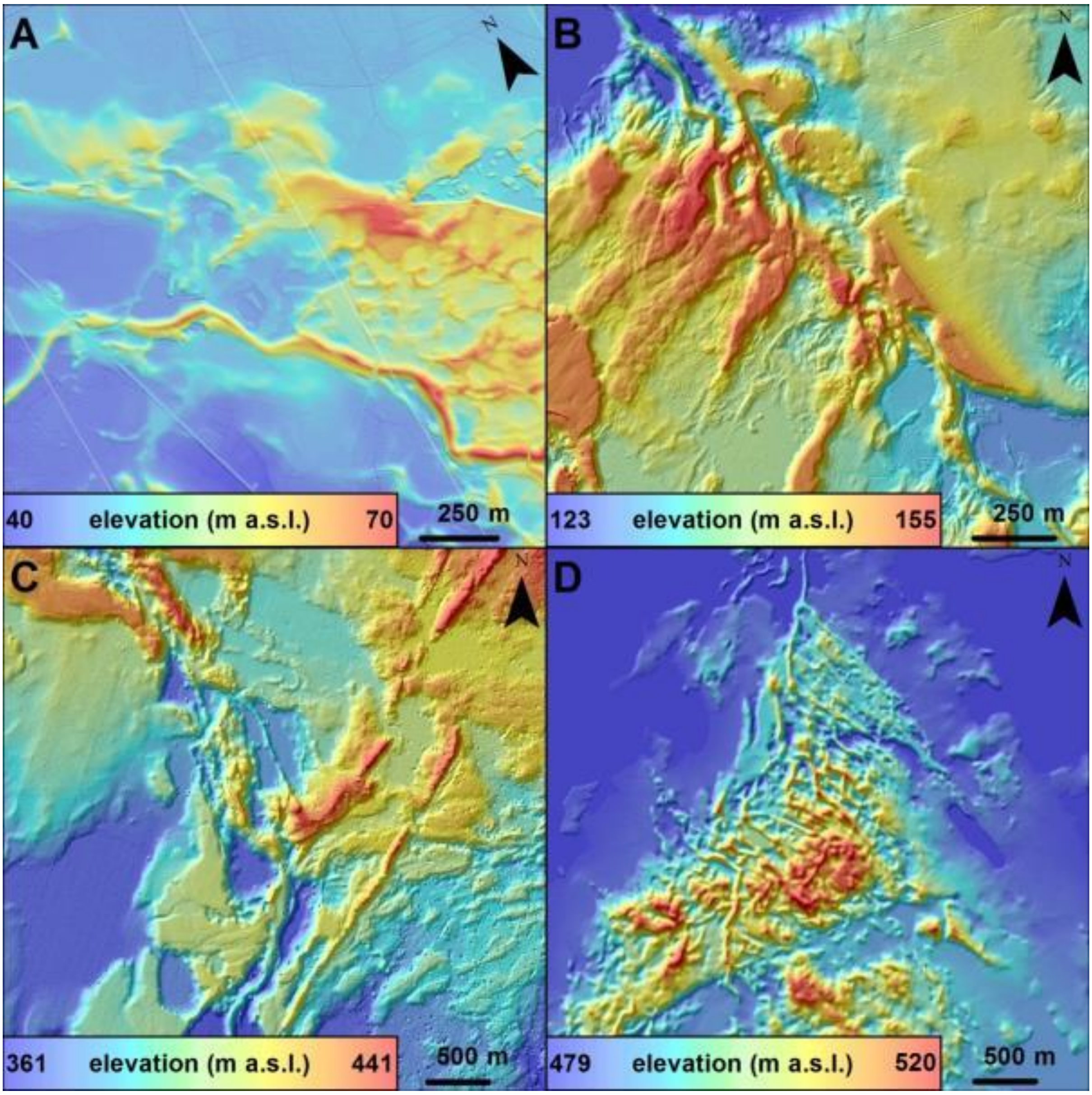

Figure 1. Examples of ice sheet-scale complex esker systems. (A) Part of the 'Esker Riada', Ireland (data supplied by Cathy Delaney). (B) Esker complex in SW Finland (data from http://gtkdata.gtk.fi/maankamara/). (C) Esker complex in NW Canada (data from https://www.pgc.umn.edu/data/arcticdem/). (D) Esker-Geometric Ridge Network complex in Wisconsin, USA (data from https://lta.cr.usgs.gov/NED)

Study areas

Hørbyebreen

Hørbyebreen is a 6.5 km long and ~1 km wide polythermal glacier located in Billefjorden, Svalbard (Figure 2). Previous studies, using Ground Penetrating Radar (GPR), have identified the thermal transition between warm-based ice further up-glacier and cold-based ice beneath the snout (Małecki *et al.*, 2013). Looped medial moraines observed on aerial photographs from 1936 indicate that Hørbyebreen surged at some point before this date (Ewertowski *et al.*, 2019) and has since undergone sustained snout recession, which has accelerated since the 1990s and is likely related to increased summer temperatures (Małecki *et al.*, 2013).

The foreland is predominantly flat (Figure 3A), with the exception of a large bedrock bump, located at the glacier terminus in the centre of flow, which protrudes up to ~60 m above the surrounding foreland (Figure 3B).

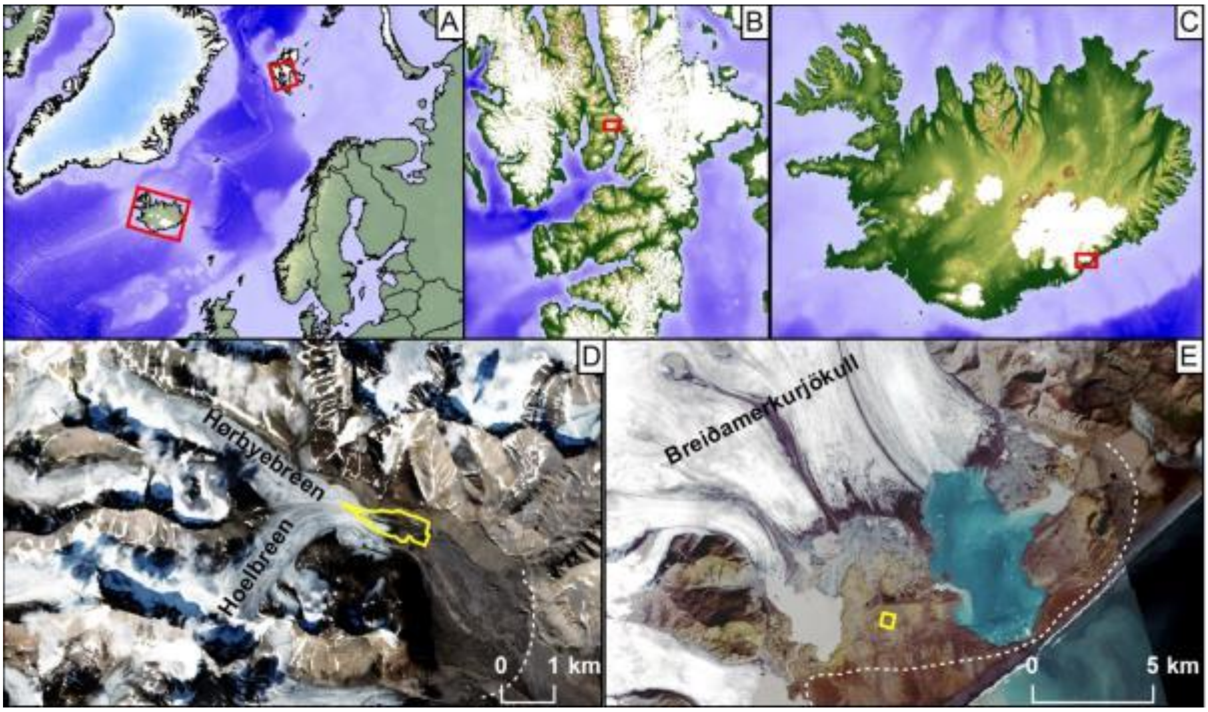

Figure 2. Locations of study areas. Red boxes in A show the locations of Svalbard (B) and Iceland (C). Red boxes in B and C show the locations of Hørbyebreen (D) and Breiðamerkurjökull (E), respectively, and the yellow boxes in D and E show the locations of the study sites. White dashed lines indicate the Little Ice Age glacier margins. Topographic and bathymetric data are from ETOPO1 (https://www.ngdc.noaa.gov/mgg/global/global.html). Glacier outlines in A, B and C are from the Randolph Glacier Inventory v.6 (https://www.glims.org/RGI/rgi60_dl.html). The satellite image in D is from Planet Labs (Planet_Team, 2017), and the satellite image in E is from Sentinel 2 (www.sentinel.esa.int).

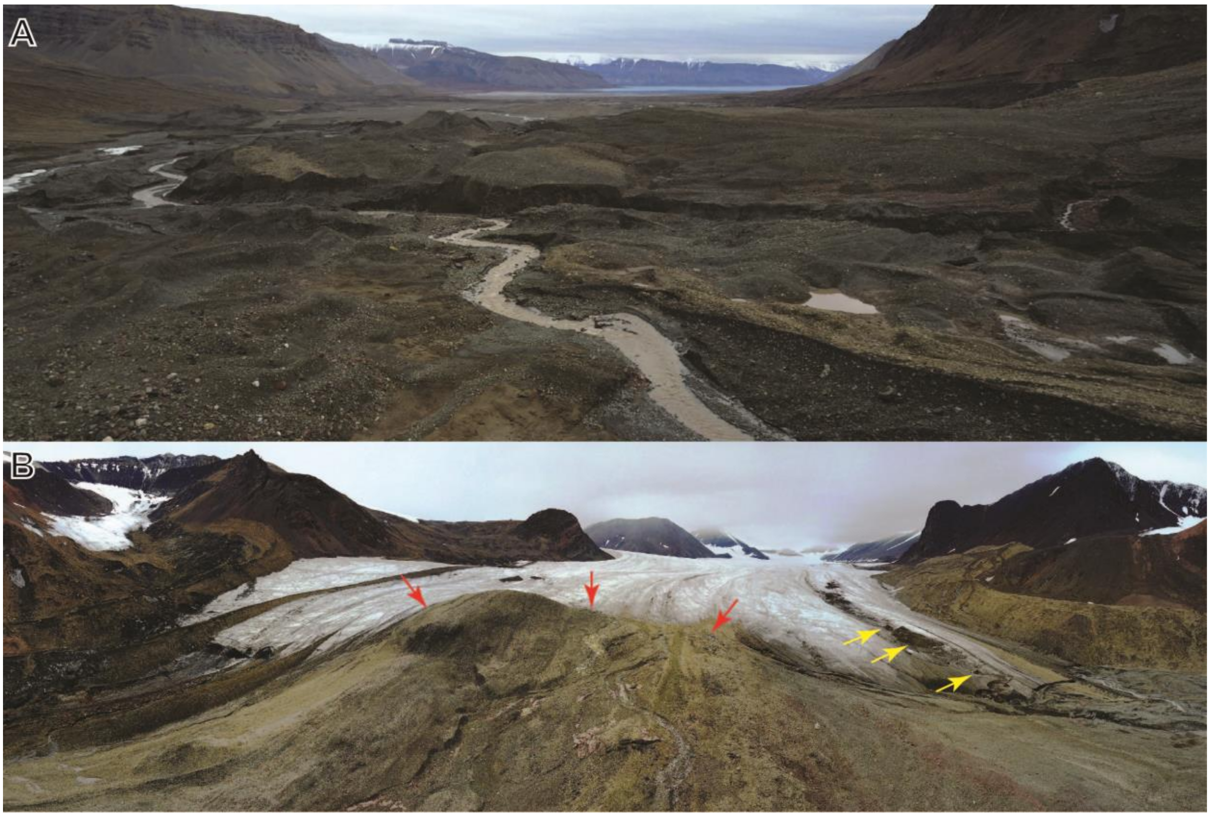

Figure 3. (A) Oblique UAV image looking ESE from the terminus of Hørbyebreen. Note the predominantly flat terrain of the distal part of the foreland, with the main relief provided by glacial deposits. (B) Oblique UAV image looking WNW showing the terminus of Hørbyebreen. Note the prominent bedrock bump in the centre of the picture (red arrows), and supraglacial debris mounds indicated by yellow arrows. Each image is approximately 1 km across.

The foreland comprises a range of glacial landforms, including a latero-frontal moraine arc, a series of eskers and geometric ridge networks of crevasse fill and hydrofracture origins, and glacial lineations (Karczewski, 1989; Karczewski *et al.*, 1990; Gibas *et al.*, 2005; Rachlewicz, 2009; Szuman & Kasprzak, 2010; Evans *et al.*, 2012). The present study focuses on the complex esker system on the northern part of the foreland, which is melting out of the glacier snout (Figure 2D).

Breiðamerkurjökull

Breiðamerkurjökull (Figure 2E) is a ~16 km wide active temperate glacier covering about 906 km^2 (Guðmundsson *et al.*, 2017). It is an outlet of the Vatnajökull ice cap in south-east Iceland. The foreland comprises an array of glacial landforms, including eskers exhibiting both 'simple' and 'complex' planforms (Price, 1969; Evans & Twigg, 2002; Storrar *et al.*, 2015). The study area (Figure 2E) comprises a complex system of eskers, termed Major Esker System 2 (MES2) by Storrar *et al.* (2015). Aerial photographs from 1945 reveal that the ice margin had retreated approximately 50 - 100 m from the esker system by this time. Since 1945, the margin has gradually retreated to the north (Guðmundsson *et al.*, 2017). The esker system was likely exposed as the glacier retreated during the 1930s (Evans & Twigg, 2002), and coincides with the location of a large medial moraine named Mavabyggdarond.

Methods

Hørbyebreen

Remotely sensed data from 2009 (a 0.4 m resolution aerial photograph orthomosaic produced from colour digital camera aerial images purchased from Norsk Polar Institute), 2013 (Multispectral satellite image from Worldview-2 satellite; 0.5 m resolution in the panchromatic and 2 m resolution in the multispectral bands purchased from Digital Globe; orthorectified using the 2009 DEM and pansharpened) and a 2017 Unmanned Aerial Vehicle (UAV) campaign (overlapping vertical aerial photographs captured on 28th August 2017 with DJI Phantom 3 and Mavic Pro quadcopters) were used to map the margin and foreland geomorphology of the Hørbyebreen study area. In addition, 3 m resolution PlanetScope imagery from 21st August 2017 was acquired for the entire glacier and foreland from Planet Labs (Planet_Team, 2017). The UAV photography was processed using Structure from Motion (SfM) photogrammetry software (Agisoft Photoscan) into a 5 cm resolution orthophoto and 16 cm resolution Digital Elevation Model (DEM), constrained by a series of ground control points visible in the UAV imagery that were surveyed using a differential GNSS system (Topcon Hiper II). The orthophoto and DEM were used to produce a geomorphological map of the study area. Alongside the 2017 UAV campaign, a Mala 100 MHz Rough Terrain Antenna (RTA) GPR was used to survey two lines on the glacier snout (Figure 4A) in order to identify the location(s) of any englacial or subglacial meltwater channels and provide some context for the topography of the bed in the snout area. The RTA antenna provides in-line data acquisition, gathered using a measured stepsize, located using GNSS. The raw GPR data were processed within Reflexw v7.5.9. To aid in the analysis of the profiles, a minimal processing sequence was developed including: static correction for time-zero drift; the removal of repeated traces where the radar unit was stationary; application of a dewow filter; positive gain function to strengthen the presence of deep reflectors; diffraction stack migration based on an assumed clean ice velocity of 0.167 m ns^{-1}. consistent with other cold-based Svalbard glaciers (Björnsson *et al.*, 1996; Stuart *et al.*, 2003); and finally the use of a low bandpass filter to reduce noise. Radargrams were then topographically corrected using elevation values from the associated GNSS trace, before being plotted within MatLab v9.1.0.441655.

Breiðamerkurjökull

The Breiðamerkurjökull esker system was surveyed using a UAV in May 2017, and processed in the same way as the Hørbyebreen UAV imagery. This resulted in a 3 cm resolution orthophoto and 6 cm resolution DEM (the difference in resolution between Breiðamerkurjökull and Hørbyebreen is due to flight parameters used). The processed orthophoto and DEM were used to produce a geomorphological map of the study area. Orthorectified and georeferenced Landmælingar Íslands aerial photographs from 1945, 1955 and 1965 were also used to track the process of esker formation through time.

Results

Glacial geomorphology of Hørbyebreen terminus and foreland

A geomorphological map of the Hørbyebreen study area from the 2017 UAV imagery is presented in Figure 4. The key glaciofluvial landforms in the area are described below.

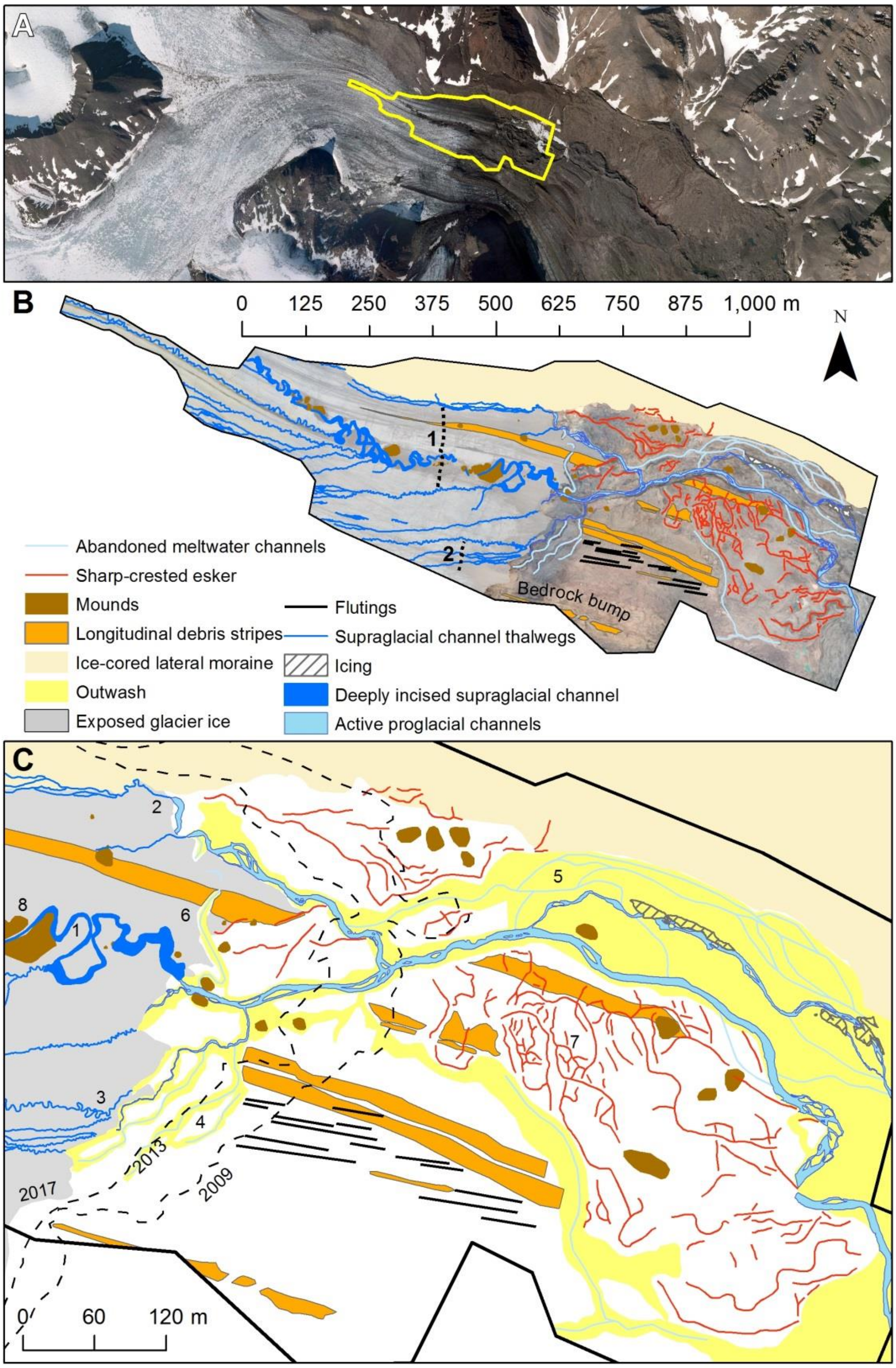

Figure 4. (A) 2009 aerial orthophoto of Hørbyebreen, with the main UAV study area in yellow. (B) 2017 glacial geomorphological map of the Hørbyebreen study area overlain on the UAV-derived orthophoto. (C) A more detailed view of the foreland. Locations of the GPR profiles shown in Figure 6 are given by dotted lines 1 and 2 in B. Numbers in C refer to locations mentioned in the text. Ice margins from a 2009 aerial photo orthomosaic and 2013 satellite image are shown as dashed lines in C. Note the expansion of the ice-cored lateral moraine in the north onto the glacier surface.

Contemporary meltwater channels

A series of active meltwater channels, typically displaying a very high sinuosity, are present on the glacier surface. Most are relatively shallow (up to a few metres), whereas one is deeply incised by >10 m (Figure 4 and Figure 5A). The smaller active channels are strongly influenced by ice structure, with meander belts confined by longitudinal debris stripes on the ice surface and channels occasionally following crevasse scars, or offset along ice faults or fractures (Figure 5).

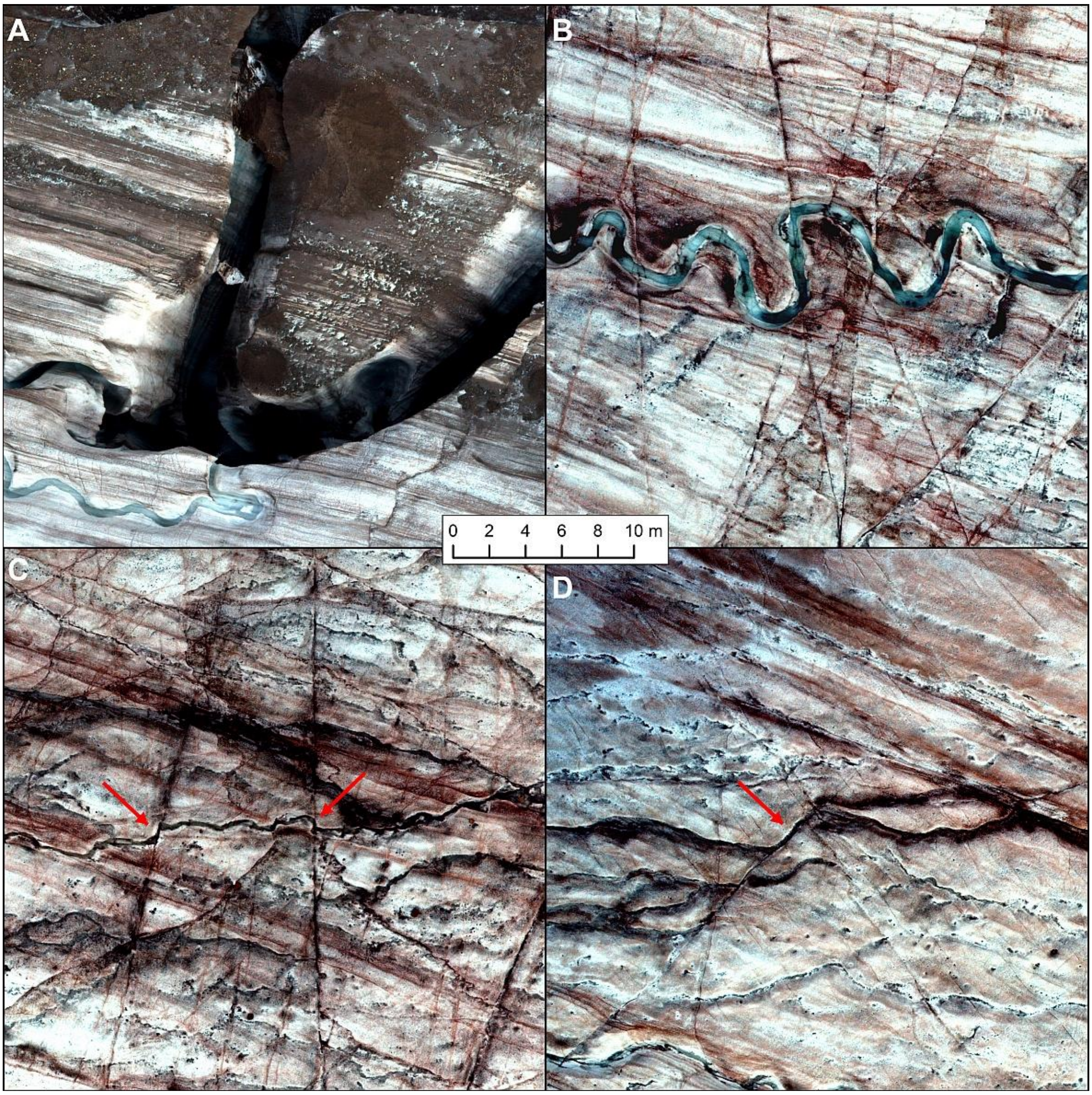

Figure 5. UAV images showing supraglacial channel morphology influenced by ice structures.

The large (up to ~5 m wide), deeply incised active channel (location 1 in Figure 4C) is less influenced by ice structure than the small channels, meandering more freely across the glacier surface. A transverse GPR profile ~240 m up-glacier from the snout (line 1 in Figure 4B) indicates that ice close to this location is ~50 m thick (Figure 6A and B). An ice bridge provided a means of surveying directly over the channel, and the resulting GPR trace reveals pronounced hyperbolae in the radargram, which occur at the location of the channel and propagate through the ice (Figure 6), indicating deep incision. In places, the top of the channel is covered by ice bridges and it becomes englacial.

Another large active channel of similar width (Figure 7; location 2 in Figure 4) emerges at the interface between glacier ice and ice-cored controlled lateral moraine at the glacier's northern margin. The GPR data indicate that this channel is subglacial at this location (right hand side of Figure 6A and B). Unlike the proglacial channels that appear largely to originate supraglacially, water within this channel has a high suspended sediment concentration, indicated by its distinct brown colour (Figure 8A). The only other significant drainage of water arriving on this part of the glacier foreland comes from a number of smaller supraglacial streams that converge where the glacier meets the bedrock bump (location 3 in Figure 4C). Drainage is forced down the northern side of the bump where it becomes confluent with another channel sourced from the large supraglacial channel towards the centre of the northern part of the glacier.

Abandoned meltwater channels

In addition to the currently active channels, a series of abandoned marginal (ice-contact) and proglacial channels are present. Abandoned marginal meltwater channels are orientated SW-NE, dictated by the topography on the bedrock bump (location 4 in Figure 4C), and NNW-SSE close to the northern valley side (location 5 in Figure 4C). A large abandoned englacial/ice-marginal channel cuts across the current glacier margin (location 6 in Figure 4C), originating from the source of the turbid meltwater (i.e. at the glacier's northern margin). This channel is ice-walled and sediment-floored (Figure 7C and D), and appears to have been abandoned due to down-cutting by the current channel (location 2 in Figure 4C) into the substrate, finding a new course to the SE (Figure 7E).

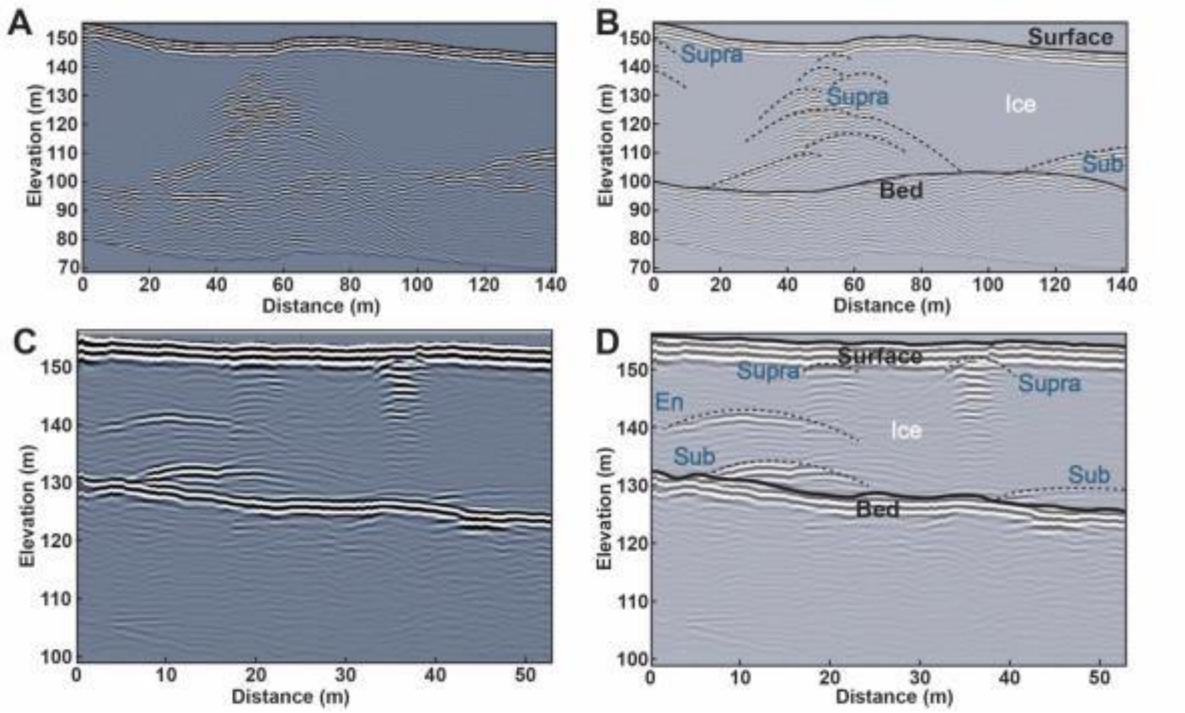

Figure 6. GPR profiles across Hørbyebreen (see Figure 4 for location). (A) Line 1 (south to north, left to right). (B) Annotated version of A. (C) Line 2 (south to north, left to right). (D) Annotated version of C. Annotations refer to the interpretation of channels as subglacial (draining on the glacier bed), englacial (draining within ice) or supraglacial (with a surface exposed to the atmosphere).

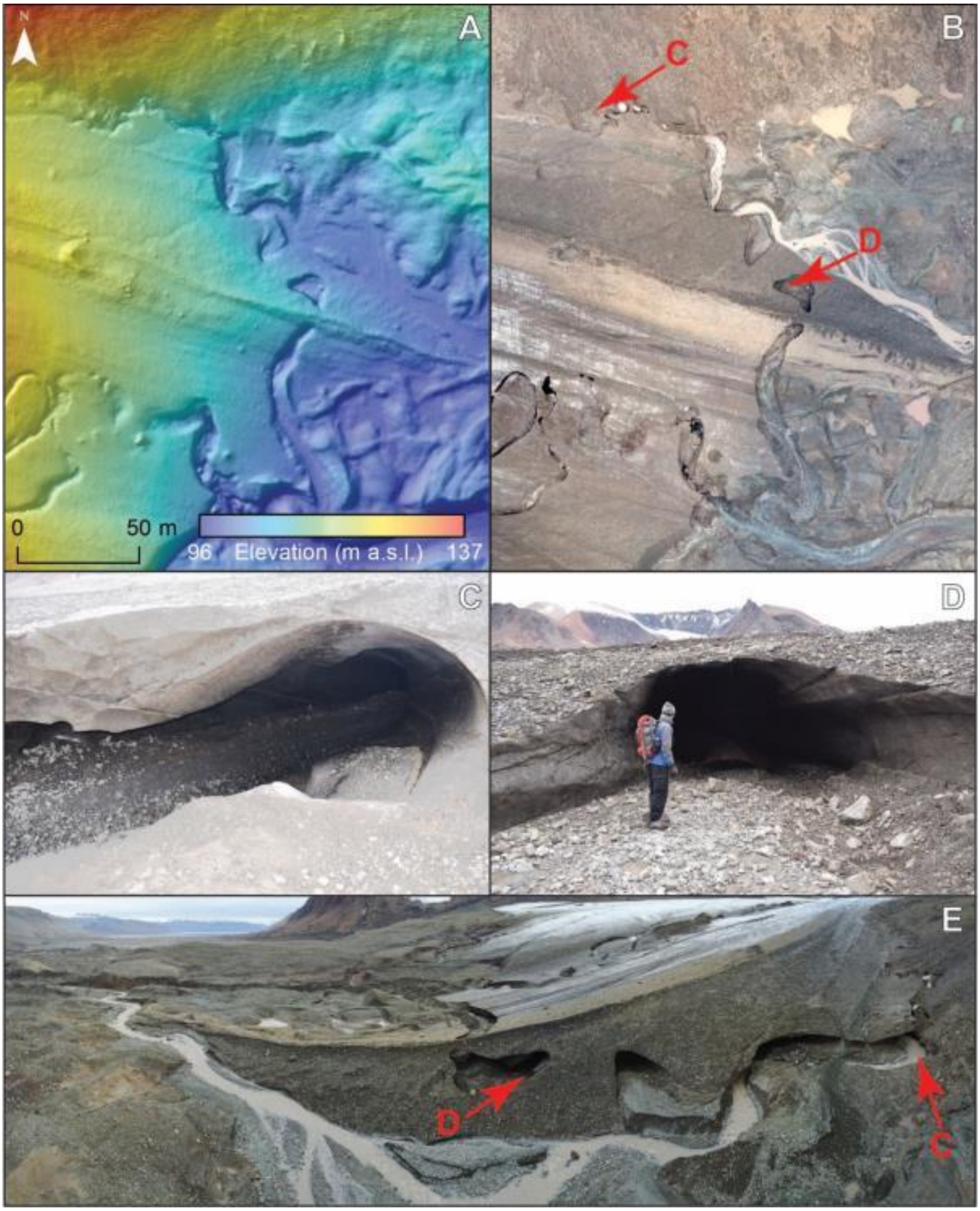

Figure 7. Sediment-floored ice marginal channels at Hørbyebreen (location 2 in Figure 4). UAV-derived (A) hillshaded DEM and (B) Orthophotograph of the glacier snout. (C) Active proglacial channel emerging from an englacial position, with stratified sediment deposited on the channel floor. (D) Abandoned pro/englacial channel with sediment deposited on the channel floor. (E) Oblique aerial panorama showing the locations of the photographs in C and D (also labelled in B). Note that D represents an abandoned course of the channel, which has subsequently incised and followed a more northerly route.

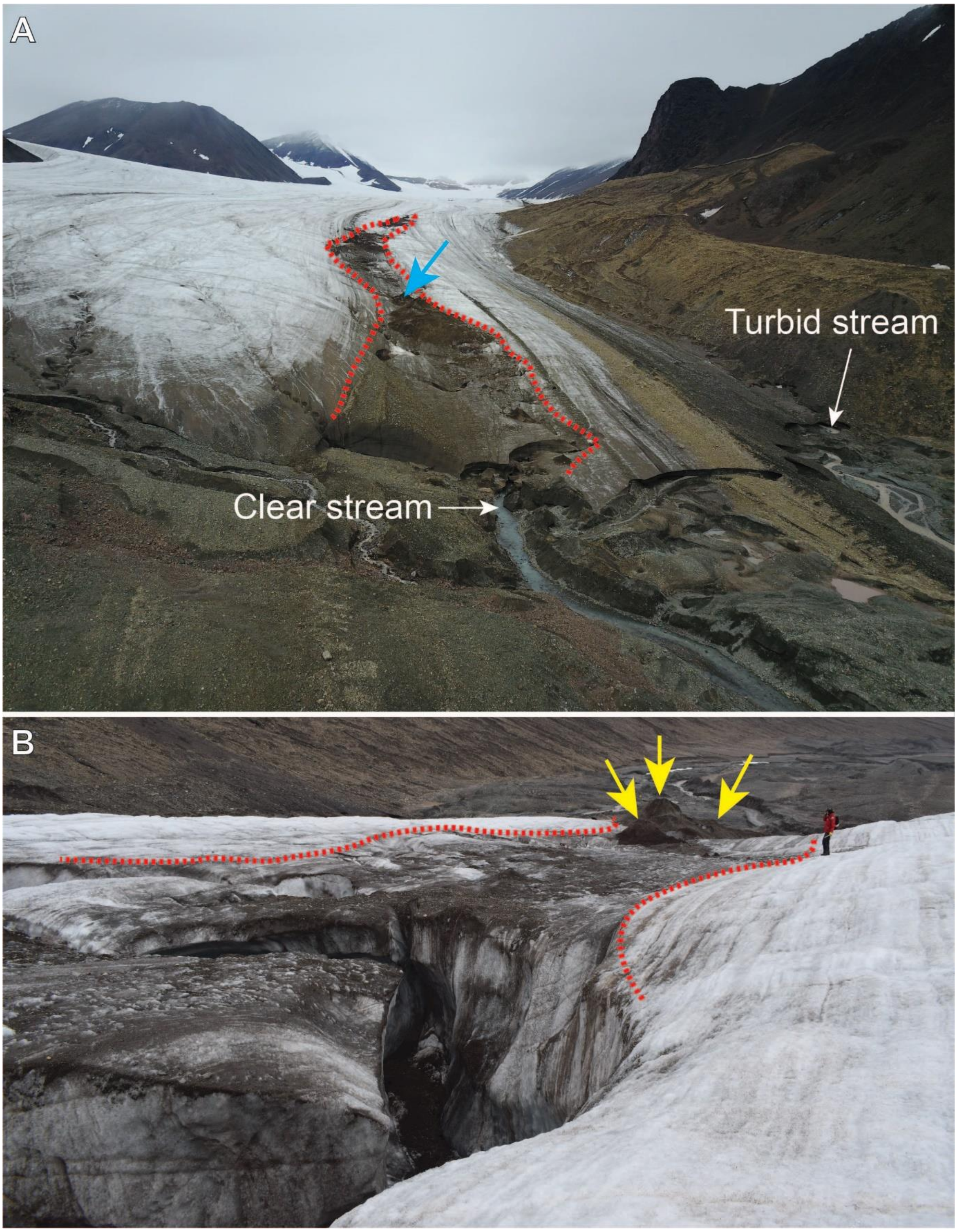

Figure 8. (A) Oblique UAV image of the terminus of Hørbyebreen, showing the incised supraglacial meltwater channel with associated debris cover (enclosed by red dashed lines). Note the two major streams emanating from the glacier, with the central stream carrying relatively clear water and the marginal stream more turbid water. (B) Ground photograph showing the incised supraglacial channel with mantled debris (enclosed by red dashed lines) and sediment mounds downstream of the

debris cover (yellow arrows). The approximate location of B is given by the blue arrow in A.

Eskers

Sharp-crested eskers are abundant and distributed across the lowest part of the foreland, where it is not occupied by proglacial streams (Figure 4B). Between 2009 and 2017 a series of eskers emerged from the northernmost part of the snout (location 2 in Figure 4C). These eskers are orientated either parallel or oblique to the glacier margin as it retreated. The eskers are cut by the proglacial channels mentioned above, and continue to the SE, where they form a complex, locally rectilinear pattern (location 7 in Figure 4C; Figure 9). In this vicinity, larger ridges up to ~ 15 m wide and ~ 10 m in relief exhibit a preferred NNW-SSE (parallel to the ice margin) or WNW-ESE (oblique to the ice margin) orientation. Smaller ridges < 5 m wide and < 3 m in relief and with no clearly prominent orientation occur between the larger ridges and in places appear to be draped over them. These eskers exhibit a complex relationship with the longitudinal debris stripes: some eskers are draped by this debris cover, whereas others are deposited on top of it. Outside of the study area, esker ridges occur downstream of the eskers described above and also on the western part of the foreland (Evans *et al.*, 2012). The former occurs as a large sinuous ridge extending downstream from the complex eskers described above (and shown in Figure 9), with a small number of smaller ridges branching from it. This esker extends to the Little Ice Age moraine and contains a large amount of buried ice (Figure 10) which has gradually melted out, resulting in surface lowering of the esker (Figure 11) and the appearance of rock-glacierised lobes on the esker flanks. Despite this surface lowering, the cross-sectional shape of the esker has remained largely intact. The latter have been mapped and described as a complex of geometric ridge networks and interlinked eskers by Evans *et al.* (2012) who interpreted them as the product of crevasse and hydrofracture infills branching from meltwater tunnels.

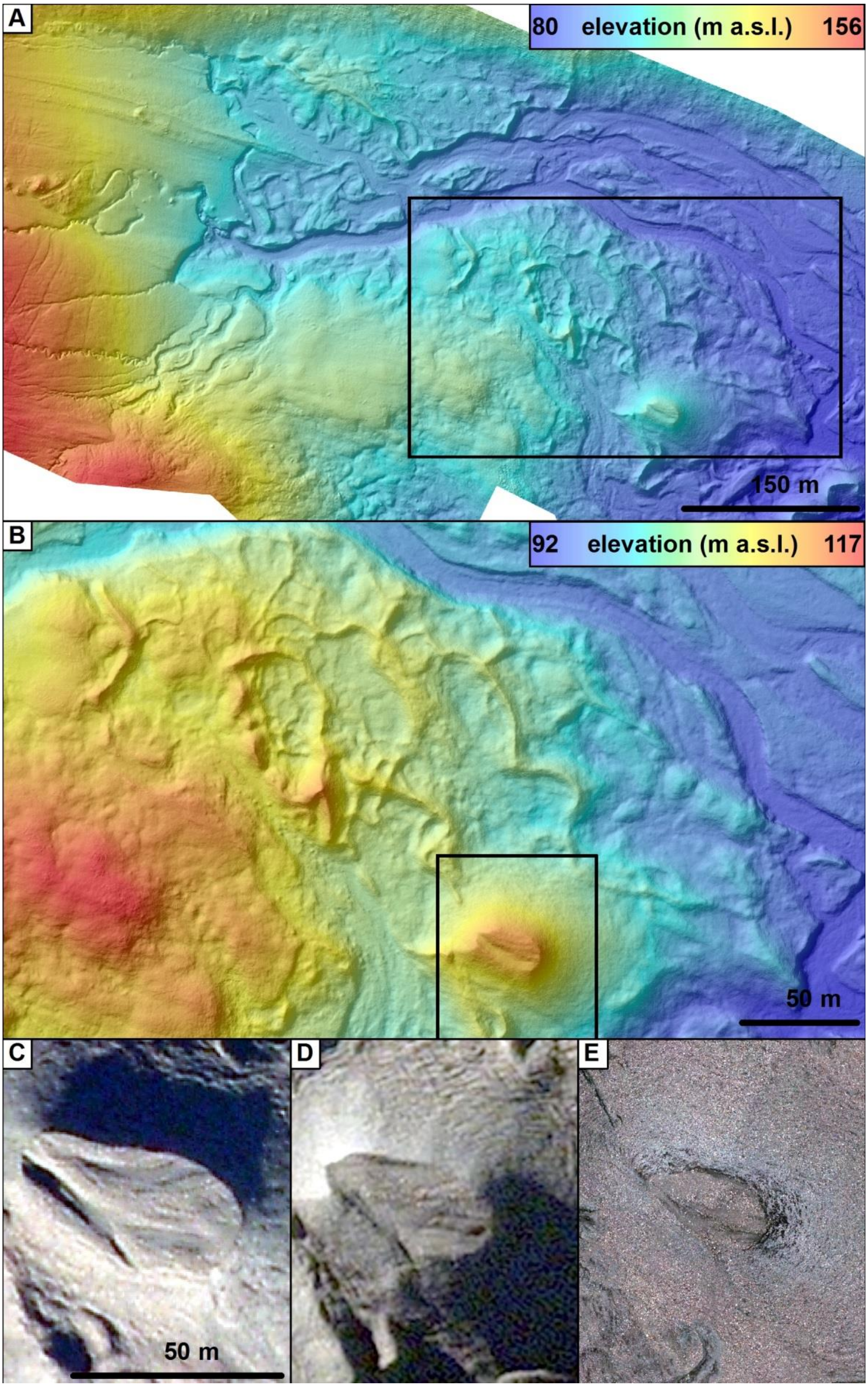

Figure 9. Hillshaded DEMs showing areas of complex esker topography at Hørbyebreen (location 7 in Figure 4). The location of B is shown by the box in A. C, D and E show aerial photographs/satellite images of the mound in the box in B in 2009, 2013 and 2017, respectively.

Figure 10. Ground view of an esker ridge (A) showing the significant ice core and relatively low concentration of debris. The red arrow indicates an exposure of debris-rich ice, likely to be basal ice, which is enlarged in (B). This esker is located just outside of the study area approximately 100 m east of the edge of Figure 4. Its structure is also typical of the eskers in the study area.

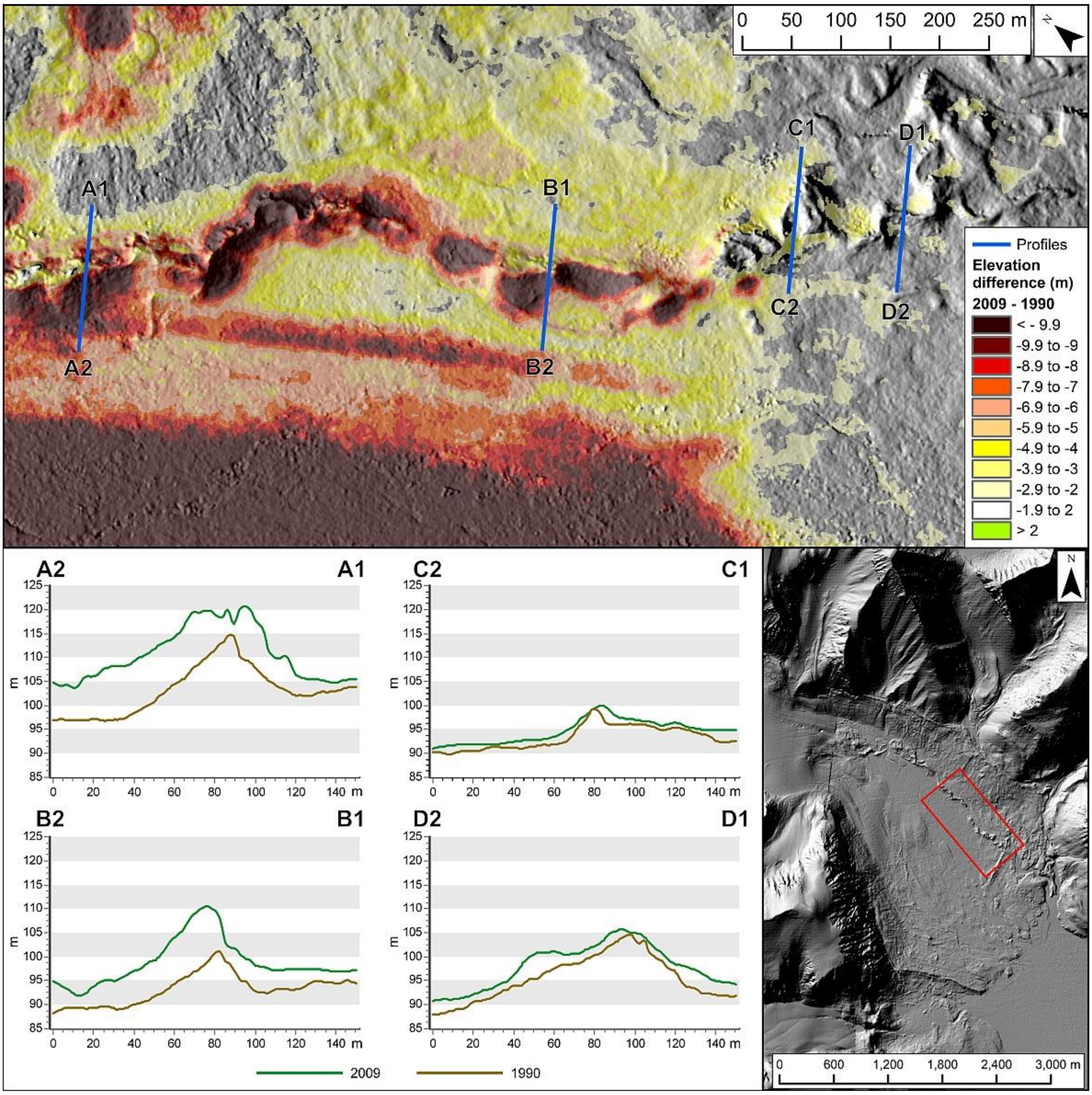

Figure 11. Topographic change in the main esker ridge downstream of the study area between 1990 and 2009. Note that as buried ice melts within the eskers, they nevertheless maintain a similar form.

Supraglacial sediment

On the ice surface, within approximately 500 m of the ice margin, chains of ice-cored sediment mounds resembling eskers are visible (location 8 in Figure 4C, Figure 8). These mounds are largely composed of ice with overlying sediment in the order of cm to 10s of cm thick. These features are located along the incised meandering channel mentioned above. In the location immediately up-ice of the supraglacial mounds, there is a thin spread of debris on the glacier surface (Figure 8B). Similar mounds can also be seen in front of the exposed glacier ice. A conspicuous flat-topped mound is visible in the centre of the bottom of Figure 9B. Close inspection of the surface of this mound reveals the remnants of braided channels in outwash and the flat top has decreased markedly in area since 2009, indicating meltout of buried ice and gradual collapse of the flanks (Figure 9C-E).

Glacial geomorphology of the Breiðamerkurjökull esker complex

In contrast to Hørbyebreen, the Breiðamerkurjökull study area was deglaciated before the first set of imagery was captured. Therefore, we do not discuss ice surface features at Breiðamerkurjökull. However, because 73 years has passed since the first set of imagery, we provide more information here about the evolution of one of the esker systems following the retreat of the ice margin. A geomorphological map of the Breiðamerkurjökull esker system is presented in Figure 12 and relates to esker number MES2 studied by Storrar *et al.* (2015).

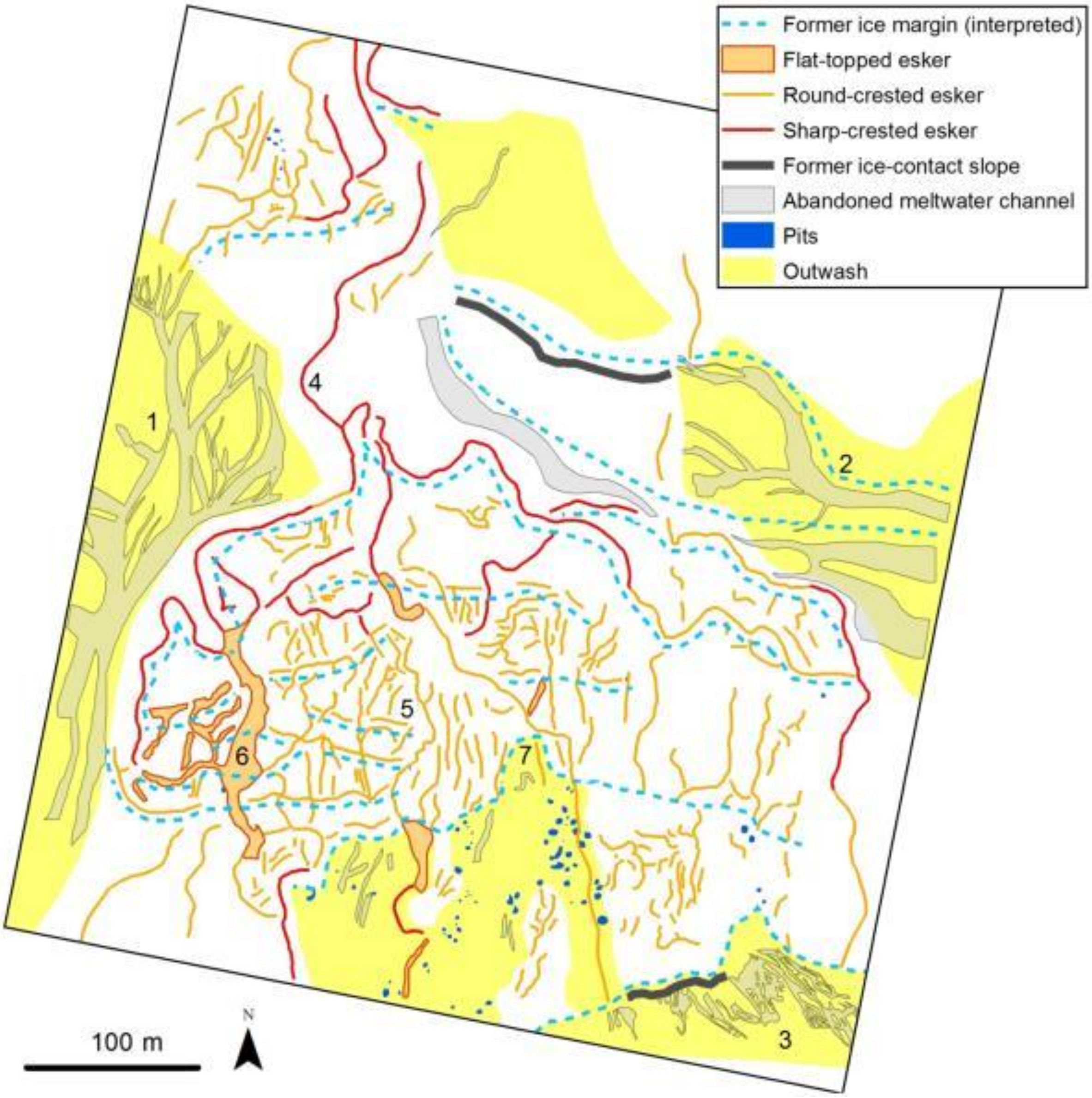

Figure 12. Geomorphological map of the Breiðamerkurjökull esker system. Numbers refer to locations mentioned in the text. Former ice margins are interpreted from ice-contact outwash deposits, marginal meltwater channels and esker orientations. Ice flow was from north to south.

Abandoned meltwater channels

Large (10s m wide) abandoned proglacial meltwater channels occur in deposits of outwash to the west (labelled 1 in Figure 12) and east (2 in Figure 12) of the study area, and smaller (<10 m wide) channels were observed to the south (3 in Figure 12). The southern channels form a distributary network on a laterally extensive outwash fan, indicating water draining to the south. The outwash fan in this location has a pitted surface and grades horizontally into round-crested and flat-topped eskers, which are described below.

Eskers

Eskers are categorised based on their planform geometry into sharp-crested, round-crested and flat-topped features (cf. Price, 1973; Shreve, 1985; Burke *et al.*, 2012b; Burke *et al.*, 2015; Perkins *et al.*, 2016). In the proximal part of the system, a prominent (~10 m high, 30 m wide) single-ridge esker (4 in Figure 12) splits into a series of smaller sharp-crested ridges, which then spread out into a fan-shaped complex of more subdued round-crested ridges (5 in Figure 12). These round-crested ridges form crudely rectilinear patterns much like those at Hørbyebreen (Figure 9), with ridges aligned E-W, approximating the former ice margin orientation, and ridges oblique to that orientation, principally in a N-S direction. In the SW part of the system, many of the eskers are flat-topped (6 in Figure 12) and in places grade into the outwash deposits mentioned above. The outwash fan in the south displays an ice-contact slope orientated approximately W-E.

Evolution of the Breiðamerkurjökull eskers

A series of aerial photographs from 1945 to 2017 (Figure 13) documents the exposure of the esker system as the ice margin retreated, probably beginning in the 1930s (Storrar *et al.*, 2015). By 1945, the glacier had retreated by 50-100 m from a pitted ice-contact outwash fan, with eskers at the proximal end (Figure 13) resting on solid ground (Welch & Howarth, 1968). At this time, the apex of the fan was close to a small embayment in the ice margin, from which a major proglacial meltwater channel issued. By 1955, the fan surface had lowered (Welch & Howarth, 1968; Price, 1969), and more eskers appeared at the proximal side, grading into a chaotic hummocky surface at the distal end. Further meltout and emergence of esker ridges took place and was complete by 1965. The high-resolution UAV imagery from 2017 reveals the detailed morphology in Figure 13.

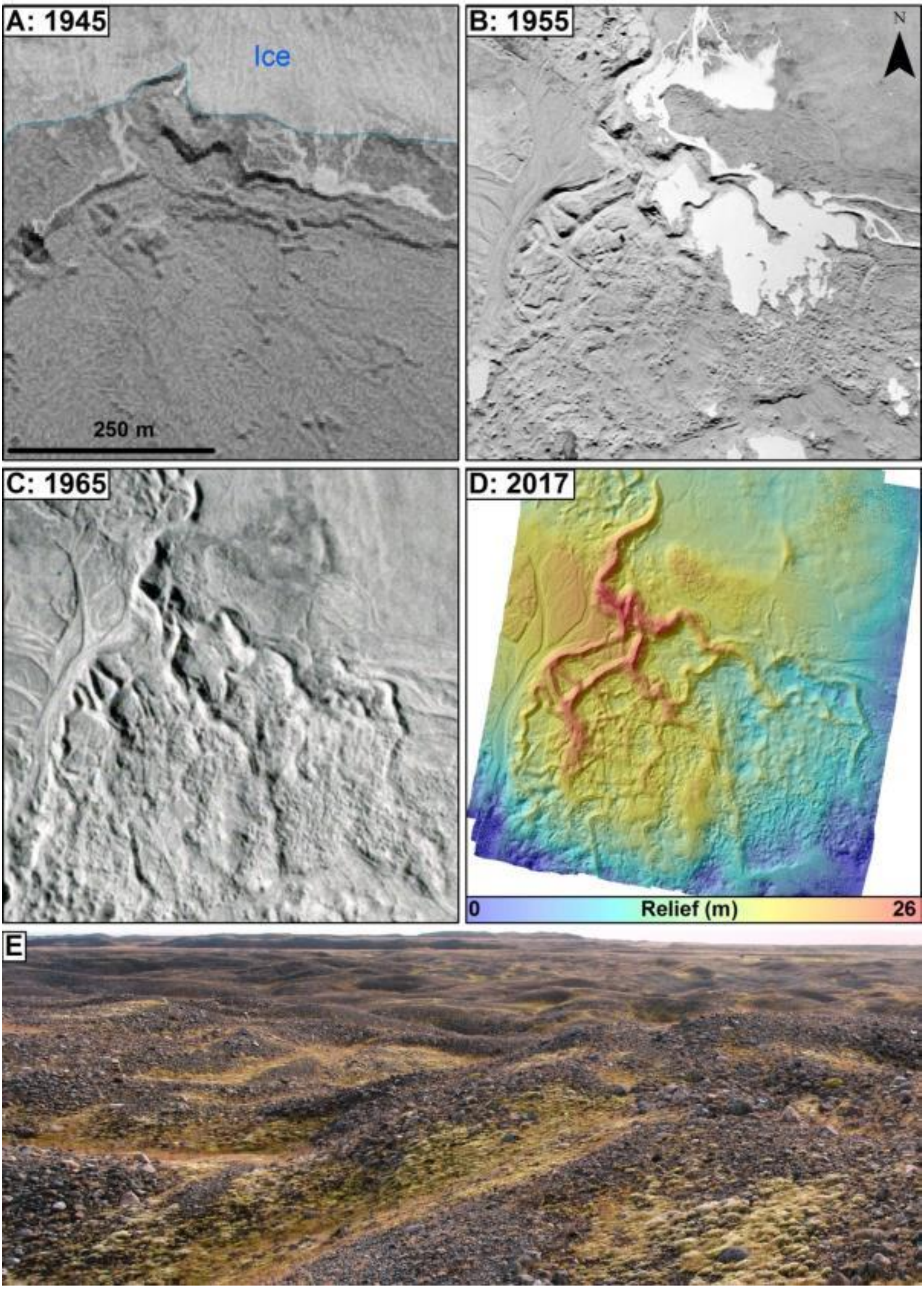

Figure 13. Evolution of the MES2 esker system at Breiðamerkurjökull from 1945 to 2017 (A-D). Aerial photographs (A-C) are from Landmælingar Íslands. Ice is digitised from the 1945 photograph in A. D is a UAV-derived DEM. The photograph in E

shows a ground view of the complex terrain taken in 2012 from approximately the centre of the aerial photographs, looking south.

Comparison of Hørbyebreen and Breiðamerkurjökull esker systems

In terms of climate, thermal regime, meltwater and sediment supply, and topography, there are notable differences between Hørbyebreen and Breiðamerkurjökull (summarised in Table 1). Differences are also apparent in the composition and cross-sectional geometry (Figure 14) of the eskers. Nevertheless, despite these differences similar complex esker plan form patterns have been observed at each location (Figure 9 and Figure 13).

Table 1. Characteristics of Hørbyebreen and Breiðamerkurjökull.

	Hørbyebreen	**Breiðamerkurjökull**
Climate	High-Arctic maritime.	Subarctic maritime.
Glacier thermal regime	Polythermal.	Active temperate.
Sediment source	Bed, lateral margins, and on the ice surface in the cirque.	Bed and medial moraine.
Local topographic context	Relatively flat foreland, constrained by valley sides.	Gentle normal bed slope.
Esker cross-sectional geometry	Sharp-crested.	Flat-topped, round-crested and sharp-crested.
Esker ridge pattern	Complex rectilinear ridges, aligned parallel and oblique to ice margin.	Complex rectilinear ridges, aligned parallel and oblique to ice margin.
Esker system shape	No discernible overarching shape.	Fan shaped.
Esker composition	Thin mantle of sediment (10s of cm thick).	Entirely made of sediment (several m thick).
Esker ice content	Significant ice core.	Assumed to be none in this part of the esker. Welch and Howarth (1968) identified significant buried ice up-glacier from the study location, but the eskers studied lay on solid ground in 1945.

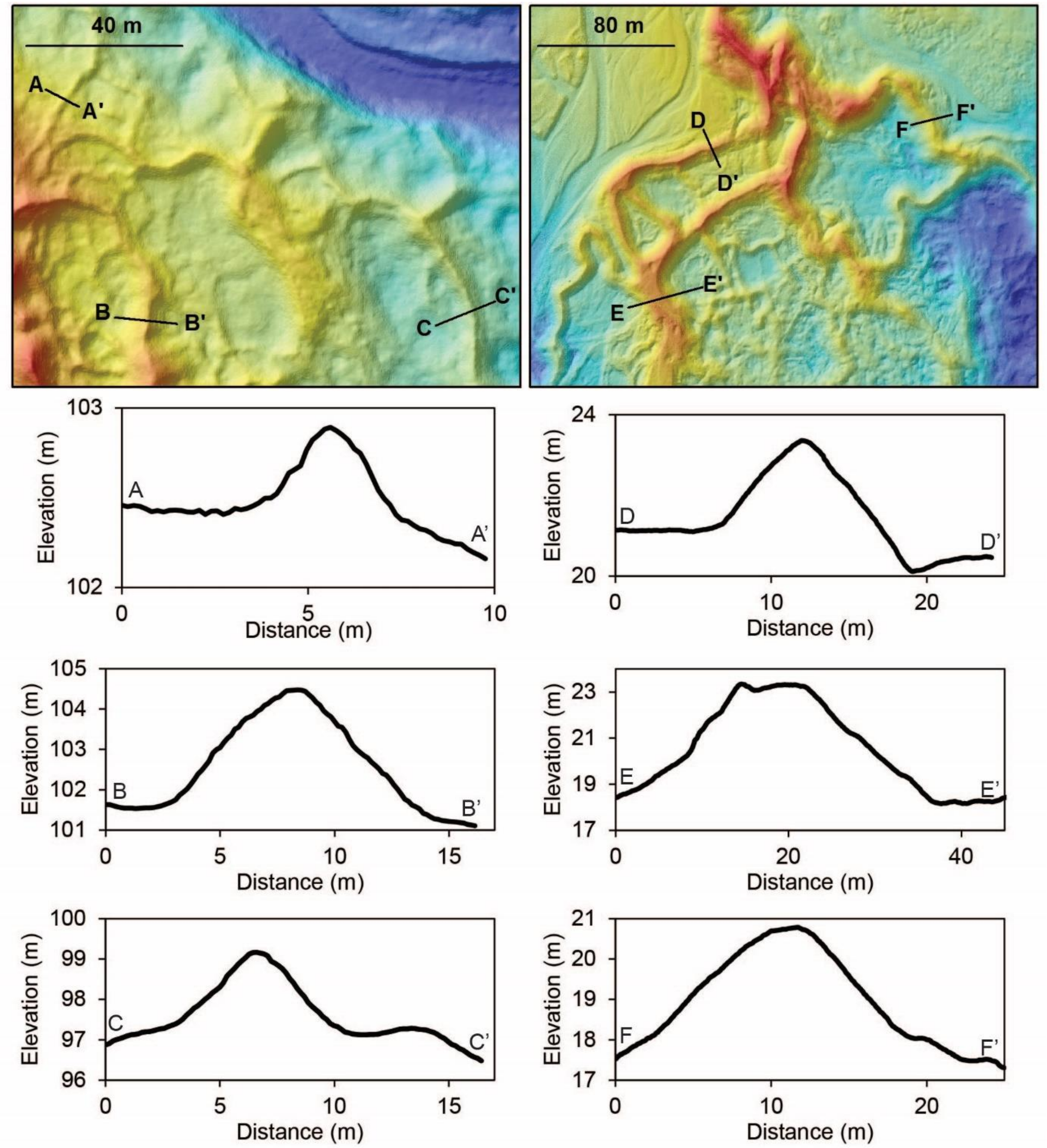

Figure 14. Selected esker cross-sectional geometry for eskers at Hørbyebreen (left) and Breiðamerkurjökull (right). Note that vertical exaggeration varies between cross-sections. Whilst eskers at Hørbyebreen exhibit primarily sharp-crested cross-sections, eskers at Breiðamerkurjökull exhibit cross-sections including sharp (D), flat-topped (E) and more rounded (F).

Discussion

Here, we present depositional models for the Hørbyebreen and Breiðamerkurjökull esker systems, summarised in Figure 15, and then discuss the broader implications of these findings.

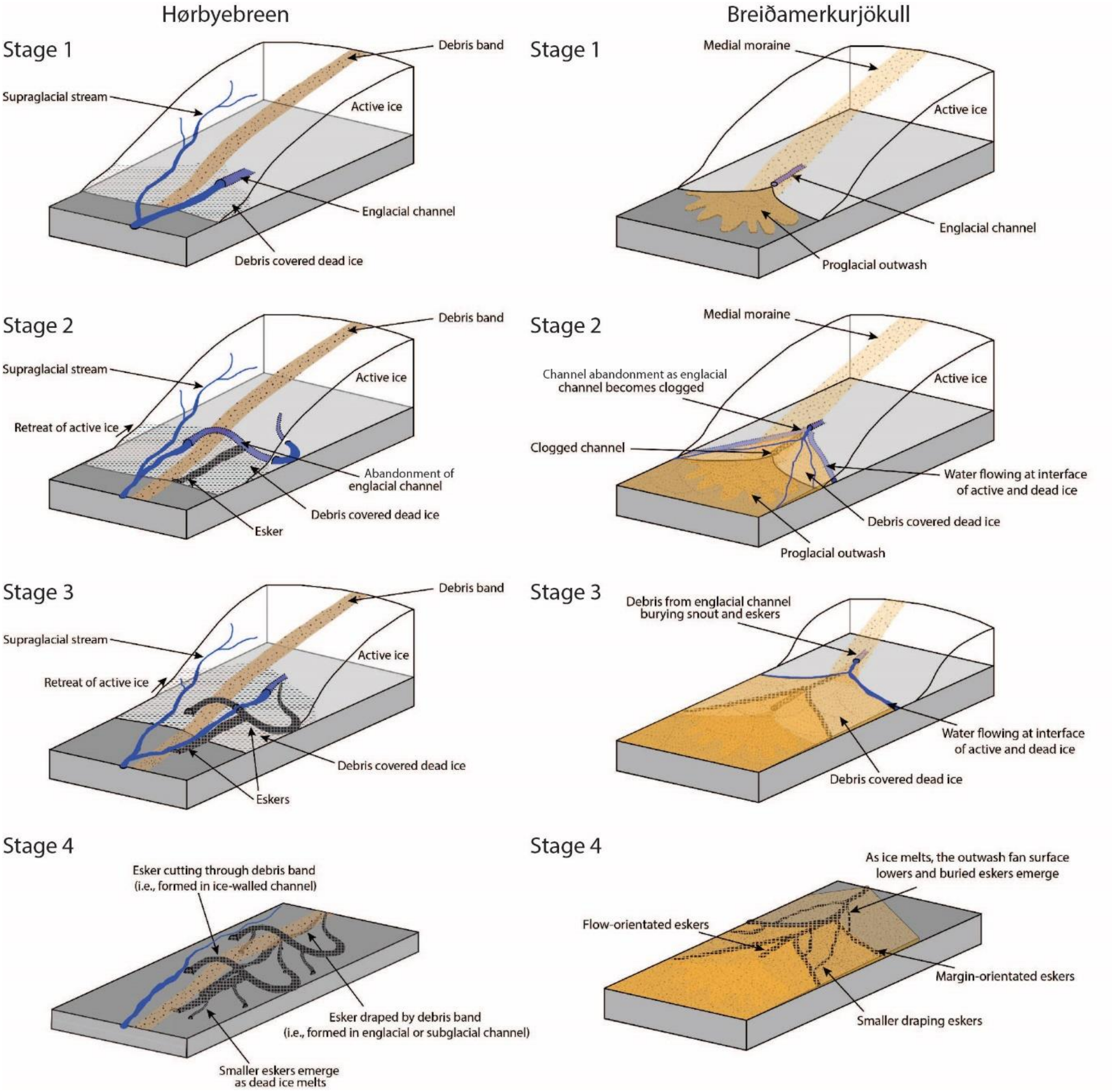

Figure 15. Conceptual diagram for the formation of complex eskers at a receding ice margin based on Hørbyebreen (left) and Breiðamerkurjökull (right).

Depositional model for eskers at Hørbyebreen

Meltwater and sediment are transported in supraglacial, englacial and subglacial channels. Turbid meltwater emerging from en/subglacial channels (Figure 6B; Figure 8A) indicates that sediment concentrations are higher than in supraglacial channels. A thin sediment layer is deposited by supraglacial meltwater, and in some places shields the underlying ice from ablation, resulting in positive relief debris cones (Drewry, 1972). Supraglacial, englacial and subglacial channel geometry is dynamic (Rippin *et al.*, 2015) and is influenced by glacier structure, such as longitudinal debris stripes (Glasser *et al.*, 2003), and the ice margin configuration at the snout (e.g.

Figure 7E). Channels *approaching* the snout are roughly aligned with the flow direction, orthogonal to the margin. Sediment begins to accumulate in these channels towards the margin, eventually resulting in sub/englacial esker ridges roughly aligned with ice flow direction.

As the glacier downwastes, portions of the snout cease to flow (i.e. dead ice) and become covered with debris (e.g. Figure 10; Figure 15, stage 1). En/subglacial channels become exhumed near the margin between active and dead ice and turn into ice-walled (i.e. sub-aerial) channels, which also fill with sediment (e.g. Figure 7 C, D). These channels are occasionally cut-off by stream/channel abandonment (Figure 15, stage 2), which likely occurs at the boundary between active and dead ice, and is driven by changes in base level as the ice margin retreats over varying topography (including the downwasting snout), as is evident in Figure 7E. These channels fill with sediment (prior to- and post-exhumation) to eventually become marginally orientated eskers (i.e. orientated approximately parallel to the ice margin; Figure 15, stage 3). Channel abandonment thereby produces diffluent esker ridges as the margin retreats back and channels are directed in different orientations. These abandonment events take place around a point source, eventually producing large eskers that are aligned with the margin, but punctuated with eskers aligned with flow direction, creating the rectilinear pattern that can be clearly seen in Figure 9.

As the ice retreats, differential ablation initiates topographic inversion, as the channel deposits insulate ice buried beneath them more than the surrounding surface (cf. Holmes, 1947; Clayton, 1964; Clayton & Cherry, 1967; Huddart, 1999; Livingstone *et al.*, 2010; Lovell *et al.*, in review). A cross-cutting and locally rectilinear pattern of esker ridges, comprising a sediment layer and ice core (Figure 10), is formed by these two orientations of ridges (Figure 15, stage 4). Sediment is deposited in channels at different elevations in the system, reflecting channels at different locations in space and time, which become superimposed on one another when the ice surface retreats and lowers (cf. Gulley & Benn, 2007). Accumulations of debris in supraglacial channels add to this process, forming ice-cored supraglacial eskers that drape sub/englacial eskers, but are unlikely to survive over longer timescales, due to the low sediment concentration. In places, mounds of ice-cored sediment are produced where isolated thicker surficial deposits insulate the ice buried beneath them. A particularly conspicuous ice-cored mound is shown in Figure 9. This mound might originate from a number of possible processes: sedimentary infill of a moulin; as an ice-walled lake plain; or as an infill of an abandoned meander cut-off relating to a high-sinuosity supraglacial channel.

Depositional model for eskers at Breiðamerkurjökull

Sub/englacial channels carry substantial bedload derived from the medial moraine. Sediment is deposited at the ice margin to form dominant and large flow-parallel eskers and a proglacial outwash fan (location 7 in Figure 12; Figure 15, stage 1).

The largest eskers are mostly sharp-crested (Figure 12; Figure 13), which may suggest that they formed in tunnels close to the ice surface (Perkins *et al.*, 2016). Englacial channels may disgorge onto the ice surface: if they have a high concentration of sediment this results in burial of part of the glacier snout, as shown in stage 2 in Figure 15. Some of the distal eskers are flat-topped, indicating that they were formed sub-aerially in an ice-walled canyons (Warren & Ashley, 1994; Perkins *et al.*, 2016).

As the proglacial outwash fan aggrades and the ice margin retreats, meltwater drainage is diverted by the topographic barrier produced by prior outwash deposition (outwash head: cf. Benn *et al.*, 2003; Evans & Orton, 2015). This produces subsidiary eskers oriented parallel to the ice margin (Figure 15, stage 2), which branch away from the main esker as channels become clogged with sediment (Storrar *et al.*, 2015). These subsidiary eskers tend to be round-crested, indicating formation in subglacial positions (e.g. Price, 1973; Perkins *et al.*, 2016). Flat-topped eskers form where channels transition from being under hydrostatic pressure to atmospheric pressure (Russell *et al.*, 2001).

Supra/englacial channels carry finer material derived from the ice surface and englacial debris, which covers the glacier snout and transitions into a proglacial outwash fan. This buries the subglacial eskers and the glacier snout with outwash, and produces a zone of dead ice at the glacier toe (Figure 15B, stage 3). As the glacier retreats, marginal channels may form between the active part of the glacier and the dead ice, in a similar fashion to that described above for Hørbyebreen. This provides an alternative or additional mechanism for the formation of margin-parallel eskers.

Once the glacier has retreated, the dead ice gradually melts out, the outwash fan surface lowers, becomes pitted, and eventually exposes the buried eskers (Figure 15B, stage 4) as shown in the time series in Figure 13.

Wider implications for esker formation

In what types of channel do eskers form (proglacial, subglacial, englacial, supraglacial)?

Meltwater has been predicted and observed to drain through all parts of a glacier: at the ice surface in supraglacial channels, within englacial channels, and at the bed in subglacial channels. Eskers at modern glaciers have been observed to form in all of these positions (e.g. Price, 1969; Fitzsimons, 1991; Huddart *et al.*, 1999; Burke *et al.*, 2009; Bennett *et al.*, 2010), however subglacial formation, in particular, is inferred for the vast majority of ice sheet-scale eskers (e.g. Punkari, 1997; Brennand, 2000; Boulton *et al.*, 2009; Storrar *et al.*, 2014a). Variations in esker cross-sectional geometry have been related to the geometry of the parent channel (Price, 1973), as well as to the type of channel, mode of deposition and modification during ice melt-out (Perkins *et al.*, 2016). Sharp-crested eskers have been inferred to reflect deposition in level or descending terrain (Shreve, 1985), or deposition and subsequent let-down in supraglacial channels (Price, 1966; Syverson *et al.*, 1994; Perkins *et al.*, 2016). Round-crested geometries have been found in a significant proportion (>80%) of eskers on the southern Fraser Plateau, British Columbia, Canada, which have been interpreted from geophysical and morphological data as having formed subglacially (Burke *et al.*, 2012b; Perkins *et al.*, 2016). Flat-topped eskers are suggested to be the result of deposition in ice walled canyons from deposition by vertical accretion in channels at atmospheric pressure (Russell *et al.*, 2001; Perkins *et al.*, 2016) or in steeply ascending tunnels with net freezing walls (Shreve, 1985). Validation of these relationships would enable the large-scale interpretation of channel types from systematic mapping of eskers at the ice sheet scale.

The eskers at Hørbyebreen are sharp-crested, and are observed to form primarily in englacial channels close to the ice margin where the ice is relatively thin (see Figure 6). These eskers contain significant ice cores (Figure 10) and so could not have formed in subglacial positions, despite the observation that at least part of the channel appears to be subglacial from GPR data (Figure 6). These observations support the suggestion that sharp-crested eskers can form by meltout of buried ice and subsequent adjustment of the cross-sectional geometry (e.g. Price, 1973; Burke *et al.*, 2012b; Perkins *et al.*, 2016), although this is not limited to supraglacial channels and can occur in shallow englacial channels. It is important to note that it is likely that the morphology of the Hørbyebreen esker system will continue to gradually change as the buried ice melts (Figure 11).

In contrast, the eskers at Breiðamerkurjökull appear to have formed in englacial, subglacial and supraglacial (ice-walled) positions and display a series of cross-sectional geometries, with the larger eskers typically being sharp-crested and the smaller subsidiary eskers being more round-crested. This could either reflect primary formation of sharp-crested eskers in englacial channels and round-crested eskers in subglacial channels (c.f. Perkins *et al.*, 2016), or post-depositional modification of sharp-crested eskers into more round-crested eskers when buried ice melts out. Flat-topped eskers are typically found at distal locations and are likely to have formed by deposition in ice-walled channels at the margin. It should be noted that eskers elsewhere at Breiðamerkurjökull (including the esker immediately up-ice of the study location) did contain ice cores (Welch & Howarth, 1968; Price, 1969).

In general, these observations provide some support for the suggestion that esker cross-sectional geometry can be related to the vertical position of the parent channel (Perkins *et al.*, 2016). However, the similarity in planform patterns between Breiðamerkurjökull and Hørbyebreen demonstrate that similar esker patterns may arise regardless of the vertical position in the glacier in which the esker originally formed. As such, the suggestion that multiple criteria need to be consulted before producing esker classifications (Perkins *et al.*, 2016) is sensible.

Why do eskers sometimes form complex systems with cross-cutting long axes when glaciological theory and associated observations suggest that tunnels largely remain stable (e.g. Boulton et al., 2007a;b)?

Eskers may produce a range of spatial patterns, from relatively simple long and straight single ridges, to complex anabranching systems of multiple ridges (Figure 1). It has been suggested, based on observations of ancient esker sediments and modern esker morphology, that complexity (both in terms of morphology and sedimentology) is driven by increases in sediment and meltwater supply (Burke *et al.*, 2015; Storrar *et al.*, 2015). Unpicking the processes involved in forming esker systems of varying complexity is key to using eskers to reconstruct the dynamics of ancient (and contemporary) meltwater drainage systems.

Eskers have not been studied extensively in Svalbard but, where present, occur at a range of sizes and degrees of complexity (Huddart *et al.*, 1999; Dowdeswell & Ottesen, 2016; Forwick *et al.*, 2016). The more unusual complex eskers at Hørbyebreen occur within a zone of flat topography, where meltwater drainage from the glacier is constrained by the lateral margin on one side, and a bedrock protrusion on the other. This means that meltwater is concentrated over a relatively small width of the glacier. Sediment supply is also high, resulting from the degradation of ice-cored lateral moraines and paraglacial slope failures as the glacier retreats, as well as debris supplied from further up-glacier in englacial debris bands and from the bed. The situation at Breiðamerkurjökull is partially comparable, in that meltwater and sediment supply are high (albeit from a different source: the Mavabyggdarond medial moraine), and the bed is relatively flat. We therefore suggest that the complex pattern of eskers is a result of this concentration of sediment in a narrow but flat section of the glacier foreland, coupled with a sufficient supply of meltwater. The increased supply of sediment means that channels can aggrade and form eskers. However, increased sediment supply alone is not sufficient to form *complex* eskers - it could simply form large single ridges. We suggest that complexity arises where sediment supply is high, but also where the drainage system structure evolves dynamically in response to the retreating ice margin; detachment of dead ice from the active glacier; deposition in association with outwash heads; and channel abandonment related to changes in base level controlled by proglacial channel evolution.

Preservation potential

Abundant ice cores and relatively low sediment volume in ice cored eskers such as those at Hørbyebreen mean that it is unlikely that the eskers will survive as distinct landforms once the ice cores melt. In contrast, the eskers studied at Breiðamerkurjökull do not contain ice cores and remain significant topographic features, and are likely to do so until the next ice advance. Eskers elsewhere at

Breiðamerkurjökull that were ice cored have exhibited topographic lowering (Price, 1969); some retained their form whilst others, such as Price's (1969) esker E5, have been almost entirely eroded. Preservation potential is therefore a critical consideration in the interpretation of ancient eskers, or indeed areas of palaeo-ice sheet beds where eskers are apparently absent. This supports the notion that, in order for eskers to survive, they must: (1) contain sufficient sediment to remain substantial topographic features following melt-out of any contained ice; (2) then avoid being eroded by the evolution of proglacial drainage systems, particularly laterally migrating proglacial channels; and (3) not be subject to any subsequent ice advance, which is likely to destroy them. Additionally, eskers may prove difficult to identify in ancient landform assemblages where they become overwhelmed with other ice-contact glacifluvial forms that evolved alongside them in a glacier karst (Huddart & Bennett, 1997; Thomas & Montague, 1997; Huddart, 1999; Livingstone *et al.*, 2010).

Esker preservation will therefore be favoured in conditions where sediment supply is high (so that features of substantial relief remain after melting), where the topography is relatively flat and wide, which minimises the risk of proglacial channels migrating through esker deposits, and where deglaciation proceeds without readvance. An exception to this is where eskers are subsequently subjected to exclusively *cold based* glaciation (Kleman, 1994). These observations help to explain why eskers are abundant on the beds of the Fennoscandian and Laurentide Ice Sheets. In both cases, the erosion of the ice sheet beds provided a supply of till to feed esker formation (e.g. Bolduc, 1992; Cummings *et al.*, 2011). Both ice sheets were centred on 'shield' terrain, which provides broad, flat beds favouring preservation of eskers, since proglacial channels have ample space to migrate laterally without eroding eskers. Shield terrain was also suggested by Clark and Walder (1994) to account for the formation of eskers rather than tunnel valleys, since channels would be incised into ice rather than sediment, although eskers do form on soft beds (e.g. Rotnicki, 1960; Shetsen, 1987; Evans *et al.*, 2006; Atkinson *et al.*, 2014; Evans *et al.*, 2014; Burke *et al.*, 2015) and moreover are difficult to map in soft bed settings and hence are likely under-represented in the landform record. Finally, deglaciation since the Younger Dryas in both North America and Fennoscandia proceeded with minimal/no readvances, particularly during the time period when most of the eskers formed (Dyke, 2004; Storrar *et al.*, 2014a; Storrar *et al.*, 2014b; Stroeven *et al.*, 2016). Eskers are less common in other ice sheet settings, such as the Cordilleran (e.g. Ryder *et al.*, 1991; Burke *et al.*, 2012a; Margold *et al.*, 2013) or Patagonian (Glasser *et al.*, 2008; Darvill *et al.*, 2017) Ice Sheets, where ice flow was more constrained by topography. Sediment supply from erosion of valley sides and bottoms would have been high, but the restriction of meltwater flows to confined valleys would have increased the chance of subsequent proglacial meltwater channels inhibiting or eroding any existing esker deposits.

Conclusions

We present evidence for the formation and evolution of complex esker systems at Hørbyebreen, a polythermal glacier in Svalbard, and Breiðamerkurjökull, an active temperate glacier in Iceland. In both locations, esker deposition, via different processes, has resulted in similar complex and locally rectilinear patterns, suggesting that esker morphology might be a product of polyphase or multi-generational development. Both of these complex esker systems have formed time-transgressively in association with a retreating and downwasting ice margin. Eskers at Hørbyebreen formed mainly in englacial positions, whilst the Breiðamerkurjökull eskers formed in subglacial, englacial and supraglacial positions. Complex eskers appear to form in dynamic systems where there is an adequate supply of meltwater, the rate of sediment deposition is high, and channel abandonment is frequent. Interaction between the active ice margin, dead ice, meltwater channels and outwash heads is also found to be an important control on the pattern of eskers at both sites. In both cases, esker pattern appears to mimic the shape of the ice margin, contrasting with the traditional assumption that eskers are usually flow-parallel features. Our observations lead us to reflect on the preservation potential of eskers. We suggest that for eskers to survive deglaciation, they must meet three criteria: (1) they must first contain sufficient sediment to remain substantial topographic features following melt-out of any contained ice; (2) they must then escape erosion by the later proglacial drainage systems, which is favoured by broad, flat topography and impeded by more mountainous terrain; (3) they must not be subject to any subsequent warm-based ice advance. Additionally, eskers may prove difficult to identify if they are overwhelmed with other ice-contact glacifluvial forms that evolved alongside them in a glacier karst. Together, these observations help to constrain the conditions under which modern complex eskers form and are likely to be preserved, which can then be applied to eskers related to late Quaternary ice sheets.

Acknowledgements

This research received funding from the European Union’s Horizon 2020 project INTERACT, under grant agreement No 730938. We thank Cathy Delaney, who supplied the Irish Lidar data used in Figure 1, and Andrew Jones, who provided the UAV data for Breiðamerkurjökull.

References

Atkinson, N., Utting, D. J. & Pawley, S. M. (2014) Glacial landforms of Alberta, Canada. *Alberta Energy Regulator, AER/AGS Map 604, Scale 1:1,000,000*.

Aylsworth, J. M. & Shilts, W. W. (1989) Bedforms of the Keewatin Ice-Sheet, Canada. *Sedimentary Geology*, 62, 407-428.

Bartholomew, I., Nienow, P., Sole, A., Mair, D., Cowton, T. & King, M. A. (2012) Short-term variability in Greenland Ice Sheet motion forced by time-varying meltwater drainage: Implications for the relationship between subglacial drainage system behavior and ice velocity. *J. Geophys. Res.*, 117, F03002.

Bell, R. E., Chu, W., Kingslake, J., Das, I., Tedesco, M., Tinto, K. J., Zappa, C. J., Frezzotti, M., Boghosian, A. & Lee, W. S. (2017) Antarctic ice shelf potentially stabilized by export of meltwater in surface river. *Nature*, 544, 344.

Benn, D. I., Kirkbride, M. P., Owen, L. A. & Brazier, V. (2003) Glaciated valley landsystems. In D. J. A. Evans, *Glacial Landsystems*, 372-406.

Bennett, G. L., Evans, D. J. A., Carbonneau, P. & Twigg, D. R. (2010) Evolution of a debris-charged glacier landsystem, Kvíárjökull, Iceland. *Journal of Maps*, 6, 40-67.

Björnsson, H., Gjessing, Y., Hamran, S.-E., Hagen, J. O., LiestøL, O., Pálsson, F. & Erlingsson, B. (1996) The thermal regime of sub-polar glaciers mapped by multi-frequency radio-echo sounding. *Journal of Glaciology*, 42, 23-32.

Bolduc, A. M. (1992) The formation of eskers based on their morphology, stratigraphy and lithologic composition, Labrador, Canada. *Unpublished Ph.D. thesis, Lehigh University*.

Boulton, G. S., Hagdorn, M., Maillot, P. B. & Zatsepin, S. (2009) Drainage beneath ice sheets: groundwater-channel coupling, and the origin of esker systems from former ice sheets. *Quaternary Science Reviews*, 28, 621-638.

Boulton, G. S., Lunn, R., Vidstrand, P. & Zatsepin, S. (2007a) Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part I-glaciological observations. *Quaternary Science Reviews*, 26, 1067-1090.

Boulton, G. S., Lunn, R., Vidstrand, P. & Zatsepin, S. (2007b) Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: part II-theory and simulation of a modern system. *Quaternary Science Reviews*, 26, 1091-1105.

Brennand, T. A. (2000) Deglacial meltwater drainage and glaciodynamics: inferences from Laurentide eskers, Canada. *Geomorphology*, 32, 263-293.

Burke, M. J., Brennand, T. A. & Perkins, A. J. (2012a) Evolution of the subglacial hydrologic system beneath the rapidly decaying Cordilleran Ice Sheet caused by ice-dammed lake drainage: implications for meltwater-induced ice acceleration. *Quaternary Science Reviews*, 50, 125-140.

Burke, M. J., Brennand, T. A. & Perkins, A. J. (2012b) Transient subglacial hydrology of a thin ice sheet: insights from the Chasm esker, British Columbia, Canada. *Quaternary Science Reviews*, 58, 30-55.

Burke, M. J., Brennand, T. A. & Sjogren, D. B. (2015) The role of sediment supply in esker formation and ice tunnel evolution. *Quaternary Science Reviews*, 115, 50-77.

Burke, M. J., Woodward, J., Russell, A. J. & Fleisher, P. J. (2009) Structural controls on englacial esker sedimentation: Skeiðarárjökull, Iceland. *Annals of Glaciology*, 50, 85-92.

Burke, M. J., Woodward, J., Russell, A. J., Fleisher, P. J. & Bailey, P. K. (2008) Controls on the sedimentary architecture of a single event englacial esker: Skeiðarárjökull, Iceland. *Quaternary Science Reviews*, 27, 1829-1847.

Clark, C. D., Ely, J. C., Greenwood, S. L., Hughes, A. L. C., Meehan, R., Barr, I. D., Bateman, M. D., Bradwell, T., Doole, J., Evans, D. J. A., Jordan, C. J., Monteys, X., Pellicer, X. M. & Sheehy, M. (2018) BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British–Irish Ice Sheet. *Boreas*, 47, 11-27.

Clark, P. U. & Walder, J. S. (1994) Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. *Bulletin of the Geological Society of America*, 106, 304-314.

Clayton, L. (1964) Karst topography on stagnant glaciers. *Journal of Glaciology*, 5, 107-112.

Clayton, L. & Cherry, J. (1967) Pleistocene superglacial and ice-walled lakes of west-central North America. *North Dakota Geological Survey, Miscellaneous Series*, 30, 47-52.

Cowton, T., Nienow, P., Sole, A., Wadham, J., Lis, G., Bartholomew, I., Mair, D. & Chandler, D. (2013) Evolution of drainage system morphology at a land-terminating Greenlandic outlet glacier. *Journal of Geophysical Research: Earth Surface*, 118, 29-41.

Cummings, D. I., Kjarsgaard, B. A., Russell, H. A. J. & Sharpe, D. R. (2011) Eskers as mineral exploration tools. *Earth-Science Reviews*, 109, 32-43.

Darvill, C. M., Stokes, C. R., Bentley, M. J., Evans, D. J. A. & Lovell, H. (2017) Dynamics of former ice lobes of the southernmost Patagonian Ice Sheet based on a glacial landsystems approach. *Journal of Quaternary Science*, 32, 857-876.

Delaney, C. A., McCarron, S. & Davis, S. (2018) Irish Ice Sheet dynamics during deglaciation of the central Irish Midlands: Evidence of ice streaming and surging from airborne LiDAR. *Geomorphology*, 306, 235-253.

Dowdeswell, J. A. & Ottesen, D. (2016) Eskers formed at the beds of modern surge-type tidewater glaciers in Spitsbergen. *Geological Society, London, Memoirs*, 46, 83-84.

Drewry, D. J. (1972) A quantitative assessment of dirt-cone dynamics. *Journal of Glaciology*, 11, 431-446.

Dyke, A. S. (2004) An outline of North American deglaciation with emphasis on central and northern Canada. *Quaternary glaciations: extent and chronology*, 2, 373-424.

Engelhardt, H., Humphrey, N., Kamb, B. & Fahnestock, M. (1990) Physical Conditions at the Base of a Fast Moving Antarctic Ice Stream. *Science*, 248, 57-59.

Evans, D. J. & Orton, C. (2015) Heinabergsjökull and Skalafellsjökull, Iceland: active temperate piedmont lobe and outwash head glacial landsystem. *Journal of Maps*, 11, 415-431.

Evans, D. J., Strzelecki, M., Milledge, D. G. & Orton, C. (2012) Hørbyebreen polythermal glacial landsystem, Svalbard. *Journal of Maps*, 8, 146-156.

Evans, D. J., Young, N. J. & Cofaigh, C. Ó. (2014) Glacial geomorphology of terrestrial-terminating fast flow lobes/ice stream margins in the southwest Laurentide Ice Sheet. *Geomorphology*, 204, 86-113.

Evans, D. J. A., Rea, B. R., Hiemstra, J. F. & Ó Cofaigh, C. (2006) A critical assessment of subglacial mega-floods: a case study of glacial sediments and landforms in south-central Alberta, Canada. *Quaternary Science Reviews*, 25, 1638-1667.

Evans, D. J. A. & Twigg, D. R. (2002) The active temperate glacial landsystem: a model based on Breiðamerkurjökull and Fjallsjökull, Iceland. *Quaternary Science Reviews*, 21, 2143-2177.

Ewertowski, M., Evans, D. J. A., Roberts, D. H., Tomczyk, A. M., Ewertowski, W. & Pleskot, K. (2019) Quantification of historical landscape change on the foreland of a receding polythermal glacier, Hørbyebreen, Svalbard. *Geomorphology*, 325, 40-54.

Fitzsimons, S. J. (1991) Supraglacial eskers in Antarctica. *Geomorphology*, 4, 293-299.

Forwick, M., Kempf, P. & Laberg, J. (2016) Eskers in deglacial sediments of three Spitsbergen fjords. *Geological Society, London, Memoirs*, 46, 85-86.

Fowler, A. (1987) A theory of glacier surges. *Journal of Geophysical Research: Solid Earth*, 92, 9111-9120.

Fricker, H. A., Siegfried, M. R., Carter, S. P. & Scambos, T. A. (2016) A decade of progress in observing and modelling Antarctic subglacial water systems. *Phil. Trans. R. Soc. A*, 374, 20140294.

Gallagher, C. & Balme, M. (2015) Eskers in a complete, wet-based glacial system in the Phlegra Montes region, Mars. *Earth and Planetary Science Letters*, 431, 96-109.

Gibas, J., Rachlewicz, G. & Szczuciński, W. (2005) Application of DC resistivity soundings and geomorphological surveys in studies of modern Arctic glacier marginal zones, Petuniabukta, Spitsbergen. *Polish Polar Research*, 26, 239-258.

Glasser, N. F., Hambrey, M. J., Etienne, J. L., Jansson, P. & Pettersson, R. (2003) The origin and significance of debris-charged ridges at the surface of Storglaciären, northern Sweden. *Geografiska Annaler: Series A, Physical Geography*, 85, 127-147.

Glasser, N. F., Jansson, K. N., Harrison, S. & Kleman, J. (2008) The glacial geomorphology and Pleistocene history of South America between 38°S and 56°S. *Quaternary Science Reviews*, 27, 365-390.

Gorrell, G. & Shaw, J. (1991) Deposition in an esker, bead and fan complex, Lanark, Ontario, Canada. *Sedimentary Geology*, 72, 285-314.

Guðmundsson, S., Björnsson, H. & Pálsson, F. (2017) Changes of Breiðamerkurjökull glacier, SE-Iceland, from its late nineteenth century maximum to the present. *Geografiska Annaler: Series A, Physical Geography*, 99, 338-352.

Gulley, J. D. & Benn, D. I. (2007) Structural control of englacial drainage systems in Himalayan debris-covered glaciers. *Journal of Glaciology*, 53, 399-412.

Gulley, J. D., Spellman, P. D., Covington, M. D., Martin, J. B., Benn, D. I. & Catania, G. (2014) Large values of hydraulic roughness in subglacial conduits during conduit enlargement: implications for modeling conduit evolution. *Earth Surface Processes and Landforms*, 39, 296-310.

Gustavson, T. C. & Boothroyd, J. C. (1987) A depositional model for outwash, sediment sources, and hydrologic characteristics, Malaspina Glacier, Alaska: A modern analog of the southeastern margin of the Laurentide Ice Sheet. *Bulletin of the Geological Society of America*, 99, 187.

Hart, J. K., Rose, K. C., Clayton, A. & Martinez, K. (2015) Englacial and subglacial water flow at Skálafellsjökull, Iceland derived from ground penetrating radar, in situ Glacsweb probe and borehole water level measurements. *Earth Surface Processes and Landforms*, 40, 2071-2083.

Hebrand, M. & Åmark, M. (1989) Esker formation and glacier dynamics in eastern Skane and adjacent areas, southern Sweden. *Boreas*, 18, 67-81.

Hewitt, I. J. (2011) Modelling distributed and channelized subglacial drainage: the spacing of channels. *Journal of Glaciology*, 57, 302-314.

Hewitt, I. J. (2013) Seasonal changes in ice sheet motion due to melt water lubrication. *Earth and Planetary Science Letters*, 371–372, 16-25.

Holmes, C. D. (1947) Kames. *American journal of Science*, 245, 240-249.

Hubbard, B. & Nienow, P. (1997) Alpine subglacial hydrology. *Quaternary Science Reviews*, 16, 939-955.

Hubbard, B., Sharp, M., Willis, I., NIELSEN, M. t. & Smart, C. (1995) Borehole water-level variations and the structure of the subglacial hydrological system of Haut Glacier d'Arolla, Valais, Switzerland. *Journal of Glaciology*, 41, 572-583.

Huddart, D. (1999) Supraglacial trough fills, southern Scotland: origins and implications for deglacial processes. *Glacial geology and geomorphology*.

Huddart, D. & Bennett, M. R. (1997) The Carstairs kames (Lanarkshire, Scotland): morphology, sedimentology and formation. *Journal of Quaternary Science: Published for the Quaternary Research Association*, 12, 467-484.

Huddart, D., Bennett, M. R. & Glasser, N. F. (1999) Morphology and sedimentology of a high-arctic esker system: Vegbreen, Svalbard. *Boreas*, 28, 253-273.

Irvine-Fynn, T. D. L., Hodson, A. J., Moorman, B. J., Vatne, G. & Hubbard, A. L. (2011) Polythermal glacier hydrology: a review. *Reviews of Geophysics*, 49, RG4002.

Kamb, B. (1987) Glacier Surge Mechanism Based on Linked Cavity Configuration of the Basal Water Conduit System. *Journal of Geophysical Research*, 92, 9083-9100.

Karczewski, A. (1989) The development of the marginal zone of the Hørbyebreen, Petuniabukta, central Spitsbergen. *Polish Polar Research*, 10, 371-377.

Karczewski, A., Borówka, M., Kasprzak, L., Kłysz, P., Kostrzewski, A., Lindner, L., Marks, L., Rygielski, W., Wojciechowska, A. & Wysokiński, L. (1990) Geomorphology - Petuniabukta, Billefjorden, Spitsbergen. Adam Mickiewicz University, Poznań.

Kleman, J. (1994) Preservation of landforms under ice sheets and ice caps. *Geomorphology*, 9, 19-32.

Livingstone, S. J., Evans, D. J. A., Ó Cofaigh, C. & Hopkins, J. (2010) The Brampton kame belt and Pennine escarpment meltwater channel system (Cumbria, UK): Morphology, sedimentology and formation. *Proceedings of the Geologists' Association*, 121, 423-443.

Livingstone, S. J., Storrar, R. D., Hillier, J. K., Stokes, C. R., Clark, C. D. & Tarasov, L. (2015) An ice-sheet scale comparison of eskers with modelled subglacial drainage routes. *Geomorphology*.

Lovell, H., Livingstone, S. J., Boston, C. M., Booth, A., Storrar, R. D. & Barr, I. (in review) Complex kame belt morphology and architecture. *Earth Surface Processes and Landforms*.

Małecki, J., Faucherre, S. & Strzelecki, M. C. (2013) Post−surge geometry and thermal structure of Hørbyebreen, central Spitsbergen. *Polish Polar Research*, 34, 305-321.

Margold, M., Jansson, K. N., Kleman, J., Stroeven, A. P. & Clague, J. J. (2013) Retreat pattern of the Cordilleran Ice Sheet in central British Columbia at the end of the last glaciation reconstructed from glacial meltwater landforms. *Boreas*, 42, 830-847.

Meierbachtol, T., Harper, J. & Humphrey, N. (2013) Basal Drainage System Response to Increasing Surface Melt on the Greenland Ice Sheet. *Science*, 341, 777-779.

Nienow, P. (2014) Geoscience: The plumbing of Greenland's ice. *Nature*, 514, 38-39.

Nienow, P., Sharp, M. & Willis, I. (1998) Seasonal changes in the morphology of the subglacial drainage system, Haut Glacier d'Arolla, Switzerland. *Earth Surface Processes and Landforms*, 23, 825-843.

Nienow, P. W., Sharp, M. & Willis, I. C. (1996) Velocity-discharge relationships derived from dye tracer experiments in glacial meltwaters: implications for subglacial flow conditions. *Hydrological Processes*, 10, 1411-1426.

Perkins, A. J., Brennand, T. A. & Burke, M. J. (2016) Towards a morphogenetic classification of eskers: Implications for modelling ice sheet hydrology. *Quaternary Science Reviews*, 134, 19-38.

Piccini, L., Romeo, A. & Badino, G. (2000) Moulins and marginal contact caves in the Gornergletscher, Switzerland. *Nimbus*, 23, 94-99.

Planet_Team (2017) Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA. https://api.planet.com.

Prest, V. K., Grant, D. R. & Rampton, V. N. (1968) Glacial map of Canada. Geological Survey of Canada, Map 1253A. 1:5,000,000

Price, R. J. (1966) Eskers near the Casement glacier, Alaska. *Geografiska Annaler. Series A. Physical Geography*, 48, 111-125.

Price, R. J. (1969) Moraines, sandar, kames and eskers near Breiðamerkurjökull , Iceland. *Transactions of the Institute of British Geographers*, 46, 17-43.

Price, R. J. (1973) *Glacial and fluvioglacial landforms*. Edinburgh, Oliver and Boyd.

Punkari, M. (1997) Glacial and glaciofluvial deposits in the interlobate areas of the Scandinavian Ice Sheet. *Quaternary Science Reviews*, 16, 741-753.

Rachlewicz, G. (2009) Contemporary Sediment Fluxes and Relief Changes in High Artic Glacierized Valley Systems (Billefjorden, Central Spitsbergen). Adam Mickiewicz University, Poznań.

Rippin, D. M., Pomfret, A. & King, N. (2015) High resolution mapping of supra-glacial drainage pathways reveals link between micro-channel drainage density, surface roughness and surface reflectance. *Earth Surface Processes and Landforms*, 40, 1279-1290.

Rotnicki, K. (1960) Oz bukowsko-mosiński, Prace Kom. *Geogr. Geol. Pozn. Tow. Przyj. Nauk, t. 2, z. 2, Poznań.*

Russell, A. J., Knudsen, O., Fay, H., Marren, P. M., Heinz, J. & Tronicke, J. (2001) Morphology and sedimentology of a giant supraglacial, ice-walled, jokulhlaup channel, Skeiðarárjökull, Iceland: implications for esker genesis. *Global and Planetary Change*, 28, 193-216.

Ryder, J., Fulton, R. & Clague, J. (1991) The Cordilleran ice sheet and the glacial geomorphology of southern and central British Colombia. *Géographie physique et Quaternaire*, 45, 365-377.

Shetsen, I. (1987) Quaternary Geology, Southern Alberta. Alberta Research Council. 1:500,000

Shreve, R. L. (1985) Esker characteristics in terms of glacier physics, Katahdin esker system, Maine. *Bulletin of the Geological Society of America*, 96, 639-646.

Stearns, L. A., Smith, B. E. & Hamilton, G. S. (2008) Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. *Nature Geoscience*, 1, 827-831.

Stokes, C. R., Margold, M., Clark, C. D. & Tarasov, L. (2016) Ice stream activity scaled to ice sheet volume during Laurentide Ice Sheet deglaciation. *Nature*, 530, 322-326.

Storrar, R. D., Evans, D. J. A., Stokes, C. R. & Ewertowski, M. (2015) Controls on the location, morphology and evolution of complex esker systems at decadal timescales, Breiðamerkurjökull, SE Iceland. *Earth Surface Processes and Landforms*, 40, 1421-1438.

Storrar, R. D., Stokes, C. R. & Evans, D. J. A. (2013) A map of Canadian eskers from Landsat satellite imagery. *Journal of Maps*, 9, 456-473.

Storrar, R. D., Stokes, C. R. & Evans, D. J. A. (2014a) Increased channelization of subglacial drainage during deglaciation of the Laurentide Ice Sheet. *Geology*, 42, 239-242.

Storrar, R. D., Stokes, C. R. & Evans, D. J. A. (2014b) Morphometry and pattern of a large sample (>20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. *Quaternary Science Reviews*, 105, 1-25.

Stroeven, A. P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B. W., Harbor, J. M., Jansen, J. D., Olsen, L., Caffee, M. W., Fink, D., Lundqvist, J., Rosqvist, G. C., Strömberg, B. & Jansson, K. N. (2016) Deglaciation of Fennoscandia. *Quaternary Science Reviews*, 147, 91-121.

Stuart, G., Murray, T., Gamble, N., Hayes, K. & Hodson, A. (2003) Characterization of englacial channels by ground-penetrating radar: An example from austre Brøggerbreen, Svalbard. *Journal of Geophysical Research: Solid Earth*, 108.

Syverson, K. M., Gaffield, S. J. & Mickelson, D. M. (1994) Comparison of esker morphology and sedimentology with former ice-surface topography, Burroughs Glacier, Alaska. *Geological Society of America Bulletin*, 106, 1130-1142.

Szuman, I. & Kasprzak, L. (2010) Glacier ice structures influence on moraines developement (Hørbye glacier, Central Spitsbergen). *Quaestiones Geographicae*, 29, 65-73.

Thomas, G. S. P. & Montague, E. (1997) The morphology, stratigraphy and sedimentology of the Carstairs Esker, Scotland, U.K. *Quaternary Science Reviews*, 16, 661-674.

Warren, W. P. & Ashley, G. M. (1994) Origins of the ice-contact stratified ridges (eskers) of Ireland. *Journal of Sedimentary Research*, 64, 433-499.

Welch, R. & Howarth, P. (1968) Photogrammetric measurements of glacial landforms. *The Photogrammetric Record*, 6, 75-96.

Werder, M. A., Hewitt, I. J., Schoof, C. G. & Flowers, G. E. (2013) Modeling channelized and distributed subglacial drainage in two dimensions. *Journal of Geophysical Research: Earth Surface*, 118, 2140-2158.

Willis, I. C., Fitzsimmons, C. D., Melvold, K., Andreassen, L. M. & Giesen, R. H. (2012) Structure, morphology and water flux of a subglacial drainage system, Midtdalsbreen, Norway. *Hydrological Processes*, 26, 3810-3829.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J. & Steffen, K. (2002) Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, 297, 218-222.