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Equifinality and preservation potential of complex eskers

Robert D. Storrar, Marek Ewertowski, Aleksandra M. Tomczyk, Iestyn D. Barr, Stephen J. Livingstone, Alastair Ruffell, Ben J. Stoker & David J. A. Evans

Robert D. Storrar (r.storrar@shu.ac.uk), Department of the Natural and Built Environment, Sheffield Hallam University, Howard Street, Sheffield, S1 1WB, UK; Marek Ewertowski and Aleksandra M. Tomczyk, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poland; Iestyn D. Barr, School of Science and the Environment, Manchester Metropolitan University, UK; Stephen J. Livingstone, Department of Geography, University of Sheffield, UK; Alastair Ruffell, School of Natural and Built Environment, Queens University Belfast, UK; Ben J. Stoker, Department of Physical Geography and Geoecology, Charles University, Prague, Czech Republic; David J. A. Evans, Department of Geography, Durham University, UK

Abstract

Eskers are useful for reconstructing meltwater drainage systems of glaciers and ice sheets. However, our process understanding of eskers suffers from a disconnect between sporadic 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 field and high-resolution remote sensing studies into two esker systems that have recently emerged at Hørbyebreen, Svalbard, and one at Breiðamerkurjökull, Iceland. Despite the different glaciological settings (polythermal valley glacier *versus* active temperate piedmont lobe), in all cases a distinctive planform morphology has developed, where ridges 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. One set of ridges at Hørbyebreen is a hybrid of eskers and geometric ridges formed during a surge and/or jökulhlaup event. The other sets of ridges are eskers formed time-transgressively at a retreating ice margin. The similar morphology of esker complexes formed in different ways on both glacier forelands implies equifinality, meaning that care should be taken when interpreting Quaternary esker patterns. 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. This work, as well as previous studies, confirm that constraints on esker morphology include: topographic setting (e.g. confined valley or broad plain); sediment and meltwater availability (including surges and jökulhlaups); 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.

The nature of glacial meltwater drainage is important for understanding the response of glaciers to spatial and/or temporal 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, 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), West 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 are 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 (Fig. 1). The wealth of eskers on these palaeo-ice sheet beds means that, if correctly understood and appropriately applied, inferences can be made about meltwater dynamics at the ice sheet scale. This, in turn, may provide insights into the drainage systems and likely dynamic 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 (e.g. Price 1966; 1969; Gustavson & Boothroyd 1987; Huddart *et al.* 1999; Burke *et al.* 2008), and may serve as analogues for their late Quaternary ice sheet counterparts. 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; Fig. 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: (i) 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), and (ii) 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. 2007ab)?

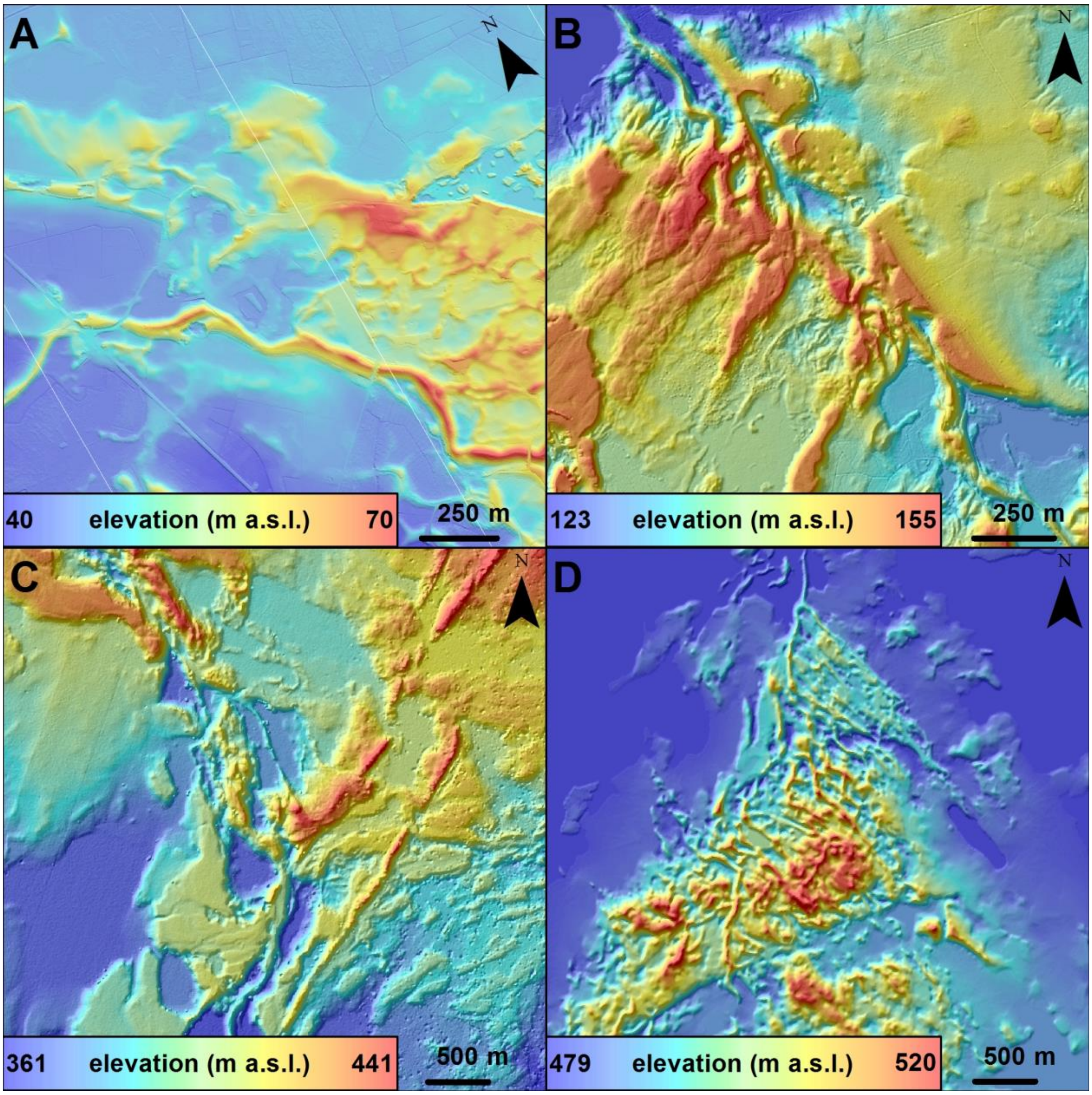

Fig. 1. Examples of ice sheet-scale complex esker systems. A. Part of an esker complex in Ireland (data supplied by Cathy Delaney). B. Esker complex in SW Finland (data from http://gtkdata.gtk.fi/maankamara/). C. Esker complex in NW Canada (data from https://www.pgc.umn.edu/data/arcticdem/). D. Esker-Geometric 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 (Fig. 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).

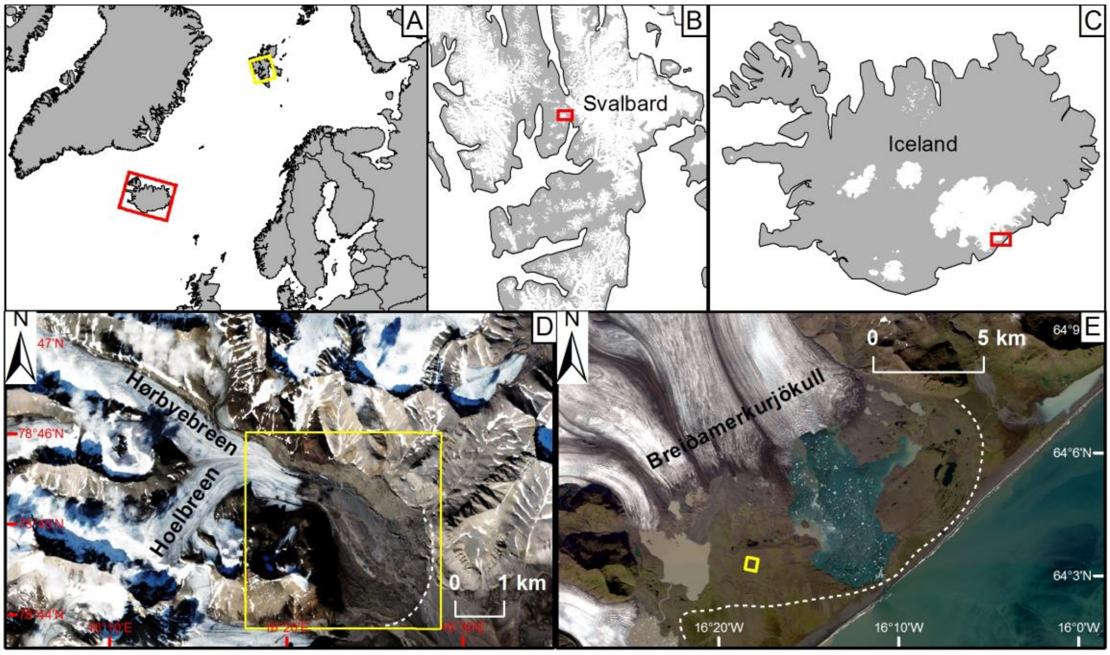

Fig. 2. Locations of study areas. Boxes in (A) show the locations of Svalbard (yellow: B) and Iceland (red: C). Red boxes in (B) and (C) show the locations of Hørbyebreen (D) and Breiðamerkurjökull (E), respectively, and the yellow boxes in (D) and (E) show the locations of the study sites. White dashed lines indicate the interpreted Little Ice Age glacier margins. Glacier outlines in (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 € is from Sentinel 2 (www.sentinel.esa.int).

The foreland is predominantly flat (Fig. 3), 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 (Fig. 3A). The foreland comprises a range of glacial landforms and sediments (Fig. 4C), including a latero-frontal moraine arc, a series of eskers and geometric ridge networks (e.g. Bennett *et al.* 1996) of crevasse fill and hydrofracture origins (Fig. 4B), and glacial lineations (Karczewski 1989; Karczewski *et al.* 1990; Gibas *et al.* 2005; Rachlewicz 2009; Szuman & Kasprzak 2010; Evans *et al.* 2012; Ewertowski *et al.* 2019). The present study focuses on the complex esker system on the eastern part of the foreland, which is melting out of the glacier snout (Fig. 2D) and on the esker-geometric ridge network complex in the west.

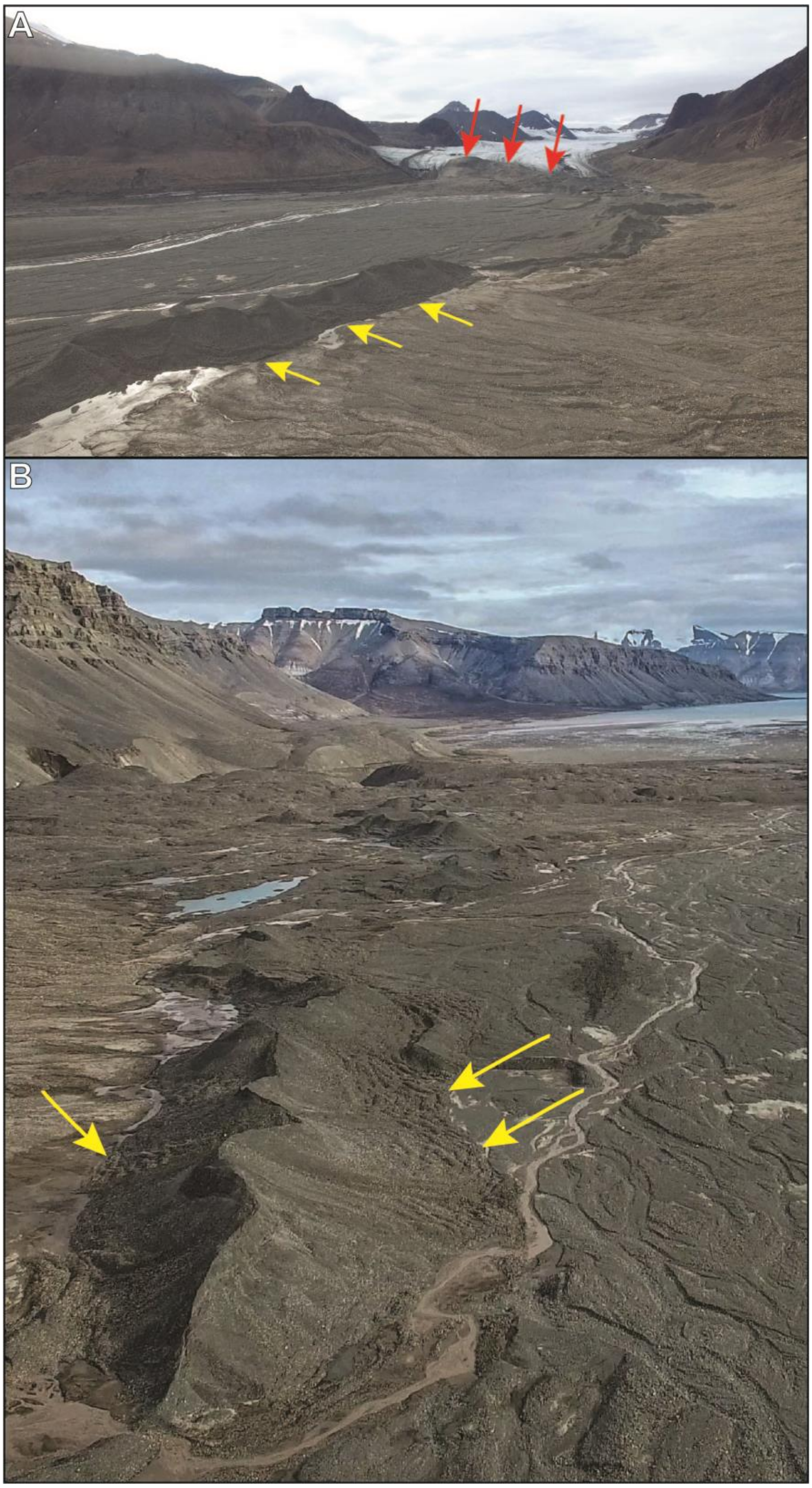

Fig. 3. A. Oblique UAV image of the snout and foreland of Hørbyebreen. Note the predominantly flat terrain, with the exception of a prominent bedrock bump in the centre of the glacier (red arrows). Also note the prominent esker in the foreground, with rock-glacierized flanks indicated by yellow arrows (also in B). B. Oblique view of the same prominent esker showing its distal side. Images courtesy of Jakub Ondruch.

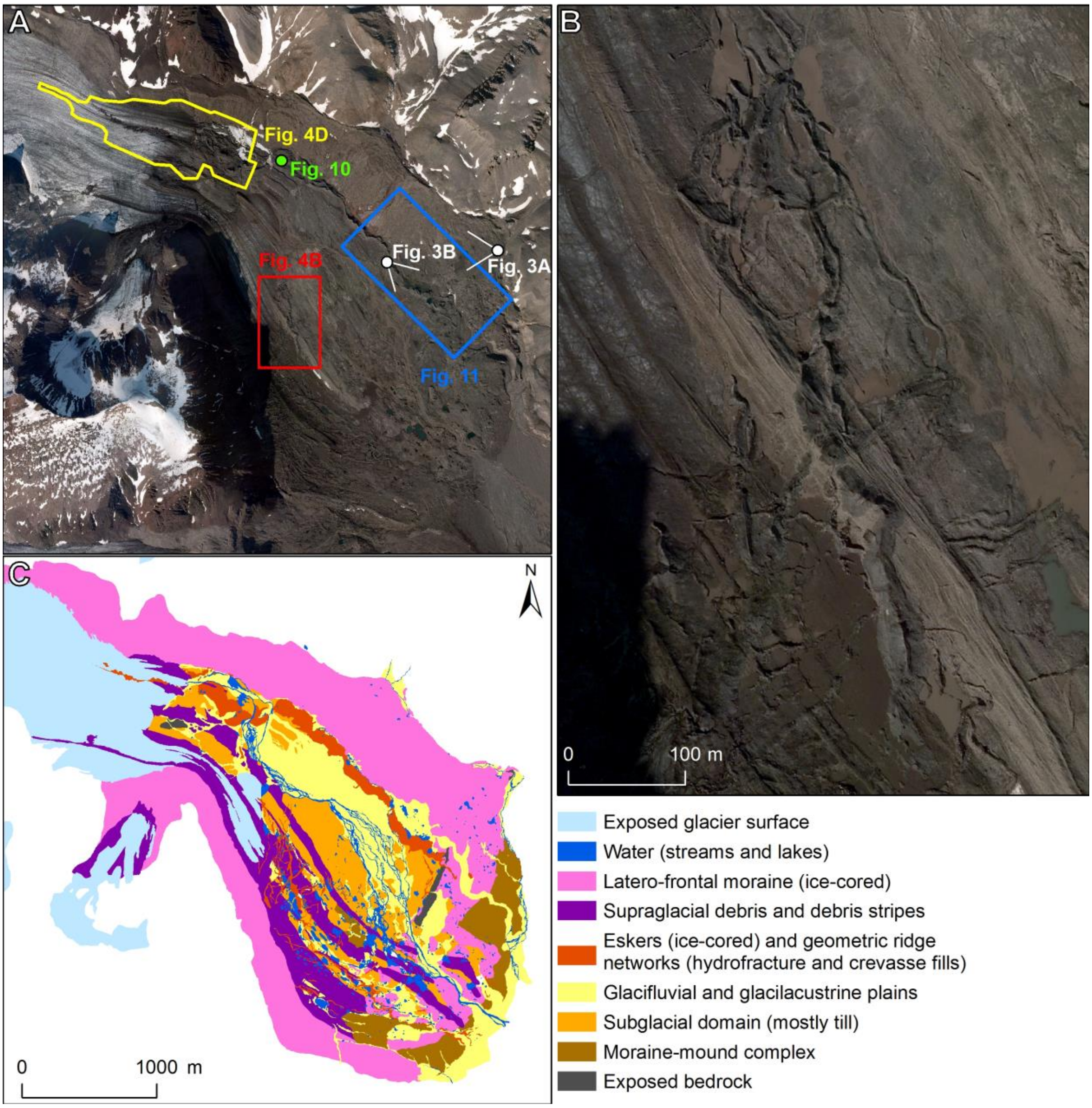

Fig. 4. Geomorphology of the Hørbyebreen foreland. A. 2009 aerial orthophoto of Hørbyebreen, with the main UAV study area in yellow. Locations of Figs. 3 (points showing locations from which photos were taken and lines indicating approximate field of view) 4B, 10 and 11 are also shown. B. Zoom-in on the 2009 orthophoto showing an area of eskers and geometric ridge networks. C. Surficial geology of the Hørbyebreen foreland after Ewertowski et al (2019). D. Detailed glacial geomorphological map of the Hørbyebreen study area overlain on the UAV-derived orthophoto. The location of Fig. 9B is shown by the black box. The white points show the locations of the images in Fig. 5. Locations of the GPR profiles shown in Fig. 6 are given by dotted lines 1 and 2 in (D). E. A more detailed view of the foreland. Circled numbers in (E) 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 (E). Note the expansion of the ice-cored lateral moraine in the north onto the glacier surface.

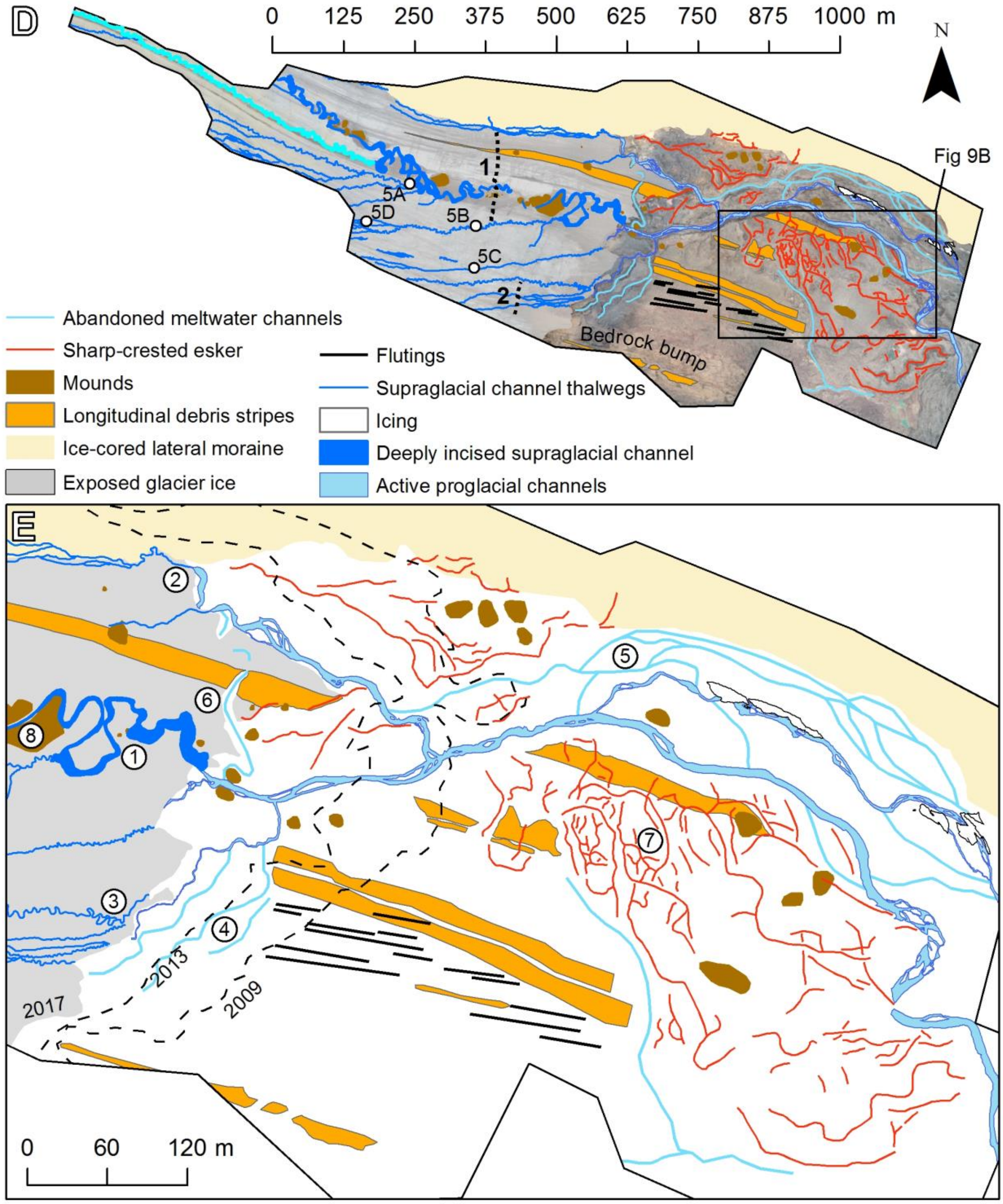

Fig. 4. (continued)

Breiðamerkurjökull

Breiðamerkurjökull (Fig. 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 (Fig. 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 shown in Fig. 4D. 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, shown in Fig. 4D. Large-format versions of the orthophoto and DEM are given in Fig. S1. Alongside the 2017 UAV campaign, a Mala 100 MHz Rough Terrain Antenna (RTA) GPR was used to survey two lines laterally across the glacier snout (Fig. 4D), including over an ice bridge spanning a large channel (allowing continuous survey), 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 uses an in-line configuration with a 1.5 m separation between the mid-point of the transmitter and receiver. Data were gathered using a measured stepsize, located using GNSS. The raw GPR data were processed within ReflexW v7.5.9. A processing sequence was developed based on similar studies of Arctic glaciers; the processing steps improved data visibility and interpretability, but preserved key reflections present in unprocessed data (Stuart *et al*. 2003; Irvine-Fynn *et al*. 2006; Cassidy 2009). The processing sequence comprises: 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, bandpass filtering with cut-offs set at a bandwidth of 1.5 times the peak frequency to reduce noise (Cassidy 2009). 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 eastern Hørbyebreen study area from the 2017 UAV imagery is presented in Fig. 4D. The key glaciofluvial landforms in the area are described below.

Contemporary meltwater channels. - A series of active meltwater channels, typically displaying a very high sinuosity (up to ~2.3), are present on the glacier surface. Most are relatively shallow (up to a few metres), whereas one is deeply incised by >10 m (Fig. 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 (Fig. 5).

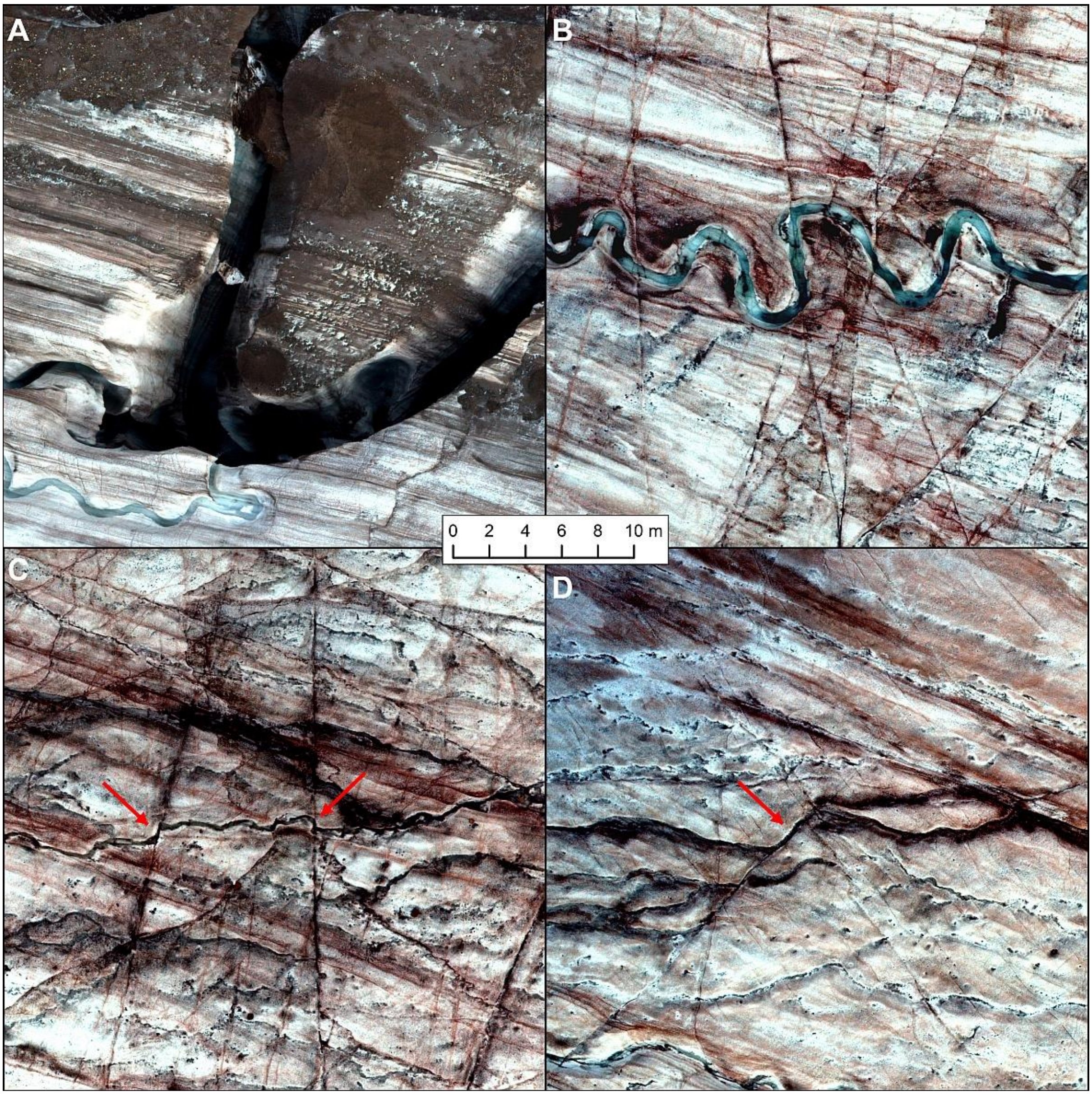

Fig. 5. UAV images showing supraglacial channel morphology influenced by ice structures. A. Deeply incised supraglacial channel (>10 m). B. highly sinuous channel, following ice structures in places. C, D. Examples of an offset of a shallow supraglacial channel along ice fault (indicated by the red arrows).

The large (up to ~5 m wide), deeply incised active channel (location 1 in Fig. 4E) 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 Fig. 4D) indicates that ice close to this location is ~50 m thick (Fig. 6A, 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 (Fig. 6), indicating deep incision. In places, the top of the channel is covered by ice bridges and it becomes englacial.

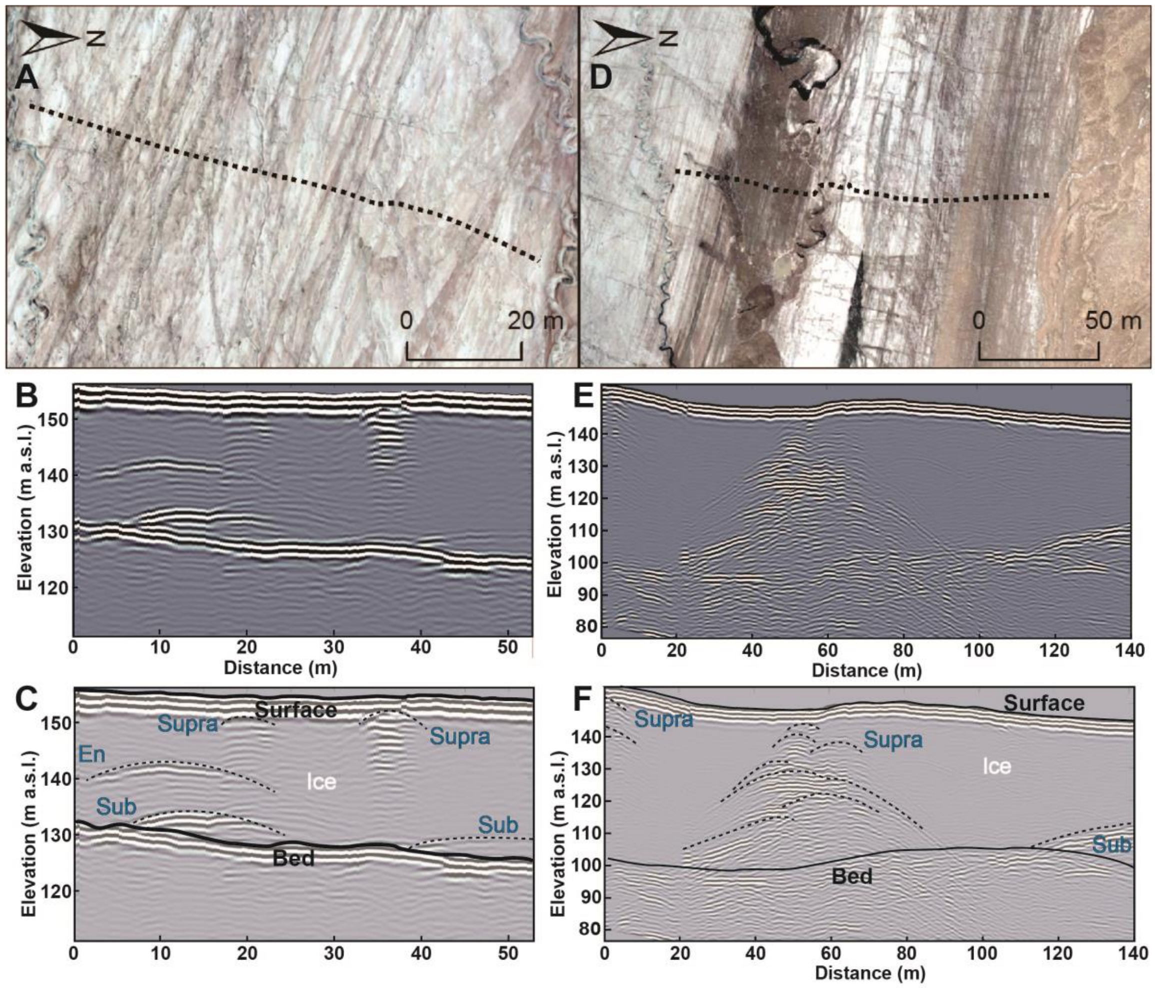

Fig. 6. GPR profiles across Hørbyebreen (see Fig. 4 for location). A. Orthophoto showing the location of line 1. B. Radargram of line A. C. Annotated version of B. D. Orthophoto showing the location of line 2. E. Radargram of line 2. F. Annotated version of E. Annotations refer to the interpretation of channels as subglacial (draining on the glacier bed), englacial (draining within ice) or supraglacial (with a surface exposed to the atmosphere).

Another large active channel of similar width (Fig. 7; location 2 in Fig. 4E) 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 Fig. 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 (Fig. 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 Fig. 4E). 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.

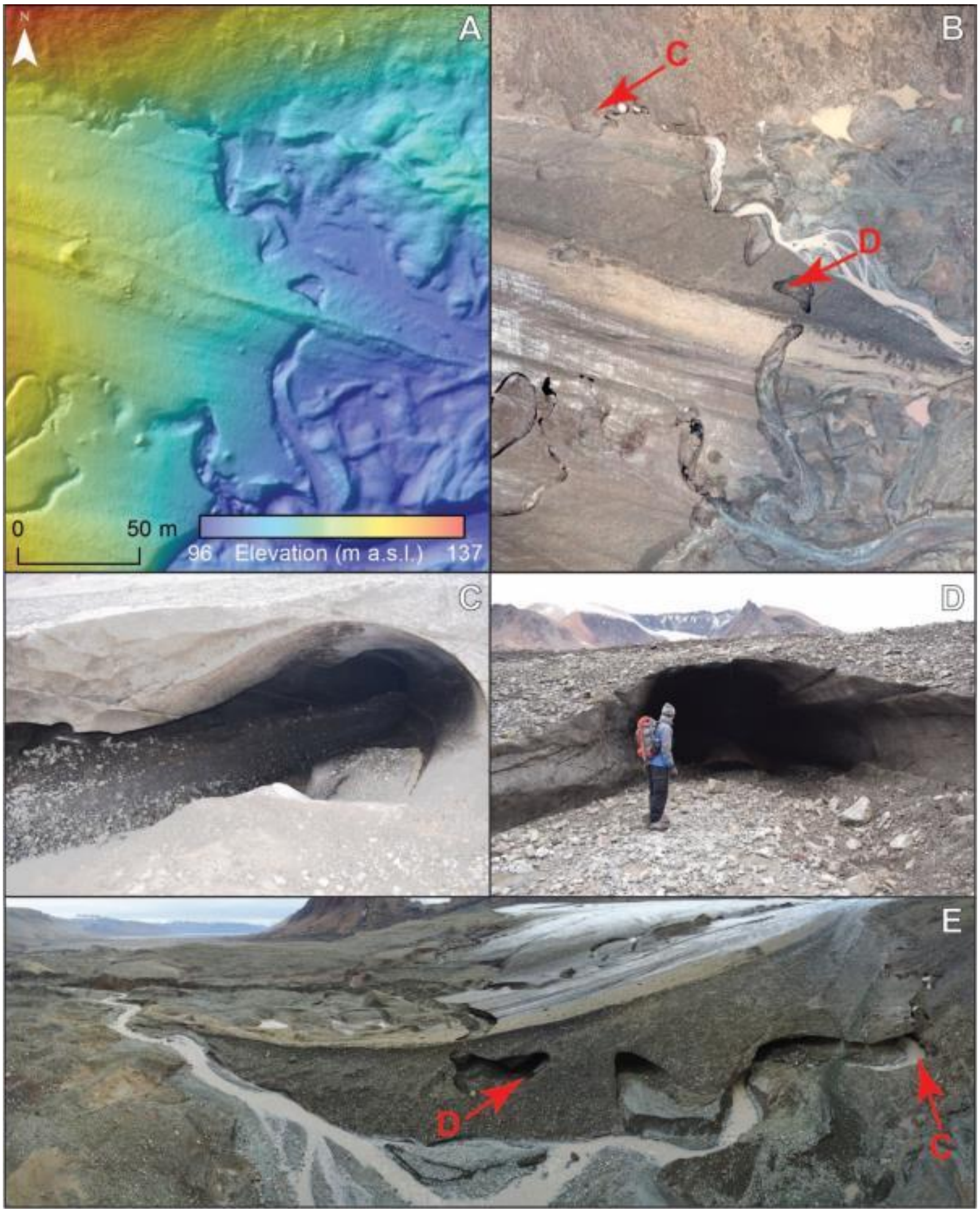

Fig. 7. Sediment-floored ice marginal channels at Hørbyebreen (location 2 in Fig. 4E). UAV-derived (A) hillshaded DEM and (B) Orthophotograph of the glacier snout. C. Active proglacial channel emerging from an englacial position, with stratified sediment deposited on the channel floor. D. Abandoned pro/englacial 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.

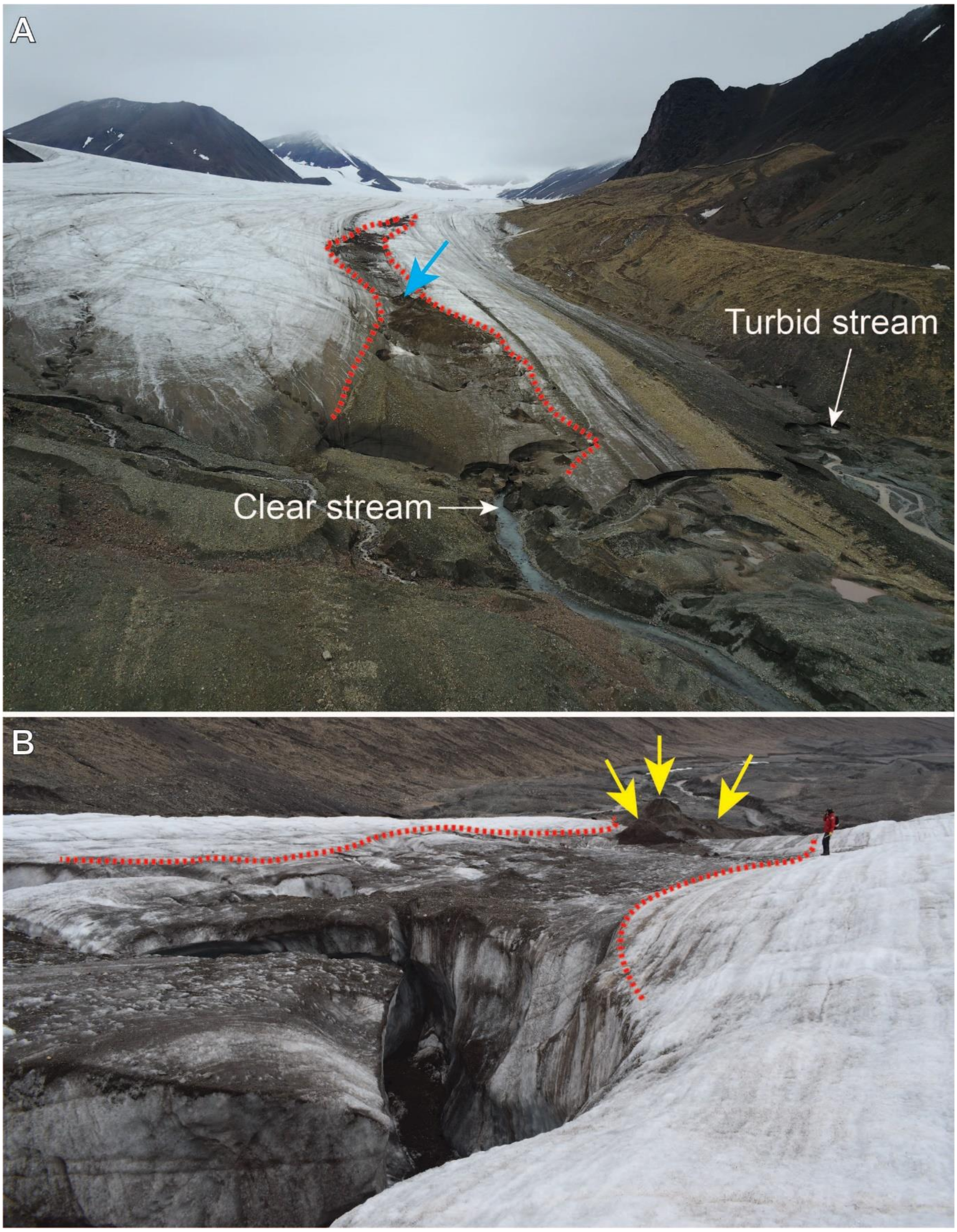

Fig. 8. A. Oblique UAV image of the terminus of Hørbyebreen, showing the incised supraglacial meltwater channel with associated debris cover (enclosed by red dashed lines). Note the two major streams emanating from the glacier, with the central stream carrying relatively clear water and the marginal 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).

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

Eskers. - Sharp-crested eskers (i.e. approximately triangular in cross-section) are abundant and distributed across the lowest part of the foreland, where it is not occupied by proglacial streams (Fig. 4D). Between 2009 and 2017 a series of eskers emerged from the northernmost part of the snout (near location 2 in Fig. 4E). 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 Fig. 4E; Fig. 9A, B). 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 (two layers of esker sediments were observed in the field separated by a layer of ice). 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 this study area, esker ridges occur downstream of the eskers described above (Figs. 3B, 4C) and also on the western part of the foreland (Fig. 4B; Evans *et al.* 2012). The downstream continuation of the eastern eskers occur as a large sinuous ridge extending downstream from the complex eskers described above (and shown in Fig. 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 (Fig. 10) which has gradually melted out, resulting in surface lowering of the esker (Fig. 11) and the appearance of rock-glacierised lobes on the esker flanks (Fig. 3), similar to rock-glacierized moraines observed elsewhere (e.g. Dyke *et al.* 1982; Vere & Matthews 1985; Evans 1993; Ó Cofaigh *et al*. 2003; Evans *et al.* 2006a, 2016). Despite this surface lowering, the cross-sectional shape of the esker has remained largely intact. The western eskers 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.

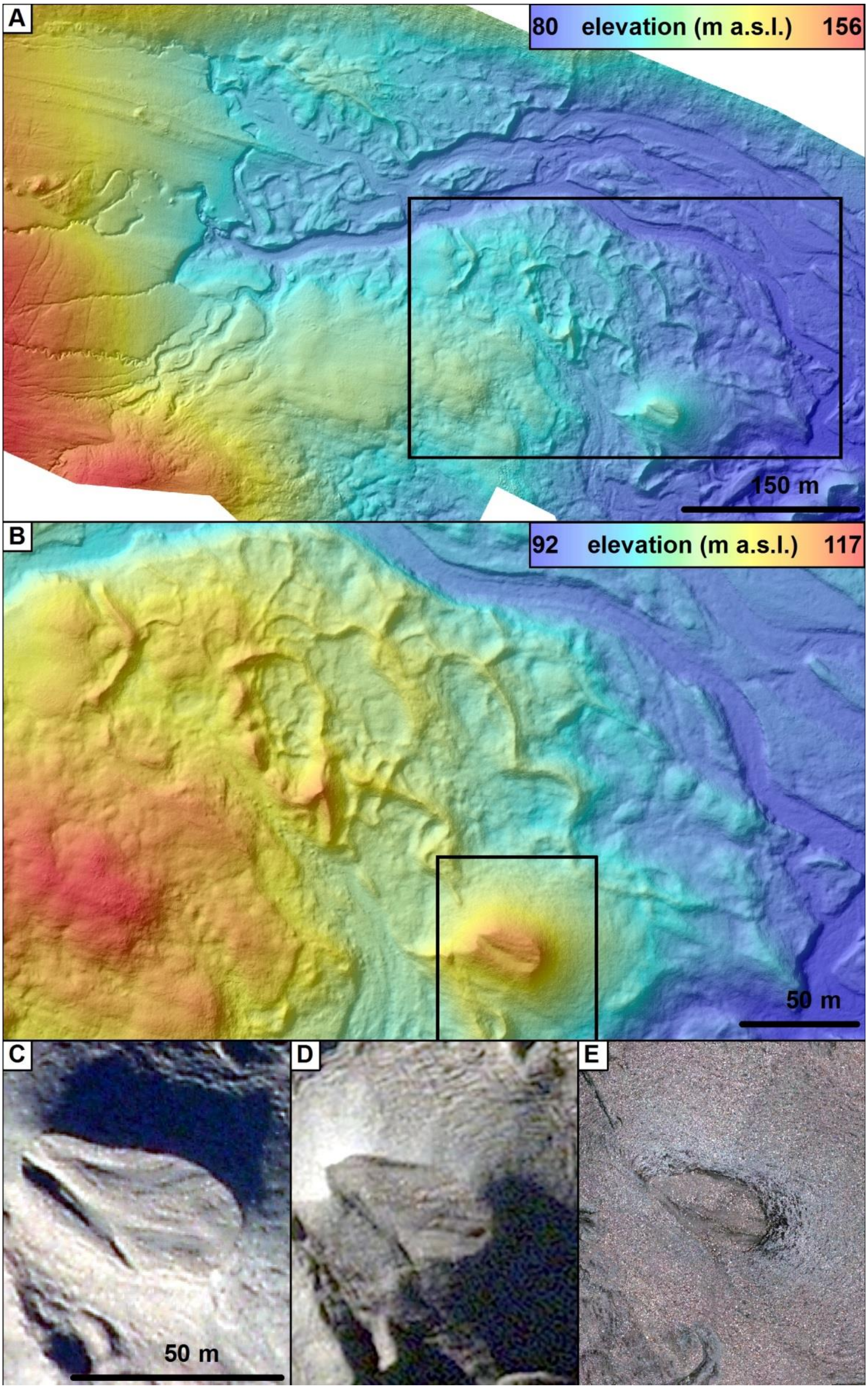

Fig. 9. A, B. Hillshaded DEMs showing areas of complex esker topography at Hørbyebreen (location 7 in Fig. 4). The location of (B) is shown by the box in (A). C, D, E. Aerial photographs/satellite images of the mound in the box in (B) in 2009, 2013 and 2017, respectively (the area is the same in each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

Fig. 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). Its structure is also typical of the eskers in the study area. The location of this esker is given in Fig. 4A.

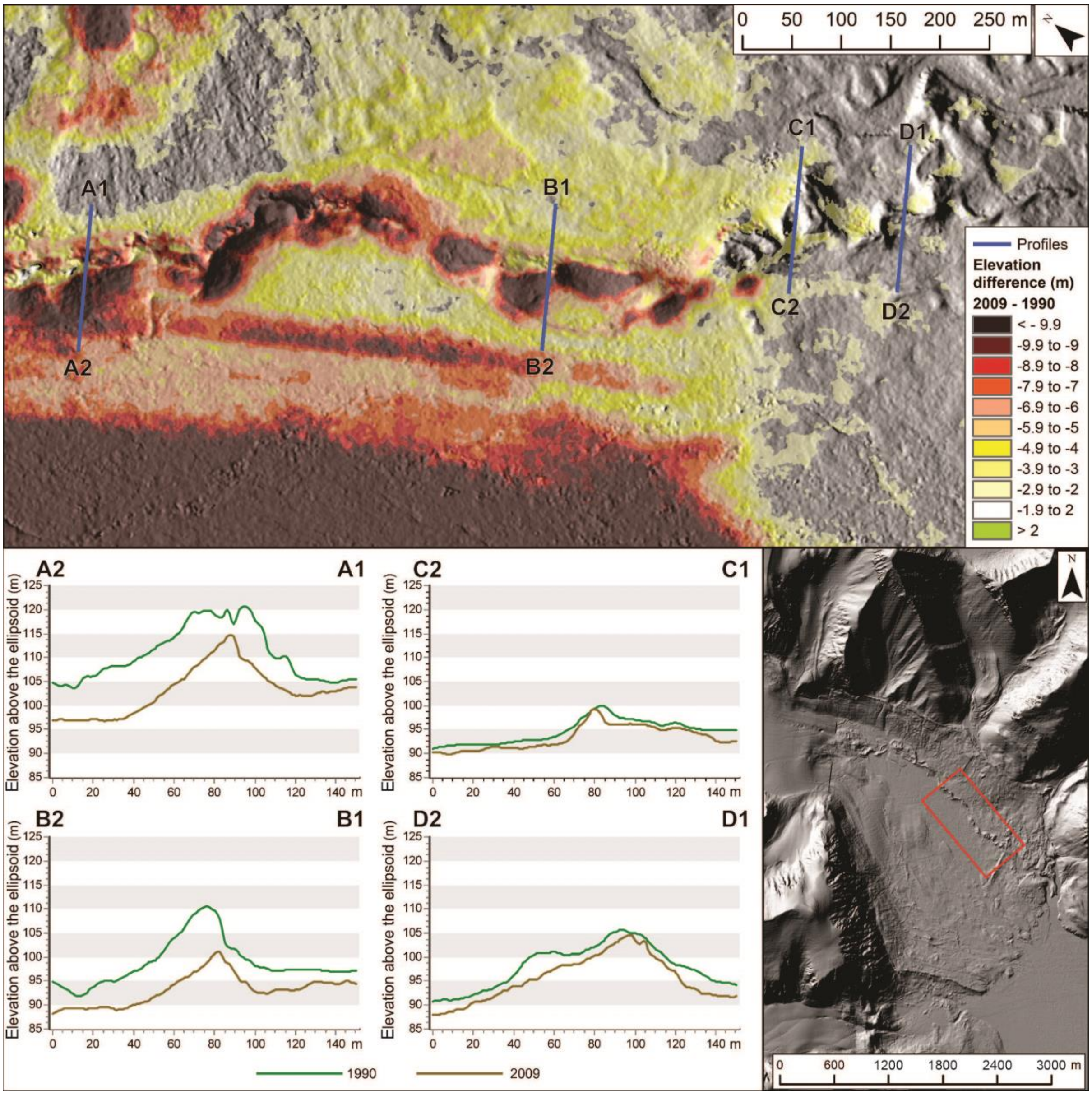

Fig. 11. Topographic change in the main esker ridge downstream of the study area between 1990 and 2009. Note that as buried ice melts within the eskers, they nevertheless maintain a similar form.

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 Fig. 4E, Fig. 8). These mounds are largely composed of ice with overlying sediment on the order of centimetres to decimetres in thickness. 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 (Fig. 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 Fig. 9B. Close inspection of the surface of this mound reveals the remnants of braided channels in outwash and that the flat top has decreased markedly in area since 2009 from the gradual collapse of the flanks, potentially indicating meltout of buried ice (Fig. 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 74 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 Fig. 12 and relates to esker number MES2 studied by Storrar *et al.* (2015).

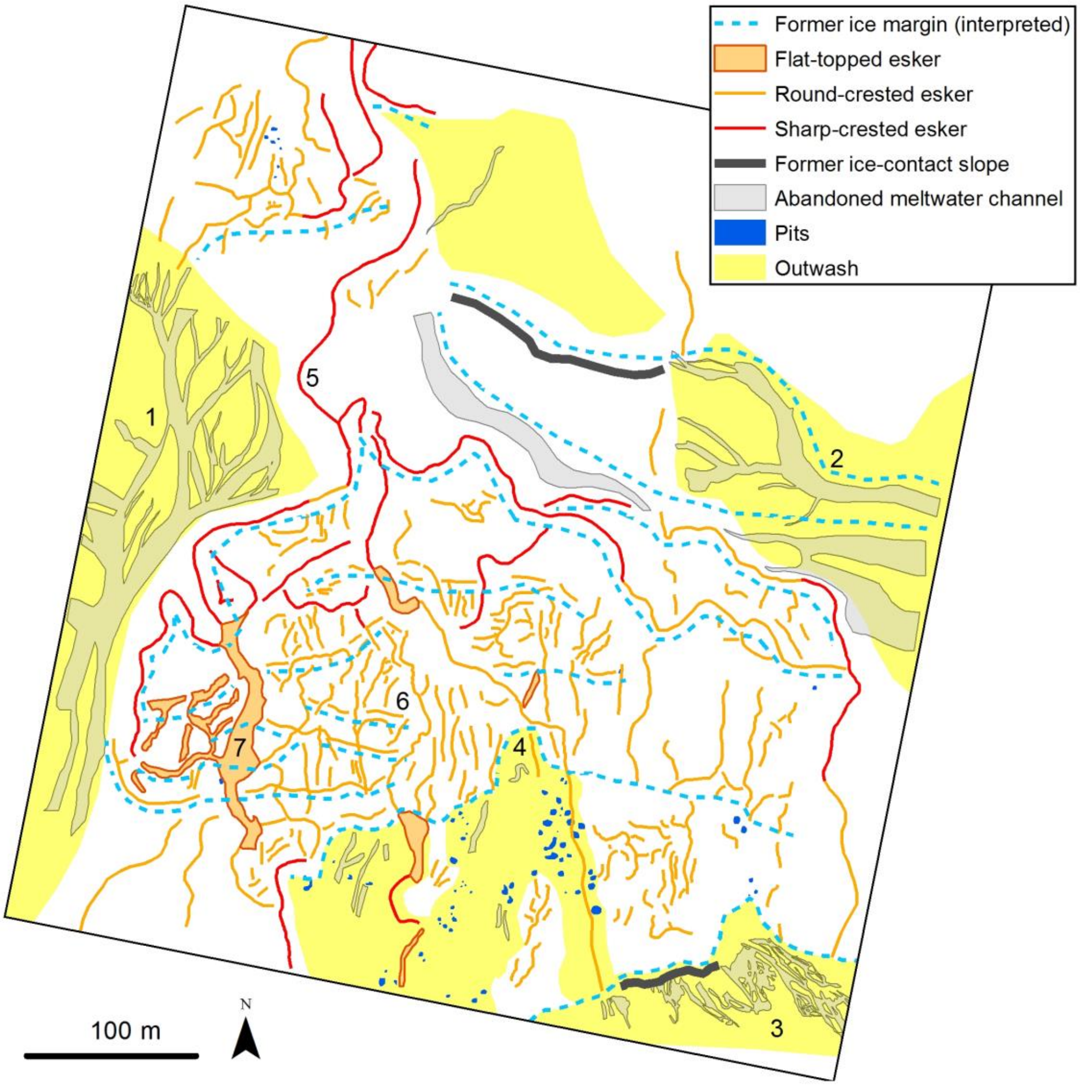

Fig. 12. Geomorphological map of the Breiðamerkurjökull esker system. Numbers refer to locations mentioned in the text. Former ice margins are interpreted from ice-contact outwash deposits, marginal meltwater channels and esker orientations. Ice flow was from north to south.

Abandoned meltwater channels. - Large (10s m wide) abandoned proglacial meltwater channels occur in deposits of outwash to the west (labelled 1 in Fig. 12) and east (2 in Fig. 12) of the study area, and smaller (<10 m wide) channels were observed to the south (3 in Fig. 12). The southern channels form a distributary network on a laterally extensive outwash fan, indicating water draining to the south. Another outwash fan indicating water draining to the south is nested inside this one, located ~100 m to the NW (4 in Fig. 12). This fan has a pitted surface and grades horizontally into round-crested and flat-topped eskers to the north, which are described below.

Eskers. - Eskers are categorised based on their cross-section geometry into sharp-crested, round-crested and flat-topped features (cf. Price 1973; Shreve 1985; Burke *et al.* 2012b, 2015; Perkins *et al.* 2016). In the proximal part of the system, a prominent (~10 m high, 30 m wide) single-ridge esker (5 in Fig. 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 (6 in Fig. 12). These round-crested ridges form crudely rectilinear patterns much like those at Hørbyebreen (Fig. 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 (7 in Fig. 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. There are no exposures through the eskers but the surface material comprises predominantly rounded gravel-cobble sized clasts similar in composition to surrounding outwash surfaces (Fig. 13E; Evans & Twigg 2002).

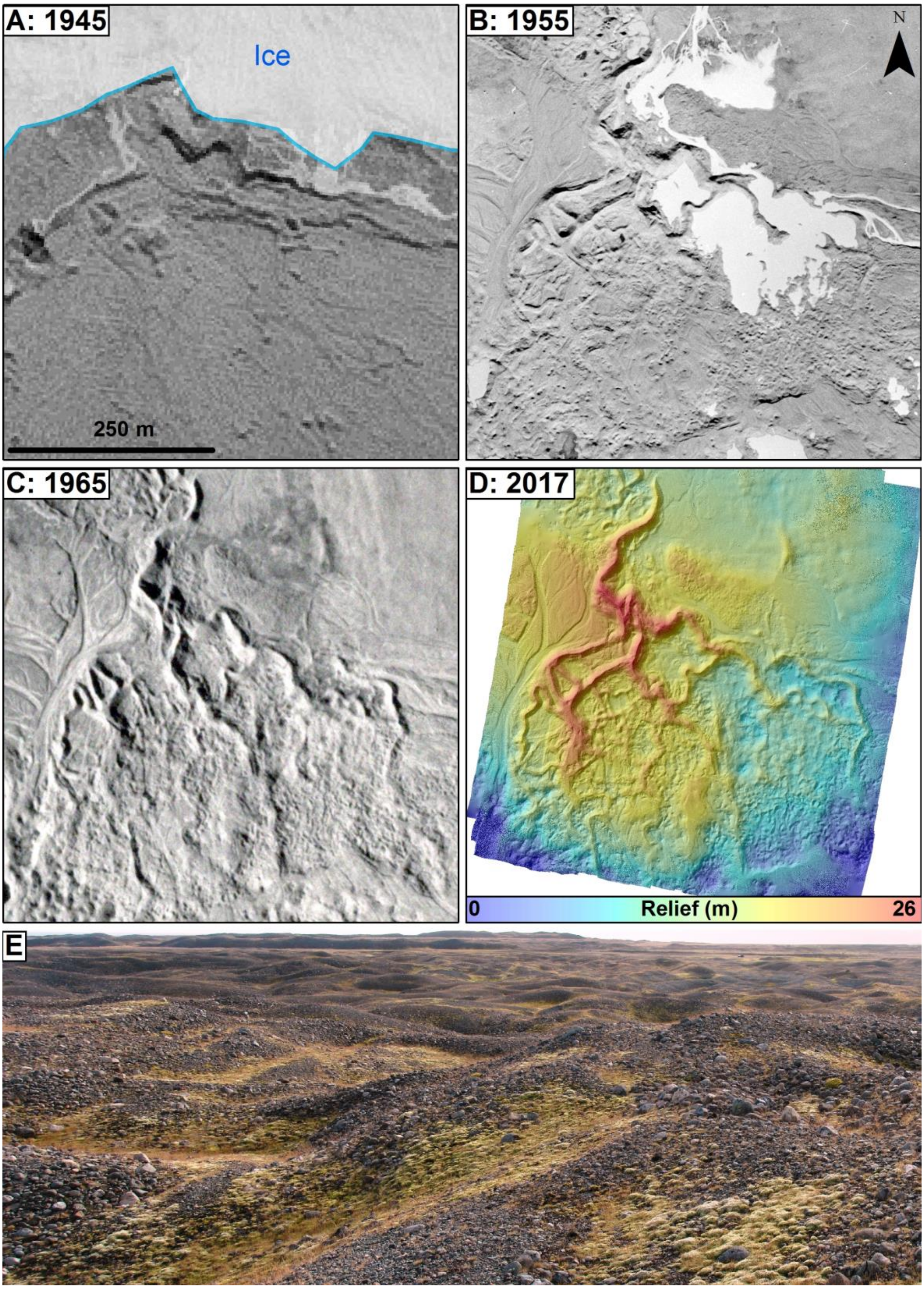

Fig. 13. Evolution of the MES2 esker system at Breiðamerkurjökull from 1945 to 2017 (A-D). Aerial photographs (A-C) are from Landmælingar Íslands. Ice is digitised from the 1945 photograph in (A). D is a UAV-derived DEM. The photograph in (E) shows a ground view of the complex terrain taken in 2012 from approximately the centre of the aerial photographs, looking south.

Evolution of the Breiðamerkurjökull eskers. - A series of aerial photographs from 1945 to 2017 (Fig. 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 (Fig. 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 Fig. 13.

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 (Fig. 14) of the eskers, which is likely due to the younger age of the Hørbyebreen eskers which contain buried ice and have not had time to settle to their angle of repose. Despite these differences, similar complex esker plan form patterns have been observed at each location (Figs. 9, 13).

Table 1. Characteristics of Hørbyebreen and Breiðamerkurjökull.

	Hørbyebreen	Breiðamerkurjökull
Climate	High-Arctic maritime. Continuous permafrost.	Subarctic maritime. No permafrost.
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. Unconfined by valley sides.
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 & Howarth (1968) identified significant buried ice up-glacier from the study location, but the eskers studied lay on solid ground in 1945.

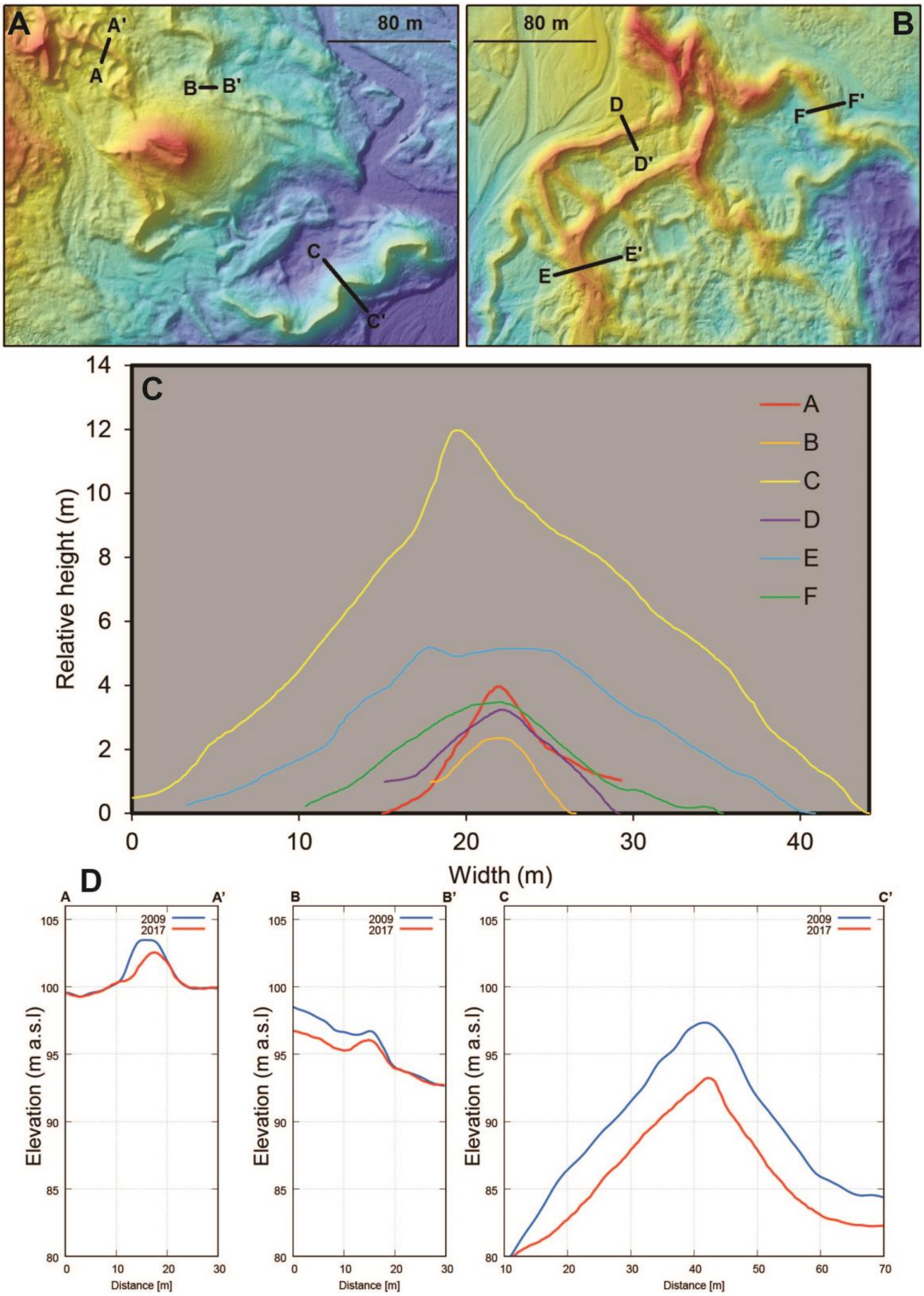

Fig. 14. Selected cross-sectional geometry for eskers at Hørbyebreen (A) and Breiðamerkurjökull (B) is shown in (C). Note that vertical exaggeration is approximately 1.92. Whilst eskers at Hørbyebreen exhibit primarily sharp-crested cross-sections with steep sides, eskers at Breiðamerkurjökull exhibit cross-sections including sharp (profile D), flat-topped (profile E) and more rounded (profile F). D. The topographic changes of the Hørbyebreen profiles between 2009 and 2017.

Discussion

Here, we present depositional models for the complex esker systems observed at east (this study) and west (based upon Evans *et al.* 2012) Hørbyebreen and Breiðamerkurjökull (this study), which we term 'laterally-confined concentrated sediment and meltwater system', 'surge/jökulhlaup event system' and 'laterally unconfined linear sediment and meltwater input system', respectively. The depositional models are summarised in Fig. 15, and we then discuss the broader implications of these findings.

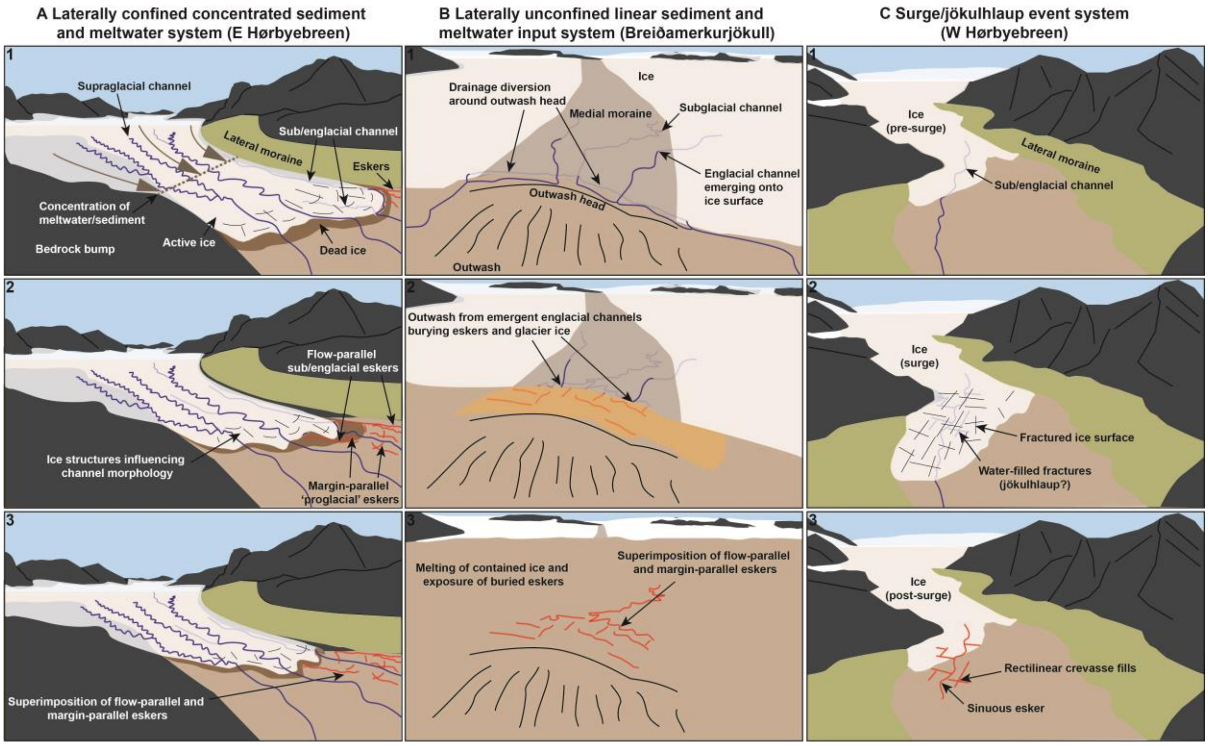

Fig. 15. Conceptual diagram for the formation of complex eskers based on (A) east Hørbyebreen, (B) Breiðamerkurjökull, and (C) west Hørbyebreen.

Laterally confined concentrated sediment and meltwater system (east Hørbyebreen)

At east Hørbyebreen ice is laterally confined by bedrock, such that sediment and meltwater supply through the glacier snout is enhanced by a bottleneck effect.

Meltwater and sediment at east Hørbyebreen are transported in supraglacial, englacial and subglacial channels. Turbid meltwater emerging from en/subglacial channels (Figs. 7B, 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 (e.g. Rippin *et al.* 2015) and is influenced by glacier structure, such as longitudinal debris stripes (cf. Glasser *et al.* 2003), and the ice margin configuration at the snout (e.g. Fig. 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 'feeder' sub/englacial (but mostly 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. Fig. 10; Fig. 15A 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. Fig. 7C, D). These channels are occasionally cut-off by stream/channel abandonment and incision of new, lower channels, 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 Fig. 7E. It is also likely that structural features in the ice will influence the location of changes in channel abandonment, as is evident by apparent structural controls on supraglacial stream form and location (Fig. 5). Downstream sections of channels become abandoned at the portal from which they previously emerged. 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; Fig. 15A stage 2). 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 (portal), 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 Fig. 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 press). A cross-cutting and locally rectilinear pattern of esker ridges, comprising a sediment layer and ice core (Fig. 10), is formed by these two orientations of ridges (Fig. 15A stage 3). 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 Fig. 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.

Laterally unconfined linear sediment and meltwater input system (Breiðamerkurjökull)

The topographic setting for esker formation at Breiðamerkurjökull differs from east Hørbyebreen in that the glacier and meltwater system is laterally unconfined, with deposition able to take place across a broad, mostly flat bed. Sediment and meltwater are concentrated along linear axes relating to medial moraines (Storrar *et al.* 2015).

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 Fig. 12; Fig. 15B stage 1). The largest eskers are mostly sharp-crested (Figs. 12, 13), which may suggest that they formed in tunnels close to or at the ice surface (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 orientated parallel to the ice margin (Fig. 15, stage 2), which branch away from the main esker as channels become clogged with sediment. Similar process-form relationships have been documented nearby to the south-west at Breiðamerkurjökull (Evans & Twigg 2002; Storrar *et al.* 2015) where eskers are formed in margin-parallel positions because of the topographic influence of an outwash head. We therefore suggest that similar processes operated in the Breiðamerkurjökull esker system discussed here. The geomorphological map in Fig. 12 provides some support for this interpretation, in that outwash fans are present in the south of the study area which are either fed by (flow-parallel) eskers, or have eskers aligned with their proximal (margin orientated) side. This pattern of feeder eskers and margin orientated eskers can be traced throughout the study area and is indicated in Fig. 12 by interpreted former ice margins. This is to some extent speculative but provides the simplest explanation based upon the available evidence and nearby analogues.

The 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), and/or where drainage enters standing water (e.g. Delaney 2001; Fard 2003).

As the ice retreats, englacial channels continue to disgorge onto the ice surface: if they have a high concentration of sediment this results in burial of part of the glacier snout by an outwash fan, producing a zone of dead ice containing buried eskers, as shown in Fig. 15B stage 2. 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, lowering the outwash fan surface, which becomes pitted, and eventually exposes the buried eskers (Fig. 15B stage 3), as shown in the time series in Fig. 13.

Surge/jökulhlaup event system (W Hørbyebreen)

The model for esker formation at west Hørbyebreen differs from the two models above in that esker formation is related more to specific glaciological events than the general topographic setting. This model is based on the work by Evans *et al.* (2012).

Initially, a simple drainage system comprising channels draining meltwater englacially and/or subglacially to the margin is in operation (Fig. 15C stage 1). The glacier then undergoes a surge, which results in the progressive fracturing of the snout (Fig. 15C stage 2). Enhanced discharge of water and sediment during the surge phase, which may be related to a jökulhlaup, then siphons water and sediment into surrounding crevasses. This results in the formation of a sinuous esker, deposited in the regular subglacial drainage system, which is linked to a geometric ridge network associated with the crevasse fills, reflecting the geometry of the structural features in the ice (Fig. 15C stage 3).

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 (which may or may not extend to the full thickness of the ice) from deposition by vertical accretion in channels at atmospheric pressure (Russell *et al.* 2001; Perkins *et al.* 2016), in steeply ascending tunnels with net freezing walls

(Shreve 1985), or by deposition in standing water (Delaney 2001; Fard 2003). 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 east Hørbyebreen are sharp-crested, and are observed to form primarily in englacial channels close to the ice margin where the ice is relatively thin (Fig. 6). These eskers contain significant ice cores (Fig. 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 (Fig. 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 (Fig. 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 (cf. 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 or standing water 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).

The eskers in west Hørbyebreen are inferred to have formed subglacially in response to an increase in the discharge of the subglacial drainage system and leakage of meltwater and sediment out into fractured ice relating to a surge and possibly jökulhlaup (Evans *et al.* 2012).

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 (Fig. 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 complex eskers at east 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 (though the glacier at this location is not topographically constrained). In west Hørbyebreen, Geometric Ridge Networks are similar in form to the complex eskers in east Hørbyebreen and at Breiðamerkurjökull, but contain straighter sections. Contrastingly, they form synchronously during discrete events, the straighter ridges related to fractures in the ice, though these may be associated with sinuous eskers relating to the wider subglacial drainage system. We therefore suggest that the complex pattern of eskers is a result of the concentration of sediment in a narrow but flat section of the glacier foreland, coupled with a sufficient supply of meltwater. This may take place gradually at a retreating ice margin or during a surge/jökulhlaup event, these two situations reflected in subtle geometric differences in the resultant ridge complexes. 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 dynamics of the ice margin, including processes such as surges; jökulhlaups; 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. These processes are very sensitive to subtle changes in conditions such as bed topography, sediment supply and meltwater supply, as well as glacier erosion, advance and retreat. Moreover, ice structures such as fractures exert an influence on the eventual drainage structure by creating weaknesses that can be exploited by thermomechanical erosion from meltwater. As such there is a degree of chaos in determining exactly where complexity in eskers will arise, but ultimately the system can be preconditioned to allow complexity by focusing large volumes of sediment and meltwater in part of the glacier drainage system.

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. However, the continuous permafrost in the area will inhibit melting from below and may allow ice cored landforms to persist for a long period of time. 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: (i) contain sufficient sediment to remain substantial topographic features following melt-out of any contained ice; (ii) then avoid being eroded by the evolution of proglacial drainage systems, particularly laterally migrating proglacial channels; and (iii) 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 & 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.* 2006b, 2014; Atkinson *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,b; 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 eroding any existing esker deposits.

Conclusions

We present evidence for the formation and evolution of two complex esker systems at Hørbyebreen, a polythermal glacier in Svalbard, and one at Breiðamerkurjökull, an active temperate glacier in Iceland. In all locations, esker deposition, via different processes, has resulted in similar complex and locally rectilinear patterns, suggesting that esker morphology might be a product of equifinality. As such, care should be taken when interpreting patterns of eskers, particularly in the Quaternary record where depositional context may be lacking, and we recommend that where possible interpretations are based on morpho-sedimentary relationships. Two of these complex esker systems have formed time-transgressively in association with a retreating and downwasting ice margin, whereas another is related to a surge and/or jökulhlaup. 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 all sites. In all 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: (i) they must first contain sufficient sediment to remain substantial topographic features following melt-out of any contained ice; (ii) they must then escape erosion by the later proglacial drainage systems, which is favoured by broad, flat topography and impeded by more mountainous terrain; and (iii) 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.

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Data sharing. - The data that support the findings of this study are available from the corresponding author upon reasonable request.

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