Controls on the location, morphology and evolution of complex esker systems at decadal timescales, Breiðamerkurjökull, SE Iceland

Robert D. Storrar *, David J.A. Evans, Chris R. Stokes, Marek Ewertowski

Department of Geography, Durham University, Durham, DH1 3LE, UK

* Corresponding author. Now at School of Geography, Queen Mary University of London, Mile End Road, London, E1 4NS

E-mail address: r. storrar@qmul.ac.uk

Telephone: +44 (0) 20 7890 2751

Abstract

This paper uses detailed mapping of eskers to address three questions which are important for reconstructing meltwater behaviour beneath contemporary and ancient ice masses: *'What controls the morphology of simple and complex esker systems?', 'How do esker systems evolve through time?'* and *'Are esker patterns compatible with the groundwater controlled hydraulic spacing of esker tunnels'.* Esker crestlines and widths are mapped on the Breiðamerkurjökull foreland for eight time slices between 1945 and 2007, from high resolution (~50 cm) aerial photography, permitting their long term morphological evolution to be analysed in a high level of detail. We find that complex eskers develop where meltwater and sediment is abundant, such that sediment clogs channels, forming distributary eskers. Isolated eskers are simpler and smaller and reflect less abundant meltwater and sediment, which is unable to clog channels. Eskers may take several decades to emerge from outwash deposits containing buried ice and can increase or decrease in size when ice surrounding and underlying them melts out. It has been suggested that groundwater-channel coupling dictates the spacing between eskers at Breiðamerkurjökull. Our results do not dispute this, but suggest that the routing of sediment and meltwater through medial moraines is an additional important control on esker location and spacing. These results may be used to better understand the processes surrounding esker formation in a variety of geographical settings, enabling a more detailed understanding of the operation of meltwater drainage systems in sub-marginal zones beneath glaciers and ice sheets.

Keywords

Esker, landform, glacial geomorphology, meltwater, Iceland, Breiðamerkurjökull

1. Introduction

Eskers are straight-to-sinuous ridges of glaciofluvial sand and gravel, formed in ice-walled meltwater channels (Banerjee & MacDonald, 1975). They are widely preserved on the beds of palaeo-ice sheets (e.g. Clark *et al.*, 2004; Boulton *et al.*, 2009; Storrar *et al.*, 2013), reflecting the configuration of meltwater channels, and can be seen melting out of contemporary glacier termini (e.g. Lewis, 1949; Stokes, 1958; Price, 1966;1969; Gustavson & Boothroyd, 1987; Syverson *et al.*, 1994; Huddart *et al.*, 1999; Burke *et al.*, 2010). These properties make eskers an invaluable source of information on the nature of meltwater flow within and beneath past and present glaciers and ice sheets (e.g. Brennand, 2000), where process observations are otherwise difficult or impossible to make. Indeed, ice dynamics are strongly influenced by the drainage structure beneath glaciers and ice sheets (e.g. Nienow *et al.*, 1998; Boulton *et al.*, 2001; Bartholomew *et al.*, 2010; Hewitt, 2013), but there remain some important gaps in our understanding. For example, observations of meltwater interactions with ice dynamics typically cover, at most, a 'melt' season or just a few years, so our understanding of their long-term effects is limited. Therefore, the evolution of esker systems can provide valuable insights into meltwater and glacier dynamics over longer timescales and provide an opportunity to refine our understanding of the interactions between meltwater drainage and glacier movement/decay.

Whilst links between eskers and glacial meltwater drainage systems have been the focus of previous research (e.g. Clark & Walder, 1994; Brennand, 2000; Boulton *et al.*, 2009), several questions must be addressed before observations on eskers on palaeo-ice sheet beds and valley glacier forelands can be extrapolated to make inferences about meltwater behaviour beneath both contemporary and ancient ice masses. This paper focuses on three of these questions, which we outline below:

What controls the morphology of simple and complex esker systems?

The varying planform morphology of esker systems is directly related to the controls on esker formation (e.g. sediment supply, flow magnitude, topographic constraints) and is thus indicative of the conditions in which the esker formed; important information when using eskers to reconstruct former meltwater behaviour. Here we use the term 'esker ridge' to refer to individual segments of eskers (i.e. continuous ridges). 'Esker' refers to a series of esker ridges which lie adjacent to each other (they can conceivably be joined into a single line). We define individual esker ridges as either 'trunk' (larger, main ridges), 'tributary' (feeding *into* trunk eskers) or 'distributary' eskers (branching *away from* trunk eskers), see Figure 1. Clusters of related eskers (aligned esker ridges and tributaries that are likely to have been connected) are termed either *simple* (predominantly trunk eskers with few tributaries or distributaries) or *complex* (containing many tributaries or distributaries, frequently anabranching). Esker planform morphology is highly variable and eskers often comprise simple systems of trunk eskers which occur in relative isolation (e.g. Aylsworth & Shilts, 1989), as well as complex systems of anabranched eskers (where multiple ridges diverge and converge), and distributary esker complexes which contain numerous branching distributaries (e.g. Price, 1966; Gorrell & Shaw, 1991; Plouffe, 1991; Margold *et al.*, 2011). Whilst these different systems are frequently described and often occur together, the factors controlling the planform morphology of esker systems have received relatively little attention.

How do esker systems evolve through time?

Eskers at the Casement Glacier, Alaska and Breiðamerkurjökull, Iceland (Price, 1966;1969; Howarth, 1971; Evans & Twigg, 2002) have previously been mapped from aerial photographs from different years to provide assessments of the temporal evolution (i.e. changing planform morphology during emergence from surrounding ice or sediment) of eskers over several decades. Eskers are seen to melt directly out of glacier snouts (e.g. Lewis, 1949) and are also seen to emerge after several years from wasting outwash deposits (e.g. Gustavson & Boothroyd, 1987), suggesting a more complex origin than simple subglacial tunnel infilling (e.g. Shreve, 1985). Notably, Price (1966;1969), Howarth (1971) and Evans & Twigg (2002) represent the only published observations of esker evolution over several years, highlighting the lack of contemporary examples of esker evolution for palaeoglaciological reconstruction.

Additionally, very few papers report on eskers in the process of emergence. Most eskers emerging from beneath present-day glaciers are relatively small, occur in isolation, and are likely controlled by drainage beneath glaciers which are heavily constrained by topography (e.g. Jewtuchowicz, 1965; Price, 1966), unlike many of the eskers preserved on palaeo-ice sheet beds (Storrar *et al.*, 2014). Only a limited number of papers have described eskers forming in larger systems, comprising two or more lobes (e.g. Gustavson & Boothroyd, 1987; Huddart *et al.*, 1999), which are more similar to former ice sheets.

Are the esker patterns compatible with the groundwater controlled hydraulic spacing of esker tunnels?

Boulton & Hindmarsh (1987) detailed the subglacial deformation of till beneath Breiðamerkurjökull and, more recently, Boulton and co-workers have developed a theory of groundwater controlled hydraulic spacing of meltwater channels that are recorded by eskers (Boulton *et al.*, 2001; Boulton *et al.*, 2007a;b; Boulton *et al.*, 2009). They suggested that the hydraulic properties of the substrate dictate the spacing of channels (and eskers) by scavenging meltwater into groundwater until it becomes saturated: at this point, meltwater drains in subglacial channels, which become optimally spaced to reflect the balance between substrate transmissivity and the supply of meltwater. This theory of groundwater controlled hydraulic spacing is discussed in section 5.7 in light of our more detailed mapping of the esker systems at Breiðamerkurjökull.

As little existing work has concentrated on appropriate modern analogues for ancient esker evolution, this paper presents the first high-resolution mapping of the evolution of simple and complex esker systems at Breiðamerkurjökull, Iceland, where such eskers are ubiquitous. We build on the legacy of esker research at Breiðamerkurjökull and utilise new mapping of eskers at high resolution using aerial photographs spanning the period 1945 – 2007, augmented by field observations. This allows detailed insights into some of the processes controlling the morphology and evolution of simple and complex eskers at one of the few glaciers where the evolution of large esker systems can be observed following their emergence from the ice. Moreover, compared with most previous studies, the snout morphology is more similar to palaeo-ice sheet settings in that large parts of the glacier are not topographically constrained (Evans & Twigg, 2002; Boulton *et al.*, 2007a).

2. Study area and a brief summary of previous work

Breiðamerkurjökull is a large (~13.5 km wide) composite glacier comprising four lobes, which we refer to as flow units 1-4 (Figure 2B). These flow units are separated by three medial moraines (Figure 2B). Breiðamerkurjökull drains part of the Vatnajökull ice cap, in south-east Iceland (Figure 2A) and has a history of surging at flow unit 4 (Björnsson *et al.*, 2003). The glacier retreated approximately 5 km from its Neoglacial maximum position in 1890 (Figure 2A), revealing a foreland with a complex glacial geomorphology (Breiðamerkursandur), covering approximately 78.3 km^2 by 2007. The substrate consists predominantly of unlithified sediment at least 120 m thick (Boulton *et al.*, 1982). Surficial sediments often comprise overridden outwash fans, which tend to have steep ice-contact faces and dip away from the glacier, producing inset overdeepenings as the ice retreats (Evans & Twigg, 2002).

Meltwater draining from Breiðamerkurjökull has led to the development and evolution of a series of proglacial lakes (labelled in Figure 2A) and rivers (Price & Howarth, 1970; Schomacker, 2010). The largest proglacial lake, which receives meltwater from flow units 3 and 4, is Jökulsárlón which is drained to the Atlantic Ocean by the river Jökulsá. Meltwater from flow units 1 and 2 drains into proglacial lake Breiðárlón, via the proglacial lake Fjallsárlón (which also receives meltwater from the neighbouring glacier Fjallsjökull) and its outlet Fjallsá. Flow unit 4 previously drained into Stemmulón via the river Stemma, until it was cut off by the larger Jökulsárlón system in the 1980s (Evans & Twigg, 2002).

Previous maps of the glacial geomorphology at Breiðamerkurjökull, based on field observations and aerial photography, were produced at a scale of 1:30,000 for the years 1945 (Howarth & Welch, 1969a), 1965 (Howarth & Welch, 1969b) and 1998 (Evans & Twigg, 2000). Seminal papers by Price and Howarth (Howarth, 1968; Howarth & Price, 1969; Price, 1969; Price & Howarth, 1970; Howarth, 1971; Price, 1971; 1982) document the evolution of complex glacial landforms using field and photogrammetric techniques, and provide measurements of the downwastage of proto-eskers from the melting of buried ice. Evans & Twigg (2002) used aerial photographs from 1945, 1965 and 1998 as well as field observations to review the glacial geomorphology of Breiðamerkurjökull and define the active, temperate glacial landsystem, whereby three depositional domains are highlighted: (1) annual moraine ridges; (2) glaciofluvial forms, including outwash fans and eskers; and (3) subglacial landforms, including flutes and drumlins. In particular, they note the historical evolution of large areas of pitted sandar, which evolved into complex esker networks by 1998 and are discussed further below. We build on and extend this work by producing new maps of the eskers at Breiðamerkurjökull in an unprecedented level of detail. This allows us to present a detailed picture of the morphological complexities of the esker systems at Breiðamerkurjökull and develop hypotheses to explain what controls this complexity.

3. Methods

Eight time intervals of high-resolution (30 – 380 cm) aerial photographs of the study area, from 1945 to 2007/9, were used to map esker ridge emergence through time. The photographs were orthorectified and georeferenced, based on control points used in the 1998 aerial photographs and related geomorphological map (Evans & Twigg, 2000; 2002). A 1 m resolution Digital Elevation Model (DEM) was produced from the 2007/9 photographs, using ground control which was undertaken in September 2013, which enabled the measurement of esker height and provides a visualisation of the topographic context (see Figure 3). Esker ridges, lakes, rivers and ice margins were identified from aerial photograph stereo pairs using a stereoscope and were digitised as shapefiles in ArcGIS 10. Esker ridges were identified as pronounced straight-to-sinuous ridges, predominantly oriented orthogonal to the ice margin (thus distinguishing them from morphologically similar push moraines in aerial photographs).

Esker ridge crestlines were mapped as polylines and, where gaps exist between nearby esker ridges, the ridges were mapped as separate features. Esker width was then mapped every 20 m along the corresponding crestline, also as a polyline. Width measurements were made visually and a line digitised between the break of slope either side of the crestline. Esker ridge height was also determined, from the 2007/9 DEM, by subtracting the minimum elevation from the maximum (crestline) elevation along each line used to measure width. In some locations, cross-sectional shape was described qualitatively based on the appearance of the esker ridges in the photographs and cross sections derived from the 2007/9 DEM. Cross-sectional shape was classified, after Burke *et al.* (2012), as either: sharp-crested (approximately triangular in cross-section); round-crested (approximately semi-circular in cross-section); or broad-crested (flat-topped). In a small number of instances, eskers were oriented parallel to the ice margin and were identified by their continuation and apparent connection with other eskers. In places, eskers are difficult to differentiate from the ridges surrounding pits in outwash. In such cases, a rule of thumb was applied such that eskers were identified when linear ridges continued beyond the edge of a depression. An example of the mapping procedure is given in Figure 4.

The resolution, sharpness and azimuth of the photographs vary between the different sets due to different camera parameters, flying heights, weather conditions and time of the day/year. A result of this is that eskers are more easily resolved in some images than others. Most photographs provided sufficient clarity to resolve eskers at a high (and comparable) level of detail (supplementary table S1 describes the main characteristics of each set of photographs and provides an indication of which are the most useful). Moreover, field observations and the highest resolution photographs suggest that most eskers in the study area (96.2% in the 2007/9 photographs) are greater than 2 m in width, within the resolvable resolution of all but the 1945 photographs. The resolution and, to a lesser extent, the quality of the 1945 photographs are poorer than the other photographs (see Table S1 for details). However, they were still used for the analysis because they are the oldest set of photographs and, as such, are invaluable for understanding the changes in the area at a key time, when many eskers began to emerge. Fewer eskers existed over a smaller area of exposed foreland in 1945 (cf. Howarth & Welch, 1969a) and so the impacts on this study of any errors associated with identifying eskers on the 1945 photographs is likely to be small. Aerial photograph interpretation was supported by observations of landform associations and ground truthing (i.e. using observations of landform continuation and limited observations of superficial sedimentary characteristics to check that mapped features are eskers) in the field in September 2011 and September 2012.

4. Results

4.1 Overview of esker systems at Breiðamerkurjökull

Mapping from eight different time slices reveals an increase in the total length of eskers from 4.7 km in 1945 to 72.1 km in 2007/9 (Figure 5). In general, most of the eskers occupy two areas, either side of Jökulsárlón (Figure 2A). In three locations, eskers are particularly densely distributed along corridors which likely relate to particular drainage systems and comprise different morphological characteristics (e.g. height, width, length) at different stages. We further explore these systems of eskers below, but refer to them generically (i.e. without any genetic interpretation) as Major Esker Systems (MES) 1-3. Table 1 provides measurements of esker width, length and planform for MES1-3 and three ‘isolated’ eskers, which are discussed in more detail in Section 4.5.

The eskers to the west of Jökulsárlón comprise MES 1 and 2 (discussed in Sections 4.2 and 4.3) and several smaller isolated eskers (discussed in Section 4.5). The largest (widest) eskers in the study area are aligned with or immediately adjacent to the medial moraine Mavabyggdarond (Figure 2B) and comprise MES1 and 2. A smaller suite of eskers near to the south-west shore of Jökulsárlón is aligned with the largest medial moraine (Esjufjallarond). Several smaller eskers, including some which were melting out of the ice margin in 2007, occur in this area that are not aligned with medial moraines. To the east of Jökulsárlón, MES3 is associated with the former drainage of the lake Stemmulón, which covered much of this area but now lies to the south-east. Several parts of the esker system became exposed as the level of Stemmulón fell. Related eskers appear to continue on the north-eastern shore of Jökulsárlón. The eskers in MES3 do not record drainage from a single drainage system but are discussed together because they collectively record the complex processes occurring in this area associated with flow unit 4. Between Stemmulón and Jökulsárlón, several smaller sinuous eskers and some zig-zag eskers occur in narrow corridors. Some smaller isolated eskers also occur on the eastern side of Jokulsarlon, and are discussed in Section 4.5. Previous work (e.g. Price, 1969; Evans & Twigg, 2002) and field observations show that many eskers across the foreland trend upslope. Taken together, our mapping from the 2007/9 photographs and associated DEM reveals that esker height (h) is closely related to width (w), the best fit being a linear regression (Figure 6) suggesting an approximate relationship of $h = 0.17w - 0.44$ ($R^2 = 0.73$).

4.2 Major esker system 1 (MES1)

The area comprising MES1 was revealed as the glacier retreated between 1903 and 1965. The southern portion of MES1 occupies a shallow trough (Figure 3) which descends from the proximal part of the system, before reaching a large outwash fan (OF) approximately 15 m tall (Figure 3), where it abruptly terminates. A total of 393 esker ridges, representing a total length of 18.9 km, were mapped within MES 1 from the 2007 photographs. We use the 1903, 1945, 1955 and 1965 margins to divide MES1 into three ‘zones’, with zone 1 being the most distal and zone 3 the most proximal (see Figure 7). In each of these zones we now describe the temporal evolution of eskers from 1945 to 2007/9. Letters in brackets refer to features annotated in Figures 3 and 7.

Zone 1:

The distal section of MES1 emerged between 1903 and 1945. In 1945, a prominent trunk esker, approximately 20 m wide, was melting out of the medial moraine Mavabyggdarond (A). This esker is dissected by a large meltwater channel (B), which was active in 1945, and then continues for a further 180 m (C) before terminating at a large outwash fan (OF). This esker is clear in each set of imagery and has not changed significantly in size since 1945, except for the distal section which appears to have increased in width from 15-20 m in 1945 to 30-50 m by 2007/9. Where it meets the outwash fan, the trunk esker is visibly sharp-crested in the imagery and appears to overlie smaller distributary esker ridges, which diverge from the trunk esker and mostly trend parallel to the ice contact face of the outwash fan, predominantly in an eastern direction. These eskers display an anabranched planform with increasingly smaller distributaries (D). There are also some small anabranching eskers to the west of the trunk esker (E), which were not evident in the 1945 photographs but which have subsequently emerged. Some of these smaller eskers terminate at, or pass around, large boulders.

Zone 2:

Zone 2 was exposed as a result of recession from 1945 to 1955. In 1955, a prominent broad-crested (flat-topped) esker 20 to 70 m wide was melting out of the ice margin. By 2007, this had decreased in width to 20 to 30 m (F) and was sharp-crested (more triangular in cross-section and with the crestline comprising a single narrow ridge: see also Burke *et al.*, 2012). To the north and west of this esker, a pitted surface is visible in the 1955 imagery, which gradually evolved into a complex assemblage of small (1.5 to 6 m wide by 2007/9) anabranching esker ridges.

To the west there is smaller (5 to 15 m wide) trunk esker, which has changed little in width from 1955 to 2007/9 (H). This branches down-ice into multiple smaller (1 to 5 m wide) distributaries which were not present in 1955 and gradually emerged between 1965 and 2007/9.

Zone 3:

At its proximal end, MES1 was melting out of the ice margin in 1965 and formed a prominent proto-esker ~35 m wide. By 2007, the prominent esker had degenerated into a series of small, fragmentary ridges 2 to 20 m wide (I). Some fragmented but well defined eskers extend up-glacier of the 1965 margin and were formed at some point between 1965 and 1980.

Summary:

MES1 consists of A large trunk esker which approaches an outwash fan. The trunk esker has decreased in width significantly since it first emerged. Where it meets the outwash fan, a series of smaller distributary eskers can be seen to branch away from the trunk esker, and these ridges decrease progressively in size with distance from the trunk esker.

4.3 Major esker system 2 (MES2)

MES2 is located immediately to the east of MES1 and was revealed as the glacier retreated between 1903 and 1965. The proximal end of MES2 is in a trough, and then ascends Nygrædnakvis (labelled NN in Figures 3 and 7), an overridden outwash fan (Evans & Twigg, 2002) approximately 20 m tall. A total of 329 esker ridges, representing a total length of 21.9 km in MES2, were mapped from the 2007 aerial photographs. We use the 1903, 1945, 1955 and 1965 margins to divide MES2 into three 'zones', with zone 1 being the most distal and zone 3 the most proximal (see Figure 8). In each of these zones we now describe the temporal evolution of eskers from 1945 to 2007/9. Letters in brackets refer to features annotated in Figures 3 and 8.

Zone 1:

In 1945, the ice margin was at the apex of a pitted fan surface. Seven esker ridges were mapped, the largest being up to 25 m wide and sharp-crested. Between 1945 and 2007/9, a large distributary esker complex (J) emerged from the formerly pitted fan surface (Figures 4 and 8). Within this distributary esker complex, there are subsets where eskers form either anabranched or distributary networks. Smaller ridges within this complex are more round-crested in cross-section than the larger, sharp-crested esker ridges.

Zone 2:

Between 1945 and 1955, the ice margin retreated from the apex of the distributary esker complex into the overdeepening north of Nygrædnakvis, forming a proglacial lake, which is evident in the 1955 photographs (Figure 8; Supplementary material S2). The 1955 photographs show a continuous trunk esker (K) 18 – 30 m wide which stretches from the fan apex to Nygrædnakvis. This trunk esker is sharp-crested at its distal end and round-crested at the proximal end. To the west of this esker, a complex system of eskers, which branched off to the west from the trunk esker, was emerging from a pitted surface in 1955. By 2007, a coherent network of round-crested anabranching and distributary eskers up to 5 m wide (L) was revealed, including a prominent sharp-crested esker 15 m wide, which was not visible in 1955. This esker is connected at each end with the large esker to the east. A large proto-esker (M) up to 40 m wide was emerging from an englacial position and disappeared into the proglacial lake in 1955, and is seen to drape the ice-proximal side of Nygrædnakvis in 2007, having decreased in size from up to 48 m wide in 1955 to just 11 m wide by 2007/9.

Zone 3:

The proximal end of MES2 began to emerge between 1955 and 1965. The most proximal eskers are relatively narrow but are continuous, forming more coherent patterns than eskers formed at a similar time in MES1. Nevertheless, some distributary patterns are observed. Gradually, the eskers become larger as they approach Nygrædnakvis; a conspicuously large, teardrop shaped feature, 110 m long and up to 70 m wide, appears to be a very large esker segment (N). This ridge was just 10 m wide in 1965. As with MES1, a few small (3-5 m wide) eskers emerged after 1965 and form a continuation of MES 2 north of zone 3.

Summary:

MES2 is characterised by relatively large continuous ridges, which climb Nygrædnakvis before descending and producing a more complex planform morphology. The system terminates in a large distributary esker complex, which evolved gradually from a relatively simple pitted fan surface in 1945 to the distributary esker complex that is evident in the 2007/9 imagery.

4.4 Major esker system 3 (MES3)

MES3 comprises the eskers around the Stemmulón system and further north, to the east of Jökulsárlón. A total of 281 esker ridges, representing a total length of 15.6 km in MES3, were mapped from the 2007/9 aerial photographs. The eskers in MES3 are located in a broad corridor of relatively low elevation terrain (Figure 3), which was occupied by extensive lakes (principally Stemmulón and Jökulsárlón), whose levels have risen and fallen, resulting in a complex history of esker emergence. MES3 was revealed following glacier recession from 1903 to 1998, though it may extend to the present margin. We use the 1945, 1965, 1980 and 2007/9 margins to divide MES3 into three ‘zones’, with zone 1 being the most distal and zone 3 the most proximal (see Figure 9). In each of these zones we now describe the temporal evolution of eskers from 1945 to 2007/9. Letters in brackets refer to features annotated in Figures 3 and 9.

Zone 1:

In 1945, the distal end of MES3 was melting out of the glacier snout, as two coherent (but fragmented) sinuous ridges approximately 10 – 15 m wide. By 2007, the southern part of the system was composed of a sharp-crested trunk esker (O) 12 – 15 m wide, with a complex system of smaller (1 – 5 m wide) distributary eskers which branch preferentially to the north (P). The trunk esker is sinuous and terminates near a large bedrock knob. Immediately in the lee of this knob, a conspicuously straight esker (Q) runs for 390 m, narrowing from 30 m at its proximal end to approximately 6 m. This esker changes from sharp-crested at its proximal side to broad-crested at its distal end. There is a network of eskers immediately to the north of the main ridge, which has a more complex history because it is associated with the Stemmulón lake system, which drained flow unit 4 until some point between 1988 and 1994. The esker system gradually emerged (and is still emerging) from the lake as the lake level drops. The changing proglacial drainage system in this sector of the foreland has also resulted in the submergence of some eskers, which were present on a small island in Jökulsárlón in 1998, but which now lie beneath the water level.

Zone 2:

The eskers in zone 2 are approximately 1 km north of those described in zone 1 and relate to a separate drainage axis (but the same flow unit). Between 1945 and 1965, two prominent (up to 11 m wide) sharp-to-round-crested zig-zag planform trunk eskers (R) were exposed, with relatively few tributaries or distributaries. The southernmost of these two eskers continued to be exposed until approximately 1980. After 1980, the drainage of a lake in the vicinity of the zig-zag eskers revealed a further continuation of the ridges up-glacier, as well as some short, fragmentary esker ridges to the south (Figure 9).

Zone 3:

Between 1980 and 1988, flow unit 4 underwent a readvance/surge of approximately 150 m. After 1988, the margin once again steadily retreated. Between 1980 and 2007/9, several sharp-crested, closely spaced anabranching esker networks (S) were exposed. Between 1998 and 2012, the margin in the north retreated rapidly by 0.9 to 1.5 km in 14 years. Relatively few eskers were exposed here after 1998 but, during fieldwork in 2012, several small proto-eskers were observed emerging on the surface of the glacier near the terminus.

Summary:

MES3 is characterised by very little change in esker width over time, in contrast with the eskers of MES1 and 2. A complex system of eskers has gradually emerged to the south of Jökulsárlón as the Stemmulón lake levels have dropped, following the switch in the east margin drainage from the Stemmulón system to the Jökulsárlón system between 1988 and 1994 (Figure 9). The system extends to the present day margin on the north-east side of Jökulsárlón and includes zig-zag eskers, which are not documented in MES1 and 2.

4.5 'Isolated' eskers

Several smaller suites of eskers have been mapped outside of MES1-3, and are associated with each of the four flow units (Figure 2B). Figure 10 shows the crestlines and widths (from first appearance to 2007) of three of the more prominent isolated eskers, from flow units 2,3 and 4. Esker A in Figure 10 formed beneath flow unit 4 prior to 1945, but the proximal section emerged after 1955. It is up to 10 m in width and is sharp-crested in the distal section, where it splits into several small (< 5 m wide) distributaries, and more round-crested in the proximal part. With the exception of the proximal part of the esker which was revealed at a later stage, there is little change in width evident in this esker between 1955 and 2007. Esker B is associated with flow unit 2 and was up to 25 m wide and broad-crested in 1955, as it emerged from flanking outwash deposits. By 2007, it had decreased in width by approximately 10 m and had evolved a sharp-crested cross section. Esker C is associated with flow unit 3 and was up to 10 m wide in 1965. By 2007 it had decreased slightly in width to between 5 and 10 m and was sharp-crested in cross section. Esker C splits into several small (< 5 m wide) distributaries at the distal end.

The isolated eskers tend to be much smaller (narrower) than the eskers of MES1-2, with a maximum width of c. 25 m, and display a much simpler planform morphology, which typically comprises single ridges along most of their length, with occasional bifurcations and sometimes terminating in small (less than 5 m wide) distributaries (Figure 10). These eskers typically exhibit little change in width over time, except where they have emerged from the surrounding topography and subsequently narrowed (A and B in Figure 10).

4.6 Chronology of esker emergence

Our mapping reveals the rate of esker emergence over the last ~70 years. In total, 26 esker ridges were mapped from the 1945 photographs, increasing gradually to 1,346 esker ridges in the 2007/9 photographs. The sum total length of exposed eskers increased steadily over this time from 4.7 km to 72.1 km (with the exception of the period between 1980 and 1998, when some eskers were submerged by lakes and others were undetected as a result of lower quality images from 1994 and 1998, resulting in an apparent decline) as the glacier retreated and eskers emerged through buried ice on the glacier foreland (Figure 5). The emergence of MES1, 2 and 3, as well as eskers outside of the MES, is shown in Figure 5. This reveals that eskers in MES1 and 3 were revealed gradually, whereas a large proportion of MES2 emerged between 1955 and 1980.

The increase in total length of eskers is broadly correlated with the amount of ice margin retreat, as well as the mean annual temperature at Fagurhólsmýri, which is the closest weather station, located 20 km south-west of the Breiðamerkurjökull foreland (Figure 5). This does not, however, simply indicate that more eskers were melting out of the glacier over the study period because many eskers were revealed some distance in front of the ice margin, several years after the glacier had retreated. The largest systems of eskers began to emerge between

1903 and 1965 and 87% of the total length of all the eskers mapped is located in front of the 1965 margin (i.e. just 62.5% of the overall observed recession). Hence, eskers may be categorised as those which are exposed immediately as they are melted out of the glacier terminus, and those which emerge gradually following the melting of buried ice. The size of eskers may change following retreat if they contain an ice core which subsequently melts out (e.g. Howarth, 1971) or are eroded by other means (such as gravitational slope processes). Indeed, it can be seen in Figures 7-10 that many eskers have decreased in width over time.

5. Discussion

5.1 Sediment and meltwater supply

MES 1 and 2 contain a diverse range of esker patterns in a relatively confined area and include the largest eskers on the foreland. As such, they are well suited for exploring the factors which control different esker morphologies. The abundance of eskers in this location may be explained by the availability of large volumes of sediment and meltwater from the medial moraine Mavabyggdarond, as noted by others (Price, 1969; Evans & Twigg, 2002). MES3 provides a contrasting scenario, where eskers are typically smaller and where the supply of sediment and meltwater is very different to MES1 and 2. Before discussing the controls on different esker morphologies, we now provide more detail on the supply of sediment and meltwater in the different sectors of the glacier.

5.1.1 Sediment

The supply of sediment in the western sector of Breiðamerkurjökull is strongly controlled by the erosion of nunataks up-glacier, which produce the large medial moraines between each flow unit (see Figure 2B). Figure 11 illustrates the association between eskers and the approximate position of the medial moraines from 1903 to 2009. It is important to note that the position of the medial moraines has migrated slowly during deglaciation, as indicated by the shades of grey. From this it can be seen that MES 1 originates from directly beneath Mavabyggdarond, whilst MES2 appears to be more offset. This may suggest that MES2 did not acquire its sediment directly from Mavabygddarond. However, the 1945 photographs show that MES2 is aligned with some smaller (but still significant) debris concentrations (Figure 11B) and it is probable that MES2 was within the zone of medial morain operation, taking lateral migration into account.

Flow unit 4, which produced the eskers of MES3 is bound on the south-western margin by the large medial moraine Esjufjallarond. A large proportion of this flow unit, however, receives no sediment from medial moraines (Figure 2B; Figure 12). Debris on the surface of the glacier tends to occur in folded bands oriented perpendicular to the ice flow direction, in sharp contrast to flow units 1-3 (Figure 12). At the terminus, debris at the glacier surface is abundant approximately 100 – 500 m up-glacier and is particularly abundant at three localities (indicated by blue lines in Figure 12B). Increased sediment abundance in these (relative) positions is evident in photographs from 1945 and 2007, and in each set of photographs the debris bands up-glacier of these high debris concentrations are folded longitudinally, suggesting that debris is preferentially concentrated along these locations. Field observations identified a large ice-cored lateral moraine on the northern margin of the glacier, and sediment in flow unit 4 is likely to be derived from supraglacial sources on the northern margin, as well as from the bed across its width (Björnsson, 1996).

5.1.2 Meltwater

Meltwater has been shown to concentrate between lobes at Breiðamerkurjökull (Thome, 1986) and elsewhere (e.g. Mäkinen, 2003; Benn *et al.*, 2009) because of the lateral convergence of supraglacial, englacial and subglacial drainage systems (Thome, 1986; Huddart *et al.*, 1999; Benn *et al.*, 2009). Boulton *et al.* (2007a) identified 16 meltwater drainage axes (Figure 2B), with typical melt season discharges of less than 10 $m^3 s^{-1}$ in all but four cases. The four drainage axes with larger melt season discharges (20 – 50 $m^3 s^{-1}$) are aligned with the former junction between Breiðamerkurjökull and Fjallsjökull, medial moraine 1, Mavabyggdarond and the central part of Jökulsárlón (Figure 2B; Boulton *et al.*, 2007a). Three of the four larger meltwater drainage axes terminate in large proglacial lakes, leaving the meltwater emanating from Mavabyggdarond as the only terrestrially terminating large drainage axis. Thus, a large regular supply of meltwater can be invoked for the formation of the eskers of MES1 and 2. In contrast, flow unit 4 is drained only by smaller streams, which have decreased in number since the Little Ice Age (Thome, 1986; Boulton *et al.*, 2007a).

Ice block scour marks in pitted outwash, which are indicative of jökulhlaup activity (Maizels, 1992;1997), have been observed on the Breiðamerkurjökull foreland on the shore of Jökulsárlón, close to Jökulsá (Evans & Twigg, 2002) and historical evidence suggests that jökulhlaups have occurred there in the past (McKinzey *et al.*, 2005), although unfortunately the timing and location of these historical events remains unknown. In addition, Price (1971) described a jökulhlaup in flow unit 1, which resulted from the drainage of an ice dammed lake which existed on the western margin in the 1960s. Ice dammed lakes presently exist up-glacier in the eastern parts of the flow units 3 and 4 (Figure 2B) and the drainage of these lakes produces periodic jökulhlaups (Björnsson, 1996). Thus, there is evidence for the occurrence of jökulhlaups in different sectors of Breiðamerkurjökull, although there is no evidence to directly link jökulhlaup events with esker formation.

We suggest that the availability of large volumes of sediment and meltwater is the reason why complex, rather than simple esker planform morphologies have developed in MES1 and 2. Below we propose depositional models for MES 1 and 2 and use these models to explain in more detail what controls the formation of different esker complexes. We also discuss what may have controlled the morphology of different parts of MES3, which do not align with a large medial moraine and so must have acquired substantial quantities of sediment from elsewhere.

5.2 A depositional model for MES1

MES1 is a *topographically constrained distributary esker complex.* Distributary eskers branch from the main part of the system, but the overall planform morphology of the distal part of the esker complex is dictated by the topographic constraint of the large outwash fan to the south (Figure 3). The trunk esker that feeds the system likely formed as the fan was being prograded, i.e. when the ice margin was at its apex in the 1930s (Boulton, 1986). At this time the fan apex was located within a re-entrant in the glacier snout (A in Figure 13), where it is likely that englacial drainage was emerging from an ice-walled tunnel because of the progradation of outwash on the fan surface, as well as the sharp-crested cross-sectional shape of the trunk esker (cf. Burke *et al.*, 2012). This trunk esker increased slightly in width between 1945 and 2007, indicating that it emerged as ice buried either side of it lowered the surrounding surface. The drainage system in the distal section of MES1 was likely dictated by pre-existing ice-contact fans and their associated overdeepenings (outwash heads; cf. Boulton, 1987; Kirkbride, 2000), whereby englacial drainage initially bypassed the overdeepening and debouched onto the fan apex in a supraglacial position (cf. Spedding & Evans, 2002; Bennett & Evans, 2012). Hence, once the glacier surface had lowered below the height of the fan apex, englacial or supraglacial meltwater issuing from the glacier snout was no longer able to drain over the fan surface and instead drained through lower elevation tunnels excavated through the snout immediately towards the east (B in Figure 13). This is recorded by the large trunk esker which approaches the fan before splitting into increasingly smaller distributary esker ridges away from the fan apex and along its ice contact face, as well as smaller eskers which the trunk esker overlies. The formation of the complex network of distributaries is likely a product of abundant sediment and meltwater derived from Mavabyggdarond, coupled with this topographic control. High sedimentation rates resulted in the frequent blocking of channels (cf. Brennand, 1994; Burke *et al*., 2012), which formed distributary eskers as meltwater was diverted around the part of the channel that became choked with sediment. Others have suggested that the formation of distributary eskers may be related to supraglacial let down (e.g. Price, 1966) or ice block melt out (Howarth, 1971). This would mean that the esker pattern reflects the former supraglacial drainage system which is unlikely in this case, since the eskers are clearly influenced by the location of the large fan (though it is conceivable that the drainage pattern itself could have been influenced by the fan, once the ice front was below the fan apex). Alternatively, flow splitting in ascending reaches (Shreve, 1985) or high pressure leakage (Brennand, 1994) may also be invoked, though these explanations are unlikely near a terrestrial ice margin, where meltwater will be close to, or at, atmospheric pressure (Hooke, 1984). Observations in the field indicate that a small number of distributary eskers near to the fan drape its former ice contact face, most likely indicating that they were deposited englacially, as the ice retreated back across the fan, which matches observations of surface lowering relating to the melting of buried ice beneath most of MES1 (Price, 1969). Indeed, the fan that was fed by MES1 also contained a considerable amount of buried ice, leading to the formation of the present pitted fan surface (Boulton, 1986). Some eskers in MES1 indicate a subglacial origin, particularly the smaller eskers to the north-west of the fan (E in Figures 3 and 7), which frequently terminate at, or pass around, large boulders, indicating that the meltwater flows in which they formed were subglacial, because the spatial relationship with the boulders was maintained following ice wastage. Esker ridges in Zone 3 have undergone considerable change since their first appearance in 1954/5, having degenerated from a large single ridge to a series of small, fragmentary esker ridges. This likely indicates an englacial origin, with melt-out of buried ice causing the destruction of the initial planform morphology. Whilst there is evidence for both subglacial and englacial/supraglacial esker sedimentation in MES1, it is often difficult to discern which process predominated.

Up-ice of the *topographically constrained distributary esker complex,* (areas B and C in Figure 3), MES1 is seen to change from a complex of smaller anabranching tributary and distributary eskers down-ice into a single larger trunk esker (shown in Figure 1). This transition occurs as the eskers ascend an overridden outwash fan, suggesting that the more complex anabranched planform morphology is associated with flat or descending topography, as has also been observed at MES2, which we now discuss in detail.

5.3 A depositional model for MES2

We interpret the distal section of MES2 as a *distributary esker fan complex,* without topographic constraint. Similarly to MES1, subglacial, englacial or supraglacial meltwater channels carried a large amount of sediment and meltwater from Mavabyggdarond to the ice margin, initiating a complex planform morphology as the sediment overwhelmed the channels to produce multiple distributary eskers. As noted above, MES2 was not directly beneath Mavabyggdarond in 1945, but was located approximately 50 m to the east. The proximal part of MES 2 is aligned with the 1965 medial moraine (Figure 11) and it is possible that the medial moraine occupied the area in which MES2 lies when it was formed, i.e. prior to 1945. In either case, we infer that the close proximity of MES2 to Mavabyggdarond explains the large quantity of meltwater and sediment that was available for esker formation. If the eskers were not formed in conduits directly beneath the medial moraine, we speculate that meltwater could easily deviate a small distance from the source, especially given the large concentrations of sediment and meltwater available.

Ridge divergence suggests that there was no topographic impediment and that the meltwater channels were at atmospheric pressure when they filled with sediment. If the channel was under hydrostatic pressure, it would be unlikely to produce divergent channels and would favour a single channel, because pressurised channels tend to capture drainage (Röthlisberger, 1972). H-channels (subglacial channels at atmospheric pressure) could also produce distributary channels, but this is unlikely to be the case here because at least part of the main esker ridge of MES2 ascends the topography (Figure 3). This indicates that meltwater emerged englacially into a network of ice-walled supraglacial channels, similar to an alluvial fan (Figure 14). Following headward migration of the channels as the ice decayed, outwash was aggraded over the snout, burying the sediment filled channels. Active recession of the glacier then followed, resulting in the gradual downwasting of the fan as the buried ice melted out, as supported by measurements of pervasive surface lowering between 1945 and 1965 (Welch & Howarth, 1968) and subsequent evolution of the fan morphology (Figure 8). Through time, the feature evolved from a flat fan (1945) to a pitted surface with a few eskers at the proximal end (1955) to more eskers and pitted outwash (1965) and then to a complex network of eskers resembling the shape of a fan by 2007 (Figures 4 and 8; see also Price, 1969; Evans & Twigg, 2002). This gradual emergence of eskers from ice buried beneath outwash is in accordance with the observations of Gustavson & Boothroyd (1987) on some eskers at the Malaspina Glacier, Alaska.

This depositional model bears some similarities to the jökulhlaup esker-forming model invoked by Burke *et al.* (2008) to explain an esker that formed during the 1996 jökulhlaup at Skeiðarárjökull. Burke *et al.* (2008) describe a transition between englacial conduit sedimentation and supraglacial ice-walled channel sedimentation during the jökulhlaup, which is similar to the explanation we present here (although the distributed fan morphology that we observe did not develop at Skeiðarárjökull). As discussed in section 5.1.2, there is evidence to suggest that jökulhlaups may have occurred in the western and central parts of the foreland. It is therefore conceivable (though speculative) that the eskers of MES2 were formed under jökulhlaup conditions, which would provide an additional explanation for the high volumes of sediment and meltwater required to build the large esker complex.

5.4 A depositional model for MES3

MES3 contains a diverse array of eskers. We interpret the complex area south of Jökulsárlón in MES 3 as a *topographically constrained distributary esker complex*, similar to MES 1. The complex morphology of parts of the system and existence of a topographic control on the western and eastern boundaries of the esker complex (illustrated in Figure 3) suggest that the planform morphology of the distributary eskers is controlled by topography, although it is less clear than in MES1 because the occupation of much of the area by lakes over the past 60 years means that the morphology of the esker system is subdued and parts have been lost through submergence or erosion by meltwater channels. Howarth (1971) produced the first detailed measurements of the main esker ridge in MES3 (the trunk esker O in Figure 3 and Figure 9) and noted that between 1945 and 1965 its surface lowered by up to 8 m, indicating the melting out of ice buried beneath the esker. Additionally, the northern edge of the system contained more buried ice. More recently, Evans & Twigg (2002) suggested that a surge mechanism may be responsible for the processes leading to the development of these eskers, based on observations on their planform, some of which (R in Figures 3 and 9) are similar to zig-zag shaped eskers produced during surges at Brúarjökull, Iceland (Knudsen, 1995; Evans & Rea, 2003), as well as the occurrence of surge-diagnostic, crevasse squeeze ridges on the northern shore of Jökulsárlón, directly up-ice from the eskers. The eastern section of Breiðamerkurjökull has a long history of surging (Björnsson *et al.*, 2003) and the occurrence of surges in the past may explain the availability of the large amount of sediment necessary to build the eskers of MES3 (Evans & Rea, 2003). A surge mechanism would also explain the availability of meltwater to construct the eskers, because a large quantity of meltwater is usually released following a surge (Kamb, 1987). The zig-zag planform of some eskers reflects deposition of sediment in water filled crevasse networks, consistent with a surge origin (Evans & Rea, 2003). Sedimentation within the crevasse network may have occurred during, or immediately after, the surge. However, not all eskers exhibit a zig-zag planform. We interpret this to suggest that the zig-zag eskers formed by crevasse infilling during surges, but the other eskers formed either following surges, when meltwater and sediment were available, or from meltwater that originated supraglacially. The correlation between esker emergence and mean annual temperature, shown in Figure 5, may lend weight to this interpretation, since more supraglacial meltwater will be produced from melting during warmer years (see also Storrar *et al.,* 2014). Supraglacially-derived meltwater would then entrain sediment as it descends englacially through the glacier. The presence of the complex eskers in MES3 is likely to be related to the periods when the most sediment was mobilised by meltwater, with simpler eskers recording less vigorous conditions. The complex form of some of the eskers in MES3 would otherwise be difficult to reconcile with the predominant esker forming processes at Breiðamerkurjökull, because there is no large medial moraine to supply the sediment, as with MES1 and 2. Whilst a surge has been reported in flow unit 3

(Björnsson *et al.*, 2003), surges are much less common there than in flow unit 4, and so we favour a surge origin for MES3 but not for MES1 and 2.

5.5 What controls the morphology of simple and complex esker systems?

Observations on the three major esker systems and 'smaller' eskers at Breiðamerkurjökull permit some conclusions to be drawn regarding the controls on the formation of: a) simple esker planform (single ridges, separate from but often associated with complexes); and b) complex esker planform (multiple ridges, either topographically constrained or unconstrained (fan-like) distributary complexes). Based on the morphometry (length, width and planform complexity) of mapped esker ridges and their occurrence in inferred areas of contrasting sediment and meltwater supply (high or low; continuous or sporadic), it is apparent that complex systems of eskers require certain conditions in order to form, which we summarise in Table 1.

Eskers are aligned with drainage outlets (Figure 2B) and debris structures in the glacier which indicate the availability of sediment (Figure 12).Thus, it is clear that the supply of meltwater and sediment is directly related to the location of esker formation. We provide the first systematic measurements of esker height and width and our measurements reveal that eskers at Breiðamerkurjökull are approximately five times wider than they are tall. This is in agreement with predictions that esker height and width are closely related (Price, 1973) and we use this relationship to relate esker width measurements to esker size, since this gives an indication of the cross-sectional area of the esker and, by extension, the volume of sediment contained within the esker. On this basis, it is clear that the largest eskers (by maximum, mean and median width) occur in MES1 and 2. The eskers of MES3 are considerably smaller and are similar in dimensions to the smaller 'isolated' eskers. Planform complexity follows a similar trend, with the most complex eskers in MES1 and 2 and the simpler planforms occurring in MES3 (though MES3 still contains a distributary planform in places) and the isolated eskers. As discussed above, we infer a large and relatively continuous supply of both sediment and meltwater through Mavabyggdarond, which we argue is critical for the subsequent development of complex esker planform.

More complex esker morphologies, such as distributary drainage patterns and anabranching networks are more likely to form (at terrestrial margins: cf. Gorrell & Shaw, 1991) if there is a large amount of sediment and meltwater in the system, such that the conduits become clogged with sediment and drainage is diverted to form new channels and new eskers (Brennand, 1994; Burke *et al.* 2012). Conversely, simpler esker planforms will result from restricted amounts of sediment or meltwater, because transport and blockage is less likely to occur. MES3 provides an example of an intermediate situation, where sediment and meltwater supply is higher during (or following) surges, but limited at other times. This results in smaller eskers which still exhibit complex planform. MES3 highlights the importance of temporal variability in sediment and meltwater supply on subsequent esker size and planform, as has been noted by others (e.g. Burke *et al.*, 2012).

5.6 How does esker morphology evolve through time?

'Simple' eskers, which emerge directly out of the glacier onto the foreland, typically change less over time than more complex esker systems following deposition. Nevertheless, simple eskers can experience surface lowering if they contain an ice core which subsequently melts out (e.g. Figure 10; Price, 1966; Price, 1969; Howarth, 1971; Schomacker & Kjær, 2008). Later erosion of sections of eskers by meltwater streams is commonplace, especially when drainage systems change frequently, as at Breiðamerkurjökull (Price & Howarth, 1970).

Eskers are frequently concealed or revealed after the glacier has retreated if, for example, they were submerged beneath a lake which subsequently drained, as with the esker complex associated with the Stemmulón system (Figure 9), or *vice-versa*. Other eskers may be overridden by readvances or surges and be removed or reworked beyond recognition. MES 1 and 2 provide pertinent examples of more complex esker systems, which may take several decades to emerge from ice buried beneath outwash, making a gradual but marked transition from a flat or pitted outwash surface to a complex network of eskers, once all the buried ice has melted (Figures 7 and 8).

Eskers at Breiðamerkurjökull appear to represent deposition in sub-, en- and supraglacial environments, enabling observations of their morphology to be tentatively linked to their position of formation. For example, eskers formed in englacial or supraglacial positions often experience substantial changes in morphology, as ice buried beneath them melts out (e.g. I in Figure 7). This process typically results in fragmentary esker ridges. In contrast, eskers deposited subglacially, such as those in the area marked ‘E’ in Figure 7, display a more coherent planform and have changed less since initial emergence. However, englacial and supraglacial eskers are not always fragmentary in planform. The trunk eskers of MES1 and 2 are likely to have been formed englacially (or supraglacially), yet they are relatively continuous. This is likely due to their larger size, such that there is sufficient material contained within the eskers for them to preserve their form during the melt-out of buried ice. Thus, the position of esker formation is related to the resultant morphology but further work, in the form of identifying sub-, en- and supra-glacial eskers, is required before more robust inferences may be made but this presents a potentially useful line of research.

5.7 Are the esker patterns compatible with groundwater controlled hydraulic spacing of esker tunnels?

Borehole measurements and observations of the subglacial till and aquifer beneath Breiðamerkurjökull have been used to suggest that water is drawn to perennial subglacial channels through groundwater (Boulton *et al.*, 2007a). Boulton *et al.* (2007a) suggest that Breiðamerkurjökull is drained along 16 main axes (shown on Figure 2B) dictated by a coupling between subglacial channels and the subglacial groundwater system, and that some of the major esker systems originate from these channels. Our mapping shows that some of the larger eskers do appear to be concentrated along the pathways proposed by Boulton *et al.* (2007a), which lends support to this hypothesis. However, it is also clear that some pathways do not appear to have generated eskers and a large number of eskers occur between two axes. Thus, whilst it appears that Boulton *et al.*'s (2007a) hypothesis operates at a large scale, other local factors, such as sediment and meltwater supply from medial moraines, surges, or jökulhlaups, are also important for esker formation. The availability of water from the lateral convergence of drainage between ice lobes, combined with the availability of sediment associated with the medial moraines themselves, as well as the possibility that meltwater and sediment are produced and mobilised during jökulhlaups and surges, provides an additional explanation for the location of the largest eskers at Breiðamerkurjökull. Importantly, the results presented above, as well as previous work (e.g. Price, 1969; Howarth, 1971), have shown that many of the eskers at Breiðamerkurjökull formed in englacial or supraglacial positions, which would mean that their location could not be directly influenced by groundwater.

6. Conclusions

Understanding the evolution of esker systems permits us to refine our understanding of the interactions of meltwater drainage and the retreat of glaciers. Detailed mapping of over 1,000 esker ridges over eight different time slices from the last ~70 years at Breiðamerkurjökull reveals complex anabranching esker networks and simpler, single ridges which emerged (mostly from the deglaciated foreland, rather than the glacier itself) at a mean rate of 1.08 m yr^{-1} and total 72 km by 2007. Esker width is found to be approximately five times esker height and esker size, location and complexity at Breiðamerkurjökull appear to be driven by sediment supply and meltwater concentrated along medial moraines, where the largest and most complex eskers are observed. In other locations, crevasse infilling during surges may explain smaller esker complexes.

Eskers at Breiðamerkurjökull are formed variously in sub-, en- and supra-glacial positions. Variations in their planform morphology suggest that englacial and supraglacial eskers are likely to be more fragmentary due to the loss of buried ice. Subglacial eskers appear to be more continuous, although the larger englacial eskers may also be continuous. Future work should focus on comparing esker morphology with position of formation.

The spacing of eskers is broadly consistent with groundwater controlled hydraulic spacing of esker tunnels (cf. Boulton et al., 2007a, b), whereby meltwater is scavenged into the groundwater system from the subglacial channels until it becomes saturated. However, not all drainage paths predicted by Boulton *et al.* contain eskers and many eskers formed englacially or supraglacially, rather than subglacially as invoked by Boulton *et al.* Consequently the pattern of development and subsequent emergence of eskers is also controlled by topography and sediment and meltwater availability, indicating that the position of eskers is not solely a result of groundwater hydraulics.

Depositional models are presented for two complex esker systems: *distributary esker complexes*, which produce distributary or anabranching eskers in a fan shape; and *topographically constrained distributary esker complexes*, which are characterised by distributary or anabranching eskers and which develop where sediment is abundant and whose planform is dictated by topographic impedances and thus not able to develop into a fan shape. These complex morphologies were created by the gradual melting out of buried ice which contained eskers beneath a layer of outwash. Both of these complex esker systems require a large supply of sediment and meltwater to form; conversely, simple esker systems predominate when less sediment and/or meltwater is available. Complex esker systems may take several decades to melt out of outwash and evolve into the complex patterns which we observe today.

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References

Armstrong, J. E. & Tipper, H. W. (1948) Glaciation in north-central British Columbia. *American Journal of Science*, 246, 283-310.

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

Aylsworth, J. M., Shilts, W. W., Russell, H. A. J. & Pyne, D. M. (2012) Eskers around the Keewatin Ice Divide: Northwest Territories and Nunavut. *Geological Survey of Canada, Open File*, 7047.

Banerjee, I. & McDonald, B. C. (1975) Nature of esker sedimentation. In A. V. Jopling and B. C. McDonald, *Glaciofluvial and Glacilacustrine Sedimentation*. Oklahoma, SEPM, 304-320.

Bartholomew, I., Nienow, P., Mair, D., Hubbard, A., King, M. A. & Sole, A. (2010) Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier. *Nature Geoscience*, 3, 408-411.

Benn, D. I., Kristensen, L. & Gulley, J. D. (2009) Surge propagation constrained by a persistent subglacial conduit, Bakaninbreen-Paulabreen, Svalbard. *Annals of Glaciology*, 50, 81-86.

Bennett, G. L. & Evans, D. J. A. (2012) Glacier retreat and landform production on an overdeepened glacier foreland: the debris-charged glacial landsystem at Kvíárjökull, Iceland. *Earth Surface Processes and Landforms*, 37, 1584-1602.

Björnsson, H. Scales and rates of glacial sediment removal: a 20 km long, 300 m deep trench created beneath Breidamerkurjokull during the Little Ice Age. *Annals of Glaciology,* 22, 141-146.

Björnsson, H., Pálsson, F., Sigurðsson, O. & Flowers, G. E. (2003) Surges of glaciers in Iceland. *Annals of Glaciology*, 36, 82-90.

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. (1986) Push-moraines and glacier-contact fans in marine and terrestrial environments. *Sedimentology*, 33, 677-698.

Boulton, G. S. (1987) A theory of drumlin formation by subglacial sediment deformation. In J. Menzies and J. Rose, *Drumlin Symposium*. Rotterdam, Balkema, 25-80.

Boulton, G. S., Dobbie, K. E. & Zatsepin, S. (2001) Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. *Quaternary International*, 86, 3-28.

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., Harris, P. W. V. & Jarvis, J. (1982) Stratigraphy and structure of a coastal sediment wedge of glacial origin inferred from Sparker measurements in glacial lake Jokulsarlon in southeast Iceland. *Jokull*, 32, 37-47.

Boulton, G. S. & Hindmarsh, R. C. A. (1987) Sediment deformation beneath glaciers: rheology and geological consequences. *Journal of Geophysical Research*, 92, 9059-9082.

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.

Boulton, G. S. & Zatsepin, S. (2006) Hydraulic impacts of glacier advance over a sediment bed. *Journal of Glaciology*, 52, 497-527.

Brennand, T. A. (1994) Macroforms, large bedforms and rhythmic sedimentary sequences in subglacial eskers, south-central Ontario - implications for esker genesis and meltwater regime. *Sedimentary Geology*, 91, 9-55.

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

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.

Burke, M. J., Woodward, J., Russell, A. J., Fleisher, P. J. & Bailey, P. K. (2010) The sedimentary architecture of outburst flood eskers: A comparison of ground-penetrating radar data from Bering Glacier, Alaska and Skeiðarárjökull, Iceland. *Bulletin of the Geological Society of America*, 122, 1637-1645.

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

Clark, C. D., Evans, D. J. A., Khatwa, A., Bradwell, T., Jordan, C., Marsh, S., Mitchell, W. & Bateman, M. (2004) Map and GIS database of glacial landforms and features related to the last British Ice Sheet. *Boreas*, 33, 359-375.

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.

Evans, D. J. A. & Rea, B. R. (2003) Surging Glacier Landsystem. In D. J. A. Evans, *Glacial Landsystems*. London, Hodder Arnold, 259-288.

Evans, D. J. A. & Twigg, D. R. (2000) Breiðamerkurjökull 1998. 1: 30,000 Scale Map. University of Glasgow and Loughborough University.

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.

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

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.

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

Hooke, R. LeB. (1984) On the role of mechanical energy in maintaining subglacial water conduits at atmospheric pressure. *Journal of Glaciology*, 30, 180-187.

Howarth, P. J. (1968) Geomorphological and glaciological studies, eastern Breiðamerkurjö kull, Iceland. *Department of Geography*, University of Glasgow. PhD.

Howarth, P. J. (1971) Investigations of two eskers at eastern Breiðamerkurjö kull, Iceland. *Arctic and Alpine Research*, 3, 305-318.

Howarth, P. J. & Price, R. J. (1969) The proglacial lakes of Breiðamerkurjö kull and Fjallsjökull, Iceland. *The Geographical Journal*, 135, 573-581.

Howarth, P. J. & Welch, R. (1969a) Breiðamerkurjőkull, South-east Iceland, August 1945. 1:30,000 scale map. University of Glasgow. 1:30,000

Howarth, P. J. & Welch, R. (1969b) Breiðamerkurjőkull, South-east Iceland, August 1965. 1:30,000 scale map. University of Glasgow.

Howarth, P.J. (1971) Investigations of two eskers at eastern Breiðamerkurjőkull, Iceland. *Arctic and Alpine Research*, 3, 305-318.

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

Jewtuchowicz, S. (1965) Description of eskers and kames in Gåshamnö yra and on Bengebreen, south of Hornsund, Vestspitsbergen. *Journal of Glaciology*, 5, 719-725.

Kamb, B. (1987) Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. Journal of Geophysical Research, 92, 9083-9100.

Kirkbride, M. P. (2000) Ice-marginal geomorphology and Holocene expansion of debris-covered Tasman Glacier, New Zealand. In M. Nakawo, C. Raymond and A. Fountain, *Devris-Covered Glaciers*, IAHS Publication. 264, 211-218.

Knudsen, Ó. (1995) Concertina eskers, Brúarjökull, Iceland: An indicator of surge-type glacier behaviour. *Quaternary Science Reviews*, 14, 487-493.

Lewis, W. V. (1949) An esker in process of formation: Boverbreen, Jotunheimen, 1947. *Journal of Glaciology*, 1, 314-319.

Maizels, J. (1992) Boulder Ring Structures Produced during Jökulhlaup Flows. Origin and Hydraulic Significance. *Geografiska Annaler. Series A, Physical Geography*, 74, 21-33.

Maizels, J. (1997) Jökulhlaup deposits in proglacial areas. *Quaternary Science Reviews*, 16, 793-819.

Mäkinen, J. (2003) Time-transgressive deposits of repeated depositional sequences within interlobate glaciofluvial (esker) sediments in Koylio, SW Finland. *Sedimentology*, 50, 327-360.

Margold, M., Jansson, K., Kleman, J. & Stroeven, A. (2011) Glacial meltwater landforms of central British Columbia. *Journal of Maps*, 2011, 486-506.

Margold, M., Jansson, K. N., Kleman, J. & Stroeven, A. P. (2013) Lateglacial ice dynamics of the Cordilleran Ice Sheet in northern British Columbia and southern Yukon Territory: retreat pattern of the Liard Lobe reconstructed from the glacial landform record. *Journal of Quaternary Science*, 28, 180-188.

McKinzey, K. M., Ólafsdóttir, R. & Dugmore, A. J. (2005) Perception, history, and science: coherence or disparity in the timing of the Little Ice Age maximum in southeast Iceland? *Polar Record*, 41, 319-334.

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.

Plouffe, A. (1991) Preliminary study of the Quaternary geology of the northern interior of British Columbia. *Current research, Geological Survey of Canada*, 91-1A, 7-13.

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. (1971) The Development and Destruction of a Sandur, Breiðamerkurjökull, Iceland. *Arctic and Alpine Research*, 225-237.

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

Price, R. J. (1980) Rates of geomorphological changes in proglacial areas. In R. A. Cullingford, D. A. Davidson and J. Lewin, *Timescales in geomorophology*. Chichester, Wiley, 79-93.

Price, R. J. (1982) Changes in the proglacial area of Breiðamerkurjökull , southeastern Iceland: 1890-1980. *Jökull*, 29-35.

Price, R. J. & Howarth, P. J. (1970) The evolution of the drainage system (1904-1965) in front of Breiðamerkurjökull *Jökull*, 20, 27-37.

Röthlisberger, H. (1972) Water pressure in intra-and subglacial channels. *Journal of Glaciology*, 11, 177-203.

Schomacker, A. (2010) Expansion of ice-marginal lakes at the Vatnajökull ice cap, Iceland, from 1999-2009. *Geomorphology*, 119, 232-236.

Schomacker, A. & Kjær, K. H. (2008) Quantification of dead ice melting in ice cored moraines at the high Arctic glacier Holmströmbreen, Svalbard. *Boreas*, 37, 211-225.

Shilts, W. W. (1984) Esker sedimentation models, Deep Rose Lake map area, District of Keewatin. *Geological Survey of Canada, Paper*, 84-1B, 217-222.

Shilts, W. W., Aylsworth, J. M., Kaszycki, C. A. & Klassen, R. A. (1987) Canadian Shield. In W. L. Graf, *Geomorphic Systems of North America*. Boulder, Colorado, Geological Society of America, Centennial Special Volume. 2, 119-161.

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.

Spedding, N. & Evans, D. J. A. (2002) Sediments and landforms at Kvíárjökull, southeast Iceland: a reappraisal of the glaciated valley landsystem. *Sedimentary Geology*, 149, 21-42.

Stokes, J. C. (1958) An esker-like ridge in process of formation, Flatisen, Norway. *Journal of Glaciology*, 3, 286-289.

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. (2014) 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. (2014) 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.

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.

Thome, K. N. (1986) Melt-water drainage pattern of composite glaciers. *Journal of Glaciology*, 32, 95-100.

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

Figures

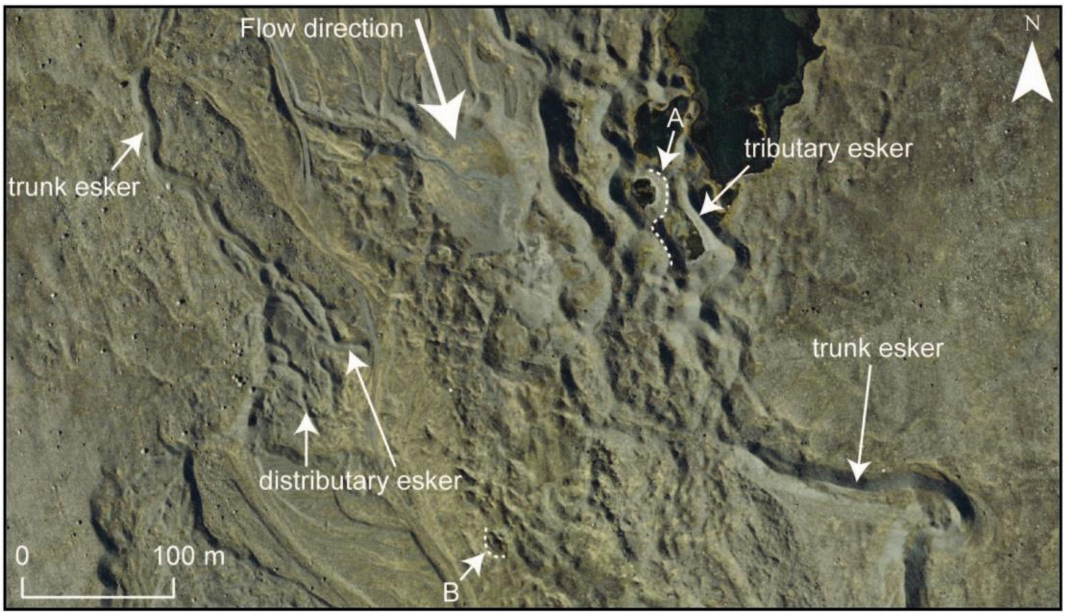
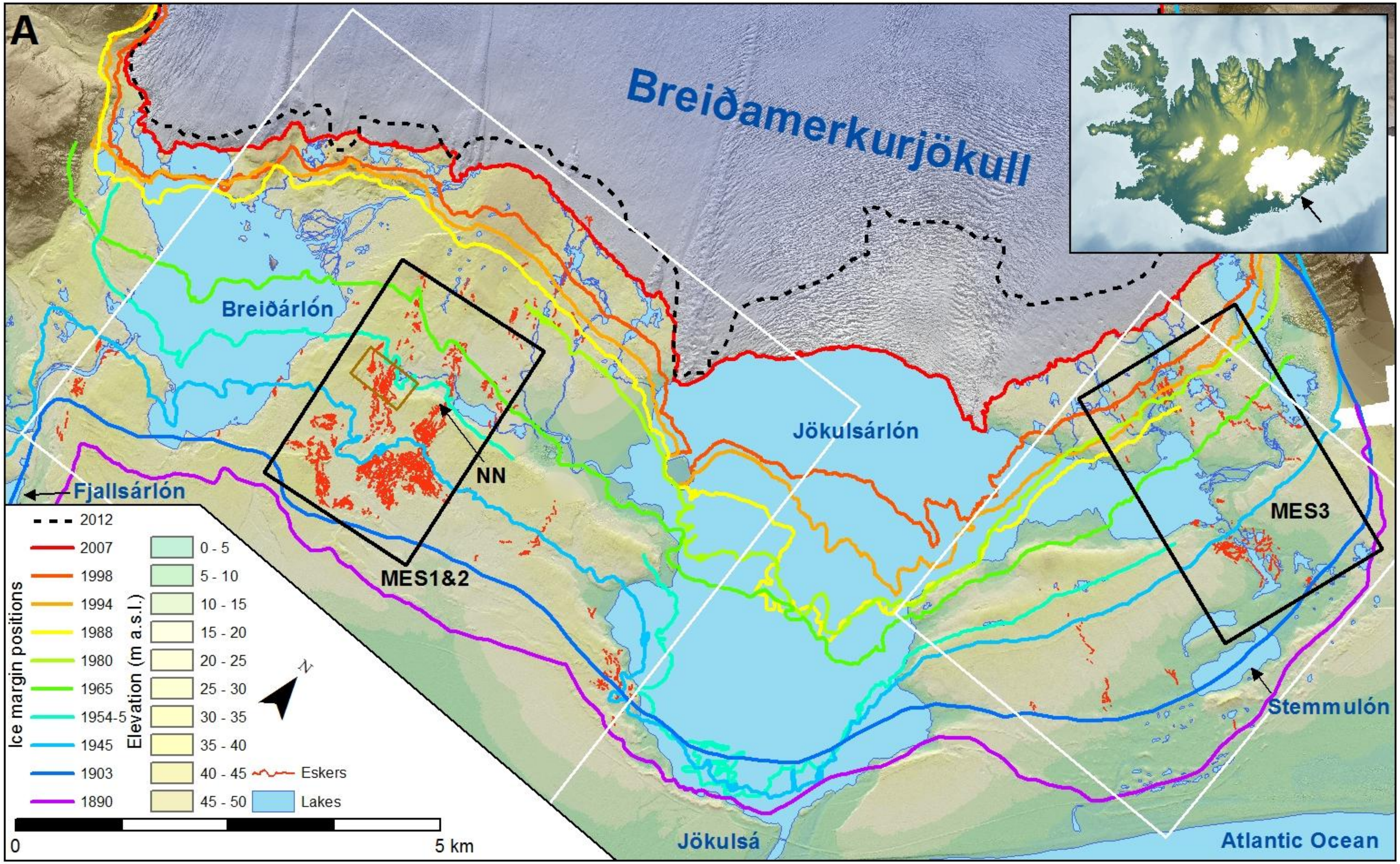


Figure 1. 2007 aerial photograph excerpt showing the terminology used to refer to different esker types. ‘Trunk’ eskers are main single ridges. ‘Tributary’ eskers are smaller ridges which join trunk eskers at their distal ends. Distributary eskers branch from trunk eskers at their proximal end. The location of this figure is shown in Figure 2. The dashed line labelled A shows a ridge that continues past a depression and is mapped as an esker. The dashed line labelled B shows a ridge that flanks a depression but does not continue past it, and so is not mapped as an esker. Copyright NERC ARSF aerial photograph 2007.



A
Breiðamerkurjökull
Breiðárlón
Jökulsárlón
NN
MES1&2
MES3
Fjallsárlón
Stemmulón
Jökulsá
Atlantic Ocean
Ice margin positions
2012
2007
1998
1994
1988
1980
1965
1954-5
1945
1903
1890
Elevation (m a.s.l.)
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
Eskers
Lakes
N
0
5 km

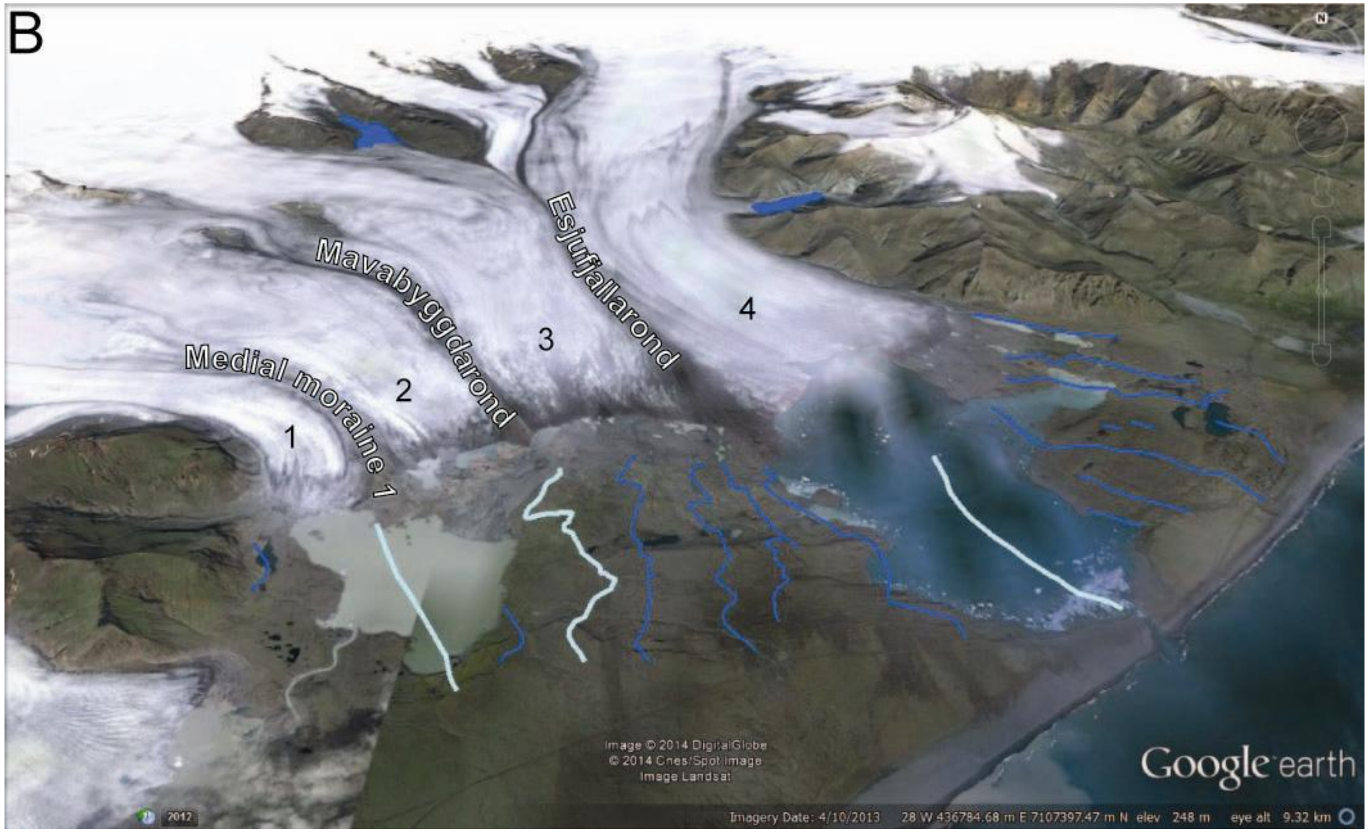


Figure 2. A) Location map showing eskers digitized from 2007/9 aerial photographs and locations mentioned in the text. Historic ice margin positions are from previous maps (Price 1980; 1982), aerial photograph mapping and Google Earth imagery (2012). Note that some margins have gaps relating to the absence of aerial photograph coverage. Breiðamerkurjökull was confluent with Fjallsjökull (to the southwest) until some point between 1945 and 1954. NN refers to Nygrædnakvis. The location of Figure 1 is shown by the brown box. Black boxes indicate the areas displayed in Figure 3. White boxes indicate the areas displayed in Figure 11. B) Oblique Google Earth view of Breiðamerkurjökull from 2012, showing the positions of medial moraines (named), flow units (numbered) and ice dammed lakes (shaded blue). The blue lines indicate the melt season meltwater drainage axes proposed by Boulton *et al.* (2007a). Dark blue indicates discharge of less than 10 $m^3 s^{-1}$ and light blue indicates discharges of 20 to 50 $m^3 s^{-1}$.

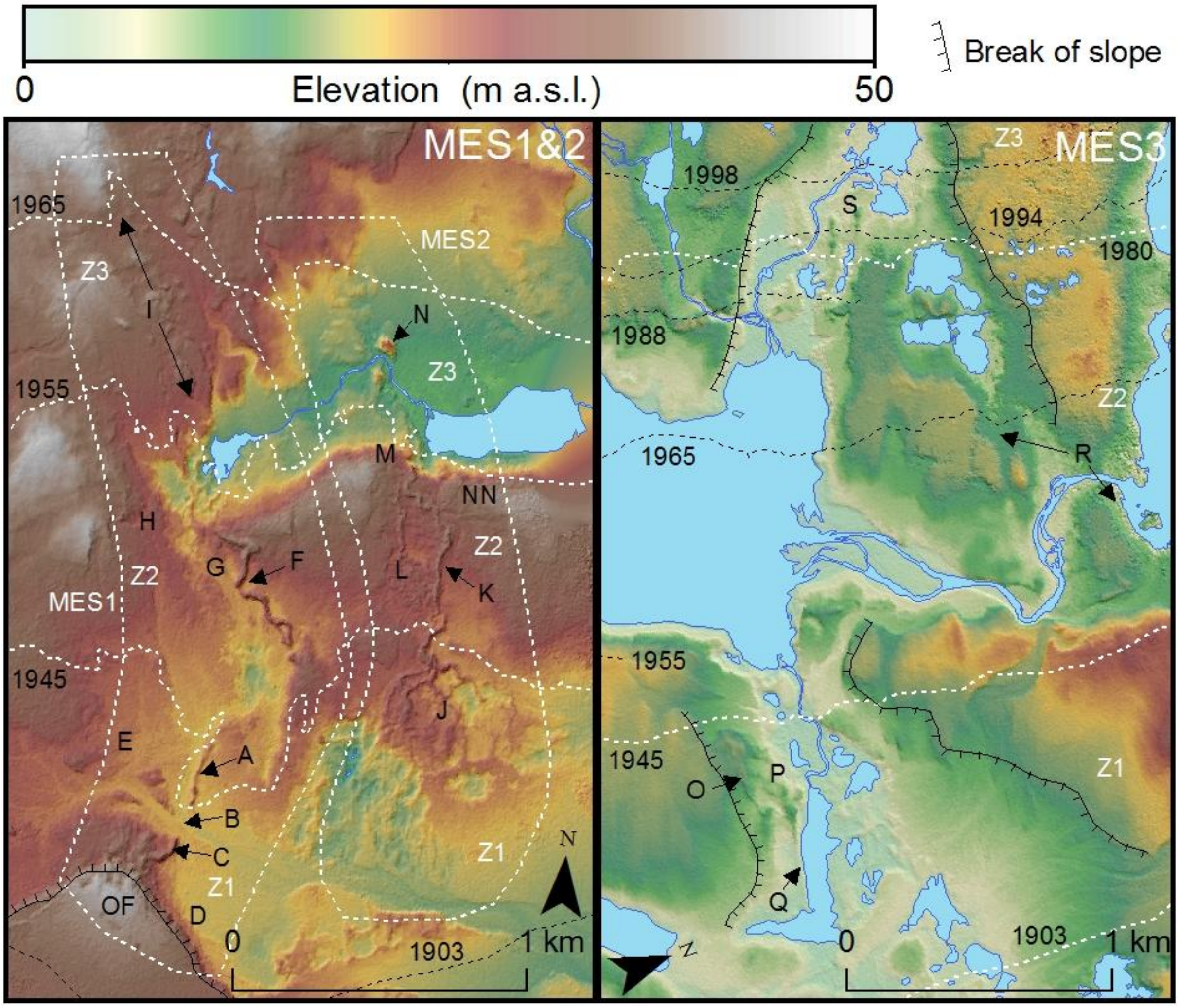


Figure 3. Detailed topography (in 2007) and ice margin positions (dashed lines) in MES1, 2 and 3 (see Figure 2 for locations). Locations referred to in the text are given by letters. NN = Nygrædnakvis. OF = Outwash fan. Zones mentioned in the text are labelled Z1-3and are enclosed by the white dashed lines.

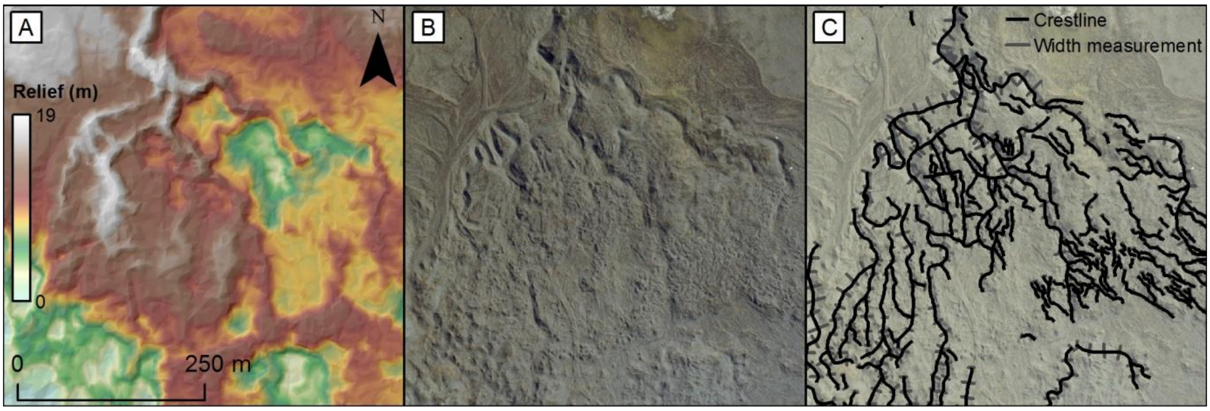


Figure 4. The distributary esker complex of MES2, shown as a DEM (left: relief relative to the lowest point in the panel), aerial photograph extract from 2007 (centre) and digitized crestlines and widths (right). Copyright NERC ARSF aerial photograph 2007.

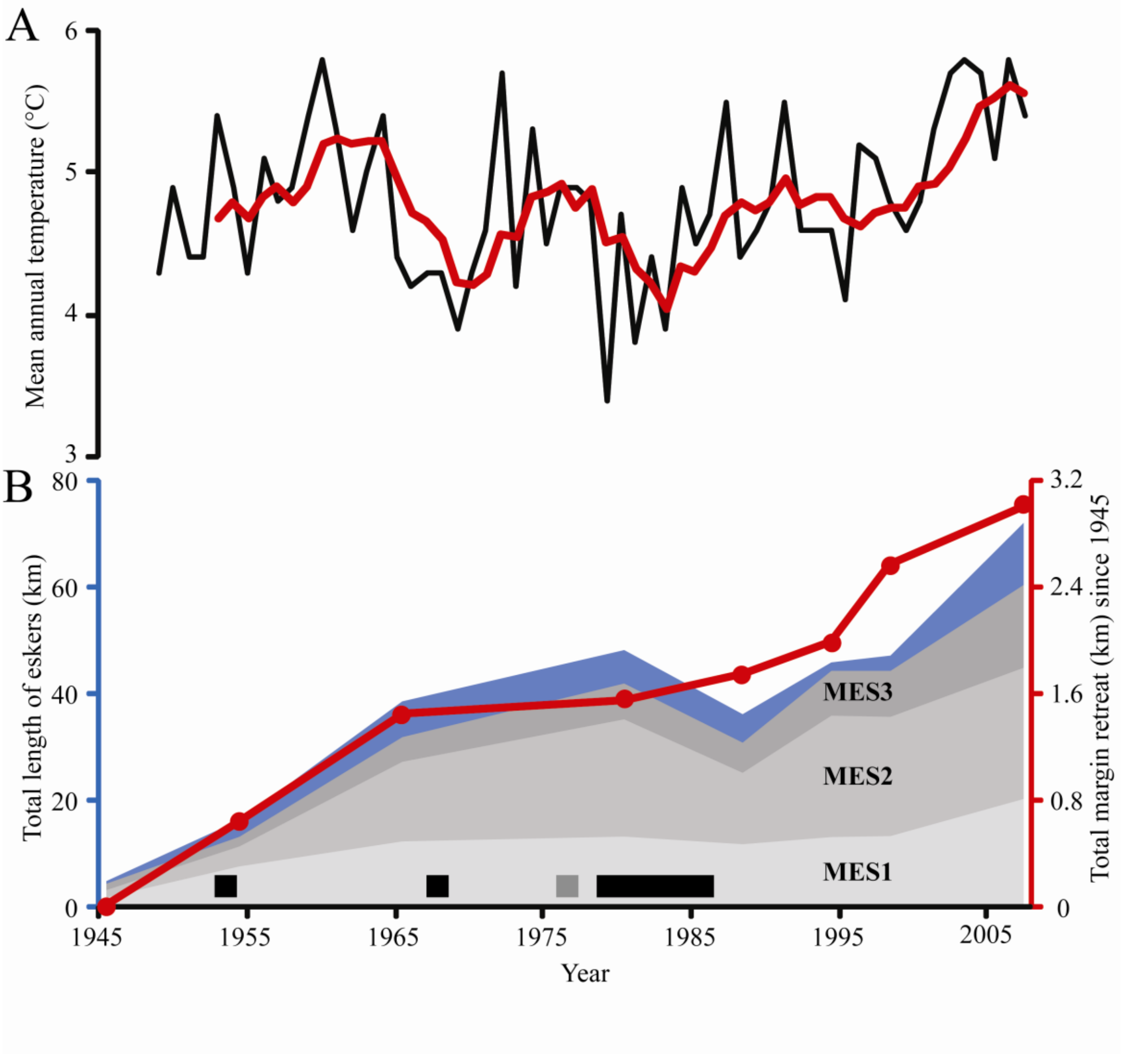


Figure 5. A) Mean annual temperature at Fagurhólsmýri, with five year moving average in red. B) Total retreat of the margin (red line) from 1945-2007 and changes in the total length of eskers (blue) and in each MES (shades of grey) from 1945 to 2007. Note that eskers appear to have declined between 1980 and 1998, which is likely related to a combination of inundation by lakes and, significantly, non-detection in lower quality photographs (see Supplementary material S1). The mean rate of esker emergence is 1.08 km yr^{-1}. Periods of surging (Björnsson *et al.*, 2003) and readvances (this paper) are indicated by squares (black = flow unit 4; grey = flow unit 3).

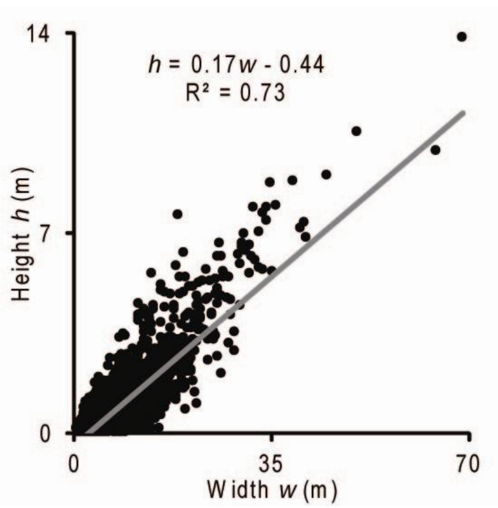


Figure 6. Measurements of esker height plotted against width for the eskers mapped from 2007/9 photographs (number of measurements = 4,190). A linear regression is shown in grey.

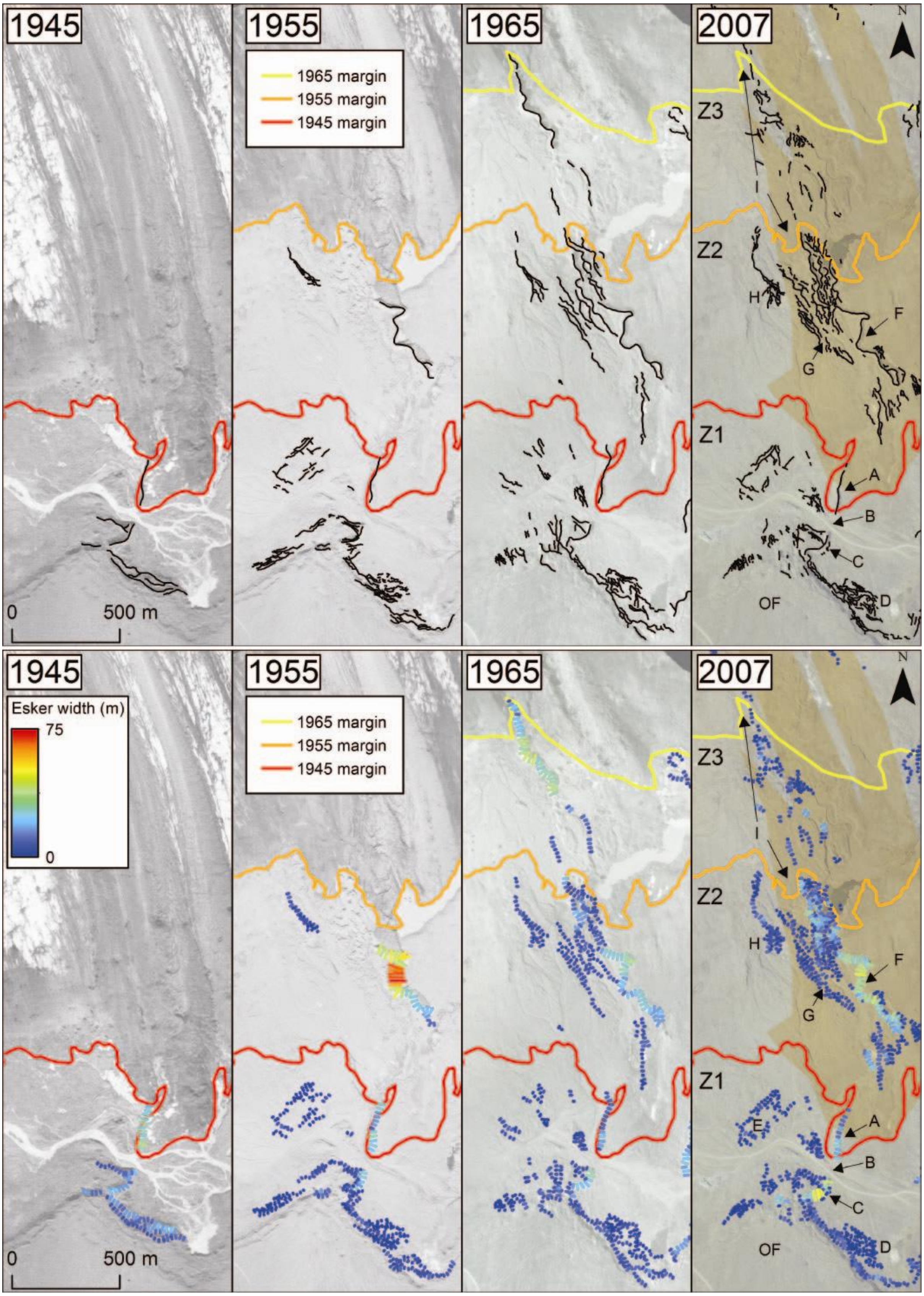


Figure 7. Esker crestlines (upper) and width measurements (lower) in MES1 from 1945, 1955, 1965 and 2007. The position of the medial moraine Mavabyggdarond in 1945 is shown in the 2007 panel by the brown shading. The colour scale for width measurements is the same across Figures 7-9 to enable direct comparison.

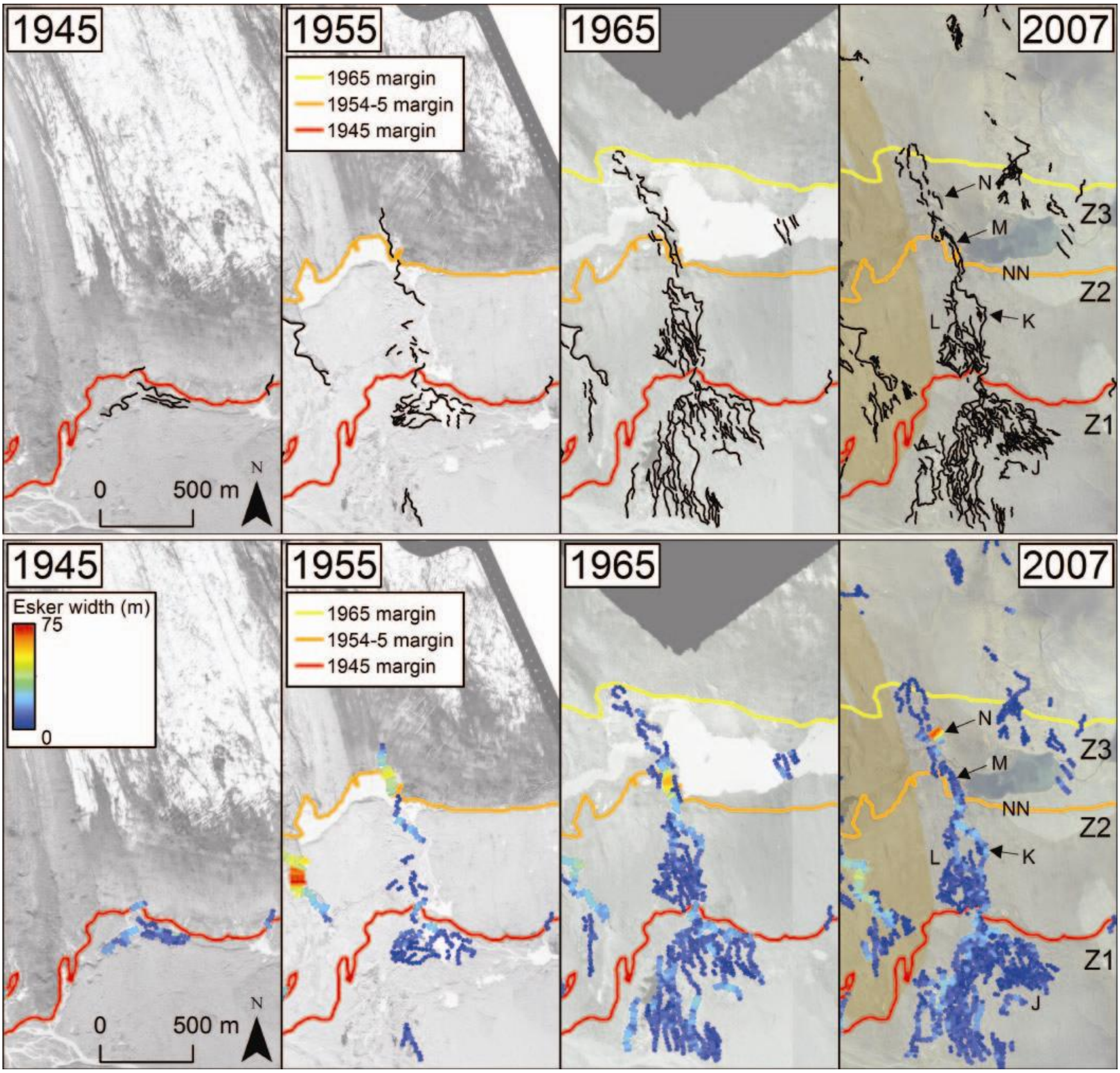


Figure 8. Esker crestlines (upper) and width measurements (lower) in MES2 from 1945, 1955, 1965 and 2007. The position of the medial moraine Mavabyggdarond in 1945 is shown in the 2007 panel by the brown shading. Note the gradual evolution of the eskers from a flat fan with a few eskers in 1945 to esker ridges in 2007.

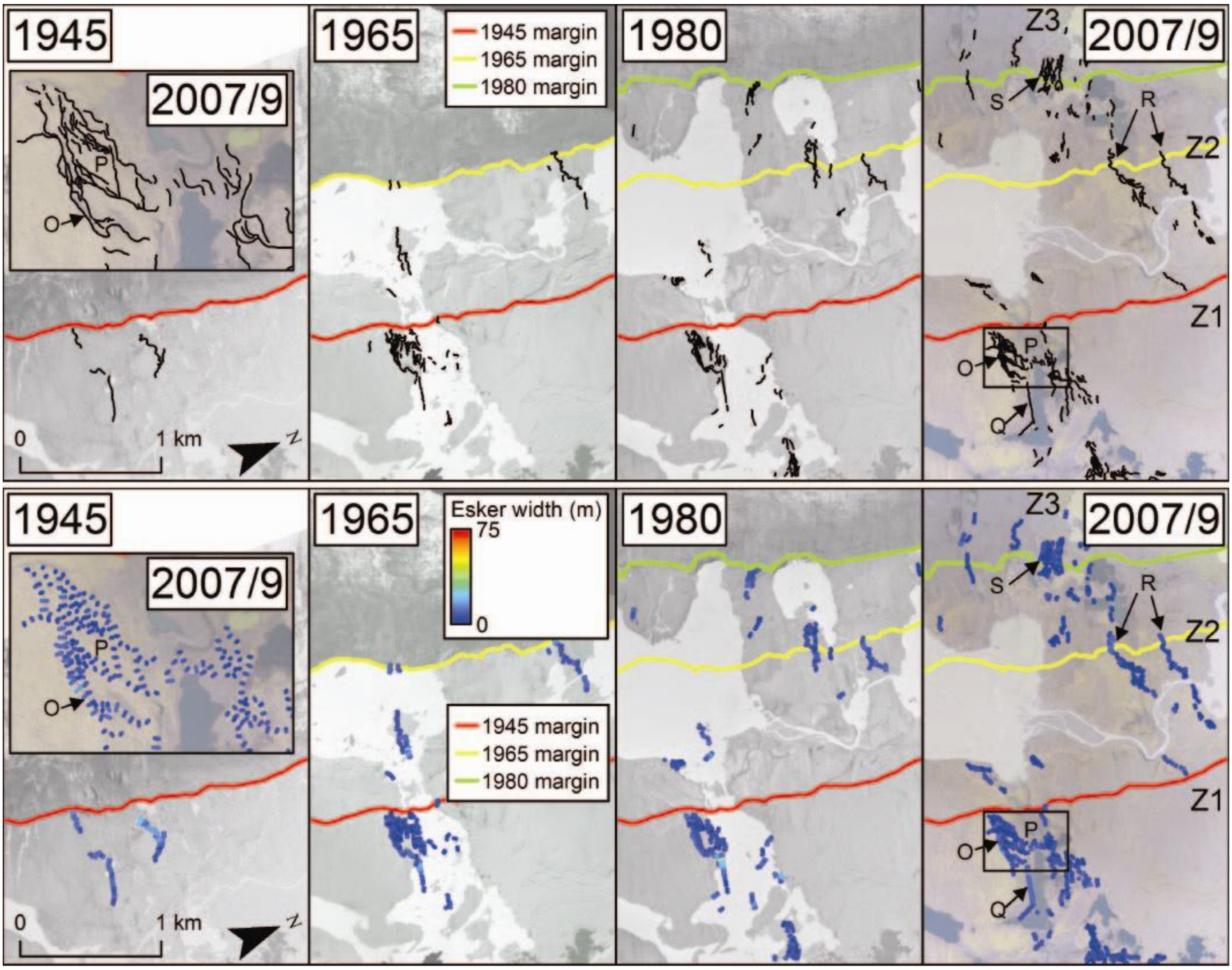


Figure 9. Esker crestlines (upper) and width measurements (lower) in MES3 from 1945, 1965, 1980 and 2007/9. The inset box from 2007/9 in the left panel shows the detailed ridge planform morphology in the area indicated by the black box in the right panel.

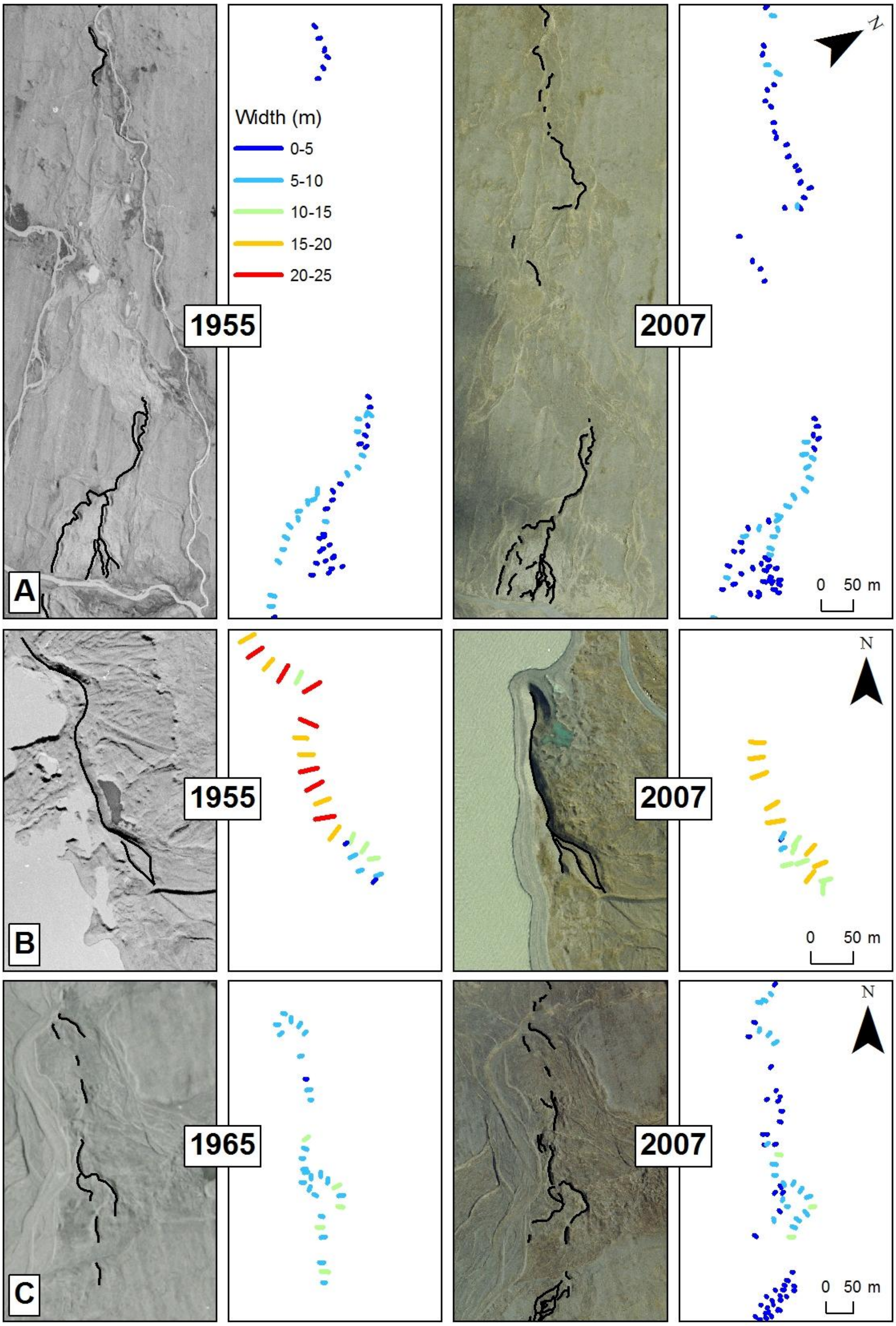


Figure 10. Planform (left) and width (right) measurements of 'simple' eskers not associated with medial moraines. In each location the first appearance of the eskers in the aerial photograph record is shown on the left, and the most recent (2007/9) on the right. Locations of A, B and C are shown in Figure 11.

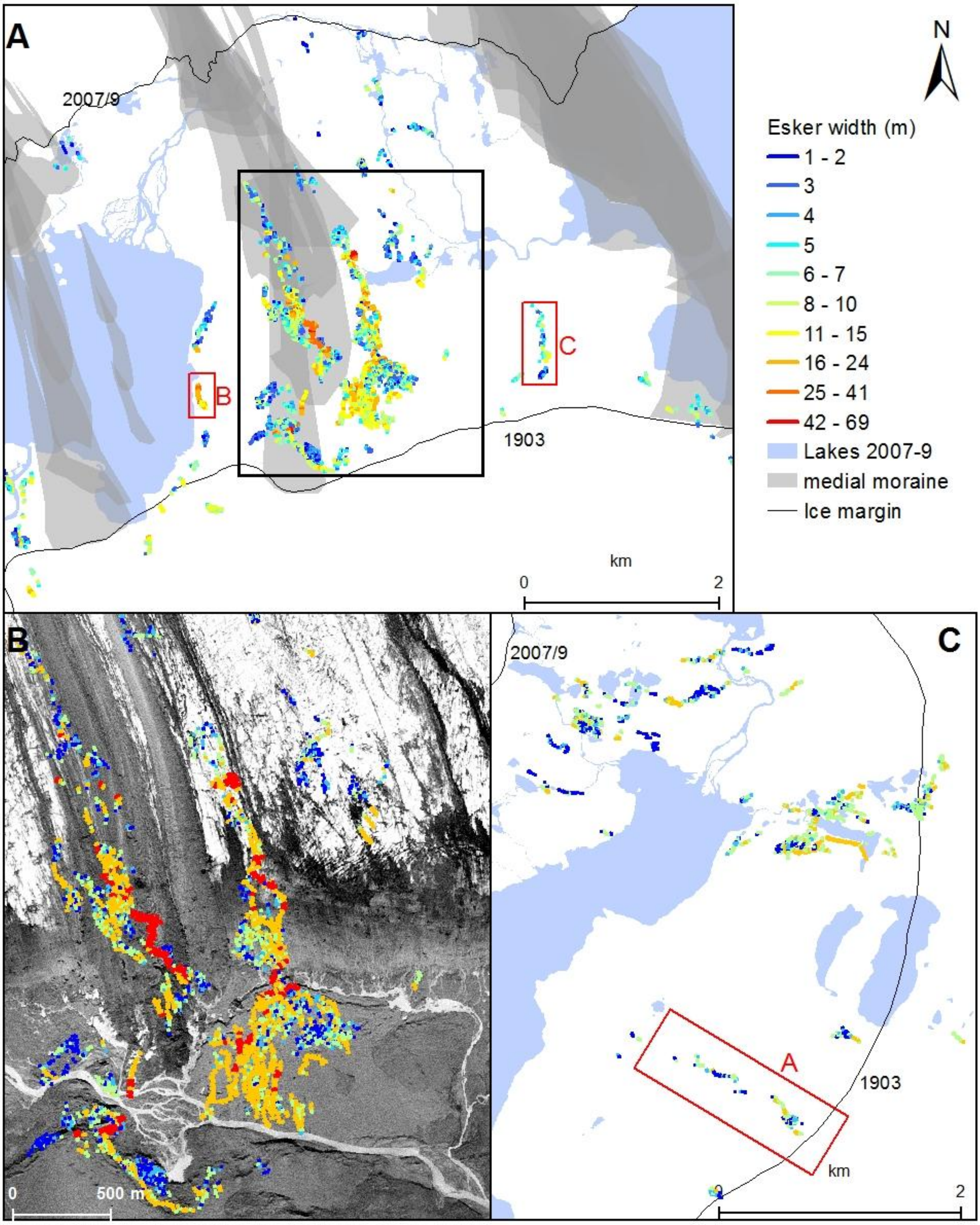


Figure 11. A) Esker width measurements from 2007/9 shown with the footprints of the medial moraines in 1903 (after Price, 1982); 1945; 1954/5; 1965; 1980; 1994; 1998; 2007/9. Darker shades of grey indicate areas located beneath several medial moraine positions. The black box indicates the location of B. The location of A is shown in Figure 2A. Note that the widest eskers are typically associated with medial moraines, whereas the eskers between medial moraines are typically narrower. B) Esker width measurements from 2007/9 superimposed on the 1945 imagery of MES1 and 2. Note the position of the medial moraine with relation to the larger esker ridges. C) Esker width measurements from 2007/9 in MES

3. The location of C is shown in Figure 2. Note the significant different in the widths of the largest eskers between MES1/2 and MES3. Red boxes (A, B and C) indicate the locations of examples in Figure 10.

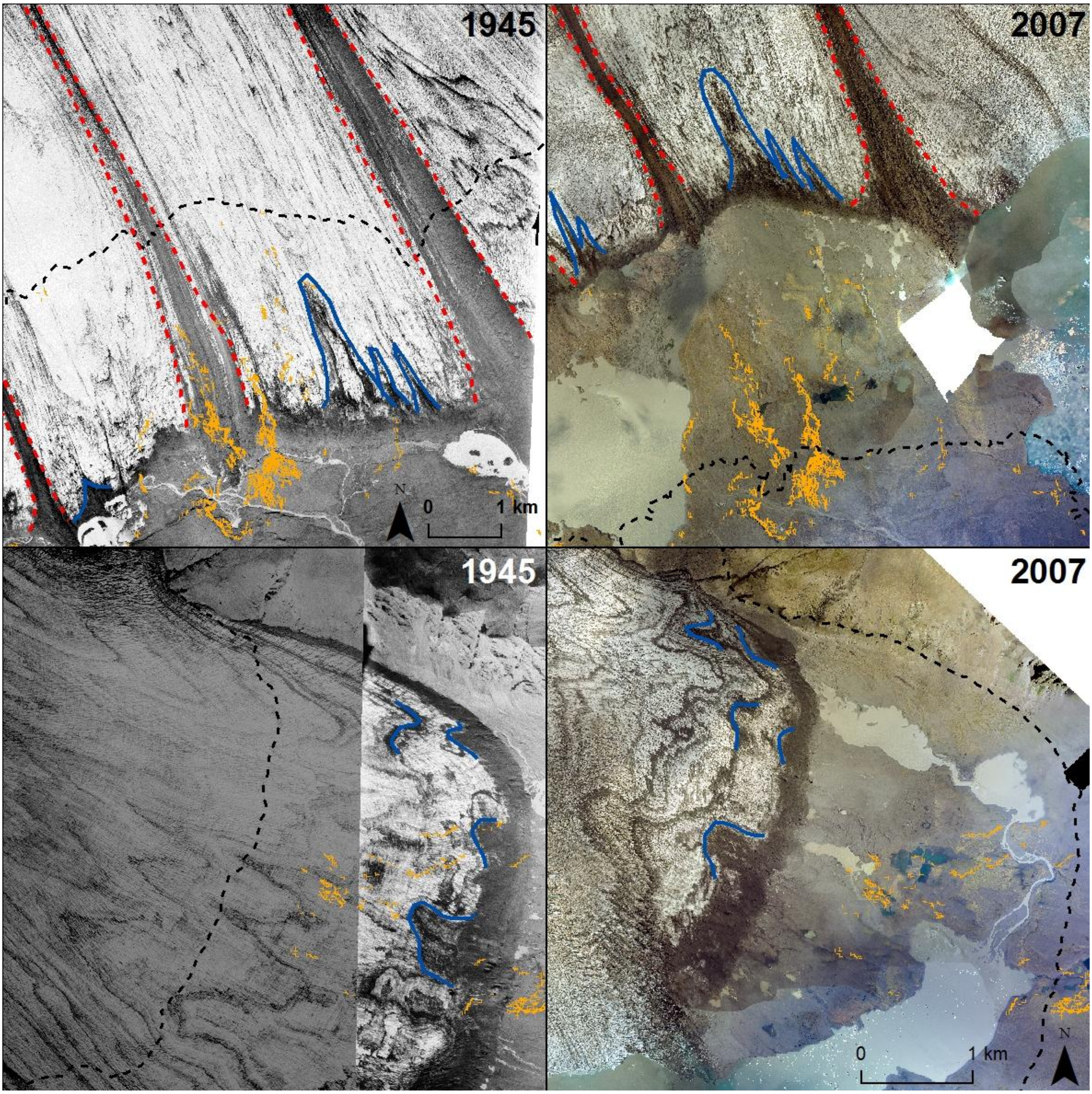


Figure 12. Aerial photographs from 1945 and 2007 showing the positions of medial moraines (red) and supraglacial debris bands (blue) which occur in the same relative position of the glacier in each set of imagery. Eskers mapped from the 2007/9 imagery are shown in orange for MES1 and 2 (upper) and MES3 (lower). Black dashed lines indicate the ice margin positions from 1945 and 2007.

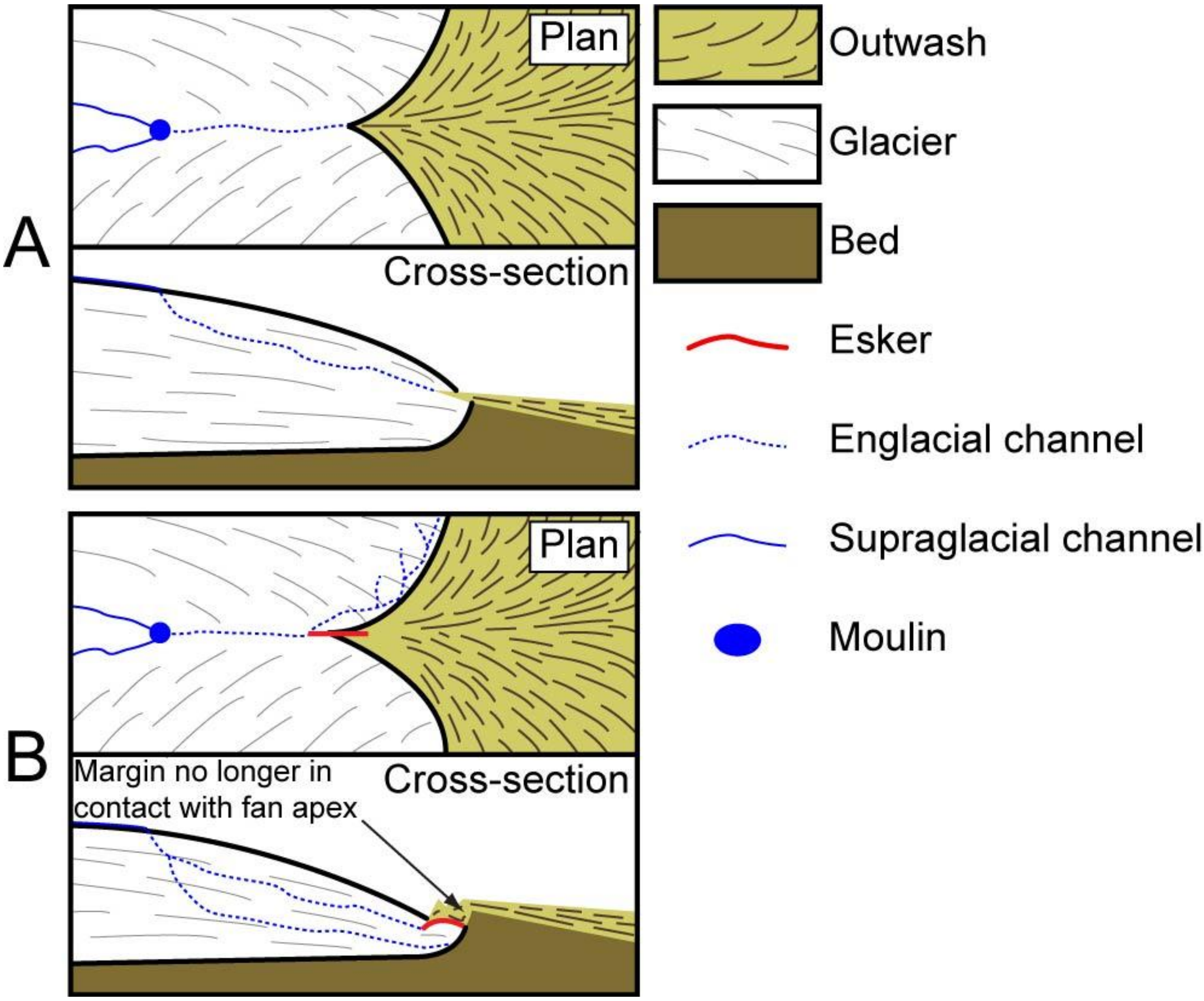


Figure 13. Depositional model for MES1. A) Englacial stream feeds the development of an ice contact fan. B) As the glacier surface lowers during retreat, drainage is impeded by the fan and meltwater is diverted along the apex of the fan. Eskers form where the channels clog with sediment. Not to scale.

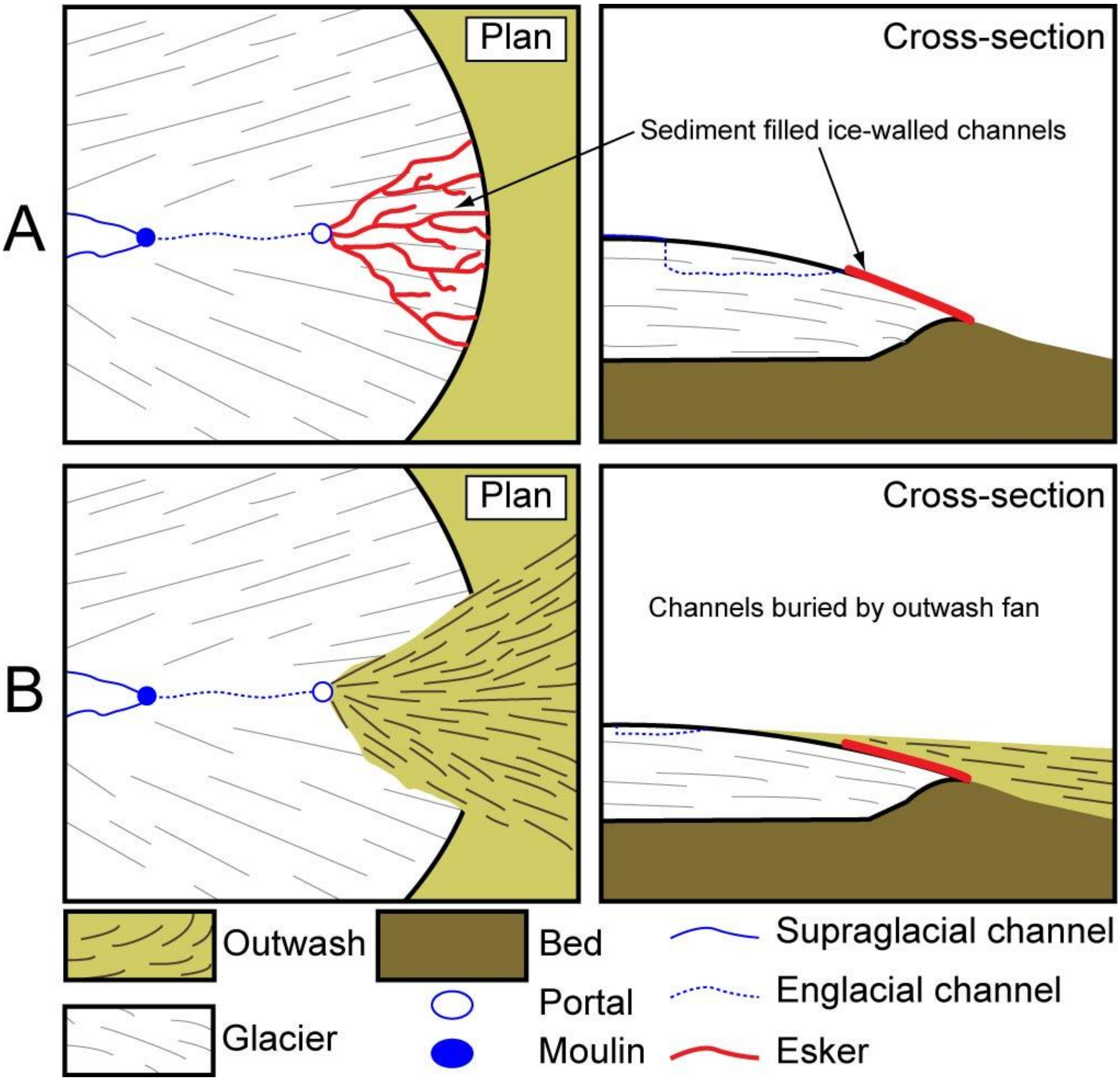


Figure 14. Depositional model for MES2. A) An englacial stream emerges on the glacier surface and water drains in supraglacial ice walled channels, which form a fan shape because they are at atmospheric pressure and unimpeded by topography. The channels then become choked with sediment. B) An outwash fan subsequently aggrades over the ice-walled channels, burying the channels and ice. The network of eskers preserved in the channel system is gradually lowered onto the bed and emerges as the ice melts out. Not to scale.

Table

Table 1. Morphometric data for esker mapped from 2007/9 imagery.

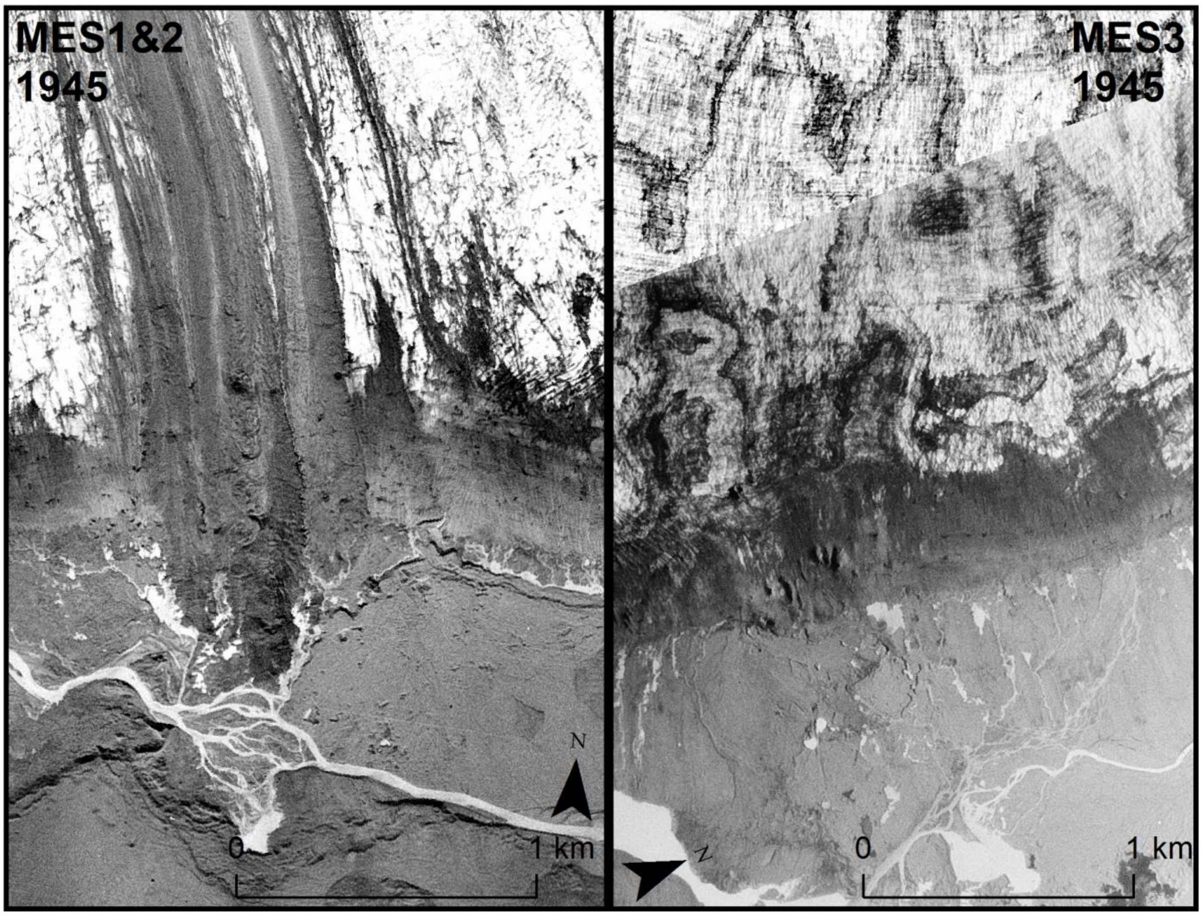
	MES1	**MES2**	**MES3**	**Isolated**
Length:				
Maximum	684 m	621 m	483 m	276 m
Mean	48 m	67 m	55 m	46 m
Median	32 m	40 m	40 m	31 m
Standard deviation	61 m	77 m	56 m	44 m
Width:				
Maximum	45.0 m	68.9 m	16.3 m	30.5 m
Mean	7.0 m	8.3 m	5.0 m	5.9 m
Median	4.7 m	6.6 m	4.5 m	4.4 m
Standard deviation	6.4 m	5.8 m	2.5 m	4.8 m
Planform morphology (generalised)	Complex	Complex	Simple-complex	Simple
Inferred sediment supply:				
Quantity	High	High	High	Low
Rate	Continuous	Continuous	Sporadic	Continuous
Inferred meltwater supply:				
Quantity	High	High	High	Low
Rate	Continuous	Continuous	Sporadic	Continuous

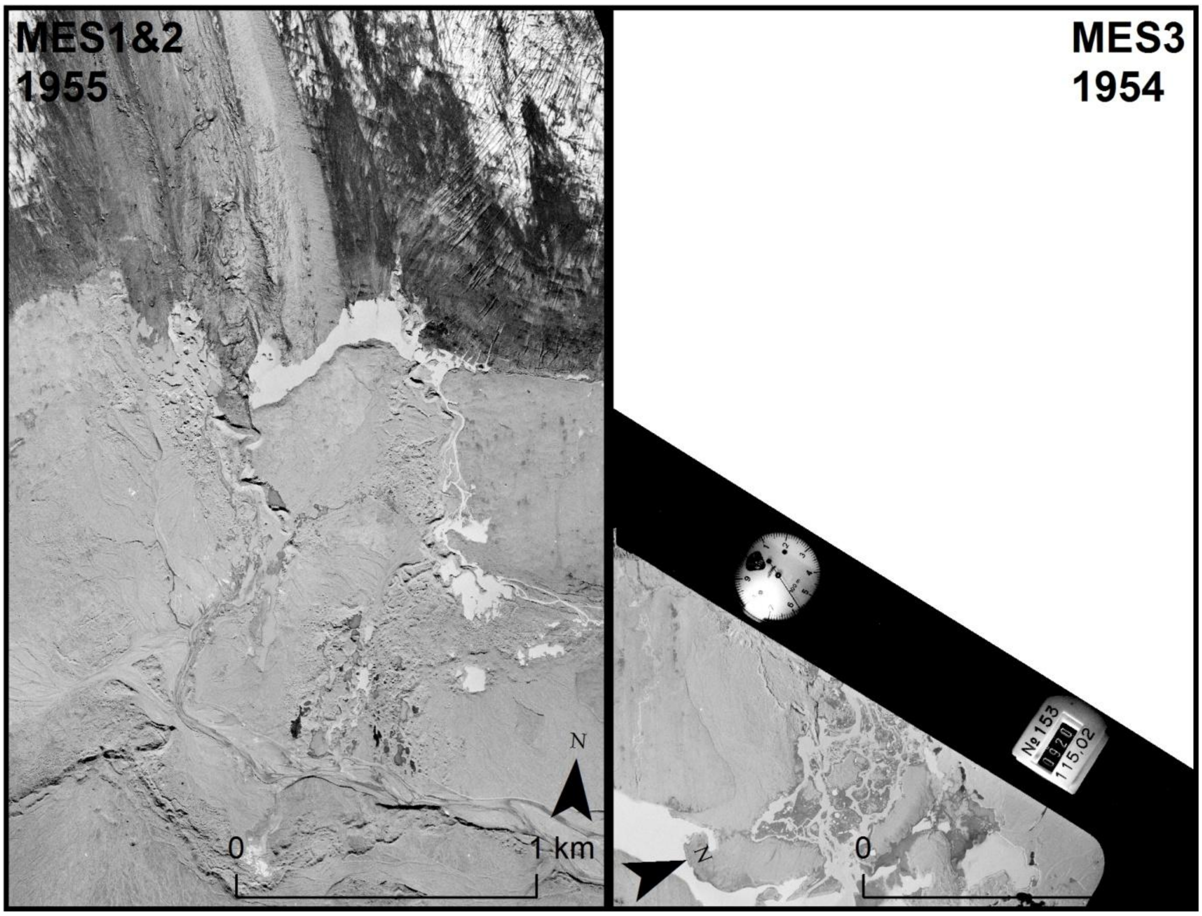
Supplementary material.

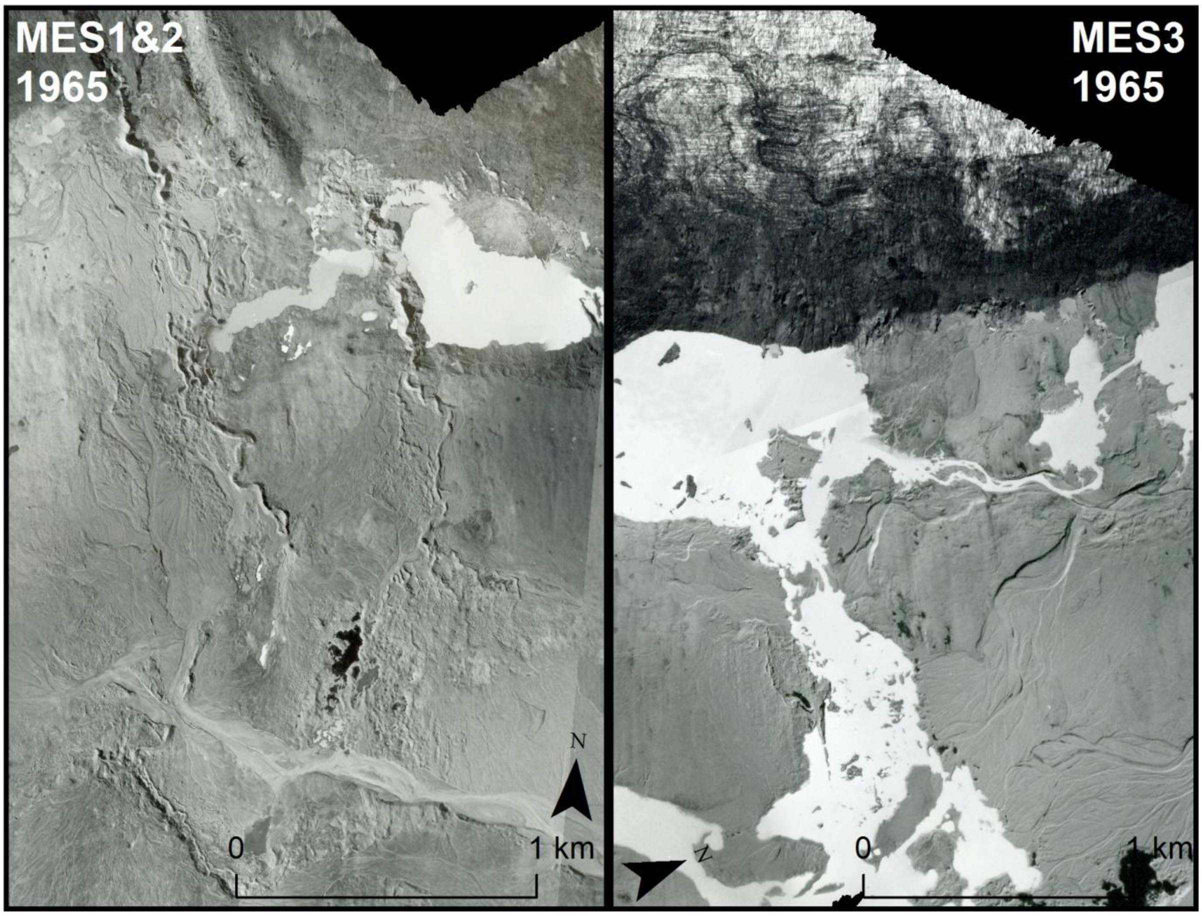
S1. Aerial photograph properties.

Date	**Coverage**	**Number of photographs**	**Approx. azimuth (°)**	**Approx. resolution (cm)**	**Sharpness**
1945	Complete	15	190	380	v. grainy
15/9/1954 14/9/1955	Partial Partial	6 3	190 210	39 39	excellent excellent
24/8/1965	Complete	42	315	65	excellent
18/9/1980	Partial	6	250	52	v. good
28/8/1988	Complete	14	270	56	grainy
9/8/1994	Complete	15	130	55	v. grainy
22/8/1998	Complete	36	100	125	v. good
3-4/7/2007 9/6/2009	Complete	113 157	270 180	30 & 45 30	excellent

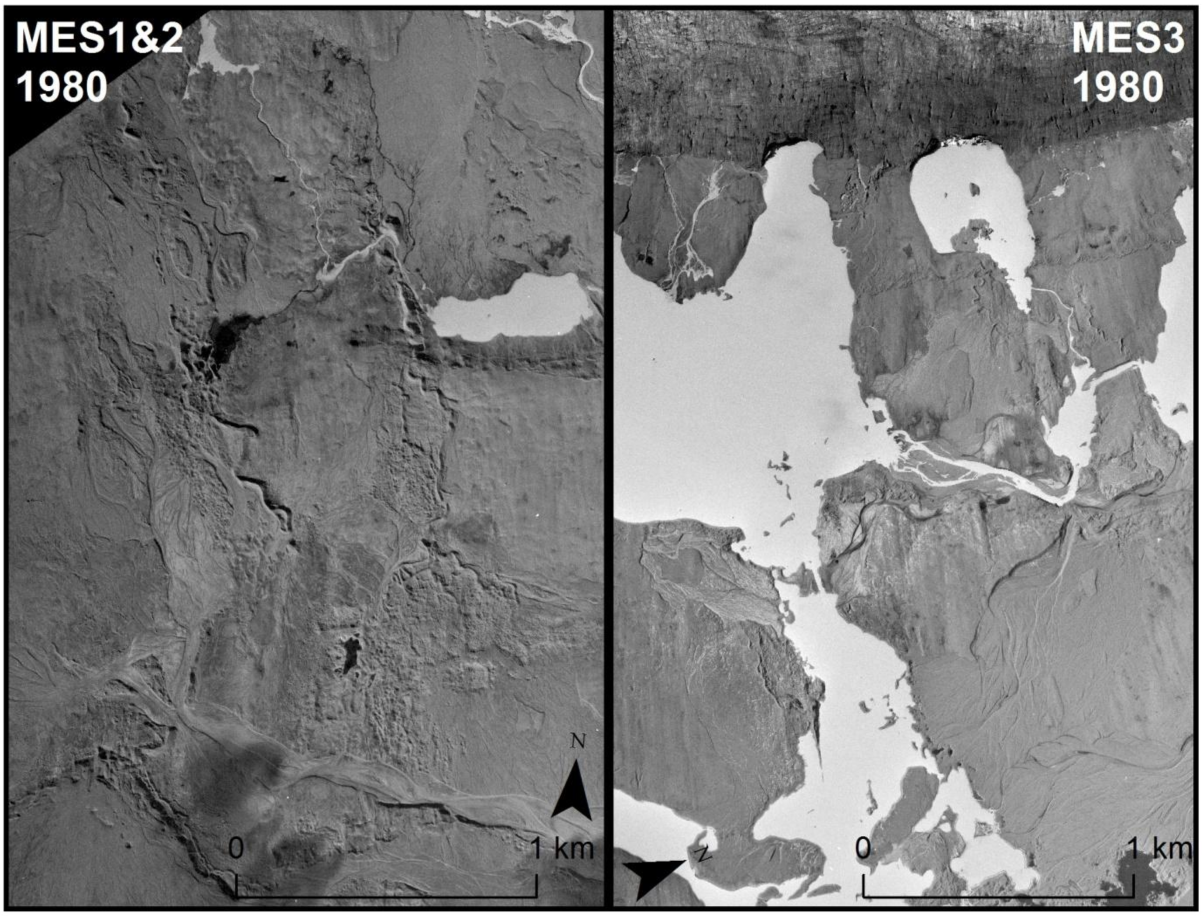
S2. Aerial photographs for MES1-3 from 1945, 1954/5, 1965, 1980, 1988, 1994, 1998, 2007/9.



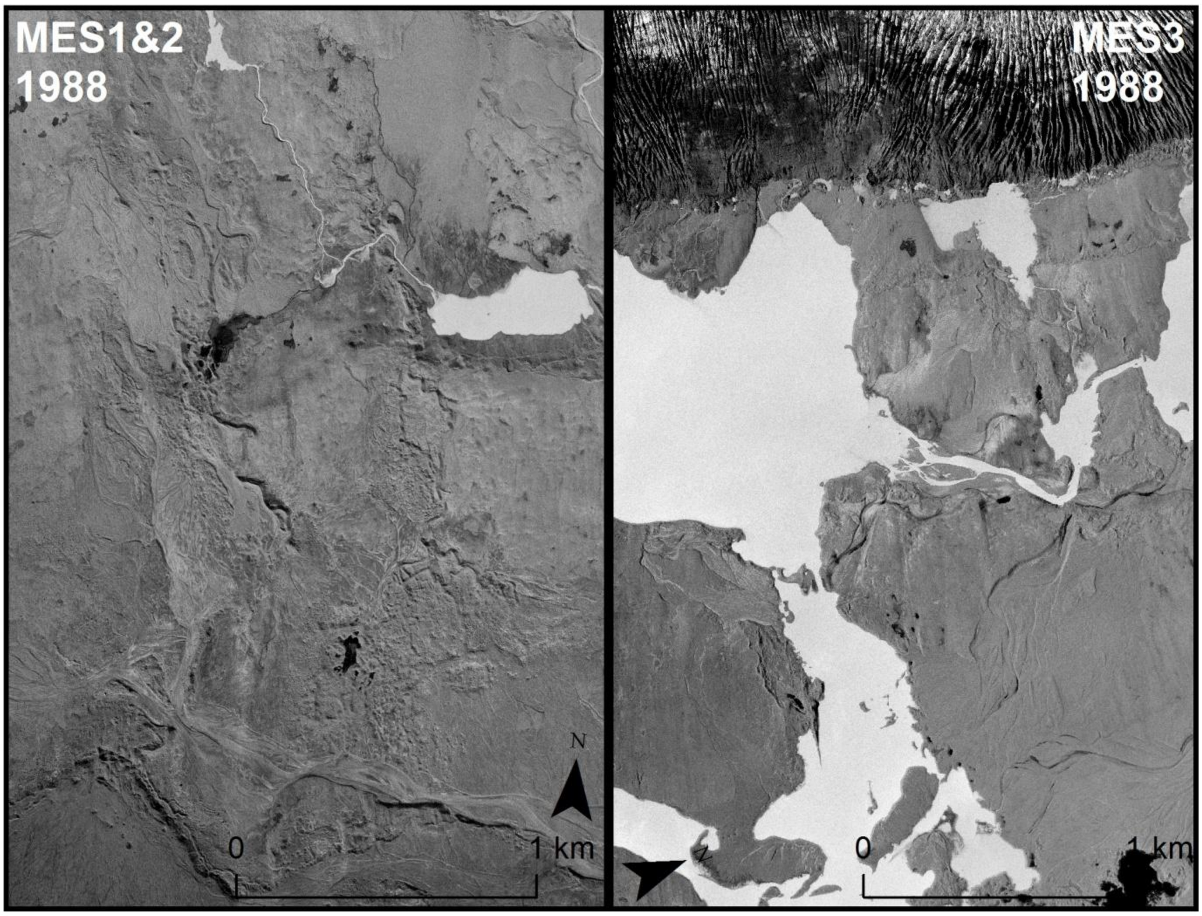

MES1&2
1955
N
0
1 km
MES3
1954
N
0



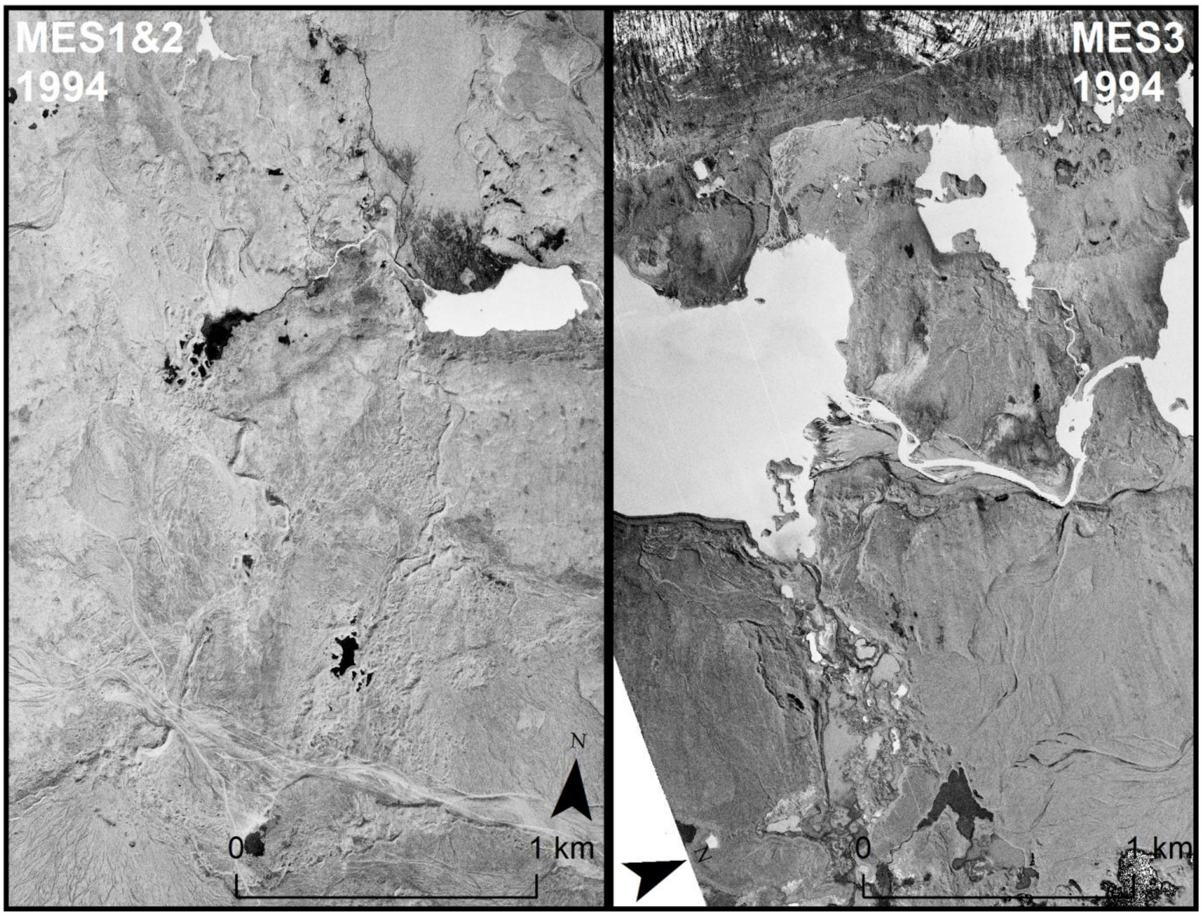
14

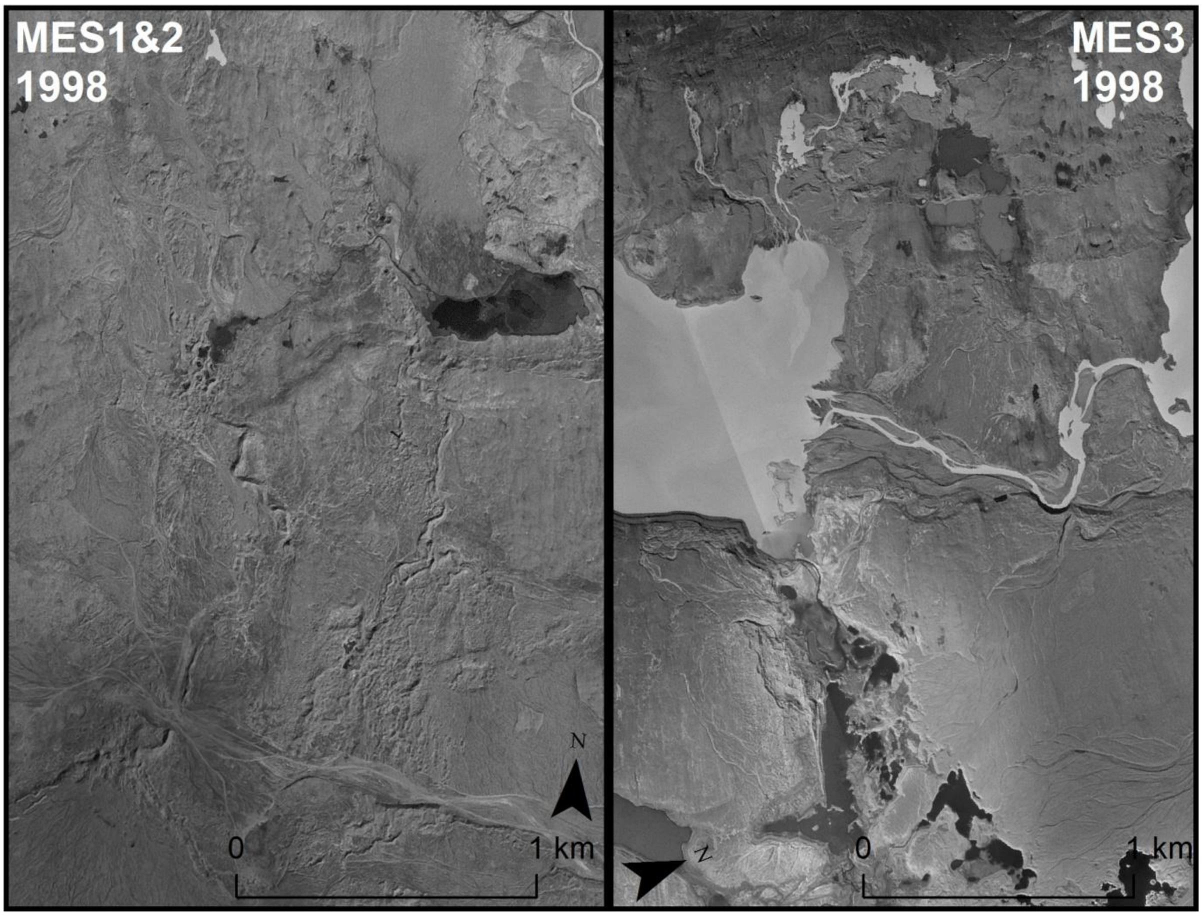

MES1&2
1980
N
0
1 km
MES3
1980
N
0
1 km

16

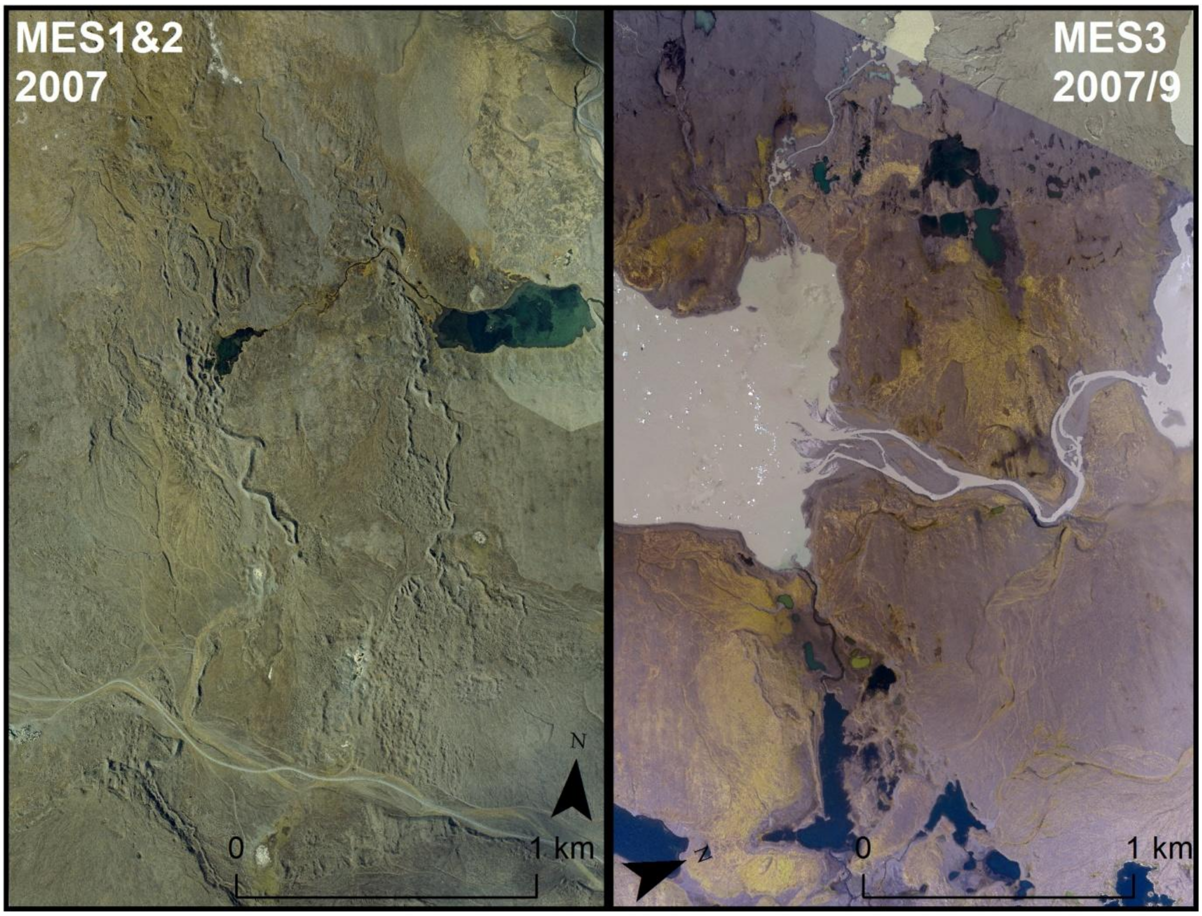


17





18


MES1&2
2007
N
0
1 km
MES3
2007/9
0
1 km