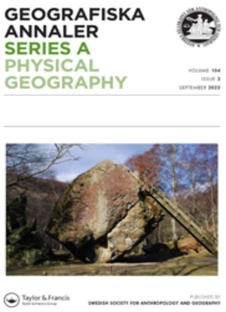

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Geomorphological map of Breiðamerkursandur 2018: the historical evolution of an active temperate glacier foreland

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ABSTRACT
We present a geomorphological map of Breiðamerkursandur, the outwash plain and foreland of Breiðamerkurjökull, an outlet glacier of the Vatnajökull ice cap, Southeast Iceland. We trace the glacial retreat of the glacier snout since its historical late nineteenth century Little Ice Age (LIA) maximum extentand the concomitant development of the glacial drainage pathways. Since the outlet began retreating from its LIA terminal position, a 120 km^2 area of foreland has been exposed. The mapped geomorphology is a supplementary continuation of previous surveys in the 20th century, which highlighted the geomorphology and ice margin for the years 1945, 1965 and 1998. Since the 1998 landsystem map, Breiðamerkurjökull has retreated a further 0.6–4.0 km and 29 km^2 has been exposed. This new map was prepared with the use of remote sensing, LiDAR DEM, a range of oblique aerial photographs and satellite images, written documents, in-field survey measurements and refined landform classifications to more accurately trace the position of the retreating snout and its outlet streams over the last 130 years.

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Breiðamerkurjökull; glacial landsystem; sandur development; historical evolution

Introduction – rationale, study area details and research history

The repeat survey, quantification and analysis of modern glacial process-form regimes are crucial to understanding spatial and temporal evolution in glacial geomorphology. Such endeavours also deliver invaluable analogues and genetic models that inform palaeoglaciological reconstructions and the deciphering of palaeoclimate indicators within the geomorphology of ancient deglaciated terrains (e.g. Evans, Archer et al. 1999; Kjær and Kruger 2001; Evans 2003, 2013; Bennett and Evans 2012). Icelandic glaciers and their deglaciating forelands have long been utilized in such research (e.g. Þorarinsson 1939; Price 1969; Eyles 1983a; Kruger 1994; Maizels 1997; Evans and Twigg 2002; Russell et al. 2006; Evans 2009; Schomacker et al. 2009), especially those of the south coast and Breiðamerkurjökull in particular. Here the post-Little Ice Age (LIA) recession of glaciers is well documented both in historical archives and aerial imagery and thereby can be linked to the geomorphological signature of glacier snout behaviour. Consequently, short timescale glacial process-form regimes can be reconciled with climate trends at relatively high resolution (e.g. Boulton 1986; Evans and Twigg 2002; Bradwell et al. 2013; Chandler et al. 2016a, 2016b, 2016c; Evans et al. 2017a, Evans, Ewertowski et al. 2019; Evans, Guðmundsson et al. 2019; Chandler, Chandler et al. 2020; Chandler, Evans et al. 2020).

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The foreland of Breiðamerkurjökull is the most intensively and regularly mapped area of modern glacial geomorphology in the world and has been the location of some ground-breaking glacial research projects, including the subglacial deformation experiments of Boulton (1979), Boulton and Jones (1979), Boulton and Hindmarsh (1987) and Boulton et al. (2001) and the mapping of the spatial and temporal evolution of glacial process-form regimes (glacial landsystems) by Welch and Howarth (1968), Price (1969, 1970) and Price and Howarth (1970).

Breiðamerkursandur (178 km^2 in 2018) is an outwash plain deposited predominantly by the glacial meltwater rivers of Breiðamerkurjökull, the fourth largest outlet of the Vatnajökull ice cap, and the Fjallsjökull-Hrútárjökull outlet glaciers, descending from the Öræfajökull stratovolcano (Figure 1). The maritime temperate outlet glacier of Breiðamerkurjökull consists of three major ice flow units or branches (Mávabyggðarjökull [west], Esjufjallajökull [central] and Norðlingalægðarjökull [east]). They coalesce at prominent medial moraines, identified as Mávabyggðarönd, which originates at the nunatak Bræðrasker (exposed in the 1960s), and Esjufjallarönd, which initiates at the Esjufjöll mountains (Figure 1). Norðlingalægðarjökull flows down a 25 km long and 300 m deep subglacial trench (Björnsson et al. 1992; Björnsson, 1996b) presumed to have been excavated during the LIA advance, which included several surge events (Henderson 1815; Þoroddsen 1931; Þorarinsson 1943; Pálsson 1945; Watts 1962; Sigbjarnarson 1970; Björnsson,

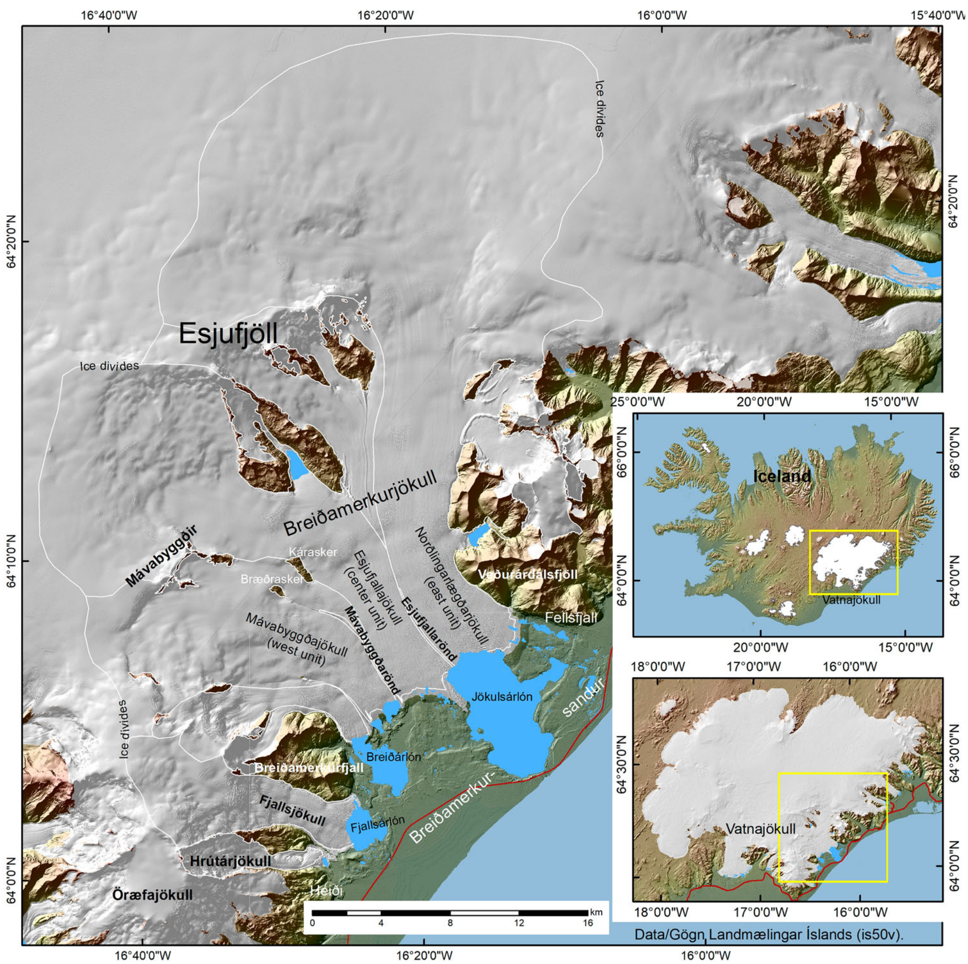

Figure 1. Location maps of Iceland, Vatnajökull and the Öræfajökull ice cap. Main map shows the details of Breiðamerkurjökull and Breiðamerkursandur.

1998b, 2009, 2016; Björnsson et al. 2003). This is the fastest flowing branch of Breiðamerkurjökull (Björnsson et al. 2001; Björnsson 2016). From the 1890s up to 2010, Breiðamerkurjökull retreated at an average of 33–59 m annually (Guðmundsson et al. 2017). However, the retreat observed in recent years has been 70–200 m a^{-1} (Evans, Guðmundsson et al. 2019).

Numerous studies report on Breiðamerkurjökull's LIA advance and its post-LIA retreat since the late nineteenth century to its current position 4–8 km behind the late historical maximum extent (Þorarinsson 1943; Todtmann 1960; Price and Howarth 1970; Boulton et al. 1982, 1988; Price 1982; Bogadóttir et al. 1986; Víkingsson 1991; Björnsson et al. 1992, 1999, 2001, 2003; F. Björnsson 1993, 1996a, 1998a; H. Björnsson 1996b, 1998b, 2009; Evans and Twigg 2000, 2002; Jóhannesson et al. 2005; Nick et al. 2007; Guérin et al. 2010; Schomacker 2010; Bergsdóttir 2012; Ólafsson 2013; van Boeckel 2015; Guðmundsson and Björnsson 2016; Jónsson 2016; Guðmundsson et al. 2017; Guðmundsson and Björnsson 2020; Storrar et al. 2017; Evans, Guðmundsson et al. 2019). After this glacier retreat over >130 years, an area ∼120 km^2 of relatively flat, low-elevation foreland has been uncovered. The elevation ranges from sea-level to 65 m a.s.l. (Björnsson et al. 1992, 2001; Björnsson 1996b; Björnsson and Pálsson 2008; Guðmundsson et al. 2017; Guðmundsson and Björnsson 2020). The Breiðamerkursandur foreland is presently demarcated by the ∼16 km long terminus of the glacier in the northwest and the Atlantic coastline in the southeast. Extensive proglacial lakes, Jökulsárlón, Breiðárlón and Fjallsárlón, occupy the major glacial erosional features created during the LIA. These lakes first appeared in the 1930s and have gradually expanded as glacier recession continued (Björnsson 2009). The tidal lagoon of Jökulsárlón occupies the southern part of the inland subglacial trench, which extends northwards beneath the glacier to the base of the Esjufjöll mountains (Björnsson 1992, 1996b). From 1991 to 2018 this lagoon grew rapidly, attaining an areal extent of 27 km^2. Breiðárlón (5.9 km^2 in 2018) and Fjallsárlón (3.7 km^2 in 2018) are located in a shallower subglacial trench (Guðmundsson et al. 2019). Numerous smaller lakes and ponds are distributed across the foreland, constituting a total water surface area of 40 km^2.

The earliest maps of the area focussed on the coastline, but "Breija Merkur Jokull" was identified on Knopf's map of 1734 (Hermannsson 1931). Pioneering glaciologist Sveinn Pálsson's 1794 map of Vatnajökull clearly identifies Breiðamerkurjökull, and the Danish Coastal Survey map of Iceland in 1818 and the 1831–1843 maps by Björn Gunnlaugsson show the glacier to be coalescent with Fjallsjökull (Gunnlaugsson 1844; Sigurðsson 1978; Pálsson 2004). Breiðamerkursandur and the terminus of Breiðamerkurjökull are identical on these maps, together with the position of the river Jökulsá. The first accurate survey of the glacier snout was by the Danish General Staff (Geodetic Institute) in 1903, which resulted in the production of a 1:100,000 scale map portraying the snout position at the early stages of its recession from the Little Ice Age maximum limit but provided only rudimentary details of the freshly created morainic landforms. Later mapping undertaken by Todtmann (1960) recorded the state of glacial landforms at the time of her expeditions in the 1930s and 1950s. An early example of the application of precise ground survey techniques are the 1951 plane table maps by the Durham University Expedition, which depicted the Breiðamerkurjökull foreland and the Esjufjöll nunatak (Lister 1953).

More advanced levels of photogrammetry were applied by the University of Glasgow from 1964 to 1967 when they undertook the first detailed geodetic surveys of the Breiðamerkurjökull and east Fjallsjökull forelands (Price 1968), producing two 1:30,000 scale maps for 1945 and 1965 (Howarth and Welch 1969a, 1969b; see Evans 2009 for a review). The wealth of glacial landforms had been previously identified by Okko (1955) and this was captured on 1945 US Army aerial photography for production of the 1:250,000 and 1:50,000 scale maps of Iceland. The 1965 aerial photography was initially required by the Icelandic Roads Department, because they were about to construct a road bridge over the Jökulsá, but the involvement of the University of Glasgow justified the novel experimentation with different types of film, including panchromatic, colour, false colour and infra-red (Welch 1966, 1968). The ground survey control was established from two base camps, one at the Breiðá Hut in the west and one below the Brennhóla alda moraine in the east and amounted to 50 ground control points. The resulting photogrammetry and mapping by Welch (1967) and Howarth (1968) produced a 1965 map of the glacier snout and its foreland at a scale of 1:15,000, from which Howarth and Welch (1969a, 1969b) then produced 1:30,000 colour maps of the snout and foreland for 1965 and 1945, with the latter based on the US Army photography.

The 1945 and 1965 maps were used in the compilation of a time series that utilized also the 1903 and 1951 maps of the Danish General Staff and Durham University respectively, 1930s historical documents (used to compile a composite map of the west and east forelands in 1937 and 1931 respectively) and aerial photography for 1960/61, 1964 and 1980 (Price and Howarth 1970; Price 1982). This time sequence demonstrated how the foreland evolved during ice recession, focussing particularly on the evolution of proglacial drainage networks and their change from early proglacial sandur fans to later ice margin-parallel drainage, in places through lakes, that was constrained by depressions between overridden moraine ridges. It also delivered the first systematic quantification of spatial and temporal changes in proglacial landforms and was to contribute significantly to the development of process-form models in glacial research (cf. Price 1969, 1970; Clayton and Moran 1974; Eyles 1983a, 1983b).

A key contribution that emerged from this survey work was the charting of the evolution of glacifluvial landform assemblages, wherein it became clear that eskers and kame and kettle topography should not be genetically separated but rather regarded as occupying various stages on a spatial and temporal continuum related to the same process-form regime (cf. Welch and Howarth 1968; Howarth 1971; Price 1982). Especially important in this respect was the identification of large volumes of buried glacier ice on the foreland and the development of eskers in englacial drainage networks, rather than exclusively in subglacial tunnels as was traditionally advocated. The burial of large parts of the snout was seen to have taken place once the ice margin had retreated inside the broad arcuate ridges that forced proglacial drainage to flow ice-marginal parallel rather than directly to the coast in outwash fans (Price and Howarth 1970); we now know these ridges to be overridden outwash heads or complex push moraines (Boulton 1987; Evans and Twigg 2002; Denis et al. 2009). Repeat photography and ground survey enabled the University of Glasgow project to record the impacts of a catastrophic depositional event with unprecedented accuracy. This was related to the sudden drainage of an ice-dammed lake on the west side of Breiðamerkurjökull (reported by F. Björnsson 1962, a local farmer and scholar from Kvisker), that resulted in the dumping of large volumes of glacifluvial sediment over the snout and a small ice-cored outwash fan, which were then observed to develop into pitted outwash over the period of 5 years (Price 1971).

A map covering the same area and at the same scale as the 1945 and 1965 maps was produced for 1998 by Evans and Twigg (2002) utilizing the ground control markers established in 1965, this time being tied into the Icelandic GPS network and new aerial photography. In addition to charting significant glacier snout recession, especially over the Jökulsarlón trench, this survey recorded the more advanced stages of glacifluvial landform evolution 20 years after the Welch and Howarth (1968) study. The eskers of west Breiðamerkurjökull in particular had evolved significantly from their 1945–1960s appearance of being lowered and getting more complex over time to their 1998 emergence through chaotically downwasting surfaces of ice-cored outwash. Hence, over the timespan of 1945–1998, they had developed into a ‘fan-shaped’ pattern of ridges emanating from a single large esker ridge at the apex of the ‘fan’. Utilizing aerial photography taken in 2007 by the Airborne Remote Sensing Facility of NERC UK, in addition to the archive of aerial photographs dating back to 1945, Storrar et al. (2015) confirmed the tendency for eskers to not only lower due to ice core melt-out (cf. Price 1969; Howarth 1971) but also for complexity to increase over time, especially if they displayed relatively complex, multi-ridged forms when they first emerged from the downwasting snout. Additionally, eskers also emerged long after the glacier had retreated due to their initial submergence beneath a lake that subsequently drained. Moreover, Storrar et al. (2015) confirm that the more complex esker systems may take several decades to emerge from ice buried beneath outwash and that this results in a gradual transition from flat or pitted outwash surfaces to complex esker networks (cf. Welch and Howarth 1968; Price 1969; Howarth 1971; Evans and Twigg 2002).

The eastern part of Fjallsjökull and its foreland appear partially on the Breiðamerkurjökull maps produced by Howarth and Welch (1969a, 1969b). However, separate 1945 and 1965 maps of the whole Fjallsjökull snout and foreland were produced but never initially published; they existed as drafts and were included in the 1968 QFSG (QRA) field guide (Price and Howarth 1968). The maps were finally finished and published by Evans et al. (2009) together with a 1998 map, the latter being created from the aerial photography used for the Evans and Twigg (2002) survey. The Fjallsjökull map series highlights the impact of the mid-1990s readvance (Evans and Chandler 2018) in that it depicts the glacier margin re-attaining its 1965 limit, when it constructed the push moraine complex reported by Evans and Hiemstra (2005) as an exemplar of sub-marginal till thickening. It also depicts the development of localized but nonetheless substantial glacier snout burial by glaciofluvial outwash, which has resulted in the emergence of very large kettle holes and collapsed kame terraces and outwash spreads. The most recent mapping of Fjallsjökull and its foreland is that of Chandler, Chandler et al. (2020) and Chandler, Evans et al. (2020), who used Light Detection and Ranging (Lidar) data captured in 2011–2012 to produce a 1: 15,000 scale map as well as a 1: 2,000 map of the southern glacier margin using UAV imagery captured in 2019. This update of the Fjallsjökull glacial landform patterns provides important details of a tripartite landform zonation in the active temperate glacial landsystem. This is defined by changes in moraine morphology and the nature of proglacial outwash deposition: Zone 1 or the outer foreland, characterized by proglacial outwash fans, overridden moraine arcs and broadly linear recessional moraines; Zone 2 or the middle foreland, containing sawtooth moraines and linear sandar; and Zone 3 or the innermost foreland, comprising extremely sawtooth and hairpin moraines as well as associated crevasse-squeeze ridge limbs. This landform zonation has been recorded by landsystem compilations at other Icelandic south coast glacier forelands (cf. Evans et al. 2016, 2017a, Evans, Ewertowski et al. 2019) and reflects spatio-temporal changes in moraine-forming processes and outwash deposition dictated by changes in snout morphology and proglacial drainage characteristics. Importantly, Chandler, Chandler et al. (2020) also identify localized (azonal/intrazonal) sediment-landform assemblages that are representative of very recent accelerated snout recession in the region, more specifically the localized development of ice-cored terrain and an ice-cored esker complex in association with the uncovering of a depositional over deepening.

The review above clearly demonstrates the value of continued repeat surveying of deglaciating forelands in the pursuance of a more comprehensive understanding of glacial process-form regimes. Our knowledge of temperate glacier landform evolution in particular has developed significantly as a result of the repeat map compilations of southern Icelandic glacier forelands. The map we present here constitutes a continuation of the mapping of the Breiðamerkurjökull foreland that began in 1904, and in addition to charting areas only very recently uncovered by ice recession, it provides an unprecedented higher level of detail of glacial landforms over the whole foreland based upon recently acquired higher resolution aerial imagery. More specifically, the map concentrates on the historical development of proglacial outwash networks, which we have dated and charted also at an unprecedented level of accuracy.

Data and methods

The new map was constructed by using ESRI ArcGIS based on remote sensing but it takes a variety of data sources into consideration (Table 1). Alongside field inspection, a LiDAR DEM of the region, surveyed in 2010–2012 (Jóhannesson et al. 2011, 2013), and high resolution aerial photographs were used for geometrical identification of the morphology of Breiðamerkursandur. The DEM was also used to georectify aerial photographs, digitize terminus positions, and re-project the horizontal positioning of maps. The georectification of aerial photographs was carried out by identifying 30–50 common control points on each image or map and the LiDAR DEM, using

Table 1. Data used for construction of the Breiðamerkursandur geomorphological map of 2018.

Id	Year	Data type	Spatial res. (m)	±(m)	Purpose
DCS[a], BG[b] DGS	1818, 1844, 1904	Maps	–	20	Terminus position, rivers
AMS	1945	–			
Durham	1951	–			
AMS	1945–1946	Aerial images	1.0 × 1.0	5	Terminus, proglacial foreland, lakes and rivers
NLSI	1954, 1955, 1960,	–	0.5 × 0.5	5	Terminus, proglacial foreland, lakes and rivers
	1964, 1980–1982,	–	–		
	1988–1989, 1990–1991, 1994	–	–		
Loftmyndir ehf	1998	–			
	2003		0.5 × 0.5	1	Terminus, proglacial foreland, lakes and rivers
Landsat 1–5	1973–1986	Satellite	60 × 60	30	Terminus, proglacial foreland, lakes and rivers
Landsat 7–8	2000–2018	images	15 × 15	5	
Lidar	2010–2012	DEM	2 × 2	<0.5	Terminus, proglacial foreland, lakes, rivers, georectification
Various material and field studies	1815–1950	Oblique photos	–	–	Terminus, proglacial foreland, lakes and rivers
		Written	–	–	

[a]DCS 1818. *Voxende Kaart over den östlige Kyst af Jisland fra Mulehavn i Hierads-Floin-Bugt til Jngolfs-Höfde-Huk*. Danish Coastal Survey 1801-1818. Copenhagen. Webpage: https://islandskort.is/en/map/show/125.
[b]Björn Gunnlaugsson & Olaf Nikolas Olsen 1844. *Uppdráttr Íslands*. Hið íslenska bókmenntafélag. Webpage: https://islandskort.is/is/map/show/599.

ArcGIS tools for re-projection and warping. The oldest maps inspected are from the Danish Coastal Survey of Iceland, published in 1818 and Gunnlaugsson (1844). The Danish General Staff (DGS), is based on triangulation surveys in 1903 and 1904 in SE-Iceland (DGS 1905a, 1905b) and the C762 maps of the US Army Map Service (AMS), based on aerial photographs taken in 1945 and 1946 (AMS 1951).

The accuracy of older maps is variable. The DGS maps (1905) needed horizontal corrections by a few tens of metres but they are estimated to be accurate within ±20 m after re-projection on the glacier foreland. The glacier marginal position of 1903 was delineated from the map, with corrections based on identified landforms, rivers and the position recorded (in metres) by local farmers at that time. The AMS (1951) sheets are relatively accurate in comparison with the LiDAR DEMs, with an estimated horizontal accuracy of ± 5 m after correction with respect to the LiDAR DEMs. The Durham University map (1951), assembled from triangulation survey, is reasonably accurate when compared with the LiDAR DEM, but contains minor deviations in elevation. The DGS and Durham maps were used to delineate the terminus for their respective years, as other data of higher resolution do not exist. Maps produced from available aerial photographs were taken into consideration but the high-resolution originals were used for digitization.

The terminal position for several other specific years, in the period from 1954 to present, was digitized from aerial photographs in the database of the National Land Survey of Iceland (NLSI), Landsat images (Landsat 1–5 and 7–8, courtesy of the US Geological Survey), the aerial image database of the company Loftmyndir ehf, and LiDAR DEMs of the Vatnajökull ice cap and its foreland (Jóhannesson et al. 2013). Landsat 1 provided a 60 m/px resolution from 1973, but more recently the satellite images, especially Landsat 7–8 with its 30 m (spectral) and 15 m (panchromatic) pixel resolution, have been used to the trace the position of the terminus more or less annually. These datasets are the most detailed available and cover glacier variations since the 1990s.

Once these data had been used to delineate the terminus position for specific years, the existence of several time gaps became evident. Terminus variations between 1903 and 1945 are especially vague, because the survey data necessary to trace these changes are patchy. We filled these gaps where possible by using oblique photographs, written accounts and in-field measurements of terminal positions from the database of the Iceland Glaciological Society (available at 'https://islenskirjoklar.is'; Sigurðsson 1998). These additional sources of information, when combined, extend the temporal coverage of identified terminal positions of Breiðamerkurjökull in this period and chart the progress of the retreat. Especially useful were written descriptions, comments and small cairns that were established by local residents, who in the 1930s began to mark and measure annually the ever-growing distance to the glacier terminus. These surveys merge with and are then superseded by aerial photographs, forming a continuum of documented terminus positions every year from the 1920s to the present.

Genetic classifications of surficial materials and landforms are based on field-based surveys and sampling over numerous field seasons since 1998 and build upon previous work as reported in Price (1969) and Evans and Twigg (2002). Features were mapped onto hard copy aerial photographs, satellite images and DEMs during fieldwork prior to final map compilation in ArcGIS, following protocols outlined in Chandler et al. (2018).

Results

The combined mapping output (scale 1:24,000 when printed on A0 paper) is available at high resolution in Supplementary Information file S1 and replicated in Figure 2. This presents the geomorphology of Breiðamerkursandur and the glacier foreland up to the position of the 2018 terminus of Breiðamerkurjökull. It supplements the topography exposed by the retreating glacier in the interval between 1998 and 2018 to the geomorphology of pre-1998 retreat, presented by Evans and Twigg (2002; cf. Howarth and Welch 1969a, 1969b). It also replicates the colour palette employed on earlier maps but takes advantage of technical improvements and high-resolution data acquired since their publication.

We now first briefly review the mapped surficial geology units and glacial geomorphology in order to update and refine those compilations from 1945, 1965 and 1998 (cf. Evans and Twigg 2002). We then present in greater detail the evolutionary stages of the glacier snout and its associated foreland features based upon our re-examinations of combined new and existing datasets, including: (1) the development of Breiðamerkurjökull's terminal/end moraine from the late nineteenth century to the 1930s; (2) the detailed retreat pattern of the Breiðamerkurjökull terminus from the turn of the twentieth century to the present; and (3) the detailed development of the relict channels and fans created by glacial meltwater runoff and comprising the Breiðamerkursandur.

Summary and update of the glacial geomorphology of the Breiðamerkurjökull foreland

As the focus of this study is on historical developments of the glacier margin and the proglacial drainage, and the wider surficial geology and geomorphology is an update of that produced in previous maps (see Evans and Twigg 2000, p. 2002 for details on surfaces pre-dating 1998), we only briefly review the main surficial geology units and their associated landforms here. Similarly, the process-form regimes represented by the landform-sediment associations of typical active temperate glacial landsystems in Iceland are presented in detail elsewhere, hence the examples used here are selective and date partly from the post-1998 period.

Previous maps of the glacial landsystems of the active temperate glaciers of southern Iceland have identified areas of 'till and moraines'. We similarly highlight this former subglacial and glacier sub-marginal surface but classify it as 'fluted till' and include a further surficial unit called 'moraine' (Figure 2); the latter recognizes only the more substantial moraines, usually composed of multiple, densely-spaced/partially stacked ridges (cf. Kruger 1993). Between these larger moraines, the fluted till is characterized by parallel-sided minor flutings, often initiating at lodged stoss boulders and composed of subglacial traction till (cf. Boulton 1987; Benn 1995; Benn and Evans 1996; Evans, Roberts et al. 2018; Figure 3a) and inset sequences of densely-spaced, minor recessional moraines

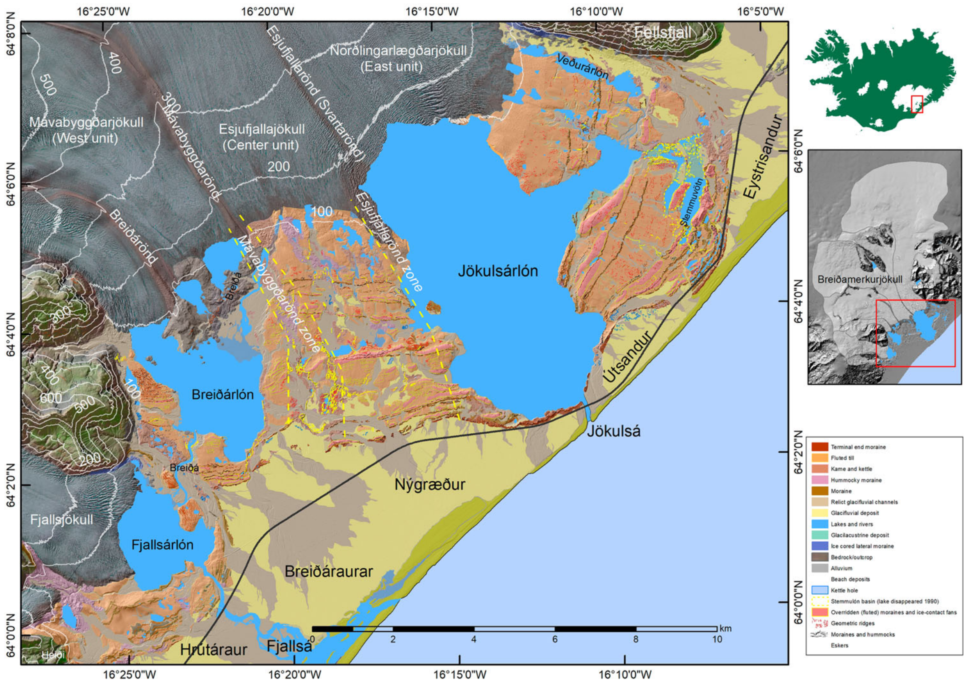

Figure 2. Geomorphological map of Breiðamerkursandur in 2018 (scale 1:24,000) portraying surficial geology and geomorphology. See Supplementary Information for high-resolution format designed for printing on A0 size paper.

that may exhibit sawtooth planforms (cf. Sharp 1984; Boulton 1986; Evans and Twigg 2002; Evans et al. 2016, 2017a; Chandler et al. 2016a, 2016b, 2016c; Chandler, Chandler et al. 2020; Everest et al. 2017; Figures 3b and 4). Also evident in increasing numbers on the eastern part of the foreland are geometric ridges, previously mapped as 'crevasse squeeze/fill ridges' (Figures 4 and 5). These were regarded as part of a surge landsystem signature in this area by Evans and Twigg (2002) but more recent recession has exposed extensive networks of such ridges that appear to be related to the intensive crevassing created at the calving margin in Jökulsárlón. Although non-surge crevasse squeeze ridges are also appearing in increasing numbers in association with the extended limbs of hairpin-shaped push moraines and longitudinal crevasses at other active temperate snouts in southern Iceland (e.g. Evans et al. 2016; Evans, Ewertowski et al. 2018; Evans, Roberts et al. 2018; Chandler, Chandler et al. 2020; Chandler, Evans et al. 2020), the recession of the eastern lobe of Breiðamerkurjökull since the 1980s has revealed a subglacial footprint (Figures 2 and 4) that clearly relates to the mini surges observed in that area (cf. Boulton 1986; Boulton et al. 2001; Björnsson et al. 2003; Björnsson and Pálsson 2008).

Areas mapped as 'hummocky moraine' are only locally present on the foreland (Figures 2 and 6a), where they have been associated with the melt-out of medial moraines, best exemplified in the Mávabyggðarönd zone (Evans and Twigg 2002). Such locations are normally the only parts of active temperate glacier snouts where there is a suitable supraglacial sediment cover to form chaotic hummocks during melt-out. However, the recent recession of both Fjallsjökull and Breiðamerkurjökull has exposed significant areas of unstable bedrock cliff and this has given rise to the delivery of supraglacial debris to their true left margins and the subsequent development of a previously absent map unit, designated here as 'ice-cored lateral moraine' (Figure 6b).

Previously included as part of the till and moraine map unit by Evans and Twigg (2000, 2002), we map the outermost LIA moraine separately as 'terminal end moraine', because it forms a major component of the historical reconstructions highlighted in this study (Figures 2 and 7). It also

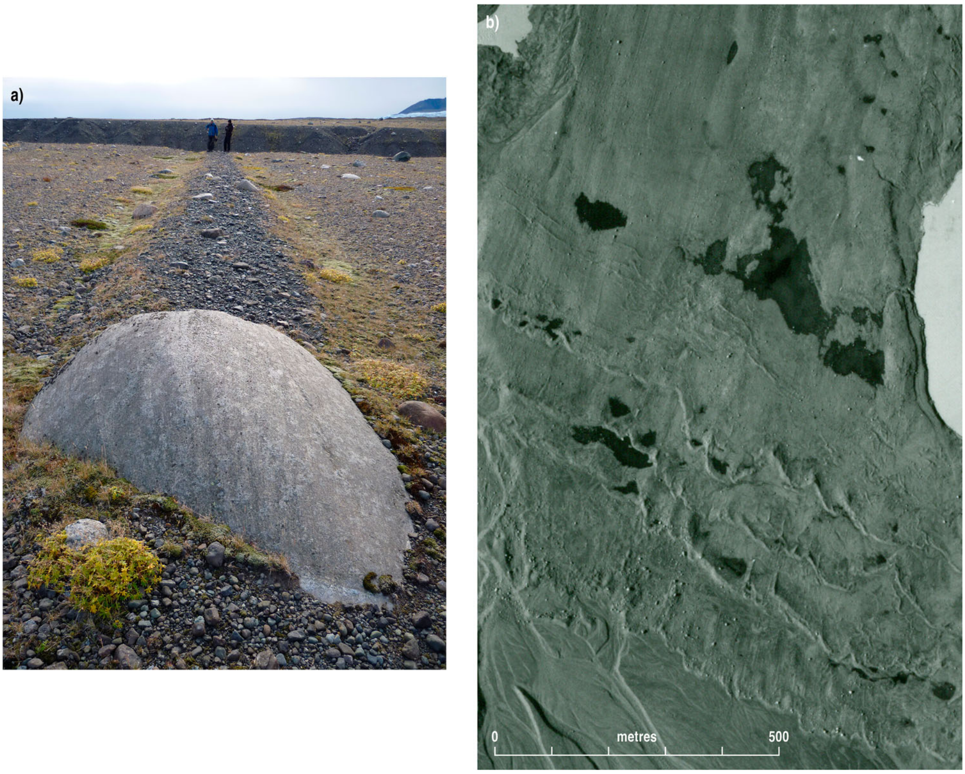

Figure 3. Characteristics of the fluted till and moraine mapping units: (a) typical stoss-and-lee fluting on the western Breiðamerkurjökull foreland, with lodged stoss boulder displaying ice flow parallel surface striae; (b) aerial photograph extract (NERC ARSF 2007), showing inset sequence of push moraines with largely sawtooth planforms and associated fluted till. The larger ridges are classified as the 'moraine' map unit and the smaller ridges are included in the fluted till map unit.

appears to have a complex genesis comprising repeated push and dump processes over a relatively substantial time period in contrast to the minor recessional push moraines of more recent age (Figure 4; cf. Price 1970; Sharp 1984; Evans and Hiemstra 2005; Chandler et al. 2016a, 2016b, Chandler, Chandler et al. 2020; Evans, Roberts et al. 2018).

Broad, low-amplitude ridges with fluted/drumlinized surfaces have been increasingly recognized on active temperate glacier forelands in Iceland (Figure 8). They have been interpreted as overridden ice-marginal landforms, comprising either asymmetrical ice-contact outwash fans, complex push moraine ridges relating to periods of significant glacier stillstand or glacitectonic thrust moraines such as Brennhóla alda (e.g. Boulton 1987; Evans and Twigg 2002; Denis et al. 2009; Evans et al. 2009, 2016, Evans, Ewertowski et al. 2018; Evans, Roberts et al. 2018, Evans, Ewertowski et al. 2019; Chandler, Chandler et al. 2020). Initial construction of these landforms was at some time prior to the LIA maximum. Their subsequent overriding and subglacial streamlining occurred during the advance to the LIA limit and hence we classify these features as 'overridden moraine/ice-contact fan' (Figure 2).

Areas of 'kame and kettle' are localized concentrations of glacifluvial deposits that have been subject to extensive collapse due to ice melt-out. Larger kettles have been mapped as individual features and may be of substantial size, documenting the extensive burial of large areas of downwasting glacier snout (Price 1969; Evans and Twigg 2002; Evans et al. 2009; Chandler, Chandler et al. 2020; Figure 9a). Extensive areas of complex esker evolution (cf. Price 1969, 1980; Howarth 1971; Evans and Twigg 2002; Storrar et al. 2015) are also mapped as kame and kettle but do include highly fragmented esker ridges as well as more continuous ridges mapped separately as 'eskers' (Figures 4 and

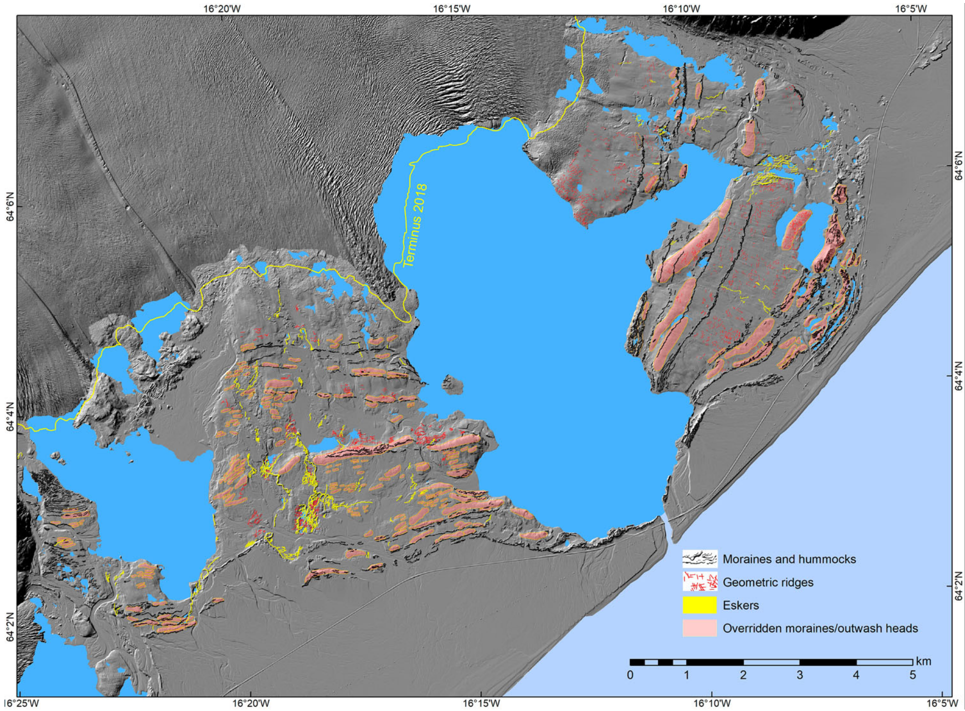

Figure 4. Geometric ridges (crevasse infills), moraines and eskers on Breiðamerkursandur.

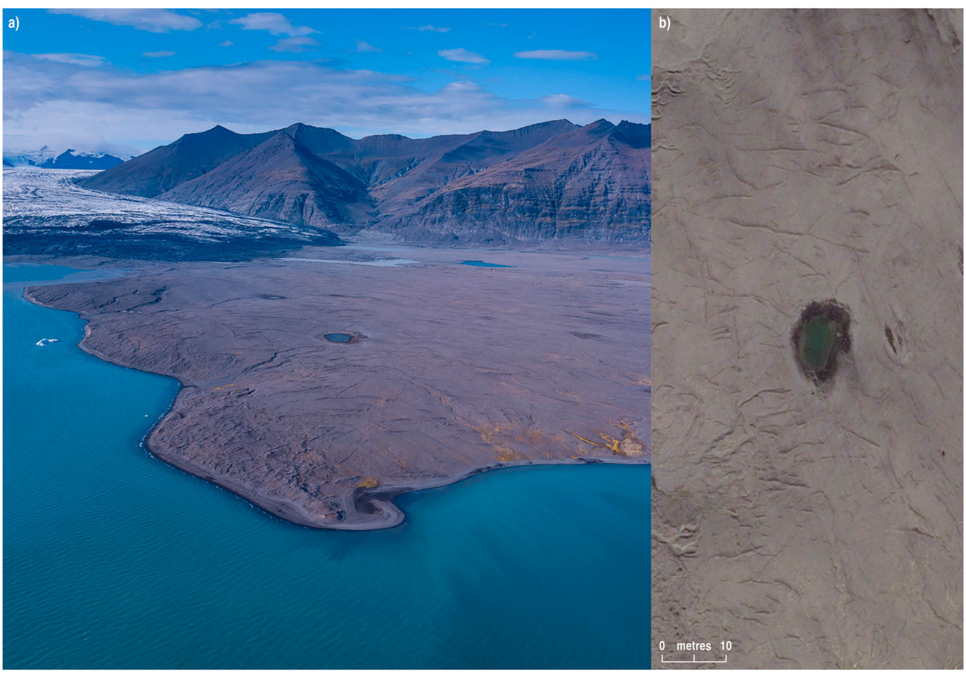

Figure 5. Geometric ridges (crevasse squeeze ridges) in the fluted till map unit on the eastern foreland: (a) oblique aerial view taken in August 2019 by Þorri Arnason; (b) vertical aerial image extract from Google Earth 2019.

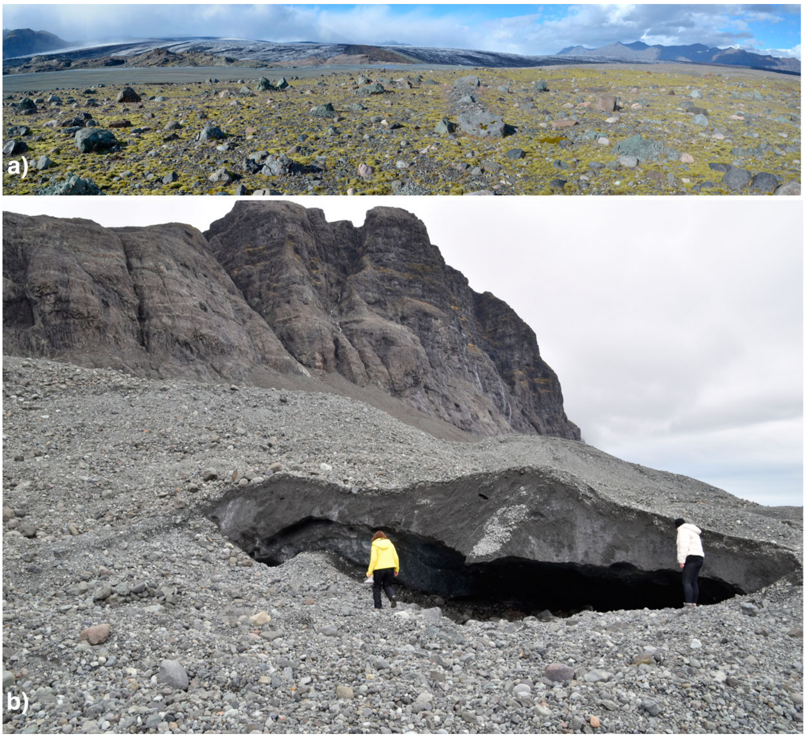

Figure 6. Characteristics of supraglacial landforms: (a) medial moraine composed of scattered boulders cloaking the subglacial flutings in the Mávabyggðarönd zone; (b) ice-cored lateral moraine on the east foreland.

Figure 7. Physical characteristics of the 'terminal end moraine' map unit on the southwestern shore of Jökulsárlón.

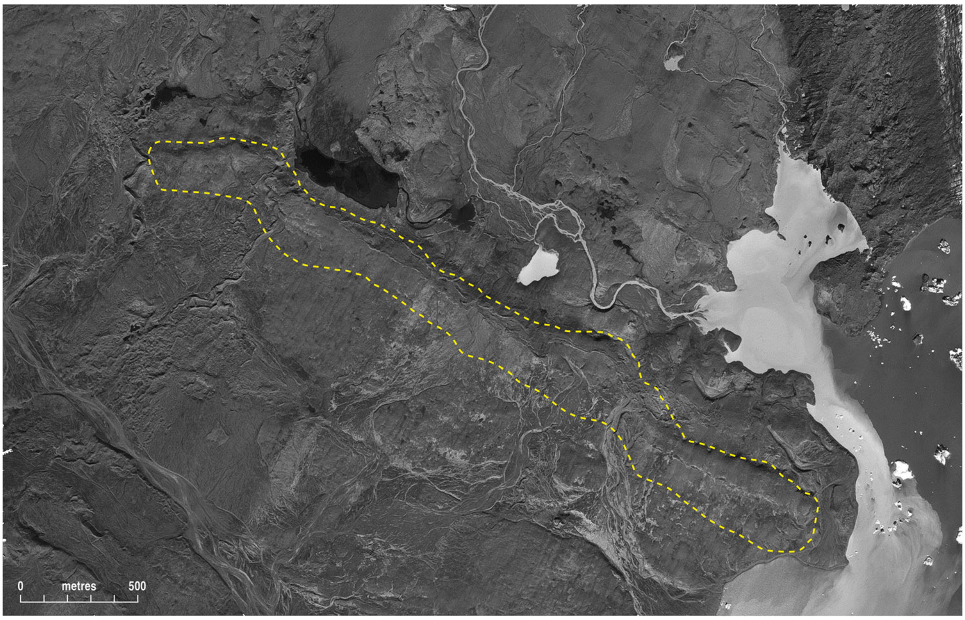

Figure 8. Aerial photograph extract (Landmælingar Island/University of Glasgow 1998) showing the characteristics of a typical 'overridden moraine/ice-contact fan'. Outlined by yellow dashed line is the ridge named Nygrædnakvis on the 1965 and 1998 University of Glasgow maps (re-named here Nygrædnakvislar) and is thought to be a glacially overridden ice-contact fan adourned with flutings and minor push moraines.

9b). Our kame and kettle classification has also been applied to a complex landform assemblage that lies in the corridor of glacifluvial deposits at the former coalescence zone between Fjallsjökull and Breiðamerkurjökull, which Chandler, Chandler et al. (2020) map as an area of 'ice-cored hummocky terrain' (Figures 2 and 9c). The fluted surface of this terrain indicates that it is a pre-advance assemblage of ice-cored outwash that is gradually collapsing due to melt-out.

The sediments deposited in formerly more extensive proglacial lakes on the foreland are mapped as 'glacilacustrine deposit'. They cover only small areas around the existing lakes and locally include some weakly developed lake shorelines (Figure 2).

Unlike previous maps of the Fjallsjökull and Breiðamerkurjökull foreland, the widespread glacifluvial deposits are classified as two separate map units in order to differentiate styles of landform development (Figure 2). Unconstrained deposition in outwash sandur fans and heavily pitted outwash and kame terrace terrain is classified as 'glacifluvial deposit', whereas constrained deposition in incised and terraced outwash and linear/ribbon sandar (cf. Price 1969; Evans and Twigg 2002; Evans and Orton 2015; Evans et al. 2016; 2017a, 2017b; Evans, Ewertowski et al. 2018, Evans, Ewertowski et al. 2019; Chandler, Chandler et al. 2020) is classified as 'glacifluvial river bed (ribbon sandur)'. The apexes of outwash fans are commonly associated with breaks in the crests of moraines and/or the moraines lie along the tops of ice-contact faces. In contrast, linear or ribbon sandar predominantly run parallel to moraines and ice-contact faces (Figure 10a). Pitting on sandar surfaces likely records former jökulhlaup influences on the discharges that constructed them, each pit representing the melt-out of ice blocks (Maizels 1992, 1997; Evans and Twigg 2002; Russell et al. 2006; Guðmundsson and Björnsson 2020: Figure 10b).

Non glacial materials on our map include 'beach deposits' developed along the coast and 'alluvium' deposited in fluvial systems not directly fed by glacial meltwater. Also mapped are areas of 'bedrock' where it has emerged during recent downwasting of the glacier snouts and is most prominent as glacially abraded gabbro outcrops on the north shore of Breiðárlón (Figure 2).

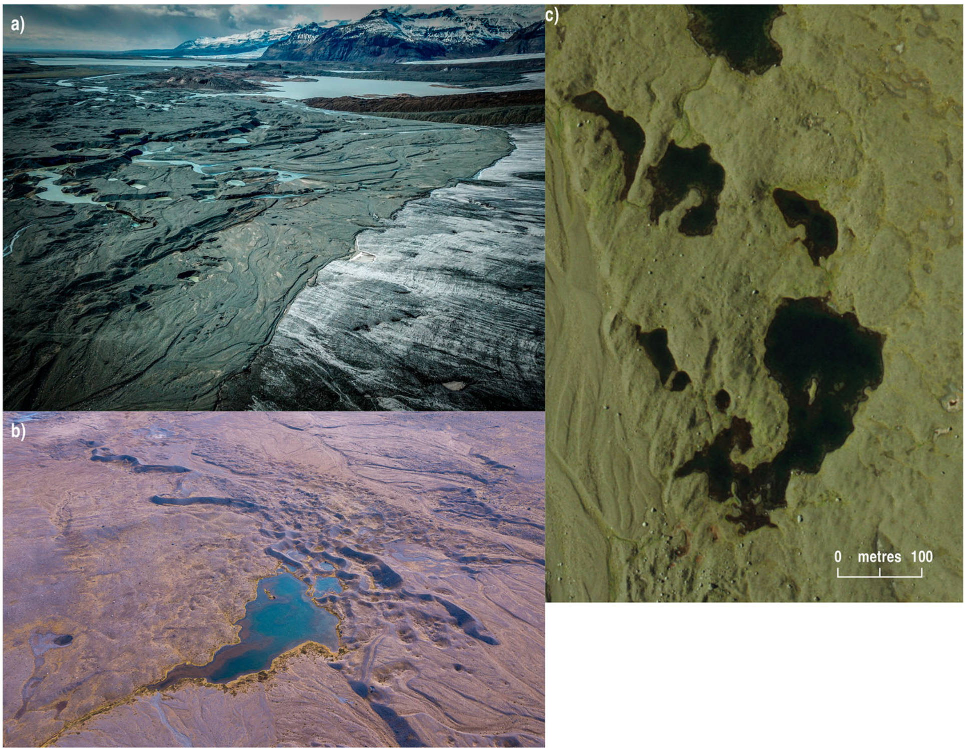

Figure 9. Characteristics of the 'kame and kettle' and 'eskers' map units: (a) oblique aerial view of rapidly developing kame and kettle topography initially deposited as a linear/ribbon sandur over the western snout margin from 1970s-2010s (photo by Rob Storrar 2018); (b) esker and kame and kettle terrain on the western foreland (esker complex MES 1 of Storrar et al. 2015; photo by Þorri Arnason); (c) aerial photograph extract (NERC ARSF 2007) of Chandler, Chandler et al.'s (2020) and 'ice-cored hummocky terrain' in the former coalescence zone between Fjallsjökull and Breiðamerkurjökull.

Topographic cross-profiles over the glacier foreland provide clear morphological signatures of the land facets that make up the active temperate glacial landsystem (Figure 11). Each facet comprises an association of land elements or sediment-landform associations. Cross profile 1-1' represents a long profile through the ice-contact fan that developed in the 1930s in a re-entrant along the glacier margin in the Mávabyggðarönd medial moraine zone. The profile displays the shallow distal and steep and pitted proximal slopes of a typical ice-contact fan, in this case being connected at its pitted apex to the esker network MES 1 of Storrar et al. (2015). Also captured in this profile are the minor push moraines developed in esker gravels on the proximal slope. An example of a profile of an outwash fan emanating directly from complex push moraines is cross profile 3-3'. This is a diagnostic push moraine-outwash fan land element pairing (land facet) developed at advancing and/or quasi-stable ice margins (Thompson and Jones 1986), typified here by the LIA terminal end moraine and the Útsandur proglacial outwash fan (Figure 10). A third style of proglacial outwash fan development is represented by cross profile 4-4', which depicts the extensively pitted surface of a jökulhlaup-fed sandur, exemplified by the 1860 ice-contact fan, inset proximally by the later 1912 path of the Jökulsa. Extensive areas of glacifluvially buried parts of the downwasting snout (cf. Price 1971) are represented by cross profile 7-7', which depicts terraced and pitted inset linear/ribbon sandar that developed around the east margin of Breiðamerkurjökull from 1900 to the 1940s and continues to collapse due to ice melt-out today, giving rise to a series of inset kame terraces. Glacially overridden landforms are represented by cross profiles 2-2' and 5-5', which show the overridden asymmetrical profile of a large ice-contact fan near Nýgræðnakvíslar (Figure 8) and the smoothed cross profiles of two inset overridden complex push moraines on

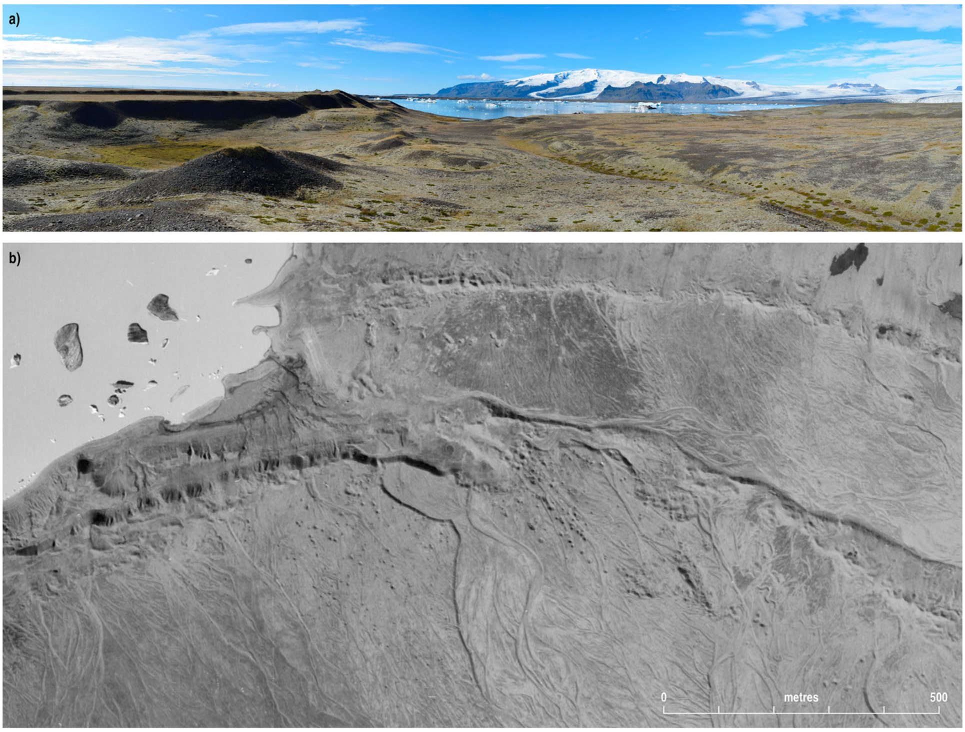

Figure 10. Characteristics of the glacifluvial sediment-landform associations: (a) view across the complex inset sequence of glacifluvial landforms of the Útsandur area of southeast Jökulsárlón. The left skyline shows the surface of the main Útsandur outwash fan with its ice-contact slope and associated moraine forming the shadowed cliff. Inset below that surface in the middle and foreground are the terraced and locally pitted remnants of ribbon sandur; (b) aerial photograph extract of the same area (Landmælingar Islands 1954), showing the pitted surfaces of the Útsandur, created by jökulhlaups in the period 1860-1904.

the east shore of Jökulsárlón, respectively. Finally, the complex assemblage of large landforms associated with the former surging of the east margin of Breiðamerkurjökull is represented in cross profile 6-6’, which shows the smoothed profiles of overridden thrust moraines, the lake surfaces of two thrust mass source depressions, including Stemmuvötn, and the sharp relief of the

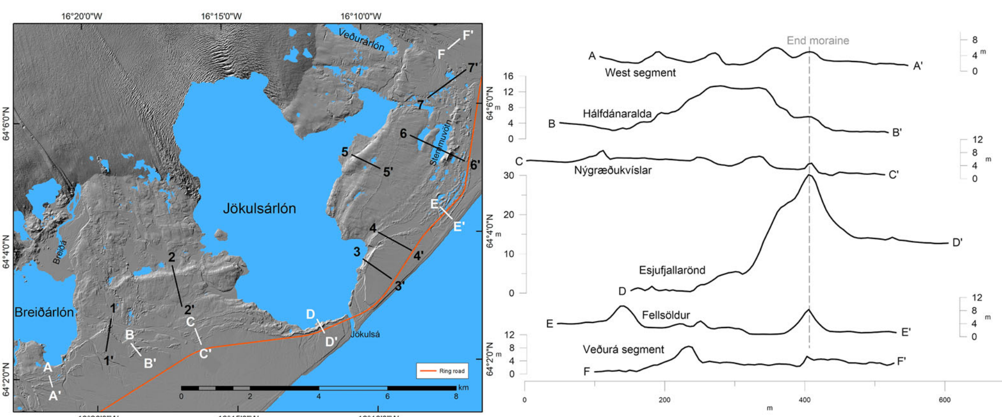

Figure 11. Cross profiles of selected sediment-landform associations (land facets of the active temperate glacial landsystem) on the Breiðamerkurjökull foreland. Inset map shows cross profile locations.

surge-related thrust moraine Brennhóla alda. These can be contrasted with the low amplitude hummocks of overridden minor push moraines and recessional moraines between Brennhóla alda and the coast.

Development of Breiðamerkurjökull's terminal/end moraine (late nineteenth century-1930s)

The prominent end moraine on Breiðamerkursandur, which runs almost uninterrupted for >20 km, reflects the vastness of the former LIA terminus of Breiðamerkurjökull (Figure 2). This was connected to Fjallsjökull and Hrútárjökull, forming a continuous ice margin stretching for 27 km between Heiði and Fellsfjall. It is possible that different parts of Breiðamerkurjökull's long terminus were attained at different times or were subject to variable oscillations, because the snout is composed of three major flow units, descending from separate accumulation areas. According to F. Björnsson (1998a), the flow units or sub-lobes advanced more or less simultaneously in the nineteenth century. Generally, snout activity was considerably slower and with less impact west of the Esjufjallarönd medial moraine, in contrast to the east, where the advances lasted longer and surge events were observed on several occasions (Björnsson et al. 2003; Björnsson and Pálsson 2008). In the late eighteenth and early nineteenth centuries, locals noticed that the eastern lobe seemed to surge at five-year intervals, then gradually retreated between events but never as far back as its pre-surge position (Frisak 1813; Henderson 1815; Pálsson 1945).

The conventional view is that the terminal moraine demarcates the 1890 LIA maximum extent (Evans and Twigg 2002; Evans, Guðmundsson et al. 2019), but this is a simplification. Advances along the western margin of Breiðamerkurjökull are presumed to have lasted until 1870–1880s, with little activity taking place up to a decade later and the snout margin remaining more or less stable at the outermost moraine. In 1893–1894, the westernmost segment (Figure 12a), where the outlet adjoined Fjallsjökull, remained inactive but located in its outermost position, which it had reached before 1880 (F. Björnsson 1998a). We therefore assume that the end moraine here must have developed over ~15–20 years. Despite being assumed as inactive, the snout produced at least two moraines with indications of ice overridding. By 1904, the glacier had retreated >300 m from the terminal moraine. Slightly further east, F. Björnsson (1998a) suggests that the snout margin in 1880 was located a short distance behind the end moraine. To the west of Hálfdánaralda, sparse and detached patches of the moraine demarcate the location of the LIA maximum extent. Assuming it had reached its maximum extent in the 1870s, this part of the snout first developed a moraine and then retreated a short distance before remaining inactive for a short time (F. Björnsson 1998a). The subsequent gradual retreat of Breiðamerkurjökull in the twentieth century in this area led to the progressive incision of the moraine by the river Breiðá and other outwash streams that sporadically changed their courses until the mid-1950s.

At the Hálfdánaralda segment (Figure 12a), the glacier remained at its maximum extent in the 1870s but was inactive. It had retreated >300 m near Hálfdánaralda but only by ~70 m at the end of Esjufjallarönd in 1904. In 1909 the whole ice margin had retreated >300 m from the terminal moraine. The Hálfdánaralda segment was still at the end of the Mávabyggðarönd medial moraine in 1903, with the main branch of the river Breiðá located to the east of it. This segment records several short advances or marginal oscillations. In 1904 the outlet of the Breiðá migrated to a small medial moraine west of Mávabyggðarönd. Hálfdánaralda was part of the Mávabyggðarönd and attached to it later than ~1904, and its development lasted for 25–30 years. In 1909 the river Breiðá had changed course once again and flowed eastwards, indicating that Hálfdánaralda had been detached from the glacier. The segment between Hálfdánaralda and the Esjufjallarönd medial moraine may have developed in a similar way to the westernmost segment. Where the glacier snout was not debris covered, it retreated faster from its maximum position, and deposited a somewhat lower relief moraine relative to areas covered by the medial moraine, such as the moraine remnants at the former

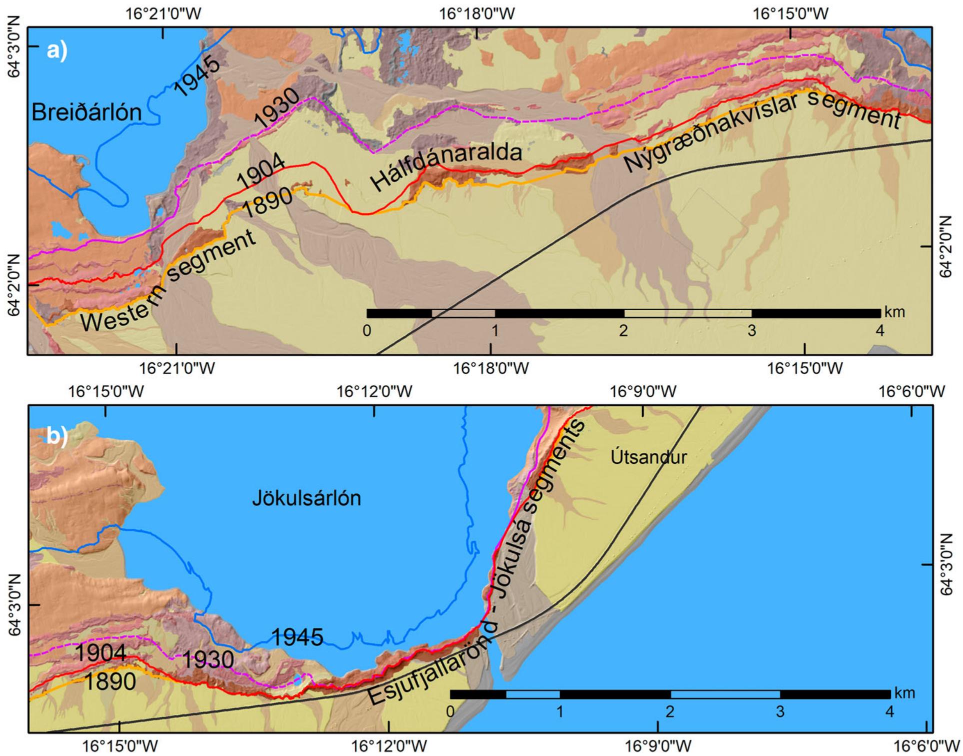

Figure 12. The western section of terminal moraine at Breiðamerkursandur: (a) Western, Hálfdánaralda and Nýgræðnakvíslar segments; (b) the Esjufjallarönd and Jökulsá segments.

positions of Hálfdánaralda and Esjufjallarönd (Figure 13). The Breiðá and Nýgræðnakvíslar rivers breached the end moraine in a few locations in the first half of the twentieth century (Figure 12a).

Closer to, and in front of, Esjufjallarönd (Figure 12b), the snout appears to have behaved differently. This is the most extensive part of the terminal moraine. Despite the fact that the exact terminal position of Esjufjallarönd in 1870–1880 is not well known, F. Björnsson (1998a) suggests that changes in this area were slow and the ice was advancing. However, the eastern flow unit underwent occasional pulses, commonly witnessed near the Esjufjallarönd medial moraine and at the river Jökulsá by travellers at the turn of the twentieth century (F. Björnsson 1998a; Björnsson et al. 2003; Guðmundsson and Björnsson 2020). In 1906 no moraine had developed in front of Esjufjallarönd or at the Jökulsá (Figure 14) but was well established before 1927. This part of Breiðamerkurjökull continued to advance to its maximum extent in 1933 and moved over the terminal moraine on both sides of the Jökulsá without removing them (F. Björnsson 1998a). In 1931 the ice was a little inside the terminal moraine, and a small terminal lake formed near the moraine, the predecessor of Jökulsárlón. The moraine segment in this area indicates repeated advances of the ice margin around the terminus of Esjufjallarönd (cross profile D-D' on Figure 13). By the time it was detached from Esjufjallarönd, this moraine segment had developed for a period of ~20–25 years.

On the east bank of the main channel of the Jökulsá, the terminal moraine developed before 1904. Here, a sequence of moraine ridges indicate several advances in the early twentieth century, related to activity in the Jökulsá-/Esjufjallarönd segment of the snout (Figure 12b). These multiple ridges coalesce to a single moraine further east. Directly east of the Jökulsá main channel, the moraine has been eroded by late nineteenth century meltwater incisions (Figure 15a). This complex terminal segment indicates prolonged terminal activity, interlinked with fluctuations of the Jökulsá

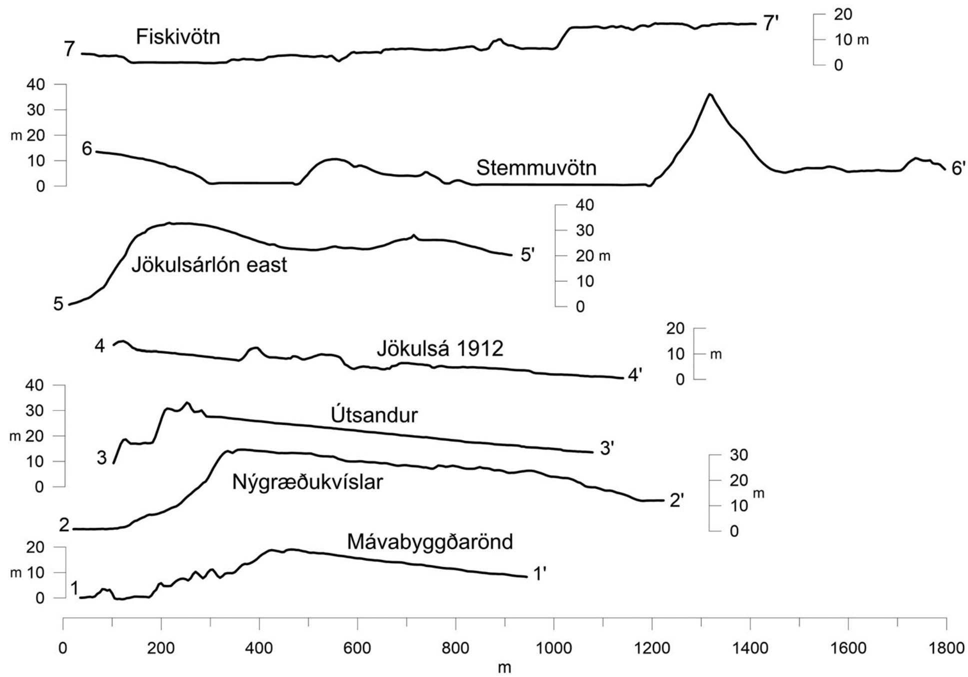

Figure 13. Selection of cross profiles of the LIA terminal end moraine to demonstrate spatial differences in size/volume. Hálfdánaralda (B-B′) and Esjufjallarönd (D-D′) moraines formed where the medial moraines terminated. Inset map on Figure 11 shows cross profile locations.

meltwater outlet. In the period 1860–1890, the river occupied this area and together with the smaller river Stemma developed an outwash fan. The Jökulsá changed course and flowed towards the river Stemma twice in the early decades of the twentieth century. Numerous kettle holes are most likely related to this activity (see below). The glacier margin east of the river Stemma, the Fellsöldur segment (Figure 15a and b), was noticeably dynamic in the eighteenth and nineteenth centuries. After 1869, it was less than 230 m from the sea and subsequently advanced, reaching the coast in 1878. There it remained until it started to erode sometime after 1880. Activity but no advance in the glacier snout was noted in 1894 but it had retreated ~43 m from its maximum extent by that time (Þoroddsen 1959; F. Björnsson 1998a). Ten years later, the snout was 200–300 m behind the end moraine. It is likely that the Fellsöldur segment of the moraine developed for a

Figure 14. Jökulsá á Breiðamerkursandi and the terminus of the Breiðamerkurjökull outlet glacier in 1902. This former river bed is still visible at in the glacifluvial outwash landforms near the Jökulsá. Photograph by D. Bruun. National Museum of Denmark.

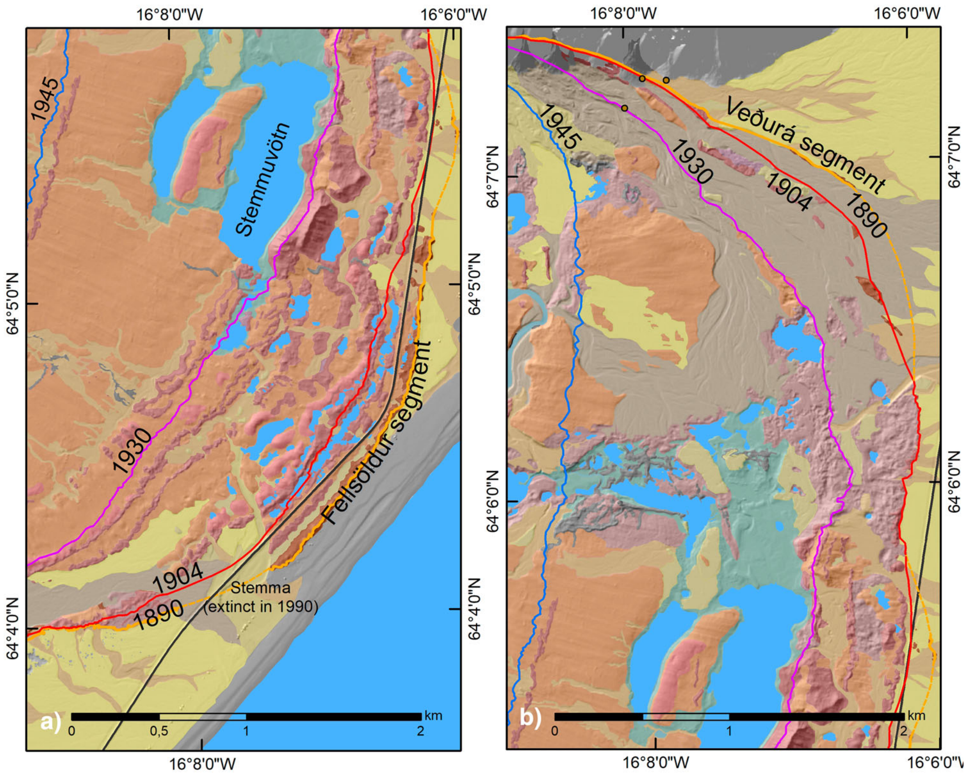

Figure 15. The eastern section of the terminal moraine at Breiðamerkursandur: (a) the Fellsöldur segment; (b) the Veðurá segment.

decade or more. Further east of the Fellsöldur segment, where the branches of the former river Brennhólakvíslar exited the glacier, the DGS map indicates that no moraine had formed by 1904, with the exception of fragments close to the Fellsfjall (the Veðurá segment, Figure 15b). Whether or not this records a later advance by the glacier snout at that time is unknown.

In summary, over the period 1870–1880, Breiðamerkurjökull had reached its historical LIA maximum extent. The terminus remained in this position, with variably timed oscillations taking place along several segments of the margin until 1890 or even later. The terminal moraine is therefore a complex that gradually developed over 15–25 years along with the superimposition of medial moraines in the Hálfdánaralda and Esjufjallarönd areas. The latter started to develop in the twentieth century, with the terminus reaching its maximum extent in 1933. The formation of the terminal end moraine as a single feature therefore developed over the period of 60–70 years.

Detailed retreat pattern of the Breiðamerkurjökull margin (early twentieth century to present)

Several papers have addressed the marginal changes of the retreating Breiðamerkurjökull, usually for specific years when the snout has been captured in maps and available aerial photographs, but since 2000 by annual monitoring using satellite imagery (Todtmann 1960; Welch 1967; Price and Howarth 1968, 1970; Price 1982; Evans and Twigg 2002; Evans, Guðmundsson et al. 2019). Since terrestrial or aerial surveys were carried out sporadically in the early twentieth century, published maps illustrate only some dated terminal positions, between which exist substantial gaps in the timeline. The longest uncharted interval is between the DGS 1904 and AMS 1945 surveys when very few records were preserved. According to F. Björnsson (1998a), the retreat was rather gradual until the 1930s but the rate of the retreat has varied along the terminus, dictated by different rates of downwasting and, more latterly, ice calving into proglacial lakes.

Some photographs taken over the period 1912–1935 have made it possible to demarcate segments of the terminus at specific years. Additionally, members of the Icelandic Glaciological Society (Jöklarannsóknafélag Íslands) have monitored a number of outlet glaciers in Iceland, including Breiðamerkurjökull, and the local farmers from Kvísker and Reynivellir carried out annual measurements of the position of the terminus from 1932. The late Kvísker siblings preserved some local oral tradition that has been useful in estimating changes of the terminus in the first decades of the twentieth century. The farmers also noted exceptional changes, like significant glacial advances or depleted river courses. These comments are of great value in tracing the development of the terminus and its oscillations as well as related landform evolution. Four baselines anchored at various points along the former terminus were established to measure the snout activity on an annual basis. Occasionally their trajectory needed to be adjusted when the glacier margin became inaccessible because of proglacial lake formation. The general method was to estimate snout change in metres and build cairns to mark the position of the ice margin each year, thereby creating a transect line of cairns. Unfortunately, due to their small size and poor resilience to the weather, many of the cairns were totally or temporarily lost and hence the transects could no longer be traced. A number of the surviving cairns or markings have now been coordinated, and this has enabled the recovery of data for the reconstruction of annual terminus retreat in several areas (Figures 16 and 17). With this diverse database we traced the position of the glacier margin since the maximum extent in the late nineteenth century to present. At several sections, the terminal position was traceable in historical order of several decades. Additional data on the river tracts and channels provided valuable information for tracing or locating marginal changes for specific years. These features improve our potential to date landforms, obtain an overview of morphological development and constrain the colonization rates of vegetation.

The graph in Figure 18 is a simplification of the ice retreat across the Breiðamerkurjökull snout since the late nineteenth century. Annual changes were measured at 24 baselines, distributed at approximately every kilometre along the snout. From left (west) to right (east), the lines E-1 to E-11 cover the eastern flow unit, M12 to M-18 the central flow unit and V-19 to V-24 the western flow unit. The maximum extent is demarcated by the horizontal zero line at the base, representing 1890 or the beginning of the retreat. The coloured lines are based on firm data on marginal positions (distance in metres on left vertical axis) from the terminal moraine in specific years (right vertical axis), using aerial or terrestrial oblique photographs, satellite images, maps and measurements cairns. The grey lines indicate the average annual retreat between the well identified terminal positions. The graph clearly depicts the variations in the retreat rates between the three major flow units/lobes. This ranges from a retreat of up to 8 km by the Norðlingalægðarjökull flow unit to 4.5–5.5 km for the Mávabyggðajökull flow unit. The rates of recession reflect also the impacts of climate variation on the glacier. In the first decades of the twentieth century the snout was largely retreating rather slowly at ~10–20 ma^{-1}. The exception to this was the section of Esjufjallarönd-Jökulsá (A-9 to M-12) where the glacier advanced until 1933 (Björnsson 1996a). The 1930s then turned warmer and the recession along the glacier margin accelerated along with the initial formation of the proglacial lakes. After 1945, climate warming slowed and the pace of retreat fluctuated from being rapid to slow over an interval of several years. The period 1970–1995 was one of relative cooling and the retreat slowed down significantly. Since the prominent re-advance of the early 1990s, a strongly warming climate has driven a phase of fast to rapid retreat (see Evans, Guðmundsson et al. 2019 for further details).

In addition to these climate drivers of snout recession, there is a clear pattern emerging that demonstrates the increasing impact of ice calving into the Jökulsárlón tidal lake (Figure 18). This

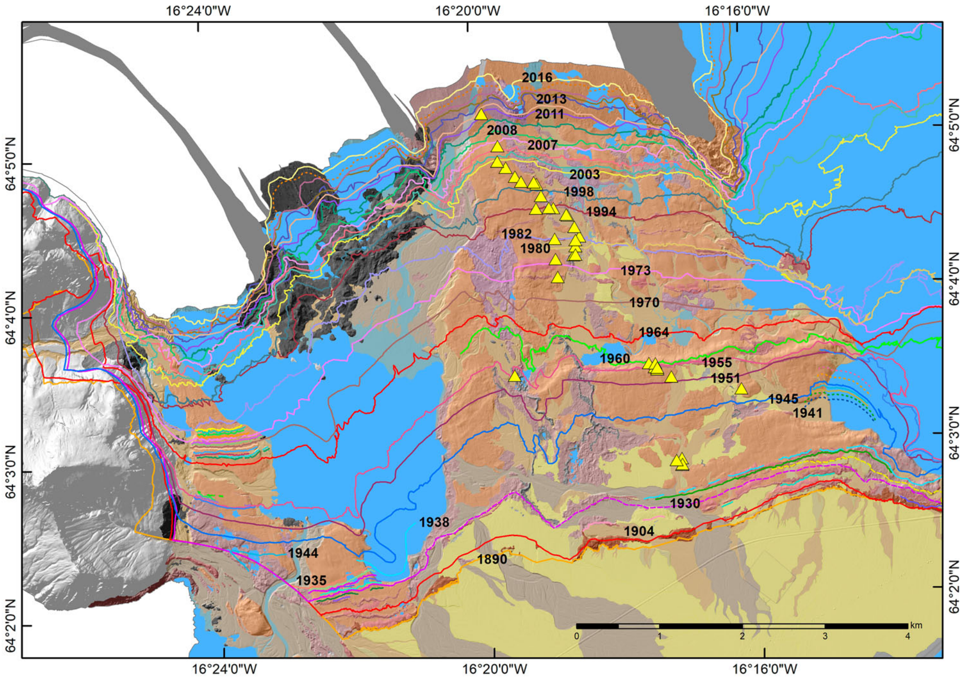

Figure 16. Historical ice marginal position for Breiðamerkurjökull, west of Jökulsárlón. Yellow triangles mark locations of remaining measurement cairns built in the twentieth century.

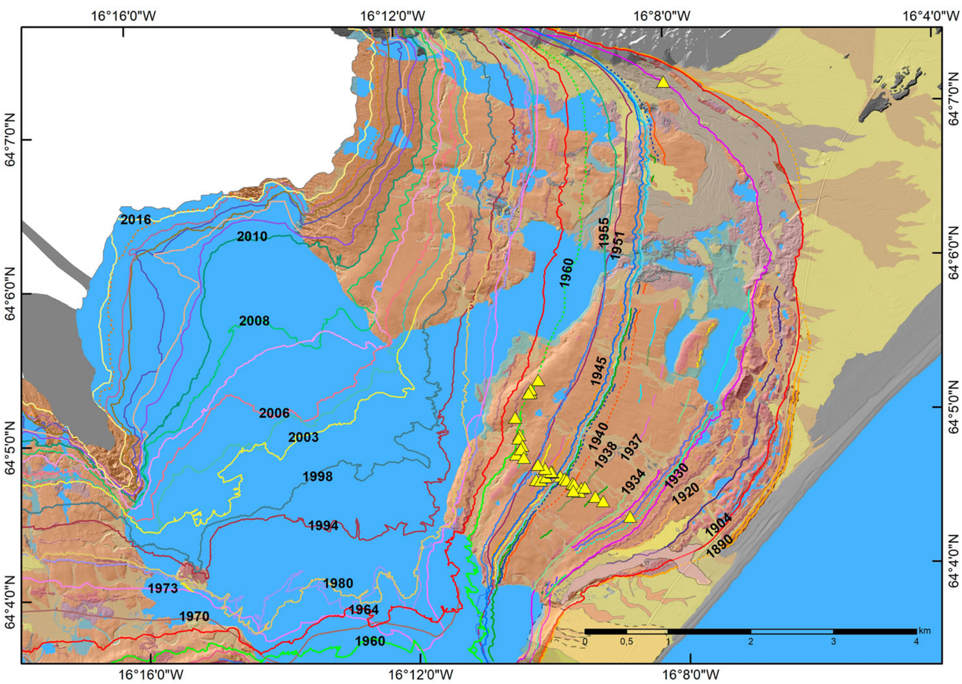

Figure 17. Historical ice marginal position for Breiðamerkurjökull, east of Jökulsárlón. Yellow triangles mark locations of measurement cairns built in the twentieth century.

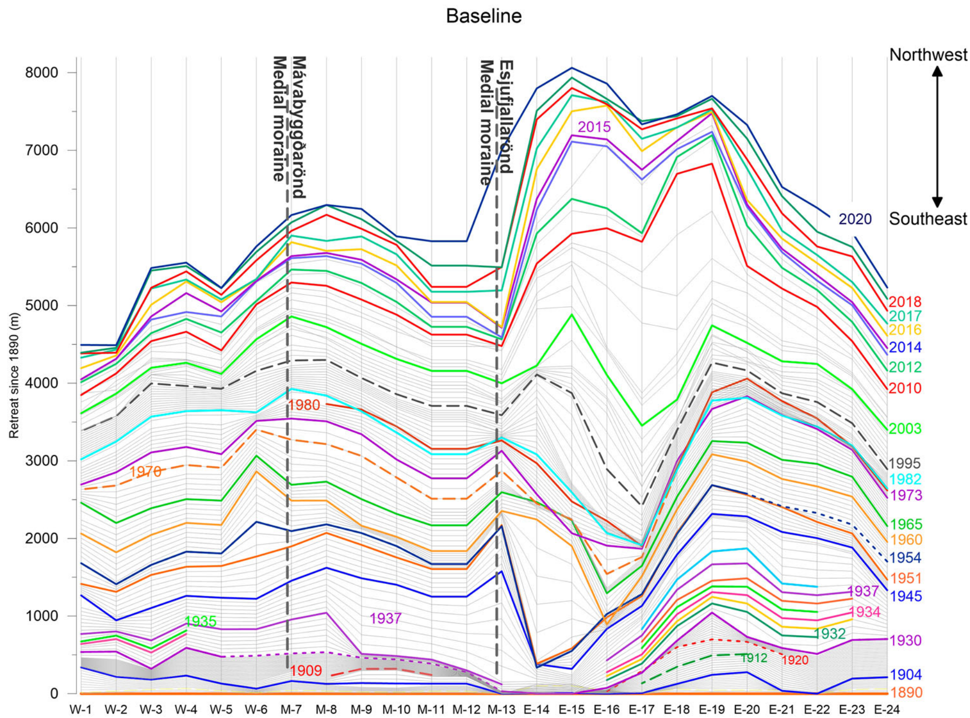

Figure 18. The retreat pattern of the three major ice flow units of Breiðamerkurjökull.

lake formed in the 1930s and grew steadily until the mid-1950s. Then it expanded rapidly on its west side for a few years and remained at that shape, gradually enlarging until the 1980s, after which a new calving period began. Since the turn of the twenty-first century the ice calving has been rapid, especially between 2003 and 2010, and annual retreat of the ice front has ranged from 0.25 to 0.4 km. Seawater enters the lake during high tide and the circulating current brings relatively warm, salty water under the ice front, thereby likely accelerating the calving (e.g. Rignot et al. 2010; Schild et al. 2018; Bevan et al. 2019; Ólafsson 2013). Currently, about 8 km of water separates the ice front from the south coast. This is in distinct contrast to the ice recession rates in the Breiðárlón proglacial lake, west of Jökulsárlón, which is not tidal nor as deep and hence induces slower melting and calving (cf. Baurley et al. 2020).

Development of relict channels and fans of the Breiðamerkursandur

In the late eighteenth and the nineteenth centuries, several glacial meltwater drainage pathways from Breiðamerkurjökull were already recognized by name, indicating well-established sources during the LIA advance (Pálsson 1945; Þoroddsen 1959; Ólafsson and Pálsson 1978). These rivers terminated at the coast or in estuaries, but when the glacier began retreating from its terminal moraine, the drainage changed significantly. This development of the drainage system of Breiðamerkurjökull between 1904 and 1965 was detailed by Welch (1967), Price (1969, 1970) and Price and Howarth (1970). In the twentieth century and later, the changes in the meltwater drainage pathways resulted in their decanting into the developing proglacial lakes, gradually reducing the number of streams actually reaching the coast. Currently, the Fjallsá and Jökulsá carry all the glacial meltwater to the sea. The sequential chronological development of the drainage system of Breiðamerkurjökull is presented on the maps in Figures 19–23, a sequence largely elucidated by Flosi Björnsson (1993, 1996a). The main meltwater rivers at the turn of the twentieth century were: Múlakvísl, Hrútá and

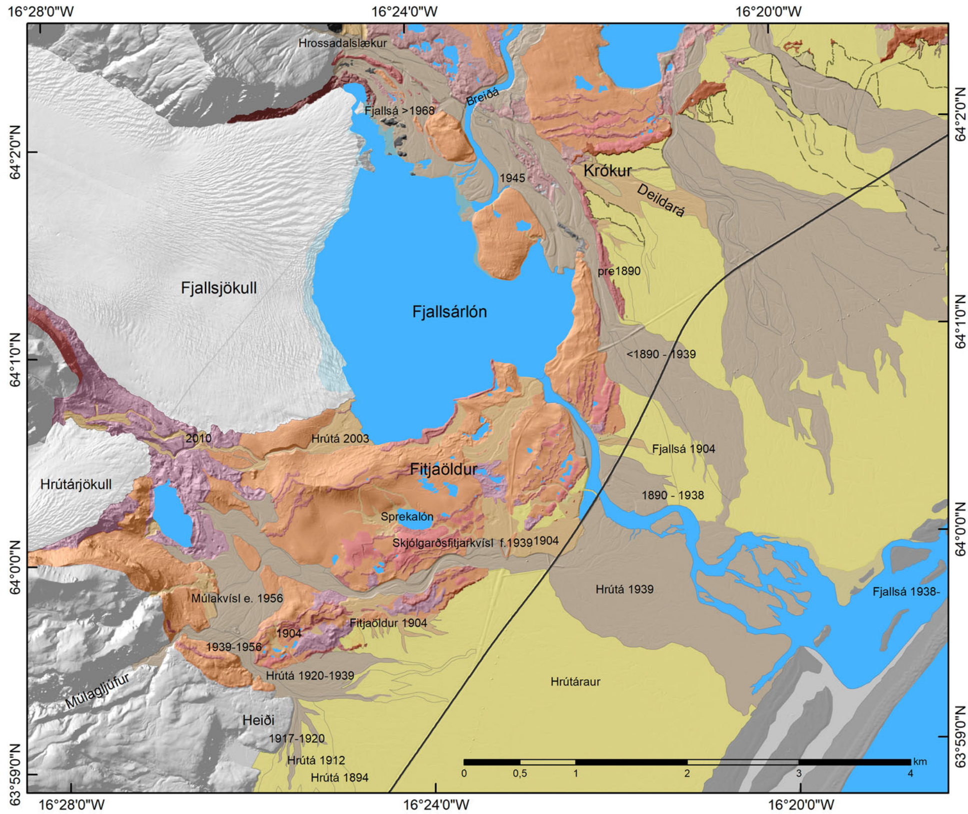

Figure 19. Historical evolution of the glacial rivers Múlakvísl, Hrútá and Fjallsá since the nineteenth century to present.

Fjallsá (Figure 19) in the west and draining the Kvískerjajöklar, Hrútárjökull and Fjallsjökull outlets, respectively; Deildará, Breiðá and Nýgræðnakvíslar (Figure 20), west of Esjufjallarönd; and Jökulsá (Figure 21) and the two Stemma rivers, Brennhólakvíslar and Veðurá (Figure 22), east of Esjufjallarönd.

Initially, the river Múlakvísl joined the Hrútá in front of Múli, were its outlet persisted until the 1930s. Before that the Hrútá drained onto the Hrútáraurar but flowed occasionally close to the Kvísker hayfields from 1894 to the late 1930s. From 1939 the outlet of Hrútá migrated gradually further east, as a consequence of the progressive retreat of Hrútárjökull. The river Múlakvísl then became detached, flowing alongside Heiði or directly across Hrútáraurar. In 1956, it burst towards the northeast to re-join the Hrútá (F. Björnsson 1996a). The Hrútá outlet remained near the medial moraine of Hrútárjökull-Fjallsjökull until the glaciers were separated in the first decade of the twenty-first century (F. Björnsson 1996a). The river developed a subglacial channel and a lake near the snout of Fjallsjökull and eventually found its way to the Fjallsárlón lake, where it terminates at present (Figure 19).

The Fjallsá, presently the second voluminous river of Breiðamerkursandur, may have flowed close to its current riverbed or < 1 km further west in the early nineteenth century, based on the Gunnlaugsson map of 1844. Decades later its stable outlet was located near the coalescent corner of Fjallsjökull and Breiðamerkurjökull, named 'Krókur', with the river expanding on the flat outwash plain but occasionally streaming near Fitjaöldur in the 1890s (F. Björnsson 1996a). The outlet of Fjallsá remained at Krókur until the glacier retreated off its LIA maximum position, at which time the river was routed between the end moraine and the ice (Figures 19, 20 and 23). The Fjallsá was constrained to this riverbed until 1938, when in the wake of a jökulhlaup it migrated to a new

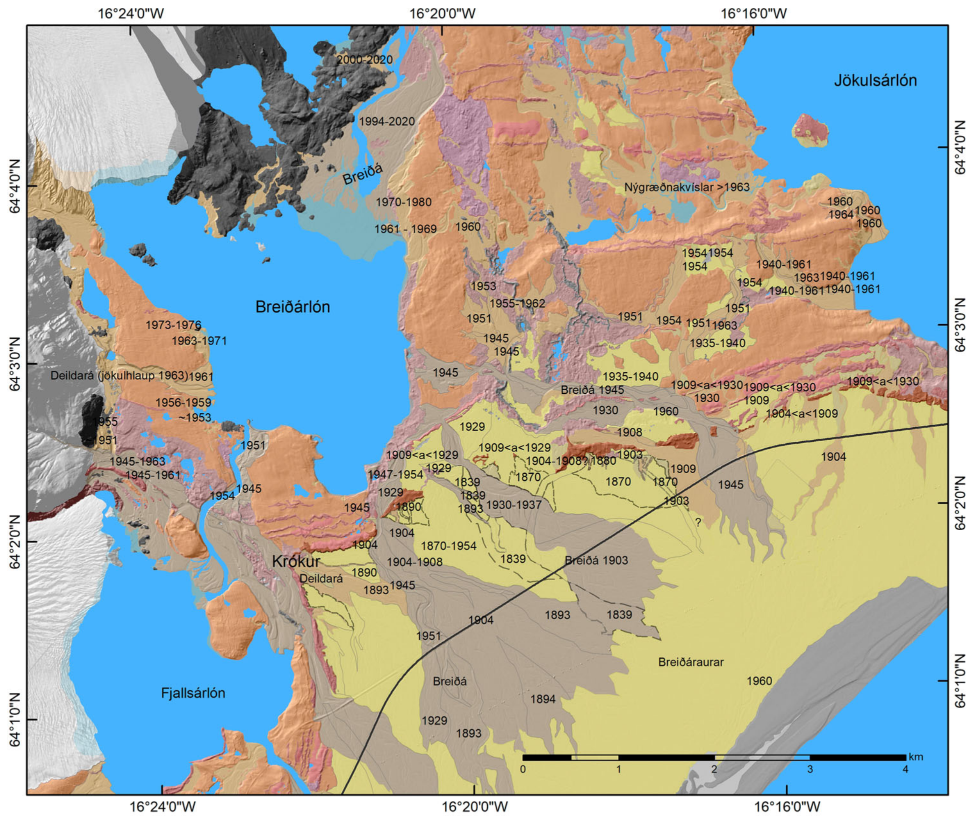

Figure 20. Historical evolution of the glacial rivers Deildará, Breiðá and Nýgræðnakvíslar from the nineteenth century to present.

one, again closer to the ice margin. A proglacial lake began developing in the late 1930s, with the river draining into it and then flowing along a former riverbed between the high moraine of Fitjar, which it then incised and widened for it to eventually become the current watercourse (Herforingjaráðið 1905; AMS 1951; F. Björnsson 1996a). In the 1950s two lakes appeared and were connected by the Fjallsá until they eventually merged into one lake. Currently, the Fjallsá emerges at the easternmost tip of Fjallsjökull below Breiðamerkurfjall, and then flows into the Fjallsárlón lake and out again to the sea.

The river Deildará (Figure 20) drained the westernmost segment of Breiðamerkurjökull. In the late nineteenth century, it flowed from Krókur and joined either the Fjallsá or sporadically the nearby Breiðá on the outwash fan. At the turn of the twentieth century it changed course to join the Fjallsá until the 1960s. The Jökuldalur jökulhlaups of 1963 breached a channel and redirected Deildará to the Breiðárlón terminal lake (F. Björnsson 1996a). The predominantly small river remained in this channel until ~2008, when it developed another course to the lake, closer to the retreating snout of Breiðamerkurjökull.

The river Breiðá (Figure 20) is the third most voluminous river on Breiðamerkursandur. Currently it consists of two separate stretches, the first emerging from Breiðamerkurjökull and flowing for ~2 km to the Breiðárlón lake and the second flowing from the lake and into Fjallsárlón. Pálsson (1945) described it as small glacial melt river in 1794. The Gunnlaugsson map (1844) locates the river approximately in the eastern of two dominant parallel riverbeds, about 1 and 2.1 km east of Krókur, respectively. In 1893–1894 the river flowed along the western pathway, as did it in 1904, but in 1903 and 1908–1909 it drained the east side of Mávabyggðarönd and flowed east. The river then again migrated to the western pathway and remained there until the

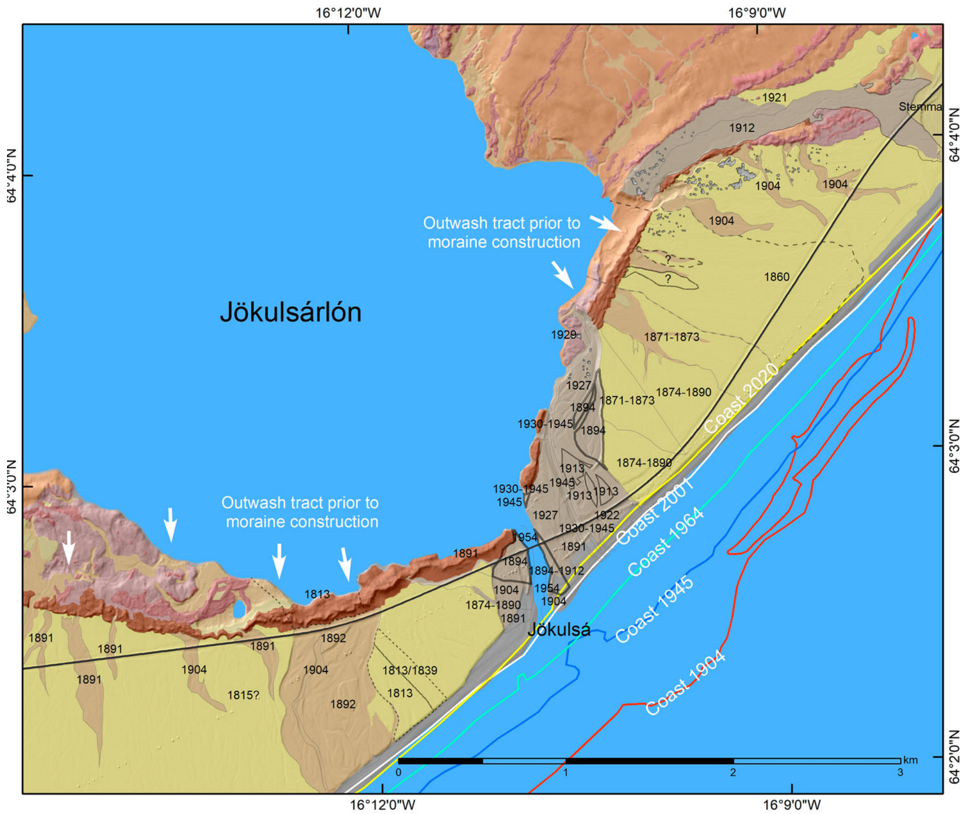

Figure 21. Historical evolution of Jökulsá from the nineteenth century to present.

1930s. According to F. Björnsson (1996a), Breiðá emerged close to a small medial moraine located east of the westernmost terminal moraine in the late 19th to early twentieth century. However, the river tended to emerge from various locations over the distance of a few kilometres along the margin, sometimes located east of Mávabyggðarönd. These fluctuations resulted in the development of an extensive, flat outwash fan. The Breiðárlón terminal lake began to form around 1932 and it later became clear that the river originated from it (F. Björnsson 1996a). In the 1940s, the river flowed to the east from the lake then migrated into its old watercourse to the south. In 1954, Breiðá breached an ice barrier and changed course to the west, joining Fjallsá in front of Breiðamerkurfjall. It has maintained this channel but now terminates in Fjallsárlón. After the Breiðárlón lake formed, the river exited subglacially directly into it. It then later flowed into the lake near the east bank in the 1980s but by about 1995, after substantial glacier retreat and significant glacifluvial deposition had formed an outwash tract, the Breiðá emerged to the east of Mávabyggðarönd. The outwash tract is partly ice-cored and this will likely influence the future course of the river. A recently developed proglacial lake located east of Breiðárlón will eventually dominate the area and the Breiðá will again flow subglacially directly into it.

Characterized predominantly by low water flow, the branches of Nýgræðnakvíslar emerged from the central ice flow unit (Esjufjallajökull), usually close to Mávabyggðarönd, about 4.5 km west of Jökulsá. These branches are not mentioned explicitly in the nineteenth-century references, except Þoroddsen (1959), who remarks in his 1894 journey that the locals have recently started to collectively call them Nýgræðukvíslar. The indication is they first appeared in the nineteenth century and usually flowed in channels constrained by the coalescence of the outwash fans of Breiðá and Jökulsá. They changed course early in the summer of 1963,

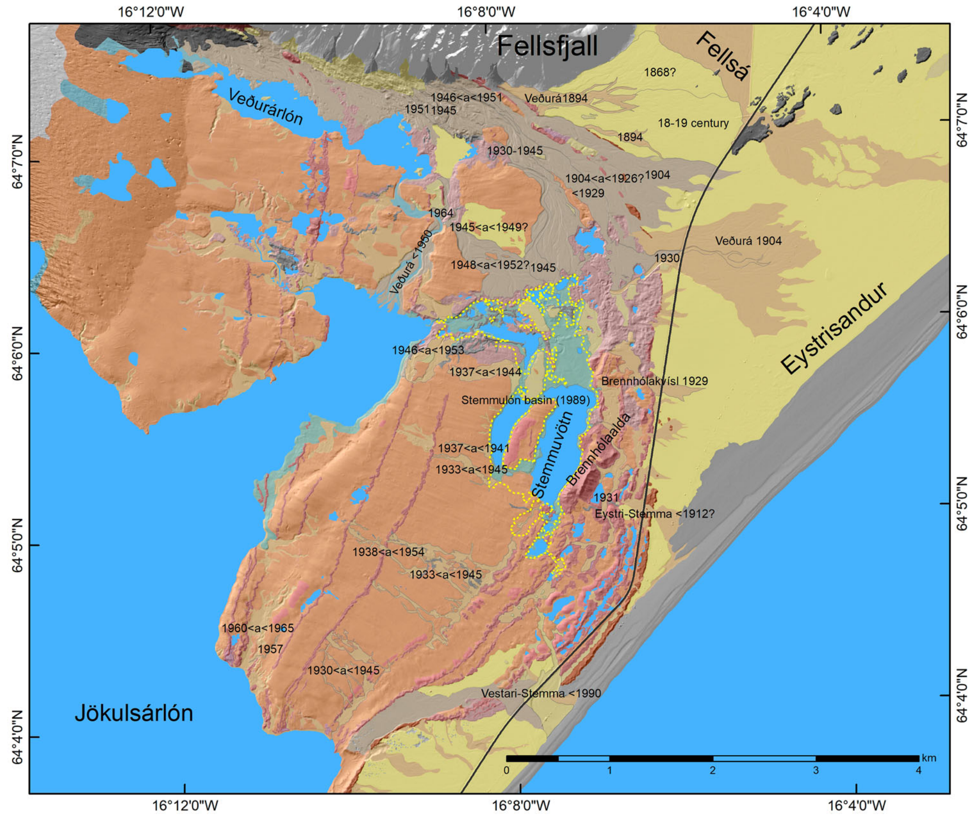

Figure 22. Historical evolution of the rivers Stemma, Brennhólakvísl and Veðurá from the nineteenth century to present.

flowing east into Jökulsárlón (F. Björnsson 1996a). The branches have maintained a channel below the prominent slope located 2.3 km north of the terminal moraine, a feature that continues to emerge as snout retreat proceeds.

The Jökulsá á Breiðamerkursandi drains the Jökulsárlón tidal lagoon (27 km^2). Until a bridge was established in 1967, this was one of Iceland's most infamous rivers and for travellers moving on horseback was the greatest obstacle on the only road along this part of the south coast. The river Jökulsá is amongst the most voluminous rivers in Iceland, with an estimated average flow rate of ~ 250–300 m^3/s. Ocean tides influence the inflow and outflow of glacial water, resulting in a much higher maximum rate of flow (Guðmundsson and Björnsson 2020). The Jökulsá is also the shortest glacial river in the country, as the length of the current channel is only 0.6 km long (Figure 21). The Jökulsá has remained in this channel since the 1930s but started to develop it in the late nineteenth century (F. Björnsson 1993; Guðmundsson and Björnsson 2020). Before that it migrated over the outwash fan, occasionally in several branches or as a single channel (Þoroddsen 1959). Dry outwash tracts and channels on either side of the current channel reflect the former behaviour of the river. The geomorphology indicates that the migrating river deposited an ~8 km wide delta before it began to incise channels (Guðmundsson and Björnsson 2020). During the LIA advance, the wide fan gradually extended outward by >1 km, mainly due to sediment deposition by the Jökulsá river and a few other meltwater streams. The first reliable location of the Jökulsá is marked on the Danish Coastal Survey map, published in 1818–1826 from a survey in 1812–1813 (Sigurðsson 1978). The Gunnlaugsson map (1844) locates it at the same place. Björnsson (1993) reports the frequent relocation of the river in the latter half of the nineteenth century and when the DGS surveyed the area in 1904 the river had once again changed course and extended

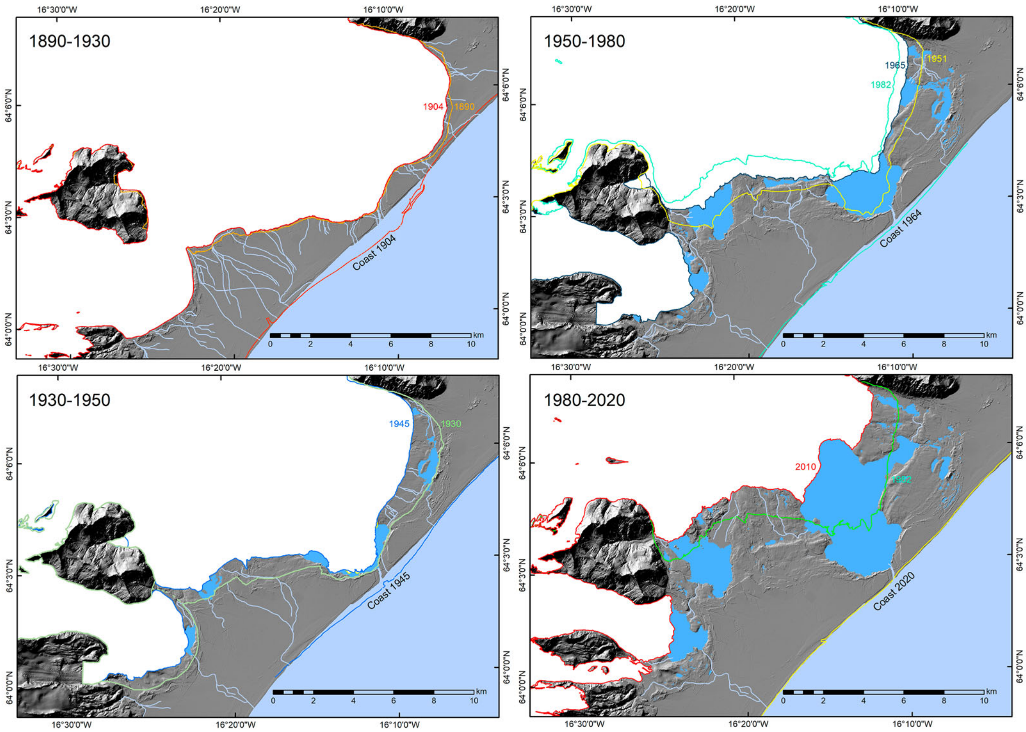

Figure 23. Summary map sequence showing the historical evolution of the proglacial drainage patterns on the Breiðamerkurjökull foreland. Although several outlet streams are depicted in some areas for specific time periods (i.e. 1890-1930), predominantly only one outlet would have operated at a time but channel switches were numerous and frequent.

the coastline. In 1912–1913 and 1921 the Jökulsá changed course and flowed east towards the river Stemma, inside the end moraine, and then returned west to its usual course. Both incidents occurred when substantial activity and advance was witnessed along this part of the east lobe. Shortly before 1920 the Esjufjallarönd/Jökulsá segment became thicker and advanced slowly, an event which lasted until 1933 (F. Björnsson 1993, 1998a). The pitted outwash in the vicinity is thought to be related to this activity, as the river repeatedly flowed across the ice margin. At the turn of the twentieth century, the glacier margin started to retreat slowly and in the 1930s terminal lakes were formed. With the formation of the Jökulsárlón tidal lagoon, glacifluvial deposition on the coastal shore terminated and was replaced by progressive coastal erosion. Since the 1930s, ~0.9 km has been eroded from the coast. A 0.65 km wide strip now remains between the coast and the Jökulsárlón tidal lagoon, were the river Jökulsá and the remains of its former outwash channels are located. The river relocated occasionally until Jökulsárlón began to form around 1933, when the outlet finally stabilized. The Jökulsá outwash tracts and channels that were formed in the nineteenth and twentieth centuries are presented in Figure 21.

The two Stemma rivers and Brennhólakvíslar channels (Figure 22) first appeared in the nineteenth century. Prior to that, no river emerged from the terminus east of Jökulsá except the Veðurá near Fellsfjall. The Stemma rivers were rather small until they were joined by the Veðurá. Flosi Björnsson (1996a) notes that this took place in the summer of 1929, but an oblique photograph taken onboard the airship Graf Zeppelin in July 1930 show the Veðurá still located in its initial course and flowing east. Flosi Björnsson (1993) notes that the Veðurá did not flow in its usual channel in 1926, which indicates occasional relocation before eventually changing course around this year. At the same time, the Stemma flowed in a system of channels and ponds from each side of the thrust moraine Brennhóla alda. Around 1930 a proglacial lake started to form behind

Brennhóla alda, later forming Stemmulón, with the Stemma flowing out from the south shore of lake. The river maintained a stable path, and even after it turned into a larger watercourse due to its adjoining with the Veðurá, the majority of the deposition was into the lake (F. Björnsson 1996a). In September 1990 this river disappeared when the last ice threshold separating Stemmulón from Jökulsárlón was breached and its water accumulated in Jökulsárlón. The following year, Stemmulón, which had reached an area of 3.6 km^2, became part of Jökulsárlón (Imsland 1990; Guðmundsson et al. 2019).

The river Veðurá (Figure 22) flowed over the Veðuráraurar outwash in the 1700s (Sýslulýsingar 1744–1749). Pálsson (1945) commented in 1794 that the river was rather small and emerged close to the base of Fellsfjall, flowing towards the east. Henderson (1815) on the other hand briefly described it as wide river to cross and noted remnants of peat and tree trunks on its banks. Flosi Björnsson (1996a) explains this apparent contradiction by suggesting that, compared to other rivers on the Breiðamerkursandur, Veðurá was small but could carry larger discharges in early summer when the snow was melting in the mountains. In 1869 a jökulhlaup in the Veðurá resulted in the devastation of the farm Fell. A possible cause was a release of an ice-dammed Iake in Veðurárdalsfjöll, but in a contemporary journal it is reported that Jökulsá rushed east and merged with Veðurá and both rivers ruined the farmhouses (Norðanfari 1870). On the DGS map (1905) the river is merged with the Brennhólakvíslar branch, heading east. Brennhólakvíslar was a small channel that emerged from what appears now as a small patch of pitted outwash and hummocky moraines. It had disappeared most likely by 1929, according to F. Björnsson (1996a). In the first decades of the twentieth century, and along with the gradually retreating glacier margin, Veðurá continued to emerge at the base of Fellsfjall but flowed southward close to the glacier margin and then turned east. This continued until 1929–1930, when it joined the developing proglacial lake Stemmulón and river Stemma. By this time it had formed several terraces at the foot of Fellsfjall. In the 1930s, the Veðurárlón proglacial lake started to develop (Guðmundsson et al. 2019), with Veðurá first terminating in it and then flowing out from it. In the early 1950s, the Veðurá had migrated to, and formed a riverbed at, the glacier terminus, where it began to incise, later producing its present day channel and flowing out from the Veðurárlón terminal lake.

Discussion

The development of process-form models (landsystems) at Breiðamerkurjökull/Fjallsjökull based upon semi-continuous monitoring and experimentation has established the foreland as the most widely cited and one of the most influential in glacial geomorphological research. This has been a consequence of well-documented and/or surveyed changes around the glacier margins over a timescale and at spatial scales suitable to the development of process-based modern analogues, which are critical to quantification in geomorphology but often difficult to procure in glacial systems (Price 1980). In this respect, the Breiðamerkurjökull/Fjallsjökull foreland has become a continuously evolving modern analogue for science and education, where quantification of glacial processes has taken place in real time, at timescales ranging from hours (e.g. Boulton and Hindmarsh 1987), to days (e.g. Björnsson 1962; Boulton et al. 2001), to years (e.g. Price 1970, 1971; Howarth 1971; Boulton 1986; Evans and Hiemstra 2005; Chandler, Chandler et al. 2020) to decades (e.g. Price and Howarth 1970; Price 1982; Storrar et al. 2015). The range of process-form regimes thereby displayed has established the foreland as the exemplar for the active temperate glacial landsystem. Additionally, historical observations have been critical to developing the concepts of landsystem switching and overprinting and azonal and intrazonal changes in landsystem signatures (*sensu* Evans 2013), which at Breiðamerkurjökull and Fjallsjökull have included the juxtaposition of localized surge events (Boulton et al. 2001; Evans and Twigg 2002; Björnsson et al. 2003), climatically-driven glaciological changes (Guðmundsson et al. 2017; Evans, Guðmundsson et al. 2019), topographically-controlled changes to the morphology and structural architecture of the thinning glacier snouts (including calving; Guðmundsson and Björnsson 2016; Storrar et al. 2017), and fundamental changes to proglacial drainage networks in response to the changing topography of deglaciating forelands (Price and Howarth 1970; Figure 23).

Our study constitutes not only a continuation of the observations on process-form regimes and landsystem change at active temperate glacier snouts in a warming climate but also the further refinement of the temporal scales of change. Technological advances in data collection and mapping have made it possible to accrue more details, increase resolution and reduce geometrical distortion so that the resulting maps have become more nuanced and more accurate. This development, of not only landsystem models for different glacierization styles but also the recognition of their tendency to evolve at various spatial and especially short temporal scales, addresses a need for continued monitoring of Icelandic temperate glaciers to assess the impacts of ongoing climate change, both on geomorphic systems (e.g. Bennett et al. 2010; Bennett and Evans 2012; Bradwell et al. 2013; Evans et al. 2016, 2017a, Chandler et al. 2016a, 2016b; Evans, Ewertowski et al. 2019, Chandler, Chandler et al. 2020; Chandler, Evans et al. 2020) and on glacier recession rates and dynamics (e.g. Sigurdsson et al. 2007; Hannesdóttir et al. 2014, 2015; Phillips et al. 2014; Guðmundsson and Björnsson 2016; Guðmundsson et al. 2017; Storrar et al. 2017; Dell et al. 2019; Evans, Guðmundsson et al. 2019).

Over the last 130 years, the retreat of Breiðamerkurjökull has uncovered a land area of more than 120 km^2. The most prominent changes between 1998, the previous map compilation year (Evans and Twigg 2000), and 2018, the year presented in our new map, have been an ice margin retreat of 0.6–4.0 km, the deglaciation of ∼29 km^2 of foreland, and the expansion of Breiðamerkursandur by approximately 20% to its present area of 178 km^2. Approximately 50% of the area uncovered since 1998 is water surface and in 2018 water covered around 22% area of the Breiðamerkursandur; Breiðárlón expanded from 5 km^2 to 5.8 km^2 (16%) and Jökulsárlón from <15 km^2 to 27 km^2 (80%).

This significant expansion in lake water over time has been concomitant with changing drainage patterns, as first documented by Todtmann (1960) and then surveyed in greater detail by Price and Howarth (1970). Our more precise dating has further detailed the temporal scale of these changes, wherein significant switches in meltwater river courses are seen to have taken place, often at sub-decadal to annual timescales (Figure 23). The general trend in proglacial drainage identified by Price and Howarth (1970) was a change from unrestricted outwash sandur fans to restricted or linear (ribbon) sandar. This trend has since been identified in other southern Iceland glacier forelands (e.g. Evans and Orton 2015; Evans et al. 2016) and, due to increasing rates of snout recession and expanding foreland areas, can be now confidently explained as a function of increasing topographic control. This has been conditioned by the uncovering of glacially overridden, elongate landforms (large push moraine complexes and ice-contact fans) that lie ice-flow transverse and hence divert and constrain proglacial meltwater streams.

Glacifluvial landforms and deposits are those most prone to change over the historical timescale presented here. This has necessitated some changes to genetic classifications. Particularly prominent has been the aggradation of glacifluvial outwash over large areas of the downwasting glacier snouts, a phenomenon well documented initially by Price (1969, 1971). This has been observed in at least one instance to have resulted from ice-dammed lake outburst floods (Björnsson 1962; Price 1971), whereby snout thinning has led to the release of lakes that were dammed in side-valleys. The extensive tracts of collapsed, ice margin-parallel sandur on the eastern foreland, dating to 1904–1930s, are the largest of this type of ice-cored outwash and were initially deposited as kame terraces up against the ice-contact slope of the Veðurá outwash head (cf. Evans and Orton 2015) but have gradually evolved into kame and kettle topography. A more recent example of this style of sandur to kame and kettle development is that of the glacifluvial depositional environment along the margin of the Mávabyggðarjökull ice flow unit (Figure 9a), which from the 1970s has accumulated as ribbon sandur but since the early years of the twenty-first century has gradually collapsed due to ice melt. More complex has been the emergence of eskers through downwasting ice-cored outwash fans and medial moraines; together with evidence of localized esker collapse this has helped to elucidate the spatial and temporal evolution of meltwater drainage systems and the up-ice migration of englacial tunnel networks and supraglacial fan progradation (Price 1969; Howarth 1971; Evans and Twigg 2002; Storrar et al. 2015).

In addition to these prominent glacifluvial examples, a further excellent example of linking historical observations with landforms to demonstrate unequivocal process-form regimes in glacial environments is that of the east Breiðamerkurjökull surges. Historical documentation of surges by the Norðlingalægðarjökull flow unit has been linked with the construction of the Brennhóla alda thrust moraine (Todtmann 1960), a diagnostic landform for the surging glacier landsystem and thereby used to identify surge overprinting in an active temperate setting by Evans and Twigg (2002). Although Björnsson et al. (2003) report only major surges (most recently in 1954, 1969 and 1978), mini-surges have been observed. For example, Boulton (1986) reports that a 200 m advance constructed a prominent push moraine in the early 1980s and Boulton et al. (2001) conducted subglacial till deformation experiments during a mini-surge in 1996. The post 1990s exposure of the eastern foreland presented and mapped in this study has verified a strong surging glacial landsystem signature, suggesting that mini-surges are strongly imprinted on the active temperate recession in the ice flow unit nourished by the eastern Vatnajokull ice cap (Breiðabunga).

The increased precision in dating the snout recession and landform emergence presented in this study has facilitated a more nuanced analysis of the timescales of geomorphic change in temperate glacial systems as first documented by Price (1980, 1982). Moreover, it has further emphasized the rapidity of change as first charted by Price and co-workers at Breiðamerkurjökull as well as the critical role of widespread buried glacier ice in such change, a phenomenon previously regarded as more diagnostic of the realm of jökulhlaup-influenced forelands at low altitudes in southern Iceland (Fay 2002; Everest and Bradwell 2003; Russell et al. 2006; Blauvelt et al. 2020).

The higher resolution chronology presented here for the entire foreland of Fjallsjökull and Breiðamerkurjökull provides an unprecedented opportunity to develop conversions of relative to absolute age dating techniques, specifically for lichenometry but also for the use of Schmidt hammer R-value dating. Previous developments of lichenometry based on a moraine sequence on part of the western foreland by Evans, Guðmundsson et al. (2019) can now be expanded over a greater area and for a larger range of glacial landforms, more specifically for glacifluvial assemblages (cf. Thompson and Jones 1986; Evans, Lemmen et al. 1999).

Conclusions

Employing recently acquired LiDAR imagery we have compiled a 1:24,000 scale geomorphological and surficial geology map of the glacial landsystem of Breiðamerkurjökull, a maritime active temperate outlet glacier of Vatnajökull, Southeast Iceland, at a greater level of detail than previously achievable. This also includes ~29 km^2 of foreland that has been uncovered by the retreating snout between 1998 (the last survey date) and 2018. Additionally, using a diverse data set we have traced with unprecedented accuracy the annual position of the terminus of Breiðamerkurjökull since its maximum LIA extent in the late nineteenth century to the present, revealing details on the geomorphic development of the terminal end moraine, medial moraine activity, the contrasting recessional behaviours of the terrestrial versus calving glacier margins, and the historical development of the proglacial outwash tracts of the rivers draining Hrútárjökull, Fjallsjökull and Breiðamerkurjökull.

The prominent LIA maximum end moraine was not constructed all at the same time but developed instead over several decades at different rates across the foreland. The western part of the terminus reached its maximum extent in the 1870s and remained more or less inactive after gradually forming the moraine. The eastern part of the terminus was active until as late as 1894. The development of the end moraine east of Fellsöldur was not completed until after 1904. The main sections of the terminal end moraine developed for 15–25 years but as a single feature it took >60 years to form, from ~1870 to 1933.

The marked pattern and relatively rapid pace of recession along Breiðamerkurjökull's lake-terminating margin is reflected in sustained periods of rapid calving. These include a period of a few years in the late 1950s when the ice front retreated 1.6 km in the western part of the lake, the period 1989–1994 when a 1.5 km wide ice tongue calved into the lake, and the period 2006–2011 when the calving front retreated by up to 2.35 km or 0.47 km a^{-1}.

In addition to being a modern exemplar for the active temperate glacial landsystem, the occurrence of documented surges and surge-diagnostic geomorphology at eastern Breiðamerkurjökull qualify its foreland as a further exemplar of spatio-temporal landsystem switching and overprinting.

Significant changes in meltwater river courses have occurred at sub-decadal to annual timescales, with the general trend from unrestricted sandur fans to restricted or linear (ribbon) sandar, which we can now confirm to be a function of increasing topographic control over time due to the gradual uncovering of glacially overridden push moraine complexes and ice-contact fans.

A significant component of rapid landscape change and landsystem development is related to glacifluvial process-form regimes in association with increasingly large areas of glacier ice buried by esker networks and outwash. The increasing role of ice-dammed lake outburst floods as well as ribbon sandar development over thinning snout margins has resulted in extensive tracts of pitted ice margin-parallel sandur, kame terraces and kame and kettle topography. It has also become increasingly more evident that ice-cored eskers are emerging not just through downwasting outwash fans and medial moraines but also from former englacial drainage tunnels that connected with ice-contact slopes on outwash heads.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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