Reviewed research article

Nunataks and medial moraines of Breiðamerkurjökull, southeast Iceland

Snævarr Guðmundsson[a], Helgi Björnsson[b], David J. A. Evans[c] and Finnur Pálsson[b]

[a] *South East Iceland Nature Research Center, Höfn in Hornafjörður, Iceland*

[b] *Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland*

[c] *Department of Geography, Durham University, South Road, Durham DH1 3LE, UK*

Corresponding author snaevarr@nattsa.is https://doi.org/10.33799/jokull2024.74.001

Abstract — *Nine nunataks have been exposed during the post-Little Ice Age recession of Breiðamerkurjökull, an outlet glacier of the Vatnajökull ice cap in Southeast Iceland. The outlet is fed by three branches that originate from the central ice cap. We analyse from digital elevation models (spanning 131 years, with the Equilibrium-Line Altitude (ELA) rising from 1000 m to 1200 m) the changes in the surface elevation and the development of the medial moraines originating from the nunataks. Elevation changes surrounding the nunataks in the central ablation zone show that ice flow compensated for about half of the lowering due to negative mass balance (up to 40 m from 2000 to 2022). During the 20th century, the internal driving stresses of the large ice branches (flow units) caused lateral displacement of medial moraines (up to 500 m), but as the glacier receded in the early 21st century, the subglacial topography started to dictate the migration patterns of the medial moraines. The Breiðamerkurjökull medial moraines are of the Eyles and Rogerson (1978) ISI and AD1 and AD3 types, whose historical lateral migration in some areas will disrupt their eventual accumulation as unbroken linear features on the deglaciated foreland, giving rise instead to gently inclined or folded englacial debris banding and ultimately the production of a supraglacial veneer.*

INTRODUCTION

Nunataks are rock outcrops, mountain ridges, or peaks that protrude from the surface of glaciers. The term is derived from the Greenlandic 'nunataq' (lonely peak), signifying an isolated rock or mountain peak surrounded by a glacier (Neuendorf, 2005; Ballantyne, 2013). In Iceland, they are named 'jökulsker', meaning a skerry or outcrop enveloped by the glacier. Nunataks are critical to the development of medial moraines, especially the ice stream interaction (ISI), below firn-line ablation-dominant (AD1) and subglacial rock-knob ablation-dominant (AD3) types of the Eyles and Rogerson (1978) scheme of medial moraine genetic classification. Rockfall material from nunataks also feeds supraglacial lateral moraines and can feed englacial debris bands where it descends into marginal crevasses (Small *et al.*, 1979; Small and Gomez, 1981; Small, 1987).

The identification of former nunataks in glaciated terrains (palaeonunataks) using trimline evidence (Ballantyne, 2013; Rootes and Clark, 2020, 2022) has been controversial in debates over palaeoglaciological reconstruction since the recognition of potential glacial refugia and altitudinal weathering zones in the mountains of eastern North America and Scandinavia (Ives, 1978; Marquette *et al.*, 2004; McCarroll 2016). Medial moraines associated with palaeonunataks predominantly have a poor preservation potential, but where they are preserved have been employed in improving our understanding of the interactions between rock slope processes (extraglacial debris provision) and glacial transport mechanisms (e.g. Ballantyne and Dawson, 2019). Like all aspects of palaeoglaciological reconstruction, our understanding of palaeonunataks and medial moraine construction relies ultimately on the appreciation of modern analogues, of which there have been very few that have reported on the spatial and temporal emergence and development of nunataks and medial moraines over historical timescales (e.g. Eyles and Rogerson, 1978; Vere and Benn, 1989; Guðmundsson and Björnsson *et al.*, 2016; Brook *et al.*, 2017). Hence, in this paper, we analyze the response of glacier ice and the development of emerging medial moraines and nunataks in Breiðamerkurjökull, a maritime temperate outlet glacier of the Vatnajökull ice cap in Southeast Iceland, since the late 19th century to provide quantified observations on such features in thinning ice caps more generally.

STUDY AREA AND SITE–SPECIFIC CONTEXT

General background

Breiðamerkurjökull is one of the most studied glaciers in Iceland. In the last few decades, its terminus behaviour, mass balance, recession rates and internal dynamics, together with the geomorphological development of the foreland, have been surveyed and analysed (Thorarinsson, 1943; Todtman, 1960; Price, 1969, 1982; Price and Howarth, 1970; Sigbjarnarson, 1970; Boulton *et al.*, 1982, 1988; Bogadóttir *et al.*, 1986; Boulton, 1986; Víkingsson, 1991; Björnsson *et al.*, 1992, 1999, 2001, 2003; F. Björnsson, 1993, 1996, 1998; H. Björnsson, 1996, 1998b, 2009; Evans and Twigg, 2000, 2002; Jóhannesson *et al.*, 2005, 2006; Nick *et al.*, 2007; Dąbski and Angiel, 2010; Guérin *et al.*, 2010; Schomacker, 2010; Bergsdóttir, 2012; Guðmundsson, 2014; van Boeckel, 2015; Storrar *et al.*, 2015, 2017; Jónsson, 2016; Brandon *et al.*, 2017; Pálsson, 2018, 2019, 2021, 2022, 2023; Guðmundsson and Björnsson, 2016, 2020a; Guðmundsson *et al.*, 2017, 2019; Evans *et al.*, 2019; Guðmundsson and Evans, 2022). Since 2004, detailed reports on Breiðamerkurjökull's mass balance and various other aspects have been published annually, providing accurate records of the glacier's budget and runoff (Pálsson, 2023).

Breiðamerkurjökull is the fourth-largest outlet glacier of the Vatnajökull ice cap. It is a complex of several ice flow units emerging from separate accumulation areas and converging in a wide outlet glacier. The feeder ice systems for this complex comprise the steep valley glaciers from the Mt. Öræfajökull stratovolcano and two relatively flat ice flow units, one emerging between Mt. Mávabyggðir and Mt. Esjufjöll and the other from the Vatnajökull basin (Björnsson, 1998a, 2009). The three main ice flow units, commonly acknowledged as Mávabyggðajökull, Esjufjallajökull and Norðlingalægðarjökull, are here referred to as the west, center and the east ice flow units (Sigbjarnarson, 1970; Björnsson, 1996, 1998a). Its surface altitudinal range is from 0 m to ∼1900 m, and the accumulation areas of the three main flow units vary in size. According to results from mass balance measurements taken over several decades, the average altitude of its ELA is 1150 m (Pálsson, 2023). The data demonstrate persistent negative annual net mass balance and indicate that for recovery, the ELA would need to remain at ∼960 m and expand the accumulation area ratio (AAR) from 0.6 to >0.7.

The west flow unit is fed by glaciers originating in the northeast flanks of Öræfajökull and Hermannaskarð pass (two-thirds) and from the valley south of Mt. Mávabyggðir. Its accumulation area, above an elevation of 1150 m, spans ∼46 km^2, accounting for ratio of 0.32 AAR of the unit, and is slightly less than ½ (48.5%) of the size of the center flow unit accumulation area (again above 1150 m), which measures 95 km^2. The AAR of the center is 0.49. Additionally, in comparison with the accumulation area of the east flow unit, which is 337 km^2, the center flow unit accumulation area corresponds to less than ⅓ (28.2%). The AAR of the East unit is 0.7, if the calving process to Jökulsárlón lake is excluded. The west flow unit accumulation area is only about a tenth of that of the east flow unit (13.7%). For the west flow unit to maintain a similar ice throughput to the center and east flow units, there must be substantial ice mass production in Öræfajökull and rapid ice movement through the ELA. The accumulation areas of Esjufjöll (22 km^2) and the Þverártindsegg massif (5 km^2) are comparatively insignificant, exerting only minor influence on the main ice flow units.

Breiðárrönd, which is the third most prominent medial moraine in the Breiðamerkurjökull complex, divides the west unit into two sub-units. The center unit originates in Snæhettudalur valley, between Mávabyggðir and Esjufjöll, and is bounded to the north by the Mt. Esjufjöll massif and Mt. Snæhetta (1745 m). The east unit moves down the valley east of Esjufjöll, with origins from the central Vatnajökull ice cap, Norðlingalægð, Brúarjökull and Breiðabunga.

The main ice flow units merge in the wide, low-elevation valley separating the Öræfajökull strato-volcano and the Veðurárdalsfjöll mountain massif in Suðursveit district (Figure 1). The unit confluences are marked by prominent medial moraines, identified as Mávabyggðarönd and Esjufjallarönd, but several other inconspicuous medial moraines occur on

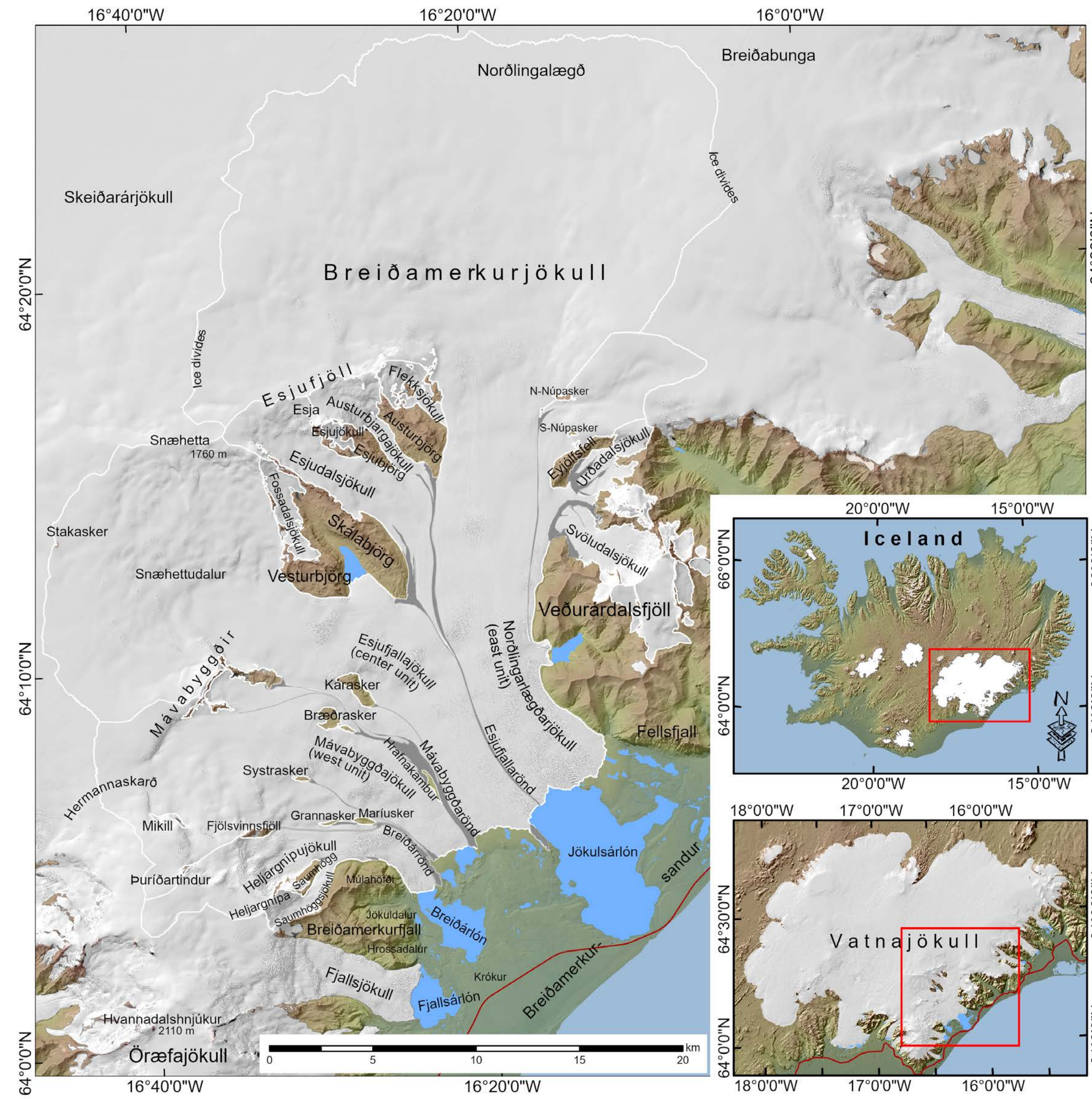

Figure 1. Location maps Breiðamerkurjökull and Breiðamerkursandur. Pléiades ©CNES (2021), Distribution AIRBUS DS. – *Yfirlitskort af Breiðamerkurjökli og Breiðamerkursandi.*

the glacier surface, including Breiðárrönd. The rapid changes of the calving front at Jökulsárlón have in recent decades, shifted the ice divides, previously defined by the Esjufjallarönd, west into the lower part of the center unit (Guðmundsson and Björnsson, 2016; Storrar *et al.*, 2017). The main ice flow units can be sub-divided into smaller components or sub-units by the tracing of the medial moraines and ice divides (Guðmundsson, 2014). In this paper, the identity of glacier flow units is related to local place names, which are sparse in the glacial areas. They are presented in Table 1, along with numerical information of altitude, area and length. Furthermore, we identify previously unnamed nunataks and medial moraines to facilitate narration and geographical descriptions. In those cases, we looked for nearby place names or the appearance of definite landforms, as regional settlers used to do.

Nunataks are numerous in Iceland's largest ice caps, both in the accumulation and ablation zones. Several nunataks protrude from the surface of Breiðamerkurjökull (Figure 1). Some are peaks or rocks that rose above the glacier during the Little Ice Age, along with the Mt. Mávabyggðir and Mt. Esjufjöll massif. However, nine nunataks, presented here, have been exposed after 1930 as a result of glacier recession. A few of these have been investigated for plant colonization and vegetation development (Flosi Björns-

Table 1. Glaciological components of Breiðamerkurjökull with adjoining valley glaciers, including individual glacier flow units (column 1), center lines, and ice divides. Details include the elevation of the ice divide or head of the flow units above sea level (col. 2), snout elevations (col. 3), the length of each flow unit (col. 4), and flow unit area size (col. 5). The bold numbers represent the totals for each of the major flow units and mountain areas (based on Guðmundsson, 2014). – *Jökularmar Breiðamerkurjökuls (2021) ásamt aðliggjandi daljöklum (1 dálkur). Mesta hæð á ísaskilum eða toppi jökularms (2. dálkur). Minnsta hæð yfir sjávarmáli við sporð (3. dálkur). Lengd (4. dálkur) og flatarmál (5. dálkur). Feitletruðu tölurnar eru heildartölur fyrir helstu jökularma eða aðliggjandi fjallasvæði (byggt á Guðmundsson, 2014).*

	Glacier branches (in 2021)	Head (m)	Snout (m)	Length (km)	Area (km^2)
Mávabyggðajökull – West unit					**143**
i.	*Saumhöggsjökull*	1540	380	6.6	5.1
ii.	*Heljargnípujökull*	1900	20	16.4	31.4
iii.	*Öræfajökull – Hermannaskarð*	1760	40	18.6	106.4
Esjufjallajökull – Center unit					**193**
iv.	*Mávabyggðir N – Snæhetta*	1745	0	28.6	192.8
Mt. Esjufjöll – Valley glaciers					**~54**
v.	*Fossadalsjökull*	1640	900	4.7	5.1
vi.	*Esjufjöll –Esjudalsjökull*	1700	500	16.0	32.3
vii.	*Esjufjöll –Esjujökull*	1560	980	1.8	1.1
viii.	*Esjufjöll – Austurbjargajökull*	1580	660	9.4	10.2
ix.	*Esjufjöll – Flekksjökull*	1500	800	4.5	4.8
Norðlingalægðarjökull – Eastern unit					**488**
xii.	*Norðlingalægð – Breiðabunga*	1700	0	40.6	447.8
xiii.	*Eyjólfsfell – Núpasker*	1360	400	19.0	30.9
xiv.	*Urðadalsjökull – Snæfell*	1140	660	20.0	4.9
Mt. Þverártindsegg mountain massif					**~26**
xv.	*Svöludalsjökull*	1440	680	5.6	11.7
xvi.	*Skrekkur (2 glaciers)*	1540	~800	1.6	1.4
xvii.	*Fellsárjökull*	1500	640	5.3	9.2
xviii.	*Other small glaciers (total of 7)*	–	–	–	3.05
Total area of Breiðamerkurjökull, including Mt. Esjufjöll and Þverártindsegg massif in 2021					**903**

son, 1951; Hálfdán Björnsson, 1958; Einarsson, 1946; Sigurðsson *et al.*, 2020).

Medial moraines, mostly composed of supraglacial sediment that originates from the nunataks and the Mt. Mávabyggðir and Mt. Esjufjöll massif, are actively transported by the glacier to the terminus. The medial moraines not only emphasize that Breiðamerkurjökull is made up of several adjoining ice flow units but also reflect another aspect of the glacier recession beyond the obvious terminal retreat and surface lowering, and that is the ice dynamic response to outlet glacier thinning.

In the last few centuries, Breiðamerkurjökull has undergone major changes. It is assumed that in the relatively warmer climate following the settlement of Iceland, in the late 9th century, glaciers were much smaller than now. During the cooler climate period after 1250, they advanced down valleys and extended into the lowlands. Most of the Icelandic glaciers reached their maximum extent in the 18th and 19th centuries (Helgi Björnsson, 2009). In the late 1870s, after progressive, longstanding advance of several kilometers, Breiðamerkurjökull's margin was nearing the coast, within only 230 m of the sea (Watts, 1962). Shortly after, it reached its maximum extent in historical time and presumably in the Holocene (Thoroddsen, 1892; Thorarinsson, 1943; Tómasson and Vilmundardóttir, 1967; Björnsson, 1998a; Evans *et al.*, 2019; Guðmundsson and Evans, 2022). The estimated surface area of Breiðamerkurjökull at that time was 1020 km^2, and its thickness was such that no nunataks protruded from the ice surface in the valley between Mt. Öræfajökull and Veðurárdalsfjöll massif (Figure 1). However, before the end of the 19th century, the glacier had begun to recede. That recession has continued at various rates, with the result that the terminus of Breiðamerkurjökull has retreated between 4.5 and 8.5 km since its maximum extent (H. Björnsson, 1996; Guðmundsson and Evans, 2022).

In 1894, the terminus had retreated 43 m from its end moraine east of the river Jökulsá, and a decade later another 100–300 m (Thoroddsen, 1895; DGS, 1905). In the first decades of the 20th century, Breiðamerkurjökull continued retreating slowly (F. Björnsson, 1998). In the decades after 1925, the climate warmed in comparison to previous decades, resulting in the glacier retreating more rapidly than before (Evans *et al.*, 2019).

From 1890s to 1930 the terminus retreated 0.4–1.0 km (see Table 2). In the years 1930–1945 it retreated 0.6–1.5 km. The ice surface lowering increased rapidly during this period (Guðmundsson and Björnsson, 2017). Between 1936 and 1940, the nunatak Kárasker (Figure 1) appeared. A comparison of the 1890 and 1945 DEMs indicates that at the nunatak's location, the surface dropped by >1 m/year on average during the 55-year period, while it lowered $\sim$0.5 m/year on average on the adjoining glacier branch. This suggests a distinction between ceased ice flow on the nunatak compared to the continuous ice flow of the glacier branch.

After the mid-1950s, a moderate but variable glacial retreat was recorded. These were decades of variable warmth; however, temperatures declined as the 1960s progressed (Evans *et al.*, 2019). Most glaciers in Iceland, monitored by the Icelandic Glaciological Society, retreated between 1930–1960 (Sigurðsson *et al.*, 2007; Hannesdóttir *et al.*, 2020). In 1945–1965, Breiðamerkurjökull retreated 0.9–1.3 km. In this period the Bræðrasker nunatak (1960) appeared in the glacier. The ice surface had lowered on average of 0.8 m/year since 1890, which is a little less than at Kárasker.

From 1965 to 1995, the climate cooled and, early in this period, coastal drift ice years became more frequent than in previous decades (Sigurdsson *et al.*, 2007; Evans *et al.*, 2019). Glaciers either remained inactive, advanced, or receded slower than before (Sigurdsson *et al.*, 2007). However, Breiðamerkurjökull continued retreating, and in the period 1965–1980 it retreated 0.6–1.0 km. In this period, the remote nunatak Nyrðra-Núpasker became exposed (1970s), at an altitude of about 1000 m. In 1980–1995, the terminus of Breiðamerkurjökull remained in a passive position (Table 2), retreating in some sectors and slightly advancing in others. Short sectional advances are also known in the east flow unit during this period (Björnsson and Pálsson, 2008).

After 1995, glacier down-wasting accelerated as a consequence of a warming climate. Between 1995 and

Table 2. Breiðamerkurjökull's recession from the 1890s to 2021. The western and eastern sections are defined by the glacial river Jökulsá. – *Hop Breiðamerkurjökuls frá 1890 til 2021. Hörfun sporðsins (í km) yfir umrædd tímabil og ársmeðaltöl (AAR), fyrir vestur- og austurhluta jökulsins, sem aðgreinast af Jökulsá.*

Breiðamerkurjökull		Western section		Eastern section	
Period	No. of years	Retreat (km)	AAR (m/yr)	Retreat (km)	AAR (m/yr)
1890-1930	40	0.4-0.5	10-12	0.5-1.0	12.5-25
1930-1945	15	0.6-1.0	40-67	1.2-1.5	80-100
1945-1965	20	0.9-1.3	45-65	~0.9	45
1965-1980	15	0.9-1.0	60-66	0.6-0.8	40-53
1980-1995	15	~stable position		~stable position	
1995-2010	15	0.4-1.0	26-66	1.0-1.4	66-93
2010-2021	11	0.9-1.0	81-90	1.2-1.3	110-120

2010 the terminus of Breiðamerkurjökull retreated 0.4–1.4 km. During this period, Maríusker (2000), Syðra-Núpasker (2006), and Systrasker (2008) appeared in the glacier. Climate warming has decreased slightly since 2010, but the terminus of Breiðamerkurjökull has continued retreating rapidly. Between 2010 and 2021 it retreated 0.9–1.3 km. In this period, the nunataks Grannasker (2010), Hrafnakambur and Grjóthöfði (in 2016) appeared on the glacier surface.

Most studies highlight rapid response to climate fluctuations over the last century. These include some short re-advance phases (Evans *et al.*, 2019) as well as mini-surges by Norðlingalægðarjökull or the east flow unit (Boulton, 1986; Boulton *et al.*, 2001; Björnsson *et al.*, 2003; Björnsson and Pálsson, 2008) but the overall trend has been one of marked recession. In 2021, after a recession period lasting approximately 130 years, the area of Breiðamerkurjökull alone was 878 km^2. The glacier had then shrunk by 142 km^2, or just over 1 km^2/year on average (Guðmundsson *et al.*, 2017; Guðmundsson and Evans, 2022). On several occasions in the second decade of the 21st century, a section of the 15 km long terminus has retreated more than 200 m per year. The equilibrium line altitude (ELA) during the recession of Breiðamerkurjökull has risen from approximately 700 m in the 1890s and varied from around 1100 m to 1200 m in recent decades (Thoroddsen, 1892; Pálsson, 2023).

The above details indicate that a major factor driving the mass loss of Breiðamerkurjökull is the presence of the proglacial lakes that began to form in the 1930s, especially the Jökulsárlón tidal lagoon. Jökulsárlón expanded gradually until the second half of the 20th century, with occasional periods of increased calving, the first between 1954 and 1960 and shortly before the turn of the 21st century. A further active calving period occurred between 2001 and 2010 (Evans *et al.*, 2019; Guðmundsson and Evans, 2022). The mass loss into the lake has been significant. Relatively warm, salty seawater enters the lake during high tide, and the circulating current brings it under the ice front, stimulating the calving. Despite accelerated ice flow, the glacier snout does not keep up with the ice mass loss into the lake (Björnsson *et al.*, 2001; Bergsdóttir, 2012; Brandon et al, 2017). Currently, the calving process is responsible for one-third of the mass loss of Breiðamerkurjökull, and the glacier has lost up to 0.5 km^2 per year into the lake since the 1990s, keeping its total mass balance negative.

Nunataks in Breiðamerkurjökull

At the turn of the 20th century, although the terminus of Breiðamerkurjökull had retreated from the end moraine on both sides of the Esjufjallarönd medial moraine, the eastern margin remained not far from the coast. Several peaks on the upper slopes of Öræfajökull (Figure 2) lay beyond the Little Ice Age advance limits, and north side of the Mt. Veðurárdalsfjöll massif (Mt. Eyjólfsfjall) was partially covered by the glacier. But overall, the wide valley occupied by the Breiðamerkurjökull snout was an unbroken ice surface with no protruding nunataks. It is likely that a small distinct outcrop at an altitude of 1600 m in Snæhettudalur valley, clearly visible in aerial photographs from 1946 (AMS, 1951), was ice-free in the accumulation area due simply to its elevation. Another remote nunatak, previously identified as Stakasker (Desolate Nunatak), is located at the ice divide between Breiðamerkurjökull and Skeiðarárjökull (Guðmundsson, 2014), and it can also be identified on aerial photographs from 1946.

Mt. Esjufjöll and Mt. Mávabyggðir are massive nunataks within the boundary of Breiðamerkurjökull. The Esjufjöll massif is formed of four parallel ridges identified as Vesturbjörg, Skálabjörg, Esjubjörg and Austurbjörg, to the southeast of Mt. Snæhetta (1745 m), which is a 15 km long subglacial mountain ridge (Figure 1). The east section of the ridge is occupied by a few minor peaks that protruded from the glacier at the end of the 19th century. However, from the basin of the 4 km long, vertical cliff of Mt. Mávabyggðir, two sharp ridges now stretch prominently but they were mostly covered by the glacier at the turn of the 20th century.

No written sources mention the nunataks in Breiðamerkurjökull before 1900, except Mt. Mávabyggðir and Mt. Esjufjöll (Pálsson, 1945; Thoroddsen, 1895). In 1903–4, geodetic surveys were carried out in the region by the Danish General Staff (DGS). The surveyors mapped the nunataks in the field and identified some of them with names (DGS, 1905). On their maps, a number of elevation marks are recorded on the ice surface, including crevassed bumps on the glacier surface, from which rocks later protruded. These important data therefore give an indication of the thickness of the ice cover on the top of the nunataks at the turn of the 20th century.

In recent decades, the retreat and volume loss of Breiðamerkurjökull have been estimated on a few occasions (Sigbjarnarson, 1970; Björnsson, 1996; Guðmundsson *et al.*, 2017). The studies reveal that above an altitude of 1800 m at the caldera of Öræfajökull, the ice surface elevation has remained similar. However, at the terminus, where the ablation is greatest, the surface drop has been extremely rapid (Guðmundsson *et al.*, 2012; Hannesdóttir *et al.*, 2014, 2015; Guðmundsson and Björnsson, 2020b). Assessments of the analyses have been based on a linear

Figure 2. View southwest from the Vesturbjörg mountain ridge of the Esjufjöll massif, across mid-Breiðamerkurjökull towards the stratovolcano Öræfajökull. At lower elevation on Breiðamerkurjökull, south of Mávabyggðir, nunataks have appeared since the late 1930s. – *Útsýni til suðvesturs frá Vesturbjörgum í Esjufjöllum, yfir miðbik Breiðamerkurjökuls, til Öræfajökuls. Neðar á Breiðamerkurjökli, sunnan við Mávabyggðir, hafa jökulsker komið í ljós frá því á þriðja áratug 20. aldar.* Oblique aerial photograph:/*Flugmynd:* S.G., September 9th, 2021.

surface reduction over time. As the surface lowering of Breiðamerkurjökull has increased, the nunataks have become more prominent. The aim here is to estimate the ice surface lowering using the nunataks as reference marks (dip-sticks; e.g., Mackintosh *et al.*, 2007) and then trace changes in the medial moraines of Breiðamerkurjökull. In addition, we chronicle the developments in the nunataks' existence.

Medial moraines at the turn of the 20th century

A handful of sources written in the 18th and 19th centuries mention the medial moraines on Breiðamerkurjökull. Undoubtedly, people must have noticed these striking features and even known their origin, but rarely wrote about them. The pioneering glaciologist Sveinn Pálsson (1762-1840) noted in his diary the view from Öræfajökull on August 11, 1794, of the two prominent medial moraines he could trace downslope from Mt. Esjufjöll to the glacial river Jökulsá (Pálsson, 1945). In his writings, Pálsson considered the medial moraine of Esjufjallarönd to divide Breiðamerkurjökull into separate units at the river Jökulsá (F. Björnsson, 1951). He described the western part as more rugged, crevassed, and debris-covered, in contrast to the eastern part, which he claimed was smoother and less silty (Pálsson, 1945). The description verifies that the Jökulsá river debouched east of the Esjufjallarönd medial moraine in the late 18th century. The proximity of the river to the "dirty" part of Breiðamerkurjökull (i.e., Esjufjallarönd) is also noted in a few other 19th-century sources (Henderson, 1815; Thieneman, 1824; Gadde, 1983 [written 1857]; Holland, 1863; Thoroddsen, 1895), supporting the observation that the river was more or less attached to the medial moraine. Nevertheless, there are documented instances of the river breaking out of these confines and debouching from unexpected places (Norðanfari, 1870; F. Björnsson, 1993).

It cannot be excluded that the cartographer Björn Gunnlaugsson (1844) may have identified the Esjufjallarönd medial moraine on his map of Iceland in 1839 when he drew a district boundary from Jökulsá towards the north, 13 km up the glacier. The Englishmen E. T. Holland and C. W. Shepherd rode across Breiðamerkursandur on August 13, 1861. Holland (1863) noted the view and said (F. Björnsson, 1984): "As we rode on, I spotted one or two medial moraines on the glacier. They descend from Breiðamerkurmúli, a peculiar grassy mountain inside the glacier." Despite the disorientation of its origin, it is more likely that any of the three prominent medial moraines, Breiðárrönd, Mávabyggðarönd or Esjufjallarönd, were identified by Mr. Holland and Shepherd.

The Swedish geologist Carl W. Paijkull (1836–1869) crossed Breiðamerkursandur in 1868. He assumed that the three conspicuous medial moraines indicate that the outlet glacier is formed of four units (Paijkull, 1868). In 1893, the Englishman Frederick W. W. Howell wrote: “On a later visit, I discovered that the medial moraine is a range of ice hills a hundred feet in height, bearing its load of sand and stones from certain peaks upon Vatnajökull which are not marked upon the usual map. For the last ten miles of its course, its average fall amounts to about one hundred and twenty feet per mile”.

When describing the outlet glaciers in southeast Iceland in 1895, the geologist Þorvaldur Thoroddsen (1895) recognized the medial moraines. He observed, "From there [the river Jökulsá], there is a wide stripe of gravel and boulders heading up the glacier; it runs along the entire middle glacier, to Mt. Esjufjöll and is 2–3 [Danish] miles long (one Danish mile = 7.532 km)." Then he continued: "Between the westernmost and center glaciers, there is a great stripe of gravel heading towards Mt. Mávabyggðir, and there is an inlet up to the main glacier in front of the joints, ... There, the river Breiðárvötn outlets the glacier, but Jökulsá appears to the streak that heads towards Mt. Esjufjöll. The main water accumulates in both places at the joints of the glacier."

Medial moraines were depicted on the DGS maps at the beginning of the 20th century (DGS, 1905). Besides confirming the survey team's ambitious cartography, the bands indicate how prominent they were on the glacier surface. However, not all of them are drawn right up to their places of origin on Breiðamerkurjökull. The medial moraines are also featured on most glaciers on the AMS map series (AMS, 1951). On Breiðamerkurjökull, the bands are identical with those shown on the DGS maps (i.e., only Esjufjallarönd is depicted up to its origin).

METHODS AND DATA

The work presented here is based on fieldwork, remote sensing and published maps utilizing a selection of DEMs and ESRI ArcGIS. Using visually selected longitudinal profiles parallel to the ice movement direction over the nunatak location and the year 2021 as a reference frame, the objective was to estimate the ice surface lowering and nunatak areal expansion since the late 19th century, when nunataks were submerged, up to the present day. The medial moraines of Breiðamerkurjökull, many of which emerge from the nunataks, were also delineated using a wealth of aerial photographs and Landsat satellite images.

Historical changes were estimated from a selection of maps (the oldest being the DGS map of 1905), aerial photographs taken in 1945–1946 and the derived maps of the US Army Map Service (AMS) , and the aerial image databases of the National Land Survey of Iceland (NLSI) and the company Loftmyndir ehf for specific years in the late 20th century. To trace the recent changes in the area size of the nunataks, Landsat images (Landsat 1–5 and 7–9, courtesy of the US Geological Survey), especially recent Landsat 7–9 with its 30 m (spectral) and 15 m (panchromatic) pixel resolution, have been used. The Landsat 1 image from 1973 with a resolution of 60 m/px was used to trace medial moraines and nunataks. LiDAR DEMs of the Vatnajökull ice cap and its foreland (Jóhannesson *et al.*, 2011, 2013) were the source of the data for the first part of the 21st century.

To estimate the subsequent elevation changes of the glacial surface around and above the nunataks, a selection of DEMs was used. A high-resolution DEM of the region was produced from an airborne lidar survey in 2010–2012. It was also used to generate derivational DEMs of Breiðamerkurjökull between 1945 and 1890. The reference LiDAR DEM has a resolution of 5x5 m/px, with horizontal and vertical (x, y, z) deviations of <0.5 m (Jóhannesson *et al.*, 2011, 2013).

The additional 1945 and 1890 DEMs were previously made for volume change estimations of the outlet (Guðmundsson *et al.*, 2017). The modification of these DEMs relied on the reference DEM from 2010 and maps produced from the contemporary surveys of the Danish General Staff (DGS, 1905) and the later American Map System of the US Navy (AMS, 1951).

The DGS map series is based on a triangulation survey conducted in 1903 and 1904 by the Danish General Staff (DGS, 1905). The DGS maps needed horizontal corrections by a few tens of meters, but they are estimated to be accurate within $\pm$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 and rivers, and the position was recorded (in meters) by local farmers at that time.

The AMS (1951) sheets are relatively accurate in comparison with the Lidar DEMs 2010, with an estimated horizontal accuracy of $\pm$5 m below 600 m a.s.l., after correction with respect to the Lidar DEMs. The C762 maps of the AMS were based on photogrammetry of aerial photographs taken in 1945 and 1946 (AMS, 1951). Above 600 m, the reconstructed 1890 and 1945 DEMS were derived by vertically lifting the elevation (y) of the glacier surface of the LiDAR DEM (x) from 2010–2011, using the least-squares relationship, and based on the lateral 1945 and LIA extent. The uncertainty in the reconstructed 1890 and 1945 DEMs is estimated at $\pm$10 m over the entire glacier surface. It was estimated quantitatively based on the different data sources, but the assessment has been defined in Guðmundsson *et al.* (2017).

The NLSI aerial photographs required rectification, which was accomplished using ESRI ArcGIS. The georectification was carried out by identifying several control points on each image or map and the LiDAR DEM using ArcGIS tools for re-projection and warping. The 2010 DEM also made it possible to georectify AMS aerial photographs and re-project the horizontal positioning of the 1904 and 1945 maps. The datasets are listed in Table 3. The area size and development of the nunataks were estimated using ESRI ArcGIS and supplied data, including Pleiades DEM for 2021.

A set of Pleiades (CNES, 2021) DEM, from optical stereo images, acquired on August 31 and September 1, 2021, corrected for horizontal and vertical deviation by the National Land Survey of Iceland (NLSI), serves as the reference for the year 2021. They also

Table 3. Data utilized to evaluate changes in the area of nunataks, the elevation of the ice surface, and to determine the position of medial moraines from the 1900s to the present. – *Gögn sem voru notuð til að meta breytingar á flatarmáli jökulskerja, yfirborðshæð jökulsins og til að ákvarða stöðu urðarrana frá 1900 til 2021.*

Photo origins	Year	Data type	Spatial res. (m)	±(m)	Purpose
DGS	1904,	Maps	–	20	Nunataks, medial moraines
AMS	1945	–		5	Nunataks, medial moraines
Durham	1951	–		5	Medial moraines, terminus
AMS	1945-1946	Aerial images	1.0x1.0	5	Nunataks, medial moraines, terminus
NLSI	1954, 1955, 1960, 1964, 1980-82, 1988-89, 1990-91, 1994, 1998	– – –	0.5x0.5 – – –	5	Nunataks, medial moraines, terminus
Loftmyndir ehf	2003, 2013, 2021	–	0.5x0.5	1	Medial moraines, terminus
Landsat 1-5	1973-1986	Satellite images	60x60	30	Nunataks, medial moraines, terminus
Landsat 7-8	2000-2018		15x15	5	
SPOT	2004	–	7x7	5	
Lidar	2010-2012	DEM	2x2	<	Nunataks, medial moraines, terminus, georectification
Arctic DEM	2021	–	5x5	0.5	
RES survey	1991	–	100x100	?	
Derived DEMs	1890, 1945	–	50x50	?	
Various material and field studies	1815-1950	Oblique photos	–	– –	Nunataks, medial moraine, terminus
		Written	–		

provided the opportunity for recent area estimations of the nunataks. Furthermore, a DEM was acquired from a radio echo sounding (RES) survey carried out in 1991 (precision barometry, Loran-C, GPS), resulting in DEMs of both the surface and the bed of the glacier (Björnsson, Pálsson and Guðmundsson, 1992; Björnsson and Pálsson 2020). These DEMs were used to estimate the surface elevation near the nunataks in 1890, 1945, 1991, 2010 and 2021.

The delineation of medial moraine positions and lengths, and their development, are based on the same data set (see Table 3). To estimate changes in the medial moraines, the georeferenced old maps, aerial photographs, and satellite images (Landsat 7 and Landsat 8) were used for comparison. For lateral displacement estimations of the Esjufjallarönd and Mávabyggðarönd, several reference points with an interval of 1 km, located in a line parallel with the medial moraines, were selected. From these the termini of the outlet and the moraine itself were digitized. The distance from each reference point to the center of the medial moraine was then measured.

RESULTS

The nunataks

The Breiðamerkurjökull nunataks (Figure 3) are typically composed of bedrock, usually covered with an unsorted mixture of undifferentiated glacigenic material. In the late 20th century, Flosi Björnsson from Kvísker, who measured Breiðamerkurjökull, noted several protrusions in the Mt. Esjufjöll massif (Rist, 1985). The 1991 radio echo sounding surveys on Breiðamerkurjökull not only revealed deep trenches and sub-valleys in the glacier base but also subglacial

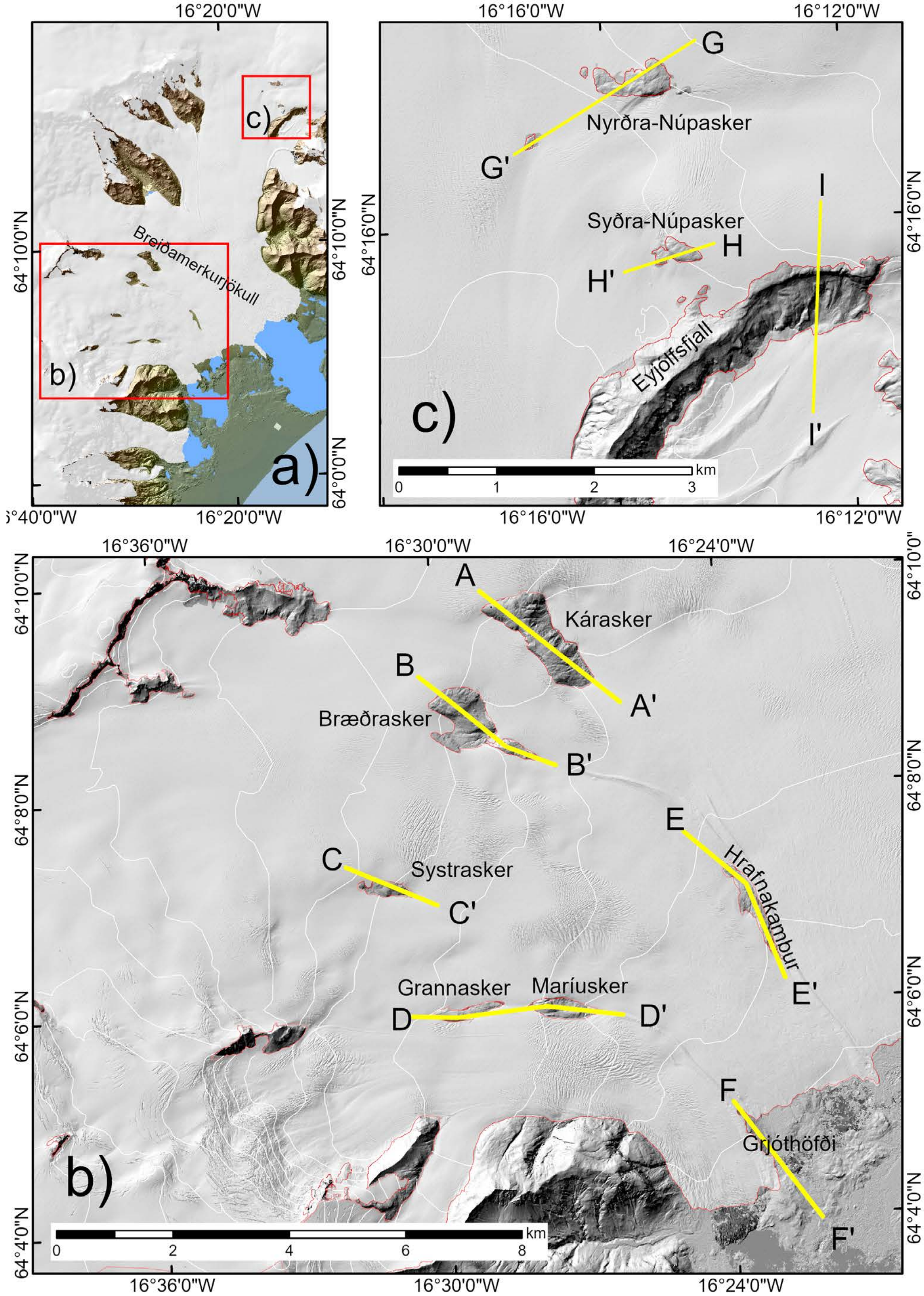

Figure 3. The profiles (yellow lines) measured across the nunataks of Breiðamerkurjökull. – *Þversnið (gular línur) sem voru mæld yfir jökulsker í Breiðamerkurjökli.*

mounds and mountain peaks (Björnsson, Pálsson and Guðmundsson, 1992). It was predicted that with the ongoing thinning of Breiðamerkurjökull, these features would later emerge as nunataks.

Kárasker

This nunatak is made of intrusive rocks, dikes, and fine-grained basalt. The late Björnsson brothers from the nearby farm Kvísker (referred to as the Kvísker brothers) were the first to notice this nunatak (Figures 3b and 4) in 1940. They named it Kárasker in honor of a local hero from the historic farm Breiðá, named Kári Sölmundarson. They assumed it first appeared after 1935 but definitely before 1940 (S. Björnsson, 1958). Helgi Arason (1893–1972) from the nearby farm of Fagurhólsmýri took a photo across the area in 1935, showing no sign of the nunatak, which emerged one or two years later. Based on an AMS aerial photograph (September 1946), Kárasker consisted of three flat rock surfaces, roughly 0.14 km^2 (14 ha) in size, and later merged into a single protrusion. In 2021, the area was 1.27 km^2.

Kárasker rises to an altitude of 760 m. In 2021, the glacier surface south of the nunatak (profile A-A' in Figure 3b) was at an elevation of 400 m. When Breiðamerkurjökull was at its maximum extent at the end of the 19th century, the ice surface above the then-submerged Kárasker was at an elevation of 700–860 m a.s.l. On the DGS map (1905), a crevassed bulge elevated to 862 m and located west of the nunatak, reveals the subglacial existence of Kárasker. The nunatak first protruded $\sim$0.5 km southeast of this bulge. While the surface elevation of the deflected glacier alongside Kárasker lowered by about 30 m in the period 1890–1945 (55 years), the ice over the nunatak shrank by $\sim$60–90 m, an average >1.0 m/year (Figure 5). The overall surface lowering between 1890–2021 (131 years) was 120 m, averaging 0.9 m/year. The detailed temporal changes, based on the DEM selections previously described, are detailed in Table 4.

Bræðrasker

The lower part of Bræðrasker is gabbro, and the upper part is mainly basalt with multiple dikes. This nunatak became exposed in 1960 (Figures 3b and 4). However, a depression that formed in the glacier two years earlier became an indication of what could be expected (S. Björnsson, 1958). The Icelandic botanist Eyþór Einarsson (1929–2021) named it Bræðrasker (the Brother's Nunatak) in honor of the Kvísker brothers (Elín Pálmadóttir, 1968). Eyþór, together with the Kvísker brother Hálfdán Björnsson (1927–2017), having monitored the progress of vegetation colonization in the Kárasker nunatak, instantly started observations of Bræðrasker (Guttormsson, 1968). An AMS aerial photo from 1945 shows the depression in the glacier where the nunatak appeared later, together with the Mávabyggðarönd moraine that emerges from it. In 2021, Bræðrasker's area was 0.98 km^2.

The Bræðrasker nunatak rises to an altitude of 730 m. In 2021, the glacier below (section B-B' in Figure 3b) was at an elevation of 450 m. In the 1890s, the ice surface, then above the submerged Bræðrasker was at an elevation of 700–830 m and the ice thickness was 100–120 m (Figure 5). The total surface lowering of the period 1890–2021 was 150 m, or an average of 1.15 m/year. The temporal changes, based on the DEM selections previously described, are detailed in Table 5.

Maríusker and Grannasker

These nunataks are mostly plutonic rock and acidic basalt (Sigurðsson, 2003). In the last two decades, three nunataks have become exposed near the Breiðárrönd medial moraine. Two of them, Maríusker and Grannasker (Figures 3b and 6), join the same mountain ridge, which is currently mostly covered by glacier ice. Maríusker appeared in the year 2000 (Björn J. Björnsson, 2005). Initially, it was identified as Systrasker (see later) due to a misunderstanding (Sigurðsson *et al.*, 2020). The nunatak is almost 2 km north of Breiðamerkurfjall. In 2002, the Kvísker brothers became the first visitors, intending to examine plant colonization (H. Björnsson, 2003). Three years later, 15 species of plants were found in it (Björn J. Björnsson, 2005). In 2005, Hálfdán Björnsson at the Kvísker farm named it after the entomologist María Ingimarsdóttir, who at that time conducted biological studies on a few nunataks of Breiðamerkurjökull (H. S. Guðmundsson, 2012). In 2021, the area of Maríusker was 0.28 km^2.

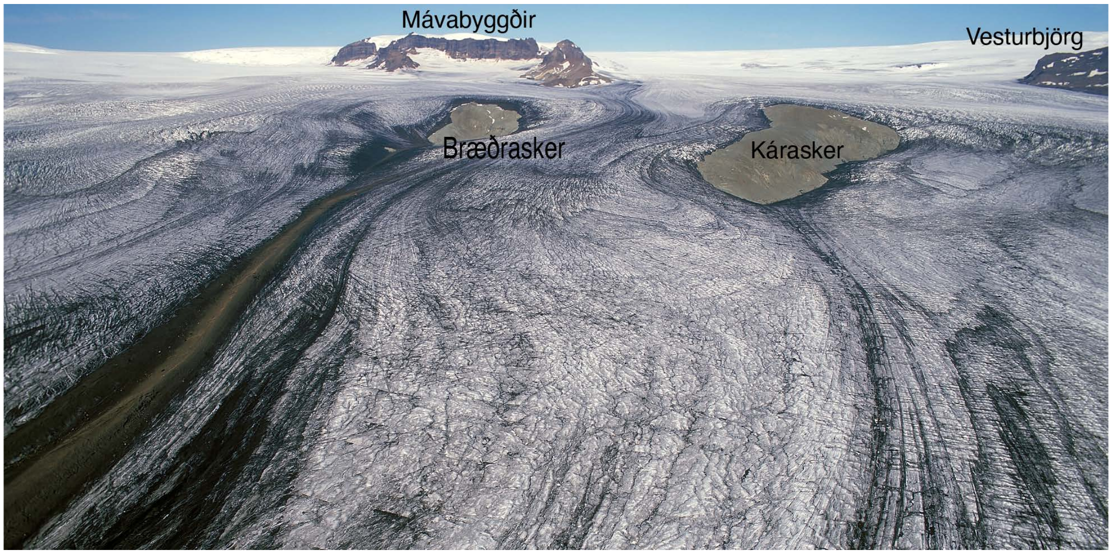

Figure 4. The nunatak Kárasker. The Mávabyggðarönd medial moraine (left) originates from Bræðrasker, below the cliffs of Mávabyggðir. – *Jökulskerin Kárasker og Bræðrasker. Mávabyggðarönd á upptök í Bræðraskeri, neðan við Mávabyggðir.* Oblique aerial photograph:/*Flugmynd.* S.G., August 17, 2006.

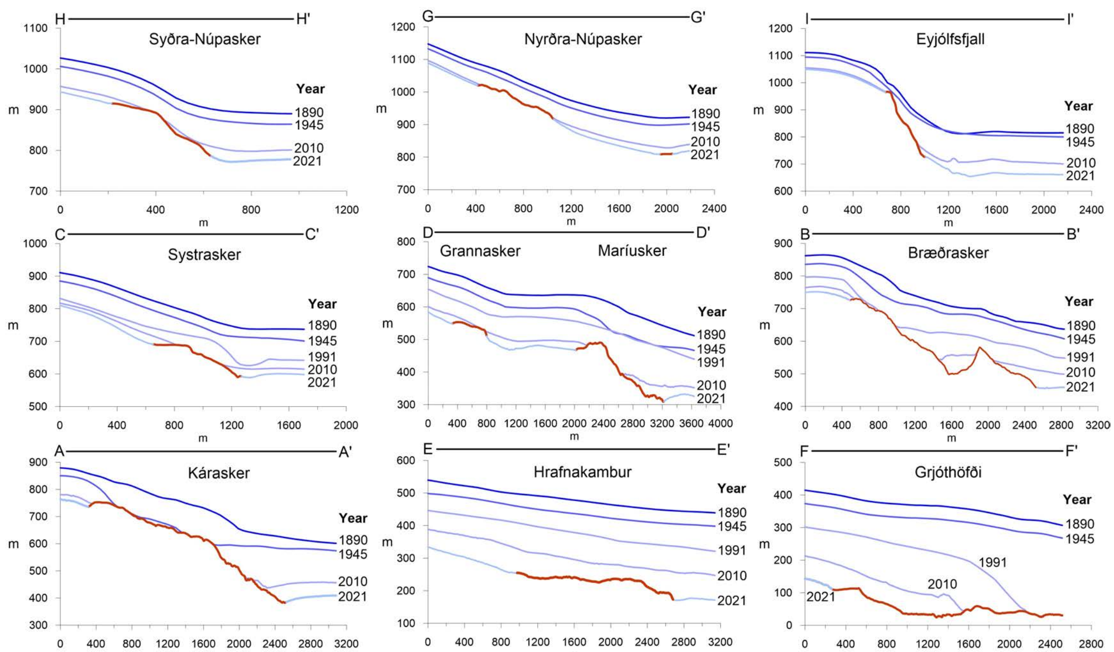

Figure 5. Cross-sections of the nunataks in Breiðamerkurjökull, depicted in Figure 3, arranged by elevation. Profile length on the x-axis and altitude a.s.l. on the y-axis. The ice surface in 1890, 1945, 1991, 2010, and 2021 is presented by blue lines. The upper panels contain the highest nunataks. – *Þversnið af jökulskerjum í Breiðamerkurjökli sem sýnd eru á 3. mynd. Hæð y.s. á lóðás og lengd sniða á þverás. Bláar línur sýna yfirborð jökulsins árin 1890, 1945, 1991, 2010 og 2021.*

Table 4. Glacier surface changes at selected nunataks of Breiðamerkurjökull. Average surface lowering (m/year) and annual mean for three periods. – *Breytingar á yfirborði jökuls við valin jökulsker í Breiðamerkurjökli. Í 2. og 3. dálki er hæð jökulskerja y.s. og yfirborðshæð jökulsins miðuð við árið 1890. Meðalyfirborðslækkun (m/ár) er sýnd fyrir þrjú millitímabil auk ársmeðaltals miðað við allt tímabilið.*

	Altitude (m)		Average ice surface lowering							
Nunatak	Peak	is* (1890)	1890-1945	m yr⁻¹	1945-2010	m yr⁻¹	2010-2021	m yr⁻¹	Total (m)	Avr m yr⁻¹
Stakasker	1492	1480*[1]	0	0,0	-11	-0,2	-3	-0,3	-14	-0,1
N-Núpasker	1020	1060	-25	-0,5	-35	-0,5	-15	-1,4	-75	-0,6
S-Núpasker	890	950	-25	-0,5	-35	-0,5	-20	-1,8	-85	-0,6
Urðadalsjökull	960	1000	-15	-0,3	-100	-1,5	-40	-3,6	-155	-1,2
Kárasker	760	810	-60	-1,1	-45	-0,7	-15	-1,4	-120	-0,9

*is = glacier surface elevation in the 1890s, *[1] Based on derived ice surface elevation.

Table 5. Glacier surface changes at selected nunataks of Breiðamerkurjökull. Average surface lowering (m/year) and annual mean for four periods. – *Breytingar á yfirborði jökuls við valin jökulsker í Breiðamerkurjökli. Í 2. og 3. dálki er hæð jökulskerja y.s. og yfirborðshæð jökulsins miðuð við árið 1890. Meðalyfirborðslækkun (m/ár) fyrir fjögur millitímabil auk ársmeðaltals miðað við allt tímabilið.*

	Altitude (m)		Average ice surface lowering									
Nunatak	Peak	is* (1890)	1890-1945	m yr⁻¹	1945-1991	m yr⁻¹	1991-2010	m yr⁻¹	2010-2021	m yr⁻¹	Total (m)	Avr m yr⁻¹
Bræðrasker	730*[1]	800	-55	-1.0	-40	-1.1	-25	-1.3	-20	-1.8	-160	-1,2
Systrasker	690	800	-35	-0.6	-50	-1.1	-27	-1.4	-28	-2.5	-140	-1,1
Grannasker	530*[1]	660	-40	-0.7	-35	-0.8	-50	-2.6	-25	-2.3	-150	-1,2
Maríusker	490	600	-45	-0.8	-40	-0.9	-50	-2.6	-25	-2.3	-160	-1,2
Hrafnakambur	260	475	-40	-0.7	-60	-1.3	-80	-4.2	-70	-6.4	-249	-1,9
Grjóthöfði	115	380	-40	-0.7	-70	-1.5	-114	-6.0	-70	-6,4	-295	-2,2

*is = glacier surface elevation in the 1890s. *[1] measured below the current peak.

Figure 6. The two nunataks in western Breiðamerkurjökull, Maríusker and Grannasker. View towards the Öræfajökull stratovolcano with its protruding peaks and nunataks. – *Jökulskerin Maríusker og Grannasker í vestanverðum Breiðamerkurjökli. Í baksýn er Öræfajökull með tindum sínum og jökulskerjum.* Oblique aerial photo:/*Flugmynd.* S.G., Sept. 9, 2021.

In 2021, the ice surface below the 490 m high Maríusker remained at an elevation of 320 m. In the late 19th century, the ice surface height above the then-submerged Maríusker and Grannasker (profile D-D' in Figure 3b) extended from 600 to 660 m, resulting in an ice thickness of 120–130 m (Figure 5). The total surface lowering in 1890–2021 was 160 m, or an average of 1.2 m/year, (Table 5).

Grannasker reaches a height of 555 m. The nunatak was first identified and named by two ecologists in 2016 (NÍ, 2016). However, satellite images and DEMs revealed its existence (Figure 5) in 2010. It is located to the west of Maríusker (Figure 3b). In 2010, the distance between these nunataks was ∼1.4 km but was less than 1.3 km five years later. In 2021, they were separated by 360 m of ice, and they will likely connect in the next few years or decade. In 2021, the area size of Grannasker was approximately 0.16 km^2. The surface lowering from 1890 to 2021 was 150 m, or ∼1.15 m/year, (Table 5).

Grjóthöfði

The third nunatak located near the Breiðárrönd medial moraine, we identify as Grjóthöfði (Rubble head) due to its appearance as a striated promontory covered with an unsorted mixture of glacigenic debris. This protuberance consists of basalt on top of tillite. One of the authors of this paper (S.G.) explored it in July, 2017. His conclusion, presented here, is that it emerged about 0.4 km up glacier of the terminus in 2016 (Figure 3b). The glacier retreated rapidly in the following years, and completely vanished south of the 115-meter-high nunatak in 2021 (Figure 7).

When Breiðamerkurjökull was at its maximum extent in the late 19th century, the glacier surface above the nunatak (profile F-F', Figure 3b) was at an elevation of 380 m, and the ice thickness 265 m (Figure 5). The total surface lowering for the period 1890–2021 was 295 m, an average of 2.2 m/year, (Table 5).

Systrasker

A Landsat-7 satellite image confirms that this nunatak (Figures 3b and 8) emerged in the summer of 2008. Based on the results of the RES survey on Breiðamerkurjökull in 1991, one of the authors, Helgi Björnsson, predicted that a nunatak would appear there after a few years due to continuing glacier recession. He suggested its name should honor the sisters at Kvísker farm, both named Guðrún (Björn J. Björnsson, 2005). However, before it became exposed, Maríusker appeared, which at first was assumed to be the Systrasker nunatak. This confusion caused the first articles, which were written in the first decade of the 21st century, to propose Maríusker nunatak as Systrasker (Sigurðsson *et al.*, 2020). In 2021, the area size of Systrasker was 0.17 km^2.

In 2021, the glacier surface below the 690-m-high Systrasker (C-C' in Figure 3b) remained at an elevation of 590 m. In the late 19th century, the ice surface above the then-submerged Systrasker was at an elevation of about 750–820 m and, therefore, its thickness on Systrasker was 130 m (Figure 5). The total surface lowering of the period 1890–2021 was 140 m, or 1.1 m/year, (Table 5).

Figure 7. View from the Grjóthöfði promontory down the Breiðárrönd medial moraine. Note that to the east (left), the glacier had disappeared when the image was taken. – *Útsýni frá Grjóthöfða niður Breiðárrönd. Þegar myndin var tekin var jökullinn til austurs (vinstri) horfinn framan við skerið.* Photo:/*Ljósmynd.* S.G., July 7, 2021.

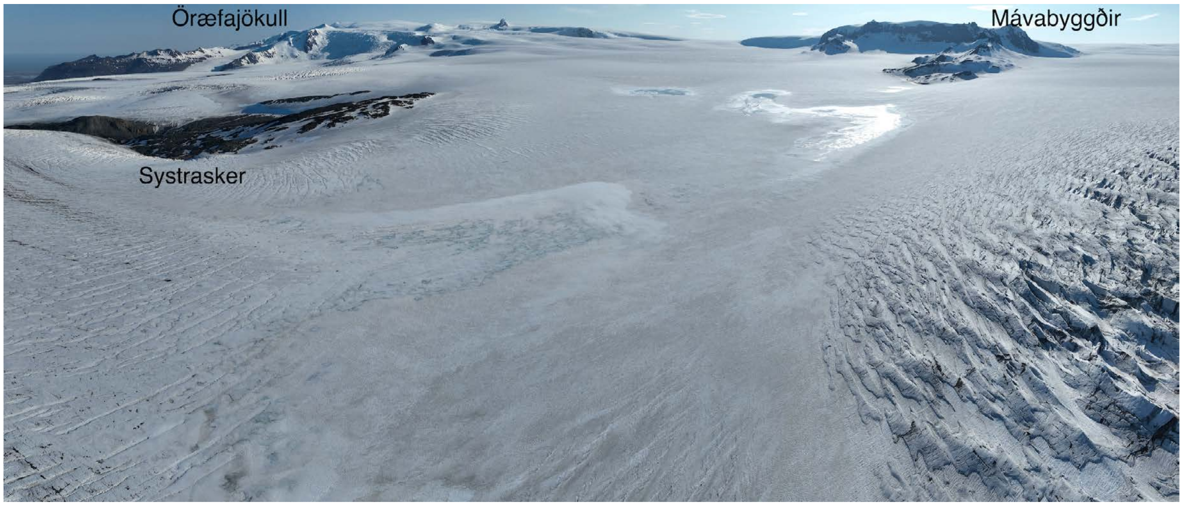

Figure 8. The nunatak Systrasker and Mávabyggðir. – *Systrasker og Mávabyggðir.* Oblique aerial photograph:/*Flugmynd.* S.G., May 31, 2023.

Hrafnakambur

This nunatak (Figures 5 and 9) is composed of rapidly cooled basalt, acidic basalt, and tuff, exposing some dikes. It is identified here as Hrafnakambur (Raven's Crest). It is vaguely visible on satellite images from 2016, mainly because it was attached to the Mávabyggðarönd medial moraine and hence was only noticed later. In 2021, the area size of the 1.1 km long and 150 m wide nunatak was 0.35 km^2.

At the end of the 19th century, the surface of the Breiðamerkurjökull above Hrafnakambur (profile E-E' in Figure 3b) was at an elevation of 490 m, and the

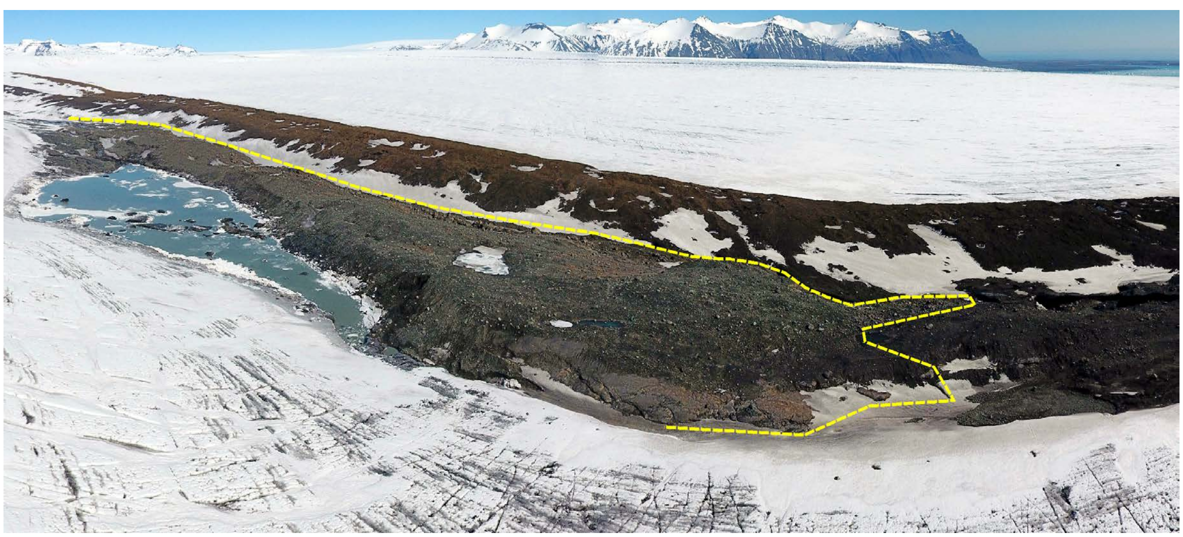

Figure 9. The Hrafnakambur nunatak is attached to the Mávabyggðarönd medial moraine. In the spring of 2020, a lateral lake (moat) formed on the west side of the nunatak. – *Jökulskerið Hrafnakambur, við vestanverða Mávabyggðarönd. Vorið 2021 myndaðist jaðarlón vestan skersins.* Oblique aerial photograph:/*Flugmynd.* S.G., April 24, 2020.

nunatak was submerged under 240 m of ice. The total surface lowering therefore amounts to an average of 1.9 m/year for the 131 years until 2021, (Table 5).

Eyjólfsfjall og Urðadalsjökull

The remote Mt. Eyjólfsfjall adjoins a mountain crest that encloses, together with Mt. Snæfell, a glacier-filled valley, which we identify here as Urðadalur. It is covered with an almost 2 km wide and 4 km long Urðadalsjökull, whose three medial moraines demarcate the ice tongue and extend to Breiðamerkurjökull (Figures 3c and 10). Eyjólfsfjall is mostly made of basalt and rhyolite. The identification of the nunatak was by Danish surveyors who, in 1904, honored their guide, Eyjólfur Runólfsson of the farm Reynivellir, then district administrative officer (Guttormsson, 1993). At that time, the crest rose to a height of about 160 m above the glacier and reached 1.75 km to the east before disappearing into the glacier. In 1945, this crest had extended to a length of 2.1 km due to ice thinning. Now, a more than 4 km-long rocky edge extends closer to the rim at Kálfafellsdalur. In the future, the crest will become more prominent because the ice flow from above and into the Urðadalur continues to thin out and may eventually cease to enter into it. In 2021, the area of Eyjólfsfjall was 2.67 km^2.

At the mouth of the valley, south of Eyjólfsfjall, the glacier surface has lowered by 100 m since the end of the 19th century. The cross-section in Figure 5 is, however, to the east (profile I-I' in Figure 3c), where the glacier was about 30–60 m thick and covered the crest of Eyjólfsfjall when the DGS survey was carried out in 1904. There, the edge of the mountain is at an altitude of 960 m. The ice surface lowering here has been interesting. From 1890 to 1945 (55 years), the glacier receded 20–40 m, or 0.3–0.7 m/year. On an AMS aerial photograph from 1945, conspicuous crevasses indicate the presence of a submerged crest, and to the south of it, a valley (later Urðadalur). Then the crest east of Eyjólfsfjall gradually began emerging in the 1970s. Shortly after the turn of the 21st century, the glacier ice vanished from the crest, with a 1.38 km wide valley glacier remaining. In the late 19th century it was 3.8 km wide.

From 1890 to 1945 (55 years), the surface of Urðadalsjökull lowered 15 m, or 0.3 m/year on average. From 1945–2010 (65 years), the surface lowered 100 m or 1.5 m/year on average. During 2010–2021, the surface level dropped 40 m, or an average of 3.6 m/year The total surface lowering in the period 1890–2021 was 155 m, or 1.2 m/year, Table 4).

Núpasker

Three nunataks appeared north of Eyjólfsfjall after the 1970s. These are the promontories of a mountain crest encircling a subglacial valley (Figures 3c, 10 and 11). We identify them here as Syðra-Núpasker and Nyðra-Núpasker, located about 1 km and 3 km north of Eyjólfsfjall (Figure 10). From an image taken by the Landsat-1 satellite in 1973, it can be verified that the northern nunatak was exposed at that time. The Syðra-Núpasker, however, appeared in the years 2006–2007.

Nyrðra-Núpasker is currently made up of two nunataks, formed from tuff and acidic basalt. The main nunatak is located on a slanting slope at an altitude of about 920 to 1020 m. In 2018, the other nunatak began to emerge in a glacial depression below the main nunatak, at an altitude of 810 m (Figures 3c and 5). Based on the constructed 1890 DEM, we can infer that at the end of the 19th century, the ice surface above the then-submerged northern nunataks (profile G-G' in Figure 3c) was at an elevation of 1000–1090 m, covering it with 70–80 m thick ice. The total surface lowering in the period 1890–2021 was ∼75 m or 0.6 m/year on average, (Table 4).

The Syðra-Núpasker (profile H-H' in Figure 3c) is at an altitude of 930 m, but in 2021 the glacier below it was at an altitude of about 790 m (Figure 5). At the end of the 19th century, the ice surface above it was at an elevation of 1000 m, and the nunatak was buried under 70–90 m of ice. The total surface lowering in the period 1890–2021 was 0.6 m/year on average.

Stakasker

This nunatak is located in the ice divide between Breiðamerkurjökull and Skeiðarárjökull, about 11 km north of Hermannaskarð, and 7 km southwest of Snæhetta (Figure 1). The name of Stakasker (Desolate nunatak, 1492 m) comes primarily from how remote it is in the accumulation zone of the glacier (Figure 12a,b). The top of this nunatak is composed of

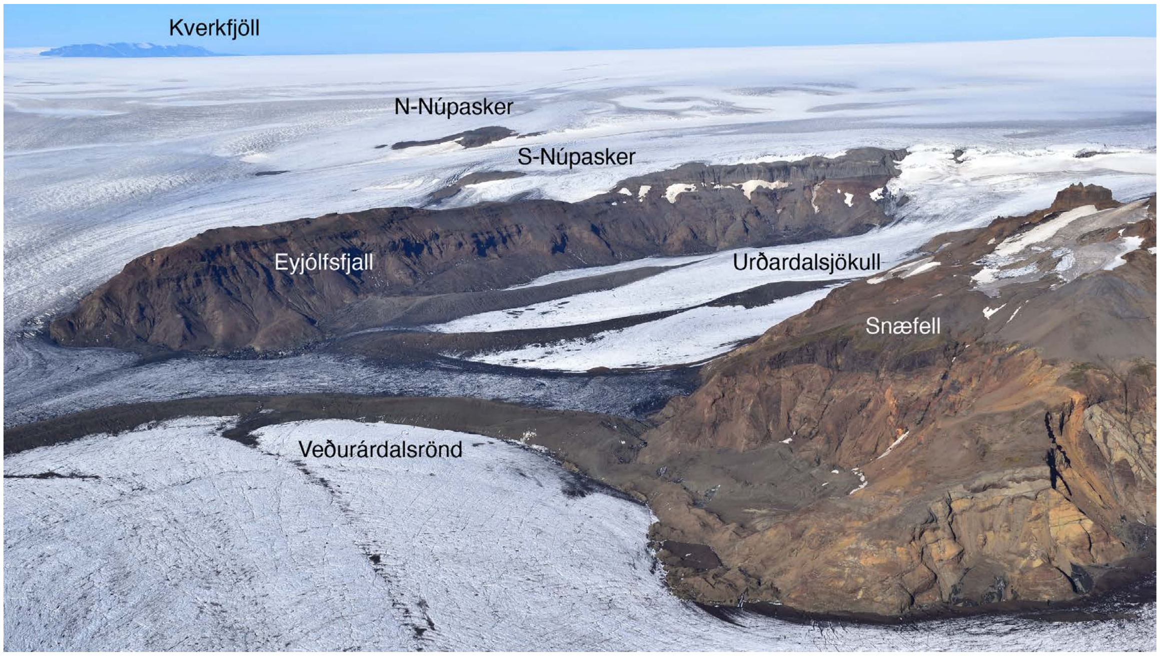

Figure 10. The mountain crest Eyjólfsfjall, Urðadalsjökull and the two Núpasker nunataks. The Veðurárrönd medial moraine sways left from the light-colored slopes of Snæfell. – *Fjallskamburinn Eyjólfsfjall, Urðadalsjökull og Núpaskerin tvö. Urðarraninn Veðurárrönd sveigir frá ljósum hlíðum Snæfells.* Oblique aerial photo:/*Flugmynd:* S.G. September 9, 2021.

Figure 11. View southwest from the nunatak Nyrðra-Núpasker. – *Útsýni til suðvesturs frá jökulskerinu Nyrðra-Núpaskeri.* Photo:/*Ljósmynd:* S.G. May 31, 2023.

rapidly cooled basalt. It can be spotted in AMS aerial photographs taken in 1946 on Vatnajökull. In 2010, the nunatak was about 5–15 m higher than the glacier surface, and its area was about 0.003 km^2. Whether it protruded from the glacier during the previous century is not known; however, its protrusion is not unlikely given its location at the ice divide. The glacier surface surrounding Stakasker had lowered by about 14 m between 1945 and 2010, (Table 4).

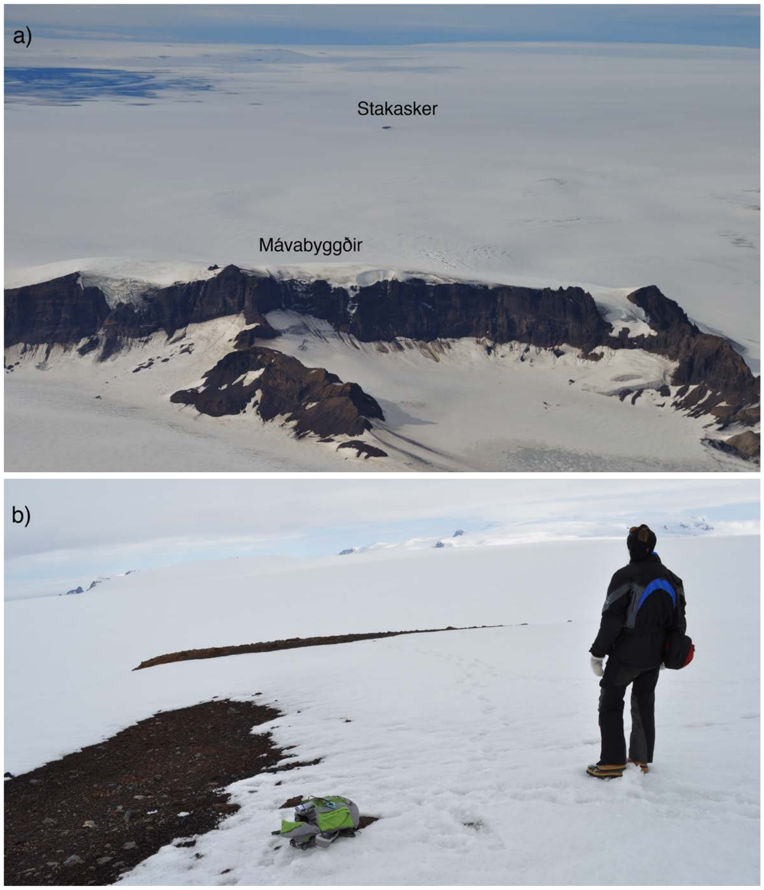

Figure 12. a) The Stakasker nunatak, on the border of Breiðamerkurjökull and Skeiðarárjökull, northwest of Mávabyggðir. b) View towards south from Stakasker. – *a) Jökulskerið Stakasker á mörkum Breiðamerkurjökuls og Skeiðarárjökuls. Mávabyggðir í forgrunni. b) Útsýni frá Stakaskeri suður til Öræfajökuls.* Photos:/*Ljósmyndir:* S.G., September 13, 2014 (a) and June 4, 2012 (b).

Summary of the nunataks

A comparison of glacier surface elevation and temperature measurements over the melting season, at the nearby farm Fagurhólsmýri (Figure 13) demonstrates the surface lowering since the late 19th century. The glacier's lower portions are melting more rapidly, as evidenced by a steeper slope. Profiles along the main ice flow units (Figure 14) depict a similar pattern (i.e., faster ablation closer to the terminus).

The results of ice surface change calculations obtained using the DEMs of Breiðamerkurjökull are presented in Tables 4 and 5. The tables show the surface lowering over the periods 1890–1945, 1945–2010, and 2010–2021, at the high-elevation and lower elevation nunataks (Table 4) for which it was possible to use the 1991 DEM. The expectation was to estimate an even more rapid progression of glacier changes between 1995 and 2010.

Length-sections along the eastern and center flow units of Breiðamerkurjökull (Figure 14) reveal a marked surface difference between the two profiles, one terminating in the Jökulsárlón lake and the other subaerially. The transport of ice down Breiðamerkurjökull is compensated by about 1/3 of the mass loss in the ablation zone (Figure 15). In the period 2000 to 2020 the cumulative mass balance at 350 to 480 m a.s.l. was -120 m elevation but the glacier surface elevation was only lowered by 80 m. In the accumulation zone the surface elevation remained constant due to vertical emergence flow of the glacier.

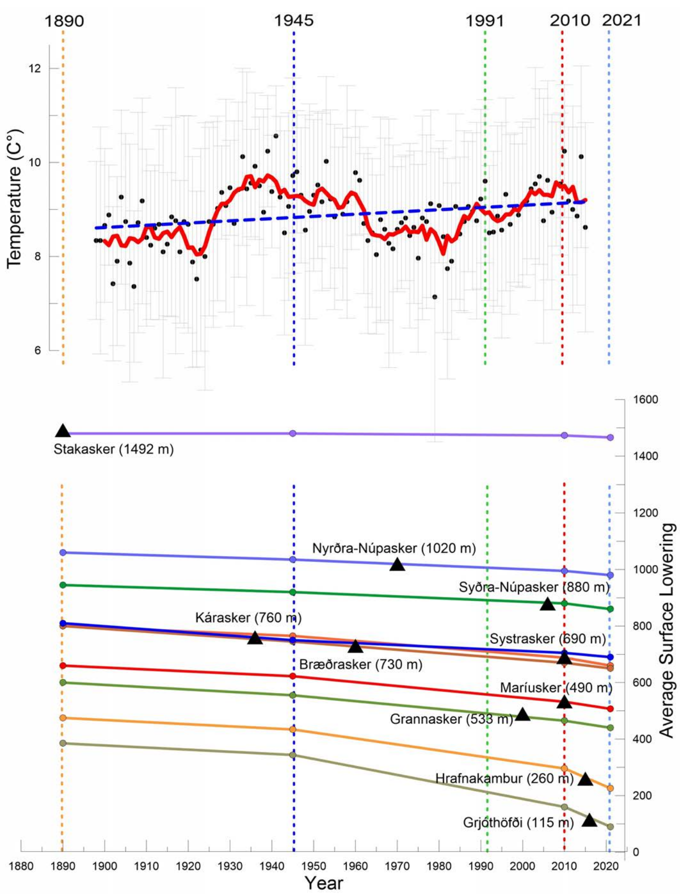

Figure 13. Above: Temperature at Fagurhólsmýri, 1898–2015. Source: Meteorological Office of Iceland. Each point represents average temperature of five months (MJJAS), considered the main annual melting season of Breiðamerkurjökull, with standard deviation (grey lines). The 5-year average (red line) and the overall linear trend (blue dashed line) reflect increasing temperature since the beginning of the 20th century. Vertical dashed lines refer to DEMs used for comparison. Below: Glacier surface elevation changes (multicoloured lines), based on the DEMs, indicate surface lowering since the late 19th century. Black triangles represent nunatak elevation at the year they became exposed. – *Ofar: Hitastig á Fagurhólsmýri 1898–2015. Heimild: Veðurstofa Íslands. Hver punktur táknar meðalhita fimm mánaða (MJJÁS), sem má telja meginleysingatímabil Breiðamerkurjökuls ásamt staðalfráviki (gráar línur). Fimm ára meðaltal (rauð lína) sem og meðaltalið (bláa strikalínan) endurspegla hækkandi hitastig frá upphafi 20. aldar. Lóðréttar brotalínur vísa til landlíkana sem notuð voru til samanburðar. Neðar: Yfirborðslækkun við jökulskerin, 1890–2021. Þríhyrningar sýna hæð jökulskerja árið sem þau komu fyrst í ljós. Breytingar á hæð jökulsins (marglitaðar línur) endurspegla yfirborðslækkun frá því seint á 19. öld.*

The medial moraines

Multiple medial moraines extend from nunataks and mountains to the terminus of Breiðamerkurjökull. Medial moraines are longitudinal supraglacial debris stripes that result from a range of glacial debris entrainment and transport processes. The classification scheme of Eyles and Rogerson (1978) is widely employed for medial moraine types. Under this classification scheme, the medial moraines of Breiðamerkurjökull are likely evolving as ice stream interaction (ISI) and ablation dominant (AD) types 1 and 3. The ISI type medial moraines form at the intersection of ice flow unit boundaries, where debris is delivered to the flow unit intersections by adjoining supraglacial lateral moraines. A temporal evolution of AD medial moraine types at Breiðamerkurjökull likely involves first the development of AD3 types, where debris is elevated from the bed in the lee of ice-covered rock knobs by converging ice flow (e.g. Vere and Benn, 1989). Glacier thinning then causes such rock knobs to form nunataks and consequently AD1 type medial moraines develop in the lee of the nunataks, where rockfall debris enters the heavily crevassed ice and then becomes exposed downglacier by ablation.

A comparison of georeferenced aerial photographs and the 1991 RES data, which shows the subglacial terrain beneath Breiðamerkurjökull (Björnsson, Pálsson and Guðmundsson, 1992), makes it possible to trace medial moraines that emerge from the glacier surface in the ablation zone to origins that may

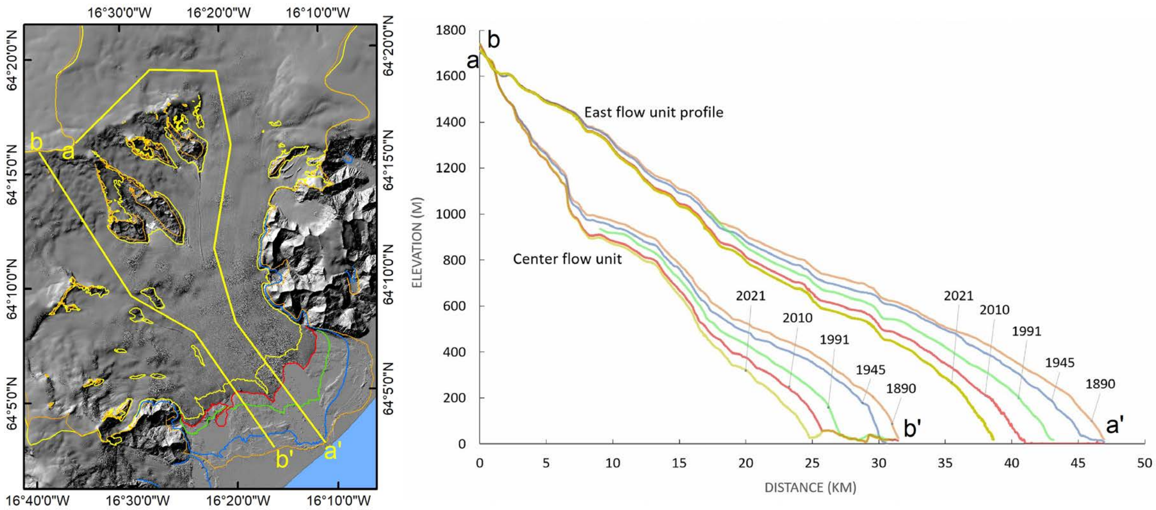

Figure 14. Length-sections down the eastern (a, a') and center (b, b') ice flow units of Breiðamerkurjökull, demonstrating the glacier retreat and surface changes from 1890 to 2021. – *Langsnið niður austurarm (a, a') og miðarm (b, b') Breiðamerkurjökuls endurspegla hörfun jökulsins og yfirborðsbreytingar frá 1890 til 2021.*

appear in the future with the ongoing rate of recession (i.e. from AD3 to AD1 types). Where the debris appears on the ice surface, it forms an insulating layer that slows melting. As a result, the medial moraines are frequently ice-cored stripes covered with supraglacial debris, rising higher than the glacier surface on either side (Anderson, 2000; Benn and Evans, 2010). In the region of Southeast Iceland, medial moraines are locally referred to as „-rönd", meaning a band or strip. Consequently, the identity of the medial moraines usually ends with this word.

The Hrossadalur medial moraine

The Breiðamerkurjökull and Fjallsjökull outlets merged in front of Mt. Breiðamerkurfjall prior to 1700 and remained coalescent until the 1940s. A medial moraine, described by Björnsson (1984) as low and inconspicuous, formed south of the Hrossadalur valley. It is visible on a photograph from 1935, but is not identified on the 1904 DGS map. The glaciers had completely separated in 1946 (F. Björnsson, 1998) and now a scatter of debris from this weakly developed medial moraine can be traced on the foreland.

Saumhöggsrönd

Saumhöggsrönd, the westernmost medial moraine of Breiðamerkurjökull, extends from Saumhögg and Mt. Heljargnípa to the east, north of Breiðamerkurmúli. This band is composed of a thin surface cover of silt and sand, as well as unsorted angular and subangular pebbles and boulders. It consists of basaltic rock and fragments of plutonic rock (Figure 16).

Saumhöggsrönd is not marked on either the DGS or AMS map. However, aerial images from 1945 show the moraine curving north of Múlahöfði and terminating at the mouth of the Jökuldalur valley. South of it is Saumhöggsjökull, the westernmost flow unit of Breiðamerkurjökull, which drains the flanks of Mt. Káratindur and Heljargnípa (Figure 1). In the first half of the 20th century, this glacier terminated in the Jökuldalur valley, but the medial moraine may have been located even further south in the 19th century. The Jökuldalur was ice-dammed, forming a glacial lake which regularly drained and created annual jökulhlaups. In 1904, its areal extent was about 0.5 km² (F. Björnsson, 1962; Guðmundsson *et al.*, 2019).

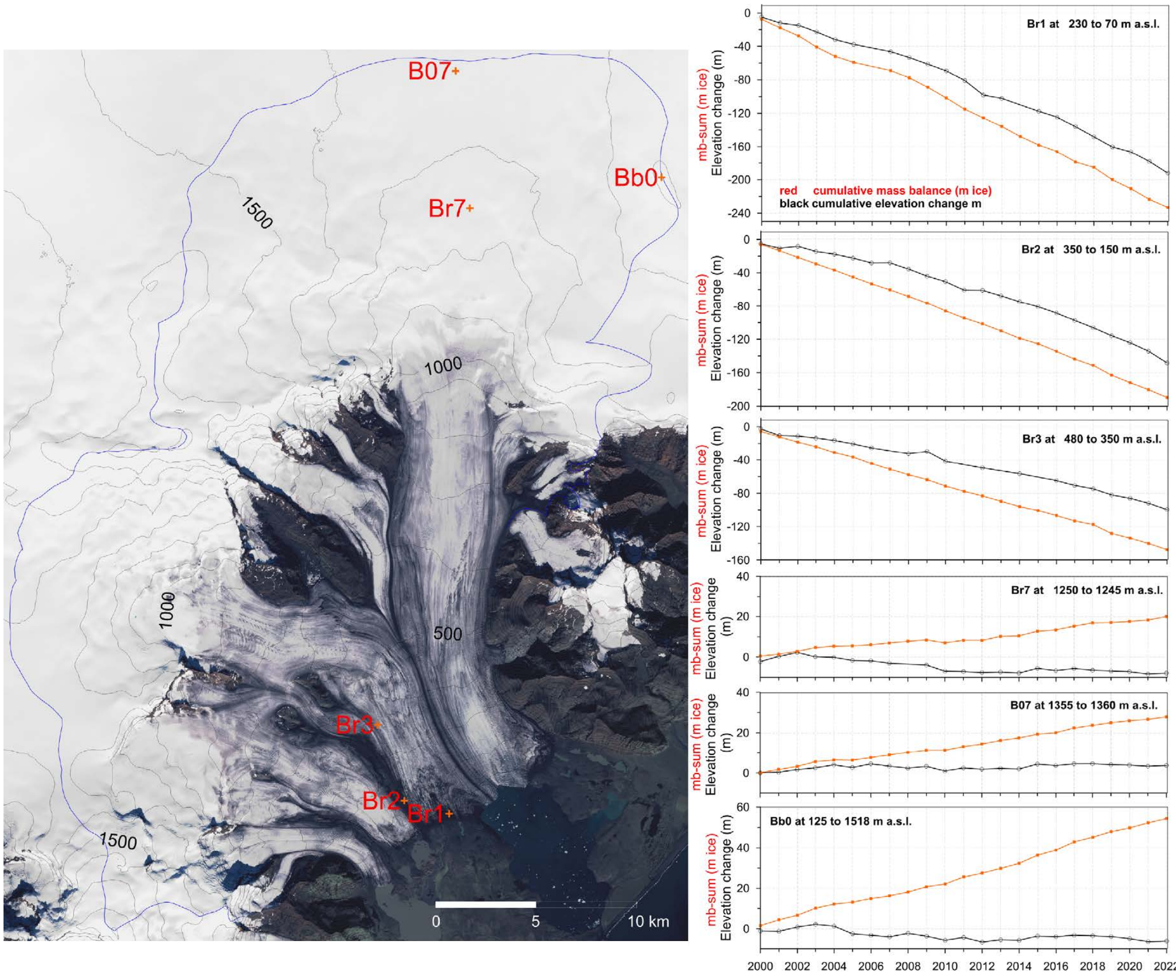

Figure 15. Left: Mass balance survey sites on Breiðamerkurjökull. Sentinel-2 satellite image, Sept. 23, 2022. Right: Cumulative mass balance for the period 1999–2000 to 2021–2022, compared to elevation change at the survey sites measured with the Global Navigation Satellite System (GNSS instruments). – *Staðsetning afkomumælistaða á Breiðamerkurjökli á Sentinel-2 gervihnattamynd frá 23. september 2022. Línuritin sýna uppsafnaða afkomu á mælistöðunum tímabilið 1999–2000 til 2021–2022, borin saman við hæðarbreytingar á sömu stöðum sem mældar eru með Global Navigation Satellite System (GNSS) tækjum.*

The Saumhöggsjökull medial moraine retreated from 5.6 km in 1945 to 4.8 km in the 1970s, when the moraine terminated on Breiðamerkurmúli. The medial moraine was 2.8 km long in 2021. Saumhöggsrönd is about 20–30 m wide east of Saumhögg but expands to 10 m wide where it currently terminates on Breiðamerkurmúli. Since 1945, the moraine has migrated 140 m to the south on a 1 km-wide section facing the valley occupied by the glacier. The shift in the years 2010–2021 accounted for half of the preceding seven decades. The lateral shift indicates less ice moving down the valley than previously. Nonetheless, the medial moraine has maintained a consistent orientation (Figure 17).

Figure 16. Crossing the rock debris of the Saumhöggsrönd medial moraine. – *Gengið yfir auri drifna Saumhöggsrönd.* Photo:/*Ljósmynd:* S.G., July 28, 2011.

Breiðárrönd

Breiðárrönd (or Vesturrönd, see F. Björnsson (1985)) is located to the east of Saumhöggsrönd and forms the third-largest medial moraine in Breiðamerkurjökull. It outlines the western section of the west flow unit, which drains the northeastern flanks of Öræfajökull, identified as Heljargnýpujökull. Additionally, it is the only ice flow unit that terminates in the proglacial lake Breiðárlón. The medial moraine originates from Mt. Fjölsvinnsfjöll and the Maríusker nunatak. The Breiðárrönd medial moraine turns sharply to the southeast 5 km east of Fjölsvinnsfjöll, from Maríusker nunatak down to the terminus (Figure 18). The moraine debris is composed of rhyolite and basalt. A small portion of the debris is subrounded by glacial transport, the majority of clasts being angular. The glacigenic debris (diamicton) is coarse-grained and contains boulders. The debris is thick enough to significantly reduce the ablation of the underlying ice so that near the glacier terminus the medial moraines rises tens of meters above the glacier surface (Figure 19).

On the DGS map, Breiðárrönd is drawn more than 4 km up the glacier from the terminus before disappearing about 2.3 km east of Breiðamerkurmúli. On the AMS map, it extends 3.4 km up the glacier. However, on the 1945 aerial photos, the medial moraine is traceable to Mt. Fjölsvinnsfjöll. An oblique aerial photograph in the Kvísker collection, taken in 1938, also confirms its existence. We believe the upper part of Breiðárrönd, no matter how indistinct it was, existed during the DGS survey in 1904, although it is not depicted on the map. East of Fjölsvinnsfjöll, Breiðárrönd has remained 10–30 m wide but has been close to 250 m wide at the terminus since the turn of the 20th century. In 2021, the Breiðárrönd medial moraine extended 9 km from the base of Mt. Fjölsvinnsfjöll to the terminus.

At the turn of the 20th century, the ice surface near Mt. Fjölsvinnsfjöll was 80–100 m above the current elevation and about 120 m higher where Grannasker and Maríusker now protrude from the glacier north of Breiðárrönd. At that time, Breiðárrönd terminated about 260 m east of Krókur, which is the inlet

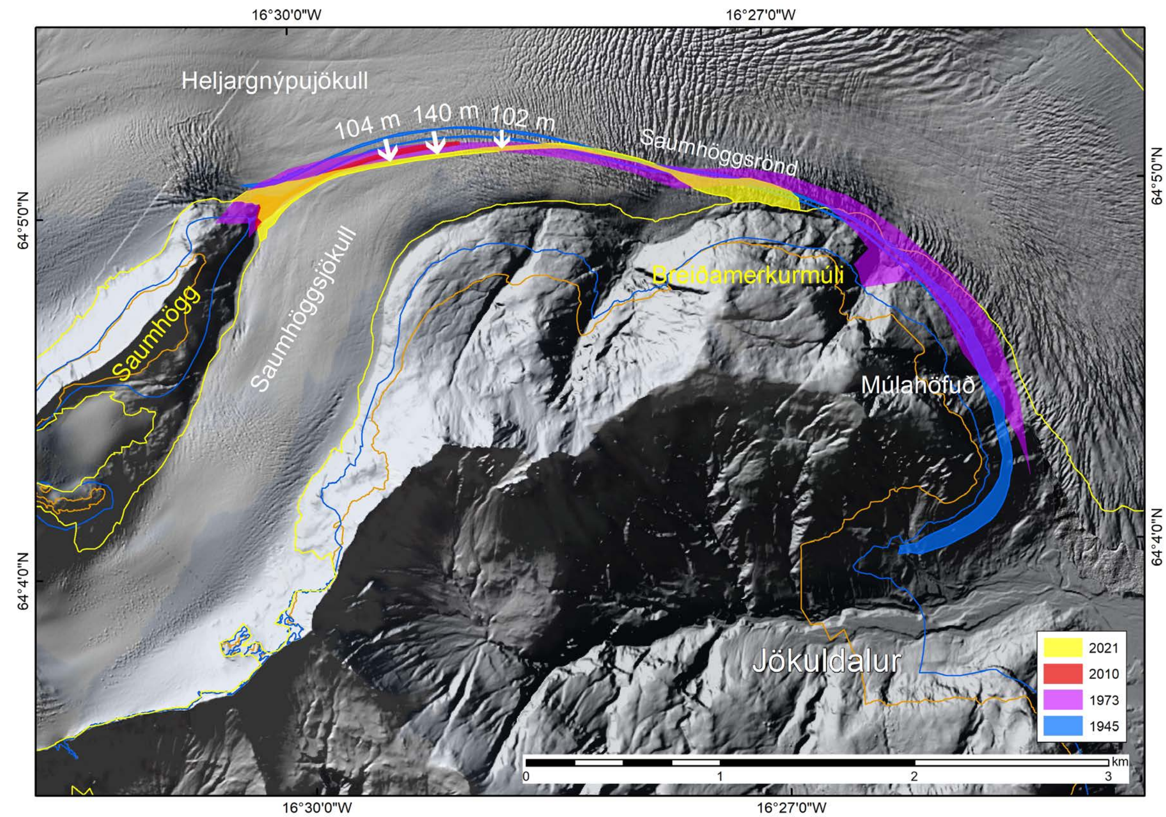

Figure 17. The migration of Saumhöggsrönd, based on its location in 1945 (blue), 1973 (violet), 2010 (red), and 2021 (yellow). The orange line shows the glacier margins at LIA's maximum extent, around 1890. – *Hnik Saumhöggsrandar, miðað er við staðsetningu hennar 1945 (blá), 1973 (fjólublá), 2010 (rauð) og 2021 (gul). Rauðgul lína sýnir jaðar jökulsins við hámarksútbreiðslu, um 1890.* Satellite image:/*Gervihnattamynd:* Sentinel 10/23/2022.

where Breiðamerkurjökull and Fjallsjökull adjoined. This area now forms the southernmost cove of the proglacial lake Breiðárlón, which began to form in the 1930s, east of Breiðárrönd (Figure 18b). The glacial river Breiðá debouched there in 1903 and 1904 but migrated further east before the proglacial lake developed (DGS, 1905; F. Björnsson, 1998; Guðmundsson and Evans, 2022). Later, in tune with glacier retreat, the lake gradually stretched to the south of the medial moraine. Simultaneously, another lake formed to the west of the moraine in 1945–1950, and these two lakes merged in front of it in 1954 (F. Björnsson, 1996; Guðmundsson *et al.*, 2019). This resulted in the medial moraine terminating in the lake until around 1980. Then ice retreated out of the lake and onto a rocky hill (Rist, 1982). Traces of Breiðárrönd remain south of the lake and on those rock outcrops north of it.

Breiðárrönd has shifted westward by 180–300 m since the mid-20th century. Earlier migrations cannot be determined. Closer to Mt. Fjölsvinnsfjöll and to the east of Maríusker, a shift of about 80 m has taken place since the 1970s (Figure 18a).

Systrarendur

Breiðárrönd is depicted as 0.9–1.1 km wide over the first kilometer up ice from the terminus, according to the 1904 DGS map (Figure 18). Not only did supraglacial deposition expand the moraine at the terminus, but also smaller medial moraines emerged

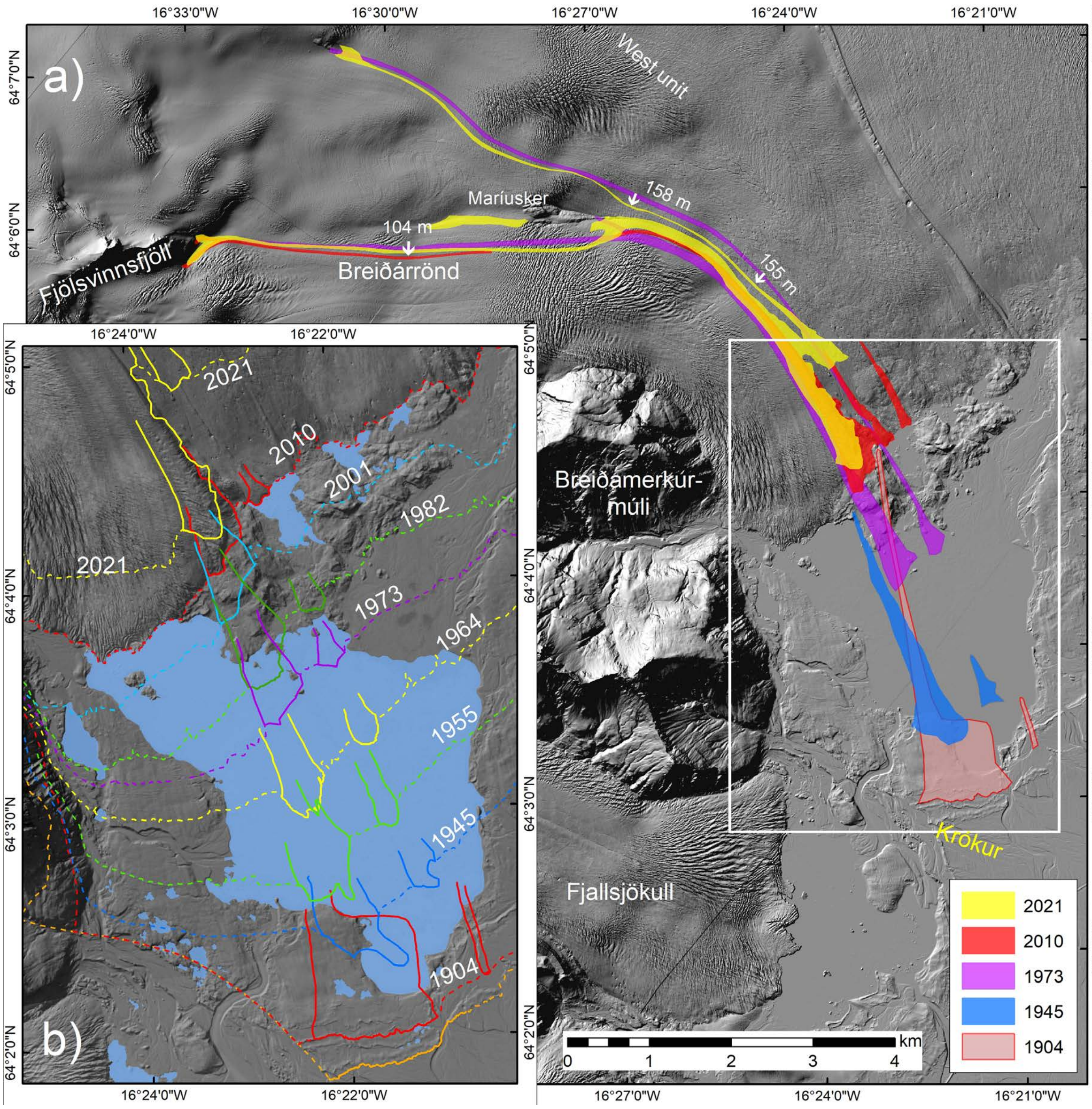

Figure 18. a) The development of Breiðárrönd and nearby medial moraines (Systrarendur), and b) its terminus position since the early 20th century. *– a) Breytingar Breiðárrandar og nærliggjandi urðarrana (Systrarendur), og b) endamörk þeirra frá því snemma á 20. öld.*

close and running parallel to Breiðárrönd. This batch of inconspicuous medial moraines are identified here as Systrarendur (-rendur is the plural form of '-rönd') because one of them originates at Systrasker nunatak. The others are traced to the Maríusker and Grannasker nunataks. In 2021, they appeared about 130, 270, and 770 m east of Breiðárrönd. These have become more apparent as the glacier recedes.

The Grannasker and Maríusker medial moraines run contiguously east of Breiðárrönd, extending

Figure 19. The Breiðárrönd medial moraine. – *Breiðárrönd.* Photo:/*Ljósmynd:* S.G., July 28, 2011.

∼3.3 km to the terminus. They are mostly vague on the surface, but emerge from the glacier about 340 m above the terminus and are around 80 m wide at most. The glacigenic debris is mostly light-colored basalt and plutonic rock pebbles, and the grain size is dominated by sand and gravel containing a considerable number of sub-rounded and rounded clasts. In 2022, where this debris emerged from the glacier surface close to the terminus, it had been locally reworked into an esker (Figure 20). The juxtaposition of medial moraines and englacial eskers in particular is a common landform relationship on Breiðamerkurjökull and one that is entirely predictable, because sedimentation in ice-walled tunnels requires the availability of large volumes of englacial debris that is afforded by medial moraines. Moreover, meltwater drainage pathways driven by supraglacial melt are concentrated in the suture zones between ice flow units and hence major tunnels tend to be in the same locations as medial moraine debris septa (Price, 1969; Evans and Twigg, 2002; Storrar *et al.*, 2015, 2020).

A little further east of the Maríusker medial moraine, the Systrasker moraine appears (Figure 21). On the AMS map, there is no indication of it, but the 1945 aerial photographs distinctly show it disappearing into the glacier where it was mostly under 80–90 m of ice. The Systrasker medial moraine was 7.3 km long in 2021 but vaguely traceable on the surface up to almost 5 km from the Maríusker nunatak. The width at that time was about 10 m, but it gradually widened to 120 m at about 2.3 km above the terminus. The poorly sorted debris consists of a mixture of basalt, gabbro and rhyolite, subrounded to angular clasts up to boulder size.

A comparison of satellite images taken in 1973 and 2021 indicates that the medial moraine shifted by 150–160 m to the southwest and migrated closer to Breiðárrönd over that time period (Figure 18).

Yet another vague medial moraine emerges from beneath a crevassed bulge, approximately 1.5 km north of Maríusker but it cannot be traced to a nunatak. On the DGS map, the moraine is depicted

Figure 20. The Maríusker medial moraine. – *Urðarraninn frá Maríuskeri.* Photo:/*Ljósmynd:* S.G., July 26, 2022.

as being 0.7 km up from the terminus of the glacier and 1.2 km east of Breiðárrönd (Figure 18a). It is similarly depicted on the AMS map, but its width is greater, and it is situated 0.5 km east of Breiðárrönd. However, aerial photographs from 1945 reveal that the medial moraine can be traced higher up the glacier. In 2021, this moraine measured about 4.5 km in length. The clasts in the glacigenic debris consist mainly of subtypes of basalt, ranging from very angular to subangular in form, along with tuff fragments and tephra. Additionally, moss-clad pebble-sized sandy gravel aggregates (jöklamýs or glacier mice; Eythorsson, 1951) are numerous in the moraine; such features are common in areas of thin supraglacial debris cover with abundant tephra content (Benn and Evans, 2010). The debris is spread thinly over the ice and hence its insulation effect is small and the medial moraine has no significant relief (Figure 22).

Mávabyggðarönd

Mávabyggðarönd, the second-largest medial moraine on Breiðamerkurjökull, separates the western and central ice flow units of Breiðamerkurjökull and in

Figure 21. The Systrasker medial moraine. In the distance to the left is the Breiðárrönd medial moraine. – *Urðarraninn frá Systraskeri. Fjær er Breiðárrönd.* Photo:/*Ljósmynd:* S.G., July 26, 2022.

Figure 22. The easternmost medial moraine on the west ice flow unit of Breiðamerkurjökul. – *Austasti urðarraninn á vesturarmi Breiðamerkurjökuls.* Photo:/*Ljósmynd:* S.G., July 26, 2022.

2021 it measured 250–300 m wide at the terminus. Mávabyggðarönd is a fusion of medial moraines originating from Mt. Mávabyggðir, as well as those from the Bræðrasker, Kárasker, and Hrafnakambur nunataks (Figures 3 and 23). The two longest medial moraines extend from Mávabyggðir but are difficult to trace high up on the glacier. They are linked to the two rock ridges in Mávabyggðir. The northern medial moraine, referred to here as Fingurbjargarrönd, measured about 13 km in length down to the terminus in 2021, while the southern one, Kaplaklifsrönd, originating from the Kaplaklif ridge, measured 15 km long. These moraines manifest as 20 m wide parallel bands in the glacier between the Kárasker and Bræðrasker nunataks.

The Kaplaklifsrönd merges with Bræðraskersrönd, the medial moraine from Bræðrasker, approximately 1 km east of the nunatak, and by then is 70 m wide. Fingurbjargarrönd joins them about 4 km southeast of Bræðrasker, having expanded to about 100 m wide at that point. In 2021, Bræðraskersrönd measured just over 8 km in length. Káraskersrönd, which was 8.3 km long in 2021, connected with the medial moraine fusion about 1 km up ice of the terminus (Figure 23). Bræðraskersrönd is indistinct where it is less than 20 m wide, but it widens to 70 m close to the terminus. About 2.5 km up ice of the terminus, Mávabyggðarönd veers around the side of the east slope of Hrafnakambur. Another medial moraine joins there, contrasting the west side with its light coloured basaltic debris (Figure 24).

The debris cover on the west side is mostly composed of sand and silt, and contains gravel and pebbles with rounded or sub-angular forms. The primary content is a mixture of debris from Bræðrasker and Mávabyggðir, featuring predominantly red-brown tuff, fragments of rhyolite, and grayish subtypes of basalt. The main ridge comprises silt and sand interspersed with angular or sub-angular cobbles and boulders, which constitute approximately 30% of the debris. Conversely, the debris originating from Kárasker (Figure 25) and adjoining the east side of the main ridge, forms a layer of silt and sand. It is scattered with greyish basalt cobbles and boulders, creating a contrast with the main moraine ridge. The majority of this debris is considerably rounded or sub-rounded.

The DGS map from 1904 depicts Mávabyggðarönd as being located 2.7 km east of Breiðárrönd, and 8.5 km up-ice from the terminus. The medial moraine splits apart about halfway indicating that two separate medial moraines existed already in the early 20th century. At that time, Mávabyggðarönd was about 21 km long extending from Mt. Mávabyggðir and, at the terminus, more than 0.5 km wide. On the AMS map, the Mávabyggðarönd is composed of four stripes, and the longest is 5.2 km (Figure 23a). The aerial photographs from 1945 confirm its position but the stripes are rather vague except near the terminus, where its expanded width was 0.75 km and it was 10–20 m higher than the glacier surface.

Between 1904 and 1945 the glacier terminus and the outer edge of the medial moraine retreated towards the north, but the moraine changed orientation gradually towards the north-northwest after 1945 (Figure 23b). This shift spanned many decades. Simultaneously, Mávabyggðarönd migrated west, south of the Kárasker and Bræðrasker nunataks. Over a period of 76 years, a segment of Káraskersrönd moved >0.5 km, and Bræðraskersrönd about 0.25 km towards the west. Concurrently, the coalescence point, where the medial

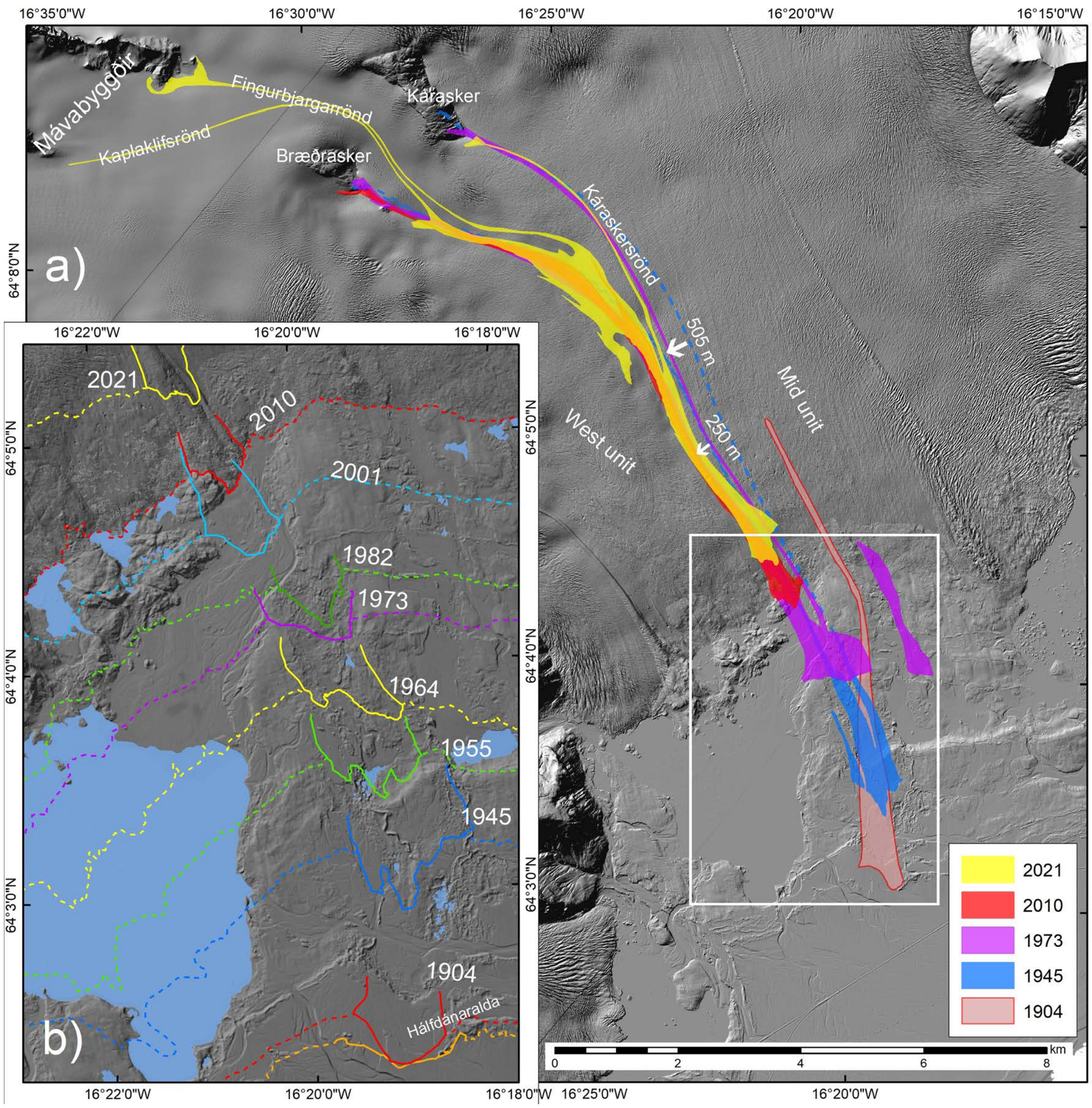

Figure 23. a) The development of the medial moraine Mávabyggðarönd and b) its terminus position since the early 20th century. – *a) Þróun Mávabyggðarandar, og b) endamörk hennar frá því snemma á 20. öld.*

moraines fused, moved >6.5 km to the north in an up glacier direction (Figure 26).

In 2021, the west ice flow unit had retreated more than 5.8 km from its maximum extent in the late 19th century. The Hálfdánaralda end moraine remains as the outermost locality of the former Mávabyggðarönd. Since the medial moraine did not terminate in a proglacial lake, its former position can be traced on Breiðamerkursandur. North of Hálfdánaralda, a band of rock debris, erratics, eskers, kames, and kettle holes marks the path where it terminated throughout the 20th century (Price, 1969; Evans and

Figure 24. The medial moraine Mávabyggðarönd, showing its mixed colors due to the different debris origins. – *Litblönduð Mávabyggðarönd, vegna uppruna urðarrana frá mismunandi skerjum.* Photo:/*Ljósmynd:* S.G., July 26, 2022.

Twigg, 2000, 2002). These landforms developed through the interaction of meltwater and supraglacial hummocky moraine formation in association with the medial moraine debris septa; englacial tunnels also created eskers in this setting (cf. Levson and Rutter, 1989). The Breiðá glacial river also discharged from the glacier close to the Mávabyggðarönd (Figure 23b), although it temporarily changed course in the 19th and 20th centuries (F. Björnsson, 1998; Guðmundsson and Evans, 2022).

Esjufjallarönd

Esjufjallarönd, which separates the central and eastern ice flow units, is the longest medial moraine complex on Breiðamerkurjökull and currently terminates in Jökulsárlón (Figures 27a,b and 28a,b). It consists of two main medial moraines, each composed of smaller septa-controlled ridges originating in the Mt. Esjufjöll massif. The eastern main moraine, identified here as Austurbjargarönd, was 18 km long down to the terminus in 2021. It comprises two longitudinal debris septa, the larger one coming from Austurbjörg and the other from Esjubjörg (Esjubjargarönd). Austurbjargarönd is about 100 m wide where it meets Esjubjargarönd, 2 km to the south. They run parallel, approximately 120–140 m wide for the next 7-8 km and merge southeast of Skálabjörg. At that point, the medial moraine narrows due to its attenuation in response to increased ice flow velocity. The western main medial moraine is identified as Skálabjargarönd, which in 2021 measured 11.7 km down to the terminus. Three inconspicuous medial moraines emerge from Esjudalsjökull and join Skálabjargarönd. Skálabjargarönd is widest south of Skálabjörg but narrows to <30 m where it meets Austurbjargarönd, approxi-

Figure 25. The medial moraine Káraskersrönd contrasts the east side of Mávabyggðarönd (to the left) with its mixed colors related to different debris origins. – *Káraskersrönd sameinast austanverðri Mávabyggðarönd (til vinstri) sem verður mislit vegna mismunandi uppruna setsins.* Photo:/*Ljósmynd:* S.G., July 26, 2022.

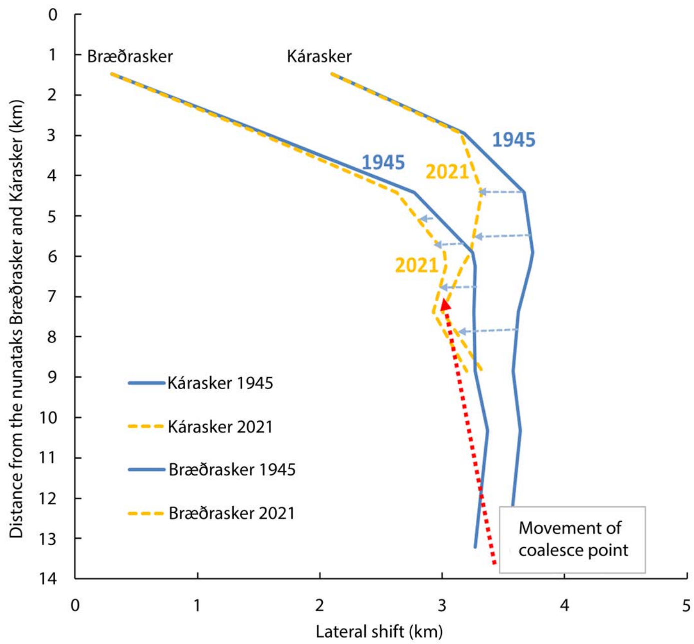

Figure 26. The displacement of Mávabyggðarönd that occurred between 1945 and 2021 on a 10 km long section south of the Bræðrasker and Kárasker nunataks. – *Tilfærsla Mávabyggðarandar sem varð á 10 km löngum kafla sunnan við Bræðrasker og Kárasker á árunum 1945 til 2021.*

mately 4 km south of Skálabjörg. In recent decades, they have merged, but in the 20th century, they ran parallel, separated by Esjudalsjökull. The debris is a mixture of rock fragments from various sources, including basalt, rhyolite, tuff, and tillite and is dominated by silt and sand (Figure 28a).

Esjufjallarönd is the only medial moraine that is delineated to its origin on the DGS map. The glacial river Jökulsá usually discharged east of Esjufjallarönd or near it (F. Björnsson, 1998; Guðmundsson and Björnsson, 2020a). However, after the proglacial lake was formed, the medial moraine terminated on its western bank. According to the DGS map, the two main medial moraine components merged about 6 km south of Skálabjörg. The length to the terminus was 20.6 km from Skálabjörg and 25.2 km from Austurbjörg. The measured width appears to be between 120 and 90 m, but extends to 200 m after the merging and gradually widens to 2.2 km at the terminus. A comparison with the AMS map and aerial photographs from 1945 reveals that the medial moraine had only retreated a few hundred meters in the first half of the 20th century (Figure 27a). It terminated in the proglacial lake Jökulsárlón in 1945, but this section had retreated slowly since its maximum extent in the 1930s (F. Björnsson, 1998; Guðmundsson and Evans, 2022). Aerial photographs from 1945 show that the two parallel medial moraines forming Esjufjallarönd were separated nearly all the way from their sources to the terminus. Skálabjargarönd medial moraine was about 30–50 m wide, while Austurbjargarönd was close to 100 m wide. The gap between them was occupied by the Esjudalsjökull outlet glacier of Esjufjöll

More changes have been observed in Esjufjallarönd than in the other medial moraines on Breiðamerkurjökull, especially in the last few decades. Throughout the 20th century, the supraglacial debris of Esjufjallarönd remained denser and more prominent on the surface of the glacier compared to recent decades. The ongoing thinning of the glacier and the increased speed of the ice being drawn down into Jökulsárlón has attenuated the medial moraine down the glacier. In addition to this, another kinematic phenomenon has occurred in Breiðamerkurjökull and recorded by Esjufjallarönd (Björnsson *et al.*, 1999, 2001, 2003). For most of the 20th century, Esjufjallarönd gradually migrated to the west. This sub-

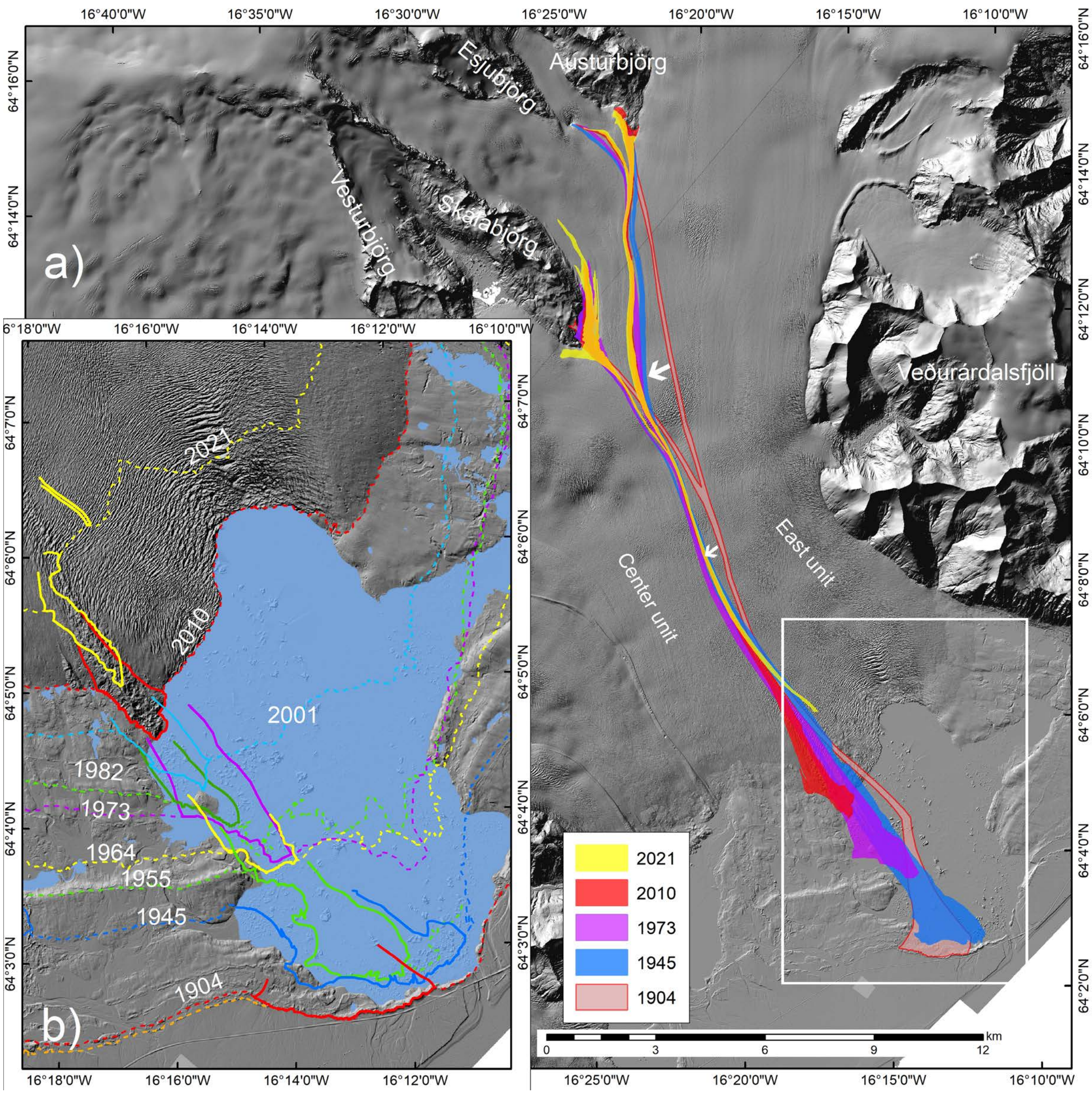

Figure 27. a) The development of the medial moraine Esjufjallarönd and b) its terminus position since the early 20th century. – *a) Breyting Esjufjallarandar og b) endamörk hennar frá því snemma á 20. öld.*

tle movement has taken place almost all the way to Mt. Esjufjöll, but the shift was greater near the terminus and decreased up the glacier. (Figure 29 shows the sequence of events. The green dot, which is the islet Skúmey, is used here as a reference mark for the following chronological details:

1. When the DGS survey was conducted in 1904, the entire medial moraine was east of Skúmey. The DGS map delineates a conspicuous curve, but it is unknown whether or not it is a surveying error. However, this detail does not affect the shift, as that is based on the position of Esjufjallarönd in 1945.

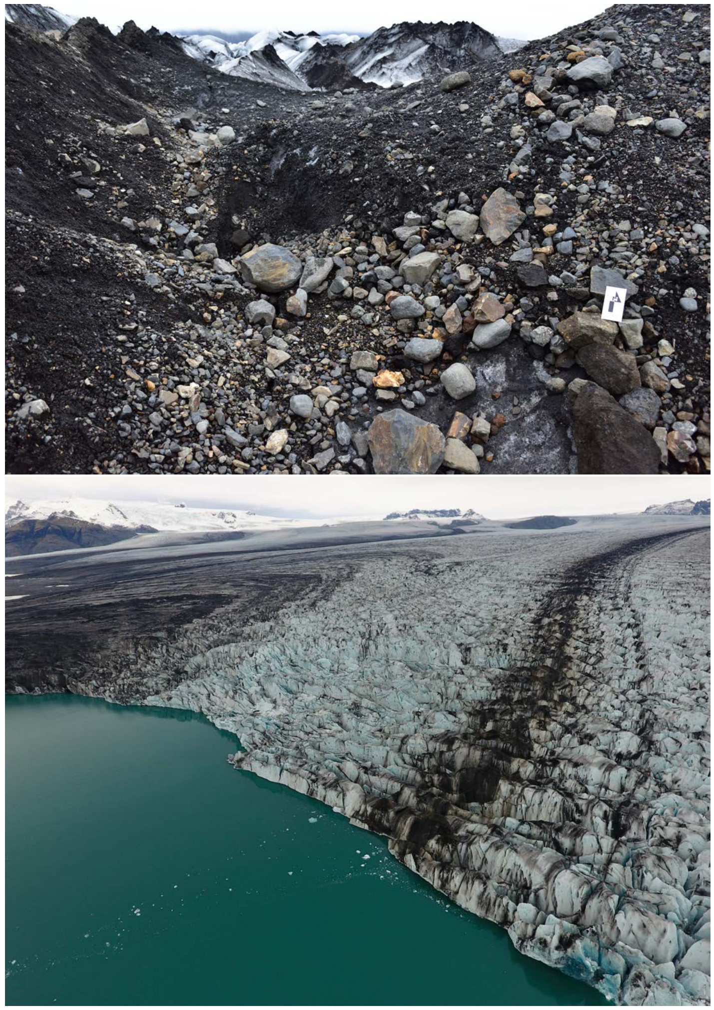

Figure 28. Esjufjallarönd: Top: The rock debris on the surface of the medial moraine. Below: The moraine terminating in Jökulsárlón after its migration to the east between 2004 and 2016 due to the snout thinning. – *Esjufjallarönd: Ofar: Set á yfirborði randarinnar. Neðar: Endamörk randarinnar* í Jökulsárlóni eftir að hafa færst til austurs á árunum 2004 til 2016 vegna jökulrýrnunar. Photos:/*Ljósmyndir*: S.G., July 21, 2022 (left) and October 5, 2021.

2. In 1945, the western border of Esjufjallarönd lay above the eastern edge of the Skúmey.
3. In 1954, Esjufjallarönd began to migrate over the eastern side of Skúmey.
4. In the 1960s (frames 1960 and 1965), Skúmey was entirely under Esjufjallarönd. At that time, the glacier terminus had retreated 2.9 km to the west of Jökulsárlón and calved into the lake. Skúmey remained subglacial, 1 km inside the terminus.
5. In the 1970s, Skúmey was under the middle of the medial moraine, but only a few years later it emerged from under the receding glacier margin. The south coast of Skúmey was first exposed in 1976–1977, and the glacier finally retreated from it entirely in the year 2000 (Guðmundsson *et al.*, 2018).
6. By 1982, the Esjufjallarönd had migrated >0.4 km to the west in this area.

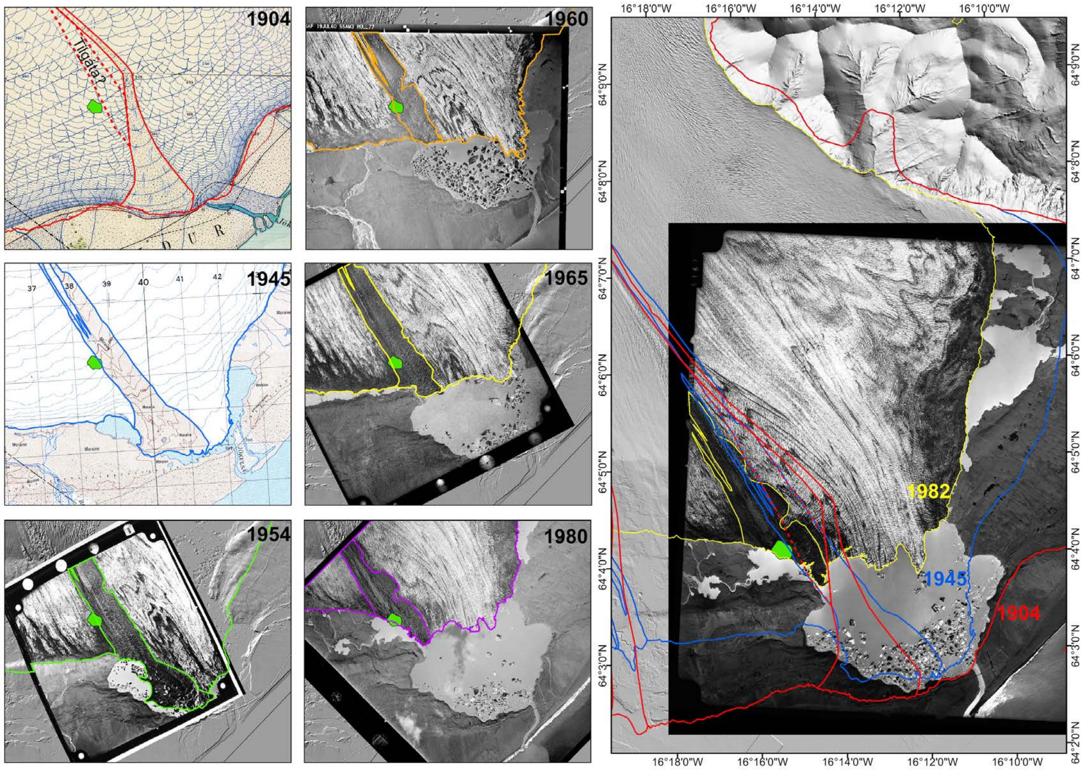

Figure 29. The shift of the medial moraine, Esjufjallarönd, as revealed using the reference mark of Skúmey (green dot). – *Hliðrun Esjufjallarandar, verður ljós þegar notað er viðmiðunarmerki, í þessu tilfelli Skúmey (grænn punktur).*

Esjufjallarönd's shift extends as far as 2.5 km south of Skálafellsbjörg, where it has remained stable. A possible explanation is that a subglacial peak appears to control the glacial flow (Figure 30). This peak was discovered in the RES survey in 1991 (Björnsson, Pálsson and Guðmundsson, 1992) and its location is indicated by a crevassed bulge on the glacier surface. A subglacial trench remains in the bed to the east of the peak, extending to the rim of the offshore shelf. The trench, along with others under Breiðamerkursandur, was excavated by previously more extensive Pleistocene glaciers but filled with river and estuarine deposits during the Holocene. During the Little Ice Age, Breiðamerkurjökull removed this unconsolidated sediment from the trenches (Boulton *et al.*, 1982; Bogadottir *et al.*, 1986; Björnsson, 1996, 1998b). As the glacier retreated, glacial lakes immediately formed in them, the largest being Jökulsárlón, Breiðárlón, and Fjallsárlón.

Esjufjallarönd runs parallel to and above the western slope of the subglacial trench. After 2005, the lower section of Esjufjallarönd began to move back eastwards, a consequence of rapid calving in Jökulsárlón and the lowering of the glacier surface above the lake, and bed landscape diverting the flow of the now considerably thinner ice at the current calving edge, diverting flow eastward. Consequently, the eastern part of the center ice flow unit began to draw down towards the lake. As a result, the ice divide shifted to the west from Esjufjallarönd into the center ice flow unit (Figure 30). The east ice flow unit has therefore encroached on the eastern part of the center ice flow unit, along with the Esjufjallarönd medial moraine, which now terminates in Jökulsárlón (Guðmundsson and Björnsson, 2016; Storrar *et al.*, 2017).

Over the same period, the coalescence point of Skálabjargarönd and Austurbjargarönd gradually

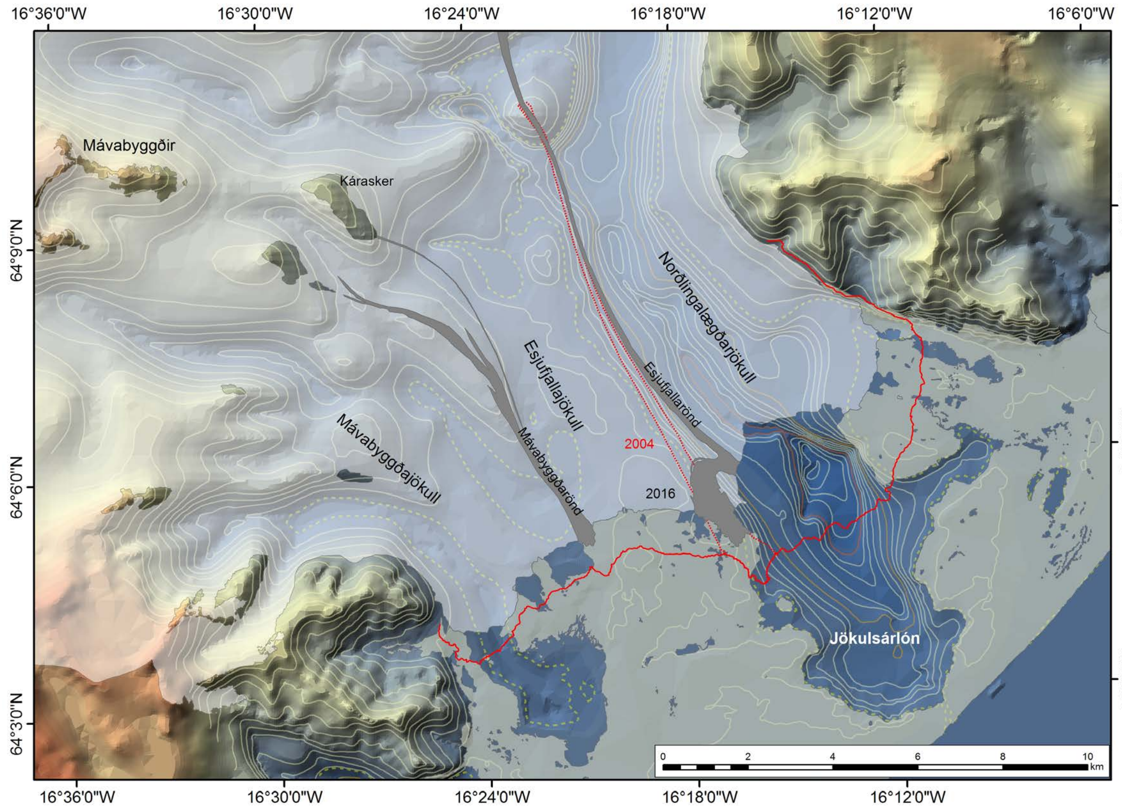

Figure 30. Subglacial topography and medial moraine development at Breiðamerkurjökull: Hillshaded DEM of the glacier bed from a RES survey (Björnsson, Pálsson and Guðmundsson, 1992) and overlaying ice surface Lidar data from 2010 (Jóhannesson *et al.*, 2011). The Esjufjallarönd medial moraine is marked for 2004 (red line) and 2016 (dark gray line). Breiðamerkurjökull is semi-transparent to reveal the bed beneath it. The trench under the east flow unit is delineated with depth contours every 20 m. Esjufjallarönd is situated above the western slope of the trench. About 2.5 km south of Skálafellsbjörg, the medial moraine passes over a subglacial peak, where it has not shifted. – *Landslag undir Breiðamerkurjökli og framvinda hliðrunar Esjufjallarandar: Hlíðaskyggt hæðarlíkan af botni jökulsins, samkvæmt íssjármælingum (Björnsson, Pálsson og Guðmundsson, 1992). Yfirborð jökulsins er samkvæmt Lidar gögnum frá 2010 (Jóhannesson o.fl., 2011). Esjufjallarönd er hnituð fyrir árin 2004 (rauð lína) og 2016 (dökkgrá lína). Breiðamerkurjökull er hálfgagnsær til að jökulbælið sjáist. Rennan undir Austurarminum er með 20 m dýptarlínum. Esjufjallarönd er ofan við vesturhlíð rennunnar. Um 2,5 km sunnan við Skálafellsbjörg liggur Esjufjallarönd yfir fjall í jökulbælinu en þar hefur hún ekki hliðrast.*

moved further north towards Esjufjöll, above the aforementioned subglacial peak, and simultaneously shifted to the west (Figure 31). This movement can be linked to the progressive recession of glaciers on Mt. Esjufjöll. There remain five steep valley glaciers (Table 1) with independent but small accumulation areas. The small area of accumulation and rapid ice movement mean that they respond quickly to climatic changes. Since 1995, these small outlets have receded rapidly. As an example, the terminus of Fossadalsjökull, a 6.6 km-long glacier occupying the Fossadalur valley in Mt. Esjufjöll, converged with an ice flow unit from Snæhettudalur. It began to break up rapidly after 1995 and subsequently formed the proglacial lake Fossadalslón in just a few years. About 25 years later, the glacier tongue had retreated

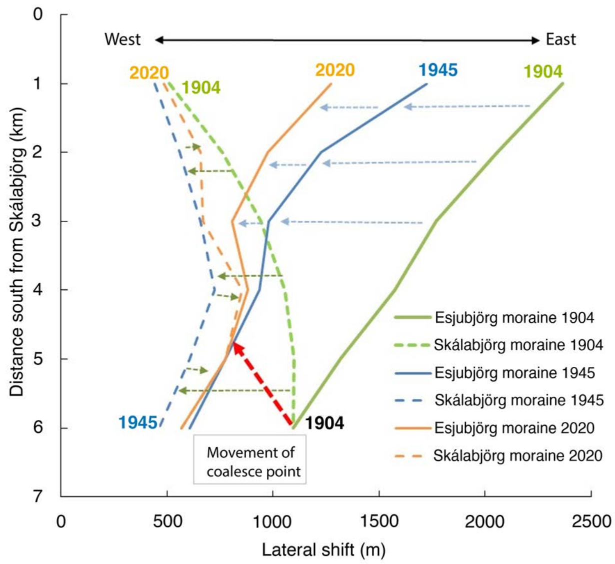

Figure 31. The shift of the Esjufjallarönd medial moraine and the coalescing point of the Skálabjargarönd and Austurbjargarönd on a 6 km long section, 1904–2020. – *Hliðrun Esjufjallarandar og samrunapunkts Skálabjarga- og Austurbjargaranda á 6 km löngum kafla suðaustan við Skálabjörg í Esjufjöllum á árunum 1904 til 2020.*

by 4.6 km. A similar sequence of events can be traced on all these glaciers. Three of them, Esjudalsjökull, Austurbjargajökull and Flekksjökull, moved a short distance alongside Breiðamerkurjökull. Esjudalsjökull is the largest glacier/ice flow unit and the only one that reached the terminus of Breiðamerkurjökull, which it no longer does. In the middle of the 20th century, Esjudalsjökull separated the two main medial moraines in a 100 m wide gap down to the terminus. The gap had disappeared in the first decade of the 21st century, and the coalescence point moved to the north by almost 1.5 km. As the glacier tongues in Esjufjöll have receded, Austurbjargarönd has shifted west, because the east ice flow unit of Breiðamerkurjökull transports much more ice mass from Vatnajökull than the center ice flow unit.

Veðurárrönd and Urðadalsjökull

The Veðurárrönd terminal moraine skirts the junction of Svöludalsjökull in the remote Veðurárdalsfjöll massif and Breiðamerkurjökull, in a 3.5 km-long arc (Figure 32). The place name first appears on the DGS map, suggesting that the Danish surveyors who measured here in 1904 identified it as such. It is an ice-cored end moraine (controlled moraine, sensu Evans, 2009) interwoven with lateral hummocky moraines on both sides of the Svöludalsjökull outlet, forming a 5.6 km long complex. The surface is covered with a layer of fragmented rock debris. It is uniform and rounded in cross-section but steeper on the proximal side, facing Svöludalur. The moraine is currently about 25–35 m higher than the ice surface on both sides. The DGS map indicates it was about 20 m above the ice surface in 1904, slightly lower than its state after the mid-20th century.

According to the DGS map, the arc-like end moraine was 3 km long but included a smaller bend in its form. The probable reason is the resistance of the Breiðamerkurjökull margin, which was also thicker at that time. The moraine was 400–700 m further south in the mouth of the valley than later (Figure 32). It was about 50 m wide but is currently 170–200 m wide. The DGS map indicates the elevation of Veðurárrönd to be 824 m in 1904. In 1945, that section of the moraine was at an altitude of 800 m, but it had dropped to 700 m in 2010. The moraine and the entire glacier surface have therefore dropped by 120 m since the beginning of the 20th century: 20 m from 1904–1945 and 100 m between 1945–2010. In 1945, Veðurárrönd had advanced north of the mouth of Svöludalur and was located not far from its current location (Figure 32). Since then, the curved end moraine has moved about 0.5 km further to the west and 0.3 km to the north but has remained unchanged below Mt. Snæfell.

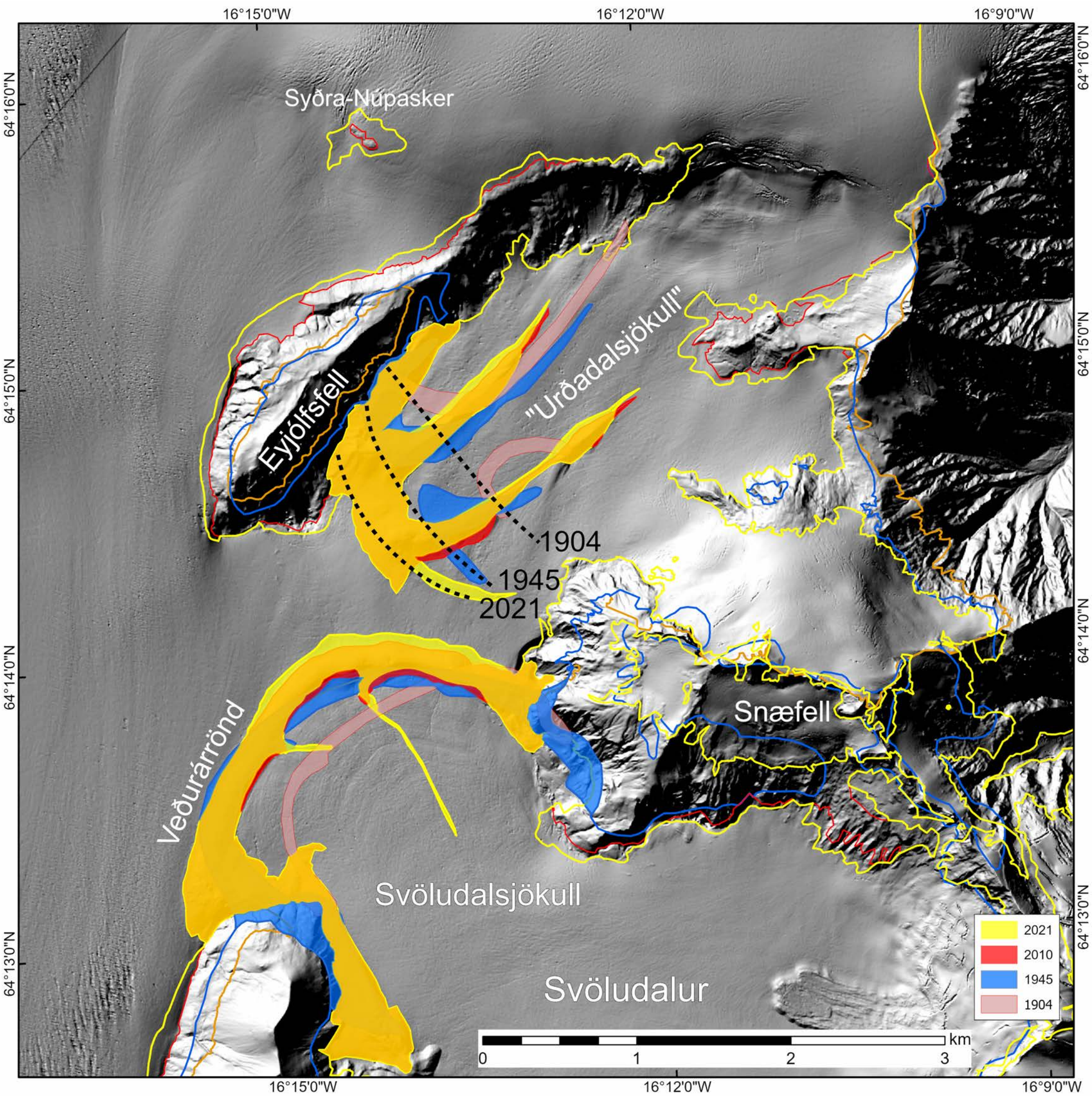

Figure 32. The Veðurárrönd complex and the Urðadalsjökull medial moraines south of Mt. Eyjólfsfjall. – *Veðurárrönd og urðarranarnir, á Urðadalsjökli, sunnan við Eyjólfsfjall.*

The glacier between Mt. Eyjólfsfjall and Mt. Snæfell, previously identified as Urðadalsjökull, maintained a similar thickness for several decades in the 20th century because it was supported by a secondary glacier flowing from Breiðabunga, over the mountain ridge connecting to Eyjólfsfjall and into the valley. However, the ice mass influx has gradually decreased, and Urðadalsjökull began to recede in the second half of the 20th century for that reason. When the supporting glacier stops feeding the Urðadalsjökull outlet, the entire glacier surface in Urðadalur valley will be below the equilibrium line altitude (ELA) and in the ablation zone.

Urðadalsjökull is composed of three narrow ice flow units, resulting in two medial moraines and an ice-cored lateral moraine that curves like an end moraine and converges with the confluence with Breiðamerkurjökull (Figure 32b). The DGS map and a photograph taken by the Dane Daniel Bruun from above Veðurárdalsfjöll in 1904 confirm that these medial moraines were located 800 m further east in the valley than now, due to the dominance of Breiðamerkurjökull. At that time, the ice surface was less steep and at a higher altitude. The length of the northern medial moraine was about 1.5–2 km, at an elevation of 840–870 m. It curved slightly to the north, towards Eyjólfsfjall. On the southern medial moraine, the Danish surveyors measured its altitude at 828 m.

In 1945, the medial moraines had shifted 0.3–0.4 km to the southwest down the valley, but the glacier surface was still at the same height as 55 years earlier (Figure 32b). The longer northern moraine had been modified into an even greater curve, extending to the lateral moraine of Eyjólfsfjall. In 2021, the moraines had moved an additional 0.4 km, but their altitude had dropped by 120 m since 1904.

Changes and displacements of the medial moraines in Breiðamerkurjökull are presented in Table 6. The origin and length of the moraines are estimated from the DGS map (1904) or AMS aerial photographs (1945), compared with the length in 2021.

DISCUSSION

The historical emergence and evolution of Breiðamerkurjökull's nunataks and medial moraines

The impact of the current climate on the glaciers of southeast Iceland has been widely charted as a pattern of accelerating snout recession (e.g. Björnsson *et al.*, 1992; Evans et al, 2019; Guðmundsson and Evans, 2022; Pálson, 2023). The concomitant emergence and enlargement of nunataks and medial moraines, as well as the displacement of medial moraines in response to changing ice flow patterns, is significantly less well documented (e.g. Guðmundsson and Björnsson, 2016; Storrar *et al.*, 2017). The assessment of the retreat of the Breiðamerkurjökull terminus and ice surface lowering in particular is based on measurements and analyses of various data sources dating back to 1890 (Björnsson, Pálsson and Guðmundsson, 1992; Guðmundsson and Evans, 2022; Pálson, 2023). In summary, Breiðamerkurjökull reached its maximum extent around 1870–1880 and its terminus occupied that position more or less passively over the next few decades while downwasting. After 1890, it began to retreat slowly on both sides at Esjufjallarönd (F. Björnsson, 1998; Guðmundsson and Evans, 2022). The nunatak Kárasker first emerged in the late 1930s, followed by the Bræðrasker nunatak in 1960 and Nyrðra-Núpasker in the 1970s. Since the beginning of the 21st century, numerous nunataks have ap-

Medial moraine	Origin	Length (km)		Lateral Displacement (LD)			
		1904	2021	Length (km)	LD (km)	years	Avr. myr^{-1}
Saumhöggsrönd	Saumhögg	5.6$_{(1945)}$	2.8	1.4	140	1945-2021	1.8
Breiðárrönd	Fjölsvinnsfjöll	13.5	9.6	~4.0	104	1973-2021	2.1
Maríuskersrönd	Maríusker	6.1	4.7	—	—	—	—
	Grannasker	—	—	—	—	—	—
Systraskersrönd	Systrasker	10.1$_{(1973)}$	7.3	6.2	158	1973-2021	3.3
Mávabyggðarönd	Mávabyggðir	21.0	15.1	<5.0	250	1945-2021	3.2
	Hrafnakambur	—	2.4	—	—	—	—
Káraskersrönd	Kárasker	13.7$_{(1945)}$	8,3	7.5	505	1945-2021	6.6
Bræðraskersrönd	Bræðrasker	14.3$_{(1945)}$	8.4	—	—	—	—
Esjufjallarönd	Skálabjörg	20.4	11.8	23.8	600	1904-2005	5.9*[a]
	Austurbjörg	25.1	17.5	8.3	970	2005-2021	60.5*[b]

*[a] Westward lateral displacement. *[b] Eastward lateral displacement.

Table 6. The medial moraines of Breiðamerkurjökull and their displacements since the turn of the 20th century. – *Hliðrun á urðarrönum Breiðamerkurjökuls frá byrjun 20. aldar.*

peared: Maríusker (2000), Syðra-Núpasker (2006), Systrasker (2008), Grannasker (2010), and Hrafnakambur, and Grjóthöfði in 2016.

Due to the glaciological complexity of Breiðamerkurjökull, the impact of glacier recession is manifested not only in a retreating terminus and ice surface lowering. The different fluxes and vigour of the main ice flow units, as well as the recession of the smaller tributary glaciers are reflected in the development and migration of the medial moraines. Furthermore, valley glaciers in the Mt. Esjufjöll and Veðurárdalsfjöll massif have thinned and retreated rapidly in the last decades. Several are still confluent with the center or the east ice flow units, but their surface lowering reflects the reduced ice flux. As the Breiðamerkurjökull snout draws back, the coalescence points of the medial moraines migrate up glacier. Glacier tongues in Innri-Veðurárdalur and Fossadalur in Mt. Esjufjöll have become detached, and consequently glacier-dammed lakes have formed, which are potential jökulhlaup sources.

Ongoing ice thinning has resulted in some examples of significant medial moraine migration where smaller tributary ice flow units have been moved laterally by the main glacier and their trunk has narrowed as a consequence. For example, Saumhöggsjökull (Figure 17), the westernmost tributary glacier of the Breiðamerkurjökull complex, has narrowed and its medial moraine with Heljargnípujökull has migrated southward by 140 m, intensifying in recent decades. A similar displacement of over 100 m has occurred over the same time period on the upper section of the Breiðárrönd medial moraine, on the other side of Heljargnýpujökull (Figure 18). In contrast, the lower section of Breiðárrönd has remained relatively stable, indicating a more balanced ice mass flow on either side of it. However, the Systrasker medial moraine has gradually migrated closer to Breiðárrönd, as a result of the recession of the glacier flow unit between Maríusker and Systrasker. The 1904 map shows the two medial moraines separated by more than 1 km at the terminus; in 1945, the distance between them was 0.6 km, 0.5 km in 1973, and 0.3 km in 2010. The Systrasker medial moraine shifted up to 160 m towards the southwest between 1973 and 2021. This indicates that the stability of medial moraines during overall ice recession, and hence their accumulation as an unbroken linear feature on deglaciated forelands (e.g. Eyles and Rogerson, 1978; Levson and Rutter, 1989; Evans and Twigg, 2002; Ballantyne and Dawson, 2019), is not always guaranteed. Moreover, the displacement of medial moraines gives rise to gently inclined or even folded englacial debris banding, which produces longitudinal foliation and later melts out as a supraglacial veneer often with weakly defined linearity (Jennings and Hambrey, 2021).

Even on deglaciated forelands, medial moraine alignments can record shifts in ice flow unit dominance over time. For example, the Mávabyggðarönd medial moraine exhibited westward displacement in its upper section, a migration of the Bræðraskersrönd and Káraskersrönd coalescence point, and a shift in its orientation on the foreland in the first half of the 20th century. At that time, Mávabyggðarönd terminated where Hálfdánaralda is located (Figure 23). The DGS map shows the lower section of the medial moraine heading north, with a conspicuous curve to the north-northwest, about 4.3 km above the snout margin. In the mid-20th century, Mávabyggðarönd terminated about 1.7 km north of Hálfdánaralda, still curving to the north-northwest about 1 km up glacier of the terminus. The medial moraine has left traces on the foreland indicating that the direction of Mávabyggðarönd at the snout terminus shifted by 34° from 1904 until the middle of the 20th century. In 1945, the Bræðraskersrönd and Káraskersrönd coalesced just above the terminus, but the coalescence point had moved >6.5 km higher on the glacier in 76 years. The medial moraines have also shifted 0.25 and 0.5 km to the west, respectively. The retreat and the migration of the coalescence point are signs of a reduced supply of ice in a limited area south and east of Mt. Mávabyggðir. At that location, the glacier surface, which was previously in the accumulation zone in the early 20th century, has since lowered significantly and is now below the ELA. As a result, the massive center flow unit has moved the Káraskersrönd towards the west while simultaneously being shifted by the east flow unit, which transports the largest ice mass in the Breiðamerkurjökull complex.

The westward migration of the Esjufjallarönd medial moraine in the 20th century is linked to the reduction of the center flow unit and smaller glaciers on Mt. Esjufjöll. AMS aerial photographs from 1945 confirm that Esjudalsjökull separated the medial moraines of Skálabjargarönd and Austurbjargarönd almost all the way to the terminus. Between 1904 and 1982, Esjufjallarönd migrated at least 0.4 km westward. Simultaneously, the teminus of the center flow decreased from 4.8 km in 1904, to 4.1 km in 1945, 3.7 km in 1973 and 3.1 km in 2010. This indicates that the greater ice mass transport from the east flow unit shifted the whole center flow unit. The impact is clearer when examining the upper sections of Skálabjargarönd and Austurbjargarönd medial moraines. The rapid retreat of small, highly responsive valley glaciers in Esjufjöll led to the east flow unit moving into the vacated space by 0.5–1.5 km in the valley east of Esjufjöll. Consequently, with Esjudalsjökull receding, like other glaciers in Mt. Esjufjöll, the coalescence points of Skálabjargarönd and Austurbjargarönd have migrated >13 km closer to Esjufjöll.

In addition to changing dominance in ice flow units, medial moraine migration may increasingly be driven by ice margin flow patterns. For example, the sudden eastward shift of Esjufjallarönd is attributed to rapid calving and ice surface lowering above Jökulsárlón, which caused a large segment of Breiðamerkurjökull to draw down towards the lake. The eastern section of the center flow unit and Esjufjallarönd both moved into the depression as a result and consequently, the ice divide, once marked by Esjufjallarönd, has shifted west into the center flow unit (Guðmundsson and Björnsson, 2016).

CONCLUSIONS

We have utilized a DEM from LiDAR survey in 2010, a DEM derived form optical images from the Pleiades satellite in 2021, a DEM acquired from the 1991 precision barometric survey, and derived DEMs referenced to 1890 and 1945 to assess surface changes at selected nunataks in Breiðamerkurjökull, a maritime active temperate outlet glacier of Vatnajökull in Southeast Iceland. This has facilitated the charting of the glacier surface elevation at the end of the 19th century through the mid-20th century. Throughout this period, Landsat satellite images, aerial photographs, maps, written documents, and field studies have been employed to track the evolution of the prominent medial moraines of the glacier, thereby constituting a modern analogue of such medial moraine development on thinning ice caps more generally.

The nunataks are situated at different altitudes and were submerged by various depths of ice at the end of the 19th century. The ice surface lowering at their respective locations aligns well with the overall glacier surface development, particularly where topographical features like mountain ridges or other glaciers do not impede observations. The most substantial surface lowering occurs at lower altitudes. We presume a minor surface decline at elevations above 1800 m. The average annual glacier surface lowering since the end of the 19th century at an elevation of 1490 m is estimated to be -0.11 m/year, indicating a surface lowering of $\sim$14 m over the period. This trend is consistent with a surface lowering of: $\sim$92 m at a rate of -0.70 m/year at 1000 m altitude; $\sim$157 m at a rate of -1.2 m/year at an altitude of 600 m; and of -292 m at a rate of -2.23 m/year at a height of 100 m.

Any deviations from these overall trends are localised. For example, the surface of Urðadalsjökull, south of Mt. Eyjólfsfjall, remained more or less at the same elevation until the mid-20th century, because an extraneous glacier flow unit originating in the glaciated Mt. Breiðabunga nourished the glacier. Along with the thinning of this feeder glacier, the surface of Urðadalsjökull has lowered extremely rapidly since the mid-20th century.

The development and movement of the medial moraines on Breiðamerkurjökull reflect changing glacier dynamics during recession, especially higher up in the glacier. The majority of the medial moraines have migrated or been dislocated at different magnitudes and rates since the turn of the 20th century. In general, the shift is oriented towards the west, and its impact is greater on the east side of the glacier than the west. The greatest shift occurred on Esjufjallarönd, likely due to the recession of the glaciers west of the east flow unit; these glaciers transport less mass from their accumulation areas and consequently do not impact substantially on the east flow unit. The development in the 20th century of the gradual, westward shift of about 0.8 km in the lower section of the medial moraine is strongly related to the recession of the center flow unit, the westward shift in the upper section, and the migration of the coalescence point of the two main medial moraines that form Esjufjallarönd in response to the rapid retreat of Esjudalsjökull in Mt. Esjufjöll. In contrast, after 2004, the rapid calving and ice surface lowering above Jökulsárlón resulted in Esjufjallarönd shifting to the east, where it currently terminates in Jökulsárlón. This event is unrelated to the earlier shift of the medial moraine to the west and hence is an excellent illustration of the role of subglacial topography on ice flow unit dynamics and medial moraine migration over short timescales. Much more ice mass is transported from the Vatnajökull basin, east of Mt. Esjufjöll, than from the accumulation areas of Snæhettudalur (the center flow unit) and Öræfajökull (the west flow unit). Consequently, glacier recession and variable mass fluxes between ice flow units has resulted in the center flow unit migrating westward, as reflected in the shift of Esjufjallarönd and Mávabyggðarönd.

The Breiðamerkurjökull medial moraines are of the Eyles and Rogerson (1978) ISI and AD types. A temporal evolution of the AD medial moraine types appears to involve first the development of AD3, where debris is elevated from the bed in the lee of ice-covered rock knobs, followed by the emergence of AD1 once glacier thinning causes the rock knobs to form nunataks. Historical lateral migration, due to changing dominance of ice flow units, also appears to be affecting medial moraine construction at Breiðamerkurjökull, suggesting that their accumulation as an unbroken linear feature on the deglaciated foreland is not necessarily guaranteed. This is because medial moraine displacement gives rise to gently inclined or even folded englacial debris banding, which in turn produces longitudinal foliation that later melts out as a supraglacial veneer with weakly defined linearity.

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Jökulsker og urðarranar í Breiðamerkurjökli

Breiðamerkurjökull, einn skriðjökla Vatnajökuls, hefur rýrnað og hopað umtalsvert síðan hann náði sögulegri hámarksstærð nálægt lokum 19. aldar. Þegar yfirborðshæðin fór að lækka tóku jökulsker að stinga kolli upp úr ísnum, sérstaklega á síðustu áratugum. Fyrsta skerið kom í ljós á milli 1936 og 1940 en síðan hafa átta önnur sker birst í jöklinum. Nýleg Lidar landlíkön og ýmis afleidd gögn gera mögulegt að áætla breytingar á yfirborðshæð og rúmmáli jökulsins frá þeim tíma að hann var í hámarksstöðu. Í þessari grein kynnum við mat á hve þykkur jökull lá yfir þessum jökulskerjum og áætlum yfirborðslækkunina í nokkrum milliskeiðum yfir ∼130 ára tímabil. Ásamt því rekjum við framvinduna á ísyfirborðinu við þau til þess að gera hverju jökulskeri söguleg skil.

Jökulskerin eru staðsett dreift í jöklinum og í mismunandi hæð. Þau voru á kafi í misþykkum ís í lok 19. aldar. Yfirborðslækkun jökulsins yfir þeim er í samræmi við jökulheildina, sérstaklega þar sem fjallshryggir eða aðrar hindranir trufla ekki flæðið. Hæðarbreytingar í kringum jökulsker á miðhluta leysingarsvæðisins sýna að ísflæði bætir upp um helming lækkunarinnar vegna neikvæðrar afkomu (allt að 40 m frá 2000 til 2022). Mesta yfirborðslækkun er við sporðinn en minnkar upp jökulinn. Við gerum ráð fyrir lítilli yfirborðslækkun í meira en 1800 m hæð yfir sjó. Yfirborðslækkun frá lokum 19. aldar í 1490 m hæð er metin 0,11 m/ári að meðaltali eða 14 m á tímabilinu. Í 1000 m hæð lækkaði jökullinn um 92 m eða um 0,70 m/ári, í 600 m hæð um 157 m eða 1,2 m/ári að

meðaltali; og í 100 m hæð nam lækkunin 292 m eða 2,23 m/ári, að meðaltali.

Breiðamerkurjökull er myndaður af þremur meginörmum sem eiga uppruna í misstórum safnsvæðum á Vatnajökli. Frá jökulskerjum og fjöllum í Breiðamerkurjökli liggja urðarranar, eða „rendur", niður á sporð. Rendurnar myndast þegar jöklar rjúfa bergmol úr hlíðum fjalla, eða skriðugrjót safnast á ísjaðrana. Undir fjallshlíðum geta myndast jaðarurðir en þegar jöklar skríða báðum megin við jökulsker mætist bergmol frá báðum hliðum og rennur í staka urðarrana hlémegin. Slíkir urðarranar marka mót aðskildra jökulstrauma og nefnast miðrönd. Urðarranar eiga einnig uppruna í fjallskollum sem eru enn á kafi í ís.

Flokkunarkerfi Eyles og Rogerson (1978) er víða notað til að greina urðarrana. Samkvæmt því myndast urðarranar á Breiðamerkurjökli þar sem jökulreinar renna saman (ISI gerð) og leysing er ríkjandi þáttur (gerðir AD1 og AD3). Tímabundin framvinda AD urðarrana á Breiðamerkurjökli fellur líklega í AD3-gerð, þar sem bergmol berst frá botninum hlémegin við bergkolla undir jöklinum þegar jökulstraumarnir sameinast (t.d. Vere og Benn, 1989). Rýrnun jökulsins veldur því að slíkir bergkollar verða með tímanum jökulsker og þar með myndast AD1-urðarrani hlémegin við þá, þar sem bergmol berst inn í mjög sprunginn ís og kemur síðan í ljós neðar á jöklinum vegna leysingar.

Kortlagning á legu urðarrananna allt frá byrjun 20. aldar endurspeglar ekki aðeins hreyfingu Breiðamerkurjökuls heldur innbyrðis álagskrafta stóru jökularmanna. Niðurstöður sýna jafnframt að viðbrögð jökla vegna loftslagshlýnunar birtast ekki einungis á hörfandi sporði og lækkandi jökulyfirborði heldur einnig í því að mismikið flæði jökularmanna frá safnsvæðunum veldur aflögun og hliðrun urðarrana. Sérstaklega hafa urðarranar í austanverðum Breiðamerkurjökli hliðrast til en aflögun verið minni á vesturhluta hans. Má vera að hliðrun Esjufjallarandar, sem er lengsti urðarraninn á Breiðamerkurjökli, stafi af rýrnun miðarms Breiðamerkurjökuls á 20. öld.

REFERENCES

AMS 1951. Army Map Service, Corps of Engineer (AMS C762). Sheets: 6019 I Veðurárdalsfjöll, 6019 II Breiðamerkurjökull, 6019 III Öræfajökull, 6019 IV Esjufjöll, 6020 II Vatnajökull II and 6020 III Vatnajökull III. 1:50000. Washington DC, US Army Map service. Landmælingar Íslands. www.lmi.is.

Anderson, R. S. 2000. A model of ablation-dominated medial moraines and the generation of debris-mantled glacier snouts. *J. Glaciology* 46, 459–69.

Ballantyne, C. K. 2013. Trimlines and palaeonunataks. In: Elias, S. A. and C. Mock (eds.), *Encyclop. Quaternary Science*, Second ed., Elsevier, 918–929.

Ballantyne, C. K. and A. G. Dawson 2019. Sgriob na Caillich: A landslide-sourced medial moraine on the Isle of Jura. *Scottish Geographical J.* 135, 139–149.

Benn, D. I. and D. J. A. Evans 2010. *Glaciers and Glaciation.* Second edition. Hodder, London.

Bergsdóttir, H. L. 2012. *Orkubúskapur Jökulsárlóns á Breiðamerkursandi* [The energy balance of Jökulsárlón lagoon on Breiðamerkursandur.] B. Sc. thesis, Fac. Earth Sciences, U. Iceland, 26 pp. source: skemman.is

Björnsson, B. J. 2005. Kanna jökulsker sem kom fyrst í ljós á Breiðamerkurjökli árið 2000. Fimmtán tegundir hafa fest rætur. [Investigating nunataks that first emerged on Breiðamerkurjökull in the year 2000.] *Morgunblaðið* August 22 p. 40.

Björnsson, F. 1951. Esjufjöll og Mávabyggðir. *Náttúrufræðingurinn* 21, 99–108.

Björnsson, F. 1962. Fjallsárhlaupið 1962 og athuganir á lóninu í Breiðamerkurfjalli. [The 1962 Fjallsá jökulhlaup.] *Jökull* 12, 42–43.

Björnsson, F. 1984. Íslandsferð 1861. *Skaftfellingur* 4, 30–62, (see Holland 1863).

Björnsson, F. 1993. Samtíningur um Jökulsá á Breiðamerkursandi og Jökulsárlón. [A compilation of knowledge about Jökulsá on Breiðamerkursandur and Jökulsárlón.] *Skaftfellingur* 9, 8–25.

Björnsson, F. 1996. Þættir um Breiðamerkursand. [Aspects of Breiðamerkursandur.] *Skaftfellingur* 11, 105–125.

Björnsson, F. 1998. Samtíningur um jökla milli Fells og Staðarfjalls. [A collection about glaciers between Fell and Mt. Staðarfjall.] *Jökull* 46, 49–61.

Björnsson, Há. 1958. Gróður og dýralíf í Káraskeri. Flora and Fauna in Kárasker nunatak.] *Jökull* 8, 19.

Björnsson, He. 1996. Scales and rates of glacial sediment removal: a 20 km long, 300 m deep trench created beneath Breiðamerkurjökull during the Little Ice Age. *Ann. Glaciology* 22, 141–146.

Björnsson, He. 1998a. Frá Breiðumörk til jökulsands. – Mótun lands í þúsund ár. [From Breiðamörk to a sandur plain. – A millennium of glacial geomorphology]. In: G. S. Árnason (ed.). *Kvískerjabók.* 164–176.

Björnsson, He. 1998b. Hydrological characteristics of the drainage system beneath a surging glacier. *Nature* 395, 771–774.

Björnsson, He. 2009. *Jöklar á Íslandi* [Glaciers in Iceland]. Opna, Reykjavík, 479 pp.

Björnsson, He. and F. Pálsson 2008. Icelandic glaciers. *Jökull* 58, 365–386.

Björnsson, He. and F. Pálsson 2020. Radio-echo soundings on Icelandic temperate glaciers: history of techniques and findings. *Ann. Glaciology* 61, 81, 25–34.

Björnsson, He., F. Pálsson and M. T. Guðmundsson 1992. *Breiðamerkurjökull. Niðurstöður íssjármælinga 1991* [Breiðamerkurjökull. Radio echo sounding of ice thickness 1991]. Science Inst. rep., RH-92-12, 19 pp.

Björnsson, He., F. Pálsson and E. Magnússon 1999. *Breytingar á Jökulsárlóni 1934–1998.* [The progression of Jökulsárlón 1934–1998.] Science Inst. rep., RH-99-29, 26 pp.

Björnsson, He., F. Pálsson and Sv. Gudmundsson 2001. Jökulsárlón at Breidamerkursandur, Vatnajökull, Iceland: 20th century changes and future outlook. *Jökull* 50, 1–18.

Björnsson, He., F. Pálsson, O. Sigurðsson and G. E. Flowers 2003. Surges of glaciers in Iceland. *Ann. Glaciology* 36, 82–90.

Björnsson, S. 1958. Könnunarferð í Kárasker. [Exploration of the Kárasker nunatak.] *Jökull* 8, 15–17.

Bogadóttir, H., G.S. Boulton, H. Tómasson and K. Thors 1986. The structure of the sediment beneath Breiðamerkurssandur and the form of the underlying bedrock. In: Sigbjarnason, G. (Ed.), *Iceland Coastal and River Symp. Proc.*, Orkustofnun, 295–303.

Boulton, G. S. 1986. Push moraines and glacier contact fans in marine and terrestrial environments. *Sedimentology* 33, 677–698.

Boulton, G .S., P. W. V. Harris and J. Jarvis 1982. Stratigraphy and structure of a coastal sediment wedge of glacial origin inferred from sparker measurements in glacial Lake Jökulsárlón in southeastern Iceland. *Jökull* 32, 37–48.

Boulton, G. S., K. Thors, J. Jarvis 1988. Dispersal of glacially derived sediment over part of the continental shelf of south Iceland and the geometry of the resultant sediment bodies. *Marine Geology* 83, 193–223.

Boulton, G. S., K. E. Dobbie and S. Zatsepin 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. *Quat. Int.* 86, 3–28.

Brandon, M. A., R. Hodgkins, He. Björnsson and J. Olafsson 2017. Multiple melt plumes observed at the Breiðamerkurjökull ice face in the upper waters of Jökulsárlón lagoon, Iceland. *Ann. Glaciology* 58:1–13.

Brook, M. S., W. Hagg and S. Winkler 2017. Contrasting medial moraine development at adjacent temperate, maritime glaciers: Fox and Franz Josef Glaciers, South Westland, New Zealand. *Geomorphology* 290, 58–68.

CNES, 2021. Pléiades ©CNES, Distribution AIRBUS DS.

Dąbski, M. and P. Angiel 2010. Geomorphic implications of the retreat of Breiðamerkurjökull in the southern part of the Skálabjörg ridge, Esjufjöll, Iceland. *Jökull* 60, 185–197.

Danish General Staff (DGS) 1905 - Herforingjaráðið 1905. Öræfajökull 87 SA, Öræfajökull – Esjufjöll 87 NA, Kálfafellstaður – Reynivellir 97 NV and Kálfafellstaður – Hrollaugseyjar 97 NV. 1:50.000 (1st ed.). Generalstabens topografiske Afdeling. Geodætisk Inst., Kjöbenhavn. Landmælingar Íslands.

Einarsson, E. 1964. Undraheimur Esjufjalla. [The enchanted realm of Esjufjöll.] *Þjóðviljinn* 92, III, p. 2.

Evans, D. J. A. 2009. Controlled moraines: origins, characteristics and palaeoglaciological implications. *Quaternary Science Reviews* 28, 183–208.

Evans, D. J. A. and D. R. Twigg 2000. *Breidamerkurjokull 1998.* 1:30,000 scale map. University of Glasgow and Loughborough University.

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

Evans, D. J. A., S. Guðmundsson, J. L. Vautrey, K. Fearnyough and W. G. Southworth 2019. Testing lichenometric techniques in the production of a new growth-rate (curve) for the Breiðamerkurjökull foreland, Iceland, and the analysis of potential climatic drivers of glacier recession. *Geografiska Annaler* 101A, 225–248.

Eyles, N. and R.J. Rogerson 1978. A framework for the investigation of medial moraine formation: Austerdalsbreen, Norway and Berendon glacier, British Columbia, Canada. *J. Glaciology* 20, 99–113.

Eythorsson, J. 1951. Jöklamýs. [The glacier mouse.] *J. Glaciology* 1, 503.

Gadde, N. O. 1983. *Íslandsferð sumarið 1857.* [En färd till Island sommaren 1857]. Úr minnisblöðum og bréfum frá Nils O:son Gadde. Transl. by G. Ó. Erlingsson. Hörpuútgáfan.

Guðmundsson, H. S. 2012. Áhuginn kviknaði á Kvískerjum. [The captivation was ignited at Kvísker.] *Morgunblaðið* 29. júlí.

Guðmundsson, Sn. 2014. *Reconstruction of late 19th century geometry of Kotárjökull and Breiðamerkurjökull in SE-Iceland and comparison with the present.* M.Sc. thesis, Faculty of Earth Sciences, U. of Iceland. 74 pp.

Guðmundsson, Sn., H. Hannesdóttir and He. Björnsson 2012. Post–Little Ice age volume loss of the Kotárjökull glacier, SE–Iceland, derived from historical photography. *Jökull* 62, 97–110.

Guðmundsson, Sn. and He. Björnsson 2016. Changes of the flow pattern of Breiðamerkurjökull reflected by bending of the Esjufjallarönd medial moraine. *Jökull* 66, 95–100.

Guðmundsson, Sn. and He. Björnsson 2017. Jöklabreytingar skoðaðar með gömlum ljósmyndum. *Jökull* 67, 51–64.

Guðmundsson, Sn., He. Björnsson and F. Pálsson 2017. Changes of Breiðamerkurjökull glacier, SE-Iceland, from its late nineteenth century maximum to the present. *Geografiska Annaler* 99A, 338–352.

Guðmundsson, Sn., K. Hermannsdóttir, G. Óskarsdóttir, S. G. Þórisson, H. Ævarsdóttir, D. Evans, B. Brynjólfsson and B. G. Arnarson 2018. *Skúmey í Jökulsárlóni.* Náttúrustofa Suðausturlands, Höfn í Hornafirði. 82 pp.

Guðmundsson, Sn., He. Björnsson, F. Pálsson, E. Magnússon, Th. Sæmundsson and T. Jóhannesson 2019. Terminus lakes on the south side of Vatnajökull ice cap, SE-Iceland. *Jökull* 69, 1–34.

Guðmundsson, Sn. and He. Björnsson 2020a. Um farvegi Jökulsár á Breiðamerkursandi á síðustu öldum. [Channels of the glacial river on Breiðamerkursandur.] *Jökull* 70, 119-128.

Guðmundsson, Sn. and He. Björnsson 2020b. Little Ice Age advance of Kvískerjajöklar, Öræfajökull, Iceland. A contribution to the assessment of glacier variations in Iceland since the late 18th century. *Jökull* 70, 73–87.

Guðmundsson, S. and D. J. A. Evans 2022. Geomorphological map of Breiðamerkursandur 2018: Tthe historical evolution of an active temperate glacier foreland. *Geografiska Annaler: Series A Physical Geography.* https://doi.org/10.1080/04353676.2022.2148083

Guérin, C. 2010. *Velocity field, mass transport and calving of Breiðamerkurjökull, an outlet of Vatnajökull ice cap, Iceland, studied with satellite remote sensing and continuous GPS observations.* M.Sc. thesis, Dep. Earth Sciences, U. Iceland, 83 pp.

Gunnlaugsson, B. 1844. *Map of Iceland, illustrated on four pages. By appointment of Ólafur Nikolas Ólsen.* Uppdráttur Íslands á fjórum blöðum. Eftir fyrirsögn Ólafs Nikolas Ólsen. Hið íslenska bókmenntafélag.

Guttormsson, H. 1968. Athyglisverðar rannsóknir: Landnám plantna á jökulskerjum. [Colonization of plants on nunataks.] *Austurland* 4–3.

Hannesdóttir, H., He. Björnsson, F. Pálsson, G. Aðalgeirsdóttir and S. Guðmundsson 2014. Variations of southeast Vatnajökull ice cap (Iceland) 1650–1900 and reconstruction of the glacier surface geometry at the Little Ice Age maximum. *Geografiska Annaler* 97A, 237–264.

Hannesdóttir, H., He. Björnsson, F. Pálsson, G. Aðalgeirsdóttir and S. Guðmundsson 2015. Area, volume and mass changes of southeast Vatnajökull ice cap, Iceland, from the Little Ice Age maximum in the late 19th century to 2010. *Cryosphere* 9, 565–585.

Hannesdóttir, H., O. Sigurðsson, R. H. Þrastarson, Sn. Guðmundsson, J. M. C. Belart, F. Pálsson, E. Magnússon, S. Víkingsson, I. Kalddal and T. Jóhannesson 2020. A national inventory and variations in glacier extent in Iceland since the end of the Little Ice Age. *Jökull* 70, 1–34.

Henderson, E. 1957 (written in 1815). *Iceland – or the Journal of a Residence in that island during the years 1814–1815.* Translated by Jónsson, S., from Ferðabók – Frásagnir um ferðalög um þvert og endilangt Ísland árin 1814–1815, með vetursetu í Reykjavík.

Holland, E. T. 1863. A tour in Iceland in the Summer of 1861. *Peak, Passes and Glaciers* vol I. Longman, Green and Co. London 1863 (Translated to icelandic by Flosi Björnsson 1984. Íslandsferð 1861. *Skaftfellingur* 4. 1984, 30–62).

Howell, F. W. W. 1893. Iceland pictures – Drawn with pen and pencil. *The Religious Tract Society*. 176 pp.

Ives, J. D. 1978. The maximum extent of the Laurentide Ice Sheet along the east coast of North America during the last glaciation. *Arctic* 31, 24–53.

Jennings, S. J. A. and M. J. Hambrey 2021. Structures and deformation in glaciers and ice sheets. *Reviews of Geophysics* 59, e2021RG000743.

Jóhannesson, H., S. Sigurðarson and G. Viggósson 2005. *Strandrof og strandvarnir við brúna yfir Jökulsá á*

Breiðamerkursandi. [Coastal erosion and defense of the bridge over the Jökulsá River on Breiðamerkursandur.]. Vegagerðin–Siglingastofnun, 8 pp.

Jóhannesson, H., S. Sigurðarsson and G. Viggóson 2006. Strandrof og strandvarnir við brúna yfir Jökulsá á Breiðamerkursandi. [Coastal erosion and defense of the bridge over the Jökulsá River on Breiðamerkursandur.] *Árbók VFÍ/TFÍ*, 299–307.

Jóhannesson, T., He. Björnsson, F. Pálsson, O. Sigurðsson and Þ. Þorsteinsson 2011. LiDAR mapping of the Snæfellsjökull ice cap, western Iceland. *Jökull* 61, 19–32.

Jóhannesson, T., He. Björnsson, E. Magnússon, S. Guðmundsson, F. Pálsson, O. Sigurðsson, T. Thorsteinsson and E. Berthier 2013. Ice-volume changes, bias estimation of mass-balance measurements and changes in subglacial lakes derived by lidar mapping of the surface of Icelandic glaciers. *Ann. Glaciology* 54, 63–74.

Jónsson, S. S. 2016. *Undan Jökli.* M.Sc. thesis, Dep. Earth Sciences, U. Iceland, 70 pp. Source: skemman.is

Levson, V. M. and N. W. Rutter 1989. Late Quaternary stratigraphy, sedimentology, and history of the Jasper townsite area, Alberta, Canada. *Can. J. Earth Sci.* 26, 1325–1342.

Mackintosh, A., D. White, D. Fink, D. B. Gore, J. Pickard and P. C. Fanning 2007. Exposure ages from mountain dipsticks in MacRobertson Land, East Antarctica, indicate little change in ice sheet thickness since the last glacial maximum. *Geology* 35, 551–554.

Marquette, G. C., J. T. Gray, J. C. Gosse, F. Courchesne, L. Stockli, G. Macpherson and R. Finkel 2004. Felsenmeer persistence under non-erosive ice in the Torngat and Kaumajet mountains, Quebec and Labrador, as determined by soil weathering and cosmogenic nuclide exposure dating. *Can. J. Earth Sci.* 41, 19–38.

McCarroll, D. 2016. Trimline trauma: the wider implications of a paradigm shift in recognizing and interpreting glacial limits. *Scottish Geogr. J.* 132, 130–139.

Náttúrufræðistofnun Íslands 2016. *Hlýnandi loftslag eykur tegundafjölda plantna á Vatnajökli* [Warming climate increases plant species diversity on Vatnajökull.] Available at https://www.ni.is/is/frettir/2016/08/hlynandi-loftslag-eykur-tegundafjolda-plantna-vatnajokli

Neuendorf, K. K. E. 2005. *Glossary of Geology.* Institute, American Geological Institute Springer Science and Business Media. 779 pp.

Nick, F. M., J. van der Kwast and J. Oerlemans 2007. Simulation of the evolution of Breiðamerkurjökull in the late Holocene. *J. Geophysical Res.* 112, B01103.

Norðanfari Úr brjefi af Bjarnanesi í Austur-Skaptafellssýslu, 24-10-69. 9. 1870, 6–7, p. 14.

Paijkull, C. W. 1868. *A summer in Iceland.* Transl. by M. R. Barnard, Cambridge Libr. Press, 2014, 364 pp.

Pálmadóttir, E. 1968, Athugar landnám plantna á skerjum sem koma undan jökli eða úr sjó. [Studies the colonization of plants on nunataks and islands emerging from the sea.] *Morgunblaðið* Sept. 17, p. 17,19.

Pálsson, F. 2018. *Afkoma og hreyfing Breiðamerkurjökuls og afrennsli leysingavatns til Jökulsárlóns á Breiðamerkursandi 2017. Greinargerð til Vegagerðarinnar.* [Mass balance and movement of the Breiðamerkurjökull outlet glacier and meltwater runoff to Jökulsárlón lagoon on Breiðamerkursandur 2017: Rep. to the Icelandic Road and Coastal Administr.] Inst. Earth Sci., U. Iceland, Tech. Rep., 15 pp.

Pálsson, F. 2019. *Afkoma og hreyfing Breiðamerkurjökuls og afrennsli leysingavatns til Jökulsárlóns á Breiðamerkursandi 2018. Greinargerð til Vegagerðarinnar.* Inst. Earth Sci., U. Iceland, Tech. Rep., 15 pp.

Pálsson, F. 2021. *Afkoma og hreyfing Breiðamerkurjökuls og afrennsli leysingavatns til Jökulsárlóns á Breiðamerkursandi 2020. Greinargerð til Vegagerðarinnar.* Earth Sci., U. Iceland, Tech. Rep., 12 pp.

Pálsson, F. 2022. *Afkoma og hreyfing Breiðamerkurjökuls og afrennsli leysingavatns til Jökulsárlóns á Breiðamerkursandi 2021. Greinargerð til Vegagerðarinnar.* Earth Sci., U. Iceland, Rep., RH-04-22, 12 pp.

Pálsson, F. 2023. *Afkoma og hreyfing Breiðamerkurjökuls og afrennsli leysingavatns til Jökulsárlóns á Breiðamerkursandi 2022. Greinargerð til Vegagerðarinnar.* Earth Sci., U. Iceland, Tech. Rep., RH-01-23. In Icelandic with an English abstract, 13 pp.

Pálsson, S. 1945 (written 1791–1795). *Ferðabók Sveins Pálssonar. Dagbækur og ritgerðir 1791–1794.* 2nd ed. [Sveinn Pálsson's travel journal, diaries and essays 1791–1794]. Translated and edited by Eyþórsson, J., P. Hannesson and S. Steindórsson. Örn og Örlygur, Reykjavík.

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. 1982. Changes in the proglacial area of Breiðamerkurjökull, southeastern Iceland: 1890–1980. *Jökull* 32, 29–35.

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

Rist, S. 1982. Glacier changes 1964/65–1973/74, 1974/75–1979/80 and 1980/81. *Jökull* 32, 121–125.

Rist, S. 1985. Glacier changes 1964/65–1973/74, 1974/75–1982/83 and 1983/84. *Jökull* 35, 110–119.

Rootes, C.M. and C.D. Clark 2020. Glacial trimlines to identify former ice margins and subglacial thermal boundaries: a review and classification scheme for trimline expression. *Earth-Science Reviews* 210, 103355.

Rootes, C. M. and C. D. Clark 2022. On the expression and distribution of glacial trimlines: a case study of Little Ice Age trimlines on Svalbard. *E and G Quaternary Science J.* 71, 111–122.

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

Sigbjarnarson, G. 1970. On the recession of Vatnajökull. *Jökull* 20, 50–61.

Sigurðsson, B.D., S. Heiðmarssson, H. Björnsson and E. Einarsson 2020. Gróðurframvinda á jökulskerjum í Breiðamerkurjökli í 80 ár. [The progress of plant succession on nunataks in Breiðamerkurjökull over 80 years.] *Náttúrufræðingurinn* 4–5, 225–240.

Sigurðsson, O. 2003. Jöklabreytingar [Glacier changes] 2001–2002. *Jökull* 53, 55–62.

Sigurðsson, O., T. Jónsson and T. Jóhannesson 2007. Relation between glacier-termini variations and summer temperature in Iceland since 1930. *Ann. Glaciol.* 46, 170–176.

Small, R.J., M.J. Clark and T.J.P. Cawse 1979. The formation of medial moraines on Alpine glaciers. *J. Glaciology* 22, 43–52.

Small, R.J. and B. Gomez 1981. The nature and origin of debris layers within Glacier de Tsidjiore Nouve, Valais, Switzerland .*Ann. Glaciology* 2, 109–113.

Small, R.J. 1987. Englacial and supraglacial sediment: transport and deposition. In Gurnell, A. M. and M. J. Clark (eds.), *Glaciofluvial Sediment Transfer: An Alpine Perspective.* Wiley, Chichester, 111–145.

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

Storrar, R. D., M. Ewertowski, A. M. Tomczyk, I. D. Barr, S. J. Livingstone, A. Ruffell , B. J. Stoker and D. J. A. Evans 2020. Equifinality and preservation potential of complex eskers. *Boreas* 49, 211–231.

Storrar, R. D., A. H. Jones and D. J. A. Evans 2017. Small-scale topographically-controlled glacier flow switching in an expanding proglacial lake at Breiðamerkurjökull, SE Iceland. *J. Glaciology* 63, 745–750.

Thienemann, F. A. L. 1824. *Reise im Norden Europas, vorzuglih in den Jahren 1820 bis 1821.* Leibzig. Carl Heinrich Redam.

Thorarinsson, S. 1943. Vatnajökull: Scientific results of the Swedish–Icelandic investigations 1936–37–38. Chapter 11. Oscillations of the Icelandic glaciers in the last 250 years. *Geografiska Annaler* 25, 1–54.

Thoroddsen, Th. 1892. Islands Jøkler i Fortid og Nutid. *Geografisk Tidsskrift,* Bind 11, 111–146.

Thoroddsen, Th. 1895. Ferð um Austur-Skaftafellssýslu og Múlasýslur sumarið 1894 [A journey across Austur-Skaftafellssýsla and Mulasýsla districts in the summer of 1894]. *Andvari* 21, 1–33.

Todtmann, E. M. 1960.*Gletscherforschungen auf Island (Vatnajökull). Abhandlung aus dem Gebiet der Auslandskunde.* Hamburg. Bd 65, Rh. C, Bd 19.

Tómasson, H. and E. Vilmundardóttir 1967. The lakes Stórisjór and Langisjór. *Jökull* 17, 280–299.

van Boeckel, T. 2015. *Relating Subglacial Water Flow to Surface Velocity Variations of Breiðamerkurjökull, Iceland.* M.Sc. thesis, Faculty of Earth Sciences, U. Iceland, 71 pp. Source: skemman.is.

Vere, D.M. and D.I. Benn 1989. Structure and debris characteristics of medial moraines in Jotunheimen, Norway: implications for moraine classification. *J. Glaciology* 35, 276–80.

Víkingsson, S. 1991. Suðurströnd Íslands; breytingar á legu strandar samkvæmt kortum og loftmyndum. Skýrsla fyrir Vegagerð Ríkisins. [South Coast of Iceland: Changes in the position of the shoreline according to maps and aerial photographs. Report for the National Road Administration.] Orkustofnun, Vatnsorkudeild. ÍSOR. OS-91042/VOD-07 B, 7 pp. https://gogn.orkustofnun.is/Skyrslur/OS-1991/OS-91042.pdf

Watts, W. [Lord] 1962 [written in 1876]. *Norður yfir Vatnajökul.* Jón Eyþórsson translated. Reykjavík. Bókfellsútgáfan. Originally *Across Vatnajökull or, Scenes in Iceland.* London 1876.