Reviewed research article

Timing of two paleo-positions of the Iceland Ice Sheet margin in Northeast Iceland, at 10.9 and 10.3 ka, indicated by tephrochronology

Guðrún Larsen[1], Jón Eiríksson[1], Esther R. Guðmundsdóttir[1,2], and Óskar Knudsen[3]
[1]*Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland*
[2]*Faculty of Earth Sciences, University of Iceland, Reykjavík, Iceland*
[3]*Jarðfræðistofan ehf, Hólshrauni 7, 220 Hafnarfirði*
Corresponding author glare@hi.is; https://doi.org/10.33799/jokull2024.74.047

Abstract — *The Preboreal ice-sheet in Northeast Iceland received major tephra falls during its southwards retreat. Such air fall events can affect melting of the ice sheet and cause temporary standstills or even advances if tephra thickness on ablation areas exceeds a critical limit. Tephra deposits on ablation areas may then be removed by subsequent seasonal meltwater run-off and accumulate as recognizable deposits at the former glacier margins, defining the position of the margin at a particular time. A major tephra fall of greyish-white silicic tephra with the chemical characteristics of the 10.9 ka Askja-S tephra was deposited over the ice sheet as it retreated from the northeastern lowlands (Þistilfjörður-Vopnafjörður) towards the Fjallgarðar highlands. Substantial quantities of tephra were washed off the glacier snout and ablation area onto lateral terraces at Svartfell and Langadalsá where the tephra accumulated as thick, ash-rich deposits. A fines depleted tephra containing rounded grains also forms a layer within proglacial sediments deposited in front of the presumed glacier margin. These deposits lie inside a previously recognized standstill/advance known as Bruni or Melur stage. Another major tephra fall of black tephra with chemical characteristics corresponding to those of the 10.3 ka Saksunarvatn (Grímsvötn volcano) tephra may have affected the ice sheet at the time of the eruption, causing a standstill/advance near Arnardalsá shortly after those recognized as Ánavatn and Þverá/Fiskidalur stages. A distance of about 40 km separates the two dated locations. Given the uncertainties concerning the age of the two tephra layers, an average retreat rate of the inland ice of some 60±10 m/year seems realistic. Using this rate of retreat the Ánavatn stage can be dated to 10.5 ka, the Þverá/Fiskidalur to 10.4 ka and the inland ice would have retreated behind the present edge of northern Vatnajökull at 9.5–9.6 ka. The dating of these paleoice-margins calls upon some revision of the areal extent of the Preboreal ice sheet in Northeast Iceland and implies that a corridor may have formed at Langidalur around 10.9 ka splitting the ice sheet into an isolated northern dome, separated from a southern ice-margin retreating with several advances/standstills towards south.*

INTRODUCTION

The retreat history of the inland ice in Iceland during the last 13 ka has been studied by several authors (e.g. Sæmundsson, 1995; Norðdahl and Pétursson, 2005; Ingólfsson *et al.*, 2010; Pétursson *et al.*, 2015; Benediksson *et al.*, 2023a,b, 2024) indicating rapid retreat after 11 ka to a position inside the edges of the current Vatnajökull ice sheet as early as 9 ka (e.g. Striberger *et al.*, 2012). Opinions vary about the Preboreal extent of the ice sheet in Northeast and North-central Iceland (Figure 1) and the timing of the retreat is not well constrained. Frequent volcanic eruptions took place while the ice load was diminishing with distinct peaks around 14.5 ka and between 12 and

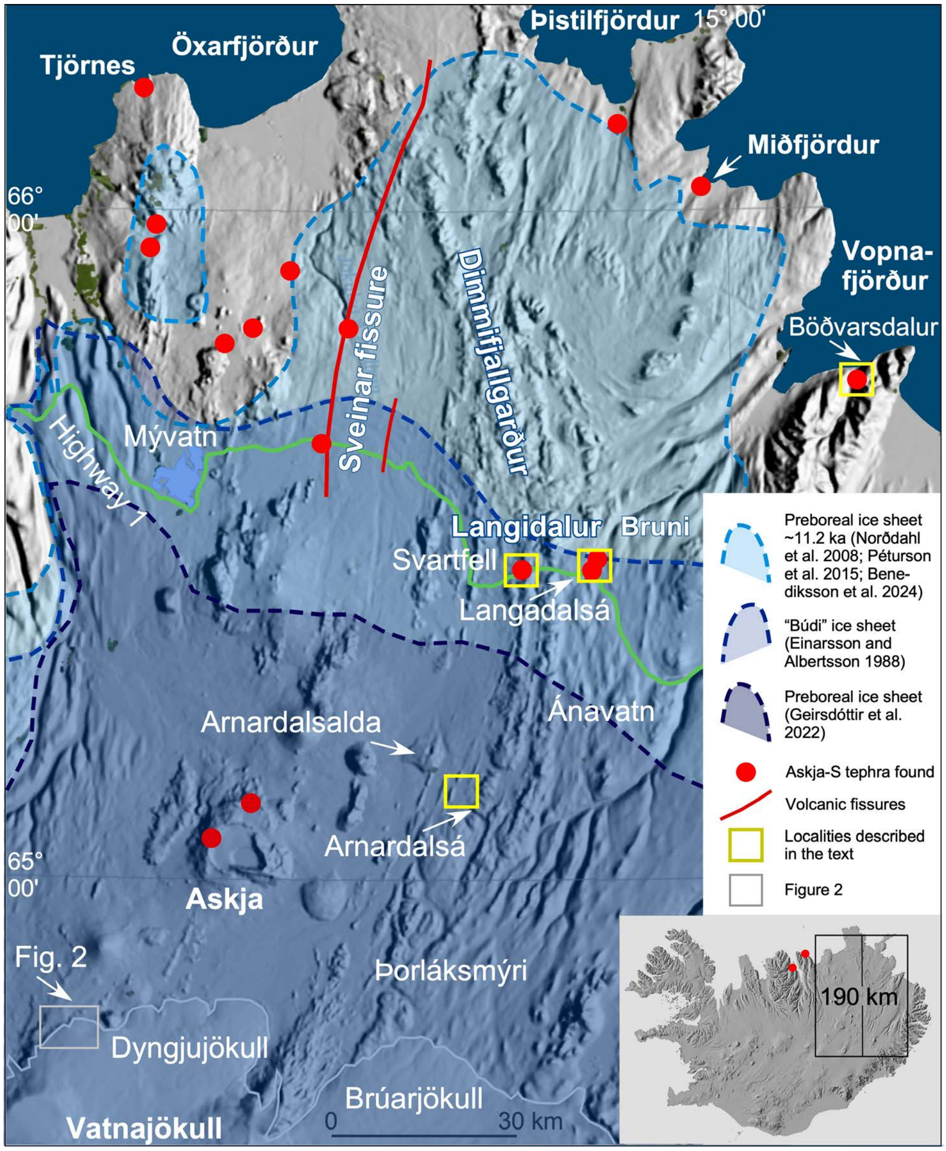


Figure 1. Northeast and North-central Iceland, landscape from ArcticDem Explorer (livingatlas2.arcgis.com). Previously published extent of Preboreal ice limit (∼11.2 ka) is shown by blue overlays, modified from references listed in the figure legend. Locations where Askja-S tephra (∼10.9 ka) is found are shown by red dots (e.g. Sæmundsson, 1991; Sæmundsson *et al.*, 2012; Sigvaldason, 2002; Sigurgeirsson, 2016; this paper). Red lines indicate volcanic fissures. Yellow squares indicate localities described in the text. Inset: IslandsDEM (National Land Survey of Iceland). – *1. mynd. Norðausturland og hálendið suður að Vatnajökli, landslag og örnefni. Áður birt norðurmörk Preboreal jökuls á Norðausturlandi eru sýnd í bláum litbrigðum. Rauðir deplar sýna hvar gjóskulagið Askja-S hefur fundist. Rauðar línur sýna gossprungur, m.a. Sveina-Randarhóla (75 km löng). Gulir ferningar marka staði sem fjallað er um í texta.*

10 ka (e.g. Maclennan *et al.*, 2002; Sigvaldason, 2002; Licciardi *et al.*, 2007). The effect of tephra fall on the retreating inland ice has however not been addressed previously. Here we use tephra and tephrochronology to provide a better constraint on the timing of retreat of the Lateglacial Icelandic ice sheet by dating the margin position of the ice sheet at the time of distinct tephra fall events and consider its influence on retreat and advances of the glacier margin.

The effect of tephra fall onto modern glaciers and ice sheets has recently been treated in several papers (e.g. Dragosics *et al.*, 2016; Möller *et al.*, 2016, 2018) describing experiments including both the effects on snow and bare ice. Previously Kirkbride and Dugmore (2003) described the effect of the Hekla 1947 tephra fall onto outlet glaciers of Eyjafjallajökull and Mýrdalsjökull, demonstrating different response to variable thickness of ash on the bare ice of the respective ablation areas that resulted in a short-term advance of one of the outlet glaciers, Gígjökull. This raises questions about the potential to discriminate between such volcanically forced and climatically forced advances (Kirkbride and Dugmore, 2003) in volcanic regions.

The effects of supraglacial debris on melting ice and snow have shown that melt rates depend on the climate and the thickness and thermal properties of the debris cover (e.g. Østrem, 1959; Driedger, 1981; Adhikary *et al.*, 1997, 2000; Krüger and Kjær, 2000; Schomacker, 2008; Schomacker and Benediksson, 2017). Two important parameters have been defined, regardless of the type of debris. The effective thickness is the thickness of debris below which ablation is increased. The critical thickness is the thickness at which the ablation rate below the debris equals that of clean ice or snow. Thickness greater than the critical thickness insulates the ice or snow and retards and even stops melting. Critical thickness for tephra on bare ice has been found to be in the range 5.5 to 15 mm (e.g. Kirkbride and Dugmore, 2003; Dragosics *et al.*, 2016; Möller *et al.*, 2016). An exception is the Ruapehu tephra with a thickness of 120 mm. Möller *et al.* (2016) concluded that ablation was reduced by $\sim$80% beneath a 10 cm (100 mm) thick Grímsvötn tephra and suggested complete insulation at 50 cm thickness.

In the present paper we focus on Northeast Iceland where a retreating ice-margin left a series of end moraines on an 80 km long stretch from the Langidalur pass (Figure 1) to the edge of current Brúarjökull (Aðalsteinsson, 1987; Sæmundsson, 1995). The aim of this study is to date two ice-marginal positions representing either stillstands or advances of the Iceland Ice Sheet (IIS) during the early Holocene deglaciation of Northeast Iceland. We argue that at least one of these events was most likely caused by substantial tephra fall upon the ice sheet, insulating the ice in the ablation area and preventing or slowing the melting for at least some years or, depending on the thickness of the tephra, a few decades. A second event may also have been influenced by a concurrent tephra fall. We refer to thousands of calibrated radiocarbon years (cal BP) as ka and for other calendar ages we report years as BCE or CE.

Geological and glacial environment

The Brúarjökull outlet glacier is the most notorious surge type glacier in Iceland (Figure 1) with documented surges in the CE 1734, 1810, 1890, 1963, leaving impressive end moraines of which the 1890 and 1964 end moraines have been studied in detail (e.g. Todtmann, 1960; Thorarinsson, 1964; Benediktsson *et al.*, 2008, 2009; Korsgaard *et al.*, 2015; Ingólfsson *et al.*, 2016). The positions of the 1810, 1890 and 1964 CE end moraines are known, partly by contemporary observations (e.g. Kjerúlf, 1962) and partly by tephrochronological observations (e.g. Thorarinsson, 1964). The maximum distance between these recent moraines and the other set of securely dated ice marginal position of the Preboreal ice sheet in Northeast Iceland is ca. 100 km and the age span covers ca. eleven millennia.

According to Sæmundsson (1995) the Vopnafjörður valley in Northeast Iceland was partly covered by ice between 11.4–11 ka (Hof-Teigur stage, 9.905±95–9.615±70 ^{14}C years). He assumed that the ice retreated rapidly inland after 11 ka, as proposed by Ingólfsson and Norðdahl (1994) towards the Bruni hill where a soil cover had developed by $\sim$9.8 ka.

Aðalsteinsson (1987; see also Guttormsson, 1987) documented ten ice-marginal positions over a 70 km distance from Sandfell (Melur stage) to Þorláksmýrar

(Þorláksmýrar stage). The resulting ice-marginal formations were interpreted as resulting from surges during the retreat of the "proto-Brúarjökull" (Brúarjökull hinn forni of Aðalsteinsson, 1987). However, the ice-marginal positions in the research area can neither be seen as formed by the forerunner to present Brúarjökull nor linked to its surging habits, keeping in mind that the IIS is thought to have disintergrated by about 9 ka so that glaciers in Iceland at that time were smaller than at present or even absent (Flowers *et al.*, 2008; Björnsson, 2009; Geirsdóttir *et al.*, 2009; Ingólfsson *et al.*, 2010; Benediktsson *et al.*, 2024) before expanding/reforming in response to cooling climate. The Melur stage may correspond to the Bruni stage of Sæmundsson (1995).

Tephrafall on glaciers and ice sheets, time markers and ablation disturbers

Tephra deposited on accumulation areas of glaciers is buried by the subsequent annual accumulation of snow, becoming incorporated in the ice and carried downglacier by ice flow. Tephra layers are preserved as distinct horizons in the ice, both in surging and nonsurging glaciers (Larsen *et al.*, 1998). They crop out in ablation areas as sinuous bands of ash and/or lapilli sized particles, dark or pale depending on the chemical composition of the tephra glass. In the ablation area the tephra is gradually released from the ice by melting and mostly transported supraglacially down the glacier margin by seasonal meltwater. Only exceptionally thick tephra layers can accumulate temporarily to form dirt cone rows where they crop out of the ice (e.g. V1477 CE tephra on Tungnaárjökull glacier, Larsen *et al.*, 1996). The residence time of tephra layers within northern and western Vatnajökull is currently 800 to 900 years (Larsen *et al.*, 1996). We propose that tephra melting out of ice in ablation areas should be referred to as "melt-out" tephra.

Tephra deposited onto the ablation areas of glaciers is not permanently buried in snow and is gradually washed off the ablation area during the following summer melting seasons. Depending on the thickness of the tephra this can be a fast process with meltwater washing the tephra off the ice in one or a few summers, if the thickness is millimetres to a few centimetres. If, however, a tephra deposit is several or tens of centimeters thick (>critical thickness) and covers large parts of the ablation area it can be expected to insulate the ice and retard melting. This could result in a temporary standstill or a minor advance, even if the glacier mass balance is unchanged or decreased, while the tephra is gradually washed off, leaving a tephra deposit at the glacier margin. An example is the tephra rich terrace marking a former ice-margin at Búðarháls, South-Iceland, correlated to the Saksunarvatn tephra (Kaldal, 1993). In the following, tephra deposited onto ablation areas will be referred to as "wash-off" tephra.

The effects of extreme tephra deposition onto ablation areas of Icelandic outlet glaciers have not been observed or monitored. The last such events occurred in 1477 CE when an up to 50 cm thick basaltic tephra was deposited onto the ablation area of Tungnaárjökull glacier (Larsen *et al.*, 2013, Figure 4.5.9) and in 1717 CE when at least 10 cm of tephra were deposited onto the ablation area of Dyngjujökull glacier (Figure 2 and Larsen and Guðmundsson, unpubl. data).

Extreme tephra fall over glaciers or ice sheets implies that a given standstill or advance of a glacier margin is not necessarily caused by climate fluctuation, as already pointed out by Kirkbride and Dugmore (2003) nor by a surge resulting from internal dynamic instability.

MATERIALS AND METHODS

Soil sections in Northeast Iceland with relevant tephra layers were sampled for chemical analyses. Tephra deposits from terraces, outwash deposits and end moraines were also sampled. Selected samples were analyzed for major element chemistry on an ARL-SEMQ microprobe at the University of Bergen (accelerating voltage of 15 kV and beam current was 10 nA, slightly defocused beam of 6–12 μm) and on a JEOL JXA-8230 electron microprobe at the University of Iceland (acceleration voltage of 15 kV, beam current of 10 nA and beam diameter of 10 μm). Natural and synthetic minerals and glasses were used as standards. During each run glass standards were regularly analyzed (Tables S1-8, see online supplements and Guðmundsdóttir *et al.*, 2011).

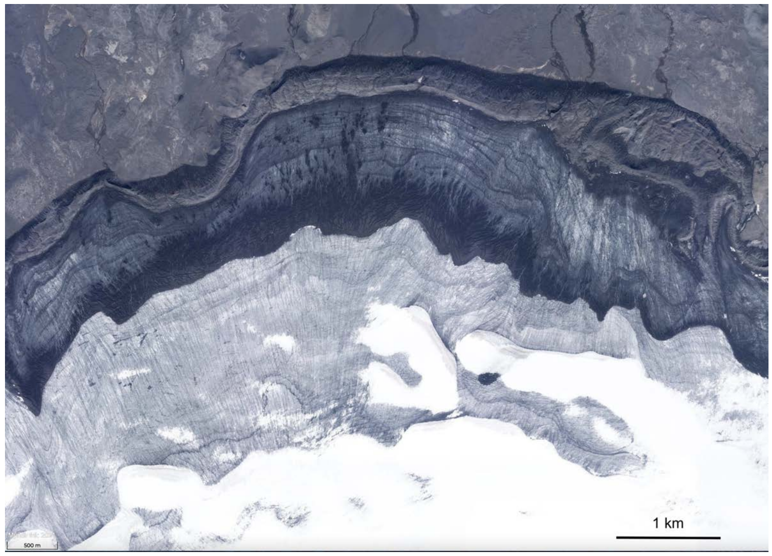


Figure 2. Black tephra melting out of the ice near the north margin of Dyngjujökull (location on Fig. 1). Aerial photograph from Loftmyndir ehf, 2021. The tephra has the chemical characteristics of Bárðarbunga volcanic system and is correlated to an eruption in 1717 CE. The tephra originally deposited onto and buried by snow on the accumulation area has now reached the ablation area and is gradually melting out. – *2. mynd. Svört basaltgjóska að bráðna út úr ís á leysingasvæði Dyngjujökuls vestan Kistufells í norðvestanverðum Vatnajökli. Gjóskulag úr gosi á eldstöðvakerfi Bárðarbungu, líklega árið 1717. Gjóskan féll á ákomusvæði jökulsins þar sem hún grófst undir snjó/ís og fluttist með skriði jökulsins niður á leysingasvæðið.*

Outline of the Preboreal tephrochronology of North and Northeast Iceland

The preservation potential of tephra layers is assumed to have been poor in the high energy terrestrial environment towards the end of last glaciation. Tephra deposited on barren ground was prone to wind and water erosion with only patches preserved where the tephra was thick enough. Tephra deposited onto vegetation would have higher preservation potential, but vegetation cover was not well developed at the beginning of the Preboreal at 11.5 ka. The best preservation potential was in lake sediments and marine sediments (e.g. Björck *et al.*, 1992; Eiríksson *et al.*, 2000).

We consulted several terrestrial sites with tephra layers from this time slice, at Böðvarsdalur in Vopnafjörður, Breiðavík in Tjörnes, Flateyjardalur, Reitsvík and Vatnamýri in Eyjafjörður (Pétursson and Larsen, 1992; Wastl, 2000; Sigvaldason, 2002; Guðmundsdóttir *et al.*, 2016; Óladóttir *et al.*, 2020) (Figures 3 and 4). The two most important tephra deposits of this period are a black, basaltic tephra from the Grímsvötn volcanic system, here referred to as ∼10.3 ka Saksunarvatn tephra (Mangerud *et al.*, 1984; Óladóttir *et al.*, 2020 and references therein) and the pale-coloured ∼11 ka silicic "S" tephra from the Askja central volcano, here called Askja-S (previously known as layer "S" of Sæmundsson, 1991, Miðfjördur tephra of Norðdahl and Hjort,1993, Dyngjufjöll tephra of Sigvaldason, 2002 and Askja-S of Sigurgeirsson, 2016). The Askja-S tephra features a range of shades from white (dry) to greyish-, pinkish- or yellow-white, depending on preservation and environment (e.g. Figures 3 and 5). Both tephra layers are found in all the soil sections and their identification is confirmed by chemistry (Tables S-1-3) and radiocarbon dating (Table 1). The exact age of these two tephra layers has, however, not been fully resolved.

The age of the Saksunarvatn tephra identified in the Greenland ice cores has a relatively narrow age range of 10.1–10.5 ka and was set at 10,347±89 years b2k (Rasmussen *et al.*, 2006) or approximately

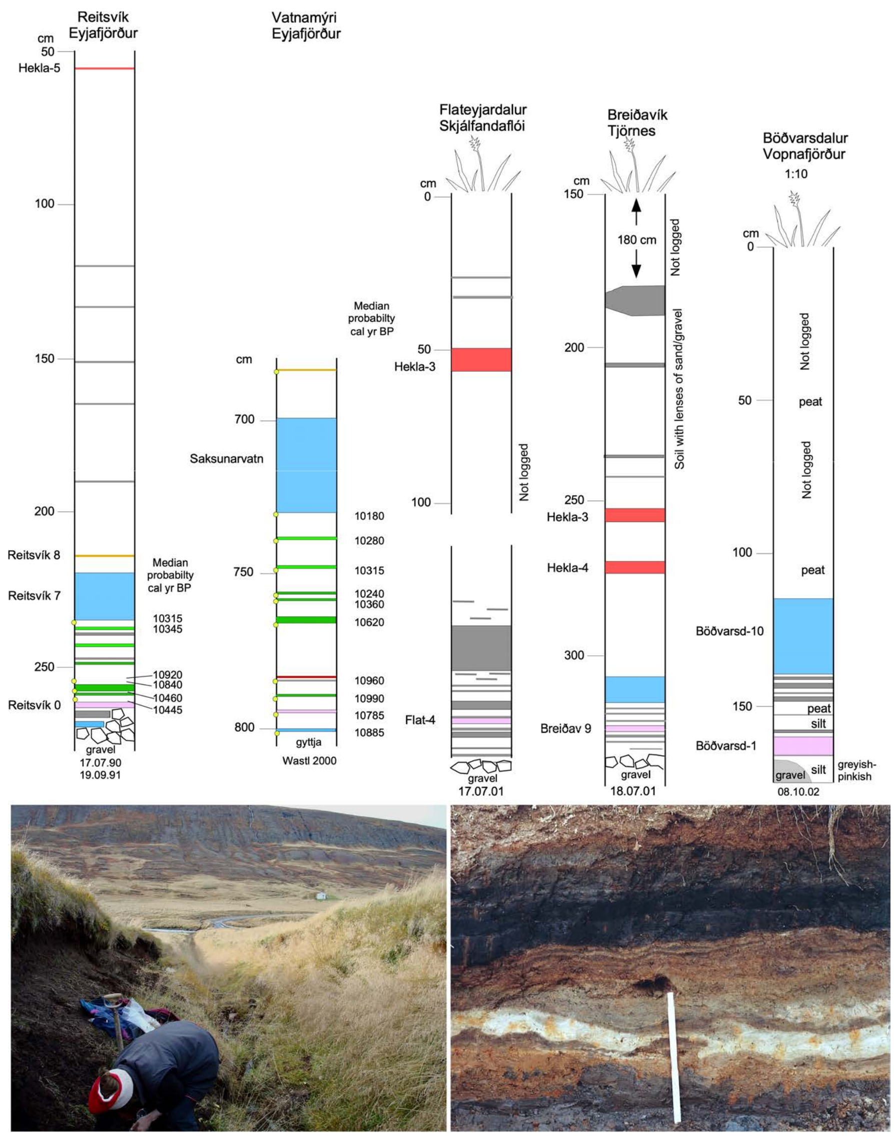


Figure 3. Top: Key sections (1:10) showing the tephra layers Saksunarvatn (blue) and Askja-S (pink) and the relevant terrestrial stratigraphy. Other analyzed tephra layers are from Hekla (red) and Bárdarbunga volcanic systems (green), those not analyzed are grey. Also shown are radiocarbon dates from Reitsvík and Vatnamýri (see Table 1). Below left: Overview from the terrace at Böövarsdalur at <100 m a.s.l. Below right: The tephra layers Askja-S, yellow-white, 1–8 cm thick, and Saksunarvatn, black, 20–25 cm thick. Apparent bedding in the lower part of the black tephra may be primary. See online Tables S-1-3 for chemical composition of Saksunarvatn and Askja-S tephra. – *3. mynd. Ofar: Lykilsnið (1:10) af elsta hluta jarðvegs frá Eyjafirði til Vopnafjarðar með gjóskulögunum sem hér er fjallað um, Saksunarvatn (blátt) og Askja-S (bleikt). Önnur efnagreind gjóskulög eru frá Heklu (rauð) og Bárðarbungukerfi (græn), annars eru þau grá. Einnig er sýndur geislakolsaldur sýna úr Eyjafirði. Neðri mynd t.v. Yfirlit, snið fremst í hjalla í <100 m y.s. Neðri mynd t.h. Ljósa lagið Askja-S neðst í "jarðvegi", hér 1–8 cm þykkt. Svarta lagið, meint Saksunarvatn, er 20–25 cm þykkt. Uppruni beggja laganna var staðfestur með efnagreiningu, sjá töflur S-1-3 í viðauka með greininni á heimasíðu Jökuls.*

Table 1. Radiocarbon dates from the lowest part of the Reitsvík soil section (unpubl. data of Olsson, Larsen and Vilmundardóttir) and the Vatnamýri core (Wastl, 2000), calibrated age and median probability according to Radiocarbon Calibration Program CALIB 8.2 (Reimer *et al.*, 2020). Also shown is the material analyzed (gyttja is organic, muddy lake deposit), position relative to the tephra layers and the source volcanic systems. Grí: Grímsvötn; Bár-Vei: Bárðarbunga-Veiðivötn; Ask: Askja. – *Geislakolsgreiningar úr neðsta hluta sniðs í Reitsvík og neðsta hluta kjarna úr Vatnamýri, Eyjafirði. Geislakolsaldur, leiðréttur aldur og aldur samkvæmt miðgildi líkinda. Einnig sést hvers konar lífrænt efni var greint, tengsl þess við gjóskulögin og uppruni þeirra.*

Sample no	Tephra	Material	Sample position, thickness/depth	Fraction	^{14}C age BP	Calibrated age range 1σ	Calibr. age – median prob. BP (1950)	Calibr.age – median prob. Bf 2000 (b2k)	Volcanic system
	Reitsvík								
U-4601	Reitsvík-7	moss	0.5-1 cm dir below	INS	9140±60	10427-10283	10317	10367	Grí
U-4602	Reitsvík-7	moss	0.5-1 cm dir below	SOL	9160±80	10530-10289	10345	10395	Grí
U-4646	Reitsvík-1	peat	0.5-1 cm dir above	INS	9510±80	11121-10659	10837	10887	Bár-Vei
U-4647	Reitsvík-1	peat	0.5-1 cm dir above	SOL	9575±105	11152-10802	10920	10970	Bár-Vei
U-4648	Reitsvík-1	peat	1 cm directly below	INS	9325±125	10742-10352	10534	10584	Bár-Vei
U-4649	Reitsvík-1	peat	1 cm directly below	SOL	9280±90	10625-10350	10459	10509	Bár-Vei
U-4657	Reitsvík-0	peat	1 cm directly above	SOL	9250±130	10616-10306	10443	10493	Ask
	Vatnamýri								
AA-23877	Dark, 716-730 cm	gyttja	730-731 cm		9030±90	10331-9974	10181	10231	Grí
AA-23878	Dark, 738.5-739 cm	gyttja	738.5-739.5 cm		9105±75	10425-10246	10282	10332	Bár-Vei
AA-23837	Dark, 747.5-748 cm	gyttja	748-749 cm		9135±65	10429-10280	10315	10365	Bár-Vei
AA-23879	Dark, 756 cm	gyttja	756-757 cm		9075±90	10454-10212	10241	10291	Bár-Vei
AA-23880	Dark, 758 cm	gyttja	758-759 cm		9175±90	10536-10293	10361	10411	Bár-Vei
AA-23881	Dark, 764-765.5 cm	gyttja	765.5-766.5 cm		9390±75	10758-10558	10619	10669	Bár-Vei
AA-23882	Dark, 784 cm	gyttja	784-785.5 cm		9630±80	11223-10847	10961	11011	Grí+Vei
AA-23883	Dark, 789.5 cm	gyttja	789.5-791 cm		9660±100	11247-10848	10990	11040	Bár-Vei
AA-23884	Light, 794 cm	gyttja	794-796 cm		9490±80	11119-10638	10787	10837	Ask+

10.3 ka. However, Bronk Ramsey *et al.* (2015) published an age of 10,176±49 years (cal BP) from their model 2 or approximately 10.2 ka. Radiocarbon dates show a range of dates from 10.6 to 9.6 ka (see Óladóttir *et al.*, 2020 and references therein). It has been postulated that several widespread Grímsvötn tephra layers were erupted between 10.4 and 9.9 ka (e.g. Jóhannsdóttir *et al.*, 2006; Thordarson, 2014) sometimes referred to as the G10 ka tephra series (Óladóttir *et al.*, 2020 and references therein). Three radiocarbon dates of peat immediately below the Saksunarvatn tephra in Reitsvík and Vatnamýri bog show an age of 10,345, 10,317 and 10,181 years cal BP as median probability, (Table 1 and Figure 3; Wastl, 2000 and this paper). Here we adopt the 10.3 ka age for the single tephra layer of Grímsvötn composition found in North and Northeast Iceland within this period and refer to it as Saksunarvatn tephra (Saksunarvatn ash of Mangerud *et al.*, 1986).

We present a map showing measured thickness of the 10.3 ka Saksunarvatn tephra in North and Northeast Iceland from Óladóttir *et al.* (2020) with new additions of localities where a single major tephra layer with these chemical characteristics is found (Figure 4a). In the two key sections in Reitsvík and Vatnamýri this tephra is confined by peat and gyttja at upper and lower boundary of the deposit (Figure 3).

The published age of the Askja-S tephra varies from 11,228±226 (Ott *et al.*, 2016) to 10,424±102 years (cal BP) (Wastegård *et al.*, 2018). Bronk Ramsey *et al.* (2015) published an age of 10,830±57 years (cal BP) from their model 2 and Kearney *et al.* (2018) published very similar results of 10,824±108 years (cal BP) or approximately 10.8 ka. Wastl (2000) shows an age of 10,785 years (medium probability, cal BP) below a thin white tephra with Askja chemical composition at nearly 8 m depth in Vatnamýri bog and two dates, 3 and 9 cm above the Askja layer of

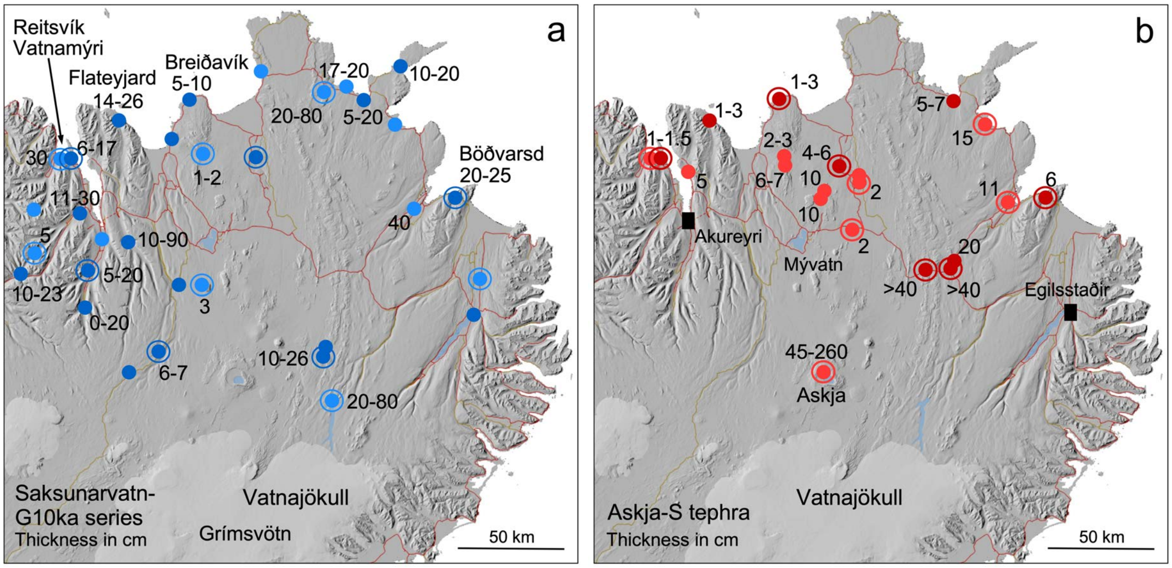


Figure 4. Localities with the tephra layers Askja-S and Saksunarvatn/G10ka series in N-, NE- and E-Iceland. Numbers refer to tephra thickness. Double circle: chemically analyzed samples. a) Saksunarvatn tephra. Dark blue: localities from Pétursson and Larsen (1992 and unpublished data), and this study. Light blue: localities from Óladóttir *et al.* (2020 and references therein) and Bender (2020). b) Askja-S tephra. Light red: localities from Sæmundsson (1991), Norðdahl and Hjort (1995), Sigvaldason (2002), Sigurgeirsson (2016), Bender (2020). Dark red: this study. – *4. mynd. Staðir þar sem gjóskulögin Saksunarvatn (a) og Askja-S (b) hafa fundist á N-, NA- og A-landi. Staðir þaðan sem gögn hafa verið birt áður eru í ljósari litum. Tvöfaldur hringur táknar efnagreint sýni.*

Figure 5. a) "Open" part of the quarry at Svartfell with patches of Askja-S tephra, yellow-white where uncovered (spade 1 m), pinkish-brown where coated by soil. b) Over 50 cm thick, waterlaid deposit of Askja-S tephra. Lowest 30 cm are uncontaminated tephra (see c). Lenses of darker sand or tephra, appear at the top. Gravel and sand below. c) Close-up of another patch with lenses of waterworn coarse ash to fine lapilli. Pit is 35 cm wide. – *5. mynd, a) „Opni"hluti námu við Svartfell. Askja-S sést sem gulleitir gjóskublettir á yfirborði (skófla) en bleikari-brúnni ef lituð af jarðvegi. Skóflan er 1 m. b) Meira en 50 cm þykkt lag af vatnsfluttri ljósri gjósku, mest aska og smágerður vikur. Neðstu ∼30 cm eru hrein gjóska (sjá c). Lög af dökku efni, sandi eða gjósku, sjást ofar.. c) Nærmynd, 35 cm breið, af byggingareinkennum lagsins og linsum af skolaðri, grófri ösku og smáum vatnsnúnum vikurkornum.*

10,990 and 10,960 years (median probability, cal BP) respectively (Figure 3, Table 1). At Reitsvík an organic sample 1 cm above Askja-S shows an age of 10,445 years (median probability, cal BP) whereas sample 5.5 cm above the Askja layer shows ages of 10,850 and 10,920 years. In both localities there is a reversal, with lower age around Askja-S than higher up in the sections, implying that 10.8 ka is probably too low. We adopt a 10.9 ka age but recognize that Askja-S may even be somewhat older.

The dispersal map of Sigvaldason (2002) shows a thickness axis trending northeast from Askja with maximum observed thickness in Miðfjörður, Bakkaflói (Norðdahl and Hjort, 1995). We have added new data to the map of Sigvaldason (2002) and refer to the tephra as Askja-S (Figure 4b).

There are three to eight tephra layers in the soil between the Saksunarvatn and Askja-S tephras, depending on the preservation potential of the respective sites. Most of those analyzed show the characteristics of the Bárðarbunga volcanic system, being too small to have affected the glacial environment (Figure 3). However, in Lake Lögurinn in East Iceland numerous Grímsvötn tephra layers have been identified in sediments in the millennia following the 10.3 ka event (Guðmundsdóttir *et al.*, 2016). These are, apparently, much smaller tephra layers that have yet to be found in terrestrial soils in Northeast and East Iceland.

Using the Askja-S tephra as a key tephra for dating in Northeast Iceland could be complicated by the younger, presumably smaller but chemically identical Askja-L tephra, about 9,400 year old (Guðmundsdóttir *et al.*, 2016) and so far only identified in Lake Lögurinn in East Iceland (see Discussion).

RESULTS

Three important locations (Figure 1) for the timing of the ice-marginal positions of the retreating IIS are described in detail below.

Böðvarsdalur, Askja-S and Saksunarvatn

The section at Böðvarsdalur lies on a gently sloping terrace at <100 m a.s.l. in a ditch on the south side of the road onto Hellisheiði eystri, about 450–500 m east of the current bridge across the Dalsá river. In the section, a layer of silty soil underlies a 1-8 cm thick yellow-white tephra of which the lowermost part appears pristine. A more peaty soil overlies the white tephra and separates it from overlying black tephra layers, which include a 20–25 cm thick black tephra (Figure 3).

Chemically, the yellow-white layer has chemistry (Table S-1) consistent with the Askja-S tephra layer in Sigvaldason (2002) and Norðdahl and Hjort (1993). The terrestrial date of Askja-S referred to here, 10.9 ka, agrees with previous conclusions by Sæmundsson (1995) that the ice-margin had retreated from the coast before 11 ka.

The chemistry of the thick black tephra (Table S-1) is consistent with the Grímsvötn volcanic system and is taken to correspond to the 10.3 ka Saksunarvatn tephra in Reitsvík and Vatnamýri. In the lowermost 7 cm of the tephra, some five indistinct 0.3 to 3 cm thick layers of fine to medium black ash can be discerned. The next 5.5 cm consist of massive sandy, fine to medium grained black ash (Figure 3). The remainder is also fairly massive with sporadic light-grey streaks, possibly containing diatoms.

Svartfell-Langadalsá, Askja-S

Langidalur valley is an east-west trending pass (∼64°27’48”N) dividing the Fjallgarðar mountain range and is currently the route of Highway 1 between North and East Iceland. In this area several gravel quarries associated with the roadworks were temporarily open. In three of the quarries, thick deposits of a greyish-white to yellow- or pinkish-white tephra were exposed, lodged within glacial and alluvial deposits.

Svartfell quarry

A small hill, Svartfell, lies at the western end of the Langidalur pass, locally narrowing the pass to 0.2 km. A 0.7 km long terrace lies along the southeast slope of the hill at ∼570 m a.s.l. The terrace may originally have filled the gap between the Svartfell and Fjallgarðar hills. The main quarry into the terrace lies north of Highway 1, originally about 500 m long with ∼100 m part still accessible (Figure 5a-c). A unit of

50–60 cm thick deposits of greyish-white to greyish-yellow tephra is exposed, overlying sand with rounded fine gravel and covered by up to 1.5 m of sand and gravel (rounded, mostly <5 cm with occasional stones up to 20 cm in diameter) where the terrace surface is least undisturbed. The tephra deposit displays a distinct base and a fairly well-defined top indicating a single, short-lived event. The tephra contains abundant fines, weak internal layering, and fines-depleted lenses with subrounded up to 1 cm long grains (Figure 5c). The tephra is mostly clean and uncontaminated by sand and gravel. South of Highway-1 the excavations have left much disturbed deposits of gravel and tephra that were not documented.

These characteristics indicate transportation in water without mixing with other sediments. It is also evident that the environment was dynamic, the tephra was covered by sand and gravel that was transported onto the terrace shortly after its deposition. Some mixing and relocation may have occurred but was apparently minimal. The direction of flow was towards northeast, into the Langidalur pass, as indicated by flow structures and depositional features.

Langadalsá quarries

The other two quarries were located at the eastern end of the Langidalur pass in a terrace and proglacial outwash plain along the southeast slope of Grenisöxl hill (Figure 6). They were inspected in the summer 2001. Both quarries have been closed, levelled, and revegetated. The quarries lie south of and inside the moraines of Bruni/Melur stage (Aðalsteinsson, 1987; Sæmundsson, 1995).

The southern quarry was dug into the relatively narrow southern end of the terrace at ∼570 m a.s.l. The section showed that a deposit of fine-grained greyish white tephra had accumulated to a thickness of >70 cm in a depression in the terrace or in a groove next to the hillside. The tephra deposit had both a well defined top and bottom, having been deposited onto black sand and fine gravel underlain by till, and overlain by bedded sand and gravel (Figure 7a-c). Small-scale cross bedding was apparent (for details see Figure S-1), but the tephra grains were not worn or rounded, implying limited transport (Figure 7a-c). The bulk of the tephra deposit contained no debris except traces near the top. The area with exposed tephra was 15–20 m long but the extent beyond that was not documented. Other nearby signs of glacial processes, such as eskers, are evident on Figure 6 (aerial photos 2000, 2001, 2017). This locality lies about 2 km inside the moraines of the Bruni/Melur stage.

The northern quarry was located about 1 km farther northeast and was excavated into the terrace, moraine mounds in front of the terrace and adjacent outwash plain (Figure 6). An approximately 30 cm thick, well-defined layer of greyish-white tephra was found buried in the alluvium below >1 m of gravel. It consisted of well-rounded pumice clasts, up to 1 cm long, fine ash was lacking except at the base and slight contamination by black sand grains was observed. The thickness of the tephra changed very little along the exposure that was some tens of metres long. Thickness of the overlying gravel deposit was about 1 m but its top had been removed. This locality lies about 1 km inside the moraines of Bruni/Melur stage.

The internal structures of the tephra in the southern quarry indicate transport in water (Figure S-1). The uncontaminated tephra deposit excludes long distance transport by a river or stream, and the limited sorting with abundant fines speak against wind transport. Apparently, the tephra had been washed onto the terrace from a slope, either the hillside above the terrace or adjacent glacier ice. The pristine (clean) appearance of the tephra and the thickness of the deposit support short-distance transport in meltwater. Flushing off a till covered hillside seems less likely than wash-off from a glacier margin. The rounded pumice clasts in the northern quarry were clearly water-transported and were subsequently buried in a fluvial deposit.

The tephra in these three quarries shows the macro-characteristics of the Askja-S tephra. A sample from the Langadalsá terrace was chemically analyzed and has the chemical character of Askja-S (Table S-2). The >70 and >50 cm thick tephra on the Langadalsá and Svartfell terraces is interpreted as wash-off from a glacier margin, the tephra deposits having been subsequently buried under meltwater runoff deposits from the glacier. Systematic search to the north and south

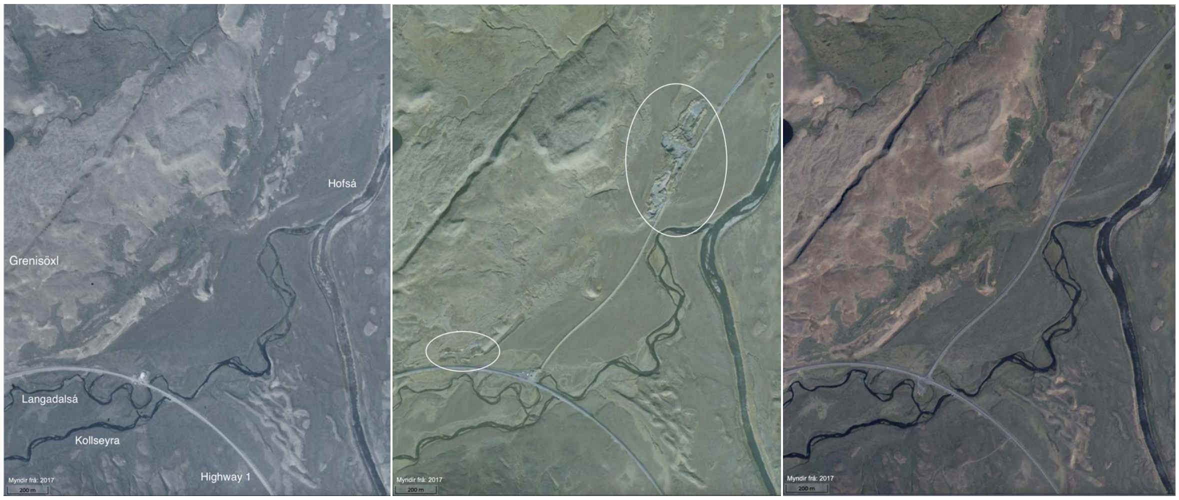


Figure 6. Aerial photographs from Map.is - Loftmyndir ehf, showing the same area at the east end of Langidalur pass in the year 2000 (left), 2001 (middle) and 2017 (right). Three rivers come together, Langadalsá, Kollseyra and Hofsá. Highway 1 passes through Langidalur. Photo to the left shows the area intact with terraces on the left side of the rivers and a set of moraines or eskers (Aradóttir *et al.*, 2024) in the area between Kollseyra and Hofsá. Middle photo shows the two quarries in 2001 encircled by white lines. Photo to the right shows the area in 2017 levelled and revegetated. Photograps in Figure 7 are from the southern quarry. – *6. mynd. Loftmyndir frá Map.is – Loftmyndir ehf af sama svæði árin 2000 (t.v.), 2001 (mið) og 2017 (t.h.). Þrjár ár koma saman, Langadalsá, Kollseyra og Hofsá. Þjóðvegur 1 er neðst t.v. á myndunum. Á myndinni frá 2000 sjást ósnertir hjallar norðan Langadalsár og Kollseyru. Á mynd frá 2001 sjást tvær efnistökunámur merktar með hvítum sporbaugum. Myndir 7 eru teknar í syðri námunni. Myndin frá 2017 sýnir svæðið frágengið. Á öllum myndunum sjást jökulgarðar og/eða malarásar milli Kollseyru og Hofsár.*

Figure 7. Quarry at Langadalsá. Arrow points to 70 cm thick deposit/lens of Askja-S tephra to the right, shovel (1 m) for scale. Excavated material is partly tephra. Horizontal area farthest to left is undisturbed terrace. b) Askja-S tephra, white where dry, pinkish to brownish when damp, mostly ash to fine lapilli. c) Close-up of the deposit. Several units with laminae, ripples, cross bedding and internal erosional surfaces indicate current of varying strengt from left to right. Detailed description in online supplements. – *7. mynd, t.v. Náma við Langadalsá. Um 70 cm þykkur stabbi/linsa af ljósri gjósku, Askja-S, lengst t.v. (ör). Uppmokstur er að hluta gjóska. Lárétta svæðið t.h. er óraskaður hjalli. Miðja. Askja-S er að mestu aska og smágerður vikur, hvít þar sem gjóskan er þurr, en bleik- eða brúnleitari þar sem hún er rök. T.h. Nærmynd af byggingareinkennum gjóskunnar, m.a. skálöguðum einingum með rofflötum inn á milli, sem benda til breytilegs straumhraða frá vinstri til hægri. Nánari lýsing er í viðauka á vefsíðu Jökuls.*

of these localities, and through the Langidalur pass, revealed no similar deposits although the thickness axis of Askja-S lies close to the area (Sigvaldason, 2002). However, and as evident from the above descriptions, the Askja-S deposit is buried below substantial thickness of glaciofluvial deposits and only becomes accessible where the overburden has been removed by heavy machinery.

The Langidalur terrace with the massive, accumulated deposit (>70 cm) of Askja-S tephra, where airfall thickness in the region was less than 10 cm, may thus be coeval with a standstill of the IIS margin close to the Melur stage of Aðalsteinsson (1987) and the Bruni stage of (Sæmundsson, 1995). The occurrences of Askja-S may be taken to indicate the position of the ice-margin at the time of the eruption of this tephra at about 10.9 ka. It is notable that no occurrences of the Askja-S tephra have been found between the two quarries despite roadwork exposures. Potential explanations are treated below. Whether the tephra fall affected the retreat of the glacier cannot be seen from the current data.

Arnardalsá, Saksunarvatn tephra

East of Arnardalsalda (Figure 8) Aðalsteinsson (1987) shows three sets of ice-contact scarps/moraines spaced about 5.5 km apart (Figure 9a). The northernmost of these is marked by a distinct ice-contact escarpment and proglacial sandur area to its north. Inside the ice-contact scarp there is a depression with hummocky moraine and a winding esker. Aðalsteinsson traced this set of moraines east across Mynnisfjallgarður to Lake Ánavatn, hence the name Ánavatn stage, and attributed it to a surge in "proto-Brúarjökull".

A less distinct ice-contact scarp with patches of proglacial sandur plains lies about 5.5 km farther south, best developed south of Þríhyrningsvatn (Figure 9a), with winding eskers that may indicate standstill of the glacier snout at this locality rather than an advance. Aðalsteinsson named it the Þverá stage and traced the ice-contact features some 12–15 km towards the east where it is also named the Fiskidalur moraine (Bjarkason, 2024).

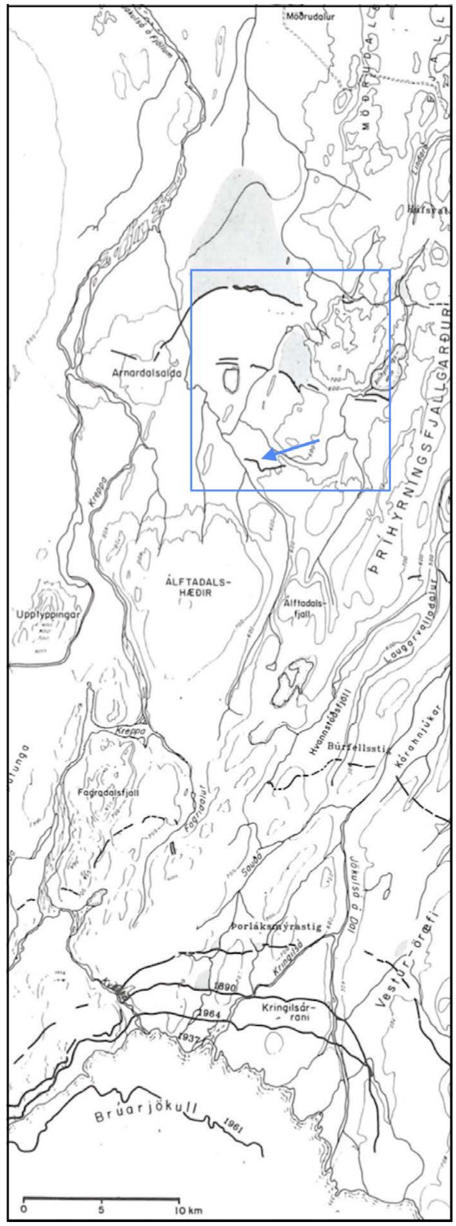


Figure 8. Part of a map by Aðalsteinsson (in Guttormsson, 1987) showing end moraines/ice marginal features formed during the retreat of the IIS margin. Blue square indicates area of Figure 9a, the arrow points to hummocky moraine overlain by black tephra on Figure 10. – *8. mynd. Hluti korts Bessa Aðalsteinssonar af ummerkjum jökuljaðra frá hörfun ísaldarjökulsins. Blár fernhyrningur sýnir svæðið á mynd 9a (loftmynd frá Map.is, áteiknuð), blá ör bendir á öldótta jökulurð sem svarta gjóskulagið á 10. mynd liggur ofaná.*

The third and southernmost ice-marginal feature is not well developed and best discernible between the rivers Arnardalsá and Þríhyrningsá (Figure 9a). There is no clear ice-contact scarp, just a change where the fluted moraine from a previous advance grades into hummocky moraine along an irregular front, here termed "contact zone". No proglacial sandur was formed. Within this zone there are areas with exposed tephra deposits lodged in basal till and glaciogenic sediments, irregular till-covered ridges and a narrow moraine ridge or an end moraine (Figure 9b) with metre-sized boulders on top. We refer to this as the Arnardalsá stage.

Densely packed, hardened deposits of irregularly bedded fine-grained sediments are lodged in basal deposits of cobbles and boulders (Figure 10a). The thickness varies from thin veneer to >60 cm. The uppermost preserved unit is up to 50 cm thick, consisting of bedded, greyish green to brown silty sand. A unit of black to brownish-black, bedded, fine-sandy tephra, up to 30 cm thick, underlies the silty sand (Figure 10b). The lower boundary is sharp but uneven, the lowest part of the tephra is black, the uppermost part acquiring more greyish hue. The tephra was chemically analyzed and the glass has the character of the Grímsvötn system, most similar to the 10.3 ka Saksunarvatn tephra (Table S-4). The lowermost unit consists of indurated, greyish green to black silt/sand, vaguely cross bedded. Thickness is unknown because the layer was not workable with a spade.

The narrow moraine ridge has some small gaps but can be followed for a distance of 0.7 km towards east from Arnardalsá. West of the river its continuation is covered by sand (Figure 9b). In front of the ridge and in the largest gap a similar sediment sequence is exposed (Figure 10c) with bedded, greyish green to brown sediment unit overlying bedded black tephra unit, 10 to over 30 cm thick, both units are hardened. Here, however, the black tephra rests on greyish silt, sand and fine gravel (Figure 10d). The tephra was analyzed chemically, and the glass has the same characteristics of the Grímsvötn system (Table S-5). Sporadic occurrences of the black tephra can be traced for about 0.4 km behind the moraine ridge.

Along the hillside where the fluted moraine is changing into hummocky moraine a brownish-black tephra layer sporadically crops out below a lag pavement (Figures S2-S3, locations on Figure 9b) sometimes appearing as a well defined 8–35 cm thick, bedded, partly hardened layer. The lowermost 8–12 cm could be primary airfall and have the chemical characteristics most similar to the 10.3 ka Saksunarvatn tephra (Tables S6-S7).

The thickness of the bedded black tephra found at the hillside and in some basal deposits as well appears to be above the critical thickness needed to slow down the melting of ice (Möller *et al.*, 2016). It seems plausible that this tephra, here taken to be the Saksunarvatn tephra, was deposited over the ice sheet when it was retreating from this area and that the insulating effect of the tephra reduced the ablation for some time leading to a standstill or minor readvance, as implied by the small moraine ridge. In front of the glacier snout the tephra may both have been deposited as airfall and as wash-off tephra, increasing the preservation potential in a barren area.

Assuming that this interpretation is correct, this modest ice contact site may provide a date for a position of the retreating margin of the IIS. The Saksunarvatn tephra was the largest basaltic tephra erupted in the Early Holocene (Óladóttir *et al.*, 2020). The correlation to this tephra places the ice-marginal position at the Arnardalsá moraine to about 10.3 ka.

Rate of retreat of the ice-sheet margin

Assuming that the deposition of Askja-S at about 10.9 ka dates the ice-margin at Langidalur, and that the Saksunarvatn tephra dates Arnardalsá moraine to 10.3 ka, the ice-sheet retreated about 40 km in 600 years or $\sim$65 m per year on average. If the age of 11 ka for Askja-S is adopted the rate of retreat would be about 55 m per year. Both are realistic values but since the date of Askja-S is not well constrained the average retreat rate of 60 ± 5 m per year is preferred here. This allows some estimates to be made about the age of other moraines, assuming that the rate of retreat was as described above, disregarding readvances.

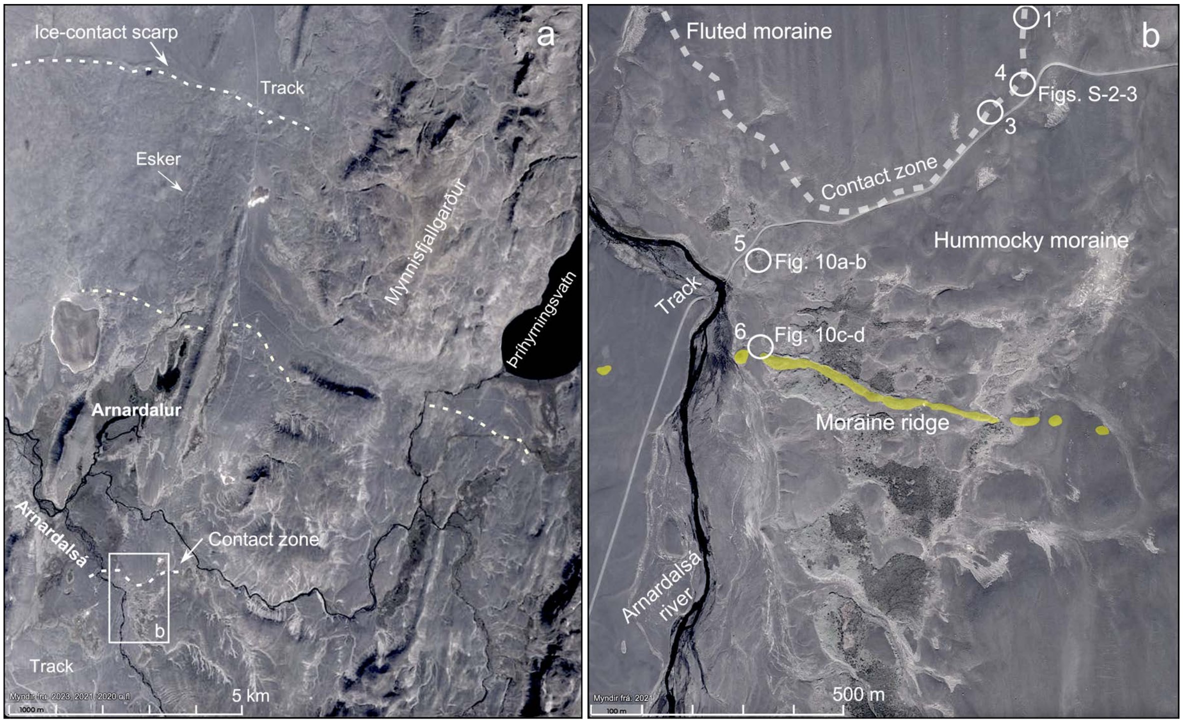


Figure 9. a) Broken white lines indicate three ice-contact/marginal moraines near Mynnisfjallgarður on an aerial photograph from Loftmyndir ehf., (see Figure 8). The northernmost marginal feature is best developed and can be traced intermittently for 40 km. The southernmost marginal feature near Arnardalsá is least developed. No efforts were made to trace this moraine farther east. White rectangle marks panel b for details. b) Close-up of the southernmost ice-contact area, featuring fluted moraine (top) and hummocky moraine with a small moraine ridge with metre-sized boulders enhanced by yellow overlay. Deposits of black tephra with chemistry similar to Saksunarvatn are found in close relationship with the moraine and the moraine ridge (see Figure 10), and along the "contact zone" between the fluted and hummocky moraine (Figure S-3). White circles show where photographs in Figures 10 and S-3 are taken and where sections were measured and sampled (numbers refer to Tables S4-S8 and Figures S-2-3). – *9. mynd, a) Ummerki þriggja jökuljaðra, slitnar hvítar línur á Loftmynd af Map.is, sjá 8. mynd. Nyrsti jaðarinn er einna greinilegastur og hægt að rekja hann um 40 km til austurs, ekki þó samfellt. Sá syðsti er ógreinilegur og sést aðeins á stuttum kafla (hvítur rammi), en við hann finnst svart gjóskulag með efnafræðileg einkenni Saksunarvatnsgjósku. b) þysjað inn á syðsta svæðið, ísjaðarsvæði, öldótta jökulurð og jökulgarð (gul þekja) með stórum hnullungum. Hringir sýna hvar myndir 10 og S-3 af tengslum svörtu gjóskunnar og jökulurðarinnar eru teknar.*

The Skessa (Skessugarður) stage of Aðalsteinsson (1987) would be about 340 years younger than Askja-S or ∼10.6 ka. The Ánavatn stage would be about 200 years older than Arnardalsá stage or ∼10.5 ka. The Þverá/Fiskidalur stage would be about 100 years older than Arnardalsá stage or 10.4 ka.

The Búrfell stage moraines lie some 22–23 km inland from the Arnardalsá moraine. Using the average retreat of 60 m/year to estimate the age it would be some 350–400 years younger than Arnardalsá stage or ∼9.9 ka.

The Þorláksmýri moraine/ice-contact lies about 33 km inland from the Arnardalsá moraine. Based on an average retreat of 60 m/year, the Þorláksmýri moraines would be about 550 years younger than the Arnardalsá stage and date to 9.7–9.8 ka.

The ice-sheet margin would then have retreated to a position inside the present margin of Brúarjökull

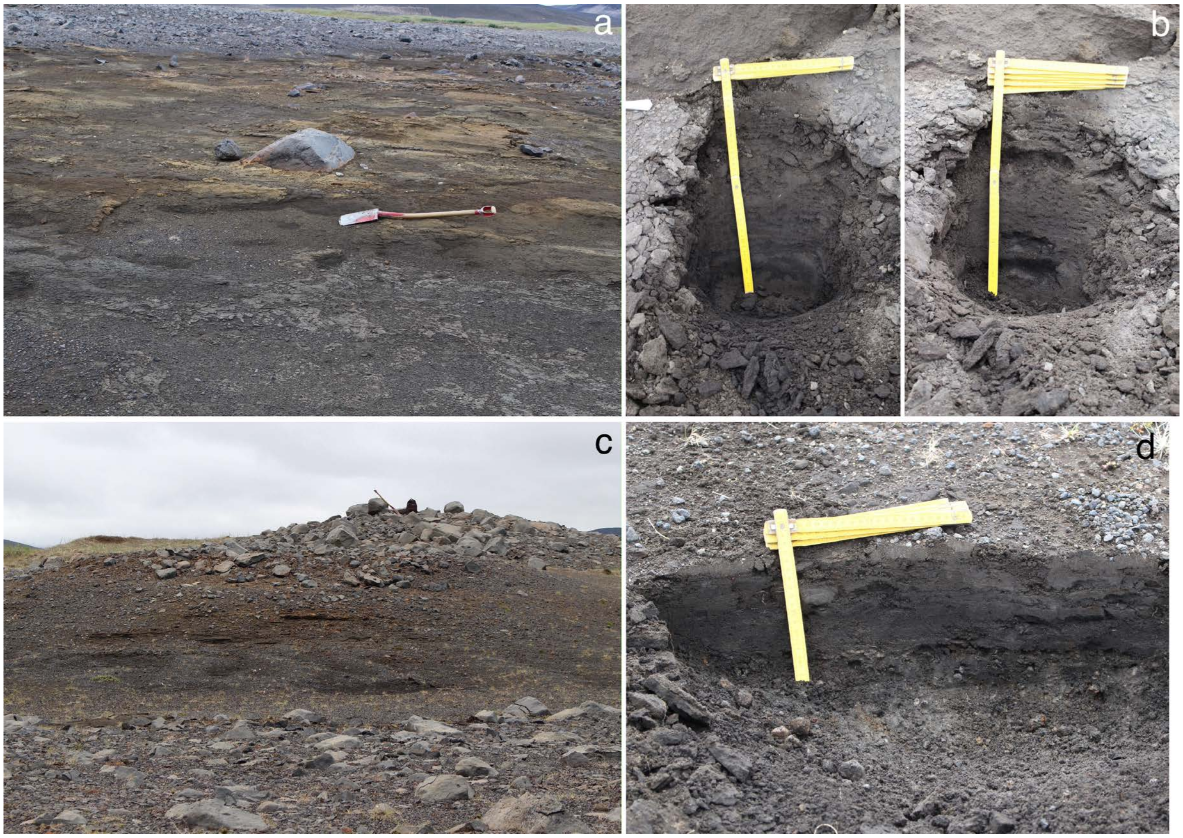
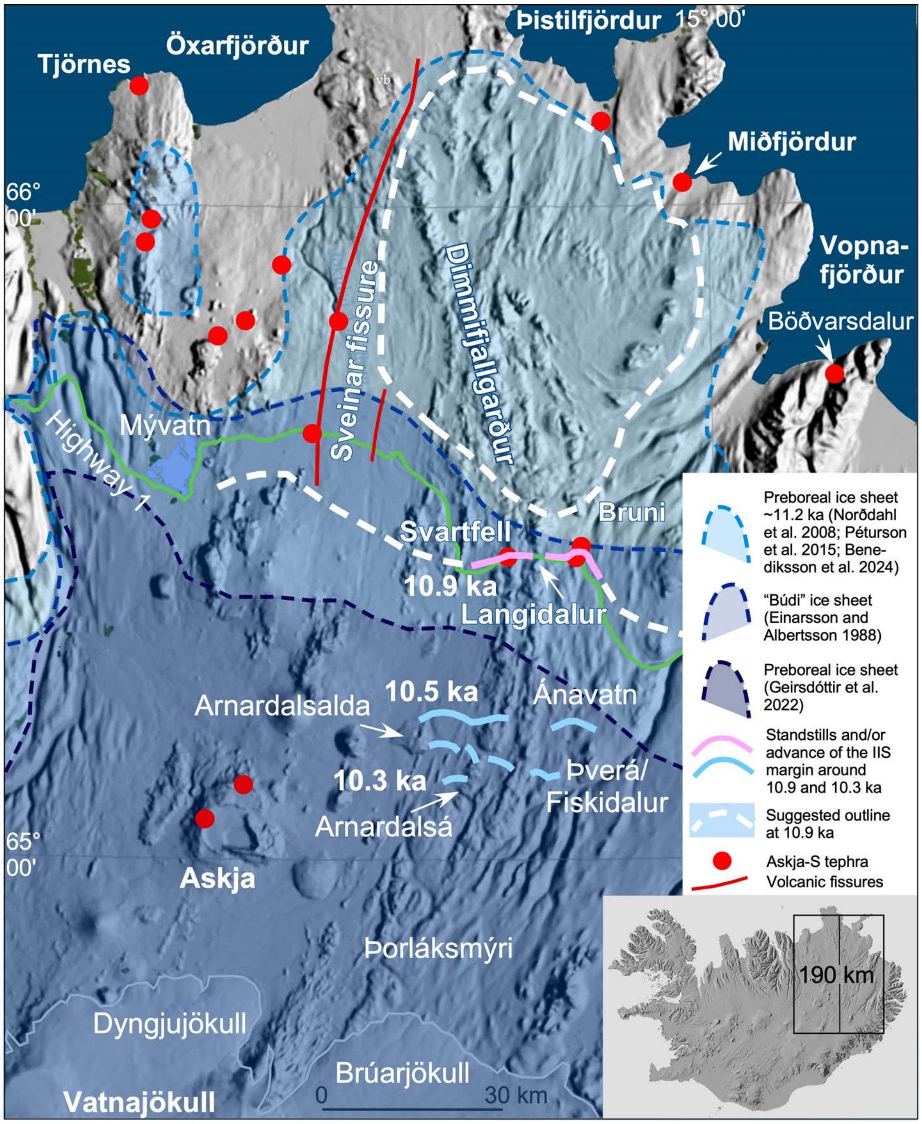


Figure 10. a) A depression in the till north of Arnardalsá. View towards east. The uppermost preserved unit is greyish green to brown silty sand. The showel (1 m) lies in a partly eroded deposit of black to brownish black tephra. The surface of the tephra deposit appears greyish black when dry. Note that colour of tephra and sediments changes depending on dampness, therefore descriptions may vary. b) Left: A deposit, 30–35 cm thick, of black to brownish-black, fine-sandy tephra with sharp but uneven lower boundary. Lowest part appears black in the photo. Greyish green silty material below. Right: Three samples were collected from base, lower middle part and near the top. c) The moraine ridge with metre sized boulders on top, spade (1 m) for scale, photo was taken across a gap in the ridge. View towards east. In the gap a brownish sediment overlies bedded black tephra unit. d) The black tephra, 10–15 cm thick, overlies greyish silt, sand and fine gravel. All units are hardened. – *10. mynd, a) Jöklabæli norðan Arnardalsár. Blettur af brúnleitu seti og svartri gjósku í dæld í botnurð. Gjóskan er grásvört á yfirborði þegar hún er þurr. b) Snið í 30–35 cm svart-brúnsvart, fínsöndugt gjóskulag, óslétt lagmót neðst. Fínna grágrænt, hart set undir. Þrjú sýni voru tekin, neðst, neðan miðju og efst. c) Litli jökulgarðurinn, myndin tekin þar sem skarð er í garðinn. Stórgrýti efst, skóflan en 1 m. Í skarðinu er brúnleitt hart set og undir því svört, hörðnuð gjóska. d) Svarta gjóskan, 10–15 cm þykk, liggur á lagi úr gráu silti sandi og fínmöl.*

10–12 km farther south at about 9.5–9.6 ka. This is somewhat earlier than previously assumed.

The Preboreal ice sheet in Northeast Iceland

The data presented here suggests that a margin of the Iceland Ice Sheet had retreated southwestwards from the Vopnafjördur lowlands to Langidalur at about 10.9 (10.8–11) ka. The Preboreal ice sheet as drawn in Norðdahl *et al.* (2008) and Pétursson *et al.* (2015) for ∼11.2 ka shows a broad ice lobe extending northwards over the Fjallgarðar highlands to Þistilfjörður and Miðfjörður (Figure 11). The new data indicate



that the west margin of that ice lobe had retreated some 15 km towards southeast before 10.9 ka. Sigurgeirsson (2016) has demonstrated that the 100 km long basaltic Sveinar fissure eruption, occurring in ice-free environment, is contemporaneous with the Askja-S eruption. This volcanic fissure is located well inside the west margin of that ice lobe indicating that the ice-margin must have been some distance farther east at the time of the the Askja-S eruption.

Together with the occurrence of Askja-S at the Svartfell and Langidalur terraces this may suggests that by 10.9 ka a corridor was forming in the ice sheet approximately where the Langidalur pass (and Highway-1) crosses the Fjallgarðar highlands. Alternatively, a narrow saddle of ice across Langidalur could explain the occurrences of Askja-S on either side of the pass and its apparent absence in the pass itself.

As this corridor developed the ice sheet to its north and south separated, leaving an independent ice dome on Dimmifjallgarður while the main ice-sheet margin retreated towards south with several standstills/readvances (Aðalsteinsson, 1987).

DISCUSSION

Askja tephra

The rhyolitic tephra found as an over 70 cm and 50-60 cm thick deposit in the Langadalsá and Svartfell terraces and as a 30 cm thick deposit buried beneath proglacial alluvial sediments all have the distinct characteristics of the Askja-S tephra. These deposits are thicker than the expected airfall Askja-S tephra based on soil sections elsewhere in North and Northeast Iceland (Figure 4b).

We argue that the thick deposits of the rhyolitic tephra Askja-S constitute tephra that was deposited onto the ablation area of a glacier and then washed off the margins onto the terraces and into the sediment in the proglacial area. The distinct deposits indicate one short event of tephra fall that was washed off the ablation area within a relatively short time and was consequently buried by the deposition of fluvial sediment on the outwash plain. It may, therefore, mark the position of the ice-margin in that particular area at the time of the Askja-S eruption at about 10.9 ka.

The possibility that the thick deposits of Askja-S at Langadalsá are melt-out tephra, that is tephra deposited onto the accumulation area of the ice-sheet, transported northwards by the ice flow and melted out some centuries later at this location, was considered. Melting out of englacial tephra from ice in ablation areas is a slow process that occurs seasonally (e.g. Larsen *et al.*, 1998) and cannot deliver such thick and clean deposits outside the glacier margin at any one time. We therefore find it unlikely that the thick deposits at Langadalsá are seasonally deposited melt-out tephra.

Shear zones in stagnating or retreating ice-margins are not very active. The present ablation areas of Vatnajökull reveal the tephra layers of the last 800 years (∼1150–1934) as dark bands, ∼7 per century (Larsen *et al.*, 1998 and unpubl.data). The number of eruptions breaking through the ice before 11 ka to deposit tephra over the ice sheet is not known but may have been lower, although probably not as low as 39 eruptions between 17 and 9 ka reported by Cook

Figure 11. Paleo-positions of the Preboreal IIS ice margin at 10.9 ka (thick pink lines) and 10.3 ka (thick light-blue line at Arnardalsá) dated by the Askja-S and Saksunarvatn tephra, respectively, are shown in relation to previously published Preboreal ice limit at ∼11.2 ka. The thick deposits of the Askja-S tephra at Svartfell and Langadalsá quarries are interpreted as a wash-off from a glacier margin close to these localities. This may indicate that an ice free corridoor was forming along Langidalur pass around 10.9 ka, leaving an independent dome on Dimmifjallgarður, as shown above. Alternatively, a narrow ice saddle across the Langidalur pass may still have existed, allowing deposition of the wash-off tephra on either side of the saddle. Possible outlines of the ice at ∼10.9 ka is shown in broken white line, taking into account localities where the Askja-S tephra has been found and the position of the associated Sveinar volcanic fissure. East of Arnardalsalda are three sets of marginal ice-contact features indicated by thick light-blue lines (modified from Aðalsteinsson, 1987, see Figure 8). At the southermost locality are thick black deposits of Saksunarvatn tephra lodged in moraine. They are interpreted as airfall on the ice margin and proglacial area at 10.3 ka, causing a short-lived advance and forming a small moraine ridge (Figure 9b). – *11. mynd. Tímasett ummerki eftir jökuljaðar fyrir 10,9 þús. árum (sverar bleikar línur) og 10,3 þúsund árum (sver ljósblá lína við Arnardalsá) eru sýndar ásamt áður birtum norðurmörkum Preboreal jökuls fyrir ∼11,2 þúsund árum, sjá 1. mynd. Askja-S, ljós um 10,9 þúsund ára gömul gjóska, myndaði þykka bunka þegar gjóska skolaðist af leysingasvæði/jaðri jökuls sem þá lá nærri Svartfelli og Langadalsá. Það gæti bent til að að geil/skil hafin verið komin í jökulbreiðuna um Langadal eins og hér er sýnt, eða að mjó jökulspöng hafi enn legið yfir miðjum Langadal. Ljósbláar sverar línur sýna ummerki þriggja jökuljaðra við Arnardalsöldu. Sú syðsta markar jökulurð og jökulgarð (9. mynd) þar sem þykk, svört basaltgjóska, Saksunarvatn, um 10,3 þúsund ára gömul, hefur varðveist. Hér er talið að gjóskan hafi fallið yfir jökulbreiðu og jökulurð framan við hana og marki kyrrstöðu eða lítilsháttar framrás jökulsins. Nyrsta bláa línan markar kyrrstöðu jökuljaðars fyrir um 10,5 þúsund árum miðað við jafna hörfun jökuls á tímabili fyrir 10,9 til 10,3 þúsund árum.*

et al. (2022). The surface of the ablation area may, therefore, have been relatively clean.

The thick Askja-S deposits in the Þistilfjörður area (Figure 4b), close to the postulated Preboreal ice-margin there (Norðdahl and Pétursson, 2005) may represent wash-off tephra from a proximal ice-margin (Figure 1). This site, located ∼70 km north of Langidalur pass, might seem to contradict our interpretation of the timing of glacier retreat south of the Bruni/Melur stage. However, this does not contradict such a process at Langadalsá if the ice sheet was already splitting up at the time of deposition (Figure 11).

The 15 cm thick tephra reported from Miðfjörður (Norðdahl and Hjort, 1993) was part of channel-fill sediments, featuring a sharp lower boundary and unclear upper boundary of the tephra, and may have been partly remobilized. The up to 8 cm thickness of the Askja-S airfall tephra measured in Böðvarsdalur implies that tephra deposited on the glacier at Langidalur was significantly thicker and well above the critical thickness. The thickness axis of Askja-S lies close to the Langidalur area, although farther to the west as shown by Sigvaldason (2002). It is therefore possible that the Askja-S tephra affected the melting of the ice sheet margin, causing a temporary standstill at Langadalsá.

Saksunarvatn tephra

Occurrences of the black basaltic tephra as a distinct layer in the ice-contact locality at Arnardalsá, where a fluted till changes into hummocky moraine (Figure 9b), can be interpreted as airfall onto glacially deposited sediments left by the retreating ice sheet margin. The Saksunarvatn tephra fall blanketed the environment but the preservation potential in an unvegetated terrain at that time is predicted to have been low. In some localities the tephra was probably reworked or eroded and locally absent as can be expected in an active glacial environment.

We further argue that the basaltic tephra was deposited onto the ablation area of the retreating ice-margin, which was lying close to or south of the present position of the moraine ridge (see Figure S-4). The black tephra within the glaciogenic sediments was either air fall or wash-off from the ablation area of the ice-margin, occasionally forming a fairly well-defined unit in depressions. Later on the tephra would either be buried by sediment washed off the ice or eroded by water circulating in its basin, where the tephra has only been sporadically preserved (Figures 10–11 and S-3)

We also argue that the deposition of an 8–12 cm thick airfall tephra onto the ablation area may have insulated the ice and temporarily retarded or stopped the melting and retreat while the tephra was washed off the ablation area, causing a minor readvance. Consequently, this location could mark the position of the glacier margin at 10.3 ka.

A short-lived readvance obviously pushed the moraine ridge into position. Our current interpretation of the course of events is shown on Figure S-4 but we are aware that more detailed study of the depositional features is needed to fully resolve the course of events at Arnardalsá around 10.3 ka.

The ice sheet

Separation of the northernmost part of the ice sheet on Dimmifjallgarður from the main inland ice (Figure 11) can help to explain the rapid retreat of the ice-sheet margin towards south. Apparent lack of moraines/standstills on Dimmifjallgarður during southwards retreat is explained if this mountain range had an independent ice dome. Assuming that the recent correlation of the 10.9 ka (11 ka) Askja-S eruption to the 100 km long Sveinar fissure with its numerous subaerial lava flows (Sigurgeirsson, 2016) is correct, then the western edge of the ice had retreated to a position east of the Sveinar fissure, defining its maximum westwards extent at that time.

We suggest the possibility that a separate ice sheet had persisted in the Dimmifjallgarður area in Bölling time, expanding again during the Younger Dryas to coalesce with the main ice sheet, to become separated again in Preboreal time. The mountain range/ridges north of the Langidalur pass reach elevations of 900±100 m a.s.l., equal to or higher than the Drangajökull area in Northwest Iceland where a separate glacier is supposed to have persisted during the Bölling deglaciation at 13.8 ka (Hubbard *et al.*, 2006; Norðdahl *et al.*, 2008; Pétursson *et al.*, 2015) and into the relatively warm early-mid Holocene (Schomacker *et al.*, 2016). The model experiments of Patton *et al.* (2017) fail to re-glaciate this region in Northeast Iceland when modelling the inland ice as a single Younger Dryas ice sheet, an additional indication that the extent of the Lateglacial to early Holocene ice sheet may need some reconsideration.

The suggestion of Aðalsteinsson (1987) that the ice-contact formations may have resulted from surging of the ice-margin rather than standstills or minor readvances is not well supported by field evidence. Surging landforms as those in front of Brúarjökull glacier, highly elongated flutes, crevasse-squeeze ridges, glaciotectonic end moraines (Ingólfsson *et al.*, 2016) and consertina eskers (Knudsen, 1995) are rare.

Tracing the Arnardalsá stage in the field farther towards east has not been attempted. The morphology (height, width, material) is similar to the Þverá/Fiskidalur stage moraine at Fiskidalur but this moraine is older than Arnardalur according to Aðalsteinsson (1987). A similar moraine in Laugarvalladalur-Meljaðrafjall some 11 km south of Fiskidalur disappears beneath thick soil, conditions that could potentially enable dating by tephrochronology or radiocarbon measurements.

Moraines of similar age as the Ánavatn-Þverá/-Fiskidalur-Arnadalsá moraines (10.5–10.3 ka) have not been described elsewhere in North Iceland. A possible candidate lies at the Hólavatn end moraine in the Eyjafjörður valley. In a now abandoned water channel that was eroded across the moraine, two tephra layers are present, a thick (∼20 cm) black tephra directly on the gravel and just above it a thin (0–2 cm) white tephra. The white tephra layer is an airfall deposit, chemically analyzed (Larsen, unpubl. data) and with the characteristics of the Reitsvík-8 (∼10.1 ka) tephra (Guðmundsdóttir *et al.*, 2016). The thick black tephra has the macroscopic characteristics of Reitsvík-7 or Saksunarvatn tephra (10.3 ka), possibly an airfall deposit. These two tephra layers in the water channel place the Hólavatn moraine before 10.3 ka. The adjacent Leyningshólar debris mounds may be of similar age.

The Herðubreið enigma

Licciardi *et al.* (2007) have assigned an age of 10.5±0.6 ka to the Herðubreið table mountain (1680 m a.s.l.), based on cosmogenic exposure dating using ^{3}He. This would indicate its emergence through an ice sheet at the Ánavatn stage, ∼10.5 ka, if both dates are correctly interpreted. This would also require a pre-eruptive ice thickness of ∼1 km in the Herðubreið area, assuming that the mountain is monogenetic and not the product of more than one eruption as argued by Werner and Schmincke (1999).

Arnardalsalda mountain (maximum elevation 712 m a.s.l.) lies about 12 km east of Herðubreið (peak to peak). The westernmost preserved part of the Ánavatn stage end moraine lies at ∼520 m a.s.l. where it ascends the northeast slope of Arnardalsalda. An end moraine (moraine ridge) runs down the NW slope of Arnardalsalda (Aðalsteinsson, 1987), possibly of the same age. Any potential westward continuation of this end moraine is now buried under Holocene lava flows. Extrapolation may place the corresponding ice-margin some 6 to 8 km north of the Herðubreið summit shield. Using the present Brúarjökull glacier as an analog (Björnsson *et al.*, 1991), the ice thickness around Herðubreið would have been ∼0.3 km. For ice thickness of 1 km at Herðubreið the ice-margin would have been some 50 km north of the mountain or north of the Mývatn area.

The age 10.5 ka is derived by assuming that there was no or minimal blanking snow cover on Herðubreið in winter-time (Licciardi *et al.*, 2007). This may be a valid assumption for the millennia at the Holocene Thermal Maximum (HTM) but not for the whole of Holocene. Assuming a blanking snow cover for two or three months a year on average, or 17% to 25% of the time, a simple correction yields ages of 12.7 and 14 ka, respectively.

SUMMARY AND CONCLUSION

Two paleo-positions of the margin of the Iceland Ice Sheet were dated at 10.9 and 10.3 ka by the tephra layers Askja-S and Saksunarvatn, respectively.

In both cases major tephra falls deposited thick (cm to tens of cm) tephra cover over the accumulation and ablation areas of the retreating inland ice in Northeast Iceland.

The 10.9 ka Askja-S sites are on the western (Svartfell) and eastern (Langadalsá) side of the Langidalur pass through the Fjallgarðar range, a few km south of the Melur/Bruni stage, but the tephra is not found in the pass itself. The 10.9 ka sites are characterized by thick deposits of almost uncontaminated yellow-white (to pinkish-white) tephra lodged in terraces proximal to ice-margins. Well sorted, rounded white pumice (fine lapilli) is buried in nearby proglacial sandur.

The 10.3 ka Saksunarvatn site lies about 40 km south of the Svartfell site. This ice-marginal position, representing either a stillstand or a minor readvance, is named the Arnardalsá stage. The site is characterized by thick black tephra deposits found as sporadic occurrences within and along the ice-marginal zone. The deposits are interpreted both as air-fall tephra and wash-off from the ice-margin.

Both the Askja-S and the Saksunarvatn tephra were chemically analyzed to confirm source volcanic systems. In case of Saksunarvatn tephra multiple sites were sampled and analyzed.

The thickness of both the Askja-S and the Saksunarvatn tephra on the ablation areas of the retreating ice sheet may have exceeded critical thickness and affected the melting of the ice for years up to decades. The Arnardalsá standstill or readvance probably results from such perturbation.

An implication is that standstills or minor readvances of retreating inland ice may be caused by other factors than climate fluctuations. The 10.9 ka Askja-S tephra formed a relatively narrow sector affecting only the ice sheet in Northeast Iceland. The 10.3 ka Saksunarvatn tephra had wider dispersal and possibly more wide-ranging effects than described here.

The location of the 10.9 ka Askja-S deposits to the west and east of the Langidalur pass in the Fjallgarðar range may invite some revision of the extent of the Preboreal ice sheet in North Iceland. Apparently a corridor was developing, either already open or with a narrow saddle in the ice sheet across the Langidalur pass, from which the ice sheet would retreat towards south and north, leaving a residual ice dome north of Langidalur pass.

Using the retreat rate between the two dated locations, the age of the Skessa stage could be about 10.6 ka, Ánavatn stage about 10.5 ka, Þverá-Fiskidalur stage about 10.4 ka, Búrfell stage about 9.9 ka, Þorláksmýri stage 9.7–9.8 ka and the ice sheet had retreated inside the present margin of Brúarjökull at 9.5–9.6 ka.

The ten documented stages of Aðalsteinsson (1987) have been postulated to be the results of surges of the Proto-Brúarjökull, analogous to present day Brúarjökull activity. This study shows that two of them may have had other causes.

These results demonstrate the need for further research of this unique series of ice contact features from the north shore of Iceland to the margin of present day Vatnajökull.

Acknowledgements

Part of the fieldwork was carried out in connection with the PACLIVA project (EVK2-CT-2002-00143) supported by the European Commission Fifth Framework Programme. G. L. thanks Halldór G. Pétursson for introducing her to the Big black tephra (Stóra svört) in North Iceland. Radiocarbon dating of the Reitsvík samples was done by Ingrid U. Olsson, University of Uppsala, in connection with an earlier study with Elsa G. Vilmundardóttir and G.L. Part of the analytical work was carried out at the University of Bergen. We thank Ívar Ö. Benediksson for critically reading and greatly improving the manuscript.

Author contributions: This project was originally proposed by O. K. and later carried out by G. L. as part of PACLIVA project with co-ordinator J. E.. Field work G. L., O. K., E. R. G., writing of ms G. L., J. E., analytical work E. R. G. and G. L.

Tímasetning jökuljaðra frá hörfunarskeiði ísaldarjökulsins á Norðausturlandi

Lega jökuljaðra frá hörfunarskeiði ísaldarjökulsins á Norðausturlandi var tímasett með gjóskulögum á tveim stöðum, við Svartfell og Langadalsá fyrir 10,9 þúsund árum og við Arnardalsá fyrir 10,3 þúsund árum (myndir 1–11). Bæði tilvikin tengjast meiriháttar gjóskufalli yfir hörfandi jökulbreiðu (retreating inland ice) á Norðausturlandi þar sem cm til dm þykkt gjóskulag lagðist yfir ákomusvæði og leysingasvæði hennar.

Eldra tilvikið markast af þykkum (allt að 70 cm) bunkum af ljósri gjósku sem sest hefur til á hjöllum við jökuljaðar og þykku lagi af skoluðum og núnum vatnfluttum vikri í jökuláreyri framan við jökuljaðar. Gjóskulagið er ættað frá megineldstöðinni Öskju og er hér kallað Askja-S (Magnús Á. Sigurgeirsson, 2016) en hefur áður verið kallað S-lag (Kristján Sæmundsson, 1991), Miðfjörður tephra (Hreggviður Norðdahl og Christian Hjort, 1993) og Dyngjufjöll tephra (Guðmundur E. Sigvaldason, 2002). Í öllum tilfellum var gjóskan á nokkru dýpi (>1 m) í efnistökunámum vegna vegagerðar og því ólíklegt að hún finnist á óröskuðu yfirborði. Ljósa gjóskan finnst beggja vegna Langadals, sem er skarð í Fjallgarðana milli Dyngjufjallgarðs að sunnan og Dimmafjallgarðs að norðan, en ekki í skarðinu sjálfu. Þetta er aðeins innar en áður skilgreind Melstig (Bessi Aðalsteinsson, 1987) og Brunastig (Þorsteinn Sæmundsson, 1995).

Tímasetningar á legu jökuljaðars fyrir 10,9 þúsund árum beggja vegna við Langadal má túlka þannig að skil (corridor) hafi verið að myndast í jökulbreiðuna á Fjallgörðunum. Óljóst er hvort ennþá var ísbrú yfir Langadal eða hvort ísbreiðan hafði þegar klofnað þegar ljósa gjóskan féll. Jökulbreiðan hörfaði síðan frá þessum skilum til suðurs en norðan skilanna varð til sjálfstæð jökulhetta með eigin hörfunarsögu (11. mynd).

Yngra tilvikið markast þykkum (allt að 30 cm) lögum af svartri gjósku sem sest hefur til í dældum í botnurð og við jökulgarð norðan við Arnardalsá og varðveist í tengslum við jökulrænt set. Gjóskulagið ber þess merki að vera loftborið, a.m.k. sums staðar, en annars staðar er það vatnshreyft og jafnvel skolað af jökuljaðri. Gjóskulagið er ættað frá Grímsvatnakerfinu og er hluti af syrpu sem kölluð er G10ka (Bergrún A. Óladóttir o.fl., 2020). Aðeins eitt þykkt svart lag, um 10,3 þúsund ára gamalt, finnst neðst í jarðvegssniðum á Norðausturlandi og er hér kallað Saksunarvatnsgjóska enda er efnasamsetning hennar líkust þeirri gjósku (Jan Mangerud o.fl., 1986).

Ef þykkt gjósku, sem fellur á jökul, er meiri en svonefnd krítísk þykkt getur gjóskuþekjan hægt á eða hindrað bráðnum á leysingasvæði um tíma (ár/ártugi). Þetta getur orsakað stöðnum og kyrrstöðu jökuljaðars í einhvern tíma eða jafnvel valdið tímabundinni framrás. Hér er talið hugsanlegt að jökulgarðinum við Arnardalsá hafi verið ýtt upp í minni háttar framrás vegna gjóskufalls á jökulbreiðuna. Tímabundin hlé (standstills) eða framskrið hörfandi jökuls geta því, a.m.k. í sumum tilfellum, stafað af meiriháttar gjóskufalli á jökul.

Miðað við meðalhörfunarhraða jökuls á tímabilinu fyrir 10,9 til 10,3 þúsund árum (án kyrrstöðu eða framrása) er Skessustig (Bessi Aðalsteinsson, 1987) um 10,6 þúsund ára, Ánavatnsstig um 10,5 þúsund ára, Þverár-Fiskidalsstig um 10,4 þúsund ára, Búrfellsstig um 9,9 þúsund ára, Þorláksmýrarstig 9,7–9,8 þúsund ára og jökuljaðarinn var kominn suður fyrir núverandi jaðar Vatnajökuls/Brúarjökuls fyrir 9,5–9,6 þúsund árum, sem er heldur fyrr en áður hefur verið talið.

Við teljum einnig hugsanlegt að norðantil á Fjallgörðunum hafi verið sjálfstæð jökulhetta á Bölling-Alleröd tíma sem stækkaði og tengdist meginjöklinum á Yngra Dryas. Það gæti skýrt hvers vegna líkanreikningar á vexti jökuls á Yngra Dryas hafa ekki getað teygt jökul norður eftir Fjallgörðunum.

REFERENCES

Aðalsteinsson, B. 1987. Jökulhörfun á Brúaröræfum. Í: *Ísaldarlok á Íslandi.* Jarðfræðafélags Íslands, Dagskrá og ágrip erinda, 10.

Adhikary, S., K. Seko, M. Nakawo, Y. Ageta and N. Miyazaki 1997. Effect of surface dust on snow melt. *Bull. Glacier Res.* 15, 85–92.

Adhikary, S., M. Nakawo, K. Seko and B. Shakya 2000. Dust influence on the melting process of glacier ice: experimental results from Lirung Glacier, Nepal Himalayas. *Debris-covered Glaciers* (Proc. workshop in Seattle, WA, USA, 2000). IAHS Publ. 264, 43–52.

Alley, R. and A. M. Ágústdóttir 2005. The 8k event: cause and consequences of a major Holocene abrupt climate changes. *Quaternary Science Rev.* 24, 1123–1149.

Aradóttir, N., Í. Ö. Benediktsson, E. G. Helgadóttir, Ó. Ingólfsson, S. Brynjólfsson and W. R. Farnsworth 2024. Ribbed moraines formed during deglaciation of the Icelandic Ice Sheet: Implications for ice-stream dynamics. *Boreas.* https://doi.org/10.1111/bor.12690

Benediktsson, Í. Ö., P. Möller, Ó. Ingólfsson, J. J. M. van der Meer, K. H. Kjær and J. Krüger 2008. Instantaneous end moraine and sediment wedge formation during the 1890 glacier surge of Brúarjökull, Iceland. *Quaternary Sci. Rev.* 27, 209–234.

Benediktsson, Í. Ö., S. Brynjólfsson and L. Ásbjörnsdóttir 2023. Glacial landscapes of Iceland from the Younger Dryas. In: Palacios D., P. Hughes, J. M. García-Ruiz, and N. Andrés (eds.), *European Glacial Landscapes* 497–507. https://doi.org/10.1016/B978-0-323-91899-2.00054-1

Benediktsson, Í. Ö., S. Brynjólfsson and L. Ásbjörnsdóttir 2023. Iceland: glacial landforms from the Bølling-Allerød interstadial. In: Palacios D., P. Hughes, J. M. García-Ruiz, and N. Andrés (eds.), *European Glacial Landscapes* 331–339. https://doi.org/10.1016/B978-0-323-91899-2.00051-6

Benediktsson, Í. Ö., S. Brynjólfsson, L. Ásbjörnsdóttir and W. Farnsworth 2024. Holocene glacial history and landforms of Iceland. In: Palacios D., P. Hughes, J. M. García-Ruiz, and N. Andrés (eds.), *European Glacial Landscapes. The Holocene* 193–224. https://doi.org/10.1016/B978-0-323-99712-6.00012-X

Bender, E. M. 2020. *Late Quaternary tephra stratigraphy and paleoenvironmental reconstruction based on lake sediments from North and Northeast Iceland.* M.S.-thesis, UiT The Arctic University of Norway, Tromsö, 155 pp.

Bjarkason, E. D. 2024. *Landmótun og jökulhörfun á Möðrudalsöræfum og Jökuldalsheiði.* MS-thesis, University of Iceland, Reykjavík, 83 pp.

Björck, S., Ó. Ingólfsson, H. Hafliðason, M. Hallsdóttir and N. J. Andersson 1992. Lake Torfadalsvatn: a high-resolution record of the North Atlantic ash zone I and the last glacial-Interglacial environmental changes in Iceland. *Boreas* 21, 15–22.

Björnsson, H. 2009. *Jöklar á Íslandi.* Bókaútgáfan Opna, Reykjavík, 479 pp.

Bronk Ramsey, C., P. G. Albert, S. P. E. Blockley, M. Hardiman, R. A. Housley, C.Ṡ. Lane, S. Lee, I. P. Matthews, V. C. Smith and J. J. Lowe 2015. Improved age estimates for key Late Quaternary European tephra horizons in the RESET lattice. *Quaternary Sci. Rev.* 118, 18–32.

Eiríksson, J., K. L. Knudsen, H. Hafliðason and P. Henriksen. 2000. Late glacial and Holocene palaeoceanography of the North Iceland Shelf. *J. Quaternary Sci.* 15, 23–42.

Dragosics, M., O. Meinander, T. Jónsdóttir, T. Dürig, G. De Leeuw, P. Pálsson, P. D. Waldhauserová and T. Thorsteinsson 2016. Insulation effects of Icelandic dust and volcanic ash on snow and ice. *Arabian J. Geosci.* 9, 126.

Driedger, C. L. 1981. Effect of ash thickness on snow ablation. The 1980 eruptions of Mount St. Helens, Washington. *US Geological Survey, Professional Paper* 1250, 757–760.

Flowers, G. E., H. Björnsson, Á. Geirsdóttir, G. H. Miller, J. L. Black and G. K. C. Clarke 2008. Holocene climate conditions and glacier variation in central Iceland from physical modelling and empirical evidence. *Quaternary Sci. Rev.* 27, 797–813

Geirsdóttir, Á., G. H. Miller, I. Axford and S. Ólafsdóttir 2009. Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. *Quaternary Sci. Rev.* 28, 2107–2118.

Geirsdóttir, Á., G. H. Miller, D. J. Harning, H. Hannesdóttir, T. Thordarson and I. Jónsdóttir 2022. Recurrent outburst floods and explosive volcanism during the Younger Dryas-Early Holocene deglaciation in south Iceland: evidence from a lacustrine record. *J. Quaternary Sci.* 37, 1006–1023. https://doi.org/10.1002/jqs.3344

Guðmundsdóttir, E. R., G. Larsen, S. Björck, Ó. Ingólfsson and J. Striberger 2016. A new high-resolution Holocene tephra stratigraphy in eastern Iceland: Improving the Icelandic and North Atlantic tephrochronology. *Quaternary Sci. Rev.* 150, 234–249.

Guttormsson, H. 1987. *Norð-Austurland, hálendi og eyðibyggðir.* Árbók Ferðafélags Íslands.

Ingólfsson, Ó. and H. Norðdahl 1994. A review of the environmental history of Iceland, 13000–9000 yr BP. *J. Quaternary Sci.* 9, 147–150.

Ingólfsson, Ó., H. Norðdahl and A. Schomacker 2010. Deglaciation and Holocene Glacial History of Iceland. *Dev. Quaternary Sci.* 13, 51–68.

Ingólfsson, Ó., Í. Ö. Benediktsson, A. Schomacker, K. H. Kjær, S. Brynjólfsson, S. A. Jónsson, N. J. Korsgaard and M. D. Johnson 2016. Glacial geological studies of surge-type glaciers in Iceland – Research status and future challenges. *Earth-Science Rev.* 152, 37–69.

Jóhannsdóttir, G., Th. Thordarson and Á. Geirsdóttir 2006. The Widespread 10 ka Saksunarvatn Tephra: A Product of Three Separate Eruptions? AGU Fall Meeting, abstract V33B-0666.

Kaldal, I. 1993. *Fróðleiksmolar um gamla gjósku í Búðarhálsi.* [Old tephra deposits at Búðarháls, South Iceland.] Vorráðstefna Jarðfræðafélags Íslands, 36–37.

Kirkbride, M. P. and A. J. Dugmore 2003. Glaciolgical response to distal tephra fallout from the 1947 eruption of Hekla, south Iceland. *J. Glaciology* 49 (166), 420–428.

Kjerúlf, Þ. 1962. Vatnajökull hlaupinn. Frásögn Þorvarðar læknis Kjerúlf 1890. Áður prentað í Ísafold 1890, 321. *Jökull* 12, 47–48.

Knudsen, Ó. 1995. Concertina eskers, Brúarjökull, Iceland: An indicator of surge-type glacier behaviour. *Quaternary Sci. Rev.* 14, 487–493

Korsgaard, N. J., A. Schomacker, Í. Ö. Benediktsson, N. K. Larsen, Ó. Ingólfsson and K. H. Kjær. 2015. Spatial distribution of erosion and deposition during a glacier surge: Brúarjökull, Iceland. *Geomorphology* 250, 258–270.

Krüger, J. and J. Aber 1999. Formation of supraglacial sediment accumulations on Kötlujökull, Iceland. J. Glaciology 45, 400–402.

Krüger, J. and K. H. Kjær 2000. De-iceing progression of ice-cored moraines in a humid, subpolar climate, Kötlujökull, Iceland. *The Holocene* 10, 737–747.

Larsen, G., M. T. Guðmundsson and H. Björnsson H. 1996. *Gjóskulög í Tungnaárjökli: gossaga, aldur íss og dvalartími gjósku í jökli.* Vorráðstefna 1996, ágrip erinda og veggspjalda, 33–35. Jarðfræðafélag Íslands, 3. apríl, Reykjavík.

Larsen, G., M. T. Guðmundsson, H. Björnsson 1996. Tephrastratigraphy of Ablation Areas of Vatnajökull Ice Cap, Iceland. In: Colbeck S. C. (ed): *Glaciers, Ice Sheets and Volcanoes: A tribute to Mark Meier.* CRREL Special Report, 96–27.

Larsen, G., M. T. Guðmundsson and H. Björnsson 1998. Eight centuries of periodic volcanism at the center of the Iceland hotspot revealed by glacier tephrostratigraphy. *Geology* 26, 943–946.

Licciardi, J. M., M. D. Kurz and J. M. Curtice 2007. Glacial and volcanic history of Icelandic table mountains from cosmogenic ^{3}He exposure ages. *Quaternary Sci. Rev.* 26, 1529–1546. https://doi.org/10.1016/j.quascirev.2007.02.016

Mangerud, J., H. Furnes and J. Jóhansen 1986. A 9000 year old ash bed on the Faroe Islands. *Quaternary Res.* 29, 262–265.

Möller, R., M. Möller, P. A. Kukla and C. Schneider 2016. Impact of supraglacial deposits of tephra from Grímsvötn volcano, Iceland, on glacier ablation. *J. Glaciology* 62 (235), 933–943.

Möller, R., M. Möller, P. A. Kukla and C. Schneider 2018. Modulation of glacier ablation by tephra coverage from Eyjafjallajökull and Grímsvötn volcanoes, Iceland: an automated field experiment. *Earth Syst. Sci. Data* 10, 53–60.

Norðdahl, H. and C. Hjort 1993. Lateglacial raised beaches and glacier recession in the Þistilfjörður-Bakkaflói area, North-eastern Iceland. *Jökull* 43, 32–44.

Norðdahl, H. and H. G. Pétursson 2005. Relative sea-level changes in Iceland: new aspects of the Weichselian deglaciation of Iceland. In: Iceland - Modern processes and past environments, C. Caseldine, A. Russel, J. Harðardóttir and Ó. Knudsen (eds). *Dev. Quaternary Sci.* 5, 25–78.

Norðdahl, H., Ó. Ingólfsson, H. G. Pétursson and M. Hallsdóttir 2008. Late Weichselian and Holocene environmental history of Iceland. *Jökull 58, 343*–364.

Norðdahl, H., Ó. Ingólfsson, E. Vogler, B. Steingrímsson and Á. Hjartarson 2019. Glacio-isostatic age modelling and Late Weichselian deglaciation of the Lögurinn basin, East Iceland. *Boreas* 48, 563–580.

Ott, F., S. Wulf, J. Serb, M. Slowinski, M. Obremska, R. Tjallingii, M. Blaszkiewicz and A. Brauer 2016. Constraining the time span between the early Holocene Hässeldalen and Askja-S Tephras through varve counting in the Lake Czechowskie sediment record, Poland. *J. Quaternary Sci.* 31, 103–113.

Óladóttir, B. A., T. Thordarson, Á. Geirsdóttir, G. Jóhannsdóttir and J. Mangerud 2020. The Saksunarvatn Ash and the G10ka series tephra. Review and current state of knowledge. *Quatern. Geochronology* 56, 101041. https://doi.org/10.1016/j.quageo.2019.101041

Patton, H., A. Hubbard, T. Bradwell and A. Schomacker 2017. The configuration, sensitivity and rapid retreat of the Late Weichselian Icelandic ice sheet. *Earth-Sci. Rev.* 166, 221–245.

Pétursson, H. G. and G. Larsen 1992. *An early Holocene basaltic tephra bed in North Iceland, a possible equivalent to the Saksunarvatn ash bed.* In: Geirsdóttir, Á., H. Norðdahl, and G. Helgadóttir (eds): Abstracts: 20th Nordic Geological Winter Meeting, 133 pp. Reykjavík.

Pétursson, H. G., H. Norðdahl, Ó. Ingólfsson 2015. Late Weichselian history of relative sea level changes in Iceland during a collapse and subsequent retreat of marine based ice sheet. *Cuadernos de Investigación Geográfica* 41, 281–277.

Reimer P., W. E. N. Austin. E. Bard, A. Bayliss, P. G. Blackwell, C. Bronk Ramsey, M. Butzin, H. Cheng,

R. L. Edwards, M. Friedrich *et al.* 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62, 725–757. https://doi.org/10.1017/RDC.2020.41

Schomacker, A. 2008. What controls dead-ice melting under different climate conditions? A discussion. *Earth-Sci. Rev.* 9, 103–113.

Schomacker, A., S. Brynjólfsson, M. Andreassen, E. R. Guðmundsdóttir, J. Olsen, J. V. Odgaardd, L. Håkansson, Ó. Ingólfsson, and N. K. Larsen 2016 .The Drangajökull ice cap, northwest Iceland, persisted into the early-mid Holocene. *Quaternary Sci. Rev.* 148, 68–84.

Schomacker, A. and Í. Ö. Benediktsson 2017. Supraglacial processes. In: Menzies and van der Meer (eds.): *Past Glacial Environments*, second ed., 159–179. https://doi.org/10.1016/B978-0-08-100524-8.00005-1

Sigurgeirsson, M. Á. 2016. Eldar í Öskjukerfi fyrir 11.000 árum. *Náttúrufræðingurinn* 86, 76–90.

Sigvaldason, G. E. 2002. Volcanic and tectonic processes coinciding with glaciation and crustal rebound: An early Holocene rhyolitic eruption in the Dyngjufjöll volcanic centre and the formation of the Askja caldera, north Iceland. *Bull. Volcanology* 64, 192–205.

Striberger, J., S. Björk, S. Holmgren and L. Hamerlík 2012. The sediments of Lake Lögurinn - A unique proxy record of Holocene glacial meltwater variability in eastern Iceland. *Quaternary Sci. Rev.* 38, 76–88. https://doi.org/10.1016/j.quascirev.2012.02.001

Sæmundsson, K. 1991. Jarðfræði Kröflukerfisins. In: Garðarson A. and Á. Einarsson (eds): *Náttúra Mývatns* 25–95. Hið íslenska náttúrufræðifélag, Reykjavík.

Sæmundsson, Þ. 1995. *Deglaciation and shoreline displacement in Vopnafjördur, northeastern Iceland.* LUNDQUA Thesis, Lund University, 106 pp.

Thomas, E. R., E. W. Wolff, R. Mulvaney, J. P. Steffensen, S. J. Johnsen, C. Arrowsmith, J. W. C. White, B. Vaughn and T. Popp 2007. The 8.2 ka event from Greenland ice cores. *Quaternary Sci. Rev.* 26, 70–81.

Thorarinsson, S. 1964. On the age of the Terminal Moraines of Brúarjökull and Hálsajökull. A Tephrochronological Study. *Jökull* 3, 67–75.

Thordarson, T. 2014. *The widespread ∼10 ka Saksunarvatn tephra is not a product single eruption.* American Geophysical Union, Fall Meeting, abstract V24B-04.

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

Wastegård, S., E. R. Guðmundsdóttir, E. M. Lind, R. G. O. Timms, S. Björck, G. Hannon, J. Olsen and M. Rundgren 2018. Towards a Holocene tephrochronology for the Faroe Islands, North Atlantic. *Quaternary Sci. Rev.* 195, 195–214.

Wastl, M. 2000. *Reconstruction of Holocene palaeoclimatic conditions in Northern Iceland based on investigations of glacier and vegetation history.* PhD. dissertation, Leopold-Franzens-Univ. Innsbruck, 176 pp.

Werner, R. and H. U. Schmincke 1999. Englacial versus lacustrine origin of volcanic table mountains: evidence from Iceland. *Bull. Volcanol.* 60, 335–354

Østrem, G. 1959. Ice melting undir a thin layer of moraine and the existence of ice cores in moraine ridges. *Geogr. Ann.* 41, 228–230.