Reviewed research article

Mid-Holocene jökulhlaups in Jökulsá á Fjöllum, northeast Iceland, correlated to a prominent eruption sequence in Bárðarbunga, indicate significant ice cover at 6.3 to 4.1 ka

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Abstract — *Numerous jökulhlaups have followed the river Jökulsá á Fjöllum in northeast Iceland during the Holocene. Some of these fall under the category of catastrophic floods that carved out the present-day Jökulsárgljúfur canyon, over 100 km north of the present-day Vatnajökull. Sedimentary beds from 16 jökulhlaups between 6.3 and 4.1 ka ago are preserved in Vesturdalur, near the north end of the canyon. Chemical composition of volcanic glass in the jökulhlaup deposits correlates to three volcanic systems beneath Vatnajökull. The characteristics of the Bárðarbunga volcanic system dominate in 12 beds, and those of Grímsvötn and Kverkfjöll in one bed each, two remain unsolved. The characteristics of the Bárðarbunga glass in the jökulhlaup sediments are mostly low TiO_2 and high MgO (TiO_2 <1.6, MgO >7.3 w%). Seventeen basaltic "Low-Ti" tephra layers from Bárdarbunga have been identified in soil sections in north Iceland from this period. Grain characteristics of the tephra indicate phreatomagmatic origin. Dispersal maps confirm source area below northwest Vatnajökull and tephra volume (bulk) of the order of 1 km^3 for the largest layers. As the preserved soil sections are distal (>50 km) from source, it is likely that only the largest tephra layers have been preserved. The mid-Holocene floods confirm the existence of glaciers on Bárðarbunga, Kverkfjöll, and Grímsvötn at that time. The magnitude of these jökulhlaups is not well constrained, but apparent cross sections out of Vesturdalur fit a peak discharge of order 50,000 m^3/s and likely total volume of a few km^3. These repeated jökulhlaups 6.3 to 4.1 ka ago did not cause large erosion at Vesturdalur. Their source areas were most likely the calderas of the central volcanoes, which may have changed in size and form since the mid-Holocene. Eruptions within the Bárðarbunga caldera are a possible source for 12 of the floods. Bárðarbunga may have hosted a geothermal area and a subglacial caldera lake similar to present day Grímsvötn, which may explain the repeated, apparently similar-magnitude jökulhlaups over this long period.*

INTRODUCTION

The northerly position of Iceland in the North Atlantic, with high annual precipitation, has resulted in extensive ice cover on the high mountains of south and central Iceland, including some of the most active volcanoes such as Katla, Grímsvötn, and Bárðarbunga (Thordarson and Höskuldsson, 2008). This combination has consequences when volcanoes jump into action. Explosive eruptions beneath glaciers can cause extensive tephra fall and large volcanogenic floods, sometimes both at the same time (Gudmundsson *et al.*, 1997, 2008). Numerous volcanogenic jökulhlaups as well as floods from glacier-dammed lakes have occurred since the end of the last glaciation.

Volcanic activity at the volcanoes beneath Vatnajökull (Figure 1) has been periodic for at least the last 1200 years and peaks every 130–140 years with up to 11 eruptions in 40 years during times of high activity (Larsen *et al.*, 1998). These volcanoes lie at or close to the center of the Iceland hotspot. This periodic activity is best developed in Grímsvötn volcanic system whereas Bárðarbunga may become active during some of the periods and occasionally Öræfajökull volcano joins in. The increased volcanic activity in Grímsvötn and Bárðarbunga since 1996 (1998, 2004, 2011, 2014-2015) can be seen as a part of such high activity (Gudmundsson *et al.*, 2012, 2016).

Recent eruption on the Bárðarbunga volcanic system (BVS), the 2014–2015 Holuhraun eruption, has sparked interest in the eruption and flood history of the ice covered part of the BVS. The Bárðarbunga central volcano is ice covered with a large 700 m deep, 65 km^2 ice-filled caldera (Björnsson and Einarsson, 1990). Its rims, covered by 150–200 m of ice, rise to 1850 m above sea level. Considerable knowledge exists on the eruption history of the subglacial part of the Bárðarbunga volcanic system for the past 10 ka (Larsen *et al.*, 1998; Óladóttir *et al.*, 2011a; Gudmundsdóttir *et al.*, 2016) and that of the subaerial SW fissure swarm for the past 8.5 ka (Vilmundardóttir, 1977; Vilmundardóttir *et al.*, 1988, 1990, 1999; Larsen, 1984; Larsen *et al.*, 2013; Hjartarson, 2011; Kaldal *et al.*, 2018).

In north Iceland evidence of large floods have been recognized in the river Jökulsá á Fjöllum for many decades (Thorarinsson, 1950; Tómasson, 1973, 2002; Sæmundsson, 1973; Elíasson, 1977; Waitt, 2002; Ahlo *et al.*, 2005; Carrivick *et al.*, 2004; van den Bilt *et al.*, 2021) but opinions differ about their number, peak flows, and origin. Most authors agree on two catastrophic prehistoric jökulhlaups, one from a glacier dammed lake in early Holocene and volcanogenic jökulhlaup in late Holocene with peak discharge as high as 1 million m^3/s.

Volcanogenic floods in south and southeast Iceland caused by eruptions of the subglacial volcanoes Öræfajökull, Grímsvötn, and Katla have been described by several authors (Thorarinsson, 1958, 1974; Haraldsson, 1981; Tómasson, 1996, 2002; Gröndal *et al.*, 2005; Larsen *et al.*, 2005; Smith and Haraldsson, 2005; Gudmundsson *et al.*, 2008; Roberts and Gudmundsson, 2015; Larsen, 2018). In historical time documented events indicate that volcanogenic jökulhlaups have the largest peak discharges, in case of Katla jökulhlaups up to 300,000 m^3/s (Tómasson, 2002).

Since the full retreat of the Icelandic ice sheet, the largest Holocene jökulhlaups in Jökulsá á Fjöllum are of volcanogenic origin. Recent research into large prehistoric floods has focused on the reconstruction of the hydraulic conditions during the events, in particular along the upper half of Jökulsá á Fjöllum. Sedimentary and erosional features indicate that these floods ranged from moderate to catastrophic in volume and peak discharge (Waitt, 2002; Ahlo *et al.*, 2005; Carrivick *et al.*, 2004).

The lower half of Jökulsá river follows a canyon, Jökulsárgljúfur, carved by numerous floods (Tómasson, 1973, 2002; Sæmundsson, 1973; Elíasson, 1977; Waitt, 2002; Kirkbride *et al.*, 2006; Baynes *et al.*, 2015). Through erosion and sediment deposition, the youngest of these have removed much of sediments and erosional landforms of older floods. A sequence of 16 mid-Holocene sand beds with sedimentary structures resembling “backflood beds” is, however, preserved in the Vesturdalur valley (part of Jökulsá canyon) and thought to result from floods with moderate volumes and discharge (Waitt, 2002), possibly below the 100,000 m^3/s peak discharge used to define catastrophic floods. However, there have also been suggestions (Kirkbride *et al.*, 2006) that at least some of those floods were megafloods (over a 1,000,000 m^3/s).

In historical time no floods that fit the category of catastrophic or megafloods have occurred in Jökulsá á Fjöllum. The last eruptions that caused significant volcanogenic jökulhlaups in Jökulsá á Fjöllum occurred in 1717, 1726, and 1729 CE (Thorarinsson, 1950, 1959; Ísaksson, 1985) with estimated peak flow of 15,000 to 20,000 m^3/s.

The origin or source area of some of the largest jökulhlaups in north Iceland has never been verified

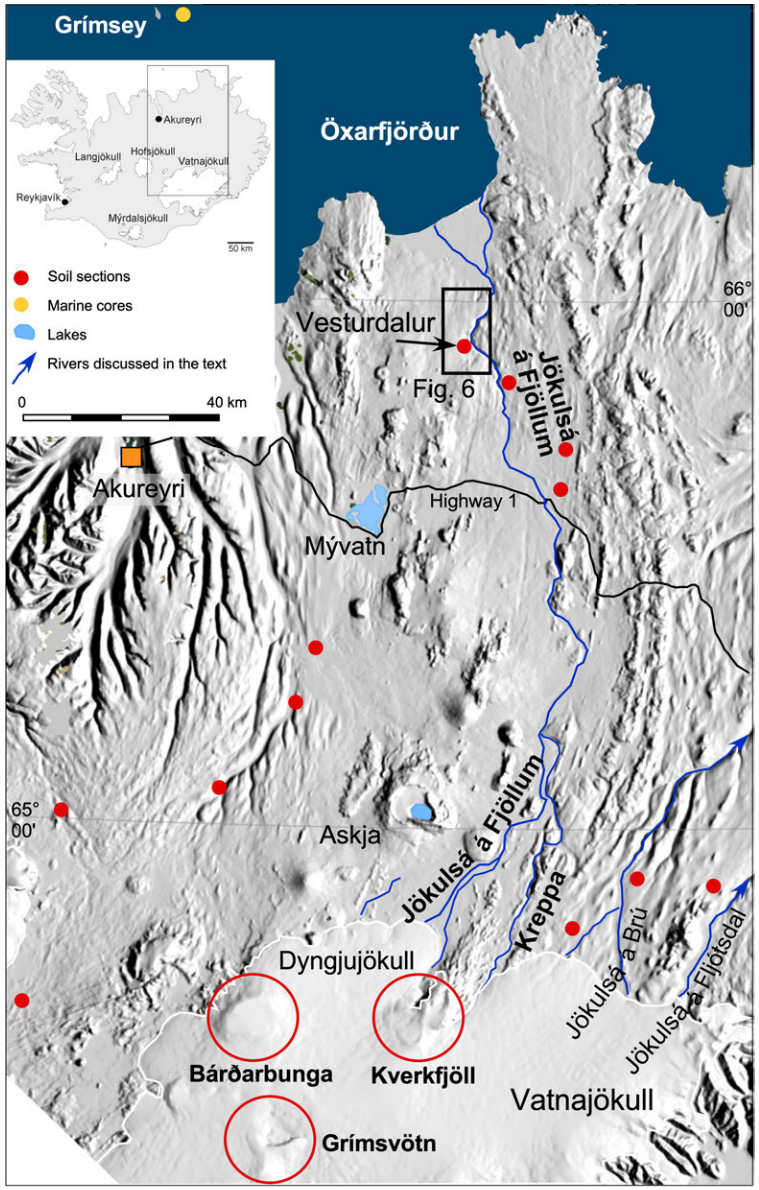


Figure 1. ArcticDEM map of Central and North Iceland showing the location of the Jökulsá á Fjöllum river and the Vatnajökull ice cap (ArcticDEM V4.1, Harvard Dataverse, V1, Porter *et al.*, 2023, http://doi.org/10.7910/DVN/3VDC4W.) The red circles mark the location of the central volcanoes Bárðarbunga, Kverkfjöll and Grímsvötn, with their ice-filled calderas. Vesturdalur area, where sediments from repeated jökulhlaups between 6.3 and 4.1 ka are preserved, is marked by a black quadrangle. – *Mið-Ísland og Norðurland frá Vatnajökli að Öxarfirði (sjá einnig innsetta mynd). Vesturdalssvæðið er afmarkað með svörtum ferhyrningi. Megineldstöðvarnar Bárðarbunga, Kverkfjöll og Grímsvötn, allar með jökulfylltar öskjur, eru afmarkaðar með rauðum hringjum. Jökulsá á Fjöllum og aðrar ár sem nefndar eru í megintexta eru sýndar í bláum lit. Hvít lína er dregin eftir vestur- og norðurjaðri Vatnajökuls. Fyrir 6,3 til 4,1 þúsund árum var Vatnajökull minni og efsti hluti þáverandi vatnasviðs ánna er nú undir jökli. Rauðir deplar sýna legu jarðvegssniða og svört lína þjóðveg 1.*

although the source has variously been suggested to be Bárðarbunga, Kverkfjöll, or Grímsvötn calderas, or large subglacial reservoirs (Sæmundsson, 1973; Tómasson, 1973, 2002; Björnsson and Einarsson, 1990; Elíasson, 1977; Waitt, 2002; Ahlo *et al.*, 2005; Carrivick *et al.*, 2004).

Here we attempt to correlate the frequent mid-Holocene (6.3 to 4.1 ka) jökulhlaups in Jökulsá á Fjöllum to a prominent Bárðarbunga tephra sequence (Óladóttir *et al.*, 2011a) by the chemical composition of volcanic glass in flood sediments and glass in airborne tephra. We also attempt to use the magma composition, the environmental conditions at that time, and the jökulhlaup characteristics to constrain the location of the eruption sites and how interaction between volcanic and geothermal activity within ice-filled calderas may help explain repeated large jökulhlaups.

ENVIRONMENTAL CONDITIONS AND EXPLOSIVE VOLCANISM IN THE CENTRAL HIGHLANDS

Glaciers and climate.

The Holocene Climate Optimum (HCO), or thermal maximum, in Iceland and on the North Iceland shelf appears to have been between 8 and 7 ka (e.g. Ran *et al.*, 2008; Larsen *et al.*, 2012; Striberger *et al.*, 2012; Karlsdóttir *et al.*, 2014; Eddudóttir *et al.*, 2015; Jiang *et al.*, 2015). This conforms to the NGRIP δ^{18}O curve that indicates the highest temperature around 8 ka whereas GRIP δ^{18}O curve indicates highest temperatures around 9 ka (Vinther *et al.*, 2006).

After the HCO a general cooling trend began with superimposed shorter cooling events (e.g. Vinther *et al.*, 2006; Ran *et al.*, 2008; Larsen *et al.*, 2012; Jiang *et al.*, 2015). Cooling events between 8.2 to 8.0, 6.7 to 6.1, 4.3 to 4.1, and 3.0 to 2.7 ka are recorded on the North Icelandic shelf (Ran *et al.*, 2008). In central Iceland two cooling events between 8.7 and 7.9 ka are recorded in the sedimentary record of lake Hvítárvatn and a significant cooling was also detected at about 6.4 ka (Larsen *et al.*, 2012). Glacial water reappeared in lake Lögurinn around 4.4 ka (Striberger *et al.*, 2012).

Glaciers in Iceland are thought to have reached their minimum extent already before the climate optimum (e.g. Norðdahl and Pétursson, 2005; Larsen *et al.*, 2012). Vatnajökull may have disappeared although the highest mountains may have been ice-capped, such as Bárðarbunga, Kverkfjöll and Grímsfjall (Björnsson, 2009). But Kirkbride *et al.* (2006) argued that a "large composite ice cap" must have existed in the Vatnajökull area through the early and mid-Holocene to generate the jökulhlaups in Jökulsá á Fjöllum. Whether the ice in the volcanic areas below present day Vatnajökull existed as separate mountain ice caps at 6.3 ka or had begun to coalesce into proto-Vatnajökull is not known.

The calderas of Bárðarbunga, Kverkfjöll, and Grímsvötn volcanoes may have been somewhat different from the current ones, the recent changes in the Bárðarbunga caldera in 2014–15 CE being a recent example (Gudmundsson *et al.*, 2016) but unless some major changes have occurred they all had capacity to hold caldera lakes. At present the Bárðarbunga caldera holds about 43 km^3 of ice up to 800 m thick (Björnsson *et al.*, 1992, Björnsson, 2009). The melting of about 10% of this ice would generate a total water volume of 4 km^3, potentially resulting in an event similar to the large Katla 1918 jökulhlaup (Tómasson, 1996). The melting of 20% of the ice in the caldera could generate a considerably larger event.

Around 6.3 ka, the rivers originating in the area now below Vatnajökull had none or a very minor glacial component. Glaciers continued growing and the first signs of glacial water in Jökulá á Fljótsdal (Figure 1) appeared about 4.4 ka (Striberger *et al.*, 2012). Jökulsá á Brú was a quiet run-off and spring-fed river flowing along a richly vegetated valley floor until about 2.6 ka when thick gravel deposits were deposited onto vegetation and soil that had formed since about 8 ka (Larsen and Óladóttir, 2015). For Jökulsá á Fjöllum no such information exists, because large late-Holocene jökulhlaups have modified the "riverbed" and removed the evidence – with the exception of the Vesturdalur sediments.

The central highlands are thought to have been largely vegetated at this time (Arnalds, 1992; Ólafsdóttir *et al.*, 2001). Remnants of old soil (histosol, andosol), with tephra layers of known age are found throughout the now desertified lava fields north of Vatnajökull. Extensive and unvegetated glacial sandur areas are unlikely to have existed when glaciers were at minimum.

Explosive volcanism and tephra layers

Numerous tephra layers have been identified in soil sections and lacustrine sediments around the present day Vatnajökull, in north, northeast, east, southeast, and central Iceland, and in marine sediments on the North Iceland shelf (Thorarinsson, 1950; Larsen and Thorarinsson, 1977; Sæmundsson, 1991; Eiríksson *et al.*, 2000; Larsen *et al.*, 2002; Sigvaldason, 2002; Kristjánsdóttir *et al.*, 2007; Óladóttir *et al.*, 2011a,b; Gudmundsdóttir *et al.*, 2012, 2016; Sigurgeirsson, 2016). The volcanic systems producing these layers have been identified by tephra dispersal and chemical characteristics (Jakobsson, 1979; Larsen, 1981; Sigvaldason, 2002; Óladóttir *et al.*, 2011a,b; Gudmundsdóttir *et al.*, 2012, 2016; Sigurgeirsson, 2016). Figure 2 shows a part of a key section for northeast Iceland at Kárahnjúkar and the relevant volcanic systems (Óladóttir *et al.*, 2011a; Larsen and Óladóttir, 2015).

Most tephra layers in the soil of north, northeast, and east Iceland are basaltic phreatomagmatic tephra layers from Bárðarbunga, Grímsvötn, and Kverkfjöll volcanic systems (Óladóttir *et al.*, 2011a), and many extend onto the North Iceland Shelf at least as far as Grímsey island (Gudmundsdóttir *et al.*, 2012) (Figure 1). They are distinguished by their chemical characteristics, in particular TiO_2, FeO, MgO, and K_2O (Jakobsson, 1979; Larsen, 1981; Óladóttir *et al.*, 2011b). Some volcanic systems on the Reykjanes Peninsula have chemical characteristics similar to Bárðarbunga (e.g. Jakobsson *et al.*, 1978; Sigurgeirsson, 1992).

Tephra layers with Bárðarbunga, Grímsvötn and Kverkfjöll characteristics have been traced back to $\sim$11 ka in soil-sections in north Iceland, to >10.4 ka in lacustrine sediments and >14 ka in marine sediments on the North Iceland shelf (Gudmundsdóttir *et al.*, 2012, 2016; and references therein).

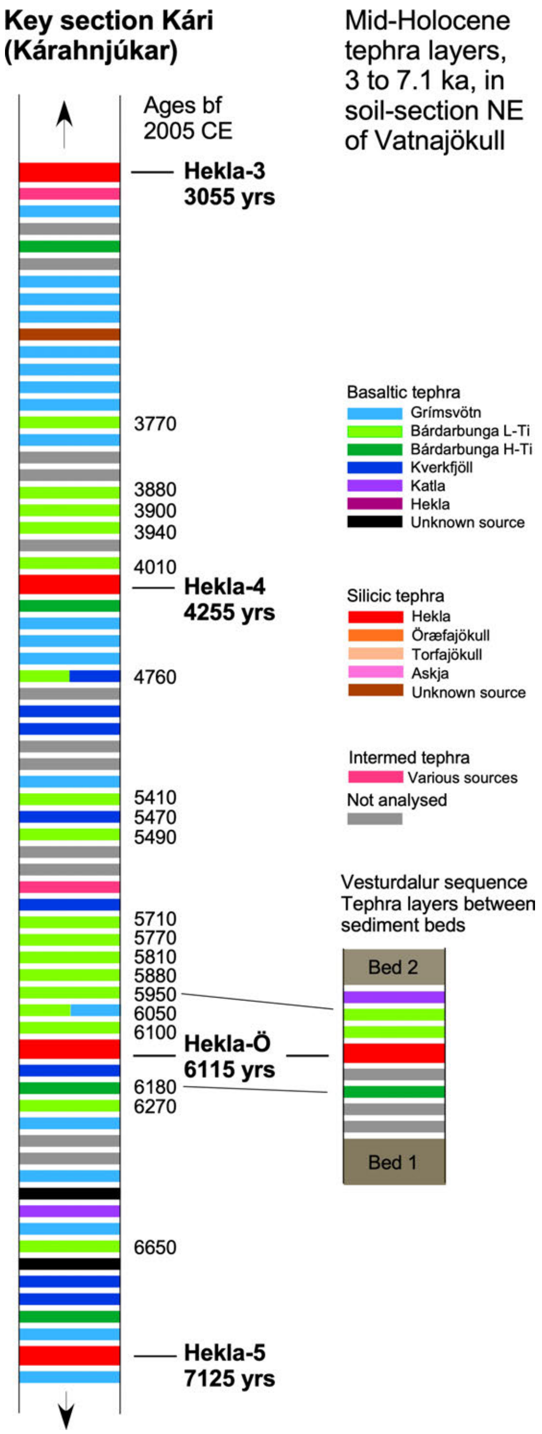
A low in the frequency of tephra layers from the Grímsvötn and Bárðarbunga volcanic systems between 9 and 7 ka in lake Lögurinn may correlate to a minimum in glacier ice extent and availabilty of meltwater to generate explosive activity. There is a 800–900 year gap with no Bárðarbunga tephra layers preserved between 9.2 and 8.4 ka, during which 10 Grímsvötn tephra layers are preserved in the Lögurinn sediments (Gudmundsdóttir *et al.*, 2016). Whether this absence of Bárðarbunga tephra is due to reduced volcanic activity at that volcano is not known. However, if Bárðarbunga was ever ice-free during the Holocene, it may have been in this period. Grímsvötn continued to emit tephra throughout this period. Caldera lakes may have provided water for interaction with the basaltic magma during such minima.

In the vicinity of the Vatnajökull ice cap the soil record extends back to $\sim$7.5 ka. The Bárðarbunga tephra record for the period 3–7.5 ka is treated below. For the Grímsvötn and Kverkfjöll tephra record see Óladóttir *et al.* (2011a,b) and Figure 2.

Bárðarbunga Low-Ti tephra layers

Basaltic tephra layers with Bárðarbunga characteristics are well presented in soils around Vatnajökull, in particular during the last 7.5 ka when robust soil and vegetation cover had been established in the highlands (Óladóttir *et al.*, 2011a,b). Between 7.5 and 3.5 ka basaltic tephra layers with TiO_2<1.6% (Low-Ti) dominated the Bárðarbunga record, whereas tephra layers with TiO_2>1.6% dominate the period 3.5 ka to present (Figure 3), see also Supplement). Two distinct peaks in Low-Ti tephra layer frequency, from 6 to 5.5 ka and 4.5 to 3.5 ka (6.1–5.4 and 4.4–3.7 ka), are prominent in key sections north of Vatnajökull, at Hreysiskvísl, Sauðárhraukar, and Kárahnjúkar (Óladóttir, 2009). Before 6 ka basaltic tephra with higher TiO_2 (High-Ti) was erupted as well.

In the following the focus is on Low-Ti tephra layers in the period 6.3 to 4.1 ka which corresponds to the period of frequent jökulhlaups recorded in Vesturdalur valley (see below). The number of Low-Ti units varies between locations/soil sections. At Kárahnjúkar, 90 km to the northeast of Bárðarbunga, 10 tephra units have been identified in this period, whereas at Hreysikvísl, 50 km to the W of Bárðarbunga, 9 tephra units have been preserved and at least 12 at Sauðárhraukar (Óladóttir *et al.*, 2011a). Cross correlation between locations indicates that some 17 Low-Ti layers could have erupted between 6.3 and 4.1 ka.



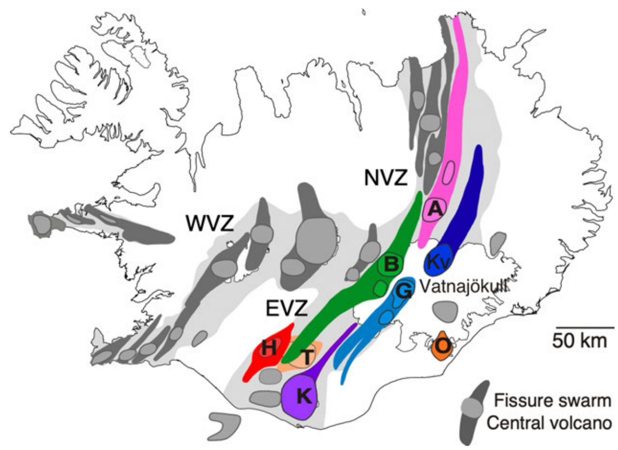


Figure 2. Part of the key-soil section at Kárahnjúkar (red dot at Jökulsá á Brú, Figure 1), showing tephra layers between 3 and 7.1 ka (marker tephras Hekla-3 and -5) modified from Óladóttir *et al.*, 2011a. The site is about 90 km ENE of Bárðarbunga, 95 km ENE of Grímsvötn and 60 km NE of Kverkfjöll. Also shown is part of the Vesturdalur sequence, see Figure 5. Inset shows the volcanic systems of Iceland, relevant systems in colour. – *Hluti lykilsniðs við Kárahnjúka, milli Heklu-3 og -5. Sniðið er 90 og 95 km ANA Bárðarbungu og Grímsvatna og 60 km NA Kverkfjalla. Gjóskulög í sniði í Vesturdal til hægri. Innsetta myndin sýnir helstu eldstöðvakerfi á Íslandi.*

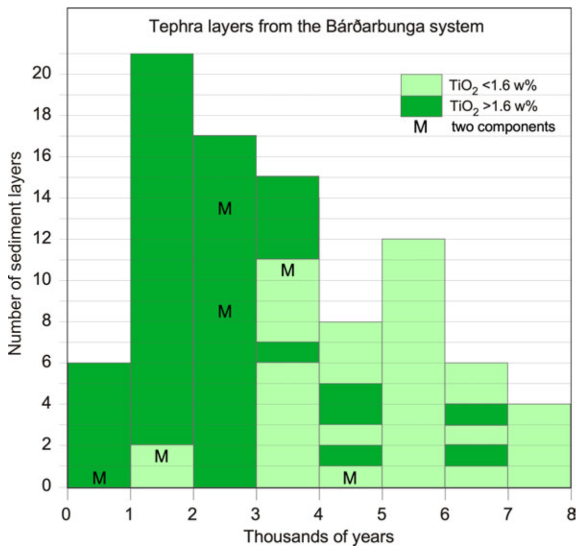


Figure 3. Bar graph (1000 year bins) showing number of recorded tephra layers with Bárðarbunga characteristics based on six soil-sections around Vatnajökull. The true eruption frequency is higher as tephra from smaller eruptions are likely missing at >50 km distance from Bárðarbunga volcano. All six soil-sections cover the period between present and 6.1 ka. Modified from Óladóttir *et al.* (2011a). – *Súlurit sem sýnir fjölda gjóskulaga með Bárðarbungueinkenni í sex jarðvegssniðum umhverfis Vatnajökul (búið að tengja milli sniða). Byggt á grein Bergrúnar Örnu Óladóttur o.fl. (2011a) en breytt til að sýna mun á efnasamsetningu gjóskunnar. Í gjósku með báðum samsetningum réði meirihluti litnum. Gjóska/kvika með Lág-Ti samsetningu var ríkjandi þar til fyrir um 3,5 þúsund árum en eftir það verður Há-Ti gjóska/kvika ríkjandi. Jarðvegssniðin eru í 60–80 km fjarlægð frá miðjum Vatnajökli og ólíklegt er að gjóskulög úr öllum sprengigosum þar hafi fallið eða varðveist í þeim sniðum.*

Mapping of the Low-Ti tephra layers shows that at least 12 layers have origin below the northwest part of Vatnajökull (Figure 4). Their eruption sites and proximal deposits now lie beneath the ice and adjacent sandur areas. The closest adequately preserved soil sections lie 50 to 80 km from Bárðarbunga central volcano, and maximum measured tephra thickness is about 6 cm. Likely the smaller tephra layers are under-represented at this distance. Figure 4 shows four of these layers as well as direction of thickness axis for the 12 layers and localities where Low-Ti tephra has been detected.

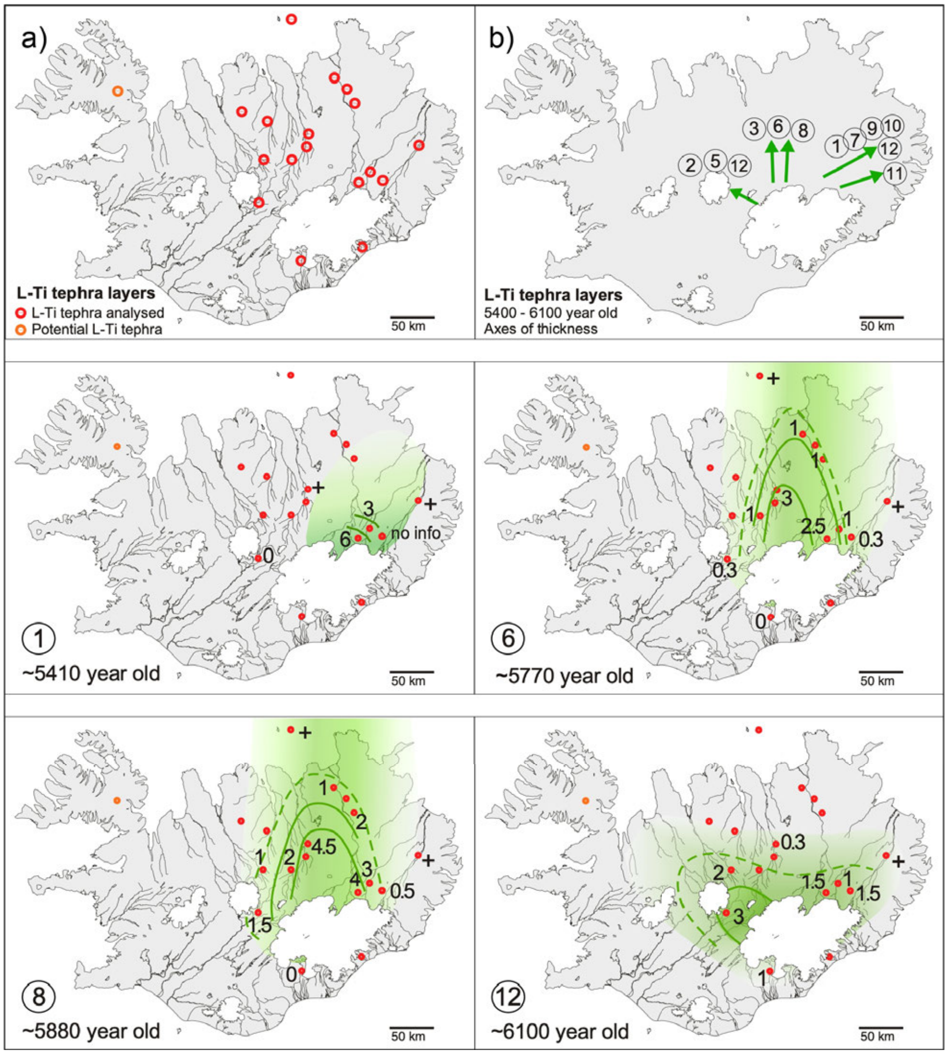
The basaltic Low-Ti tephra layers are widely dispersed, in particular those erupted between 6 and 5.4 ka. Tephra layers of the Low-Ti series have been identified in marine sediments on the North Iceland Shelf (Gudmundsdóttir *et al.*, 2012) some 210 km to the north of Bárðarbunga, and also in lake sediments in east and possibly in northwest Iceland (Gudmundsdóttir *et al.*, 2016; Harning *et al.*, 2018). Harning *et al.*, attribute the Low-Ti layers to the Reykjanes volcanic system (see Discussion). The occurrence of these tephra layers in marine sediments on the North Iceland Shelf (NIS) near Grímsey island, over 200 km from the Bárðarbunga volcanic system, shows that at least some of those layers had substantial volumes.

Volume estimates of the Low-Ti layers are hampered by lack of proximal data. The distal dispersal pattern of the two largest layers (6 and 8 on Figure 4) is similar to that of the Grímsvötn 2011 tephra which had a volume of 0.7±0.1 km^3 and maximum eruption column height of about 20 km (Gudmundsson *et al.*, 2012 and unpubl data; Hreinsdóttir *et al.*, 2014). Preliminary calculations with Tmax set at 300 cm indicate volumes in the order of 1 km^3 for these Low-Ti tephra layers. The wide dispersal supports high eruption columns, comparable to that of Grímsvötn 2011 eruption.

The phreatomagmatic characteristics of the Low-Ti tephra show that the magma was erupted in the presence of ice (meltwater) or water. Hence the most likely localities within the Vatnajökull area were ice-filled or lake-containing calderas and /or ice caps on the highest mountains.

The 6.3–4.1 ka jökulhlaup sequence in Vesturdalur

At least 16 jökulhlaups deposited stacked backflood beds in the Vesturdalur valley (Waitt, 2002). Waitt dated the sequence to 8–4 ka using tephrochronology. This sequence has now been dated to a period between 6.3 and 4.1 ka (Larsen *et al.*, 2023) and has been further extended within the Vesturdalur area (Kirkbride *et al.*, 2006; Larsen *et al.*, 2023). However, the best



exposure is still the Vesturdalur sequence (Figure 5a-c) described by Waitt (2002) and the floods will be referred to as W-jökulhlaups (W for west and Waitt).

Waitt describes 16 beds of brownish grey, strongly rippled medium to fine sand, with symmetrical to strongly asymmetric climbing ripples of variable dips. These beds lie between 180 and 190 (188) m a.s.l. They are inter-layered with yellowish to brownish aeolian silt, occasionally with tephra layers, marking periods of background sedimentation (Waitt, 2002; Kirkbride *et al.*, 2006). Waitt (2002) interprets the sand layers as resulting from a counter-clockwise eddy circulating along the west side of the valley during a succession of valley-filling floods, also pointing out resemblance to the stacks of graded beds deposited in back-flooded tributaries by the giant Lake Missoula jökulhlaups (Waitt, 1980, 1984).

Waitt (2002) considers the floods through Vesturdalur of moderate volume and discharge without defining their magnitudes further. He inferred that the outlet from the valley was "hydraulically retarding" allowing the flood water to partially pond in the valley and pointed out that younger, larger flood could have changed the topography.

Figure 4. a) Locations where the Low-Ti tephra layers have been measured and/or analysed. Red cirlces: Sections or cores with detailed stratigraphy partly or fully EPMA analysed (Wastl, 2000; Larsen *et al.*, 2002; Óladóttir *et al.*, 2011a; Gudmundsdóttir *et al.*, 2012, 2016). Orange circle: Core with potential Low-Ti tephra layers (Harning *et al.*, 2018). b) Thickness axes of 12 Low-Ti tephra layers from the period 6.1–5.4 ka. Axes of thickness and chemical characteristics indicate source area within the presently ice-covered central part of the Bárðarbunga system. c-f) Examples of dispersal (thickness in cm) of Low-Ti tephras with dispersal axes towards east, north and west. Numbers according to 4b, age according to Kárahnjúkar section in Óladóttir *et al.* (2011a). The north-trending layers 6 and 8 of an age of 5770 and 5880 years, respectively, may correlate to a group of Low-Ti layers, 5760–5900 year old in marine core MD99-2275 50 km off the north coast (Gudmundsdóttir *et al.*, 2012) – *a) Staðir þar sem Lág-Ti gjóskulög hafa verið mæld og/eða efnagreind. Rauðir hringir tákna mæld jarðvegssnið eða setkjarna þar sem gjóska úr öllum eða hluta gjóskulaga hefur verið efnagreind í örgreini (M. Wastl, 2000; Guðrún Larsen o.fl., 2002; Bergrún A. Óladóttir o.fl., 2011a; Esther R. Gudmundsdóttir o.fl., 2012, 2016). Rauðgulur hringur táknar setkjarna þar sem Lág-Ti lög er hugsanlega að finna (Harning o.fl., 2018). b) Þykktarásar 12 gjóskulaga frá tímabili fyrir 6,1–5,4 þúsund árum. Þykktarásar og efnasamsetning benda til upptakasvæðis í Bárðarbungukerfinu undir norðvestanverðum Vatnajökli. c-f). Dæmi um dreifingu Lág-Ti gjósku. Númer vísa til örva á mynd 4b, aldur er skv. lykilsniði við Kárahnjúka (2. mynd). Mesta mælda þykkt er 6 cm skammt norðan Vatnajökuls en flest lög eru þunn þegar komið er í 90 km fjarlægð frá Vatnajökli. Gert er ráð fyrir að gjóskulög 6 og 8 tengist 5760–5900 ára gömlum gjóskulögum í setkjarna MD99-2275 vestan Grímseyjar (Esther R. Gudmundsdóttir o.fl. 2012).*

Large jökulhlaups have strongly modified the lower part of the course of Jökulsá á Fjöllum in the late Holocene (Tómasson, 1973, 2002; Sæmundsson, 1973, 1991; Elíasson, 1977; Waitt, 2002; Carrivick *et al.*, 2004; Ahlo *et al.*, 2005; Baynes *et al.*, 2015) after neoglaciation set in and Vatnajökull probably began growing into a major ice cap. It is important to keep in mind that Jökulsá canyon upstream from Vesturdalur was significantly different at the time of the W-Jökulhlaups (Baynes *et al.*, 2015) as was the outlet downstream from Vesturdalur (Larsen *et al.*, 2023).

The W-Jökulhlaups ponded to the same height/-elevation at the Vesturdalur sediment sequence for over 2000 years. An effort was made to reconstruct the pre-4 ka environment in the Vesturdalur area based on previous work (Elíasson, 1977; Waitt, 2002; Kirkbride *et al.*, 2006; Sigurgeirsson, 2016; Hjartardóttir and Einarsson, 2019) and by further mapping of sediments in the Vesturdalur depression to clarify its depositional/erosional history and to allow estimates of jökulhlaup magnitude (Larsen *et al.*, 2023).

At the time of the W-jökulhlaups (6.3–4.1 ka) the Vesturdalur depression (Figure 6a, present conditions) was largely infilled by early Holocene (∼11 ka) lava flow(s) and scoria cones (Figure 6b) partly overlain by alluvium dating back to the retreat of the inland ice (Sigurgeirsson, 2016; Hjartardóttir and Einarsson, 2019; Larsen *et al.*, 2023). The ∼11 ka lava(s) had also followed and partly filled a gorge previously draining the depression (Larsen *et al.*, 2023, supplements). A canyon downstream from the depression with the present dimensions did not exist at that time. A narrow pre-flood canyon was suggested by Waitt (2002). However, the outlet from the depression must have been shallow, a deep channel would have allowed the W-jökulhlaups to gradually erode the scoria and lava out of the Vesturdalur depression and change the conditions for retaining floodwater (Larsen *et al.*, 2023). The dry gorge at Laxavogur (Figure 6a) north of the present canyon, which does not extend into the depression, may have been the outlet at this time (6.3–4.1 ka) when the river Jökulsá á Fjöllum probably had none or a small glacial component, akin to Jökulsá á Fljótsdal (Striberger *et al.*, 2012) and not much erosional power.

By mapping the extent of the W-sediments (Figure 6c) the "hydraulically retarding" part in the valley, about 0.8 km wide, could be defined and reconstructed (Figure 6d). The most likely cross section, assuming a bottom defined by the lava at 170 m a.s.l. (Figure 6b) is about 15.400 m^2 (Larsen *et al.*, 2023). Such "gate" or "outlet" could convey 43.000 to 93.000 m^3/s, depending on flow rate and surface con-

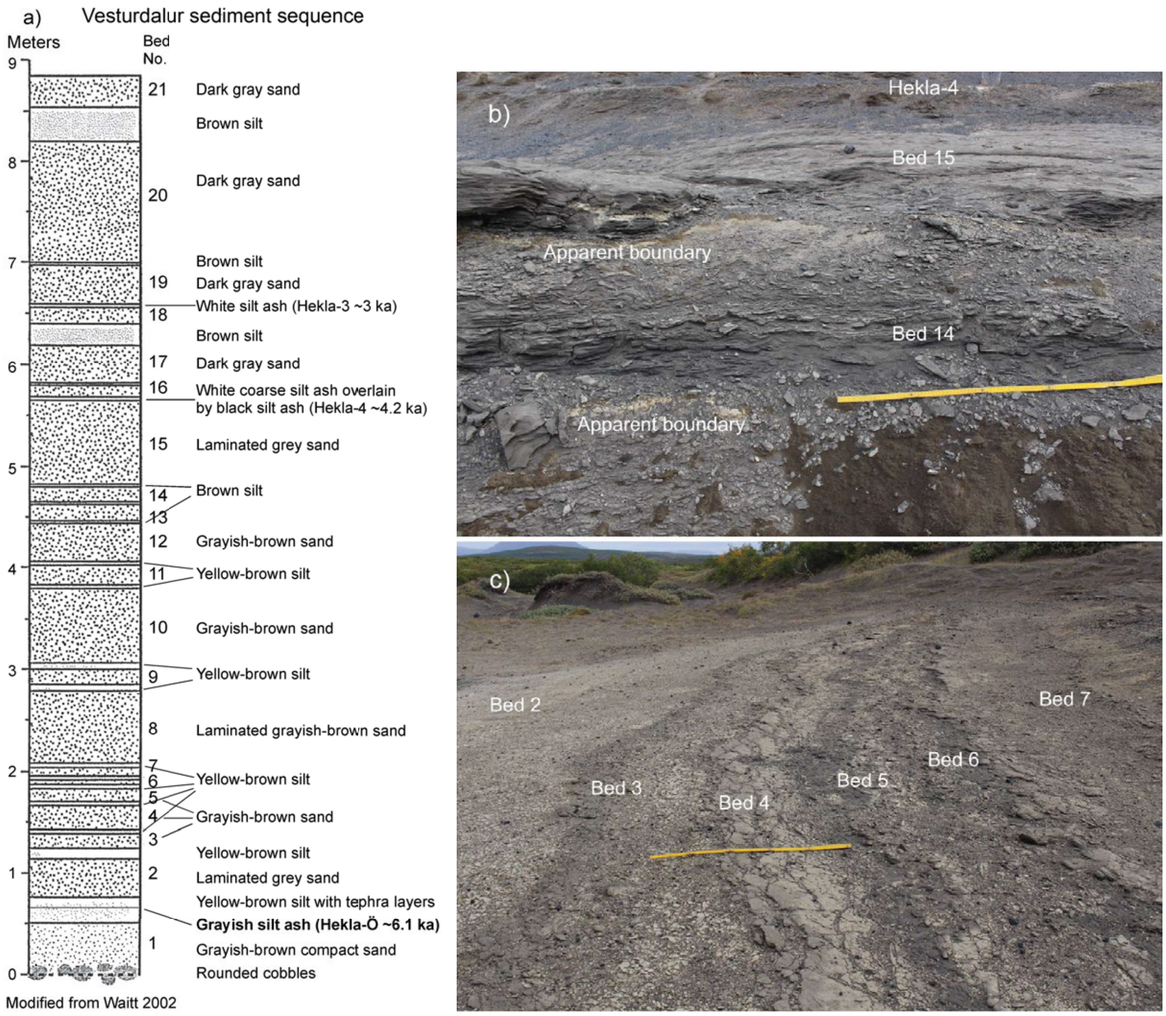


Figure 5. a) The 8–9 m thick Vesturdalur sediment sequence, modified from Waitt (2002). Beds 1–16 are waterlaid greyish brown, ripple-drifted sand. Beds 17–21 are aeolian massive sand. In the silty soil between beds 1 and 2 several tephra layers have been identified and chemically analysed, including the 6.1 ka Hekla-Ö, previously considered to be the ∼7.1 ka Hekla-5, (Waitt, 2002). Top of bed 16 is close to 188 m a.s.l. b) Upper part of the waterlaid sediments, beds 14 and 15, and the white ∼4.3 ka tephra layer Hekla-4 above bed 15. c) Lower part of the sequence, beds 2–7. Scale is 1 m long. – *a) Snið Waitts (2002) af 8–9 m þykkum setlagastafla í Vesturdal að viðbættu gjóskulaginu Heklu-Ö (6100 ára) milli setlaga 1 og 2, sbr. 2. mynd. Í neðstu sex metrunum eru 16 aðgreind setlög með misgreinilegum, siltkenndum „jarðvegi“ á milli laganna (Waitt, 2002). Neðsta setlagið liggur á stórgrýti úr misvel núnum hnullungum. Setlögin eru 10–90 cm þykk, úr glerríkum, brúngráum-grásvörtum sandi, gáróttum, skálöguðum og/eða víxllöguðum (Waitt, 2002; Kirkbride o.fl. 2006). b) Efri hluti setlagasyrpunnar, lög 14 og 15, efst sést í hvítt gjóskulag, Heklu-4. Setið er harðnað en vindsorfið. c) Neðri hluti setlagasyrpunnar, lög 2–7. Mælikvarðinn er einn metri að lengd.*

ditions (average flow rate of Ahlo *et al.*, 2007, 2005). However, if substantial sediment cover existed on top of the lava the cross-section could have been somewhat smaller. The values above should therefore be regarded as maximum estimates. See Discussion.

The W-jökulhlaups apparently did not erode or widen the outlet at Vesturdalur, ponding to largely the same elevation in the depression for more than 2000 years. This indicates limited erosional power and suggests that the above discharge estimates are on the high side for the W-jökulhlaups.

The youngest sediment layer in that sequence (bed 16) may just be the last preserved sediment layer. If that particular jökulhlaup significantly eroded the restricting channel the following jökulhlaups did not pond or reach the same level as before, leaving no evidence at Vesturdalur.

CHEMICAL CHARACTERISTICS OF THE VESTURDALUR SEDIMENTS – CORRELATION TO BÁRÐARBUNGA LOW-TI TEPHRA

Methods

We sampled the Vesturdalur sequence (Figure 5) in order to check if the glass-rich sediments held some information about the origin of the floods that deposited them. The east part of the exposure had accumulated a cover of remobilized sediments and our sampled section lies in its west part. It may therefore lie some tens of m away from the sequence described by Waitt (2002) and we cannot be certain that our sampling reflects his stratigraphy in detail in the middle part of the section.

About 50 cm thick soil with tephra layers (Figure 2, Vesturdalur section) separates the lowermost two beds (1 and 2) in the sequence. One of the tephra layer is the 6.1 ka Hekla-Ö (Gudmundsdóttir *et al.*, 2011), previously thought to be the 7.1 ka Hekla-5 tephra by some authors (e.g. Elíasson, 1977; Waitt, 2002). The 4.3 ka Hekla-4 tephra layer (Dugmore *et al.*, 1995) separates the two uppermost beds in the Vesturdalur sequence (beds 15 and 16).

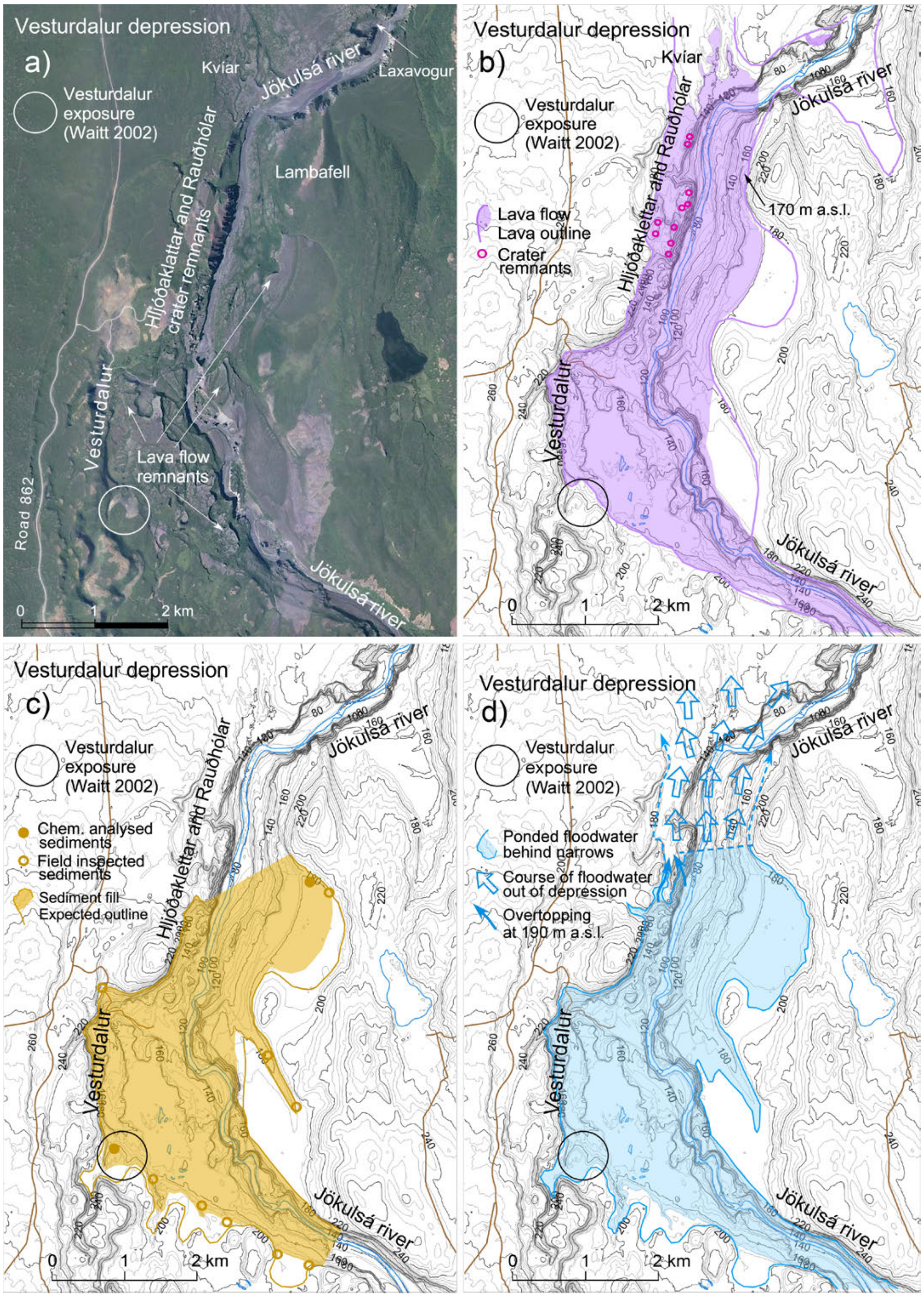
Each bed was sampled with the exception of the lowest one (1) which is almost completely indurated. Most samples were collected near the base where sedimentary structures were distinct. In some beds both fine and coarse lenses of sand were collected to check if grain size mattered. In one instance sample from the upper part of the deposit was collected as well to see if the composition had changed with time.

The samples were hand sieved and grains close to the modal grain size selected and mounted in epoxy for electron probe micro-analysis (EPMA), most often 63 or 125 micron grains. For one sample larger grain size, 250 micron, was mounted to see if that affected the composition. 20 grain were analyzed from each sample in this study. The glass grains were analyzed for major-element chemistry on a JEOL JSL-8200 super-probe at the University of Copenhagen (accelerating voltage of 15kV and beam current was 10 nA, slightly defocused beam of 7 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. See also Gudmundsdóttir *et al.* (2011).

The tephra sampled in soil sections around Vatnajökull (Óladóttir *et al.*, 2011a,b) was analyzed on a third instrument, WDS Cameca SX100 electron microprobe at the Laboratoire Magmas et Volcans, Clermont-Ferrand (acceleration voltage of 15 kV, beam current of 8 nA and beam diameter of 20–10 μm). Counting time varied from 10 to 40 s depending on the element analyzed. Glass standards were regularly analyzed. Results from different instruments may show a slight shift towards higher/lower values for some elements but these are much too small to affect interpretation/comparation of the analytical results.

Chemical characteristics of the Vesturdalur sediments

The "medium to fine sand" in the Vesturdalur sequence consists mostly of volcanic glass of basaltic composition. The glass grains are bounded by fracture planes, partly equant massive grains with thick walls between gas bubbles and partly more vesiculated grains with irregular surface, both indicative of rapid quenching. Crystals, mostly plagioclase, are


Vesturdalur depression
a)
Vesturdalur exposure (Waitt 2002)
Kvíar
Jökulsá river
Laxavogur
Hljóðaklettar and Rauðhólar crater remnants
Lambafell
Vesturdalur
Lava flow remnants
Road 862
0
1
2 km
Vesturdalur depression
b)
Kvíar
Vesturdalur exposure (Waitt 2002)
Hljóðaklettar and Rauðhólar
Jökulsá river
170 m a.s.l.
Lava flow
Lava outline
Crater remnants
Vesturdalur
Jökulsá river
0
1
2 km
Vesturdalur depression
c)
Vesturdalur exposure (Waitt 2002)
Hljóðaklettar and Rauðhólar
Jökulsá river
Chem. analysed sediments
Field inspected sediments
Sediment fill
Expected outline
Vesturdalur
Jökulsá river
0
1
2 km
Vesturdalur depression
d)
Vesturdalur exposure (Waitt 2002)
Jökulsá river
Ponded floodwater behind narrows
Course of floodwater out of depression
Overtopping at 190 m a.s.l.
Vesturdalur
Jökulsá river
0
1
2 km

present as well as whitish, sub-rounded, opaque grains (geothermal?) and occasional sub-rounded-rounded lithic grains.

The glass grains have the chemical characteristics of the Bárðarbunga, Grímvötn, and Kverkfjöll volcanic systems (Figure 7a-b, Figure 8, see also Table S-1 in Supplements). Basalt from Bárðarbunga dominates in 12 out of 15 Vesturdalur beds, basalt from Kverkfjöll and Grímsvötn systems dominate in one bed each, and one has similar amount of glass from the three systems. The Bárðarbunga glass exhibits the known range of glass compositions, including the most primitive glass sometimes correlated to the Gígöldur crater complex (Óladóttir *et al.*, 2011b). The Low-Ti glass composition is present in all 15 analysed Vesturdalur sediment beds and is the dominant component in 11 of them (Figure 7a).

Bed 8 was sampled near the base and in the upper part of the sediment. All samples from the base contain some grains with Kverkfjöll and/or Grímsvötn characteristics whereas the sample from the top contains only Bárðarbunga glass, mostly the Low-Ti component (See Figure 7b and Table S-1 in Supplements). Having obtained these results we speculate that perhaps the most representative results of the true source of the glass come from samples in the middle to upper part of each flood-bed of Vesturdalur sediment. When these "late" sediments are in transit the flood route has been cleared of the non-juvenile material which was, however, entrained into the early transported/deposited sediments.

The presence of Kverkfjöll and Grímsvötn glass as subpopulations is easily explained. Glass from eruptions in these systems was also present in the environment, possibly both as fall tephra or water-transported material. Some glass was inevitably incorporated into the jökulhlaup sediment during transport, in particular when the first part of the jökulhlaup swept through the flood channels. If we assume that these sediments were transported by meltwater floods from a source area near Bárðarbunga, Kverkfjöll, or Grímsvötn, the flood had to travel at

Figure 6. The Vesturdalur depression, extensively eroded by jökulhlaups younger than the 6.3–4.1 ka jökulhlaup sequence. a) Areal photo showing the present conditions (From Map.is – Loftmyndir ehf). The bed of the Jökulsá river is the most prominent feature, crossing the area from south to north. Circle: Exposure measured by Waitt (2002) and in the present study (Fig. 5a-c). b) Contour map (interval 5 m), showing the $\sim$11 ka lava flow that entered the depression from south (lower right corner) with possible eastern margin now covered by sediment, indicated by crimson outline. Arrow: Remnant of lava at 170 m a.s.l., defining original surface of lava flow. This lava also extended northwards into the Kvíar channel and towards east along the edge of an older lava flow. c) Extent of the 6.3–4.1 ka sediments within the Vesturdalur depression. Possible extension below younger sediments is indicated by yellow outline. d) Approximate area inundated by the 6.3–4.1 ka jökulhlaups, defined by the extent of sediments and assuming maximum water level of about 190 m a.s.l. Small blue arrows indicate localities of overtopping at approximately that elevation. Broken line indicates the narrowest (0.8 km) and "hydraulically restricting" part of the jökulhlaup path, causing floodwater ponding in Vesturdalur valley. – *a) Loftmynd sem sýnir núverandi aðstæður í Vesturdals-Hljóðaklettadæld (Map.is– Loftmyndir ehf). Farvegur Jökulsár er greinilegur eftir endilöngu svæðinu frá suðri til norðurs. Hringur: Lega sniðsins á 5. mynd. Örvar benda á leifar hraunsins í dældinni sem er mikið rofið af yngri jökulhlaupum. b) Kort með 5 m hæðarlínum af sama svæði. Upphafleg útbreiðsla hrauns í dældinni er sýnd sem rauðbleik þekja og sem útlínur þar sem það er þakið þykkum setlögum. Hraunið fylgdi farvegi Jökulsár niður í dældina, teygði sig inn í Kvíafarveg og til austurs meðfram eldra hrauni. Svört ör bendir á hraunstall í 170 m y.s sem markar upphaflegt hraunyfirborð í dældinni. c) Gul þekja sýnir útbreiðslu 6,3–4,1 þúsund ára gamalla setlaga samkvæmt kortlagninu og efnagreiningum (opnir hringir og punktar) og gul útlína sýnir líklega útbreiðslu undir yngra seti. d) Vatnssöfnun í Vesturdals-Hljóðaklettadæld í hlaupum fyrir 6,3–4,1 þúsund árum. Vatnsborð er sýnt í 190 m y.s. (án rennslishalla) og tekur mið af yfirrennsli gegnum gíga í Hljóðaklettum í þeirri hæð (litlar bláar örvar). Brotin lína sýnir hvar líkleg þrengsli voru milli Lambafells og gígleifanna í Hljóðaklettum (0,8 km nú en gígarnir voru þá e.t.v. minna rofnir) og stórar örvar sýna hlaupleiðina út úr dældinni. Þrengslin ollu vatnssöfnun í dældinni en hún virðist hafa náð svipaðri hæð yfir tvö þúsund ára tímabil sem bendir hvorki til mikils rofs né að hlaupin hafi verið hamfarahlaup.*

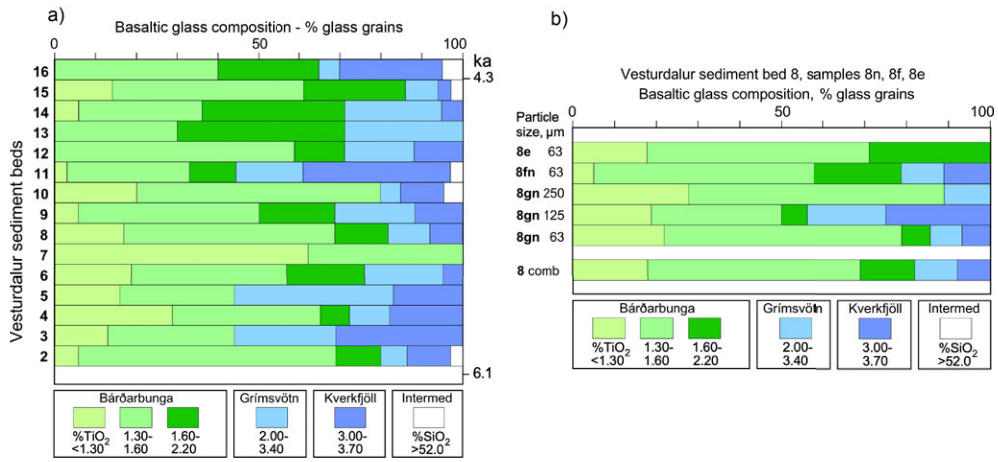


Figure 7. Proportions of glass grains from the Bárðarbunga, Grímsvötn and Kverkfjöll volcanic systems in the Vesturdalur sediment beds. 20-40 grains from each bed were analysed except 100 grains from bed 8. Preferred grain size was 63 μm. a) Beds 2–16: Bárðarbunga composition dominates in 12 out of the 15 beds analysed. Grímsvötn and Kverkfjöll compositions are the largest components in beds 5 and 11, respectively while no component dominates in bed 3. The time interval is defined by Hekla-4 (4.3 ka) and Hekla-Ö (6.1 ka) The average interval between sediments beds 2 and 15 is about 150 years but the length of intervals varied. b) Origin of glass grains in bed 8 in Vesturdalur. Three samples were collected, two from the lower part (8fn and 8gn) and one from the upper part (8e). The samples from the lower part have minor components of Grímsvötn and Kverkfjöll glass. Three different grain sizes were analysed from the coarsest sample (8ng) but no systematic trend was observed. The uppermost sample (8e) consists of solely of Bárðarbunga glass. The most likely explanation is that the first part of the jökulhlaup incorporated older material along its route and therefore the sediment in the late part better represents the primary/juvenile material erupted. – *a) Hlutföll glergerða (%) í sýnum úr setlögum 2–16 í Vesturdal. Einnig er sýnt hvar gjóskulögin Hekla-4 (4,3 þús. ára) og Hekla-Ö, (6,1 þús. ára) eru í staflanum. 20–40 glerkorn, yfirleitt í 0,063 mm stærð, voru efnagreind úr hverju lagi nema 100 korn úr lagi 8. Bárðarbungusamsetning er ríkjandi í 12 af 15 setlögum. Grímsvatna samsetning er ríkjandi í lagi 5 og Kverkfjalla samsetning í lagi 11. Hlutföll í lagi 3 benda einna helst til Bárðarbungukerfis. Að meðaltali voru um 150 ár milli hlaupanna sem settu af sér setlögin en hléin voru vafalaust mislöng. b.) Hlutfall glergerða í þrem sýnum úr setlagi 8. Sýni 8e er ofarlega úr laginu, 8fn er fínt lag neðarlega, ofan á 8gn sem er úr grófri linsu neðarlega. Einnig voru mismunandi kornastærðir efnagreindar í sýni 8gn. Athygli vekur að í efsta sýninu, í setinu sem síðast lagði af stað frá eldstöðinni, er einungis gler frá Bárðarbungukerfi – þá var hlaupið búið að hreinsa farveginn af öðru efni. Viðauki með efnagreiningum er fáanlegur hjá höfundum.*

least 190 km down to Vesturdalur and inevitably incorporated some non-juvenile material along the way. Dominant Kverkfjöll and Grímsvötn glass in two of the beds may, however, indicate input of meltwater from eruptions in these volcanoes.

If we assume that the glass-rich sediments are the product of eruptions in contact with ice or water, their source area is without doubt where either ice or caldera lakes existed at the time – or both. Proto-Vatnajökull is the only candidate for such ice contact.

As pointed out above, the Low-Ti tephra layers are prominent in soil sections in the same period as the deposition of the Vesturdalur sediments, 6.3–4.1 ka (Óladóttir *et al.*, 2011a). This is demonstrated in Figure 9 where both sediment beds and tephra layers are grouped into 500-year bins. The average interval between the sediment beds is ∼150 years but different thickness of the aeolian interbeds implies intervals of varying length. The thicker silt layers between beds 9, 10, 11 are taken to indicate longer intervals between jökulhlaups that may relate to a period of low

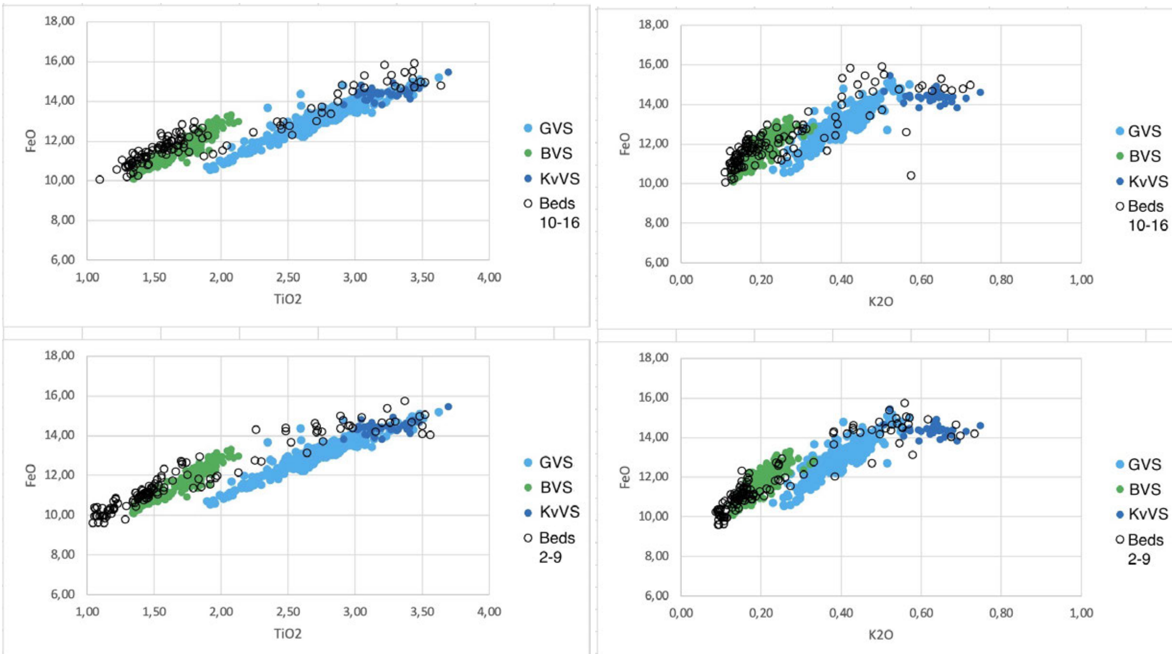


Figure 8. Biplots of TiO_2-FeO and K_2O-FeO showing how EPMA analyses of volcanic glass from the Vesturdalur sediments correlate to EPMA results of tephra layers from volcanoes below Vatnajökull ice cap (Óladóttir *et al.*, 2011b). GVS: Grímsvötn volcanic system; BVS: Bárðarbunga volcanic system; KvVS: Kverkfjöll volcanic systems. Black circles indicate glass from Vesturdalur sediment beds 2–16. Left panels: The Low-Ti glass grains form distinct clusters within the BVS field, note that those with the lowest TiO_2 are better represented in the older sediment beds 2–9 than in the younger sediment beds 10–16. Grains with "Grímsvötn" affinities are more scattered and lie above GVS field in the older sediments. Grains attributed to Kverkfjöll lie above the KvVS in the younger sediments. Right panels: The Low-Ti glass grains in all sediment beds form distinct clusters within the BVS field but with a slight overlap to the GVS field in the younger sediments. Grains with "Grímsvötn" affinities are more scattered as are those attributed to Kverkfjöll. The sediment glass was analysed on two instruments, in Reykjavík and Copenhagen. Glass from the tephra layers was analysed on a third instrument in Clermont-Ferrand. This may explain some of the scatter and shifts seen in the biplots. However, the biplots strongly support that the provenance of the dominant volcanic glass in the Vesturdalur sediments was Bárðarbunga volcanic system. – *Efnagreiningar á gleri (í örgreini) úr gjóskulögum frá eldstöðvakerfum undir Vatnajökli. BVS: Bárðarbunga, GVS: Grímsvötn , KvVS: Kverkfjöll (Bergrún A. Óladóttir o.fl. 2011b). Svartir hringir sýna gler úr setlögum í Vesturdal efnagreint á sama hátt (þó ekki í sömu örgreinum). Til vinstri er TiO_2 lagt út á móti FeO, eldri setlögin 2–9 á neðra grafi og yngri setlögin 10–16 á því efra. Lág-títan glerið myndar þyrpingar innan Bárðarbungusviðsins, í eldri setlögunum myndar glerið með lægsta TiO_2 sér þyrpingu. Gler með Grímsvatnaeinkenni hefur dreifðari samsetningu, myndar ekki greinilegar þyrpingar og í eldri setlögunum liggur það ofan Grímsvatnasviðsins. Gler með Kverkfjallaeinkenni er einnig dreift og myndar ekki þyrpingar. Til hægri er K_2O lagt út á móti FeO, eldri setlögin 2–9 á neðra grafi og yngri setlögin 10–16 á því efra. Á þessum gröfum sést einnig að lág-títanglerið myndar þyrpingu innan Bárðarbungusviðsins en gler með Grímsvatna- og Kverkfjallaeinkenni er dreift og fellur að hluta utan þessara sviða. Misræmi í efnasamsetningum má e.t.v. að hluta skýra með greiningum á þrem mismunandi tækjum. Hins vegar sýna gröfin greinilega að meirihluti glersins í setlögunum í Vesturdal er ættaður frá Bárðarbungukerfi og væntanlega í gosum undir jökli.*

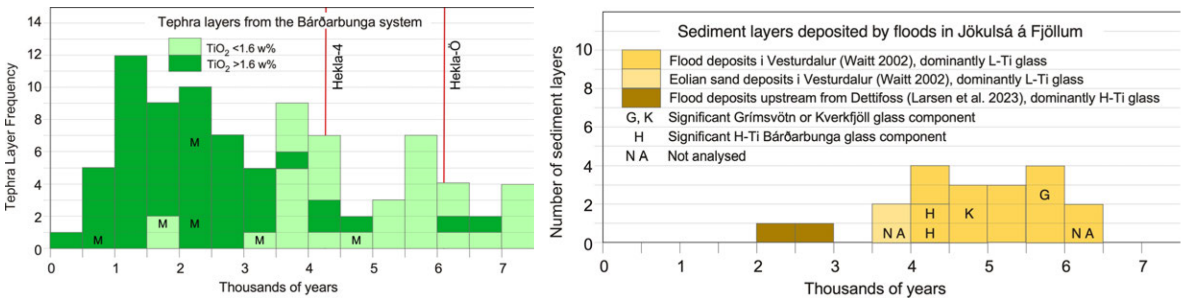


Figure 9. Left: All recorded tephra layers with Bárðarbunga characteristics, plotted in 500 year bins, based on 6 soil-sections around Vatnajökull (modified from Óladóttir *et al.*, 2011a). The Low-Ti composition prevailed between 7.5 and 3.5 ka with a few exceptions whereas from 3.5 ka to present the High-Ti composition prevails. Two peaks appear in the Low-Ti tephra, with a lull between 5 and 4.5 ka. This lull is present in all six soil-sections and may indicate fewer or smaller eruptions. Right: The Vesturdalur sediment beds deposited by jökulhlaups in Jökulsá á Fjöllum, in 500 year bins. The oldest bed in Vesturdalur predates 6.1 ka and the youngest postdates 4.3 ka. On the graph it is assumed that the thicker "soil" below sediments layers 3, 9, 10, 11 and 16 indicates intervals two to three times longer than between the other floods. Bed 11 (K) has tentative age of 4.7 ka that fits well with Kverkfjöll tephra in the Kárahnjúkar key section, see Figure 2. At least two younger deposits interpreted as eolian sand by Waitt (2002) exist at Vesturdalur. Also shown on the graph are two major deposits from younger floods in Jökulsá, preserved a few km upstream from Dettifoss. The dominant composition of the glass fraction in these deposits is that of Bárðarbunga, but now with significantly larger High-Ti component. *–T.v. Gjóskulög með Bárðarbungueinkenni í sex jarðvegssniðum umhverfis Vatnajökul (búið að tengja milli sniða) skipt í 500 ára tímabil. Byggt á Bergrúnu Örnu Óladóttur o.fl. (2011a) en breytt til að sýna mun á efnasamsetningu gjóskunnar. Gjóska með Lág-Ti samsetningu var ríkjandi milli 7,5 og 3,5 þúsund ára með nokkrum undartekningum en eftir það er Há-Ti gjóska ríkjandi. Tveir toppar í fjölda Lág-Ti gjóskulaga/gosa eru milli 4 og 3,5 þúsund ára og milli 6 og 5,5 þúsund ára. Lægð er milli 4,5 og 5 þúsund ára, annað hvort vegna færri eða minni gosa. T.h. Tilraun til að skipta setlögum/jökulhlaupum á 500 ára tímabil, miðað við að setlög 9, 10 og 11 væru frá tímabili lágrar gostíðni og lengri hléa, sbr. mynd 7b. Setlög þar sem Lág-Ti gler er ráðandi eða stór þáttur eru augljóslega frá sömu tímabilum og Lág-Ti gjóskulögin. Setlag 11 (K), þar sem Kverkfjallagler er stór þáttur, gæti tengst 4,7 þúsund ára gömlum gjóskulögum með Kverkfjallaeinkenni í Kárahnjúkasniði (Bergrún A. Óladóttir o.fl. 2011a). Setlögin hættu að hlaðast upp í Vesturdal fyrir 4,1 þúsund árum en jökulhlaupin gætu hafa haldið áfram án þess að skilja eftir setlög í Vesturdalssniðinu ef aðstæður voru breyttar. Foklögin ofan á setlögunum gætu bent til slíkra atburða. Tvö yngri setlög, þar sem H-Ti gler er áberandi þáttur í setinu eru einnig sýnd.*

tephra layer frequency between 5 and 4.5 ka (Figure 9). In the sediment sequence, this "low" between 5 and 4.5 ka is not as distinct, partly because of a sediment bed attributed to Kverkfjöll (K in Figure 9).

It seems not a coincidence that sediments deposited by floods, most likely volcanogenic jökulhlaups, in this period are dominated by the Low-Ti glass composition (Figure 9). The volcanic source of the fall tephra (Óladóttir *et al.*, 2011a) and at least 12 of the jökulhlaup sediments must be the same. The only area where presence of ice and possibly a caldera lake could provide conditions for hydromagmatic explosive eruptions of Low-Ti tephra accompanied by jökulhlaups is the Bárðarbunga volcano and its immediate vicinity.

The Vesturdalur flood routes 6.3–4.1 ka

The upper flood routes of the W-jökulhlaups are partly hidden below the present Vatnajökull ice, and the subaerial parts have been extensively modified by the late Holocene floods. It is likely that the W-jökulhlaups followed larger, older channels and gullies that previously drained glacial water and early volcanogenic floods from the retreating ice sheet. During the Holocene climate optimum these channels are expected to have been occupied by rivers of more stable flow with only a minor glacial component or none. It is also likely that some ponding occurred in the W-jökulhlaups in the same areas as did the late Holocene floods, in particular in the Möðrudalur area (e.g. Ahlo *et al.*, 2005, 2007). There is evidence that at least some of the W-jökulhlaups ponded in depressions some 15–18 km upstream from Vesturdalur (Larsen *et al.*, 2023) but the exposures are poorer than those in Vesturdalur. The oldest sediments deposited there are about 7 ka old.

The flood routes from Vesturdalur to the north coast of Iceland at Öxarfjörður may either have followed a route to the east into the Laxavogur gorge and along the edge of the obstructing lava flows or to the north across the lavas into the now dry Ásbyrgi canyon. There are indications that at least some of the 6.3–4.1 ka jökulhlaups flowed along the north channel towards Ásbyrgi canyon and left glass-rich sediments in the channel. These sediments have now been eroded by younger floods of larger magnitude but evidence is found in the soil alongside the channel as thick layers of wind- or water-carried glassy material deposited shortly before the 4.3 ka Hekla-4 tephra (Elíasson, 1977; Larsen *et al.*, 2023). A sample collected from glass-rich sediments just below the Hekla-4 tephra was analysed and has the same Low-Ti characteristics as the Vesturdaldur sediments. This confirms that the flood that deposited bed 15 in Vesturdalur flowed into and most likely through that channel into the now dry Ásbyrgi canyon.

DISCUSSION

The source of water and ice cover at 6.3 ka

The source of water in the 6.3–4.1 ka floods in Jökulsá á Fjöllum must either have been meltwater from ice or lake water. Megafloods in some parts of the world, such as the Missoula floods in North America (Bretz *et al.*, 1956; Bretz, 1959) occurred when large volumes of meltwater were accumulated in ice-dammed regions during the early part of deglaciation, in the waning stages of the last glacial period. In Iceland, several large jökulhlaups from ice-dammed lakes occurred during the deglaciation (e.g. Tómasson, 2002; Hannesdóttir *et al.*, 2009; Wells *et al.*, 2022) and postglacial, ice-dammed marginal lakes have been a source of recurring jökulhlaups (e.g. Thorarinsson, 1939). However, historical events of this type have been orders of magnitude smaller than the large jökulhlaups needed to explain the Holocene history of Jökulsá á Fjöllum. In contrast, volcano-ice interaction has repeatedly generated jökulhlaups transporting some km^3 of water and peak discharge of magnitude similar to 10^5 m^3/s. The 1996 Gjálp jökulhlaup (max. discharge $4–5\times10^4$ m^3/s) and the 1918 Katla jökulhlaup (exceeding 10^5 m^3/s) are recent examples (e.g. Gudmundsson *et al.*, 1997; Tómasson, 1996). In both cases volcanic eruptions under ice caused the melting. The main reason for the large magnitude of the Gjálp 1996 jökulhlaup was ponding of meltwater in the Grímsvötn caldera, where persistent geothermal activity has sustained a subglacial lake that can store large volumes of meltwater before it undermines the containing ice dam. In the case of Katla 1918 and earlier such events in that volcano, very large eruptions cause melting rates comparable to the discharge rate (Gudmundsson and Högnadóttir, 2005).

Our data indicate that most of the W-jökuhlaups, 6.3–4.1 ka, originated from Bárðarbunga; indicating extensive ice cover at that volcano over long periods during the early to mid-Holocene. The cause of these large jökulhlaups may have been purely volcanic, that the melting all took place in eruptions, most likely within the Bárðarbunga caldera. An alternative possible explanation is that Bárðarbunga may over this period have been similar to Grímsvötn, hosting a large geothermal area, that sustained a subglacial lake. The caldera in Bárðarbunga is considerably larger than at Grímsvötn and may have been a considerably larger storage area for meltwater.

Bárðarbunga has recently been active with a slow subsidence occurring in 2014–2015 (Gudmundsson *et al.*, 2016), resulting in enhanced geothermal activity (Reynolds *et al.*, 2019). If Bárðarbunga hosted a large geothermal area during the mid-Holocene, a large subglacial lake may have existed in the caldera, that may have periodically released large jökulhlaups. The onset of volcanic activity may even have been regulated by this behavior of the subglacial lake, as at Grímsvötn over extended periods (Thorarinsson,

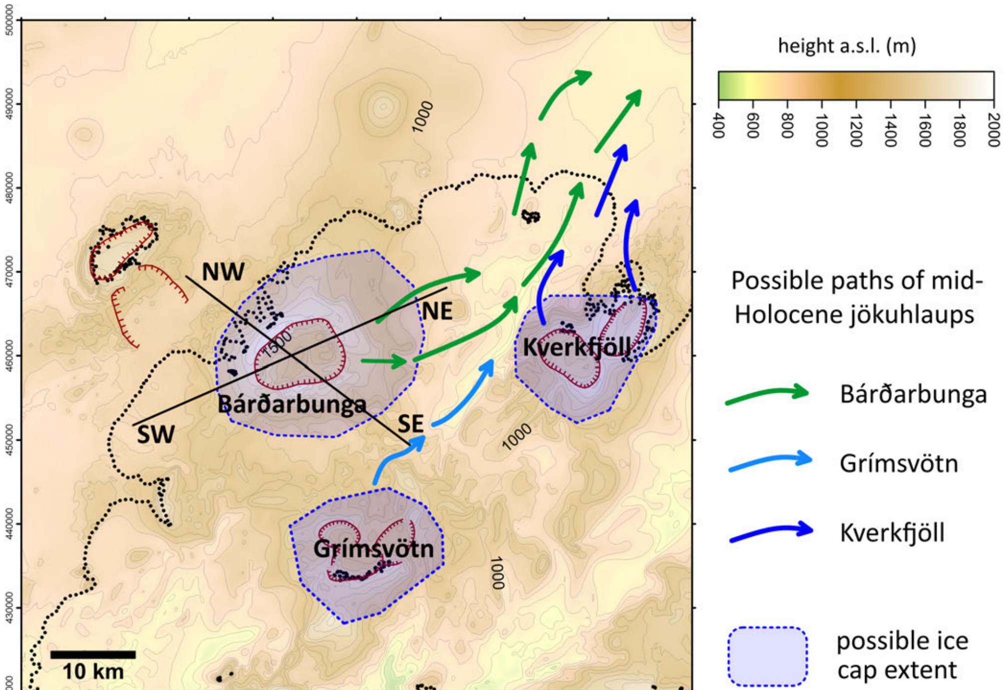


Figure 10. Present subglacial topography of the area below NW-Vatnajökull (Björnsson, 2009). The three central volcanoes of Bárðarbunga, Grímsvötn and Kverkjöll with their calderas illuminated. The map shows how each central volcano may have had a separate ice cap during the mid-Holocene, with possible pathways of jökulhlaups towards north. It is likely that the main path for jökulhlaups from Grímsvötn during this period was towards south, as it is today, while jökulhlaups towards north would also have been possible. The cross sections show the profiles in Fig. 11. – *Núverandi landslag undir norðvestanverðum Vatnajökli. Megineldstöðvarnar Bárðarbunga, Grímsvötn og Kverkfjöll með öskjum. Kortið sýnir mögulega legu jökla yfir hverri eldstöð um miðbik Nútíma, og líklegar leiðir jökulhlaupa til norðurs. Líklegt er að hlaup hafi að mestu farið til suðurs frá Grímsvötnum á þessum tíma, eins og er í dag, en hlaup til norðurs væru einnig möguleg við þesar aðstæður. Sniðin sýnd á 11. mynd merkt inn.*

1953; Björnsson, 1988; Gudmundsson *et al.*, 1995). This plausible hypothesis for Bárðarbunga remains speculative.

The glaciers covering the three large central volcanoes, Bárðarbunga, Grímsvötn, and Kverkfjöll during mid-Holocene, may have been similar to the present-day glacier covering of Katla, a few hundred square kilometers, the bulk of ice filling the large caldera (Björnsson *et al.*, 2000). Figure 10 shows schematically the possible extent of glaciers at the three central volcanoes and possible flowpaths of jökulhlaup towards north. The elevation of the rims of present-day Bárðarbunga is 1600–1800 m a.s.l. An ice cap filling the caldera to an elevation similar to or slightly lower than today (Figure 11) could be stable at equilibrium line altitude about 1600 m a.s.l.; a few hundred meters higher than at present, consistent with 2–3°C higher average temperatures than today (Anderson *et al.*, 2019; Björnsson and Pálsson, 2008; Pálsson *et al.*, 2022).

The equilibrium line altitude for a temperate glacier is primarily influenced by summer temperature and winter snow accumulation (e.g. Cuffey and Paterson, 2010). At times during the Holocene when Vatnajökull in its present form did not exist, precipitation relative to the southeast coast may have been higher at ice caps in central Iceland than today at Bárðarbunga. This might have resulted in a some-

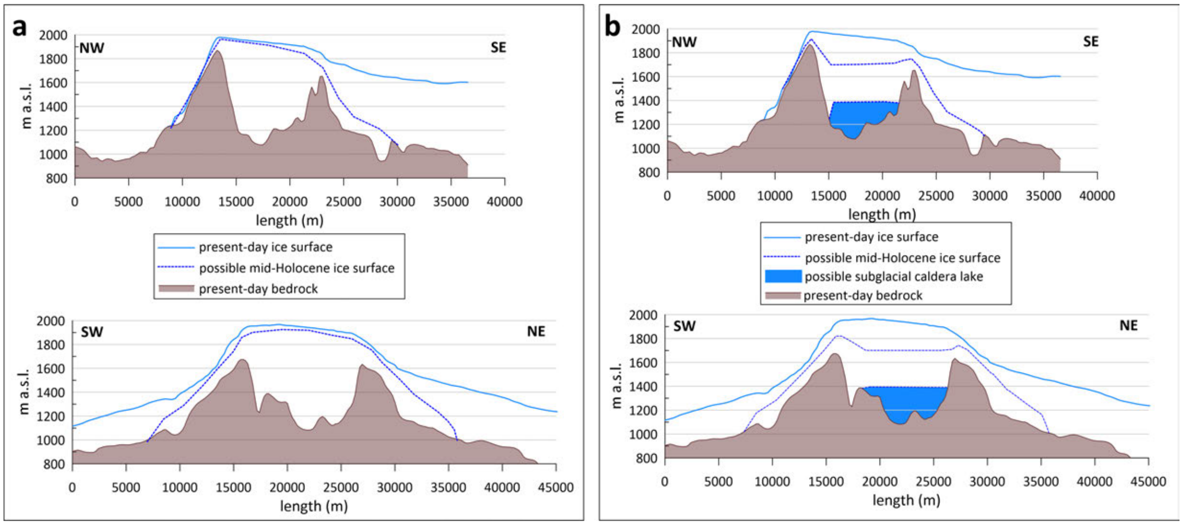


Figure 11. Cross sections through Bárðarbunga showing the present-day Vatnajökull and subglacial topography and how mid-Holocene glacial cover may have looked like. See Figure 10 for location. (a) The likely profile of a 400–500 km^2 ice cap centered on Bárðarbunga. The high rims imply that the surface elevation at Bárðarbunga may have been broadly similar to what it is today. (b) The same profiles assuming that a caldera lake, similar to the one that has existed in Grímsvötn for centuries (Björnsson, 1988; Thorarinsson, 1974). – *Þversnið gegnum Bárðarbungu sem sýna jökulyfirborð og botn við núverandi aðstæður, og mögulega legu jökuls um miðbik Nútíma, sjá staðsetningu á 10. mynd. (a) Líklegt þversnið jökuls á Bárðarbungu, 400–500 km^2 að stærð. Jaðrar öskjunnar liggja það hátt og stýra að miklu leyti hæð jökuls í öskjunni og því væri jökulyfirborð litlu lægra en er í dag. (b) Sömu snið þar sem gert er ráð fyrir vatni undir ísnum innan öskjunnar, líkt og verið hefur í Grímsvötnum í nokkrar aldir (Björnsson, 1988; Þórarinsson, 1974).*

what lower equilibrium line relative to atmospheric summer temperatures today. This may have been a contributing factor in preserving a stable ice cap on Bárðarbunga and possibly also Grímsvötn and Kverkfjöll during the relatively warm climate of the early to mid-Holocene

Figure 11 shows schematically what a mid-Holocene glacier covering Bárðarbunga may have looked like. Two possible end members are shown (Figures 11a and 11b). Figure 11a has a fully ice-covered caldera. In the event of a large eruption, e.g. of similar magnitude to Gjálp 1996 (Gudmundsson *et al.*, 1997) or Katla 1918 (Larsen *et al.*, 2021), large scale melting may produce some km^3 of meltwater during hours to days. This scenario would explain jökulhlaups similar to those seen from Katla, with the 1918 eruption being the most recent example (Tómasson, 1996). The alternative scenarios is shown in Figure 11b, where a large subglacial lake exists in the caldera, sustained by geothermal activity, similar to Grímsvötn over the last several hundred years (Thorarinsson, 1974; Björnsson, 1988).

The Bárðarbunga caldera may at times have held a caldera lake but at what time and the likely volume contained within such a lake at any time during the Holocene is not known. It is likely, however, that the Bárðarbunga system has gone through repeated large eruptive events with caldera subsidence. Eruptions on Dyngjuháls part of the volcanic system, in particular the eruption of the $\sim$15 km^3 Trölladyngja lava shield, younger than Hekla-4 tephra (Hjartarson, 2011; Sigurgeirsson *et al.*, 2015), may have caused caldera collapse at Bárðarbunga that enlarged the caldera substantially, analogous to a smaller subsidence accompanying the 2014 Holuhraun eruption (Gudmundsson *et al.*, 2016), but at a much larger scale.

The wide dispersal of the Low-Ti tephra suggests that the eruptions became subaerial during peak intensity, as is the case in eruptions within the Katla caldera where the eruption column emerges at the time of the floods. The ice thickness above the 1918 eruption site was about 300 m and the caldera floor 100–400 m above the pass through which the jökulhlaups escape, allowing rapid course of events. The 1996 Gjálp eruption, of similar magnitude as the large Low-Ti tephra layers, started below 600–700 m thick ice and became subaerial on day 4, emitting a minor tephra layer only 1–2% of total erupted volume (Gudmundsson *et al.*, 1997). The present conditions at the Bárðarbunga caldera – ice thickness of about 700 m, caldera floor at $\sim$1100 m a.s.l., the lowest pass about 250 m higher – do not favour a rapid breakthrough, indicating different conditions at 6.3–4.1 ka.

Peak discharges and number of W-jökulhlaups

The W-jökulhlaups seem to have ponded to about the same height at the Vesturdalur sediment sequence for over 2000 years, as indicated by the stacked waterlaid beds of similar grain size and sedimentary structure. This may imply floods of similar magnitude and a largely similar outflow channel from the Vesturdalur depression for 2000 years. If the restricting outlet from the depression was enlarged by the jökulhlaup that deposited bed 16 shortly after Hekla-4, similar younger floods left no record preserved today. The eruptions producing Low-Ti tephra continued for another 300–400 years until $\sim$3.7 ka. Termination of volcanogenic floods down Jökulsá á Fjöllum around 4.1 ka after the formation of bed 16 seems unlikely assuming the same source area and a growing ice sheet. However, as mentioned above, a major change at the Bárðarbunga caldera may have occurred around that time if Trölladyngja shield volcano is correctly dated as younger than the Hekla-4 tephra (4.3 ka).

Large peak flow of up to 10^6 m^3/s have been suggested for some of the floods during mid-Holocene, $\sim$6–4 ka (Elíasson, 1977; Kirkbride *et al.*, 2006). Kirkbride *et al.* (2006) considered at least the youngest floods to be "megafloods" (peak discharge exceeding 0.7×10^6 m^3/s). Waitt (2002) considered the floods to be "moderate" without mentioning likely peak discharge. Ahlo *et al.* (2005, 2007) modelled floods in Jökulsá á Fjöllum with maximum discharge of 0.9×10^6 m^3/s and 0.18×10^6 m^3/s respectively, where the average flow velocity was found to be 6 m/s and 2.8 m/s, respectively. Jökulhlaups originating in the Bárdarbunga area travelled about 190 km before entering Vesturdalur depression. Depending on the duration of the time of the maximum flow, considerable attenuation of the peak discharge may have occurred along its route, especially where ponding may have occurred within wide plains like Möðrudalur (Alho *et al.*, 2007) as well as in other areas along the route, that will modify flow velocity and peak discharge. The lowermost site in the modelling of a 14 km^3 meltwater flood with 0.18×10^6 m^3/s maximum discharge (Ahlo *et al.*, 2007) is about 45 km upstream from Vesturdalur and there the calculated average flow velocity was 2.8 m/s.

The likely cross section of the hydraulically retarding part in the Vesturdalur depression, is about 15.400 m^2 on a stripped lava surface at 170 m a.s.l. (Larsen *et al.*, 2023). If we assume an outflow velocity of 2.8 m/s when the depression had been filled to 190 m a.s.l., a peak discharge of 43.000 m^3/s is obtained. Flow velocity of 6 m/s would result in 93.000 m^3/s. It is, however, difficult to envisage series of 93.000 m^3/s floods rushing through Vesturdalur without major changes in the hydraulically retarding parts.

The W-jökulhlaups seem to have ponded to about the same height/elevation at the Vesturdalur sediment sequence for over 2000 years. This indicates that the erosional power of the jökulhlaups was not sufficient to alter significantly the topography, which suggests that the discharge estimates given above are likely on the high side for the 16 W-jökuhlaups.

The W-jökulhlaups may have continued after 4.1 ka – the Low-Ti tephra layers were erupted until at least 3.7 ka. If the jökulhlaup that deposited bed 16 significantly eroded the restricting channel the following jökulhlaups did not reach the same level as before and left no evidence at Vesturdalur.

Multiple ponding will modify flow velocity and peak discharge. We argue that erosional power was much reduced when the floodwaters entered Vesturdalur, implying low flow velocity and modest peak discharge. With the possible exception of the flood that deposited layer 16 we agree with Waitt (2002) that the W-jökulhlaups were moderate, significantly smaller than the 14 km^3 meltwater flood with 0.18×10^6 m^3/s maximum discharge modeled by Ahlo *et al.* (2007).

Jökulhlaups from Kverkfjöll and Grímsvötn

Carrivick *et al.* (2004) present evidence for at least two large jökulhlaups from Kverkfjöll volcano through Kverkfjallarani into Jökulsá á Fjöllum. These two jökulhlaups predate and postdate the $\sim$4 ka Biskupsfell eruption (Karhunen, 1988; Thordarson and Höskuldsson, 2008) but no further constraints on their age are presented. The older jökulhlaup could have contributed to the sediments in bed 11 at Vesturdalur, which has the highest percentage of Kverkfjöll glass. Each of the two Kverkfjöll calderas as defined by Thorarinsson *et al.* (1973), could be a source of substantial jökulhlaups. Carrivick *et al.* (2004) conclude that a jökulhlaup from either caldera could achieve a peak discharge of 10^5 m^3/s.

The path of Grímsvötn jökulhlaups in recent centuries has been towards south. This is largely controlled by the present configuration of Vatnajökull, with the main ice divide lying north of the volcano. This setting makes flood routes towards north highly improbable. However, a separate ice cap covering Grímsvötn, with an eruption site in the northern part of the central volcano might have sent a jökulhlaup towards north during mid-Holocene (Figure 10).

Potential correlation of the Low-Ti composition to environmental change

Tephra from Bárðarbunga volcanic system, 7.5 ka to present, display variable K_2O and K_2O-TiO_2 ratio as a function of time (Figure 12; Óladóttir *et al.*, 2011a). Radiogenic isotope ratios (Sr, Nd, Pb) compiled by Harðardóttir *et al.* (2022) support a uniform mantle source composition for Bárðarbunga basalt through the Holocene. In that case, decreasing K_2O and K_2O/TiO_2 from approximately 7 ka to 5 ka may reflect increased mantle melting, all other parameters being constant. Indeed, the warmer climate during the Holocene Climate Optimum (8–7 ka, e.g. Ran *et al.*, 2008; Larsen *et al.*, 2012; Jiang *et al.*, 2015) lead to less glacier mass and decreasing pressure on the volcano that would have resulted in increased melting. Basalts of relatively low K_2O and K_2O-TiO_2 ratio were discharged until $\sim$3.5 ka. Since 4.2 ka the glacier mass has increased (Geirsdóttir *et al.*, 2019). Basalts with increasingly higher K_2O and K_2O-TiO_2 emitted during the last 3.5 ka (High-Ti tephra) may reflect decreasing degree of mantle melting as a response to increased pressure from growing ice mass. An apparent delay of 0.7-1 ka in the response of the melting to loading and deloading may be real but needs more data to be confirmed.

Another source of the Low-Ti tephra?

Four tephra layers with Low-Ti composition, about 5.000 and 5.500 year old, were described from Gedduvatn in northwest Iceland and attributed to unknown eruption sites currently below Langjökull ice cap on the Western Volcanic Zone, based on "typical" WVZ chemical characteristics (Harning *et al.*, 2018). Some of the volcanic systems on the WVZ have very similar characteristics to that of the Bárðarbunga volcanic system (e.g. Jakobsson *et al.*, 1978; Jakobsson, 1979). Basaltic tephra is most often generated in hydromagmatic eruptions requiring the presence of water or ice (meltwater). However, according to Larsen *et al.* (2012) and Flowers *et al.* (2008) Langjökull did not exist at that time. Moreover, no thick tephra (cm to tens of cm) deposits with this affinity have been described in the Langjökull area. These tephra layers fall within the period of intense Low-Ti activity on the Bárdarbunga system and originate most likely within that system. Apparently, Harning *et al.* (2018) were not aware of the results of Óladóttir *et al.* (2011a,b) and Gudmundsdóttir *et al.* (2012a, 2016) demonstrating that the Low-Ti tephra layers are most numerous and have maximum thickness around Vatnajökull, are widely found in north, northeast and east Iceland and are also found on the North Iceland Shelf east of Grímsey.

Jökulhlaup deposits on the North Iceland Shelf?

Up to 12 Low-Ti tephra layers are found in the marine core MD99-2275 (east of Grímsey island) between 6.3 and 4.1 ka (Gudmundsdóttir *et al.*, 2012). The jökulhlaups discharged into Öxarfjördur, 60–70 km to the southeast of the core site. This is the distance that the sediment load would have to travel to deposit Low-Ti glass at the core site. The off-shore currents

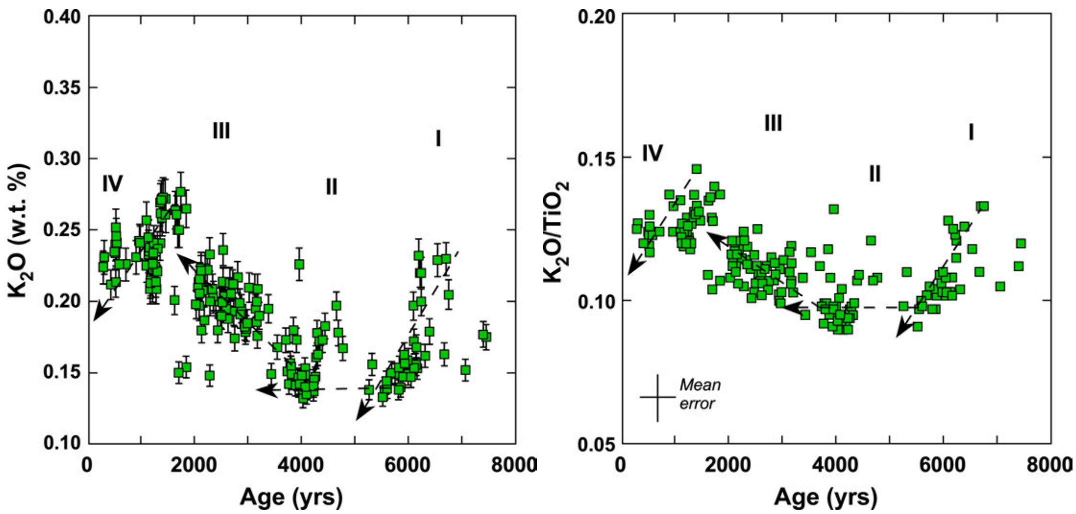


Figure 12. Changes in K_2O and K_2O/TiO_2 ratio with time for the Bárðarbunga tephra layers (all units), most likely indicating changes in mantle partial melting with time in addition to inevitable fractional crystallisation. Stages I and IV would indicate increasing mantle melting, whereas stages II and III suggest uniform and decreasing melting, respectively (see text for further discussion). – *Breytingar á K_2O and K_2O/TiO_2 hlutfalli með tíma í gjóskulögum frá Bárðarbungu (öll Bárðarbungugjóskulög úr sex sniðum). Þær má e.t.v. túlka sem breytingar í hlutbráðnun möttuls með tíma ásamt hlutkristöllun. Þeim má skipta í fjögur tímabil, breytingar í I og IV benda til vaxandi hlutbráðnunar, á tímabili II helst hún stöðug en á tímabili III fer hlutbráðnun minnkandi.*

in the area are towards east away from the core site. We therefore consider it more likely that the Low-Ti glass in the marine sediments are airfall tephra than deposits by associated jökulhlaups.

Future research – avoiding contamination

We recommend, for future work on the chemistry of the Vesturdalur sequence of sediments, and other related sedimentary sequences, that samples should be collected from middle and upper part of each bed as well as from the base, in order to avoid contamination from older material picked up from the environment when the first flood waters swept through the channels. This should provide more homogenous data and allow unequivocal correlation to source for each bed.

CONCLUSIONS

• We have for the first time employed the chemical characteristics of volcanic glass in distal jökulhlaup sediments deposited by Jökulsá á Fjöllum to determine the volcanic sources and the water/ice storage/reserve area.

• Basaltic volcanic glass, mostly Low-Ti glass, from the Bárðarbunga volcanic system dominates the sand fraction in 12 out of 15 jökulhlaup sediment beds deposited by Jökulsá á Fjöllum between 6.3 and 4.1 ka at Vesturdalur, north Iceland. Grímsvötn and Kverkfjöll glass composition dominates in one bed each.

• Glass in Low-Ti tephra layers erupted from the Bárðarbunga system during the same period has the same chemical characteristics as the glass in the sediments. Cross-correlation between sections indicates that up to 17 Bárðarbunga eruptions took place between 6.3 and 4.1 ka, the largest having tephra volumes of the order 1 km^3.

• The Bárðarbunga affinities of the jökulhlaup sediments indicate an ice cap on the volcano in the early- to mid Holocene. The Grímsvötn and Kverkfjöll glass also supports a partial ice cover of these volcanoes, implying substantial ice cover in the Vatnajökull area at 6.3 ka and possibly before 7000 ka.

• Changes in K_2O/TiO_2 ratio in Low-Ti tephra between 7.5–3.5 ka may indicate changes in the degree of mantle melting in response to glacial deloading.

• Peak discharge through the Vesturdalur area in the period 6.3–4.1 ka, may have been in the range 30,000 to 100,000 m^3/s (magnitude 4 flood) after attenuation along the 190 km travel from source.
• The average interval between the 16 floods is 150 years but different thickness of silt and "soil" between the beds indicates intervals of different length.
• The apparently similar volume and discharge of the jökulhlaups over two millennia indicate source in areas where stable conditions prevailed between 6.3 and 4.1 ka. One possibility is an ice covered caldera lake at Bárðarbunga, similar to that has existed in the Grímsvötn caldera for centuries.
• The floods may have continued after 4.1 ka although not recorded in the sediment sequence if conditions in Vesturdalur changed or the peak discharge was reduced.
• Termination of the floods shortly after 4 ka could relate to an increasing ice load. A radical change of the Bárðarbunga volcanic system, caused by the post Hekla-4 Trölladyngja eruption, may also have affected the caldera and magma system, temporarily reducing the potential to generate jökulhlaups.

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Supplementary information (available from corresponding author).

Table S-1. Major element compositions of glass grains from Vesturdalur sediment beds 2–16.
Table S-2. Major element composition of tephra layers in soil (interbed) between Vesturdalur sediment beds 1 and 2.
Figure S-1. Division of the basaltic Bárðarbunga glass into Low-Ti and High-Ti glass, using 1.6% (1.65%) as a separating value. Distinct low is observed between 1.61 and 1.70% TiO_2.

ÁGRIP

Jökulhlaup í Jökulsá á Fjöllum fyrir 6300–4100 árum tengjast sprengigosum í Bárðarbungu sem einnig dreifðu gjósku yfir A, NA, N, NV-land og landgrunnið norðan Íslands á sama tímabili. Gjóskulögin einkennast af gleri með TiO_2 <1,6 og MgO >7,3, hér nefnt lág-títan gler. Sama efnasamsetning einkennir gler í setlögum þessara jökulhlaupa.

Setlögum úr 16 hlaupum frá þessu tímabili, sem eru varðveitt í Vesturdal neðarlega í farvegi Jökulsár á Fjöllum, var fyrst lýst af Waitt (2002). Í 12 setlögum er lág-títan gler ættað úr Bárðarbungukerfi ríkjandi, og í sitthvoru setlagi er gler frá Kverkfjöllum og Grímsvötnum ríkjandi. Í einu setlagi eru hlutföllin svipuð og eitt var ekki greint. Þetta er í fyrsta sinn sem gjóskugler í hlaupseti er notað til að skera úr um upptakastað jökulhlaupa undan Vatnajökli til norðurs og tengja hlaup við gjóskulagasyrpu í jarðvegssniðum og líklegar gosstöðvar.

Umfjöllunin hér á eftir er um gjóskulög og jökulhlaupaset með lág-títan einkenni. Lág-títan gjóskulög frá þessum tíma eru amk 17 talsins, þar af finnast 12 í sama jarðvegssniðinu. Aðeins stærstu gjóskulög náðu út á svæðin utan núverandi Vatnajökuls þar sem þau gátu varðveist til framtíðar svo líklegt er að gjóskulögin/gosin séu fleiri. Útbreiðslukort af lág-títan gjóskulögunum benda til upptaka undir NV-hluta Vatnajökuls en þykkasti hluti þeirra er nú undir jökli. Dreifing gjóskunnar og samanburður við nýleg Grímsvatnalög bendir til að sum þeirra hafi verið nokkuð stór, allt að 1 km^3 nýfallin.

Sprengigosin og hlaupin urðu á tímabili þegar loftslag var að byrja að kólna eftir hlýjasta skeið á nútíma. Talið hefur verið að Vatnajökull hafi ekki verið til á mesta hlýindaskeiðinu nema e.t.v. sem jökulhettur á hæstu fjöllum, Bárðarbungu, Kverkfjöllum, Grímsfjalli. Kornagerð gjóskunnar bendir til að sprengivirkin stafi af snertingu kviku og vatns eða íss/bræðsluvatns og glerríku setlögin sem jökulhlaupin fluttu staðfesta slík samskipti. Mikil útbreiðsla gjósku gæti bent til að gosin hafi komist undir bert loft meðan mikill kraftur var í gosunum. Líklegustu gosstöðvar flestra þessara gosa eru í ísiþöktum hlíðum eða öskju Bárðarbungu.

Leiðir jökulhlaupanna næst gosstöðvunum eru nú undir Dyngjujökli en vatnsflaumurinn rann um 190 km leið niður í Vesturdal. Líklegt er að hlaupin hafi fylgt farvegum stórra eldri hlaupa frá hörfunarskeiði jökla og hafi ekki þurft að grafa nýja farvegi eða flæmast um utan farvega, sem skýrir að tiltölulega lítið er um aðkomuefni eins og bergmylsnu í hlaupsetinu. Milli setlaganna í Vesturdal eru um 150 ár að meðaltali en millilög sýna að tíminn er mislangur.

Líklegt er að jökulhlaupin hafi verið fleiri en 16. Lág-títan gjóskulög voru einkennandi fyrir Bárðarbungukerfið fyrir 7500–3500 árum, eftir það breyttist efnasamsetning kvikunnar (há-títan gjóskulög). Elsta þekkta setlag með sömu útlitseinkenni og Vesturdalssetið fannst ofan við Dettifoss og er um 7000 ára gamalt. Yngsta setlagið í Vesturdal er síðasta varðveitta setlagið en varðveisluskilyrði gætu hafa breyst. Setlögin finnast víðar í Vesturdals-Hljóðaklettakvosinni en aðstæður þar eru nú mikið breyttar vegna stórfellds rofs jökulhlaupa yngri en 3000 ára.

Waitt (2002) taldi setlögin hafa sest til í hringstreymi í uppistöðu sem myndaðist vegna tregs útrennslis hlaupvatns úr Vesturdals-Hljóðaklettakvosinni. Hann taldi að hlaupin sem fluttu setið hefðu verið „moderate“, en skilgreinir stærðina ekki frekar. Aðrir hafa talið þau „megafloods“. Hlaupin sem settu af sér setlögin í Vesturdal fylltu kvosina upp í sömu hæð í meira en 2000 ár án þess að stækka farveginn úr úr kvosinni. Þetta styður þá ályktun að hlaupin hafi ekki verið hamfarahlaup. Reiknað hámarksrennsli bendir til 30–100 þúsund m^3/s.

Meginniðurstöður

• Upptök jökulhlaupa fyrir 6300 til 4100 árum eru rakin til eldstöðva með efnagreiningum á jökulhlaupaseti.
• Sýnt er fram á tengsl milli gjóskulaga/sprengigosa af ákveðnum aldri og efnasamsetningu, og jökulhlaupa í Jökulsá á Fjöllum frá sama tímabili. Flest jökulhlaupin áttu upptök í Bárðarbungu.
• Sýnt er fram á að Bárðarbunga var hulin jökli fyrir 6300 árum og líklega fyrir 7000 árum, í lok hlýjasta tímabils á Nútíma.
• Sýnt er fram á að jökulhlaupin voru ekki hamfarahlaup en reiknað hámarksrennsli líklega 30–100 þús. m^3/s.
• Efnasamsetning lág-títan gjóskulaganna gæti bent til aukinnar hlutbráðnunar möttuls þegar jökulfarg minnkaði.

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