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RESEARCH ARTICLE

Holocene volcanic activity at Grímsvötn, Bárdarbunga and Kverkfjöll subglacial centres beneath Vatnajökull, Iceland

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Abstract Assessment of potential future eruptive behaviour of volcanoes relies strongly on detailed knowledge of their activity in the past, such as eruption frequency, magnitude and repose time. The eruption history of three partly subglacial volcanic systems, Grímsvötn, Bárdarbunga and Kverkfjöll, was studied by analysing tephra from soil profiles around the Vatnajökull ice-cap, which extend back to ~7.6 ka. Well known regional Holocene marker tephra (e.g. H3, H4, H5) were utilized to correlate profiles. Stratigraphic positions and geochemical compositions were used for fine-scale correlation of basaltic tephra. Around Vatnajökull ice-cap 345 tephra layers were identified, of which 70% originated from Grímsvötn, Bárdarbunga or Kverkfjöll. The eruption frequency of each volcanic system was estimated; Grímsvötn has been the most active with an average of ~7 eruptions/100 years (range 4–14) during prehistoric time (before ~870 AD); Bárdarbunga has been the second most active with ~5 eruptions/100 years (range 1–8); and Kverkfjöll has remained essentially calm with 0–3 eruptions/100 years but showing periodic activity with repose times of >1000 years. All three volcanic systems experienced lulls in activity from 5 ka to 2 ka, referred to as the "Mid-Holocene low". This reduced eruption frequency appears to have resulted from a decrease in magma generation and delivery from the mantle plume rather than from changes in ice-load/glacier thickness. In prehistoric time, there was a time lag of 1000–3000 years between a peak of activity at volcanoes directly above the mantle plume versus at volcanoes located in the non-rifting part of the Eastern Volcanic Zone, closer to the periphery of the island. This time-space relationship suggests that a significant future increase in volcanism can be expected there, following increased levels of volcanism above the plume.

Keywords Tephra correlation · Eruption frequency · Grímsvötn · Bárdarbunga-Veidivötn · Kverkfjöll · Iceland · Holocene

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Introduction

Plate boundaries are the most volcanically active places on Earth, and their diversity is reflected by different types of volcanism. Most of the historically documented eruptions have taken place along subduction zones (~85%; Simkin and Siebert 1994), whereas intraplate volcanism accounts for ~10% of all historically documented eruptions (Simkin and Siebert 1994) which leaves only ~5% of documented eruptions to take place on the ocean ridges. However, budget calculations of new magma reaching the surface, calculated from relative plate motions, show that ocean ridge volcanism clearly dominates the planet, accounting for ~75% of the magma production (Simkin and Siebert 2000), and emphasizing how many eruptions have not been historically documented.

Iceland is one of few places where an oceanic ridge rises above sea level and it is possible to monitor the eruptive behaviour of the ridge. Even though the crustal spreading rate in Iceland is steady (~2 cm/year; Hreinsdóttir et al. 2001) the rift zone response to it seems to be episodic (e.g. Björnsson 1985; Simkin and Siebert 2000; LaFemina et al. 2005). If the magma production rate remains constant, even though eruptions are periodic, about 6 m^3/s of magma have to be produced to account for the volume involved in construction of the volcanic island and its crust (Sigmundsson 2006). Previous studies show, however, that eruptions are not spread evenly over time and that their pattern of occurrence exhibits a degree of episodicity (e.g. Sigvaldason et al. 1992; Larsen et al. 1998; Maclennan et al. 2002; Óladóttir et al. 2005). Thus, either magma production is a periodic process or, if production is steady, then its delivery to the surface is delayed by temporary storage within the plumbing systems and/or magma chambers.

The eruption frequency in Iceland during historical time (last ~1100 years) has been calculated as averaging 20 eruptions per century, or an eruption every ~5 years (Thorarinsson and Sæmundsson 1979; Thordarson and Höskuldsson 2008). Eruptions of prehistoric time have received less attention but Jakobsson (1979) reported periodic volcanism on the Eastern Volcanic Zone (EVZ) during the Holocene peaking from ~9-7 calibrated (cal.) ka and again ~3-1 cal. ka. The volcanic history of the Katla volcano, in the EVZ, since 8.4 cal. ka, has been thoroughly studied, and shows two tephra layer frequency (TLF) peaks at 8-7 cal. ka and 4-2 cal. ka (Óladóttir et al. 2005; 2008); the silicic Holocene activity similarly shows peaks at 8-7 cal. ka and 3-1 cal. ka (Larsen and Eiríksson 2008a; 2008b).

The subglacial Vatnajökull volcanoes are amongst the most active volcanoes in the country during historical time (e.g. Thordarson and Larsen 2007), but deposits of the prehistoric period have not been thoroughly studied. The aim of this study is to evaluate the eruption frequency and volcanic history of three Vatnajökull volcanoes, Grímsvötn, Bárdarbunga and Kverkfjöll since 7.6 ka based on the tephra stratigraphy around the Vatnajökull ice-cap. A key question to be addressed is this: Have these volcanoes always been as active as observed during the last millennium or has their activity exhibited periodic or other systematic long-term changes?

Geological context

Levels of volcanic activity in Iceland are high as a result of superimposition of the North Atlantic ridge system on the Iceland mantle plume. The volcanism occurs in distinct volcanic zones composed of volcanic systems (e.g. Sæmundsson 1978; Jakobsson 1979). The most active volcanic systems are found in the EVZ, which strikes SW from the inferred centre of the mantle plume (Fig. 1) towards the central south coast of the island. This volcanic zone has been termed a propagating rift (e.g. Meyer et al. 1985) with its northern part being characterized by rift-related tectonics (faults and graben structures etc.) whereas the southern part is still a non-rifting volcanic zone (Sæmundsson 1979, LaFemina 2005).

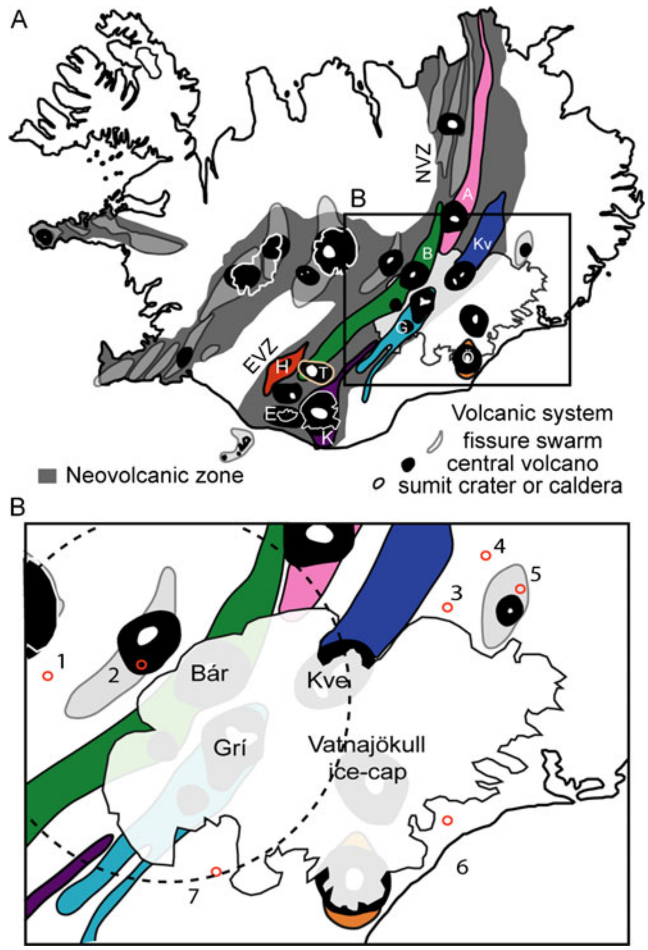


Fig. 1 **a** Map showing the position of the Neovolcanic zone and volcanic systems in Iceland. The systems of concern in this study are colour coded: Grímsvötn (G; *light blue*), Bárdarbunga (B; *green*, also referred to as Bárdarbunga-Veidivötn), Kverkfjöll (Kv; dark blue), Hekla (H; *red*), Katla (K; *violet*), Torfajökull (T; *tan*), Askja (A; *pink*), Öræfajökull (Ö; *orange*) and Eyjafjallajökull (E). The box outlines the study area. **b** Map showing the location of seven measured and sampled soil profiles around the Vatnajökull ice-cap: 1: Hreysiskvísl; 2: Nýidalur; 3: Saudárhraukar; 4: Kárahnjúkar; 5: Snæfell; 6: Steinadalur and 7: Núpsstadarskógar. Other abbreviations are: EVZ, Eastern Volcanic Zone; NVZ, Northern Volcanic Zone; Bár, Bárdarbunga central volcano; Grí, Grímsvötn central volcano; Kve, Kverkfjöll central volcano. The circle outlines the proposed mantle plume at 125 km depth (Wolfe et al. 1997). Modified after Jóhannesson and Sæmundsson (1998) and Thordarson and Larsen (2007)

Grímsvötn, Bárdarbunga and Kverkfjöll volcanic systems

The central volcanoes of the Grímsvötn, Bárdarbunga and Kverkfjöll volcanic systems, together with parts of associated fissure swarms, are located under the NW-part of the Vatnajökull ice-cap (Fig. 1). All three are characterised by basaltic eruptive products. As a consequence of magma interacting with glacial meltwater explosive eruptions are common despite basaltic magma composition. Two of the three central volcanoes, Grímsvötn and Bárdarbunga, lie close to the inferred centre of the Iceland mantle plume, while Kverkfjöll lies significantly farther from the plume centre (Wolfe et al. 1997).

The eruption history of Grímsvötn and Bárdarbunga during the last eight centuries has been established through tephra studies on outlet glaciers from the Vatnajökull ice-cap, soil profiles and written records (e.g. Thorarinsson 1950; 1974; Larsen et al. 1998; Thordarson and Larsen 2007; Larsen and Eiríksson 2008a; 2008b). The Grímsvötn volcanic system has been the most active system in Iceland during historical time, accounting for ~38% of all confirmed eruptions (Thordarson and Larsen 2007). All historical eruptions except the Laki eruption in 1783–84 took place on the ice-covered part of the system with the majority thought to have occurred within the central volcano (Thorarinsson 1974; Gudmundsson and Björnsson 1991).

The Bárdarbunga system is the second- to third-most active in historical time, along with Hekla, each producing ~13%–14% of confirmed eruptions in Iceland (Thordarson and Larsen 2007). Even though about 70% of the system is ice free (Sæmundsson 1978), only three of 23 confirmed eruptions have occurred along the ice-free fissure swarm (Larsen 1984; Thordarson and Larsen 2007). Although this system appears to have a significantly lower eruption frequency than that of Grímsvötn, during historical time activity on the two systems was often concurrent (Larsen et al. 1998; Sigmarsson et al. 2000).

The third volcanic system, Kverkfjöll, has not erupted during historical time. However, several eruptions have incorrectly been assigned to this volcano based on written records. Despite its quiescence in historical time, Kverkfjöll central volcano still features vigorous geothermal activity (Friedman et al. 1972; Björnsson and Einarsson 1990).

In the following sections the names Grímsvötn, Bárdarbunga and Kverkfjöll will refer to the central volcanoes and the ice-covered parts of the volcanic systems.

Volcanic systems producing silicic tephra marker layers

Volcanoes that have formed wide-spread silicic tephra layers of importance for this study are those of Hekla, Torfajökull, Askja, and Öræfajökull (Fig. 1). Hekla is by far the most productive volcano in terms of generating intermediate to silicic tephra (Thordarson and Larsen 2007) and is known for its wide-spread prehistoric silicic tephra, i.e. H3, H4 and H5 (e.g. Larsen and Thorarinsson 1977).

Methods

Field work and sample preparation

Much of the terrain around Vatnajökull comprises barren lava fields and sandur areas. Although undisturbed soil profiles are not abundant, seven sections, located in favourable spots for tephra deposition and preservation were measured and sampled around the Vatnajökull ice-cap (Figs. 1 and 2). These contain extensive tephra records of Holocene volcanism at Grímsvötn, Bárdarbunga and Kverkfjöll, and were studied with emphasis on deposits from prehistoric time (i.e. before ~870 AD). These sections were measured with millimetre precision and all layers of volcanic and suspected volcanic origin were sampled (for further information on field work and criteria see Óladóttir et al. 2005). After sieving, the 125 µm-size fraction was polished down to 100 µm-thick thin sections for in-situ analyses of major and trace-element chemical composition. In some cases, it was necessary to supplement this sample fraction with the 63 and/or 250 µm-size fractions.

Environmental factors controlling tephra deposition and preservation

The prime factors that influence tephra dispersal are the type of explosive activity, plume height, eruption magnitude and duration, prevailing wind direction and strength at the time of eruption. In order to obtain reliable estimates of the "true" eruption frequency for individual volcanoes it is necessary to record the tephra stratigraphy in several profiles radially around the volcano under consideration. Individual profiles in the soil cover surrounding a volcanic source are likely to record different aspects of its (explosive) eruption history, but collectively they should provide a reasonable picture of the overall story, by indicating the minimum eruption frequency.

Soil accumulation rate (SAR) age model

Previously ^{14}C-dated-tephra marker layers provide the basis for the SAR age model (using calibrated ages; Table 1). The SAR is calculated for each time period using the age difference between two dated tephra markers and the soil

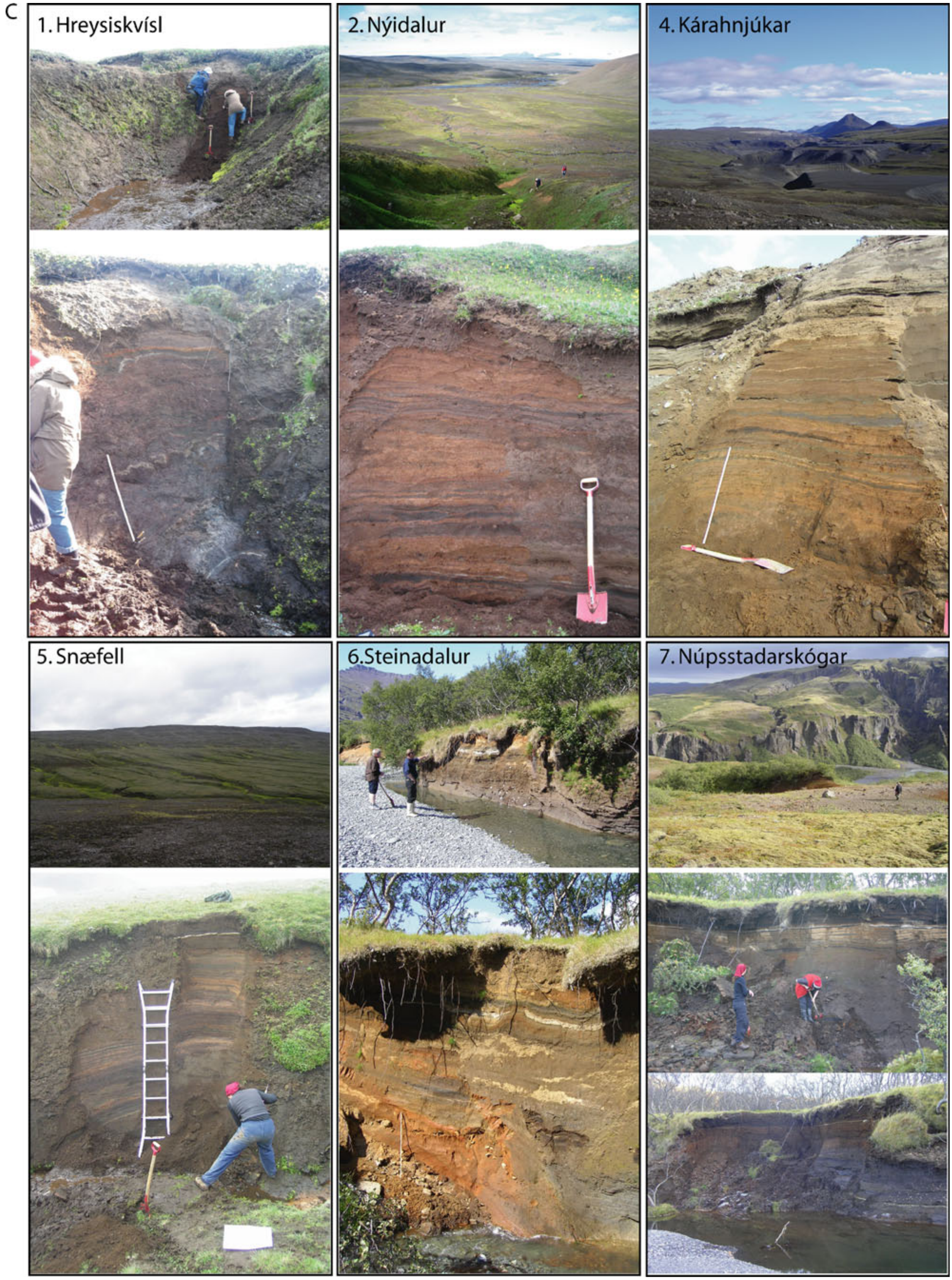


Fig. 2 Photos of the outcrops and their surroundings, lettering same as in Fig. 1b

Table 1 Tephra marker layers in the study area, their source volcanic systems and ages obtained from written documents, ice core dates, ^{14}C dates and SAR calculations

Marker layer	Volcanic system	Present in soil sec.	^{14}C dates	Calibrated/ calender yrs[a]	Bf 2005 AD	Reference
K-1918[b]	Katla	7 (L)		1918 AD	87	(e.g. Thorarinsson 1958)
Ö-1727[b]	Öræfajökull	7 (L)		1727 AD	278	(Thorarinsson 1958)
V-1477	Bárdarbunga	2–7 (R)		1477 AD	528	(Larsen 1984)
Ö-1362	Öræfajökull	1–7 (R)		1362 AD	643	(Thorarinsson 1958)
H-1158	Hekla	1–5 (R)		1158 AD	847	(Larsen 1982)
H-1104	Hekla	1,4 (L)		1104 AD	901	(Thorarinsson 1967; 1968)
Eldgjá	Katla	1,7 (L)		934 AD	1071	(Hammer et al. 1980)
V-871	Bárdarbunga	1–7 (R)		871 AD	1134	(Grönvold et al. 1995)
Hrafnkatla	Katla	1–7 (R)		[c]760 AD	1250	Mean SAR age, this study
Grákolla (G)	Torfajökull	1,3–5,7 (R)	1995±30	10 AD	1995	(Larsen and Eiríksson, unpubl. data 2009)
Askja (A)	Askja	2,6 (R)	1995±30	10 AD	1995	Same age as Grákolla[e]
Hy	Hekla	3,5,7 (L)		[d]~650 BC	2650	(Larsen unpubl. data 2009)
Hz	Hekla	3,4 (L)		[d]~750 BC	2750	(Larsen unpubl. data 2009)
UN[b]	Katla	7 (L)	2660±50 BP	845 BC	2850	(Larsen et al. 2001)
H3	Hekla	1–5 (R)	2879±34 BP	1050 BC	3055	(Dugmore et al. 1995a)
LN	Katla	1,3 (L)	3139±40 BP	1430 BC	3435	(Larsen et al. 2001)
HS	Hekla	6,7 (L)	3515±55 BP	1855 BC	3860	(Larsen et al. 2001)
H4	Hekla	1,3–7 (R)	3826±12 BP	2250 BC	4255	(Dugmore et al. 1995a)
N1[b]	Katla	1 (L)		3200 BC	5200	(Larsen et al. 2001)
HÖ	Hekla	1,3–5,7 (R)	5275±55 BP	4110 BC	6115	(Gudmundsdóttir et al. 2011)
H5	Hekla	1,3,4 (R)	6185±90 BP	5120 BC	7125	(Thorarinsson 1971)

[a] Mean calendar age, calibrated after Stuiver et al. 1998

[b] Tephra marker layers only used for SAR age calculations not for correlations

(L) and (R) indicates Local or Regional marker layer (see text for further discussion)

[c] Calculated SAR ages, this study.

[d] Unpublished SAR ages, Hekla area.

[e] Grákolla and Askja marker layers are present as separate layers in some profiles, but where their distribution overlaps they occur as a single layer consisting of a mixture of the two. This close proximity stratigraphically suggests a near synchronous deposition of these layers and therefore they have been allocated the same age

thickness separating them. An approximate age with an accuracy of ± 250 years (Óladóttir et al. 2005) can thus be calculated for each tephra layer in all profiles based on soil thickness between individual layers and the calculated SAR for each time period. This method was put to test when a tephra layer previously dated to 6160 years by SAR (Óladóttir 2009) was dated by ^{14}C measurements on organic material within the tephra layer to 5275±55 ^{14}C years BP (Gudmundsdóttir et al. 2011) or 6115±90 years (Table 1). It is important to have several dated markers at relatively short time intervals in each soil profile, because of the critical assumption that the SAR stays constant between the dated tephra marker layers (for further SAR information see Óladóttir et al. 2005). In the following sections all ages will refer to calibrated age before 2005 AD.

Correlation between soil profiles

The soil profiles were correlated using 16 tephra marker layers (Table 1, Fig. 3 and 4) most of which originated from the Hekla volcano (a total of 9). Other tephra marker layers used for correlation are from Öræfajökull (1), Torfajökull and Askja (1; G+A), Katla (3) and Bárdarbunga (2; Table 1). The tephra marker layers are mostly wide-spread silicic tephra layers that are easily recognisable in the field because of their distinct macroscopic characteristics such as colour (i.e. white or yellowish white), bedding, grain morphology or crystal content. Individual basaltic layers are more difficult to recognize in the field and therefore a series of two or more such layers are better markers. In some cases, however, distinctive basaltic tephra layers are good markers because they display readily identifiable

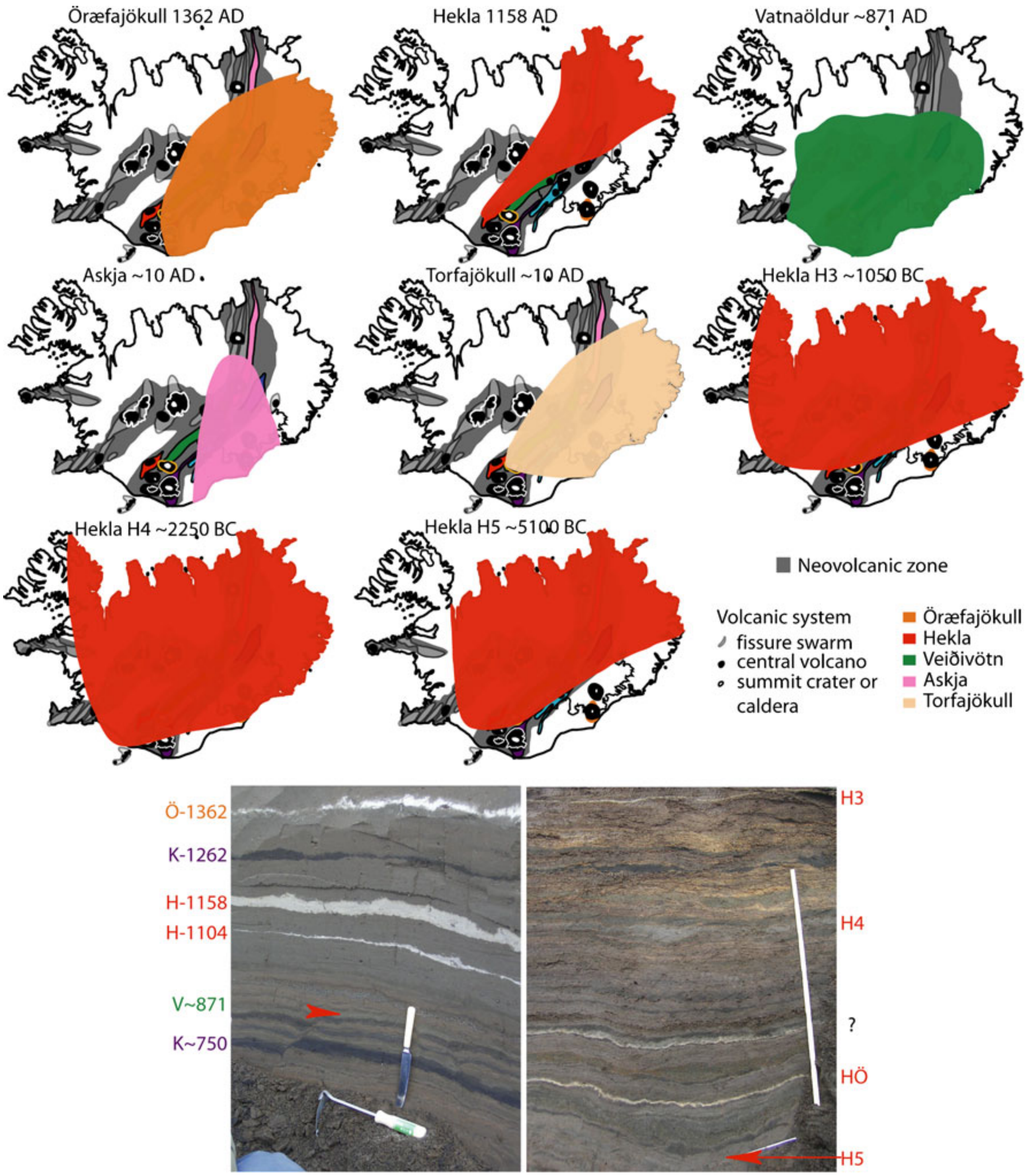


Fig. 3 On-land distribution of selected key marker tephra layers used for correlation of soil profiles around Vatnajökull ice-cap. Colour code is the same as in Fig. 1. Based on Thorarinsson (1958), Larsen and Thorarinsson (1977), Larsen (1984), Larsen (2000) and Larsen (unpubl. data 2009). Photos show Öræfajökull 1362, Hekla 1158, Vatnaöldur ~870 (V-871), Hekla 3, Hekla 4 and Hekla 5 amongst other tephra layers as observed in the Kárahnjúkar (*left*, site no. 4) and Saudárhraukar (*right*, site no. 3)

characteristics. Examples of those are the coal-black Katla tephra layers, found far away from its source as well as the so-named "Settlement Layer" from the Vatnaöldur phreato-Plinian fissure eruption in ~870 AD (V-871; Table 1) on the Bárdarbunga volcanic system, which is readily recognised by its colour of greenish-grey to greenish-black and its abundant plagioclase crystal fragments (Larsen 1984; Grönvold et al. 1995; Zielinski et al. 1997). In addition to field criteria, major-element compositions of tephra marker layers are compared with published values and used for secure identification (e.g. Dugmore et al. 1995b; Dugmore and Newton 1998; Larsen et al. 1999; 2001; 2002; Boygle 2004; Eiríksson et al. 2004; Kristjánsdóttir et al. 2007; Óladóttir et al. 2008, 2011; see online supplements).

Major-element compositions are used to determine the provenance of basaltic tephra and for correlation of individual tephra layers, or groups of layers, between soil profiles (see online supplements; Óladóttir et al. 2011). The

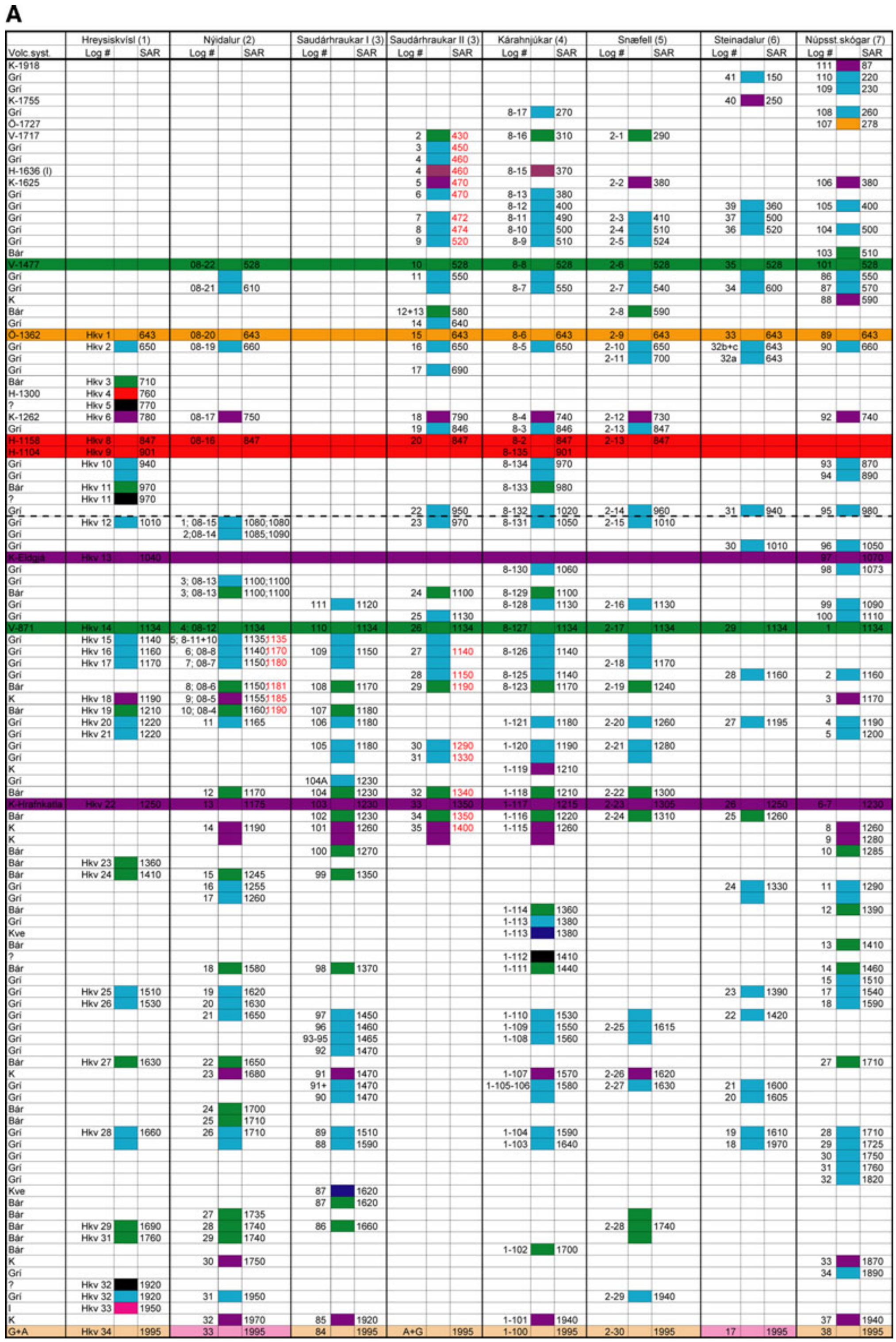


Fig. 4 Chart showing correlations of tephra between soil profiles around Vatnajökull. Tephra appearing in the same row represent one and the same eruption and the source volcano is given in the first column where Grí: Grímsvötn, Bár: Bárdarbunga, Kve: Kverkfjöll, K: Katla, H: Hekla, Ö: Öræfajökull, T: Torfajökull and A: Askja, I: intermediate unknown, and ?: basaltic unknown. The data for each profile are given in three columns where Log # = sample number; colour indicates provenance (for legend see Fig. 1) and SAR = calculated soil accumulation rate (SAR) age (see text). Tephra marker layers used for first order correlations are highlighted across all rows. Every 1000 years, as depicted from correlated tephra layer frequency (TLF) and average SAR, are indicated by horizontal broken lines. This division indicates compilation of correlated TLF and is the basis for estimated eruption frequency calculations. The layers 35 and 36 in Núpsstadarskógar are not included because they occur below a disturbed (remobilised) soil horizon

B

	Hreysiskvísl (1)		Nýidalur (2)		Saudárhraukar I (3)		Saudárhraukar II (3)		Kárahnjúkar (4)		Snæfell (5)		Steinadalur (6)		Núpsst.skógar (7)	
Volc.syst.	Log #	SAR	Log #	SAR	Log #	SAR	Log #	SAR	Log #	SAR	Log #	SAR	Log #	SAR	Log #	SAR
Bár			34	2010												
Grí					83	2040										
K															39	2090
K															40	2130
I			35	2050											41	2150
Bár			36	2060	82	2070			1-99	2080	2-31+32	2265				
Bár					81	2090			1-98	2090	2-33	2100				
Bár									1-97	2130	2-34	2100	16	2030		
Bár											2-35	2120				
Grí									1-97	2130			15	2200	42	2170
Bár					79-80	2110			1-96	2140					43	2200
K	Hkv 36	2070	37	2070												
K	Hkv 37	2130			78	2120			1-95	2140						
K	Hkv 38	2220	38	2170												
K	Hkv 39	2310	39	2260												
Bár	Hkv 40	2400	40	2490	77	2150			1-94	2180						
Grí			41	2520											44	2220
Grí			42	2590												
Bár															45	2240
I															46	2260
Kve					76	2240										
I					76	2240			1-92	2260	2-36	2220			47	2265
?					75	2280			1-91	2280	2-37	2230				
Hx															48	2280
K															49	2290
Bár					74	2290			1-91	2280	2-37	2230			50	2340
K															51	2360
Grí									1-90	2300						
Grí					73	2330			1-89	2360					52	2410
K					72	2360	78	2360	1-88	2410	2-38	2290			53	2430
K											2-39	2350				
Grí					71	2370					2-40	2360			54	2460
Grí					70	2467										
Bár					69	2470	77	2510	1-86	2480	2-41	2430				
H bas, T-lay.	Hkv 41	2640	43-44	2670	68	2490			1-85	2500						
Bár					67	2510	76	2610			2-42	2530				
Bár					66		75	2660	1-84	2560	2-43	2535				
Hy					66	2560					2-43; Å3	2535;2710			55	2600
Borrobol like					65	2610	74	2670	1-83	2590	Á4	2760				
Bár	Hre 41a	2750	45	2700	64	2650	73	2730	1-82	2620	2-44	2600				
Hz							72	2770	1-81	2670						
K	Hre 41a	2750	46a	2770											56	2620
Grí	Hre 41b	2750	46b	2771												
Grí					63	2750	71	2800	1-80	2690	2-45	2690				
Grí					62	2760	70	2820								
Grí									1-78	2720	2-46	2720				
Grí															57	2770
Grí					61	2810			1-76	2770						
Kve					60	2880			1-75	2810			14	2980		
Bár															58	2800
Grí									1-74	2850					59	2810
Bár	Hkv 42	2880	47	2900	59	2950			1-74	2850						
Bár			48	2980	58	2980	69	2940	1-73	2950	2-47	2970				
Grí									1-72	2980					60	2830
Bár					57	3020							12	3220	61	2840
K-Un															62	2850
Grí													11	3280	63	2900
Grí															64	2970
Grí															65	3040
Grí															66	3070
Grí															67	3120
Hm/n															68	3130
Grí															69	3160
H3	Hkv 43	3055	49	3055	56	3055	68	3055	1-70	3055	Å5;2-48	3055				
I					55	3070	67	3060	1-69	3060	2-49	3055				
Grí									1-68	3090						
Bár					54	3140	66	3180	1-66	3160			10	3380	70	3200
Bár							65	3190								
Grí									1-65	3200						
Grí															71	3200
Grí															72	3220
Grí															73	3240
K-Ln	HKV 44	3435					63	3435								
Grí	Hreys 44a	3500			53	3150										
Bár					52	3170					2-50	3130			74	3350
Bár							62	3480								
Grí							62	3480								
K	Hreys 53	3560													75	3560
?					51	3480	60	3530					9	3440		
Bár	Hreys 54	3670														
Grí	Hreys 55	3760			50	3550			1-61	3590	2-51	3660	8	3560	76	3590
Grí									1-60	3630	2-52	3670				
Grí					49	3590	59	3660	1-59	3660						
Grí							58	3710								
Grí	Hreys 56	3780							1-57	3710						
Bár	Hreys 57	3800			48	3740	55-57	3830	1-56	3770	2-53	3810				
K	Hreys 58	3830														
K					47	3760	54	3860			2-54	3830				
Bár							53	3940								
Bár							52	3975								
Bár							51	3980								
Bár	Hreys 59	3890					50	3982								
Bár	Hreys 60	3920			46	3940	49	4020								
Bár	Hreys 61a	4100			45	4030										
Grí	Hreys 61b	4100														
Bár							47	4050								
Bár							46	4070								
Grí					44	4070	45	4095								
Grí							44	4100	1-55	3780			7	3710	77	3790
Grí															78	3860
HS													6	3860	79	3860
Bár					43	4090	43	4105	1-54	3880	2-55	4060				
Bár									1-53	3900			5	4060		
K															80	3920
Grí															81	4020
K	Hreys 62	4190					42	4140			2-56	4180	V	4060	82	4100
K															83	4170
Bár							41	4180	1-52	3940	2-57	4230				
K	Hreys 63	4255													84	4250

Fig. 4 (continued)

Fig. 4 (continued)

basaltic tephra stratigraphy is also an important correlation tool. These correlations enable determination of the actual number of basaltic tephra layers that originated from Grímsvötn, Bárdarbunga and Kverkfjöll present in the seven soil profiles.

Analyses

Major-element analyses on individual glass grains were obtained with a WDS Cameca SX100 electron microprobe. The instrument was calibrated on natural and synthetic mineral standards and glasses (see online supplements and Óladóttir et al. 2011). Raw data were corrected by the X-PHI correction procedure (Merlet 1994).

Estimating eruption frequency from tephra layer frequency (TLF)

Soil profiles were selected to represent prehistoric TLF. Additional measurements from the historical period represented in each profile were used to compare the observed TLF with established records of historical eruptions. To obtain an estimate of the prehistoric eruption frequency, a ratio between the number of known historical eruptions and the number of preserved tephra layers from the last eight centuries of the measured soil profiles was calculated. This factor is used for adjusting the estimated eruption frequency in prehistoric time.

Results

Soil profiles and tephra provenance

The combined thickness of tephra and soil in the seven selected profiles varies from 325 to 652 cm and they cover 2530–7320 years (Table 2). The Katla 1918 AD tephra is the youngest identified layer and is found near the top of the Núpsstadarskógar profile (Fig. 1, no. 7). The oldest layer is from Grímsvötn and its position at the base of the Kárahnjúkar and Snæfell profiles (Fig. 1, no. 4 and 5) implies an age in excess of 7600 years.

Counting each primary tephra in these seven soil profiles as a separate unit, the total number of units is 747, with the

Table 2 Soil profile information

Profile no.	1	2	3	4	5	6	7
Profile height (cm)	460	325	447	560	452	327	652
Total soil thickness (cm)	214.7	211.8	209.7	377	294	203.5	282.3
Soil% in profile	46.7	65.2	46.9	67.3	65.0	62.2	43.3
No. of SAR periods	10	5	9	10	9	6	12
Duration (yrs)	6570	2530	6900	7320	7010	5910	6110
No. of tephra units	96	56	169	139	108	50	129
Youngest tephra	Ö1362	V14771	V1717 +1	V1717 +1	V1717	K1755	K1918
Oldest tephra	H5 +3	H3	H5 +2	H5 +9	HÖ +26	H4 +10	HÖ +2
Tephra per 1000 yrs	14.6	22.1	24.5	19.0	15.4	8.5	21.1
Sources of tephra units							
Grímsvötn	25	19	62	54	34	28	57
Bárdarbunga	30	20	58	44	32	10	21
Kverkfjöll	0	0	14	11	6	2	1
Katla basaltic	20	11	15	10	13	5	36
Kalta silicic	3	0	1	0	0	0	1
Hekla basaltic	3	0	1	1	0	0	0
Hekla silicic	6	2	7	7	5	2	6
Hekla T-layer	1	1	1	1	0	0	0
Öræfajökull	1	1	1	1	1	1	2
Torfajökull	1	0	4	3	3	0	1
Askja	0	1	0	0	1	1	0
Intermediate	1	1	2	2	2	0	3
Basaltic (unknown)	5	0	3	5	11	1	1

Profile no. are as follows: 1 Hreysiskvísl, 2 Nýidalur, 3 Saudárhraukar, 4 Kárahnjúkar, 5 Snæfell, 6 Steinadalur, 7 Núpsstadarskógar. Their location is shown in Fig. 1b.

Youngest and oldest tephra layers are given as the last known tephra marker layers and + no. shows how many younger/older layers are found, respectively.

source volcano identified for 710 of them. The source volcanoes for the remaining 37 cannot be determined with certainty (see details in Óladóttir et al. 2011). Of the tephra units with known sources, 279 originate at Grímsvötn and 215 at Bárdarbunga. Kverkfjöll trails behind Katla and Hekla with 34 identified units (Óladóttir et al. 2011). Thus, Grímsvötn, Bárdarbunga and Kverkfjöll together account for more than two-thirds of tephra identified in soil profiles around Vatnajökull (Table 2). This accounting method documents the number of times tephra units from particular volcanoes are found in these soil profiles, but the profiles have to be correlated on a layer by layer basis before the actual number of eruptions represented by the tephra can be determined. The correlation starts with the key marker layers.

Tephra marker layers

A total of 21 regional and local marker tephra layers are present in soil profiles around Vatnajökull (Table 1). Of those, nine silicic layers were produced by sub-Plinian to Plinian eruptions at the Hekla volcano. Four of the Hekla layers (H-1158, H3, H4, HÖ) are present in at least four soil profiles and provide key tie points. Five Hekla layers (H-1104, Hy, Hz, HS, H5) occur in fewer than four profiles and are used as local tephra markers, although the H5 layer has to be considered a regional tephra marker because of its known wide distribution (Larsen and Thorarinsson 1977).

The remaining marker tephra layers were erupted from Öræfajökull (Ö-1362, Ö-1727), Torfajökull (G), Askja (A), Katla (K-1918, Eldgjá, Hrafnkatla, UN, LN, N1) and the Bárdarbunga system (V-1477, V-871). The silicic Ö-1362, G tephra, the basaltic V-1477, V-871 and Hrafnkatla, are present in four or more soil profiles whereas the other tephra layers occur in fewer than four soil profiles. The tephra G (from Torfajökull) and A (from Askja) were erupted near-simultaneously about 2000 years ago. In some parts of the research area they overlap and merge to form a single horizon and are therefore referred to as G+A. Thus, ten layers (V-1477, Ö-1362, H-1158, V-871, Hrafnkatla, G+A, H3, H4, HÖ, H5) can be used as regional marker layers and of those Ö-1362, V-871, Hrafnkatla and G+A are present in all seven soil profiles. These ten regional tephra markers are fairly evenly distributed through time (Table 1; online supplement).

Soil accumulation rate (SAR) age model

Soil development is affected by several environmental variables such as climate, topography, drainage and vegetation (e.g. Thorarinsson 1961; Arnalds 2004). Therefore, both regional and local tephra markers are used in the model to optimize the SAR age. This results in different SAR periods used in the seven soil profiles (Tables 2 and 3; Fig. 4). Different SAR values for the same time slice in the seven profiles have little effect on age calculations but some variations in SAR age of tephra units are to be expected if the time slices are of different duration.

Tephra layer frequency (TLF) in individual profiles (local TLF)

Tephra layer frequency (TLF) histograms of 1000 year bins from individual profiles are shown in Fig. 5. The highest local TLF peak for Grímsvötn tephra is at 2-1 ka in six out of the seven soil profiles (Fig. 5). The exception is the Snæfell profile (profile 5) where TLF is highest during the most recent millennium. The last 2000 years in this profile are well constrained by marker tephra layers. This different TLF record at Snæfell could partly be explained by the thick, iron-rich soil devoid of tephra below the Hrafnkatla marker layer (see Fig. 6), indicating a temporary change in preservation conditions and lowering the 2-1 ka TLF peak. The Grímsvötn TLF is low from 6 to 4 ka in all of the profiles.

The Bárdarbunga TLF generally displays two peaks, one at ~6-5 ka and another broader peak at 3-1 ka (Fig. 5). Within the 3-1 ka peak, the western profiles Hreysiskvísl and Nýidalur (profiles 1 and 2) exhibit higher local TLF at 2-1 ka whereas in the eastern profiles of Kárahnjúkar and Snæfell (profiles 4 and 5) the peak is at 3–2 ka. These differences are difficult to relate to changes in prevailing wind direction because a similar effect is not seen in the local Grímsvötn TLF. However, they could possibly be explained by different seasonality of eruptions at Grímsvötn versus Bárdarbunga, in conjunction with variations in eruption intensity. The Bárdarbunga TLF of the last millennium is among the lowest in all profiles.

The Kverkfjöll tephra is best represented in the eastern profiles, i.e. Saudárhraukar (profile 3), which lies closest to Kverkfjöll, Kárahnjúkar (profile 4) and Snæfell (profile 5; Figs. 1b and 4). In the western profiles, Hreysiskvísl and Nýidalur, which lie farthest away from the volcanic source, no Kverkfjöll tephra is present (Fig. 5) and only one and two layers are found in the southern profiles, Steinadalur and Núpsstadarskógar (profiles 6 and 7; Fig. 5). Deposition of Kverkfjöll tephra peaks at 6-5 ka (Fig. 5). This peak coincides with a low in Grímsvötn TLF. The absence of tephra in time intervals of 4-3 ka and from 1-0 ka is evident in all profiles and those periods are thus considered ones of repose for the Kverkfjöll volcano.

Combined tephra layer frequency (TLF) after correlation of profiles

Correlation of the seven profiles enables a combined TLF to be constructed. At least 345 eruptions have contributed to the tephra record in these profiles (Figs. 3 and 5). Of

Table 3 Soil accumulation rate (SAR) calculations. Time range, soil thicness[a] and SAR are given for every SAR period in each profile

		Hreysikvisl (1)		Nýidalur (2)		Saudàrhraukar (3)		Kárahnjúkar (4)		Snæfel (5)		Steinadalur (6)		Núpsstadsk (7)	
Temphra marker layer	Time range[b]	Soil (cm)	SAR (cm/yr)	Soil (cm)	SAR (cm/yr)	Soil (cm)	SAR (cm/yr)	Soil (cm)	SAR (cm/yr)	Soil (cm)	SAR (cm/yr)	Soil (cm)	SAR (cm/yr)	Soil (cm)	SAR (cm/yr)
K1918-Ö1727	191													14.25	0.0746
Ö1727-K1625	102													5.50	0.0539
V1717-K1625	92									2	0.0217				
K1625-V1477	148									3.85	0.0260			9.04	0.0611
K1755-V1477	278											37.35	0.1344		
H1636-V1477	159							20.76	0.1305						
V1477-Ö1362	115			31.00	0.2696	16.5	0.1435	9.5	0.0826	1.6	0.0139	3.25	0.0283	5.26	0.0457
Ö1362-K1262	100														
Ö1362-H1158	204	8.75	0.0429	10.75	0.0527	23.55	0.1154	16.73	0.0820	5.35	0.0262				
Ö1362-V871	491											10	0.0204		
K1262-Eldgjá	328													17.42	0.0531
Eldgjá-V871	63													3.44	0.0545
H1158-H1104	54	0.75	0.0139					5.67	0.1050						
H1158-V871	287			34.75	0.1211	4.6	0.0160			5.6	0.0195				
H1104-V871	233	8.85	0.0380					12.51	0.0537						
V871-G + A	861	28.19	0.0327	85.28	0.0990	17.77	0.0206	41.1	0.0477	22.15	0.0257	14.77	0.0171	58.68	0.0682
G + A-UN	855													18.87	0.0221
G + A-H3	1060	17.67	0.0167	28.03	0.0264	22.41	0.0211	29.38	0.0277	15.75	0.0149				
G + A-HS	1865											31.35	0.0168		
UN-HS	1010													32.60	0.0323
H3-LN	380	3.5	0.0092			8.87	0.0233								
H3-H4	1200							29.94	0.0250	24.95	0.0208				
HS-H4	395											5	0.0127	10.85	0.0275
LN-H4	820	18.5	0.0226			23.4	0.0285								
H4-N1	945	25.1	0.0266												
H4-HÖ	1860					29.05	0.0152	32.14	0.0173	50.68	0.0266			68.05	0.0357
N1-HÖ	960	54.75	0.0570												
HÖ-H5	1010	40.1	0.0416			12.83	0.0133	16.33	0.0162						
[c]Snæ 94–98	675									65.0	0.0963				

For further information on tephra layers see Table 1

[a] total soil tickness excluding tephra layers

[b] age difference between marker layers

[c] not tephra marker layers, used to calculate SAR because the soil properties change abruptly.

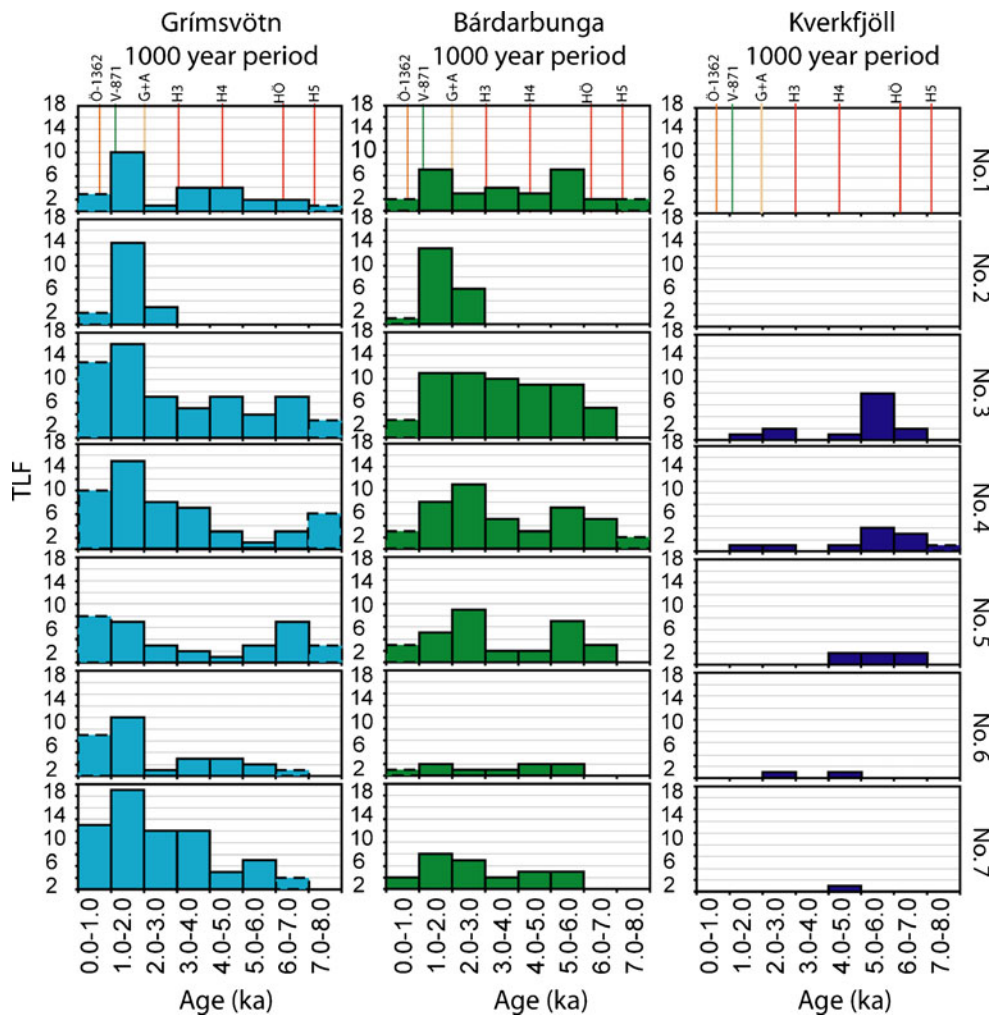


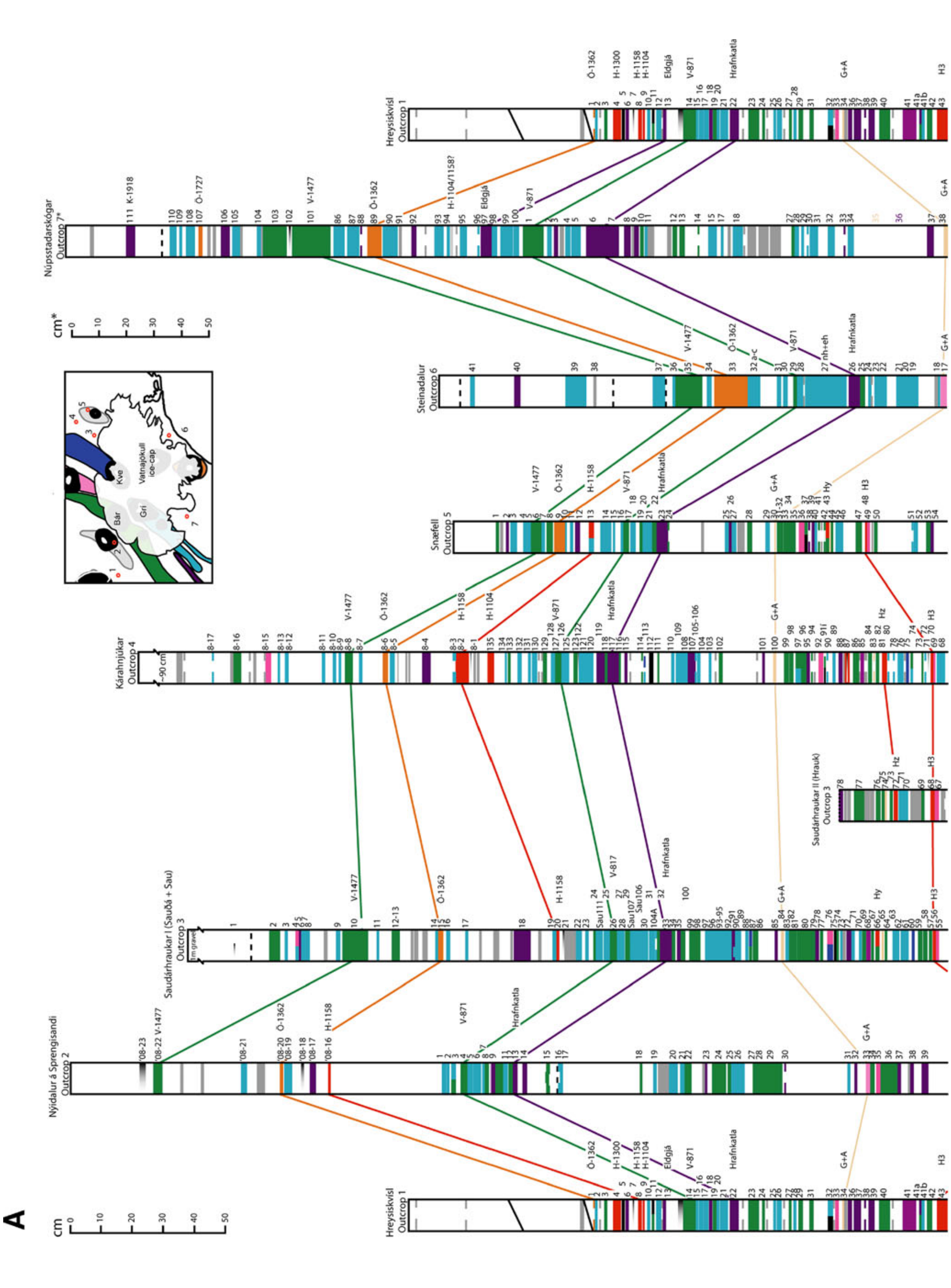
Fig. 5 Overview of TLF histograms from the seven soil profiles. Number of tephra per bin is shown on the y-axis and the x-axis shows 1 ka bin size. Profile numbers are shown on the right and refer to Fig. 1. Colour indicates tephra provenance as shown in Fig. 1. The three histograms give the TLF for each volcano. Columns with broken lines represent minimum estimates for the TLF because of incomplete soil record. Vertical lines show location of main tephra marker layers in time

these, ~70% are from Grímsvötn, Bárdarbunga and Kverkfjöll: 135 from Grímsvötn (39%), 87 from Bárdarbunga (25%) and 17 from Kverkfjöll (5%). Of all the Grímsvötn tephra 54% could be correlated from one profile to another, 62% of Bárdarbunga tephra could be correlated, as well as 65% of the Kverkfjöll tephra (Fig. 3; Table 4). The Katla volcanic system has produced 17% (57) of the identified tephra, 5% (16) originate from the Hekla system and 2% (8) are tephra marker layers from other sources. About 7% (25) of measured and sampled tephra units are of unidentified provenance.

The combined TLF can be used to estimate the eruption frequency of the volcanic systems beneath Vatnajökull (Fig. 7). The 8-6 kyr interval is covered by data from four profiles (Hreysiskvísl, Saudárhraukar, Kárahnjúkar, Snæfell) and the 6-5 kyr interval is covered by five profiles (i.e. the four mentioned above plus Núpsstadarskógar). Consequently, the earliest 2–3000 years of our record are better preserved north of the glacier than to the south.

The combined TLF histogram exhibits two distinct peaks, from 6-5 ka and 2-1 ka (Fig. 7). When broken down to specific volcanoes, a similar pattern is observed. The Grímsvötn TLF has two peaks, one at 7-6 ka and another at 2-1 ka. Between these two peaks a steady increase in the TLF is observed, from nine layers per 1000 years in the period 6-5 ka to 35 layers at 2-1 ka. The combined TLF of Bárdarbunga shows a rather steady increase to a peak of 20 preserved tephra layers 2-1 ka with an indistinct lull between 5 and 4 ka. The combined TLF for Kverkfjöll indicates that Holocene explosive eruptions at that volcano are confined to two distinct time intervals: a longer one at 8-5 ka with peak of eight tephra layers between 5-6 ka, and another more inconspicuous one at 3-1 ka, represented by four tephra layers.

Fig. 6 Correlation of tephra marker layers between profiles. Measured thickness of tephra is shown and colour refers to source volcano (see legend). Blank intervals represent soil. Numbers to the right of each log show sample numbers and tephra marker layers are indicated by their abbreviated symbol (see Table 1). Tephra marker layer correlation between profiles is indicated by solid lines. Note that profile 1 is shown twice to close the correlation around the Vatnajökull ice-cap and the Saudárhraukar profile is represented by two logs because two sections were measured at that site in order to accommodate for stratigraphic disturbance present in the main profile. Detailed correlation is shown in Fig. 4. Inset map shows profile locations (see also Fig. 1) ▶


A
Hreysiskvísl Outcrop 1
Nýidalur á Sprengisandi Outcrop 2
Saudárhraukar I (Sauðá + Sau) Outcrop 3
Saudárhraukar II (Hrauk) Outcrop 3
Kárahnjúkar Outcrop 4
Snæfell Outcrop 5
Steinadalur Outcrop 6
Núpsstadarskógar Outcrop 7*
Vatnajökull ice-cap
V-1477
Ö-1362
H-1158
H-1104
H-1300
V-871
Eldgjá
Hrafnkatla
G+A
H3
Hz
Hy
K-1918
Ö-1727

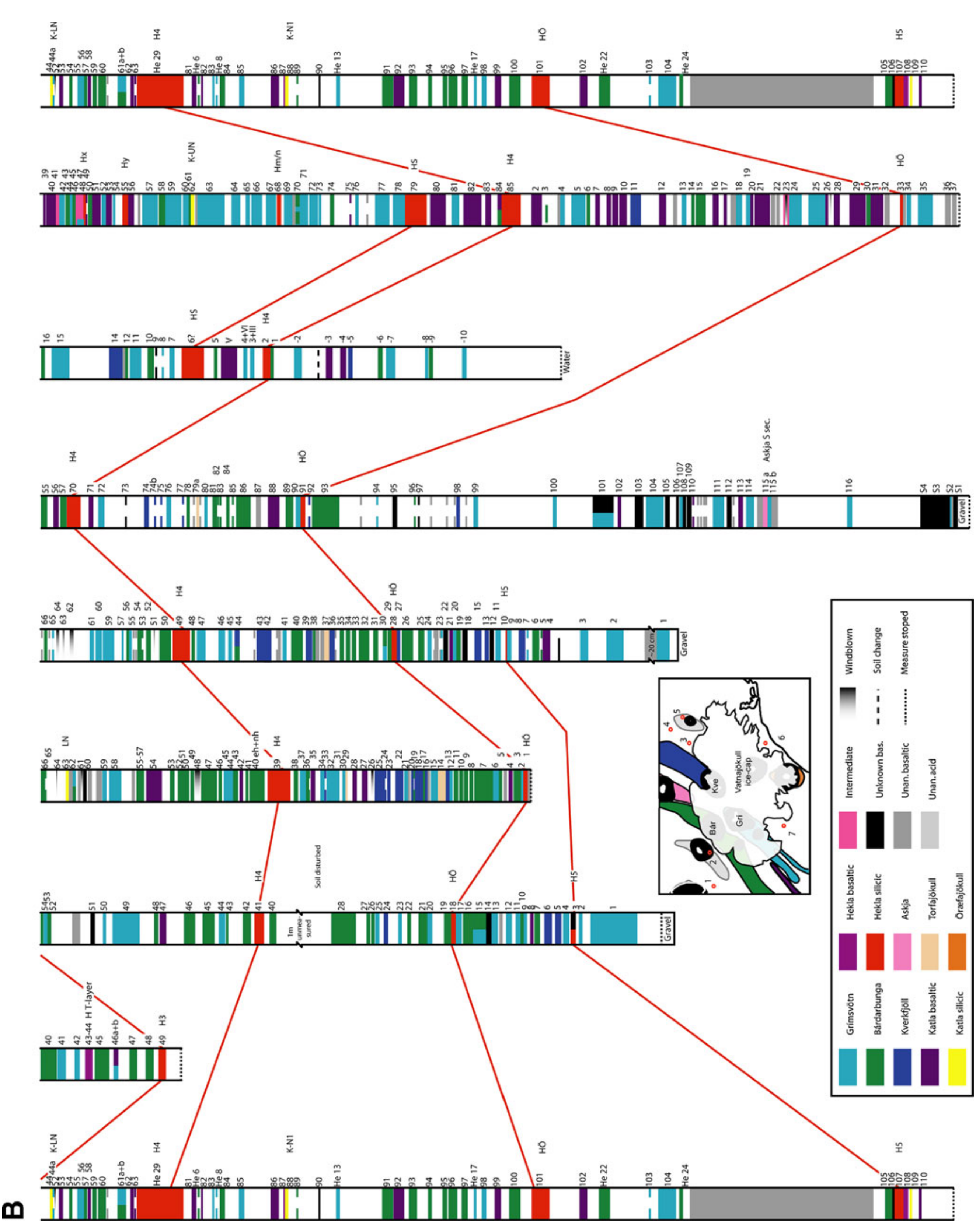

B
Grímsvötn
Bárdarbunga
Kverkfjöll
Katla basaltic
Katla silicic
Hekla basaltic
Hekla silicic
Askja
Torfajökull
Öræfajökull
Intermediate
Unknown bas.
Unan. basaltic
Unan. acid
Windblown
Soil change
Measure stoped
Vatnajökull ice-cap
Bár
Gri
Kve
Gravel
Water
Askja S sec.

Table 4 Examples of correlated Bárdarbunga and Grímsvötn tephra from the Kárahnjúkar (Kári) and Saudárhraukar (Shr.) profiles. Correlation is based on stratigraphic position, directly below the H4 tephra marker layer (see Fig. 4), and chemical composition of glass from the tephra using the average composition of the tephra units and their associated standard deviations

Vs.	Log#	Age	SiO_2	TiO_2	Al_2O_3	FeO^a	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
Bár	Kári 48		49.54	1.69	14.38	12.05	0.28	7.03	12.09	2.29	0.16	0.20	99.72
Bár	Kári 48		49.84	1.75	14.25	11.80	0.21	6.95	12.17	2.28	0.16	0.12	99.53
Bár	Kári 48		49.54	1.71	14.29	12.30	0.19	6.87	11.80	2.31	0.16	0.13	99.30
Bár	Kári 48		50.00	1.69	14.28	11.54	0.18	6.89	11.97	2.33	0.16	0.14	99.18
Bár	Kári 48		49.99	1.69	14.27	11.78	0.23	6.93	12.06	2.25	0.17	0.11	99.48
Bár	Mean	4300	49.78	1.71	14.29	11.89	0.22	6.93	12.02	2.29	0.16	0.14	99.44
Bár	SD		0.23	0.03	0.05	0.29	0.04	0.06	0.14	0.03	0.00	0.03	0.21
Bár	Shr. II 38		48.68	1.64	13.80	12.19	0.22	7.00	12.15	2.17	0.17	0.17	98.19
Bár	Shr. II 38		48.90	1.72	13.72	12.32	0.27	6.83	11.84	2.29	0.18	0.11	98.18
Bár	Shr. II 38		49.69	1.72	14.12	11.80	0.32	7.05	12.11	2.26	0.16	0.09	99.31
Bár	Shr. II 38		48.87	1.75	13.70	12.42	0.27	6.85	11.97	2.17	0.16	0.14	98.31
Bár	Shr. II 38		49.24	1.77	13.90	12.47	0.18	6.62	11.83	2.21	0.18	0.17	98.56
Bár	Shr. II 38		49.05	1.82	13.68	12.31	0.30	6.91	12.05	2.29	0.18	0.17	98.76
Bár	Mean	4340	49.07	1.74	13.82	12.25	0.26	6.88	11.99	2.23	0.17	0.14	98.55
	SD		0.35	0.06	0.17	0.24	0.05	0.15	0.14	0.06	0.01	0.04	0.44
Grí	Kári 46		48.76	2.16	14.11	11.39	0.26	6.77	11.84	2.29	0.31	0.22	98.10
Grí	Kári 46		49.40	2.46	14.04	11.72	0.19	6.51	11.21	2.46	0.34	0.15	98.46
Grí	Kári 46		49.54	2.62	13.88	12.49	0.26	6.15	10.67	2.42	0.36	0.33	98.71
Grí	Kári 46		49.36	2.24	14.25	12.09	0.21	6.93	11.36	2.52	0.30	0.22	99.48
Grí	Kári 46		49.62	2.22	14.34	11.96	0.18	6.90	11.58	2.55	0.30	0.20	99.85
Grí	Mean	4630	49.29	2.27	14.18	11.79	0.21	6.78	11.50	2.45	0.31	0.20	98.97
Grí	SD		0.37	0.13	0.14	0.31	0.04	0.20	0.28	0.12	0.02	0.03	0.83
Grí	Shr. II 37		49.25	2.22	14.01	11.80	0.14	6.89	11.58	2.33	0.31	0.17	98.70
Grí	Shr. II 37		49.22	2.31	14.09	12.06	0.27	6.74	11.50	2.34	0.30	0.21	99.04
Grí	Shr. II 37		49.29	2.31	13.79	12.11	0.16	6.78	11.55	2.33	0.31	0.31	98.94
Grí	Shr. II 37		49.42	2.31	13.97	12.25	0.15	6.63	11.51	2.42	0.30	0.26	99.22
Grí	Shr. II 37		49.47	2.33	14.07	11.92	0.27	6.76	11.57	2.48	0.31	0.23	99.42
Grí	Shr. II 37		49.27	2.36	13.99	11.88	0.16	6.81	11.39	2.30	0.33	0.25	98.75
Grí	Mean	4400	49.32	2.31	13.99	12.00	0.19	6.77	11.52	2.37	0.31	0.24	99.01
Grí	SD		0.10	0.05	0.10	0.17	0.06	0.08	0.07	0.07	0.01	0.05	0.28

Vs Volcanic System. Log# as in Fig. 4. Mean shows the average composition of the six analysed points in each tephra unit. SD is one standard deviation. Age shows calculated SAR age from each soil profile.

[a] Total Fe expressed as FeO

Discussion

Comparison of estimated eruption frequency during historical and prehistoric periods

About 64 Grímsvötn and 19 Bárdarbunga eruption events are known since 1200 AD (Larsen et al. 1998; Thordarson and Larsen 2007), but no historical eruption is known from the Kverkfjöll volcanic system (Thordarson and Höskuldsson 2002).

Only a fraction of the historical eruptions at volcanoes beneath Vatnajökull have produced tephra that was deposited and preserved in soils outside the ice-cap and the barren highland areas (Larsen and Eiríksson 2008a). Recent small eruptions at Grímsvötn, such as those of 1983 and 2004 (Grönvold and Jóhannesson 1984; Oddsson 2007), that have limited tephra dispersal and deposited little or no tephra outside the 8000 km^2 ice-cap, are unlikely to leave recognizable layers in soil in distal areas. More widespread tephra layers, such as those of the 1922 and 1934 Grímsvötn eruptions, are deposited and preserved distally. Therefore, the proportion of preserved tephra layers in the best historical highland profiles used in this study is likely to be somewhat higher than observed in the lowlands.

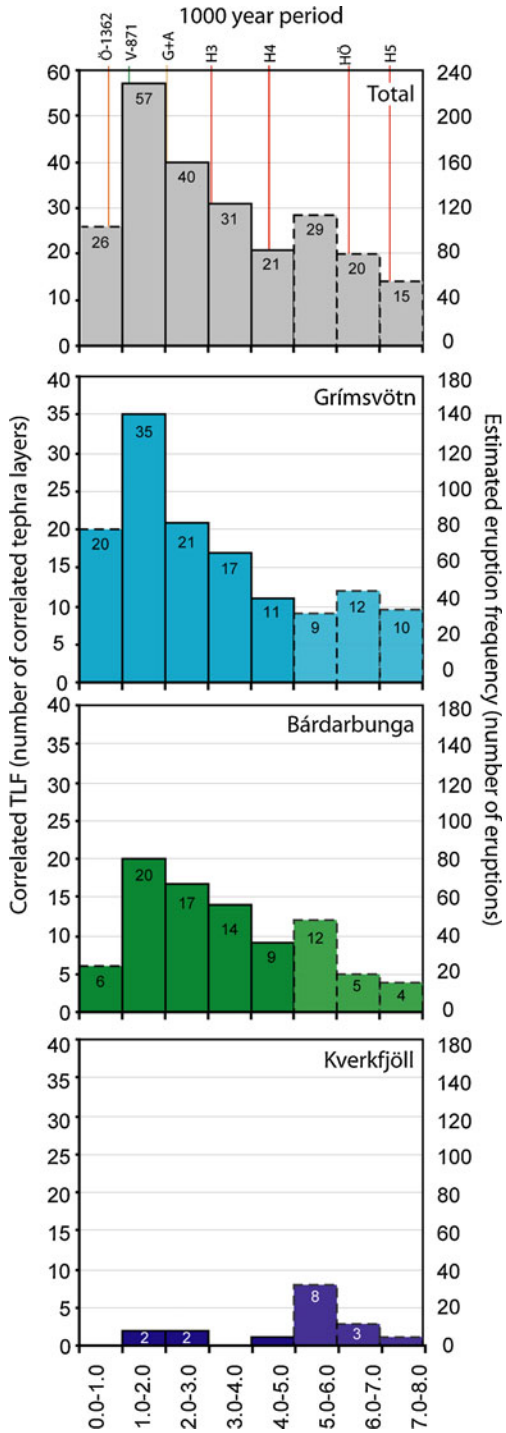


Fig. 7 Combined tephra layer frequencies (TLF; scale on left) along with the estimated eruption frequency (scale on right). Numbers in columns refer to TLF. Colours as in Fig. 1. Time scale is based on SAR calculations (see Fig. 4). Columns with broken lines represent minimum estimates for the TLF because of incomplete soil record. Also note that the data for the last time interval, 7-8 ka, only extend back to 7.6 ka (see text for further details)

Grímsvötn

The combined tephra stratigraphy from the seven soil profiles contains 16 tephra layers from Grímsvötn younger than 1200 AD (Fig. 4), or one-fourth of known eruptions. This ratio is different from the one out of five ratio given by Larsen and Eiríksson (2008a) which was deduced from soil profiles in the lowlands, farther away from the volcanic source. Using the correction factor obtained in this study, the eruption frequency of Grímsvötn during prehistoric time is ~480 eruptions during the 6500 years covered by the profiles. On average this rate amounts to ~7 eruptions per century notwithstanding that the correlated tephra stratigraphy (Fig. 7) records variable activity through time. This average rate is concordant with results of Thordarson and Höskuldsson (2008).

The minimum estimated eruption frequency at Grímsvötn is 36 layers per 1000 years in the period 6-5 ka. However, since the first 2000 years are missing from three profiles (Steinadalur, Núpsstadarskógar, Nýidalur), this assessment probably underestimates the eruption frequency in these periods. The maximum frequency is 140 eruptions in the period 2-1 ka (Fig. 7). In the last millennium (1-0 ka), the eruption frequency is still high but drops to 80 events/ 1000 yrs which is slightly higher than that estimated by Thordarson and Larsen (2007) and Larsen and Eiríksson (2008b and references therein) although still within uncertainity limits.

Bárdarbunga

Only five tephra layers from Bárdarbunga, younger than 800 years, are present in the combined tephra stratigraphy (Fig. 4). This finding gives a preservation ratio of one-fourth, in agreement with that suggested by Larsen and Eiríksson (2008a) from their study at the lowlands and as obtained for Grímsvötn in this study. The total estimated eruption frequency at Bárdarbunga during the 6500 prehistoric years is therefore ~330 eruptions and on average 48 eruptions per 1000 years or ~5 per century.

The distance of a soil profile from a source volcano does not seem to affect the preservation ratio for Bárdarbunga tephra as much as was observed for Grímsvötn tephra. Although Grímsvötn shows higher activity than Bárdarbunga, only 54% of Grímsvötn tephra layers can be correlated from one profile to another whereas 62% of Bárdarbunga tephra layers were correlated between two or more profiles. This finding may suggest that the preserved tephra layers from Bárdarbunga have wider dispersal, and accordingly, could represent more voluminous and/or longer lasting eruptions than those of Grímsvötn. Such an eruption magnitude difference could explain the lower activity in

Bárdarbunga due to an inverse relationship between eruption frequency and eruptions sizes where high frequency calls for small eruptions and vice versa (e.g. Simkin and Siebert 1994; Gudmundsson 2000).

As at Grímsvötn, the eruptions at Bárdarbunga are not equally distributed through time (Fig. 5). The combined TLF increases rather steadily during the first 7000 years, peaking in the interval 2-1 ka (Fig. 7). The estimated eruption frequency is at a minimum at 8-7 ka (16 eruptions per 1000 years), rising to 80 eruptions at 2-1 ka. Thereafter, the eruption frequency drops considerably to 24 eruptions in the last millennium or to its lowest level in the last 5000 years, even though it has had 23 confirmed historical eruptions (Thordarson and Larsen 2007).

Kverkfjöll

Kverkfjöll has not produced any historical tephra, thus it is not possible to adjust its eruption frequency as was undertaken for the other volcanoes. However, because the location of Kverkfjöll is similar to Bárdarbunga, both being in the northern part of Vatnajökull close to the glacier margins and at a similar elevation (Björnsson and Einarsson 1990), the same preservation ratio is used for Kverkfjöll and Bárdarbunga for estimating eruption frequency, i.e. one out of every four eruptions is recorded as a tephra layer. After correlation between profiles, the total number of tephra layers originating from Kverkfjöll in prehistoric time is 17, which implies an estimated eruption frequency of ~70 eruptions during the 6500 prehistoric years or 1 event per 100 years on average. However, the TLF indicates that the activity at Kverkfjöll volcano has been episodic during the Holocene with repose periods extending over more than 1000 years, including the current one (~1200 years). At the time of peak activity (6-5 ka), the soil archive contains 8 tephra layers, which leads to an estimate of 32 eruptions per 1000 years (Fig. 7). Ten tephra layers, or about 55%, are found in more than one outcrop. Kverkfjöll is less active than Grímsvötn and Bárdarbunga, with only a single peak of activity and long quiet intervals. Kverkfjöll is most active, however, when eruption frequency is also high in the other two systems (Fig. 7)

Temporal variations in the eruption frequency at Grímsvötn, Bárdarbunga and Kverkfjöll–caused by changes in environmental conditions or magma productivity?

The observed cumulative eruption frequency for Grímsvötn, Bárdarbunga and Kverkfjöll is bimodal, with peaks at 6-5 ka and again at 2-1 ka (Fig. 7, top). A low point (nadir) in eruption frequency is observed from 5-2 ka, here referred to as the Mid-Holocene low. This nadir could reflect changes in magma productivity or it could be an artifact caused by greatly reduced ice cover and consequently less explosive activity on the ice-covered parts of Grímsvötn, Bárdarbunga and Kverkfjöll.

Explosive eruptions and magma fragmentation form wide-spread tephra due to water-magma interaction, emphasizing the primordial role of ice-cover for basaltic tephra formation by the three volcanic systems. Changes in the extent of the ice may therefore influence the observed eruption frequency. In general, most eruptions taking place on a volcanic system originate in the central volcano whereas eruptions occurring only out on the associated fissure swarm are less frequent (e.g. Gudmundsson 2000). During the last two centuries, at least 20 Grímsvötn eruptions are recorded (Thorarinsson 1974; Larsen et al. 1998), of which at least one took place beyond the Grímsvötn central volcano (Þórdarhyrna 1903; Thorarinsson 1974) and another seven took place outside or partly outside the *caldera* of the central volcano (Larsen and Gudmundsson 1997). In the case of Grímsvötn it can therefore be assumed that the majority of eruptions take place at the central volcano.

The three volcanic systems have had changing ice cover since the end of the last glaciation. Kaldal and Víkingson (1990) demonstrated how the early Holocene ice sheet in South and Central Iceland retreated. The Vatnajökull ice-cap was probably significantly reduced during the Holocene Thermal Maximum (HTM), 8-7 ka (Kaufmann et al. 2004; Ran et al. 2008), before expanding again at the onset of neoglaciation. Today the central volcanoes of Grímsvötn, Bárdarbunga and Kverkfjöll are all ice covered and at present, Grímsvötn has the most extensive ice cover of the three volcanic systems, with the central volcano and 2/3 of the fissure swarm covered (Sæmundsson 1978; Jóhannesson and Sæmundsson 1998). The glaciers also retreated gradually from the Bárdarbunga system at the end of the last glaciation and the beginning of the Holocene. On the SW-part of the system, which became ice-free in the early Holocene, a peak in lava flow frequency (LFF) occurred at 9-8 ka (Vilmundardóttir et al. 2000; Larsen unpub. data 2000). Today about 60 km out of the 190 km-long volcanic system is ice covered (Sæmundsson 1978). The fissure swarm of the Kverkfjöll system is mostly ice free but the central volcano remains ice-covered (Fig. 1).

Óladóttir et al. (2007) have demonstrated that the Mýrdalsjökull ice-cap survived the HTM, thus supporting the existence of ice-cover on the central volcanoes in Vatnajökull during the Holocene, even during the HTM 8-7 ka (Kaufmann et al. 2004; Ran et al. 2008) when the ice-cap probably was significantly smaller. Consequently, it is likely that phreatomagmatic volcanism took place in Grímsvötn, Bárdarbunga and Kverkfjöll throughout the Holocene. Additionally, the HTM preceded the Mid-Holocene low by 1-3 ka making it unlikely that environ-

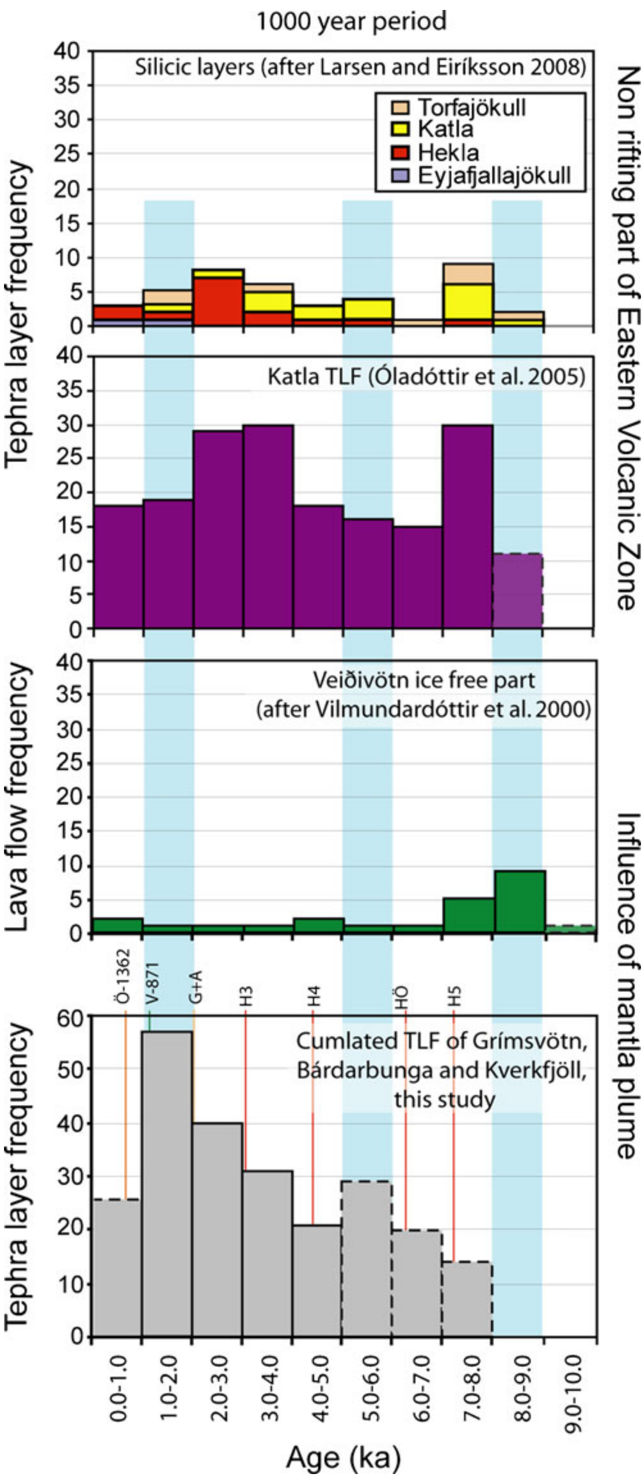


Fig. 8 Summary of eruption frequency observed in volcanic systems above the assumed Iceland mantle plume (bottom two) and those located on the non-rifting part of the EVZ (top two). Cumulated TLF for the ice-covered part of the Grímsvötn, Bárdarbunga and Kverkfjöll volcanic systems (lowest panel), lava flow frequency (LFF) for the ice-free part of the Bárdarbunga system (after Vilmundardóttir et al. 2000; Larsen unpubl. data 2000) in green, Katla in violet and silicic tephra from Torfajökull, Katla, Hekla and Eyjafjallajökull on the EVZ in tan, yellow, red and blue (after Larsen and Eiríksson 2008a). Columns cutting across panels indicate maximum plume activity. See further discussion in text

mental changes caused temporal variations in eruption frequency. That the eruption frequency minimum is not synchronous at the three volcanic systems is further evidence against this possibility. This supports the interpretation that the observed changes with time in the eruption frequency are caused by endogenous or deep-seated processes, inferred to be responsible for the Mid-Holocene low.

Spatial variations in eruption frequency

The Holocene tephra record clearly shows that Grímsvötn has had the highest eruption frequency of the three volcanic systems in postglacial times (Fig. 7). The second-most active system is Bárdarbunga (Fig. 7). Hence, the two volcanic systems located close to the assumed centre of the mantle plume (Fig. 1) are the most active ones whereas Kverkfjöll, located farther from the centre, shows much lower activity.

The eruption frequency of these volcanoes does not coincide with that of volcanoes on the southern part of the Eastern Volcanic Zone (EVZ). At the Katla volcanic system TLF is at maximum at 8-7 ka and 4-2 ka (Óladóttir et al. 2005, 2008; Fig. 8). Furthermore, dated Icelandic tephra layers of silicic composition show frequency maxima at 8-7 ka and 3-1 ka (Larsen and Eiríksson 2008a), similar to the estimated basalt eruption frequency of Katla and the overall lava age distribution on the EVZ (Jakobsson 1979). The majority of the silicic eruptions occurred at Hekla, Katla, Torfajökull and Eyjafjallajökull central volcanoes (Larsen and Eiríksson 2008a) on the southern, non-rifting part of the EVZ.

This age difference in peak eruption frequency may suggest that a magma pulse generated during or shortly after the last deglaciation and manifested in high lava flow frequency at the Bárdarbunga volcanic system at 9-8 ka (Fig. 8), was delayed for 1–2000 years on the southern, non-rifting part of the EVZ (e.g. Katla TLF peak 8-7 ka). The pattern was repeated when eruption frequency at Katla, and the volcanoes on the non-rifting part of the EVZ, peaked again at 4-2 ka, 1–2000 years later than the accumulated TLF peak at 6-5 ka from the three volcanoes under Vatnajökull. Given the clear maximum in eruption frequency above the mantle plume at 2-1 ka, a significant increase in volcanism could be expected at the volcanoes on the non-rifting part of the EVZ (Katla, Hekla etc.) in the next 1000 years. We conclude that periodic magma generation and delivery from the mantle plume are likely to control the overall eruption frequency at the subglacial Vatnajökull volcanoes, whereas diverted mantle and melt flow away from the plume core during ascent (e.g. Ito 2001) and less extensional stress regime could explain the delay in peak activity on the southern, non-rifting part of the EVZ.

Temporal variations in eruption frequencies at individual volcanic systems beneath the Vatnajökull ice-cap

The indistinct activity difference between Grímsvötn and Bárdarbunga/Kverkfjöll (peaking at 7-6 ka and 6-5 ka, respectively; Fig. 7) indicates that a postulated pulsing mantle plume is unlikely to account fully for the finer variations in eruption frequency at a given volcano. If deep-seated mantle pulses were entirely responsible for the changes in eruption frequency in these volcanic systems they should be completely synchronised, at least at Grímsvötn and Bárdarbunga, which maintain similar positions relative to the plume centre (Wolfe et al. 1997). Different structures of the magma plumbing systems beneath volcanoes have been shown to control eruption frequency in the case of Katla volcano (Óladóttir et al. 2008). There, the highest eruption frequency occurs during periods dominated by sill and dyke complexes, and a similar situation may well influence the individual eruption frequencies at the Vatnajökull volcanoes (Óladóttir 2009) resulting in a subtle time difference in eruption frequency maxima between volcanic systems.

Conclusions

Data obtained from seven soil profiles around the Vatnajökull ice-cap have revealed the prehistoric eruption history of the ice-covered part of the three volcanic systems, Grímsvötn, Bárdarbunga and Kverkfjöll, since ~7600 years ago. Correlated tephra stratigraphy based on dated marker tephra layers, soil accumulation rate age calculations and major-element chemistry of the volcanic glass, provides a record of 345 tephra layers. Of these 135 were erupted from Grímsvötn, 87 from Bárdarbunga and 17 from Kverkfjöll.

The ratio of Grímsvötn and Bárdarbunga tephra layers preserved outside the ice-cap during the last 8 centuries of historical time in Iceland was used to obtain an estimate of the actual eruption frequency in prehistoric time, yielding an estimated total of 960 eruptions in Grímsvötn, Bárdarbunga and Kverkfjöll during the last ~7600 years.

During historical and the prehistoric time assessed, the total number of eruptions on the ice-covered part of the Grímsvötn volcanic system is ~540, making it the most active Icelandic volcanic system in terms of eruption frequency. The record shows two peaks in activity, at 7-6 ka with 48 eruptions per 1000 years, and at 2-1 ka when 140 eruptions took place. Such increased eruption frequency is also observed in the Bárdarbunga volcanic system, which is the second-most active volcanic system with ~350 eruptions during the last ~7600 years. The record shows two peaks in activity, the highest at 2-1 ka as at Grímsvötn, but with an older activity peak at 6-5 ka lagging that of Grímsvötn by 1000 years. Both systems show a strong activity decrease during the last millennium.

The Kverkfjöll volcanic system has been considerably less active than Grímsvötn and Bárdarbunga, with only ~70 eruptions inferred during the ~6500 years studied during prehistoric time and none during historical time. A distinct peak is seen at 6-5 ka, with sporadic activity in the preceding and following millennia. A period of repose at 4-3 ka was followed by sporadic activity from 3-1 ka. The overall activity is relatively low at 4–32 eruptions per 1000 years.

All three volcanic systems show a lull in activity between 5 and 2 ka, referred to as the Mid-Holocene low, caused by decrease in volcanic activity that has been related to periodic variation in magma generation and delivery from the mantle source rather than to changes in environmental factors, such as changing ice load and ice cover.

Differences in the timing of maximum eruption frequency at volcanoes close to the centre of the Iceland mantle plume, and from those at volcanoes located on the non-rifting part of the Eastern Volcanic Zone (EVZ) can be explained by a model of diverted flow away from the plume core during ascent. Such a model indicates that a significant increase in volcanism may be expected on the southern EVZ in the future.

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