Reviewed research article

Postglacial volcanism in Iceland

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Abstract – *Iceland is one of the most active and productive terrestrial volcanic regions, with eruption frequency of* $\geq$*20 events per century and magma output rates of* $\geq$*5 km*^{3} *per century. Although Iceland is dominated by mafic magmatism and volcanism, as is evident from 91:6:3 distribution of mafic, intermediate and silicic eruptions, its record also features most common terrestrial magma types and eruption styles. Postglacial volcanism is confined to the neovolcanic zones where 30 active volcanic systems are responsible for most of the Holocene activity. On the basis of our current post-glacial eruption data set we estimate that Icelandic volcanism has produced around 2400 eruptions and about 566±100 km*^{3} *of erupted magma in the last 11 ka. Effusive activity accounts for ∼500 eruptions; the remainder is explosive and dictated by subglacial mafic events (∼77%), demonstrating strong environmental influence on eruption styles in Iceland. In terms of magma output the record is dominated by large volume (>1 km*^{3}*) effusive mafic eruptions. About 50 such eruptions have occurred throughout postglacial time or ∼2% of the total number of eruptions. However, collectively these events produced about 55% of the postglacial magma volume. The Eastern Volcanic Zone is responsible for >80% of the eruptions and ∼60% of the erupted magma volume and has been by far the most prolific producer among the neovolcanic zones. Furthermore, the volume of mafic effusive eruptions is not evenly distributed through post-glacial time, because only 30% (∼111 km*^{3}*) of the total volume was produced in the last 5 ka and the remaining 70% (258 km*^{3}*) between 5–11 ka. However, the production rate per millennia within these two periods appears to be fairly even, ranging from 20–30 km*^{3} *in <5 ka period and 35-40 km*^{3} *in the 5–10 ka interval. The exception is the 10–11 ka interval, when ∼70 km*^{3} *of mafic lava was formed by the effusive activity or close to double the volume produced per millennia in the period that followed.*

INTRODUCTION

Volcanism in Iceland is diverse, spanning almost the range of common terrestrial magma types and eruption styles (e.g. Thordarson and Larsen, 2007). Nonetheless, it is dominated by mafic magmatism and volcanism, representing ∼91% of the total postglacial magma output and number of eruptions. Iceland is also one of the most active and productive subaerial volcanic region on Earth, with eruption frequency of ≥20 events per century and magma output rates of ∼8 km^3 per century in historic time (i.e. over the last 1100 years). Furthermore, the volcanism is symbolized by mafic effusive eruptions, although mixed (i.e. tephra- and lava-producing) and explosive mafic eruptions are more common in Iceland than in other compatible volcanic regions. The relatively high frequency of mixed eruptions is primarily due to prolific activity at the Hekla volcano during the Holocene, whereas the mafic explosive events results from the country's geography, which promotes frequent subglacial and submarine (i.e. hydromagmatic) eruptions, including the three largest terrestrial explosive basalt eruptions in the last 10 ka (Larsen, 1984, 2005; Jóhannsdóttir *et al.*, 2006). Silicic volcanism does feature strongly in Iceland and some of the largest explosive eruptions in Europe originated at Icelandic volcanoes and produced tephra layers that now serve as time markers in Holocene sediment sequences on both sides of the North Atlantic (e.g. Hafliðason *et al.*, 2000). Consequently, Iceland is often identified as an ideal 'natural' laboratory for volcanological research and as such has attracted many researchers for more than a Century.

The task we were asked to undertake is to produce an overview of post-glacial volcanism in Iceland (i.e. over the last 11ka). Although this task may appear straightforward, the perception of the volcanism is manifold and the topic can be approached from number of perspectives. To keep the scope of the study at manageable length we limit our treatment to the subaerial part of the volcanism and focus our efforts on volcanic eruptions and their surface products. Consequently, no attempt is made here to evaluate subsurface volcanic processes despite their significance, especially in regard to volcano monitoring. Also, note all ages are given as calendar years.

In order to produce an up to date overview of the postglacial volcanic activity, we have compiled all of the eruption data available in published papers and records. Here we evaluate the results provided by this data set in terms of number of postglacial eruptions and their magma outputs. We also use this dataset to produce an overview of the eruption styles that typify Icelandic volcanism and provide some assessment of its authenticity. One aspect of the volcanic activity that is not included because of space limitations is outgassing of magmatic volatiles during eruption as well as their potential environmental and climatic effects. Studies of Icelandic eruptions and their products have contributed significantly to this branch of volcanology and appropriate bibliography to studies on this topic can be obtained from Thordarson *et al.* (1996, 2001), Nichols *et al.* (2002), Thordarson and Self (2003), Höskuldsson *et al.* (2006), Moune *et al.* (2006) and Oman *et al.* (2006); Óladóttir *et al.*, 2007.

VOLCANISM IN ICELAND

The Iceland Basalt Plateau rises more than 3000 m above the surrounding sea floor, has crustal thickness of 10–40 km and covers about 350,000 km^2. It is the only currently active part of the $\sim$2000 km-long North Atlantic Igneous Province (e.g. Gudmundsson, 2000; Saunders *et al.*, 1997). The neovolcanic zones in Iceland, which collectively cover $\sim$30,000 km^3, delineate discrete 15–50 km-wide belts of active faulting and volcanism. The nomenclature used here for individual zones is shown on Figure 1. The neovolcanic zones are further divided into volcanic systems, which can be viewed as the principal geological structure in Iceland. It is characterised by conspicuous volcano-tectonic architecture that features a fissure (dyke) swarm or a central volcano or both and has a typical lifetime of 0.5–1.5 million years (e.g. Jakobsson *et al.*, 1978; Jakobsson, 1979; Sæmundsson, 1978, 1979; Guðmundsson, 1995b, 2000). The fissure swarms are elongate structures (5 to 20 km-wide and 50 to 200 km-long) that normally are aligned sub-parallel to the axis of the hosting volcanic zone. The central volcano, when present, is the focal point of eruptive activity and normally the largest edifice within each system (Figure 1). A total of thirty active volcanic systems are identified; 3 within the RVZ, 6 in the WVZ, 2 in MIB, 5 in the NVZ, 8 in the EVZ and 3 in each of the intraplate volcanic belts (Table 1). The size of individual systems ranges from $\sim$25 to 2500 km^2 and their length from 7 to 200 km. The largest system is the Bárdarbunga-Veidivötn volcanic system and the smallest the Hrómundartindur system. Twenty systems feature a fissure swarm and 12 have well-developed and mature swarms, 5 are of moderate maturity and 4 are embryonic (Thordarson and Larsen, 2007). In total, 23 central volcanoes are known from 19 volcanic systems and 4 systems - Hofsjökull, Tungnafellsjökull, Bárdarbunga-Veidivötn and Grímsvötn - contain two central volcanoes (Figure 1; Table 1).

Spreading and rifting is not a continuous process and events on the volcanic systems are closely linked to plate movements (e.g. Sigurdsson and Sparks, 1978; Björnsson *et al.*, 1979; Brandsdóttir and Einarsson, 1979; Björnsson, 1985). Spreading takes place in

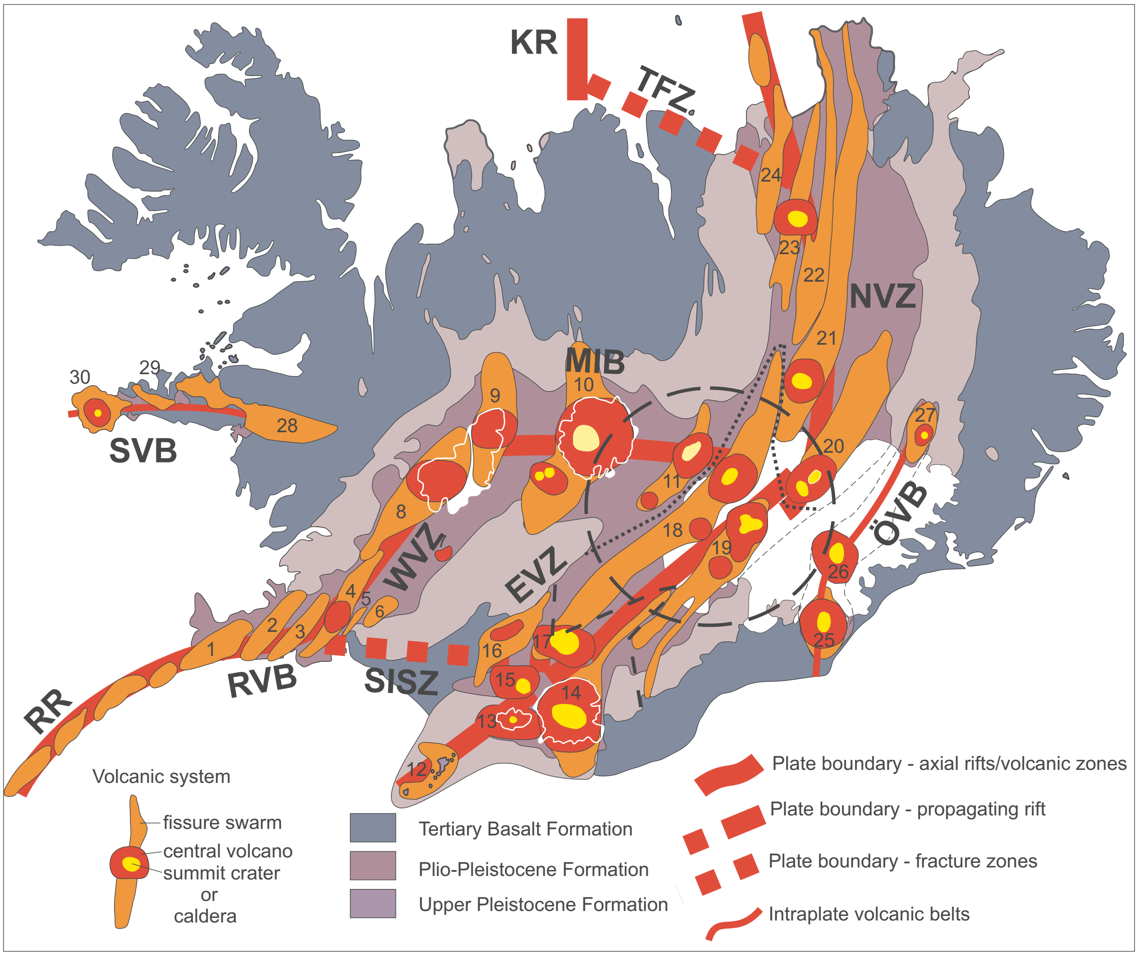

Figure 1. Distribution of active volcanic systems among volcanic zones and belts in Iceland as depicted by Jóhannesson and Sæmundsson (1998). Abbreviations are as follows: RR, Reykjanes Ridge; RVB, Reykjanes Volcanic Belt; SISZ, South Iceland Seismic Zone; WVZ, West Volcanic Zone; MIB, Mid-Iceland Belt; EVZ, East Volcanic Zone; NVZ, North Volcanic Zone; TFZ, Tjörnes Fracture Zone; KR, Kolbeinsey Ridge; ÖVB, Öræfi Volcanic Belt; and SVB, Snæfellsnes Volcanic Belt. Numbers refer to volcanic systems in Table 1. The large open circle indicates the approximate centre of the Iceland mantle plume/anomaly as depicted by Wolfe *et al.* (1997). Dotted line shows the northern limits of the East Volcanic Zone, whereas the hachured line indicates the boundary between the active and propagating rift segments of the zone. – *Einfaldað kort sem sýnir dreifingu og útbreiðslu virkra eldstöðvarkerfa og gosbelta á Íslandi. Merkingar og skammstafanir: RR, Reykjaneshryggurinn; RVB, Reykjanesgosbeltið; SISZ, Suðurlandsskjálftabeltið; WVZ, Vesturgosbeltið; MIB, Mið-Íslands beltið; EVZ, Austurgosbeltið; NVZ, Norðurgosbeltið; TFZ, Tjörnes brotabeltið; KR, Kolbeinseyjarhryggurinn; ÖVB, Öræfajökulsgosbeltið og SVB, Snæfellsnesgosbeltið. Númerin vísa til eldstöðvakerfa í töflu 1.*

Table 1. Volcanic systems in Iceland. Based on Jóhannesson and Sæmundsson (1998). – *Virk eldstöðvarkerfi á Íslandi.*

	Volcanic Zone	Name	Max. Elev.[1] (m a.s.l.)	Length (km)	Width (km)	Area (km^2)	Fissure swarm[2]	Central volcano	Name of central volcano
1	RVZ	Reykjanes/Svartsengi	163	58	13	350	xxx	d	
2	RVZ	Krýsuvík	393	55	13	300	xxx	d	
3	RVZ	Brennisteinsfjöll	621	45	10	280	xxx	d	
4	WVZ	Hengill	803	60	9	370	xxx	cv	Hengill
5	WVZ	Hrómundartindur	283	7	8	25		d	
6	WVZ	Grímsnes	214	15	8	100	xx	d	
7	WVZ	Geysir°	600	7	7	25		d	
8	WVZ	Prestahnjúkur	1400	80	27	950	xxx	cv	Prestahnjúkur
9	WVZ	Hveravellir	1000	60	18	720	xx	cv	Hveravellir
10	MIB	Hofsjökull	1763	95	38	2200	xxx	cv	Hj./Kerlingarfjöll
11	MIB	Tungnafellsjökull	1520	55	15	530	xx	cv	Tj./Hágöngur
12	EVZ	Vestmannaeyjar	283	28	25	<480	xx	d	
13	EVZ	Eyjafjallajökull	1666	30	14	300		cv	Eyjafjallaj.
14	EVZ	Katla	1450	110	30	1300	x	cv	Mýrdalsj.
15	EVZ	Tindfjöll°	1462	20	14	230		cv	Tindfjöll
16	EVZ	Hekla/Vatnafjöll	1491	60	19	720	xx	cv	Hekla
17	EVZ	Torfajökull	1278	50	20	900		cv	Torfaj.
18	EVZ	Bárdarbunga/Veiðivötn	2009	190	28	2500	xxx	cv	Bb./Hamarinn
19	EVZ	Grímsvötn	1719	100	23	1350	x	cv	Gv./Thórdarhyrna
20	NVZ	Kverkfjöll	1929	120	20	1600	xxx	cv	Kverkfjöll
21	NVZ	Askja	1510	200	20	2300	xxx	cv	Askja
22	NVZ	Fremrinámur	800	150	15	1200	xxx	d	
23	NVZ	Krafla	818	100	19	900	xxx	cv	Krafla
24	NVZ	Þeistareykir	600	90	9	650	xxx	d	
25	ÖVB	Öræfajökull	2119	20	21	250		cv	Öræfajökull
26	ÖVB	Esjufjöll°	1700	25	21	400		cv	Snæhetta
27	ÖVB	Snæfell°	1833	20	11	170		cv	Snæfell
28	SVB	Ljósufjöll	1063	80	15	720	x	d	Ljósufjöll
29	SVB	Helgrindur (Lýsuskarð)	647	30	8	220	x	d	
30	SVB	Snæfellsjökull	1446	30	20	470		cv	Snæfellsjökull

[1] Maximum elevation above sea level. [2] xxx, mature; xx, moderate maturity; x, embryonic. °No verified eruption of Holocene age.

distinct rifting episodes that usually are confined to a single volcanic system, although near-concurrent activity on two or more systems is known (e.g. Einarsson and Jóhannesson, 1989; Sigurgeirsson, 1995; Larsen *et al*. 1998). The whole system is activated in these episodes and they can last for several years to decades. It is tradition to refer to such volcanic episodes as 'Fires' (e.g. the Krafla Fires; Einarsson, 1991).

VOLCANIC ERUPTIONS IN ICELAND

Volcanoes define a wide spectrum of forms, ranging from a crack in the ground to the stately stratovolcanoes, and this variability is showcased exceptionally well in Iceland (Figure 2). The country displays all known volcano types on Earth (e.g. Thordarson and Larsen, 2007).

Despite the dominance of mafic volcanism in Iceland, the style and type of volcanic activity is very diverse and not surpassed by any other volcanic region on Earth. Emission of basalt magma has produced effusive eruptions of hawaiian and flood lava magnitudes. Expulsion of basalt, intermediate and silicic magmas have produced explosive phreatomagmatic and magmatic eruptions spanning almost the entire style range; from Surtseyan to phreatoplinian in case of 'wet' eruptions and Strombolian to Plinian in terms of 'dry' eruptions (e.g. Thordarson and Lar-

Figure 2. Examples of volcano types in Iceland: (a) Eyjafjallajökull, shield volcano; (b) Hekla, stratovolcano; (c) Öskjuvatn, caldera; (d) Eldborg á Mýrum, spatter cone (photo: Rúrik Haraldsson); (e) Eldfell on Heimaey, scoria cone; (f) Hverfjall at Mývatn, tuff cone (photo: Oddur Sigurðsson); (g) Kollóttadyngja, lava shield; (h) Eldgjá, chasm (photo: Oddur Sigurðsson); (i) Laki fissures, mixed cone row; and (j) Vatnaöldur, row of tuff cones and maars (photo: Oddur Sigurðsson). – *Ljósmyndir sem sýna algeng eldfjöll á Íslandi. (a) Eyjafjallajökull, hraunkeila; (b) Hekla, eldkeila; (c) Öskjuvatn, askja; (d) Eldborg á Mýrum, klepragígur; (e) Eldfell, gjallgígur (f) Hverfjall, sprengigígur; (g) Kollóttadyngja, hraunskjöldur, (h) Eldgjá, eldgjá; (i) Lakagígar, blandröð, and (j) Vatnaöldur, sprengigígaröð.*

sen, 2007). Consequently, the eruptions in Iceland, regardless of their environmental setting, can be purely explosive or effusive or a mixture of both. According to the classification scheme of Thorarinsson (1981a), an eruption is effusive if lava comprises ≥95% of the volume of erupted products and explosive if the DRE-volume (Dense Rock Equivalent volume) of the tephra is ≥95% of the total volume produced. Anything inbetween is considered as a mixed eruption. However, it is difficult to apply this classification scheme to Holocene eruptions because the relative proportion of tephra to lava is not known for majority of the events. Therefore, we have elected to let all identified lavas represent an effusive eruption and by the same token tephra layers mark an explosive event. However, when the same eruption is known to have produced tephra and lava, it is counted as explosive if the volume of tephra is >50% of the total DRE product volume and effusive when the corresponding value for the lava is ≥50%.

NUMBER OF ERUPTIONS AND MAGMA VOLUMES

Over the last 40 years or so a number of researchers have made an ample effort in documenting Holocene eruptive events, mapping distribution of Holocene lava and recording the tephra stratigraphy (e.g. Jónsson, 1978a, 1978b, 1983; Jakobsson, 1968, 1979; Jóhannesson, 1982, 1983; Jóhannsdóttir, 2007; Larsen, 1979, 1982, 1984, 2000; Larsen and Thorarinsson, 1977; Larsen *et al.*, 1998; 1999, 2001, 2002; Höskuldsson and Imsland, 1998; Mattson and Hoskuldsson, 2003; Óladóttir *et al.*, 2005, 2008; Steinthorsson, 1978; Sigbjarnarson, 1988, 1996; Sigvaldason *et al.*, 1992; Sigurgeirsson, 1992, 1995; Sinton *et al.*, 2005; Sæmundsson, 1991, 1992, 1995; Sæmundsson and Friðleifsson, 2001; Torfason *et al.*, 1993; Thorarinsson, 1951, 1958, 1965, 1967a, 1970, 1974, 1975; Vilmundardóttir, 1977; Vilmundardóttir *et al.*, 1983, 1988, 1990, 1999a, 1999b). Despite this effort, the record of Holocene eruptions in Iceland is not complete, which exerts some limitation on assessments of postglacial volcanism in Iceland and the overview presented here, therefore, only gives ball-park figures for the essential eruption variables. Magma volume figures are given here as DRE volumes, unless stated otherwise.

LAVA-PRODUCING ERUPTIONS

The record on number and volume of lava-producing eruptions is reasonably complete and indicates that the number of postglacial effusive eruptions is 501, thereof 56 since settlement (i.e. last 1140 yrs). However, although the 'Fires' of historic time are counted as one event, that is not the case for the prehistoric events. Individual 'Fires' in historic time typically feature several eruptions (i.e. 2–9 events) and thus it is likely that we overestimate the actual number of effusive eruptions in prehistoric time by 10–15%. Notwithstanding, these eruptions produced $\sim$390±50 km^3 of lava (Table 2). About 90% of the events are mafic and collectively account for $\sim$370 km^3 (94%) of the post-glacial lava volume. Currently, there are 29 intermediate and 15 silicic events on record, which produced $\sim$23 km^3 (5.3%) and $\sim$1.2 km^3 (0.3%) of lava, respectively. Although significant uncertainties remain regarding number and volume of events in the post-glacial lava successions, the record for individual volcanic zones is reasonably coherent and is summarized in Table 2. The compilation indicates that the volcanic zones of the axial rift (i.e. RVB, WVZ, MIB, and NVZ) have featured 288 effusive eruptions in post-glacial time, including 29 historic events, and produced $\sim$121±20 km^3 of magma. All except two of the events in our records are mafic (>99%). However, the most prolific producer of the volcanic zones is the EVZ with $\sim$163 events and lava volume of $\sim$174±10 km^3 (Table 2). EVZ is also the site for 27 out of 29 (93%) intermediate events and 12 out of 15 (80%) of effusive silicic eruptions. Additional 52 effusive eruptions are known from the off-rift volcanic belts, 50 mafic events along with one intermediate and one silicic event. Alone the SVB has 45 basalt and one intermediate eruption, with a compiled lava volume of $\sim$8 km^3 (Table 2).

TEPHRA-PRODUCING ERUPTIONS

Assessing the number and volume of Holocene tephra producing eruptions is more challenging because (a)

Table 2. Estimated number of postglacial eruptions in Iceland and their erupted volumes. – *Áætlaður fjöldi eldgosa og rúmmál gosefna á Nútíma.*

a) Number of eruptions

	Effusive eruptions		Explosive eruptions		Total	%
	Postglacial	historic	Postglacial predicted	historic		
Mafic	457	41	1772	146	2229	91
Intermediate	29	11	112	7	141	6
Silicic	15	4	48	8	63	3
Sum	501	56	1933	161	2434	
Reykjanes Volcanic Belt	111	15	33	12	144	6
Western Volcanic Zone	39	1	8	0	47	2
Northern Volcanic Zone	129	13	17	5	146	6.0
Eastern Volcanic Zone	163	25	1860	142	2023	83
Mid-Iceland Belt	9	0	0	0	9	0.4
Öræfajökull Volcanic Belt	4	1	4	2	8	0.3
Snæfellsnes Volcanic Belt	46	1	11	0	57	2.6
Sum	501	56	1933	161	2434	

b) Erupted magma volume.

	Lava	%	Tephra	%	Tephra (DRE)	%	Total	%	Total (DRE)	%
Mafic	369	93.9	367	82	149	86	736	88	518	91
Intermediate	23	5.8	25	6	11	6.5	48	6	34	6
Silicic	1.2	0.3	54	12	13	7.5	55	7	14	3
Sum	393		446		173		839		566	
Reykjanes Volcanic Belt	26	6.7	7	1.6	2.9	1.7	34	4.0	29	5.2
Western Volcanic Zone	94	24	0	0	0	0	94	11.2	94	16.6
Northern Volcanic Zone	90	23	12	3	3.3	1.9	102	12	94	16.5
Eastern Volcanic Zone	174	44	412	92.5	163.4	94.2	586	69.9	337	59.5
Mid-Iceland Belt	1	0.3	0	0	0	0	1	0.1	1	0.2
Öræfajökull Volcanic Belt	0	0	11	2.4	2.4	1.4	11	1.3	3	0.4
Snæfellsnes Volcanic Belt	8	2	4	1	1.3	0.8	12	1.4	9	1.6
Sum	393		446		173		839		566	

Sources: Jónsson, 1945; Thorarinsson, 1951, 1958, 1965, 1967a, 1970, 1974, 1975; Thorarinsson and Sigvaldason, 1962; 1972; Jakobsson, 1968, 1979b; Larsen and Thorarinsson, 1977; Vilmundardóttir, 1977; Jóhannesson, 1977, 1982; Jónsson, 1978a,b, 1983; Steinthórsson, 1978; Larsen, 2000, 2002; Jóhannesson *et al.* 1981; Vilmundardóttir *et al.*, 1983, 1988, 1990, 1999a, 1999b; Hjartarson, 1988, 2003; Jóhannesson and Einarsson, 1988; Macdonald *et al.*, 1990; McGarvie *et al.*, 1990; Sæmundsson, 1991, 1992, 1995; Róbertsdóttir *et al.*, 1992; Sigvaldason *et al.*, 1992; Thordarson and Self, 1993; Torfason *et al.*, 1993; Larsen *et al.*, 1998; 1999, 2001, 2002; Haflidason *et al.*, 2000; Hardardóttir *et al.*, 2001; Sæmundsson and Friðleifsson, 2001; Thordarson *et al.*, 2003a; Mattson and Höskuldsson, 2003; Sinton *et al.*, 2005; Óladóttir *et al.*, 2005; Jóhannsdóttir, 2007; Sigurgeirsson, 1992, 1995; Thordarson and Larsen, 2007; Larsen and Eiríksson, 2007.

<35% of explosive eruptions is registered as a tephra layer in Holocene sediment archives, (b) the postglacial tephra stratigraphy for Iceland is not complete or fully synchronized and (c) distribution of <10% of the known tephra layers have been mapped. As a result, we do not have a complete record of the number of tephra layers preserved in the Holocene sediment archives let alone the number of explosive eruptions in the last 11 ka.

As expected, the record of explosive eruptions is most comprehensive in historical times, especially in the last 800 years (i.e. since AD 1200). The existing record has been compiled from three types of archives: (a) tephra layers preserved in soil profiles across the country, (b) layers in ice cores and ice ablation areas within the Vatnajökull Glacier, and (c) information on eruptions contained in historical chronicles. It indicates that ∼156 explosive eruptions have taken place in Iceland since 1200 AD, but only 57 are registered as tephra layers in the post AD1200 soils (e.g. Thordarson and Larsen, 2007; Larsen and Eiríksson, 2007).

The AD1200-AD2004 record is dominated by activity within the EVZ volcanic systems, which are responsible for ∼87% of the recorded events. The subglacial Grímsvötn volcano has been most active, with ∼47% of the events and ∼22% (3.6 km^3) of the magma output. The Bárðarbunga-Veiðivötn, Katla and Hekla systems are accountable for ∼15%, ∼12% and ∼11% of events and ∼15% (2.5 km^3), ∼28% (4.6 km^3) and 7% (1.2 km^3) of the magma output. The remaining EVZ volcanic systems produced <3% of the explosive eruptions and ∼6% (1 km^3) of the erupted magma. Other volcanic zones collectively account for ∼13% of the events and ∼22% (3.6 km^3) of the magma output (e.g. Thordarson and Larsen, 2007).

Despite the dominance of Grímsvötn and Bárðarbunga volcanoes in the explosive eruption record, their activity has only produced 14 (<25%) out of 57 tephra layers present in the post-AD1200 soils (e.g. Thorarinsson, 1967a; Larsen, 1979; 1982; Hafliðason *et al.*, 2000; Thordarson *et al.*, 1998). The soil record is governed by the Katla and Hekla volcanoes, which have produced >55% of the tephra layers preserved in the post-AD1200 soils. The simplest explanation of this differential representation is the remoteness of Grímsvötn and Bárðarbunga and favourable position of Katla and Hekla with respect to good soil-trap sites. Conversely, the tephra-in-ice record from the Vatnajökull ice-cap is dictated by the Grímsvötn and Bárðarbunga (Figure 1). About 88% of the tephra layers in the ice originate from these two volcanoes (Larsen *et al.*, 1998).

The tephra capture frequency in post-AD1200 soil at any one site near the active volcanic zones is on the order of 1–2 layers/100 yrs. However, the composite record compiled here indicates that collectively about 7 tephra layers are incorporated into the soil cover in Iceland per Century. This value compares favourably with the first three Centuries of settlement, where total of 18 layers imply a capture rate of 6 layers/100 yrs. Thus, collectively the historic soils register <1/3 of the actual number of explosive eruptions. This information is important for assessment of number of prehistoric explosive eruptions, because the on-land tephra stratigraphy is the principal data archive. Accordingly, the prehistoric tephra stratigraphy is likely to underestimate the number of explosive eruptions in Iceland by a factor of ∼3.

The prehistoric tephra record in Iceland is impressive and has been measured in thousands of soil profiles across the country (e.g. Thorarinsson, 1958, 1967a) and steadily improved over the last 30 years by various studies. Nonetheless, majority of published records only extend back to H3 (3 ka) or H4 (4.2 ka) or H5 (∼7 ka) times (Larsen, 1979, 1984, 2002; Jóhannesson *et al.* 1981; Róbertsdóttir *et al.*, 2092; Boygle, 1999; Larsen *et al.* 2001, 2002; Hardardóttir *et al.*, 2001). Only a handful of measured sections extend beyond 8 ka (e.g. Sæmundsson, 1991; Larsen, 2000; Óladóttir *et al.*, 2005). However, recent studies of the tephra succession in lake sediments have extended the record beyond 10 ka (e.g. Jóhannsdóttir, 2007). Offshore marine sediment- and Greenland Ice-cores extend the record even further back in time although much fewer events are preserved at these far-field sites (e.g. Haflidason *et al.*, 2000; Jennings *et al.* 2002; Larsen *et al.*, 2002; Kristjánsdóttir *et al.*, 2007).

Despite the existence of extensive records for the last 7 ka in all parts of the country, the total tally of explosive eruptions represented by the tephra layers in these archives is still uncertain. The most complete records exist closest to the active volcanic zones, especially near the EVZ (Figure 3a). The soils in the Álftaver highland pasture, South Central Iceland (site 1 on Figure 3a), preserve a record extending back to ∼8.5 ka, containing about 208 tephra layers, indicating a capture of ∼2.5 layers/100 years (Óladóttir *et* *al.*, 2005; 2008). Further east, at sites 2 and 3, ∼7 ka-long records contains 73 and 25 layers, or 1 and 0.4 layers/100 yrs, respectively (Thorarinsson, 1958). Similarly long records at sites 4, 5 and 6 in the interior of North and East Iceland contain 67, 20, 11 layers each, indicating a capture of 1 to 0.2 layers per Century (Thorarinsson, 1958; Larsen *et al.*, 2002). The tephra layer capture rate in 3–7 ka-long records along the western edge of the EVZ is ∼1 tephra layer per Century (range 0.3–1.5; Thorarinsson, 1967a; Larsen, 1979), whereas in the lake sediment archive at sites 7 and 8, extending back to ≤11 ka, the rate is 1.3–1.6 layer/100 yrs (e.g. Jóhannsdóttir, 2007). Further to the NW (i.e. sites 9 to 13 on Figure 3a), the capture rate is ∼0.4 to ∼0.02 layers per 100 yrs. This information shows that the prehistoric tephra capture rate at sites near the active volcanic zones is comparable to that of historic time. It also shows that the capture rate drops off abruptly with increasing distance from the active volcanic zones (Figure 3b).

Sites 1, 4, 7, and 8 contain the most comprehensive tephra record and individually exhibit capture frequencies of 1 to 2.5 layer/100yrs. These records are likely to be complementary because of their relative position to the most active tephra producing volcanoes (see below). Their collective capture rate is ∼6.5 layers/100 yrs or identical to that obtained for historical soils. This suggests that the overall pattern of prehistoric explosive volcanism in Iceland was similar to that of the last 800 years, although the eruption pattern of individual central volcanoes changed somewhat from time to time. Furthermore, chemical analysis of the tephra succession at sites 7 and 8, which indicate that >95% of the post-glacial tephra layers originated from the EVZ volcanoes, Grímsvötn, Bárðarbunga, Katla and Hekla. It also shows that Katla and Hekla layers dominate the record, primarily because of these volcanoes are closest to these sites (Figure 3a). This conjecture can be used, along with existing data on the prehistoric tephra layers, as a template to estimate the total number of post-glacial explosive eruptions in Iceland as well as their cumulative magma output volumes. These estimates are given in Table 2, along with their likely distribution among the active volcanic zones.

If we take the numbers derived above at face value, a 6.5 layer per century capture rate indicates that the post-glacial soil and lake sediment archives in Iceland should contain >700 tephra layers. As the preserved tephra layers only correspond to one-third of the actual events, the total number of explosive eruptions in Iceland over the last 11 ka should be about 2000 events, which brings the total tally of post-glacial eruptions to just over 2400 events (Table 2) This figure corresponds to 22 events per Century, which is similar to the eruption frequency obtained by previous studies (Thorarinsson and Sæmundsson, 1979; Thorarinsson, 1981a). However, this assessment includes number of assumptions with high degree of uncertainty. It also presupposes a steady state for the activity over a period of 11 ka, which in the context of our knowledge of Icelandic volcanoes may be an oversimplification. By the same token, the total DRE volume of tephra produced is ∼173±50 km^3, indicating a total magma output of ∼566±100 km^3 for the post-glacial period. This figure suggests an average postglacial output rate of ∼5 km^3 per Century, which is lower than the 8 km^3 per Century obtained for historic time by Thordarson and Larsen (2007) by a factor ∼1.6. However, it is still significantly higher than the output rate of Hawaiian volcanoes, which is estimated at ∼3.6 km^3 (range, 2.1-4.3 km^3) per Century (e.g. Swanson, 1972; Dvorak and Dzurisin, 1993). This magma output (5 km^3/100 yrs) is about 33% and 5% of the inferred peak output rate for the Columbia River Basalt Group and the Deccan traps flood basalt provinces (Tolan *et al.*, 1989; Self *et al.*, 2006). Note, that these output figures given here are minimum values for the magma productivity at all of these provinces, because they do not account for the volume of non-erupted magma stored in lithospheric intrusions. Their productivity is likely to double or even triple if intrusive volumes are included (e.g. Dvorak and Dzurisin, 1993).

ERUPTION TYPES AND STYLES

Lava-producing eruptions in Iceland occur at monogenetic point-source and fissure type volcanoes as well as central volcanoes where such eruptions typically take place on caldera ring fractures or radial

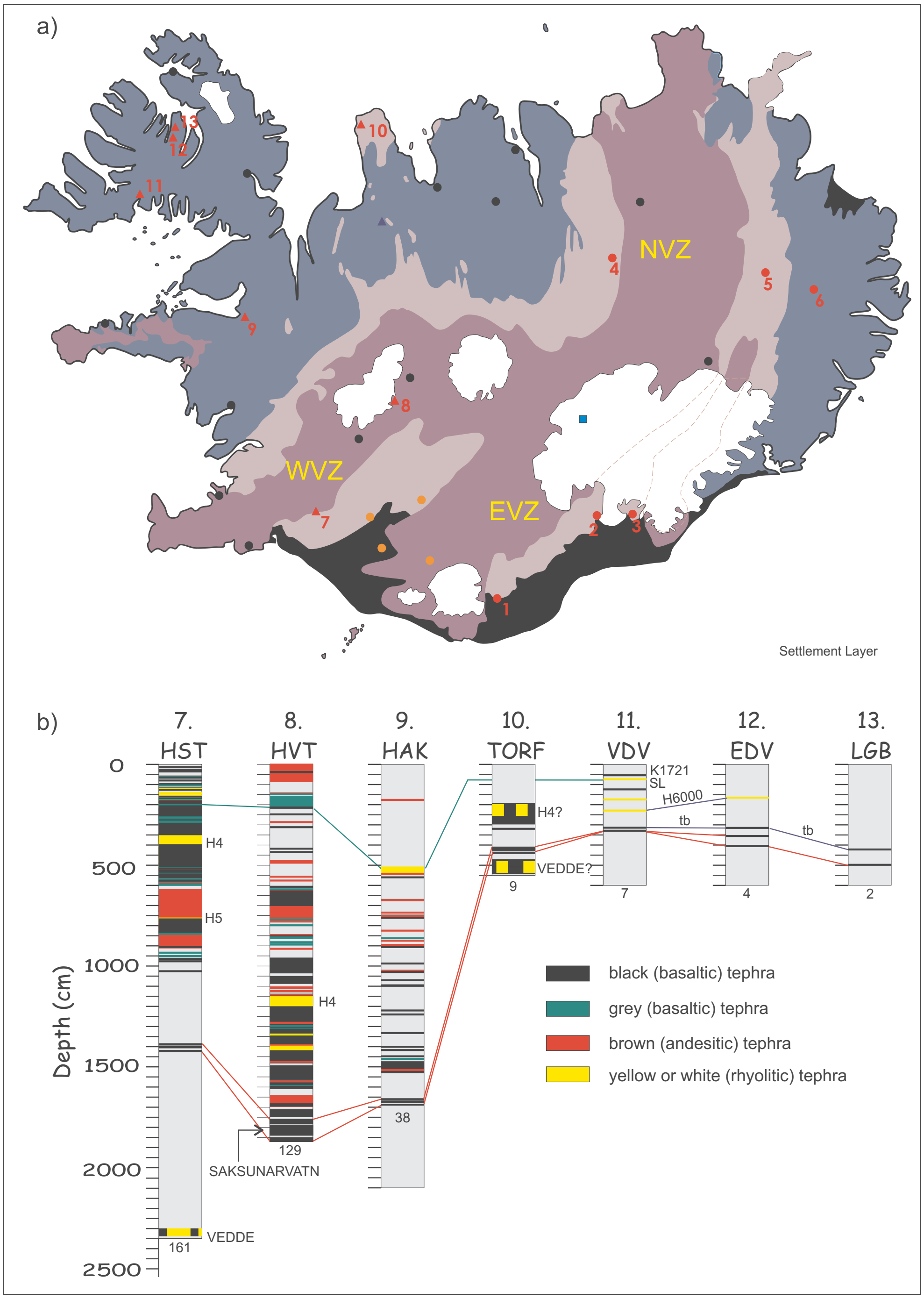
a)
13
12
11
10
9
8
7
NVZ
4
5
6
WVZ
EVZ
2
3
1
Settlement Layer
b)
7.
HST
8.
HVT
9.
HAK
10.
TORF
11.
VDV
12.
EDV
13.
LGB
0
500
1000
1500
2000
2500
Depth (cm)
H4
H5
VEDDE
161
H4
129
SAKSUNARVATN
38
H4?
VEDDE?
9
K1721
SL
H6000
tb
7
4
tb
2
black (basaltic) tephra
grey (basaltic) tephra
brown (andesitic) tephra
yellow or white (rhyolitic) tephra

Figure 3. (a) Sites of selected postglacial tephra sections in Iceland: 1. Álftavatnsafréttur (Larsen, 2000; Óladóttir *et al.*, 2005), 2. Núpstaðarskógur, 3. Bæjarstaðarskógur, 4. Svartárkot, 5. Brú, 6. Hallormstaður (Thorarinsson, 1958), 7. Hestvatn, 8. Hvítárvatn, 9. Haukadalsvatn, 10. Torfadalsvatn, 11. Vatnsdalsvatn, 12. Efstadalsvatn, 13. Laugabólsvatn (Thordarson et al., 2005; Jóhannsdóttir, 2007). (b) Change in number of tephra layers in soils with distance from active volcanic zones. The numbers at the top of each column refer to sites shown on the map in (a) and figures at the base indicate number of tephra layers in each section. Position of the Settlement layer is indicated by green connectors and the Saksunarvatn tephra horizon by the red connectors; tb, tephra layer of transitional basalt composition; H6000, Hekla tephra layer of intermediate composition and approximately 6000 years old. Both layers represent useful marker horizons in the Holocene sediments across Vestfirðir peninsula. – *(a) Staðsetning valdra gjóskusniða á Íslandi: 1. Álftavatnsafréttur, 2. Núpstaðarskógur, 3. Bæjarstaðarskógur, 4. Svartárkot, 5. Brú, 6. Hallormstaður, 7. Hestvatn, 8. Hvítárvatn, 9. Haukadalsvatn, 10. Torfadalsvatn, 11. Vatnsdalsvatn, 12. Efstadalsvatn, 13. Laugabólsvatn. (b) Breytingar a fjölda varðveittra gjóskulaga í jarðvegi með fjarlægð frá gosbeltum. Númerin ofan við hvert snið visa í staðsetningar á kortinu á mynd 3a og þau sem eru undir gefa til kynna fjölda gjóskulaga í hverju sniði.*

fissures. Purely effusive basalt and silicic events are known in the post-glacial volcanic succession, but effusion of intermediate magma without accompanying explosive phase has yet to be recorded. The basalt lava morphology spectrum spans the range of pahoehoe, rubbly pahoehoe to aa. The first two are by far the most common lava types in Iceland, representing 83% of the 190 lavas analysed so far and fissure-fed pahoehoe are as common as shield-forming pahoehoe (Figure 4). The intermediate lavas are characterized by aa and block flows, whereas silicic lavas are typically of the coulee type. No lava dome eruptions are confirmed in Iceland over the last 11 ka, although it is probable that some domes of Mýrdalsjökull, Öræfajökull and Snæfellsjökull volcanoes were formed in this period. Mixed eruptions is included here as a distinct category because they feature both explosive and effusive activity in significant proportions (Thorarinsson, 1981a). In historic time they have almost exclusively been produced by intermediate eruptions and are estimated to represent ∼6–8% of postglacial events in Iceland. With the exception of the 1973 Eldfell eruption at Heimaey (Vestmannaeyjar archipelago), mixed eruptions have been confined to the Hekla volcano (e.g. Thorarinsson 1967a, 1970; Mattsson and Höskuldsson, 2003). Therefore intermediate Hekla eruptions are taken here to typify this group (see below).

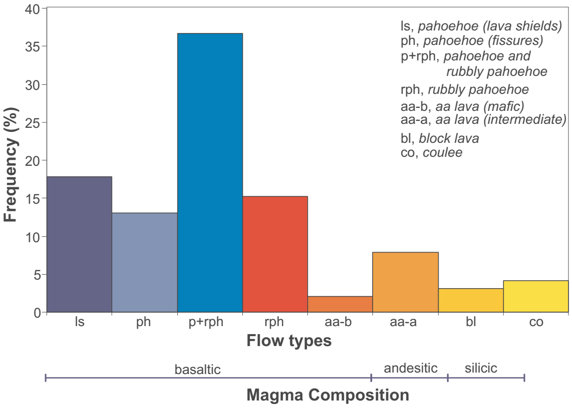

Figure 4. Frequency of lava flow types in Iceland (see key for details). – *Tíðni hraungerða á Íslandi (sjá skýringar í myndlykli).*

Explosive eruptions feature strongly in Iceland, because of high event frequency as well as particular environmental circumstances, and represent the two basic classes of 'wet' (hydromagmatic) and 'dry' (magmatic) explosive eruptions. The historic records and the estimates presented here show that three out of every four eruptions are explosive, of which ∼86% are 'wet' and 14% are 'dry'. The most active volcanoes in the country are covered or capped by a thick glacier. Also, the proximity to the North Atlantic Ocean means that numbers of the active volcanic systems extend into or are situated within the shallow ma-

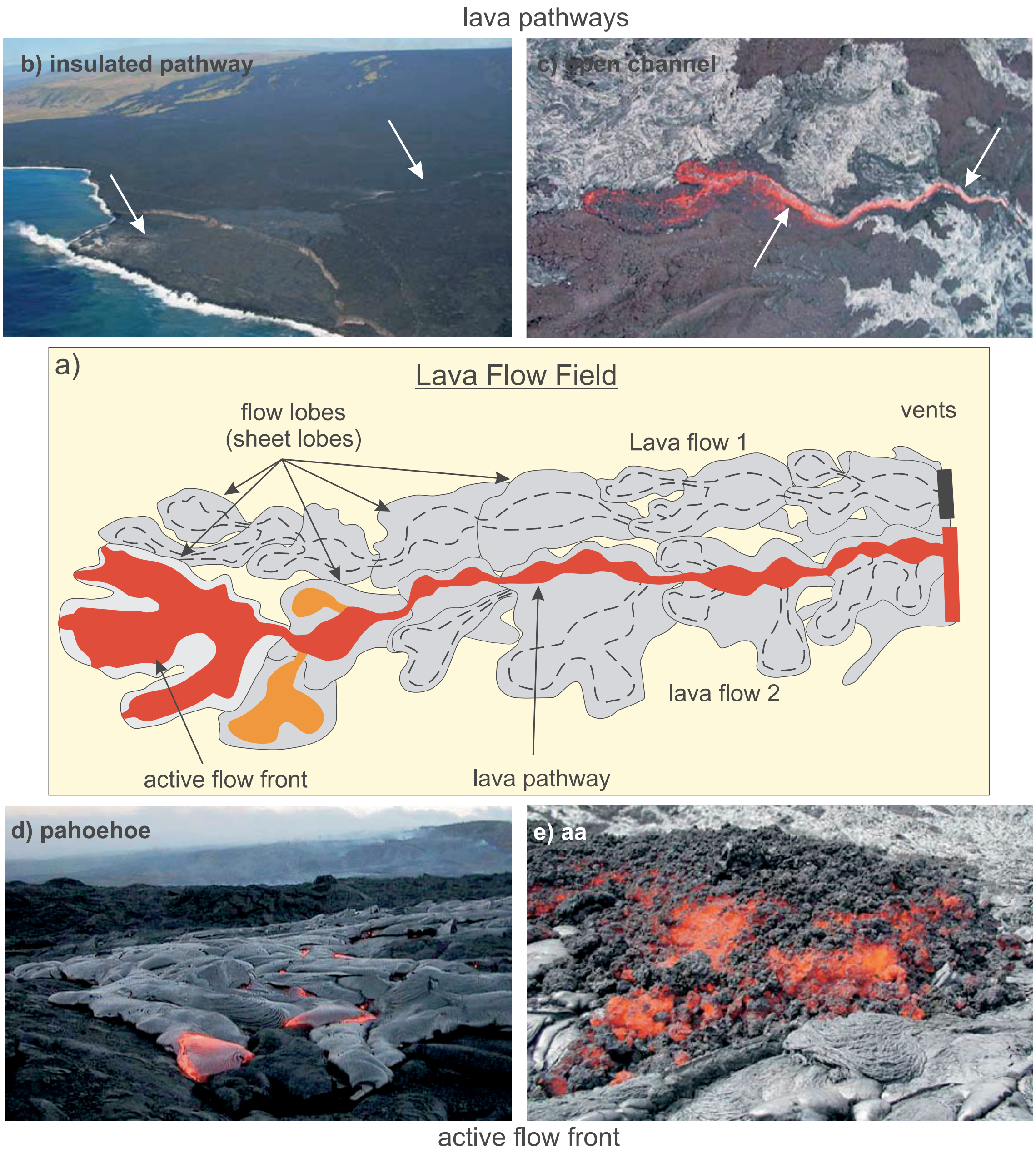

Figure 5. Volcanic architecture of lava flow fields, illustrating the key structural components: lava flows, flow lobes, closed and open transport system and active flow fronts. – *Byggingareinkenni basalthraunbreiða.*

rine environment. In addition, the land is wet because of high groundwater level induced by widespread and impermeable glacial deposits in the regolith. This abundant availability of H_2O at the surface explains the dominance of 'wet' eruptions and the elevated explosivity of mafic eruptions (>90% of all explosive events are mafic), which otherwise would be effusive or weakly explosive as exemplified by the postglacial activity on the RVB, WVZ and NVZ. Thus, it is no surprise that mafic explosive eruptions have become Iceland's trademark events as exemplified by the well-publicised eruption of Surtsey in 1963-67 (e.g. Thorarinsson, 1967b, 1967c; Walker, 1973b) and recent mafic activity at the ice-covered Grímsvötn volcano (e.g. Guðmundsson *et al*. 1997, 2002; Sigmundsson and Guðmundsson, 2004).

Silicic explosive eruptions in Iceland are confined to central volcanoes and in post-glacial time they have produced about 58 tephra layers (e.g. Larsen and Eiríksson, 2007). The existing record is noteworthy, indicating an event frequency of ∼1 eruption every 200–300 years and approaches that observed at the highly active silicic systems such as the Taupo Volcanic Zone in New Zealand (e.g. Houghton *et al*., 1995). The recurrence frequency of large events is significantly lower, or one eruption every 1000 years for events in the volume bracket of 1–10 km^3 of tephra, (0.25–2.5 km^3 DRE) and roughly one every 100.000 years for events >10 km^3 tephra (>2.5 km^3 DRE; Lacasse and Garbe-Schönberg, 2001; Thordarson and Larsen 2007). Silicic events are categorized as 'dry' (2.5% of all explosive events) and 'wet' (1.4%) eruptions. Both types have occurred at ice-free and glacier-covered volcanoes. Although, quantitative classification schemes for explosive eruptions have been introduced, first by Walker (1973b) and later by Pyle (1989) and widely used (e.g. Cas and Wright, 1987; Francis and Oppenheimer, 2004), these schemes have generally not been applied to Icelandic eruptions. For example, Walker indices have only been calculated for a handful of events and Pyle indices have only been produced for one event (Pyle, 1989). The main reasons for this shortage are lack of adequate grain size data as well as dearth of published good quality isopach and isopleth maps. As a result, styles of explosive eruptions in Iceland have been inferred on the basis of qualitative observations of the events and/or nature of their fall deposits. Although the grouping of explosive eruptions presented below is marked by these deficiencies, we have included ln(thickness) - (isopach area)$^{1/2}$ plots for several events to provide some quantification of and comparative information on the relevant explosive eruption styles, (see below).

EFFUSIVE ERUPTIONS

Mafic lava-producing eruptions are the building-blocks of Iceland and represent an assorted class of events that span a wide spectrum in terms of eruption style and magnitude. They occur on all of the vent system types mentioned above and individual eruptions can feature styles ranging from passive lava effusion to vigorous fountains to explosive phases of subplinian intensities. In terms of erupted magma volumes, they span the range from 1 m^3 to 25 km^3 (e.g. Thordarson and Larsen, 2007). For purpose of description, we divide effusive eruptions into small to medium (<1 km^3) and large ($\geq$1 km^3) volume events, where each involves a spectrum of eruption behaviour represented here by low- and high-magma discharge end-member types.

The small to medium volume effusive basalt eruptions are common in Iceland. They have typical recurrence of a few decades and as a class include low- and high-discharge events. The low-discharge events ($\leq$30 m^3/s?) are typified by submissive lava emissions or hawaiian-style of activity (e.g. Mattson *et al*., 2005a). They form pahoehoe flow fields that are characterised by thermally insulated transport system, which delivers lava from the vents to active flow front where the effective lava growth takes place via lobe to lobe emplacement and flow inflation (Figure 5). These lavas reach lengths up to 25 km when the topography is favourable (Figure 6). The high-discharge end-member ($\geq$100 m^3/s?) is characterised by strombolian vent activity and formation of channel-fed aa flows that advance relatively short distances ($\leq$13 km) because of the inefficient thermal insulation of transport system (e.g. Self *et al*., 1998; Harris and Rowland, 2001; Thordarson, 2008).

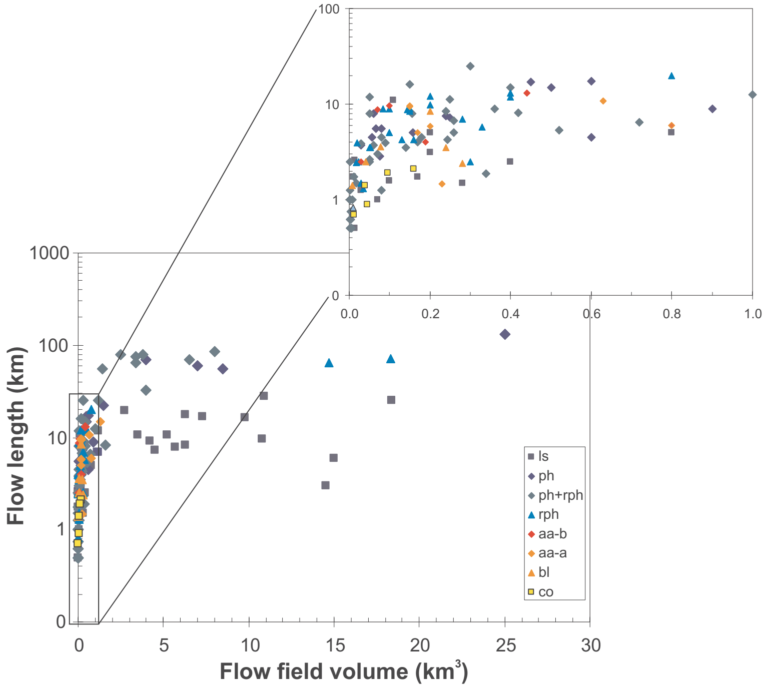

Figure 6. Plot showing length versus volume for Icelandic lava flow fields. Abbreviations are as follows: ls, pahoehoe (lava shield eruptions), ph, pahoehoe (fissure eruptions), ph+rph, pahoehoe and rubbly pahoehoe, rph, rubbly pahoehoe, aa-b, aa lava (mafic), aa-a, aa lava (intermediate), bl, block lava, co, coulee. – *Graf sem sýnir tengslin á milli lengdar og rúmmáls íslenskra hrauna. Skammstafanir: ls, helluhraun (hraunskildir), ph, helluhraun (sprungugos), ph+rph, hellu- og klumpahraun, rph, klumpahraun, aa-b, apalhraun (basalt), aa-a, apalhraun (ísúrt), bl, blakkarhraun, co, stokkahraun.*

A special class among these high-discharge and small-volume mafic eruptions are events that have produced, concurrent with fountain-fed lava flows, rather extensive welded and rheomorphic spatter aprons that mantle the landscape around the source vents (Karlunhen, 1988; Calderone *et al.*, 1990; Sæmundsson, 1991). A good example of these stunning volcaniclastic deposits is the ∼4000 ka Biskupsfell formation (∼0.038 km^3) from the Kverkfjöll volcanic system. The lava fountains of the Biskupsfell eruption formed a rheomorphic apron that blanketed the Pleistocene pillow lava ridge topography up to 1.5 km from the source fissure and supplied fountain-fed flows that reached length of ∼5 km.

Effusive eruptions typified by intermittent hawaiian and strombolian phases as well as pulsating discharge form rubbly pahoehoe flow fields. Judging from frequency distribution of flow types, this hybrid class appears to be the most common style of effusive eruption in Iceland (e.g. Guilbaud, 2006; Thordarson, 2008).

Large volume (>1 km^3) effusive events, distinguished here as flood lava eruptions, have the recurrence period of several hundred years. They are produced by relatively low-discharge central vent events as well as high-discharge fissure eruptions. Lava shields are the principal representative of the low-discharge (≤300 m^3/s?) end-member and their formation is largely confined to mid- and early-Holocene times as majority of the shields predates 3000 yrs BP (e.g. Hjartarson, 2003; Sinton *et al.*, 2005). They are thought to be produced by a long-lived (years to decades) eruptions of olivine tholeiite or picritic magmas that are fed by sustained lava lakes residing in the

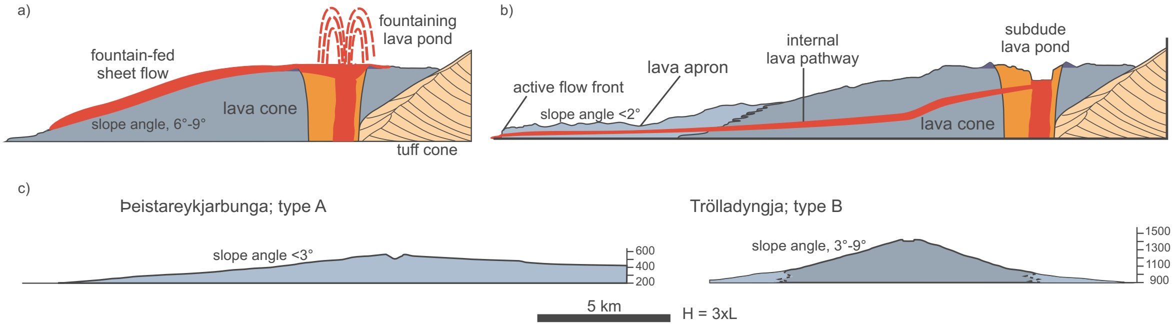

Figure 7. Growth stages of lava shields (a) the lava cone stage and (b) lava apron stage. (c) profiles of type A and B lava shields. See text for further details. – *Vaxtarstig hraunskjalda: (a) hraunkeilustig og (b) hraunsvuntustig. (c) Þversnið af A og B gerðum hraunskjalda.*

summit vent. They often, especially the olivine tholeiite events, produce vast pahoehoe flow fields that have radius (i.e. flow length) up to 28 km and volumes approaching 20 km^3 (Figure 6). Lava shields often form remarkably symmetrical volcanoes, where a lava cone with summit crater and gently sloping (3–10°) outer flanks is circumscribed by a lava apron with surface slope of 0.5–2° (e.g. Rossi, 1996). Study by Thordarson and Sigmarsson (2008) indicates that lava cones and aprons are formed in sequence rather than synchronously. The lava cones are constructed first, during periods of relatively high magma discharge and vigorous lava lake activity producing surface flows. The lava aprons are formed subsequently, when the discharge is low (<50 m^3/s?) and lava is fed passively through internal pathways from the source vent to active flow fronts out in the flow field. The lava cone is essentially constructed by overbank and fountain-fed surface flows that exhibit a distinct lava facies association characterized by shelly pahoehoe in the proximity of the vent and slabby pahoehoe and aa sheet flows in the more distal sectors (Figure 7a). The surrounding lava apron is produced by insulated transport to active flow fronts where growth takes place by lobe to lobe emplacement and flow inflation (Figure 7b). The characteristic facies association of the apron is hummocky pahoehoe featuring tumuli, lava-rise pits and flat-topped sheet lobes (e.g. Walker, 1991; Rossi, 1996; Thordarson, 2000a).

Lava shields in Iceland are typified by a spectrum of profiles that fall between two end-member types: (A) very low profile shields with <2° sloping flanks and large lava apron and (B) shields with slope angles >3°, a steepening summit-terminus profile and a well-defined, proportionally large volume lava cone (Figure 7c). Type A shields are thought to be constructed by steady, low-discharge eruptions with minimal surface flow activity, whereas type B shields are formed by eruptions supporting prolonged periods of relatively high-discharge and fountain-fed surface flows. It has been proposed that type B shields with proportionally large lava cones, such as Skjaldbreið and Trölladyngja, were formed by relatively high-discharge events (>50 m^3/s?) with sustained surface flow activity and eruption duration of years to decades. Conversely, low profile type A shields, such as Þeistareykjarbunga, were formed by low and steady effusion of lava during eruptions that lasted for decades to centuries in case of the biggest shields (Thordarson and Sigmarsson, 2008). The high-discharge (>1000 m^3/s) flood lava events are most common on, but not exclusive to, the EVZ and are some of the best studied manifestation of Icelandic volcanism (e.g. Vilmundardóttir, 1977; Larsen, 1979, 2000; Hjartarson, 1988; Thordarson and Self, 1993; Thordarson *et al.*, 2001; Thordarson and Larsen, 2007). They include the 1783–1784 AD Laki (15.1 km^3), 934–940 AD Eldgjá (19.6 km^3) and ∼8600 years BP Thjórsá (25 km^3) fissure eruptions

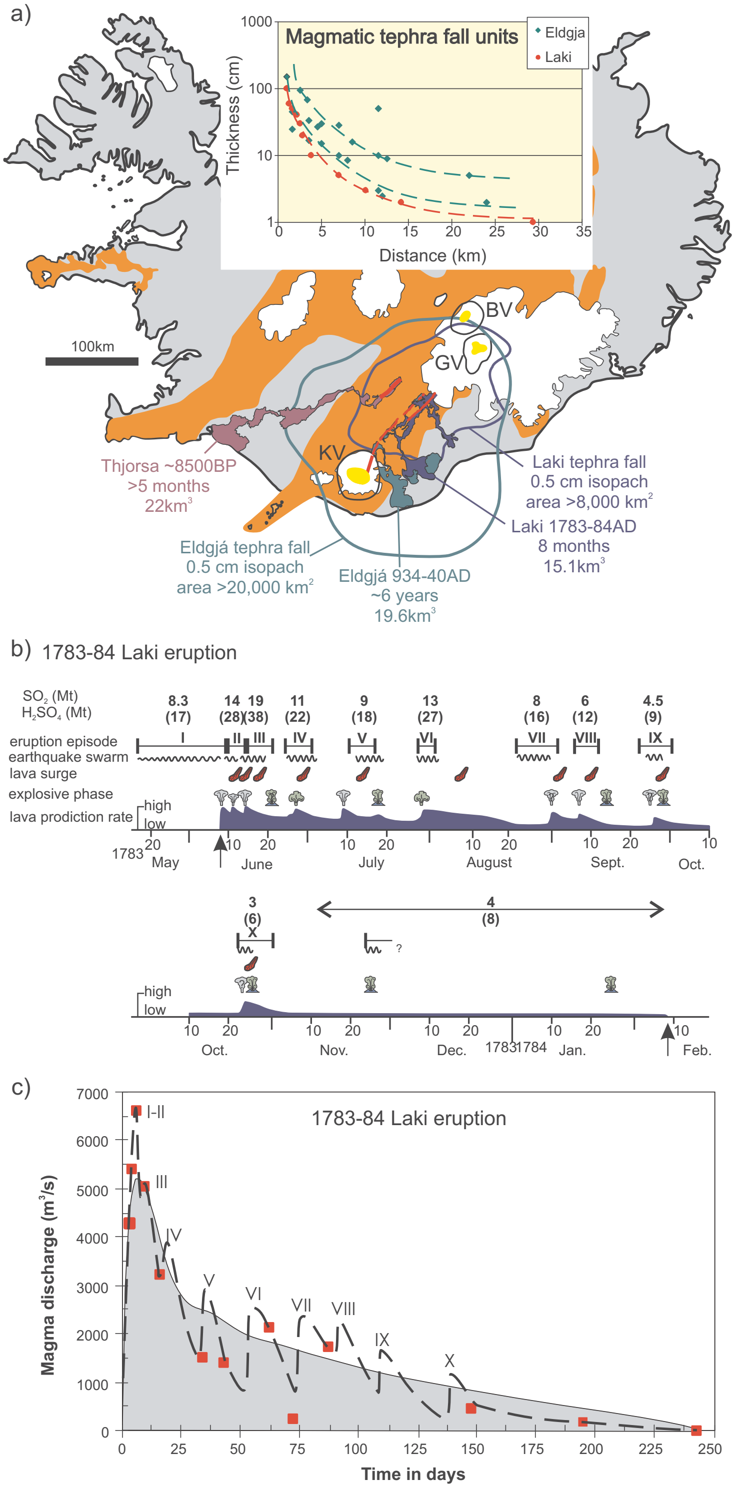

Figure 8. (a) Map of Iceland showing the 1783–84 Laki, 934–40 Eldgjá and 8.6 ka Thjórsa lava flow fields and tephra dispersal for the first two events. Abbreviations: KV, Katla volcano; GV, Grímsvötn volcano; BV, Bárðarbunga volcano. Inset shows the change in thickness for the Laki and Eldgjá tephra layers with distance from source (from Thordarson *et al.*, 2001), (b) Schematic illustration of sequence of events during the 1783–84 Laki-Grímsvötn eruptions. Extent of earthquake swarms is indicated by wiggly lines; fluctuations in lava discharge shown by shaded area (not to scale); eruption clouds denote explosive activity at Laki fissures; eruption clouds with a cone at the base denote explosive activity at Grímsvötn volcano; arrows indicate onset and termination of Laki eruption. The solid bars show the extent of each eruption episode, labelled I, II, III etc. Modified from Thordarson and Self (1993). (c) Magma discharge during Laki eruption; solid line and shaded area show the mean discharge estimated from position of the lava flow front at different times during the eruption as depicted by contemporary accounts and field observations. Broken line illustrates the anticipated variation in discharge during individual eruption episodes. Based on Thordarson and Self (1993) and Thordarson et al. (2003a). – *(a) Kort af Íslandi sem sýnir Skaftárelda-, Eldgjár- og Þjórsárhraun og útbreiðslu gjóskunnar frá Skaftár- og Eldgjáreldum. Innsetta myndin sýnir hvernig þykkt gjóskulaganna breytist með fjarlægð frá upptökum. (b) Myndræn framsetning á framvindu Skaftárelda. (c) Uppstreymi (framleiðni) kviku a tímaeiningu í Skaftáreldum.*

(Figure 8a), which have produced the longest lava flows in Iceland (65–130 km) and represent some of the largest flood lava events on Earth in post-glacial time. Recent studies, especially those focused on the Laki event (e.g. Thordarson *et al.*, 1996, 2003a; Keszthelyi et al, 2000, 2004, Guilbaud *et al.*, 2005, 2007), have played an important role in enhancing our understanding of flood basalt eruptions and their potential environmental and climatic effects (e.g. Self *et al.*, 1996, 1997, 1998, 2006; Thordarson and Self, 1996, 1998; Keszthelyi and Self, 1998). In Iceland, the flood lava events take place on 10's of km long linear vent system demarked by a row of often tightly packed cratered cones that delineate multiple fissure segments arranged in an en echelon fashion. The flood lava events are prolonged eruptions that last for months to years and feature numerous eruption episodes (Figure 8b). Each episode appears to represent a rifting event (i.e. formation of a new fissure) and begins with a short-lived explosive phase followed by a longer phase of lava emissions. The explosive phases at the beginning of each episode last for hours to days and coincide with times of peak magma discharge of ∼6–7000 m^3/s (Figure 8c). They are typified by magmatic and phreatomagmatic phases of subplinian intensities that produce widespread tephra layers of substantial volumes. For example, the 934–940 Eldgjá event formed a tephra layer that covers >20,000 km^2 within the 0.5 cm isopach and has a volume of ∼1.2 km^3 DRE or ∼5 km^3 freshly fallen (Figure 8a; Larsen, 2000). The subsequent effusive phase features relatively quiet effusion of lava at more moderate (1000–3000 m^3/s) and steadily declining discharge (Figure 8b). The flood lava flow fields consist of pahoehoe and rubbly pahoehoe (or platy-ridge lava), signifying insulated transport, growth by inflation and break-up of the original pahoehoe to form rubbly flows brought about by the highly fluctuating discharge (e.g. Keszthelyi *et al.*, 2000, 2004; Thordarson *et al.*, 2003a; Guilbaud *et al.*, 2005).

Effusive silicic eruptions are relatively rare occurrence in the Holocene and generally have produced small volume (<0.2 km^3) subaerial block lavas and coulees (Sæmundsson, 1972; Blake, 1984; Macdonald *et al.*, 1990; McGarvie *et al.*, 1990; Sæmundsson and Fridleifsson, 2001). Silicic lavas in Iceland are characterized by aspect ratios of 0.02–0.05, which is very low compared to the typical aspect ratio of ∼0.1 for the same flow types in other volcanic regions (Walker, 1973a). The low aspect ratio of the Icelandic lavas is though to reflect their relatively high (900–1000°C) eruption temperature and low viscosity (∼10^5–10^6 Pa s).

MIXED ERUPTIONS

Mixed Hekla eruptions follow a consistent pattern of activity with 3 phases. Each eruption has built over a few minutes into a vigorous subplinian to Plinian event (phase 1) characterised by high magma discharge (Figure 9a). Phase 1 is typically of <1 hr duration irrespective of the maximum intensity of the eruption (e.g. Thorarinsson, 1954, 1976; Thorarinsson and Sigvaldason, 1972a; Grönvold *et al.*, 1983; Guðmundsson *et al.*, 1992, Larsen *et al.*, 1992; Höskuldsson *et al.*, 2007). The initial phase is followed by a stepwise opening of the ∼5 km long Hekla fissure and commencement of lava fountain activity marking the onset of Phase 2 that features simultaneous sustained emission of moderately widespread tephra fall and fountain-fed aa lava (Figure 9b). The intensity of the eruption decreases sharply during Phase 2 along with a concurrent increasing in the lava to tephra ratio (Figure 9a). Phase 3 activity is characterised by discrete strombolian explosions and very low magma discharge (<20 m^3/s) and its primary contribution is to broaden and to lesser extent lengthen the aa lava flow field (Einarsson, 1949; Thorarinsson, 1976; Thordarson, unpublished observations from January and February 1991; Höskuldsson *et al.*, 2007). This sequence of events as well as styles of activity characterizes all Hekla eruptions that have been described in historical accounts. It is worth noting that the Phase 2 fountain-fed lavas formed in the eruption in 1991 makes up more than 60% of the lava flow field volume. These lavas cascaded down the slopes of the volcano and reached lengths of 4–5.5 km in less than 6 hours (Figure 9b). Observations (e.g. Einarsson, 1949; Thorarinsson, 1976; 1967a) indicate

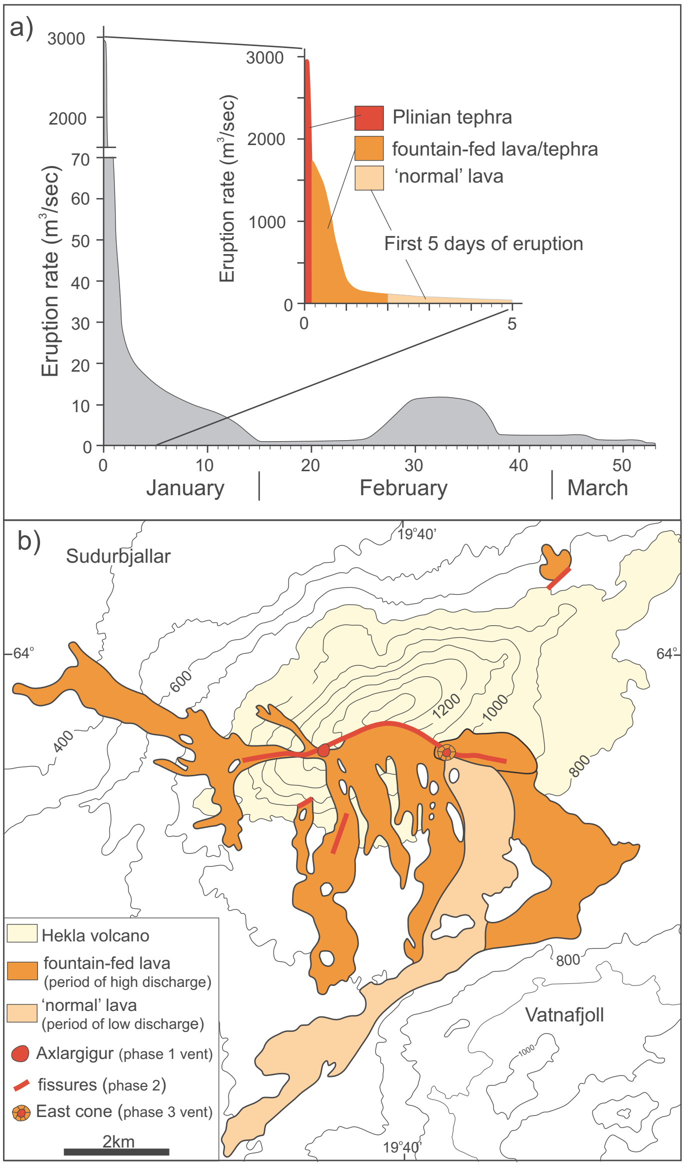

Figure 9. (a) Magma discharge versus time during the 1991 Hekla eruption including that of phases 1, 2, and 3 during first 5 days of the eruption (inset). (b) Map showing the 1991 Hekla vent system, main tephra fall sectors during phases 1 and 2 of the eruption as well as the distribution of Phase 2 fountain-fed and Phase 3 'normal' lava flows. Based on Gudmundsson *et al.* (1992) and supplemented by unpubl. data by T. Thordarson, 2008. – *(a) Uppstreymi (framleiðni) kviku a tímaeiningu í Heklugosinu 1991. (b) Kort af gígum og hraunum frá Heklugosinu 1991.*

similar behaviour in other historic Hekla eruptions, suggesting that Phase 2-like activity can produce relatively long and perceivably hazardous fountain-fed aa flows in a short period of time.

WET EXPLOSIVE ERUPTIONS

'Wet' explosive eruptions in Iceland straddle the interface of water/ice and subaerial environments and are typified by three elementary styles, which in order of increasing eruption intensity are: phreatic, phreatomagmatic and phreatoplinian (Figure 10a). With the exception of phreatic eruptions (see below), they involve physical interaction of the emerging magma with non-magmatic water, which greatly enhances their explosive power. The efficiency (power) of the explosive interaction depends principally on the water to magma mass ratio (e.g. Wohletz, 1983; 1986; Morrissey *et al.*, 2000), but other variables are also important because the process of eruption involves several interlinked mechanisms such as magma fragmentation and detonation, expulsion (jetting) of solid-steam mixture, as well as transport and deposition of the solid products. The 'wet' mafic eruptions are significantly more vigorous than their 'dry' counterparts, whereas the silicic members are typically highly explosive although their intensity is dependent on the exact eruption condition (e.g. Thorarinsson, 1967c, White and Houghton, 2000; Houghton *et al.*, 2000; Carey, 2008). Phreatic eruptions are relatively rare in Iceland, registering 0.5% of explosive events. Subglacial phreatomagmatic eruptions (75%) dominate the explosive event record, whereas the submarine and subaerial equivalents account for $\sim$6% and 0.5% each. The phreatoplinian eruptions represent $\sim$1.6% of the total explosive event tally.

Phreatic (i.e. hydrothermal) eruptions are known from three volcanic systems in Iceland - Krafla, Askja and Krýsuvík - although their occurrence is likely to be more widespread. They are typically associated with major volcano-tectonic episodes, often as discrete events during times of precursor activity and/or stages of waning activity. They also appear to be confined to high-temperature geothermal systems and most likely caused by overheating and pressurization of water and/or steam in such systems driven by sudden excess heat flux from magma at very shallow levels (e.g. Sæmundsson, 1991).

Two well-documented periods of phreatic eruptions are known in historic time. First is the phreatic activity associated with the 1874–1876 Askja Fires. The main silicic explosive eruption on 28–29 March 1875 was preceded by a series of small phreatic as well as phreatomagmatic and effusive eruption (Sigurðsson, 1875). This activity formed tephra fall deposits that are largely confined to the Askja caldera that collectively is known as unit A of the 1875 tephra sequence (Sparks *et al.*, 1981; Carey, 2008). Phreatic activity continued in the wake of the main eruption on fracture systems within the newly formed Öskjuvatn caldera and by sustained explosive activity at a crater just north of the caldera (Watts, 1876). The activity at this crater, which later became known as Víti,[1] formed fall deposits that covered the ground within 1.5 km radius of the vent (Johnstrup, 1877a,b, 1886). The second example is the 17 May 1724 Víti eruption at Krafla, which marks the onset of the 1924–1929 Mývatn Fires. This eruption formed a tephra fall deposit consisting of clay and rock fragments that extends up to 13 km southwards from the Víti crater at Krafla. In addition, small phreatic eruptions occurred at Leirhnjúkur towards the end of the Mývatn Fires. Additional five to six prehistoric phreatic eruption periods have been identified within the Krafla system (Sæmundsson, 1991). On the Krýsuvík volcanic system phreatic activity is exemplified by prehistoric maar volcano complex, Grænavatn, and associated explosion craters (Jónsson, 1978a). Grænavatn crater is $\sim$300 m in diameter, and was formed in an eruption that began with vigorous lava fountaining phase that produced small rheomorphic mafic lava flow followed by powerful phreatic explosions (Höskuldsson, unpubl. data, 2008). The Grænavatn maar is well known for the olivine-gabbro xenoliths and their occurrence in the tephra deposit suggests that the activity resulted from deep-rooted explosions, perhaps as deep as 2–3 km (Tryggvason, 1957).

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[1] Direct English translation of Víti is hell.

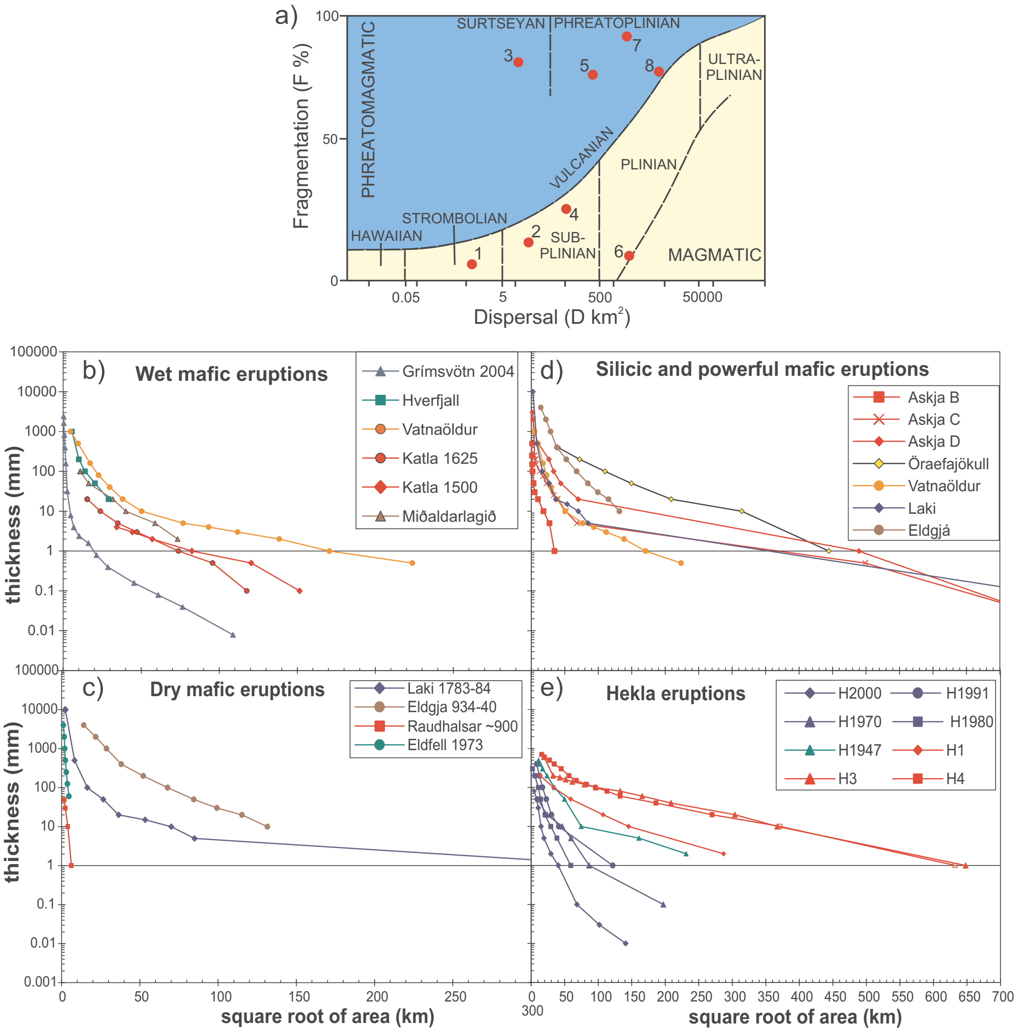

Figure 10. (a) Walker classification of explosive eruptions/eruption phases in Iceland. Events are numbered as follows: 1. 1973 Eldfell, 2. 1783-84 Laki (magmatic phases), 3. 1783-84 Laki (phreatomagmatic phases), 4. 1875 Askja (phase B), 5. 1875 Askja (phase C), 6. 1875 Askja (Phase D), 7. ∼870 AD Vatnaöldur and 8. 1477 AD Veiðivötn. Data from Self *et al.* (1974); Self and Sparks (1978); Sparks *et al.* (1981); Thordarson and Self (1993); and Larsen (2005). (b) – (e) ln(thickness) versus (area)$^{1/2}$ plots for tephra deposits produced by a range of explosive eruptions in Iceland (see key for details). Steep negative slopes indicates deposit geometry approaching that of a cone, whereas shallow slope indicates a sheet-like geometry. Please note the scale change for the x-axis between plots b-c and d-e. See text for further details. Data obtained from tephra dispersal maps by Thorarinsson (1958, 1967a, 1970, 1976); Thorarinsson and Sigvaldason (1972); Self *et al.* (1974); Jóhannesson (1977); Larsen and Thorarinsson (1977); Larsen (1979, 1984, 2000); Grönvold *et al.* (1983); Sæmundsson (1991); Larsen *et al.* (1992); Thordarson and Self (1993); Haraldsson (2001); Oddsson (2007) and Carey (2008). – *(a) Tegundargreining á íslenskum gosum samkvæmt Walkers flokkuninni. (b) – (e) Gröf sem sýna breytingu á ln(þykkt) á móti (flatarmáli)*$^{1/2}$ *fyrir valin íslensk gjóskulög.*

Phreatomagmatic (or surtseyan; Walker, 1973b; Figure 10a) eruptions occur as discrete events at polygenetic central volcanoes, monogenetic central as well as fissure vent systems and span the range of subglacial, subaerial and submarine environments. The event record is dominated by explosive basalt eruptions from three ice-covered central volcanoes, Grímsvötn, Bárðarbunga and Katla (Figure 1), accounting for $\sim$60% of the total event tally. These explosive subglacial eruptions are typically small (mean volume $\sim$0.1 km^3; range, 0.01 to $\sim$1 km^3) and are estimated to have produced $\sim$20% of the mafic magma volume erupted in post-glacial time. Driven by explosive water to magma interactions these eruptions are typified by 'surtseyan-like' activity featuring both events of 'continuous uprush' and intermittent 'rooster-tail' jets.[2] They are known to maintain 6–15 km high eruption columns, suggesting that the former style is the principal eruption mechanism (e.g. Guðmundsson and Björnsson, 1991; Guðmundsson *et al.*, 1997; Larsen, 2000; Sigmundsson and Guðmundsson, 2004). Although these subglacial eruptions are highly explosive, their tephra dispersal power is weak to modest (Figure 10b), because only small proportion of the magma thermal energy is partitioned into driving the eruption plume. Most of the energy is taken up by the processes of magma fragmentation and ice melting (e.g. Guðmundsson, 2003, 2005). However, as shown on Figure 10b, there are noticeable exceptions to this blueprint because the tephra fall from the largest historic Katla eruptions (e.g. in 1625 and 1755) have significantly more extensive distribution with ash fall observed as far as mainland Europe (e.g. Thorarinsson, 1981b).

Despite their small size, the subglacial eruptions generate some of the most catastrophic natural events in Iceland; known as jökulhlaup (i.e. glacial flash flood), and discussed elsewhere in this issue.

About 20 submarine (i.e. surtseyan) eruptions are known in historic time, or $\sim$10% of the events on record, and are estimated to have delivered <2.5% of the erupted basalt magma volume. In the last 800 years they have been most frequent on the offshore segment of the RVB, but also have occurred on the submarine extension of the NVZ and within the Vestmannaeyjar volcanic system (e.g. Thorarinsson, 1965). Many more submarine events are inferred from prehistoric geological record, including the Sæfell tuff cone (diatreme) on Heimaey along with additional 60 submerged surtseyan vents within the Vestmannaeyjar volcanic system (e.g. Mattsson and Höskuldsson, 2003; Mattsson *et al.*, 2005b). In addition, at least three events are known within the RVB (e.g. Jónsson, 1978a).

The Surtsey volcano, the westernmost island of the Vestmannaeyjar archipelago, is undoubtedly the most renowned of the Icelandic submarine events. It was formed by a prolonged eruption between November 1963 and June 1967, producing a 6 km long east-northeast trending submarine ridge that rises from a depth of 125 m and covers 14 km^2. Its most prominent feature is the island of Surtsey, a submarine table mountain that consists of two abutting 140 m high tuff cones and a small pahoehoe lava flow field (e.g. Kjartansson, 1966a,b; Thorarinsson, 1967b,c). The island was immediately proclaimed a nature reserve because of the unique opportunity to study the development of life on a new land (e.g. Friðriksson, 1994).

Subaerial mafic phreatomagmatic eruptions have occurred sporadically throughout postglacial times. They are not confined to specific regions or volcanic systems but appear to have formed in range of environments, including eruptions through shallow lakes, flood plains and fault systems acting as channels for groundwater. In terms of style they span a similar spectrum as the subglacial eruptions, but are on av-

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[2] Surtseyan eruptions are characterized by two distinct eruption styles – rooster tail and continuous up-rush events – each driven by copious tephra-rich explosions on the time scale of seconds to minutes. Rooster tail events typify the activity when external water has a ready access to the vent(s). They originate from intermittent shallow explosions in a water-filled vent, each producing vertical to sub-horizontal black tephra jets that typically reach heights/distances of <1000 meters. Continuous uprush events take place when the access of water to the vent(s) is restricted and originate from explosions rooted deeper within the vent. They produce 0.5 to 2 km-high vertical black tephra-rich columns (momentum jets) with muzzle velocities up to 100 m s^{-1}, and are known to support 6–15 km high eruption columns. Continuous uprush events are normally more powerful than the rooster-tail events because of more favourable water to magma mass ratio. Based on Thorarinsson (1967b,c).

erage more powerful (Figure 10b). In total, twelve subaerial phreatomagmatic events are known in postglacial time, either as individual eruptions or phases within larger events. They occurred on the following volcanic systems: Krafla, Askja, and Hengill as well as on the subaerial segments of the Kverkfjöll, Grímsvötn and Bárðarbunga-Veiðivötn systems. Historic events include three eruptions within the Askja volcano (i.e. 1867, 1875 and 1926; Jónsson, 1945; Thordarson, unpubl. data 2008) and two phreatomagmatic phases in the 1783–1784 Laki flood lava eruption (Thordarson and Self, 1993). Notable prehistoric events are those of the 3 ka Hverfjall and 7–8 ka Hrossaborg in North Iceland, both of which produced prominent tuff cones as well as pyroclastic density current and tephra fall deposits (Thorarinsson, 1952a,b; Einarsson, 1965; Sæmundsson, 1991; Miller *et al.*, 1989).

Rootless cone groups are the most common subaerial phreatomagmatic landforms in Iceland (e.g. Thorar-

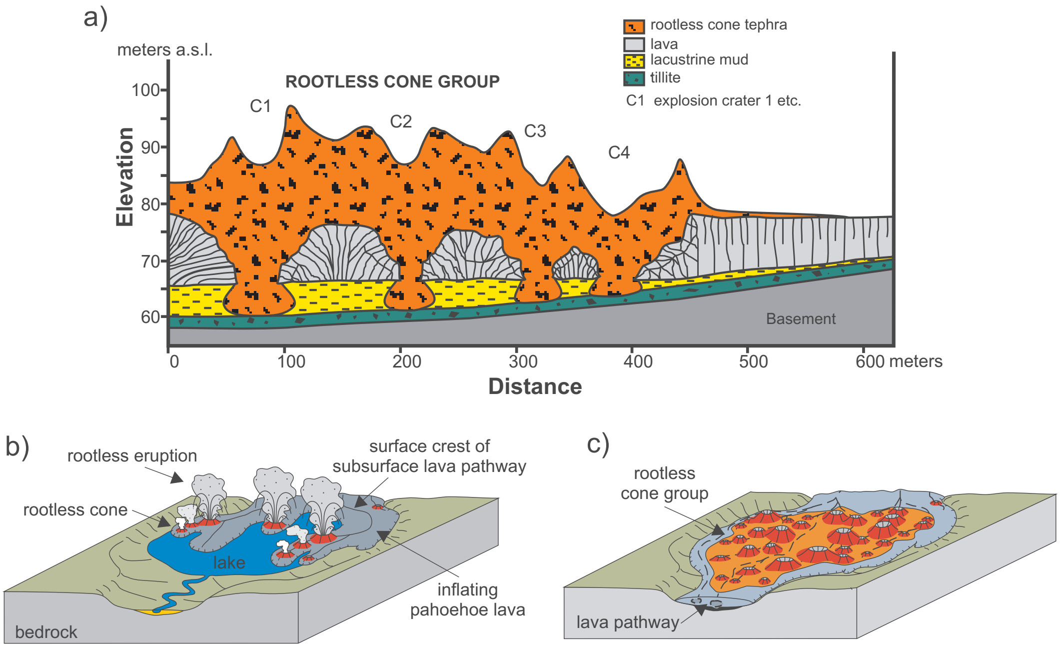

Figure 11. (a) Schematic cross section through a rootless cone group. The cones typically rise 2–35 m above host lava surface and their basal diameters range from 5–450 m (see key for details). (b) Formation of the rootless cone groups. The lava has covered a water-logged basin and thickened by flow inflation. Initially the lava enters the wetlands as relatively small pahoehoe lobes from a set of frontal breakouts at the active lava fronts. The insulating crust seals the lobe interiors from the water-logged environment and the lobes inflate and expand laterally in response to continued injection of lava. The internal pathways (or lava tubes) are thus extended to new breakout points and the process repeats itself, extending the lava further across the wetlands. Another consequence of this process is that the lava behind the active flow fronts increases in thickness by inflation and preferably so over the internal pathways. Consequently, the pathways begin to sink into the soft mud on the lake bottom and cracks open in the base of the lava allowing the glowing hot lava to flow straight into the water-saturated mud and initiate steam explosions. (c) A fully developed rootless cone group. After Fagents and Thordarson (2007). – *Stílsett (a) þversnið í gegnum gervigígaþyrpingu, (b) teikning sem sýnir myndun gervigígaþyrpinga og (c) fullmynduð þyrping.*

insson, 1951, 1953). They are positive landforms consisting of 10s–1000s closely packed crater cones that cover an area ranging from 0.5 km^2 to >100 km^2. They are without exception associated with tube-fed pahoehoe and rubbly pahoehoe flow fields and the cones rest directly on the host lava flow (Figure 11a). The cone groups are situated where the lava advanced over wetlands, such as shallow lakes, fluvial plains or swamps. Each cone is formed by a phreatomagmatic eruption driven by explosive interaction (i.e. physical mixing) between degassed liquid lava and water-logged substrate (e.g. Thordarson *et al.*, 1992; Thordarson, 2000b; Fagents and Thordarson, 2007). These are sustained (hours to days) eruptions, as is evident from the distinctive internal layering of each cone. The cones typically feature two distinct structural components; a lower well-bedded sheet-like sequence consisting of 0.2–0.6 m thick lapilli tephra beds alternating with <0.2 m thick mud-rich and cross-bedded ash beds and a upper indistinctly bedded cone-forming sequence consisting of several 0.5–1.5 m thick spatter beds, often capped by a 1–2 m-thick welded to rheomorphic layer. The upward increase in grain size of these deposits emulates the attenuation of explosive power during individual rootless eruption. The cone conduits are crudely funnel-shaped, extending from the flow base up through coherent lava and terminating in a bowl-shape crater represent volcanic vents (Figure 11a). These conduits have lateral feeders (i.e. lava tubes), hence the name 'rootless' eruptions, cones and cone groups.

Formation of rootless cone groups requires the lava to cross wetlands and a simultaneous initiation of rootless eruptions through contact between hot lava and external water, constructing cones on top of actively advancing lava that are in no way modified by its movements. As shown on Figure 11b, this can only be accomplished if the lava is flowing within preferred internal pathways (e.g. lava tubes) beneath a stationary crust. If the explosions are powerful enough, they burst through the overlying lava to emerge as rootless eruptions that build cones around the vents (Figure 11b). At any site, the eruption stops when the supply of water (i.e. mud) and/or lava runs out. As the flow migrates across the wetlands, the explosive vents follow and, in doing so, gradually build a group of rootless cones on top of the lava (Figure 11c).

Phreatoplinian eruptions represent only 1.6% (24 events) of post-glacial explosive eruptions in Iceland, yet are a diverse group that includes silicic eruptions from ice-free and ice-capped central volcanoes as well as large volume mafic fissure eruptions (Sparks *et al.*, 1981; Larsen *et al.*, 2001; Larsen, 1984; 2005). The unifying feature of the phreatoplinian eruptions is that they all involve interaction of highly vesicular magma with surface water, have Walker F indices of $\geq$80% and form widespread thin tephra blankets dispersed over areas of 10^4 to 10^6 km^2 (Figure 10a,d). However, their tephra volumes vary by >2 orders of magnitude, from 0.01 to 5 km^3. The Icelandic record also includes the only verified historical example of silicic phreatoplinian eruptions (1875 AD Askja C) on Earth and is one of the type-eruption for this style of volcanism (e.g. Self and Sparks, 1978; Carey, 2008). Another historic example is the 1206 AD dacite eruption at Hekla, which formed the olive grey layer; an important tephra marker horizon in South Central Iceland (e.g. Larsen, 1979; Thordarson *et al.*, 1998). The 1821 AD and 1613 AD dacite eruption of Eyjafjallajökull most likely fall also under this eruption category, along with 17 prehistoric events, including the twelve Katla events that produced the SILK tephra layers (e.g. Larsen *et al.*, 1999; 2001).

The explosive fissure eruptions of Vatnaöldur ($\sim$870 AD) and Veiðivötn (1477 AD) can now be added to the list as type examples of mafic phreatoplinian eruption (e.g. Larsen, 1984, 2005). Both of these eruptions produced widespread tephra layers (1–1.5 km^3 DRE) that cover more than half of the country (Figures 10a,d and 12a). In terms of intensity and size they are only superseded by the three early Holocene ($\sim$10–10.5 ka) mafic phreatoplinian eruptions at Grímsvötn that collectively produced the Saksunarvatn tephra layer (Jóhannsdóttir *et al.*, 2006), which extends to the continents on both sides of the North Atlantic (Figure 12b).

DRY EXPLOSIVE ERUPTIONS

According to the classification of Walker (1973b) the styles of 'dry' eruptions are in order of increasing

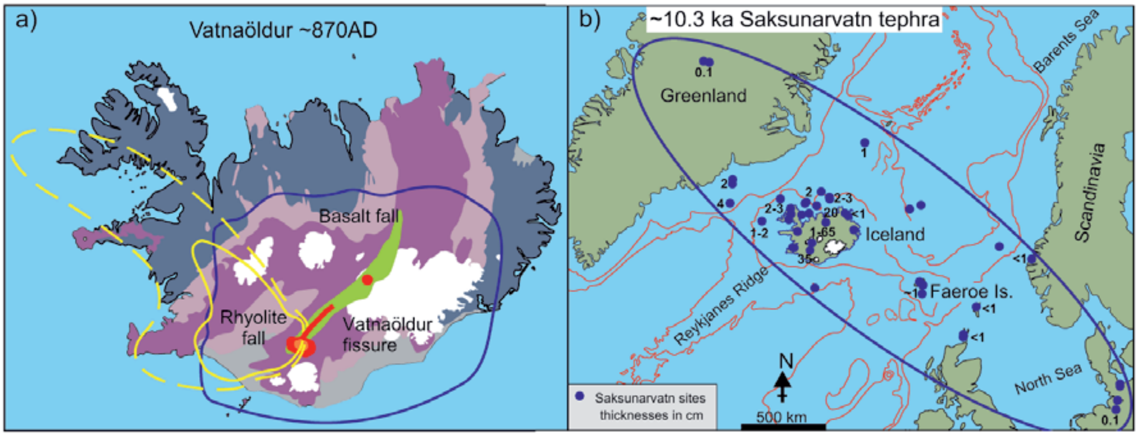

Figure 12. (a) Coverage of the Vatnaöldur ∼870 AD tephra (i.e. Settlement Layer) in Iceland; solid line represents the 0.5 cm isopach of the basaltic (blue) and rhyolitic (yellow) component, respectively. The broken line indicates the known extent of the rhyolite tephra. Modified after Larsen (1984). (b) Map showing the known distribution of the ∼10 ka Saksunarvatn tephra (Jóhannsdóttir *et al.*, 2006). – *(a) Útbreiðsla Vatnaöldugjóskunnar (þ.e. Landnámslagsins) frá 870 e.kr. (b) Útbreiðsla Saksunarvatngjóskunnar sem myndaðist fyrir um það bil 10.000 árum.*

intensity - hawaiian, strombolian, subplinian, vulcanian and Plinian - reflecting the fundamental difference between weak and powerful eruptions resulting from contrasting magma rheologies (e.g., Vergniolle and Mangan, 2000; Cashman *et al.*, 2000). All of the 'dry' explosive eruption types, except vulcanian, are represented in Icelandic eruption record (Figure 10a). Strombolian and 'hawaiian' explosions are typified by low-discharge events (10^{-1} to 10^2 m^3/s) producing tephra deposits that are largely localised about the vent(s) as steep sided cones (Figures 4d-e). Although number of eruptions or phases of eruptions in Iceland have been identified as strombolian (Thorarinsson and Sigvaldason, 1972; Thorarinsson *et al.*, 1973; Gudmundsson *et al.*, 1992), only one has been verified as such by Walker indices, namely the 1973 Eldfell eruption at Heimaey (Figure 10d; Self *et al.*, 1974). Occurrence of 'hawaiian' eruptions is inferred from presence of spatter cones and tephra fall of very limited dispersal, but none have been verified in a quantitative manner (Figure 10a). The explosive phases of the ∼900 AD Rauðhálsar eruption at Snæfellsnes might be the closest Icelandic example of explosive 'hawaiian' activity (Figure 10d; Jóhannesson, 1977).

High-discharge (up to 6600 m^3/s) mafic explosive phases produced by flood lava eruption in Iceland have produced tephra layers with dispersal patterns that fall between subplinian and Plinian deposits (Figures 10a,c,d; Thordarson and Self, 1993; Thordarson *et al.*, 2001). These high-discharge explosive phases occur at the beginning of eruption episodes and are short-lived (hours to days). They are driven by extremely efficient outgassing and very high gas flux that results in two-phase (annular) conduit flow producing gas-charged spray-like fountains that could be coined as vigorous 'hawaiian' activity (Thordarson *et al.*, 1996). In addition, this process results in volatile-depletion of the lower (later erupted) part of the magma column and subsequent transformation to strombolian and hawaiian activity as individual eruption episodes proceed.

Thirty-eight post-glacial 'dry' explosive silicic eruptions (∼2.2% of the total explosive event tally) appear to be classical subplinian to Plinian eruptions as their fall deposits consist of fines-poor pumice beds and exhibit dispersal patterns typical of such events (Figure 10d-e). The record includes several major Plinian events, namely the prehistoric ∼12 ka

Vedde event (>3.3 km^3) at the Katla volcano, $\sim$7 ka H5 (0.7 km^3),$\sim$4.2 ka H4 (1.8 km^3), $\sim$3.8 ka HS (0.45 km^3) and $\sim$3.1 ka H3 (2.2 km^3) eruptions at Hekla (e.g. Larsen and Thorarinsson, 1977; Lacasse *et al.*, 1995). In historic time the main eruptions are that of $\sim$870 AD Torfajökull (0.1 km^3), 1104 AD Hekla (0.5 km^3), 1158 AD Hekla (0.1 km^3), 1362 AD Öræfajökull (2 km^3) and 1875 AD Askja (0.3 km^3) and span the range of subplinian to Plinian (Figures 10d-e; Thorarinsson, 1958, 1967a, 1970b; Larsen, 1992; Larsen *et al.*, 1999; Sparks *et al.*, 1981; Carey, 2008). At least two of these eruptions, the 1875 AD Askja and 1362 AD Öræfajökull, reveal a fairly complex eruption history. The 28–29 March 1875 Askja event involved four distinct eruption phases, identified as units B, C1, C2, and D within the deposits, representing rapid shifts from 'dry' to 'wet' to 'dry' eruptions and changes in vent positions (e.g. Carey, 2008). The eruption began with a subplinian phase (B). After about 9 hour-long pause the eruption picked up its intensity with $\sim$1 hour-long phreatoplinian event (C1) followed by an $\sim$2 hour-long drying-out phase characterized by pyroclastic density currents (C2). The eruption culminated in a 5–6 hour-long Plinian phase (D). The main eruption at Öræfajökull volcano took place in early June 1362 (Thorarinsson, 1958). It began with a weak phreatoplinian phase immediately followed by an intense collapsing-column phase producing pyroclastic density currents that reached >10 km from the source vent. The event was punctuated by a powerful Plinian phase (T. Thordarson and Á. Höskuldsson, unpubl. data, 2008).

CONCLUDING REMARKS

Postglacial volcanism in Iceland is confined to discrete segments commonly referred to as the neovolcanic zones, which by definition occupy about one third of Iceland (Figure 2). The volcanic system is recognized as the principal structure of the neovolcanic zones and currently 30 active systems are identified in Iceland (Figure 1). However, although the 'volcanic system' is a useful concept and at first glance appears to be a robust volcano-tectonic identity, it is important to keep in mind that we have yet to pinpoint the volcano-tectonic or petrochemical parameters that uniquely define a 'volcanic system'. This is not a trivial matter because candid examination of geological maps and existing petrochemical data sets shows that the separation of many systems (e.g. 1-2-3, 4-8-9 and 18-21-22-23-24 on Figure 1) is not clear cut and their boundaries are, more often than not, ambiguous. Inevitably, a more detailed interdisciplinary research is required to clarify this issue because the concept of the volcanic system currently underpins our understanding of Icelandic volcanism and geology.

The data compiled for this study indicates that Iceland has featured about 2400 eruptions in the last 11 ka and that these eruptions have expelled about 566$\pm$100 km^3 of magma. However, and respectfully recognizing the ample efforts of previous researchers, this assessment is hampered to a degree by imperfect postglacial eruption record, which largely stems from lack of comprehensive and precise basic factual information, such as eruption size, intensity and frequency. Notwithstanding the data base that we have compiled for this study from existing publications is neither complete nor flawless. Although we are of the opinion that the results extracted from it on number of postglacial eruptions and their magma output are of the correct magnitude, the exact numbers should not be taken too literally as well as applied cautiously and with proper judgement. However, despite these limitations, some useful inferences can be made on the basis of the current postglacial eruption data set:

1. Postglacial magma output in Iceland is about 5 km^3/century or about 1.4 times that of the volcanism in Hawaii, implying that Iceland is most productive of the currently active terrestrial hotspots. However, when it comes to number of eruptions Iceland is no match to Hawaii, where the event frequency is 3–5 times higher.

2. Frequency distribution and magma volume proportions of mafic, intermediate and silicic eruptions is approximately 91:6:3 (Table 2), underlining the governance of mafic magmatism. However, it does not support the notion that activity in Iceland is typified by bi-modal (basalt-silicic) magmatism (e.g. Jónasson, 2007).

3. EVZ is responsible for >80% of all Holocene

eruptions and $\sim$60% of the erupted magma volume, reinforcing the conclusion put forth by Thordarson *et al*. (2003b), that the EVZ has been the most prolific producer of eruptions and magma in Iceland over the last 11 ka. Among the main volcanic zones the RVB has the lowest productivity, whereas the WVZ has the fewest eruptions and highest mean volume per event (Table 2).

4. Lava volume produced by mafic effusive eruptions is not evenly distributed across the Holocene. About 30% ($\sim$111 km^3) of the total volume was produced in the mid- to late-Holocene (i.e. post-5 ka) and the distribution is fairly even per millennia, except for the period 2–3 ka, when lava production appears to have dropped by factor of $\sim$3. The remaining 70% ($\sim$258 km^3) were erupted in the early- to mid Holocene (i.e. pre-5 ka) and the volume distribution appears to be fairly even with respect to time (i.e. around 35–40 km^3 per millennia), except that about one third (70 km^3) this volume appears to have been erupted between 10–11 ka.

In spite of the dominance of mafic magmatism, the diversity of Icelandic volcanism is undisputable and highlighted by the fact that it features close to all known terrestrial volcano and eruption types (e.g. Thordarson and Larsen, 2007; Larsen and Eiríksson,). However, the current postglacial eruption data set only allows first order grouping of events; into the basic categories of effusive, mixed and explosive postglacial eruptions. A more sophisticated classification is currently only applicable to a small selection of events because the necessary data has yet to be obtained for majority of the events on the record. Therefore, it is impossible at this stage to make a conclusive assessment of the eruption styles that typify Icelandic volcanism. However, the analysis presented here clearly indicates dominance of subglacial explosive mafic events, >75% of the total eruption tally, when it comes to number of eruptions. This is primarily an artefact of environmental factors because the most active central volcanoes in the country are situated beneath or capped by a glacier. When it comes to magma output the story is very different. The record is dominated by large volume (>1 km^3) effusive mafic eruptions. About 50 such eruptions have occurred throughout postglacial time, or 2% of the total eruption tally, at recurrence frequency of 300-500 years, yet they produced about 55% of the postglacial magma volume.

Acknowledgements.

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ÁGRIP

Ísland er eitt virkasta og afkastamesta eldgosasvæði á yfirborði jarðar með gostíðni upp á $\geq$20 aburði á öld, sem framleiða að meðaltali $\geq$5 km^3 af kviku á hverjum 100 árum. Þrátt fyrir að basísk eldvirkni sé ráðandi á Íslandi (90% allra gosa), þá eru allar eldgosa- og kvikugerðir jarðar þekktar hér á landi. Eldvirkni á Nútíma afmarkast við virku eldgosabeltin og þá helst við eldstöðvakerfin 30 sem þar er að finna. Sú eldgosaskrá sem nú liggur fyrir bendir til þess að um 2400 eldgos hafi átt sér stað á Íslandi á síðustu 11000 árum og að þau hafi samanlagt framleitt um 566$\pm$100 km^3 af kviku. Hraungos, að meðtöldum flæðibasaltgosum (>1 km^3), eru um 500 talsins en afgangurinn eru sprengigos af ýmsum gerðum. Algengust eru basísk gos í jökli eða 77% allra sprengigosa, sem sýnir glöggt áhrif umhverfis á hegðun íslenskra eldgosa. Hvað varðar kvikuframleiðni, þá er framlag flæðibasaltgosa mest. Um 50 slík gos hafa orðið á Nútíma, eða aðeins um 2% allra atburða, en framleiddu samt 55% af heildarrúmmáli gosefna. Austurgosbeltið hefur verið afkastamest með >80% allra eldgosa og $\sim$60% gosefna. Að auki, er rúmmál basaltkviku ekki jafndreift í tíma, því aðeins 30% ($\sim$111 km^3) af heildarrúmmáli basískra gosefna kom upp í gosum á síðustu 5000 árum og 70% ($\sim$258 km^3) á tímabilinu 5–11000 ár. Kvikuframleiðnin innan hvors tímabils virðist hafa verið nokkuð jöfn, eða á bilinu 20–30 km^3/1000 ár á síðustu 5000 árum, 35–40 km^3/1000 ár á tímabilinu frá 5–10.000 ár. Tímabilið 10–11.000 ár stendur upp úr hvað þetta varðar, því þá virðist framleiðnin hafa verið tvöfalt meiri eða $\sim$70 km^3/1000 ár.

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