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New estimates of sulfur degassing and atmospheric mass-loading by the 934 AD Eldgjá eruption, Iceland

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Abstract

The 934 AD Eldgjá basaltic flood lava eruption in southern Iceland is the largest on Earth in the last millennium. The Eldgjá fissures produced 19.6 km^3 of transitional basalt in a prolonged eruption that featured at least eight distinct episodes and may have lasted for 3–8 years. The atmospheric SO_2 mass loading by Eldgjá is determined by new measurements of pre-eruption and residual sulfur contents in the products from all phases of the eruption. A pre-eruption sulfur content of ~2150 ppm indicates that the magma carried 232 Mt of SO_2 to the surface, where vent and lava flow degassing released 219 Mt into the atmosphere. This value corresponds to a potential H_2SO_4-aerosol yield of ~450 Mt, increasing previous H_2SO_4-aerosol mass estimates by a factor of 2.6–4.5. Approximately 79% of the original sulfur mass was released at the vents, indicating ~185 Mt SO_2 were discharged into the atmosphere above the Eldgjá fissures and carried aloft by the eruption columns to upper tropospheric and lower stratospheric altitudes (~15 km). Consequently, only ~35 Mt SO_2 escaped from the lava into the lower troposphere. These estimates of the SO_2 mass loading from Eldgjá make it the greatest known volcanic pollutant of recent history, exceeding that of 1783 AD Laki and 1815 AD Tambora eruptions by factors of 1.8 and 2.0–2.8, respectively. However, the intensity of climatic effects deduced by the Eldgjá event are not thought to have surpassed that of Laki or Tambora because the eruption was prolonged and subsequently the sulfur emissions were drawn out over several years. The lack of detailed historic records for this period make estimates of the effects of long term but significant release of SO_2 (30–70 Mt/yr) on the atmosphere uncertain. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Eldgjá; Basalt; Melt inclusions; Sulfuric degassing

1. Introduction

In the last 250 years widespread aerosol plumes from sulfur-rich eruptions have caused significant atmospheric perturbations on a hemispheric to global scale. Such eruptions are often cited as one of the principal forcing elements of short-term climate change (e.g. Pollock et al., 1976; Self et al., 1981; Rampino and Self, 1984; Hoffmann, 1987; Robock, 1991). The sensitivity of climate to such short-lived forcings is important, because of its immediate impact on human activities and the biosphere. Furthermore, these forcings must be accounted for when assessing the effects of anthropogenic greenhouse gases on

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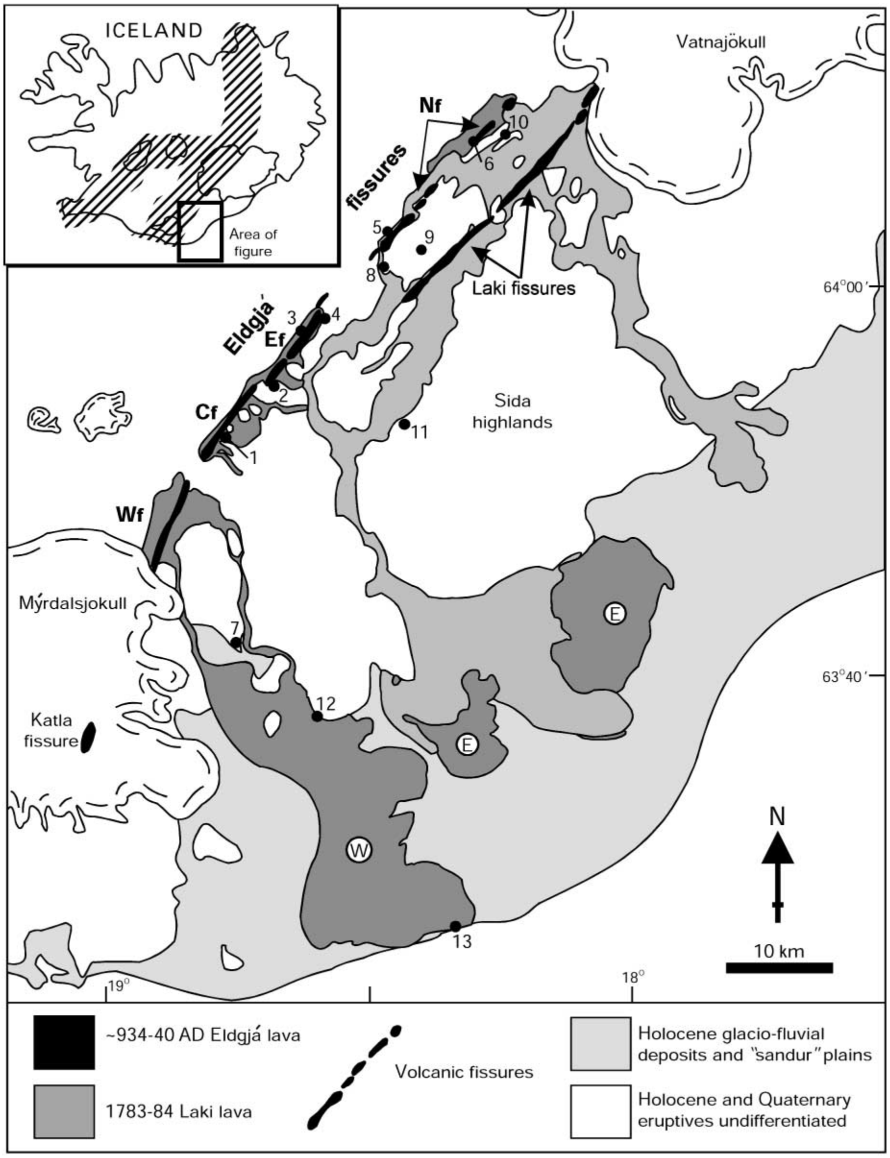

Fig. 1. Map of the Eldgjá fissures and lava flow field, Iceland, showing locations (numbered 1–12) of observations and where samples used in this study were collected (see also Table 1). Eldgjá fissure segments and lavas are indicated as follows: Wf, Western fissure; Cf, Central fissure (Eldgjá proper); Ef, Eastern fissure; Nf, Northern fissure (also known as Kambagígar cone row); W, Western lavas; E, Eastern lavas. Western lavas originated at the western fissure, which is now partly buried under Mýrdalsjökull (ice cap). Eastern lavas originated from the central, eastern and northern fissures. Katla fissure in south Mýrdalsjökull was active in 1918 (see text). Also shown are the 1783–84 AD Laki fissure and lava flow field, which covers a large part of the eastern Eldgjá lavas.

earth's climate (e.g. Hansen et al., 1993). Climatically significant eruptions in the era of instrumental weather observations (i.e. last 100 years) are few and therefore analysis of volcano-climate interactions has involved evaluating the impact of eruptions from the more distant past. The key volcanological parameters for assessing the potential impact of historic and pre-historic eruptions are accurate estimates of atmospheric mass-loading of sulfur along with a realistic evaluation of the eruption dynamics (e.g.

Sigurdsson, 1990; Gerlach et al., 1994; Thordarson, 1995; Self and King, 1996). Several techniques are used to estimate the potential atmospheric sulfuric aerosol yield of past eruptions and are based on: (a) the record of volcanically induced acidity in ice cores (e.g. Hammer, 1977; Hammer et al., 1980; Clausen and Hammer, 1988; Zielinski et al., 1994); (b) historic accounts of atmospheric turbidity (Stothers, 1984, 1996a,b); and (c) direct measurements of volatile concentration in eruptive products (e.g. Rose, 1977; Devine et al., 1984; Sigurdsson et al., 1985; Thordarson et al., 1996).

Basaltic flood lava eruptions, like the 934 AD Eldgjá eruption, are likely to contribute to short-term climate forcings because they are capable of releasing huge amounts of sulfur into the atmosphere (Rampino et al., 1988). The high sulfur yield of flood lava eruptions is a direct consequence of high sulfur concentrations in basalt melts at reservoir depths and the high degree of sulfur degassing during explosive episodes at the vents and/or fountaining episodes during an eruption. Consequently, prolonged high-discharge flood lava eruptions are capable of maintaining elevated atmospheric concentrations of H_2SO_4-aerosols because their plumes are continually replenished in SO_2 by the eruption columns (Sigurdsson, 1990; Wallace and Carmichael, 1992; Thordarson and Self, 1996).

This study presents new sulfur and major element analyses obtained from glass inclusions in phenocrysts and quenched products from the 934 AD Eldgjá flood lava eruption, representing all stages of the eruption. New estimates for the amount of sulfur released by the eruption are given, increasing previously published estimates by a factor of 2.6 to 4.5 or to 220 Mt of SO_2. We also discuss the possible impact of the eruption on the environment and climate.

2. The Eldgjá eruption

2.1. Eruption history

The Eldgjá eruption in southern Iceland is one of the two most voluminous and vigorous basaltic flood lava eruptions on Earth in the last millennium (Miller, 1989; Larsen, 1990). The other being the nearby 1783 AD Laki eruption (Thordarson and Self, 1993). The Eldgjá vent system belongs to the Katla volcanic system of the Eastern Volcanic Zone (Jakobsson, 1979b). It outcrops as a sequence of discontinuous fissures trending roughly N45°E from the edge of the Mýrdalsjökull glacier in the west to within 5 km of Vatnajökull ice cap in the east (Fig. 1). The total volume of lava erupted by the >57-km-long fissure system is estimated to be 18.3 km^3 and the explosive activity produced ~1.3 km^3 of tephra, giving a total erupted volume of 19.6 km^3 (Larsen, 1990; Miller et al., 1997).

The Book of Settlement (*Landnáma*), a detailed 12th century compilation of the early settlements in Iceland, states that the early settlers in the area now covered by the Eldgjá lavas were forced off their farmlands by a lava flow from an eruption in the highlands to the north (Fig. 1). Thoroddsen (1925) was the first to suggest that these descriptions referred to the Eldgjá eruption, which was later confirmed by tephrochronological studies, showing that the eruption took place in the early 10th century (Larsen, 1979). Elevated SO_4^{2-} concentrations spanning several annual layers and a large acidity peak in Greenland ice cores correlate with the Eldgjá eruption, indicating that the eruption occurred in the time interval 933–941 AD (Hammer, 1984; Zielinski et al., 1995).

The internal stratigraphy of the Eldgjá tephra deposits shows that the eruption featured phases of vigorous explosive activity and intense lava fountaining, in addition to the outpouring of large volumes of lava (Larsen, 1990, 1993; Miller, 1989). Persistent occurrences of thick (10–70 m) near-vent accumulations along the entire length of the erupting fissures, consisting of scoria fall deposits, welded spatter, and clastogenic lavas, are evidence of intense fire fountaining activity. Occasionally these formations cap the tops of the surrounding highs and peaks, rising 50–200 m above the floor of the adjacent vents. At proximal and medial localities (<30 km from source), the tephra deposit is characterized by distinct strombolian and phreatomagmatic fall units (Fig. 2), which originated from different segments of the fissure system. Most of the phreatomagmatic units (<4% of the total volume erupted) originated at the westernmost fissures which erupted through the Mýrdalsjökull glacier and are typically composed of poorly sorted ash, consisting of angular, blocky clasts that are poorly to moderately vesicular (5–50 vol.%). The

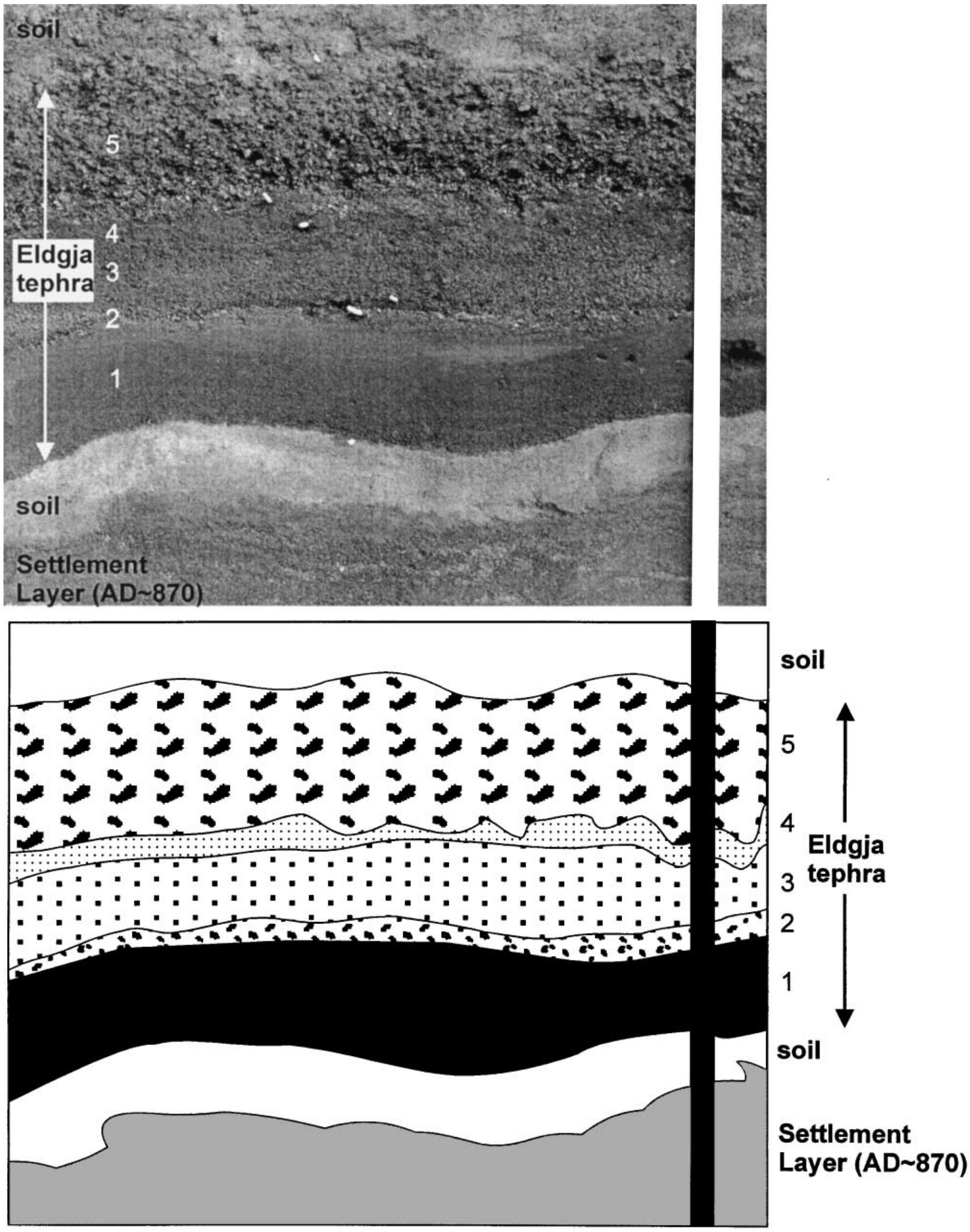

Fig. 2. Photograph and line drawing of Eldgjá tephra layer at section 13 (Leidólfsfell) where it consists of five separate fall units (1–5): (1) Phreatomagmatic fall unit; black very fine to fine ash, 6.0–9.0 cm thick. (2) Strombolian fall unit; fine lapilli scoria, 0.5–1.5 cm thick. (3) Strombolian fall unit; brown medium to coarse grained ash, 4.0 cm thick. Brown color is caused by high abundance of golden yellow–brown, highly vesicular clasts. (4) Strombolian fall unit; a shiny black medium ash, 3.0 cm thick. (5) Strombolian fall unit; black fine to medium lapilli scoria. Tephra layer at bottom of photograph is the Settlement Layer produced by ~870 AD Vatnaöldur eruption (Larsen, 1984). Light blebs in center of photograph are markers inserted at contacts of Eldgjá fall units. Scale is 40 cm long.

strombolian tephra units and the lavas (>96% of the total volume) were erupted by the subaerial part of the fissure system (Larsen, 1990). The strombolian units are moderately to well-sorted scoria lapilli, composed of moderately to highly vesicular clasts (50–90 vol.% voids). Clasts are either partly or wholly coated by thin fluidal skin, formed by fusion of the outer surfaces during extrusion (Thordarson et al., 1996). The strombolian tephra also contains a small, but variable amount of Pele's hair and tears. The large volume of the tephra deposit (1.3 km^3) produced by the eruption, along with its wide dispersal (the 0.5 cm isopach is at ~100 km from source), indicate vigorous explosive activity that produced the strombolian and phreatomagmatic deposits (Larsen, 1990, 1993; G. Larsen, unpublished data 1998).

2.2. Previous estimates on the sulfur yield of the Eldgjá eruption

Palais and Sigurdsson (1989) obtained a petrologic estimate of the atmospheric SO_2 yield from the Eldgjá eruption of 55 Mt of SO_2 from a single sample of strombolian scoria fall deposit collected at Úlfarsdalssker (Section 9; Fig. 1 and Table 1). Their results indicate a potential H_2SO_4-aerosol yield of ~105 Mt, which is ~4 times lower than ours (Miller et al., 1996). The main reasons for this difference are: (1) the smaller eruption volume of 9 km^3 used in their calculations, compared to the 19.6 km^3 of this study; and (2) a lower estimate of pre-eruption sulfur content. Palais and Sigurdsson (1989) used an averaged value from all analyzed glass inclusions, regardless of their major element composition. As will be demonstrated below, a range of major element and sulfur concentrations characterizes the glass inclusion population in Eldgjá phenocrysts. Inclusions with compositions compatible with that of the bulk of the Eldgjá products have the highest sulfur content, and therefore an averaged value underestimates the amount of sulfur dissolved in the bulk magma prior to eruption.

Hammer et al. (1980) and Zielinski et al. (1995) used Greenland ice-core acidity data to estimate the atmospheric H_2SO_4-aerosol loading by the Eldgjá eruption, obtaining 165 and 93 Mt, respectively. The method used to estimate the amount of SO_4^{2-} in the atmosphere from ice cores is based on studies of the global stratospheric distribution of radioactive nuclides from atmospheric nuclear bomb tests (Clausen and Hammer, 1988). It assumes middle to upper stratospheric loading and global dispersal for the volatile mass. The method appears to give reasonable estimates for the atmospheric volatile mass-loading by some explosive eruptions, because the distribution of aerosols may have been analogous to that of radionuclides after the bomb tests. They were also characterized by near-instantaneous volatile release and >20 km high eruption columns. However, the Laki flood lava eruption in Iceland featured 13–14 km high eruption columns (Thordarson and Self, 1993) and the atmospheric mass-loading of volatiles was confined to the lower stratosphere and troposphere (Fiacco et al., 1994; Grattan and Charman, 1994; Thordarson, 1995; Grattan, 1998). Consequently, the estimated aerosol dispersal and concentration by the methods employed on ice core data may not be applicable to all flood lava eruptions. Firstly, the atmospheric circulation and the time constants for growth and removal rates of aerosols are fundamentally different for the stratosphere and troposphere (e.g. Holton, et al., 1995; Jaenicke, 1993) and therefore the model results in a misrepresentation of the aerosol mass-loading from flood lava eruptions. Secondly, the dispersal of <20 km high volcanic plumes and aerosols from Icelandic eruptions is controlled by the westerly jet stream (Thorarinsson, 1981; Jónsson, 1990). Thus, the plumes have to circumnavigate the Northern Hemisphere to reach the Greenland ice cap, which takes about 4–6 weeks at 60°N at a typical velocity of 5–10 m/s (e.g. Fiacco et al., 1994). A considerable portion of the aerosol mass is dispersed at upper tropospheric altitudes (~5–10 km at 60°N), where the atmospheric residence time of the aerosols is of the order of days to weeks. Consequently, a significant proportion of the aerosols is removed from atmosphere before the plume reaches Greenland. Therefore, the Greenland ice core signal may only represent the lower stratospheric component of the aerosol cloud from Icelandic flood lava eruptions.

3. Samples and analytical procedure

Samples used in this study include representation of

Table 1
Eldgjá samples and sample locations

Locality	Sample number	Sample type	Formation
1. Central fissure	E50-1	Strombolian tephra	Vent accumulations
2. Eastern fissure	E35-1	Strombolian tephra	Vent accumulations
3. Eastern fissure	E45-1	Phreatomagmatic tephra	Vent accumulations
4. Eastern fissure	E42-1	Strombolian tephra	Vent accumulations
5. Northern fissure	E22-1	Strombolian tephra	Vent accumulations
6. Klettaeyjar	E13-2	Strombolian tephra	Fall unit 1 of 6[a]
	E13-1	Phreatomagmatic tephra	Fall unit 2 of 6
7. Leidólfsfell	28891-11	Phreatomagmatic tephra	Fall unit 1 of 5[a]
	28891-10	Strombolian tephra	Fall unit 3 of 5
	28891-09	Strombolian tephra	Fall unit 4 of 5
	28891-08	Strombolian tephra	Fall unit 5 of 5
8. Kambar	14891-09	Strombolian tephra	Fall unit 2 of 3
9. Úlfarsdalssker	16883-s5-1[b]	Strombolian tephra	Fall unit 1 of 1
10. Stakafell	E4-1	Phreatomagmatic tephra	Fall unit 1 of 3
	E4-2	Mixed tephra[c]	Fall unit 2 of 3
	E4-3	Phreatomagmatic tephra	Fall unit 3 of 3
11. Hólmsá River	16792-09	Glassy basal selvage	Pahoehoe flow lobe

[a] Units are counted from base up within the tephra layer (see also Fig. 2).
[b] Analyzed by Palais and Sigurdsson (1989).
[c] Appears to be a mixture of phreatomagmatic and strombolian tephra. Simultaneous fall from two vents?

all products of the Eldgjá eruption, including the vent deposits, tephra fall units and lavas (Fig. 1 and Table 1). Locations 1–5 indicate samples collected from vent deposits. Samples from locations 6 and 7 represent tephra fall units that are primarily derived from the Western, Central and Eastern fissures, whereas samples from locations 8–10 are fall units from the northern fissure. Lava flow samples were collected at location 11.

Major and volatile element analyses of glass inclusions and groundmass glass were obtained by an automated, wavelength dispersive, Cameca SX 50 electron microprobe at the University of Hawaii and Texas A&M University, USA, using the analytical procedures given in Thordarson et al. (1996). Precision (2σ) for major elements is better than 1% and the estimated precision for sulfur is 45 ppm. Raw data were corrected using the standard Cameca ZAF procedures.

4. Data presentation

4.1. Petrology and major element chemistry

The 934 AD Eldgjá products are sparsely porphyritic ($\leq$2 vol.%) transitional alkali basalts, containing $\leq$2 mm subhedral to euhedral phenocrysts of plagioclase (An_{65-92}), clinopyroxene ($En_{40}Fs_{17}Wo_{43}$–$En_{46}Fs_{8}Wo_{46}$), olivine (Fo_{70-89}), and magnetite. The phenocrysts are embedded in holohyaline groundmass in tephra clasts, whereas in the lavas the groundmass is hypo- to holocrystalline. The Eldgjá products show small variations in major element concentration, with MgO and FeO contents ranging from 4.7–5.9 to 14.6–16.7 wt.%, respectively (Table 2). Eldgjá whole-rock compositions are slightly more magnesian than eruptives from the Katla central volcano, but fall well within the compositional field of the Katla volcanic system (Fig. 3). The bulk of the erupted tephra has groundmass glass compositions identical to and slightly more evolved than the whole-rock compositions (Fig. 4a–c). There is no difference between the composition of the groundmass glass in strombolian and phreatomagmatic tephra clasts. In addition, the tephra contains clasts that have groundmass glass compositions of tholeiitic affinities. These are fresh ash to lapilli size scoria clasts with morphologies identical to other juvenile tephra clasts. At most localities these occur as sporadic clasts (<5 vol.%) in the tephra and vent deposits, with the exception of the northeasternmost

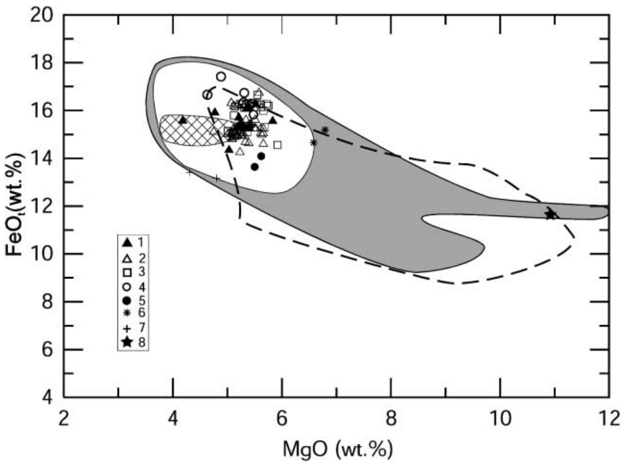

Fig. 3. Variation diagram showing range of whole-rock compositions from the Eldgjá eruption products. Whole-rock compositions fall within the field outlining magma compositions from the Katla volcanic system. Melt inclusions trapped in phenocrysts are also plotted, showing that inclusions of bulk Eldgjá compositions cluster with the whole-rock data and that the composition of the other inclusions is compatible to that of known melt compositions within the Eastern Volcanic Zone. Eldgjá whole-rock analyses are indicated by symbols 1. lava, 2. tephra, 3. vent deposit. Melt inclusions are shown by the symbols 4. Transitional basalt, bulk Eldgjá compositions, 5. Transitional basalt, low TiO_2 compositions, 6. Tholeiite, high TiO_2 compositions, 7. Tholeiite, high MgO compositions; 8. Olivine tholeiite composition (see also Table 3). Fields are as follows: whole-rock compositions of eruptives from the Katla central volcano (cross-hatched pattern); glass compositions of quenched eruption products from the Katla volcanic system (white); quenched glass and melt inclusion compositions from the Eastern Volcanic Zone (shaded grey and broken line, respectively). In addition to the sources given in Table 2 the data used to construct this diagram are from Steinthorsson (1977), Einarsson (1982), Larsen (1982), Devine et al. (1984); Grönvold and Johannesson (1984), Meyer et al. (1985), Metrich et al. (1991), Thordarson (1995); Thordarson et al. (1996, 1998), Thordarson, unpublished data, and data from this study.

Table 2
Composition of Eldgjá eruption products; major element (wt.%) and sulfur (ppm)

Abbreviations are as follows: w-r, average whole rock lava and tephra composition. Data from Robson (1957), Thorarinsson (1958), Jakobsson (1979), Wood et al. (1979), Óskarsson et al. (1982), Steinthorsson et al. (1985), Einarsson et al. (1980), Miller (1989), D.J. Miller and Th. Thordarson unpublished data. p and s indicate groundmass glass composition of phreatomagmatic and strombolian tephra. Also shown is the composition of the tholeiitic component in the Eldgjá eruptives. *N*, number of analysis; s.d., standard deviation (2σ)

Magma type	Lithology	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	S	*N*	Ti/Fe
Transitional alkali basalt	w-r	46.97	4.46	12.74	15.34	0.21	5.28	10.06	2.89	0.69	0.52	99.17	100	75	0.22
(bulk Eldgjá)	s.d.	0.67	0.21	0.62	0.61	0.02	0.26	0.39	0.16	0.09	0.12	0.87	30		0.02
	p	46.66	4.19	12.90	15.16	0.22	5.41	10.38	2.83	0.64	0.44	98.83	1110	84	0.21
	s.d.	0.41	0.36	0.35	0.51	0.03	0.41	0.55	0.12	0.13	0.11	0.50	275		0.01
	s	47.01	4.67	12.57	15.77	0.23	5.07	10.01	2.87	0.75	0.52	99.41	445	88	0.23
	s.d.	0.61	0.21	0.48	0.67	0.03	0.32	0.33	0.18	0.08	0.10	0.50	130		0.01
Tholeiitic component	p1	49.05	1.90	13.93	11.81	0.19	7.23	12.36	2.24	0.22	0.17	99.09	980	17	0.12
	s1	49.55	1.78	13.94	12.67	0.22	7.03	11.95	2.06	0.26	0.15	99.61	200	3	0.11
	p2	49.00	2.31	13.39	13.18	0.21	6.47	11.35	2.41	0.28	0.22	98.81	1040	29	0.14
	s2	50.09	2.38	12.62	14.74	0.24	5.66	10.56	2.54	0.32	0.24	99.40	705	8	0.11
	p3	49.09	3.15	12.37	15.79	0.25	4.96	9.55	2.64	0.43	0.33	98.57	1545	19	0.15
	s3	49.50	2.98	12.90	14.57	0.23	5.34	9.91	2.75	0.44	0.32	98.94	895	9	0.16

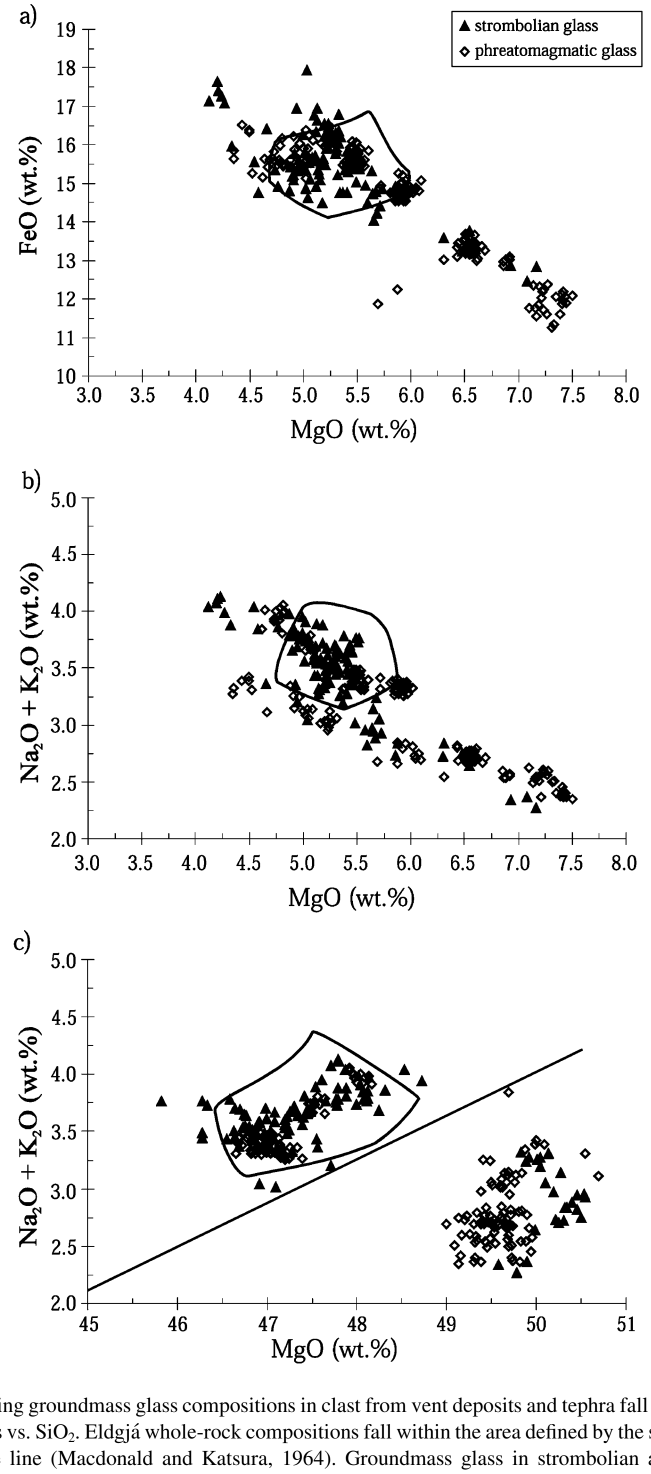

Fig. 4. Variation diagrams showing groundmass glass compositions in clast from vent deposits and tephra fall units: (a) FeO vs. MgO; (b) Total alkalis vs. MgO; (c) Total alkalis vs. SiO_2. Eldgjá whole-rock compositions fall within the area defined by the solid polygon and the solid line in (c) indicates the Hawaii divide line (Macdonald and Katsura, 1964). Groundmass glass in strombolian and phreatomagmatic tephra are indicated by solid triangles and open diamonds, respectively.

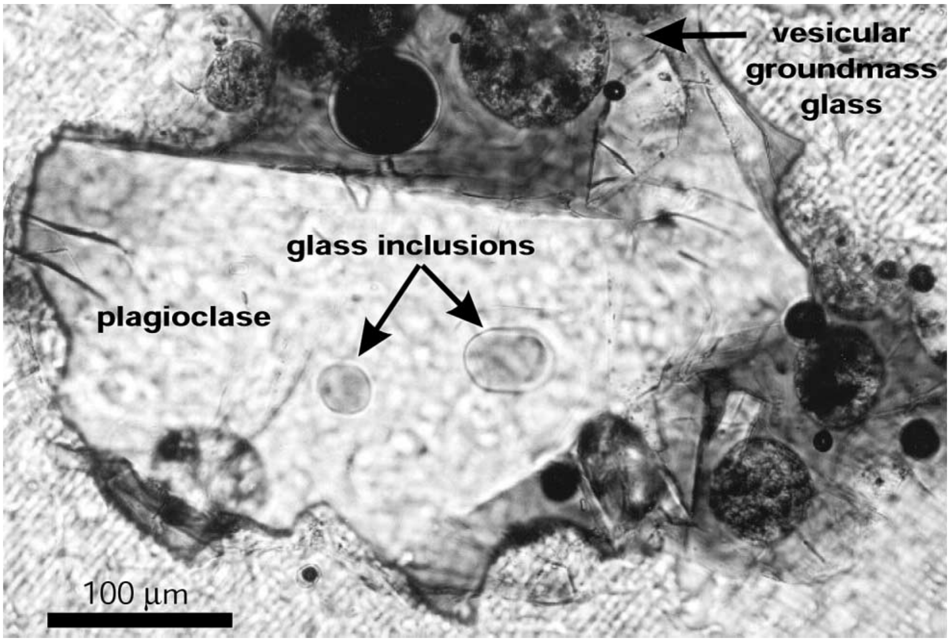

Fig. 5. Two round Eldgjá glass inclusions in plagioclase contained in a small vesicular clast. The larger inclusion (~50 mm long) was analyzed and contains 2095 ppm. The smaller inclusion has a diameter of ~30 mm. Scale bar is shown at the bottom left. From sample 13-2, section 1 at Klettaeyjar.

tephra section (locality 10) where they are the most abundant clast type. Despite the clear distinction in the groundmass glass compositions, the field evidence and grain morphologies show that both clast types are juvenile products of the 934 AD Eldgjá eruption. This suggests that the Eldgjá fissures erupted two magma types; a transitional alkali basalt magma which forms the bulk volume (>99.5%) of the eruptives and a minor volume of Ti-rich tholeiite magma (Fig. 4a–c).

All of the Eldgjá phenocryst phases contain clear, light brown glass inclusions ranging from 10 to 200 μm in diameter (Fig. 5). We analyzed a total of 13 glass inclusions trapped in plagioclase and clinopyroxene from mineral separates obtained from 4 samples (Table 1). Eight inclusions hosted by plagioclase (An_{65-69}) and clinopyroxene ($En_{41}Wo_{43}Fs_{16}$) have evolved transitional basalt compositions. Six of the melt inclusions closely match the bulk composition of the Eldgjá magma, and two have slightly less evolved compositions (Figs 3 and 6). Host mineral compositions are consistent with the evolved nature of these melts (Table 3a). The other five inclusions have tholeiitic compositions that are compatible to melts produced in the Eastern Volcanic Zone (Fig. 3). The data also shows that major element abundances of 12 of the analyzed inclusions are similar to the composition of the two magmas produced by the Eldgjá eruption and therefore may be regarded as representative of the pre-eruption magma compositions (Fig. 6). More importantly the six melt inclusions listed in Table 3b have compositions that are identical to that of the bulk Eldgjá products (Table 2) suggesting no or minimal post-entrapment crystallization of the host minerals. Similar results were obtained for melt inclusions in phenocrysts from the eruptives of the neighboring Laki fissures, where host mineral crystallization introduced a small error (<6%) in the measured sulfur content of the melt inclusions (e.g. Metrich et al., 1991).

4.2. Sulfur chemistry

The total range in measured sulfur content in the glass inclusions is 900–2425 ppm. Inclusions of the bulk Eldgjá composition have the highest sulfur content (mean 2155 ± 165 ppm), whereas the

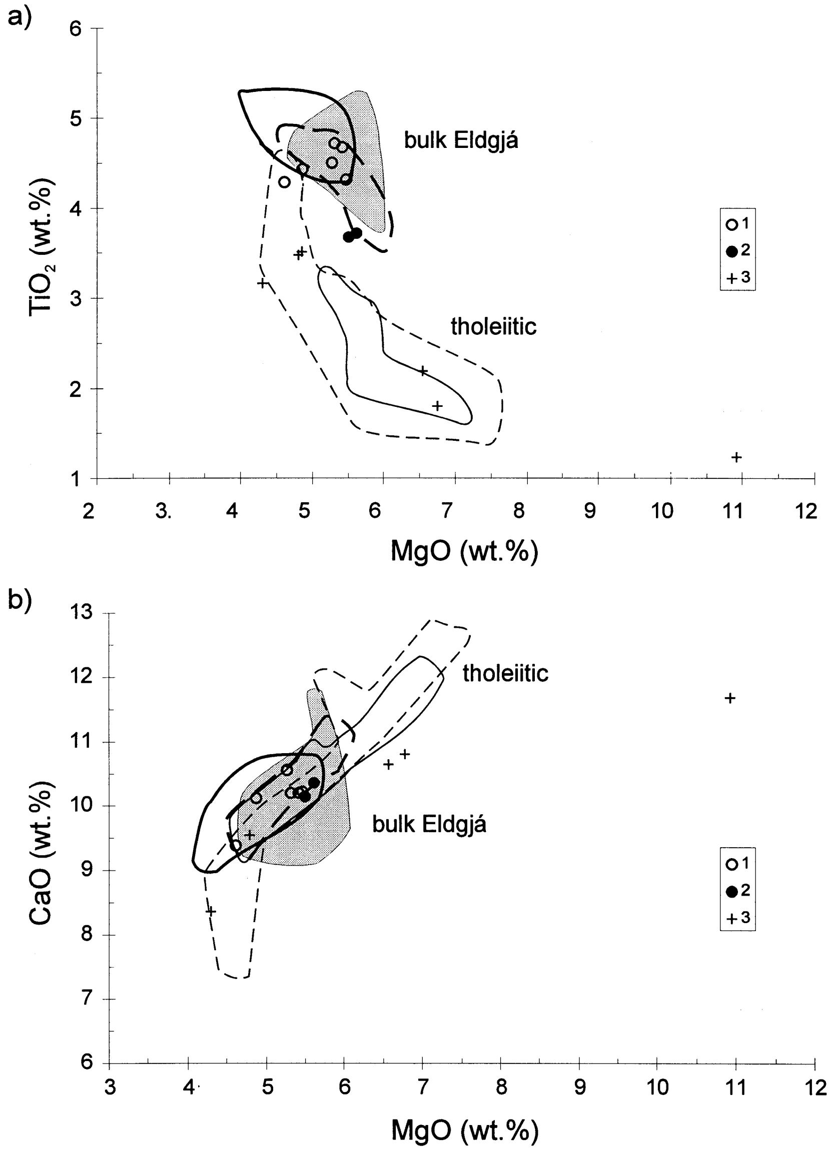

Fig. 6. Variation diagrams comparing glass inclusions and Eldgjá eruptives: (a) TiO_2 vs. MgO; (b) CaO vs. MgO. Melt inclusions generally fall on the trend defined by the magma products. (1) Inclusions of bulk Eldgjá composition; (2) low TiO_2 transitional inclusions; (3) Tholeiitic inclusions. Fields are as follows: whole-rock lava and tephra (solid line); groundmass glass of phreatomagmatic and strombolian tephra, broken and solid lines, respectively. Heavy and thin lines indicate transitional basalt and tholeiitic basalt compositions.

remainder contains <1500 ppm sulfur (Table 3). There is a positive correlation between sulfur and FeO content in the Eldgjá inclusions, and they fall on the S–Ti/Fe trend defined by glass inclusion data from Icelandic basalts and groundmass glass data from MORBs (Fig. 7). The sulfur content of groundmass glass in tephra clasts irrespective of major element compositions ranges from 200 to 1545 ppm (Table 2). Considering only glass with bulk Eldgjá compositions (Fig. 7), the high and variable sulfur content in groundmass of phreatomagmatic clasts (mean 1110 ± 275 ppm) contrasts with

Table 3
Glass inclusions of bulk Eldgjá composition; major elements (wt.%) and sulfur (ppm). N_i, number of inclusions; N_a, number of analysis; plag, plagioclase; cpx, clinopyroxene. Other abbreviations as indicated in Table 2

Inclusion	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	S	N_a	Host
a)														
Egi13-2-6652	47.04	4.29	12.89	15.76	0.22	5.44	10.17	2.62	0.61	0.42	99.81	2423	2	cpx ($En_{41}Wo_{43}Fs_{16}$)
Egi13-2-6653	46.09	4.47	12.56	16.61	0.19	5.25	10.51	2.72	0.67	0.42	99.82	2097	1	plag (An_{69})
Egi4-3-6771a	46.02	4.63	12.20	16.07	0.22	5.22	10.03	2.75	0.67	0.44	98.58	2078	2	plag (An_{65})
Egi4-3-6771b	45.95	4.59	12.19	16.04	0.22	5.33	10.04	2.80	0.70	0.49	98.68	2110	1	plag (An_{65})
160888-5-1, 6	47.32	4.21	12.55	16.42	0.34	4.54	9.23	2.75	0.53	0.47	98.36	2280	1	cpx
160888-5-1, 7	46.27	4.39	12.41	17.31	0.32	4.83	10.04	2.64	0.53	0.47	99.21	1957	1	cpx
Average	**46.45**	**4.43**	**12.47**	**16.37**	**0.25**	**5.10**	**10.00**	**2.71**	**0.62**	**0.45**	**99.08**	**2155**	**6**	
s.d.	**0.58**	**0.17**	**0.26**	**0.55**	**0.06**	**0.34**	**0.42**	**0.07**	**0.07**	**0.03**	**0.64**	**165**		

b) Glass inclusions of other compositions; major elements (wt.%) and sulfur (ppm)

Inclusion type	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	S	N_i	N_a	Host
Low TiO_2 transitional	46.95	3.60	14.23	13.51	0.23	5.42	9.98	2.32	0.68	0.51	97.41	1340	2	2	cpx
s.d.	0.83	0.01	0.79	0.23	0.04	0.05	0.10	0.70	0.05	0.00	0.54	235			
High TiO_2 tholeiite	50.43	3.24	12.75	13.00	0.30	4.46	8.76	2.80	1.16	0.97	97.84	1385	2	2	cpx
s.d.	1.08	0.20	0.11	0.23	0.16	0.32	0.77	0.01	0.18	0.02	0.50	70			
High MgO tholeiite	50.54	2.01	12.90	14.95	0.23	6.69	10.73	1.50	0.38	0.19	100.3	1285	2	3	plag (An_{86})
s.d.	0.58	0.28	0.20	0.42	0.01	0.17	0.16	0.55	0.06	0.04	0.30	190			
Olivine tholeiite basalt	48.41	1.20	12.53	11.41	0.22	10.71	11.46	1.84	0.19	0.08	98.21	900	1	1	plag (An_{90})
s.d.															

relatively low and tighter clustering of sulfur abundances in strombolian clasts (mean 445 ± 130 ppm). The sulfur content in the groundmass glass of other compositions show the same general trend, although the data set is not as comprehensive (Fig. 7). The sulfur content of a single sample from the quenched glassy selvage of the Eldgjá lava is 130 ppm, which is almost double the value of 70 ppm given by Torssander (1989) for the sulfur content of crystalline lava.

5. Sulfur degassing

5.1. The petrologic method

The petrologic method has been successfully used to estimate the potential atmospheric sulfur yield from both explosive and effusive eruptions (e.g. Devine et al., 1984; Palais and Sigurdsson, 1989; Andres et al., 1991; Metrich et al., 1991; Thordarson et al., 1996). However, the method gives minimum estimates for the volatile mass released by an eruption because the mass balance calculations are entirely derived from the total volume of erupted magma and ignores the possible contribution from unerupted melts (e.g. Devine et al., 1984; Sigurdsson, 1990; Allard et al., 1994; Allard, 1997). The atmospheric mass-loading of sulfur in explosive eruptions can be regarded as instantaneous, because the volatiles are released in a single or a series of explosive events lasting several hours up to a few days. However, this approach is not directly applicable to flood lava eruptions that can last for months to years, or even decades, and often feature a series of eruption episodes as new batches of magma are injected into the conduit system. These episodes may be separated by significant time intervals (days to months) and usually begin with a short-lived explosive phase that leads into a longer lasting effusive phase (Thordarson and Self, 1993; Self et al., 1997). Detailed studies of the 1783–84 AD Laki eruption have shown that the magma degassing in flood

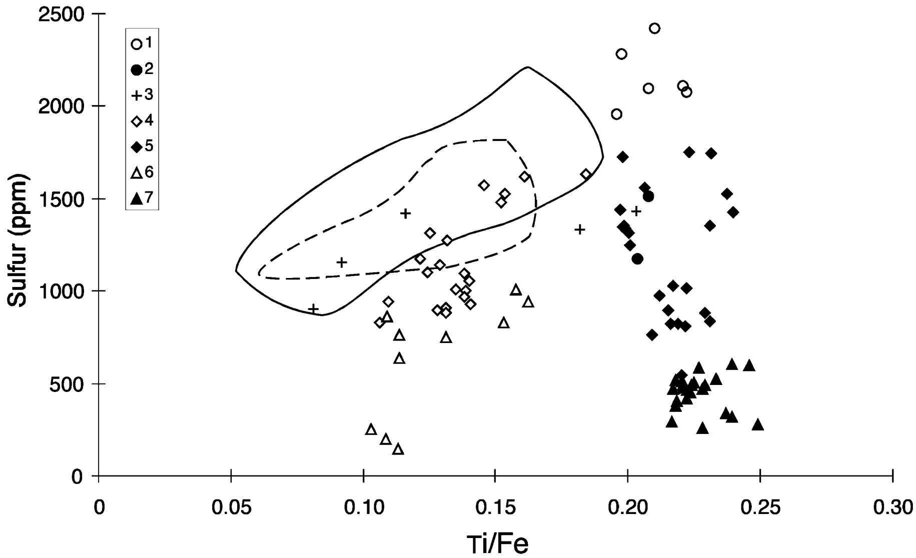

Fig. 7. S (ppm) variation as a function of Ti/Fe in Eldgjá samples. Note the negative degassing trend defined by progressive decrease in S-content from melt inclusions, through phreatomagmatic to strombolian tephra. 1. Melt inclusions of Eldgjá bulk composition, 2. low TiO_2 transitional basalt melt inclusions, 3. tholeiitic melt inclusions, 4. tholeiitic phreatomagmatic tephra, 5. phreatomagmatic tephra of bulk Eldgjá composition, 6. Tholeiitic strombolian tephra, 7. strombolian tephra of bulk Eldgjá composition. Solid line outlines the compositional field of melt inclusions trapped in phenocrysts from the Grímsvötn and Veiðivötn volcanic systems of the Eastern Volcanic Zone (Metrich et al., 1991; Thordarson, 1995; Thordarson et al., 1996). Broken line outlines the sulfur compositional field of MORB basalts as defined by the data from Mathez (1976) and Aggrey et al. (1988).

lava eruptions occurs in two distinct stages: (1) as the magma moves up through the conduit and erupts from the vents; and (2) during and immediately after lava emplacement (Óskarsson et al., 1984; Thordarson et al., 1996). Most of the magma degassing occurs in the first stage because two-phase flow develops as the magma ascents through the conduit. More than 80% of the volatile mass is released into the atmosphere by the explosive activity at the beginning of each eruption episode and is carried to 5–15 km altitudes by the associated eruption columns. Lava degassing only accounts for 15–20% of the volatile mass released and this volatile discharge is confined to the lower troposphere. The volatile budget model is illustrated in Fig. 8 and the general procedures of the mass balance calculations are given in Table 4. This degassing model conforms to the established eruption history of Laki (Thordarson and Self, 1993) and the mass-loading of sulfate aerosols predicted by the model are consistent with independent estimates obtained by using information on atmospheric turbidity over Europe in 1783 (Stothers, 1996a; Thordarson et al., 1996).

In estimating the atmospheric sulfur release by the Eldgjá eruption, we have made the following assumptions. Firstly, only the sulfur data from samples of bulk Eldgjá compositions is used in our calculations; the sulfur contribution of the tholeiitic melt is ignored, because volumetrically it is insignificant (<0.5% of the erupted volume). Secondly, undegassed magma in the reservoir prior to eruption is represented by inclusions of bulk Eldgjá composition, containing 2155 ± 165 ppm sulfur and the volume of magma contributing to the atmospheric venting of sulfur is equal to the erupted magma volume (i.e. 19.6 km^3). Thirdly, the bulk of the magma volume (>96%) was erupted from subaerial fissures where the activity was not effected by magma to water interactions. Thus, we assume that the total magma volume was subjected to the two-stage degassing process described previously. The volume of phreatomagmatic tephra (<4% of the total volume) is equivalent to the amount of melt in which degassing was suppressed by interaction of magma and external water and is ignored in the calculations.

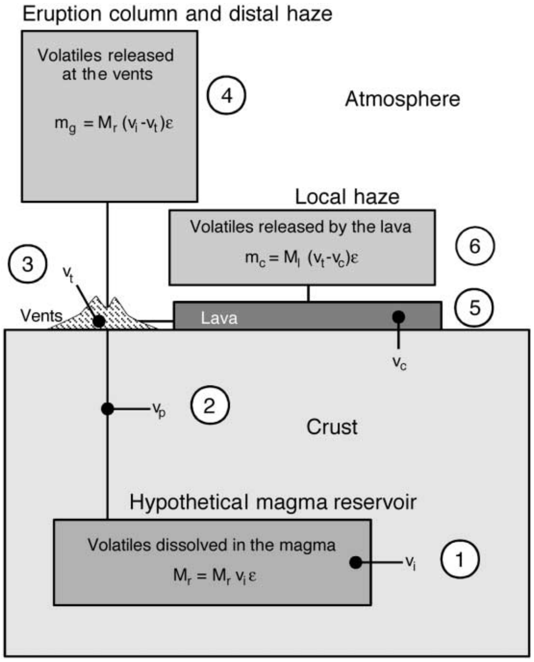

Fig. 8. Illustration outlining the volatile budget model for basaltic flood lava eruptions. (1) Hypothetical magma reservoir. (2) Quenched magma fraction with suppressed degassing due to interaction with external water, represented by phreatomagmatic tephra at the surface. (3) Degassed pyroclastics, represented by vent accumulations and strombolian tephra. (4) Eruption columns (lava fountain plus convection column) containing the total amount of volatiles released at the vents. (5) Lava flow. (6) Lower tropospheric haze produced by lava degassing. Equations are explained in Table 4.

5.2. Application

Given the stated assumptions, the total mass of SO_2 ($m_{s,r}$) dissolved in erupted portion of the Eldgjá magma amounts to ~232 ± 18 Mt (Table 5). The total amount released by the Eldgjá eruption is the difference between the original mass ($m_{s,r}$) dissolved in the magma and the mass retained in solidified eruption products ($m_{s,s}$). This difference indicates that ~96% of the sulfur escaped from the magma during the eruption, equivalent to a total mass of ~219 ± 20 Mt SO_2 (Table 5). The sulfur content (mean 1110 ± 275 ppm) in the groundmass glass of the phreatomagmatic clasts shows a wide range, falling between that of the inclusions and the strombolian tephra (Tables 2 and 3). This evidence indicates that the phreatomagmatic tephra represents quenched melt where degassing was arrested by explosive magma to water interactions at depth in the conduit. The consistently lower and less variable sulfur content of the groundmass glass in strombolian clasts (mean 445 ± 130 ppm) represents the sulfur concentration of the magma as it flowed away from the vents as lava (Thordarson et al., 1996). The difference between the sulfur values of the inclusion and the strombolian tephra can be taken as the fraction released by the magma at the vents, indicating ~80% degassing. Thus, ~184 ± 32 Mt SO_2 ($m_{s,t}$, Table 5) were discharged into the atmosphere above the Eldgjá fissures. The sulfur content of the lava (100 ± 30 ppm) is taken as the fraction of volatiles contained in the lava after emplacement and cooling. The difference between sulfur content of the strombolian tephra and the lava quantifies the average SO_2 mass released during emplacement and crystallization, which amounts to ~35 ± 16 Mt SO_2 (Table 5).

6. Discussion

6.1. Eruption dynamics and magma degassing

In the previous section we assumed that the magma degassing during the Eldgjá eruption occurred in two stages and our calculations indicate that the total SO_2 mass released by the magma at the vents and by the lava flow was ~184 and ~35 Mt, respectively. These results suggest that the magma lost ~80% of its volatile mass into the atmosphere before flowing away from the vents as lava. This disproportionate degassing has important implications for assessments of the atmospheric SO_2 loading and the climatic impact of the Eldgjá eruption. Therefore it is imperative to consider the justifications for using the two-stage degassing model. As mentioned above, the model was established by studies of the 1783–84 AD Laki eruption in southern Iceland and thus by location, eruptive volume, effusive and explosive products morphologies, and eruption dynamics, appropriate for application to Eldgjá. Despite the compositional differences of the erupted magmas, transitional alkali basalt (Eldgjá) and evolved tholeiite (Laki), the products of these two eruptions are very similar. Both are flood lava eruptions, with >92% of the magma volume erupted as lava. The tephra deposit

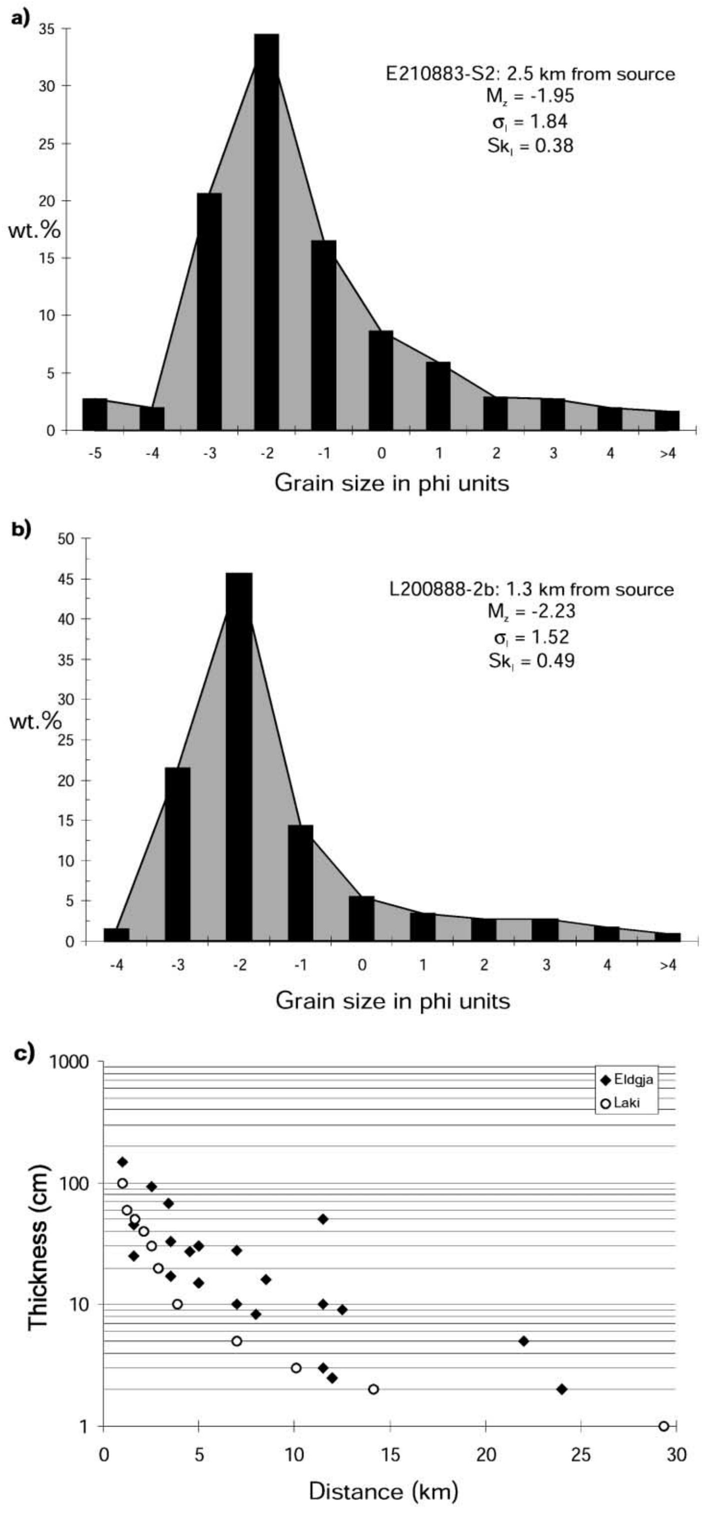
a)
E210883-S2: 2.5 km from source
M_z = -1.95
σ_I = 1.84
Sk_I = 0.38
wt.%
Grain size in phi units
b)
L200888-2b: 1.3 km from source
M_z = -2.23
σ_I = 1.52
Sk_I = 0.49
wt.%
Grain size in phi units
c)
Eldgja
Laki
Thickness (cm)
Distance (km)

Table 4
Volatile budget calculations

Volatile mass	Mass balance	Explanations
Mass dissolved in magma	$m_{x,r} = M_r \epsilon v_{x,i} = \rho V \epsilon v_{x,i}$	Total mass ($m_{x,r}$) of a volatile element x dissolved in magma residing in a reservoir (r) at depth and effectively involved in the eruption. M_r is the total mass of erupted magma and $v_{x,i}$ is the mass fraction of the volatile element x in glass inclusions (i). ϵ is a constant required to convert pure element to the species assumed to be present in the magma. V is magma volume and ρ is magma density
Mass released by magma	$m_{x,e} = m_{x,g} + m_{x,s} = (v_{x,i} - v_{x,s})\epsilon M_r$	Total volatile mass ($m_{x,e}$) that escapes from the magma upon eruption is calculated by taking the difference between the mass fraction of volatile element x in glass inclusions ($v_{x,i}$) and solidified eruption products ($v_{x,s} = N_t v_{x,t} + N_l v_{x,c}$). N_t and N_l are mass proportions of tephra and lava, respectively
Mass released at vents	$m_{x,g} = (v_{x,i} - v_{x,t})\epsilon M_r$	Volatile mass ($m_{x,g}$) that escapes from the magma at the vents (g) is calculated by taking the difference between the mass fraction of volatile element x in glass inclusions ($v_{x,i}$) and in the groundmass glass of the strombolian tephra ($v_{x,t}$)
Mass released by the lava	$m_{x,c} = (v_{x,t} - v_{x,c})\epsilon M_l$	Volatile mass released into the atmosphere by the lava during and after emplacement is calculated by taking the difference between the mass fraction of volatile element x in groundmass glass of strombolian tephra ($v_{x,t}$) and in crystalline lava ($v_{x,c}$). M_l is the mass of lava
Mass retained by solidified eruption products	$m_{x,s} = (v_{x,t}\epsilon M_t + v_{x,c}\epsilon M_l)$	Volatile mass retained by the tephra and lava after solidification; $v_{x,t}$ and $v_{x,c}$ are the mass fractions of volatile element x in the tephra and the lava; M_t and M_l are the mass of tephra and lava, respectively

from both eruptions consists of several strombolian fall units intercalated with lesser phreatomagmatic units. At Laki the tephra fall units correlate with distinct eruption episodes from different segments of the vent system which were separated by days to weeks (Thordarson and Self, 1993). Each of these episodes started with a vigorous explosive phase, followed by a voluminous and longer lasting outpouring of lava. Dispersal patterns of the Eldgjá fall units also indicate that each originated from different segments of the vent system suggesting that the Eldgjá eruption also featured a series of similar eruption episodes (Larsen, 1990, 1993). At medial localities, the tephra deposit is composed of one or two phreatomagmatic and up to six strombolian fall units (Fig. 2), suggesting that at least eight eruption episodes occurred during the Eldgjá event. The grain-size distribution of the strombolian tephra from Eldgjá is identical to that of Laki (Fig. 9a and b), indicating that the strombolian activity in both eruptions included similar magma fragmentation processes. In both cases, the strombolian tephra contains an abundance of frothy clasts (50–90 vol.% voids) with fused outer surfaces and Pele's hair, suggesting eruption at high velocities by hot, well insulated, gas-rich fountains (Thordarson et al., 1996). Furthermore, both eruptions show the same sulfur degassing trend (Fig. 10). Together, these observations suggest identical eruption

Fig. 9. Histogram showing grain-size distribution of proximal strombolian fall unit from: (a) the Eldgjá eruption at 2.5 km from the source vents; and (b) the Laki eruption at 1.3 km from the source vents. Also shown is the graphic mean (M_z), the calculated inclusive graphic standard deviation (σ_I) and skewness (Sk_I). (c) Changes in thickness with distance from source for strombolian fall units from Eldgjá (filled diamonds) and Laki fissures (open circles).

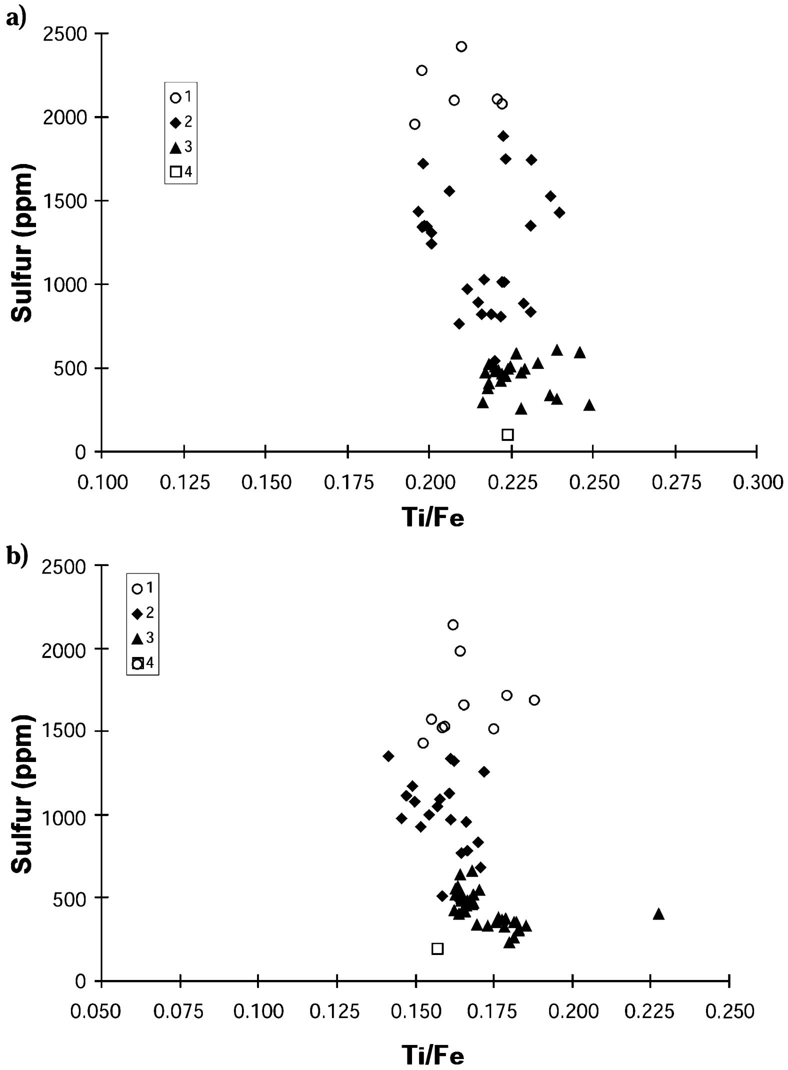

Fig. 10. Sulfur (in ppm) variation as a function of Ti/Fe in Eldgjá and Laki eruption products: (a) Eldgjá; (b) Laki. Note that both eruptions have very similar sulfur degassing trend. (1) Inclusions; (2) phreatomagmatic tephra; (3) strombolian tephra; (4) crystalline lava.

Table 5
Estimates on the mass of volatiles in megatons (Mt) dissolved in the Eldgjá magma prior to eruption and released by various phases during the eruption. Total volume of magma used in the calculations is 19.6 km^3, assuming magma density of 2750 kg m^{-3}. p- and s-tephra refer to phreatomagmatic and strombolian tephra, respectively)

	Inclusions	p-tephra	s-tephra	Lava
Measured S-content (ppm)	2155 ± 165	1110 ± 275	445 ± 130	100 ± 30
Original SO_2-mass ($m_{s,r}$) in magma (Mt)	232 ± 18			
SO_2-mass released by magma (Mt)		Total ($m_{s,e}$) 219 ± 20	At vents ($m_{s,g}$) 184 ± 32	By lava ($m_{s,c}$) 35 ± 16

styles for both eruptions and a common control on magma degassing.

Recurrence of eruption episodes and high degree of vent degassing in flood lava eruptions, such as Laki and Eldgjá, is attributed to efficient and accelerated exsolution of volatiles during ascent (Vergniolle and Jaupart, 1986; Thordarson et al., 1996). Consequently, two-phase flow dominates the early stages of each eruption episode, resulting in vigorous explosive activity and bulk discharge of volatiles. The highest eruption columns are also produced by these explosive phases, implying that a large proportion of the volatile mass released upon eruption was injected into the atmosphere at the maximum altitude reached by the columns. This initial bulk degassing leads to gradual, but rapid, transition from two-phase to homogenous flow, resulting in eruption of partly degassed magma, corresponding to the more voluminous lava-producing phase of the eruption episodes.

The total volume of tephra produced by the neighboring 1783–1784 AD Laki fissure eruption is 0.4 km^3. The 0.5 cm isopach for the tephra fall is at 45–60 km from the source and was deposited from 7 to $\geq$13 km high eruption columns (Thordarson and Self, 1993). The larger tephra volume (1.3 km^3) and wider dispersal implies a greater vigor for the explosive activity at Eldgjá. At an equivalent distance from source the strombolian fall units from Eldgjá are generally thicker and coarser grained than those from Laki (Fig. 9c). This relationship suggests that the vigor of the explosive activity at Eldgjá exceeded that of Laki and that the Eldgjá eruption columns were at least equivalent to and most likely somewhat higher than those at the Laki fissures. Additionally Katla, which is the central volcano related to the Eldgjá fissure system, erupted basaltic magma in 1918 producing 14–16 km high eruption columns. It is likely that the maximum height reached by the Eldgjá columns was similar (Larsen, 1993).

The Laki eruption lasted for ~8 months (8 June 1783–1787 February 1784), but little is known about the duration of the Eldgjá eruption. Evidence from the Greenland ice cores suggests that the acid deposition from the Eldgjá eruption occurred over at least 2 years and possibly as much as 8 years. In comparison the acid deposition from Laki lasted 1–1.5 years (Fiacco et al., 1994). According to electric conductivity measurements (ECM), the acid precipitation (H_2SO_4 + HCl + HF) from Eldgjá spans 1–3 years, peaking at 935 ± 2 AD in the Crete ice core (Hammer et al., 1980; Hammer, 1984) and at 938 ± 4 AD in the GISP2 ice core (Zielinski et al., 1995). Furthermore, the 10th century biannual SO_4^{2-} time series from the GISP2 core shows large positive residuals for SO_4^{2-} over the interval 933–941 AD, suggesting a prolonged volcanically derived H_2SO_4 deposition that lasted for at least 6 years and possibly up to 8 years (Zielinski et al., 1994). Eldgjá is the only large eruption known from this period and it is reasonable to assume that it is the sole contributor to this H_2SO_4 deposition onto Greenland. Previously, the prolonged acid deposition from Eldgjá has been attributed to stratospheric loading of aerosols (Hammer, 1984; Zielinski et al., 1995). However, stratospheric removal rates of volcanically derived aerosols are <3 years (Jaenicke, 1993), thus a 6–8 year duration for the H_2SO_4 deposition can only be achieved by the prolonged eruption, which in this case must have lasted for at least 3 years.

Additional evidences for prolonged activity at Eldgjá are derived from the studies of the lava flows. Large proportions of both Eldgjá and Laki lava flow fields are inflated pahoehoe; clearly illustrated by common occurrences of flat-topped sheet lobes and lava rise plateaus, along with flow structures such as tumuli, lava-rise pits, inflation clefts, and lava-rise sutures (Walker, 1991; Self et al., 1997). Such pahoehoe flow fields are formed by lobe to lobe emplacement and consist of numerous decameters to kilometers long flow lobes. The thickness of the upper crust on inflated pahoehoe lobes is proportional to the time it took to form each lobe (e.g. Hon et al., 1994). Measured crust thickness on two Eldgjá lobes at localities 11 and 12 (Fig. 1), indicate an emplacement time of ~2 and ~4 months, respectively (Thordarson and Self, 1998). It is unlikely that they were formed simultaneously, because they are separated by 25 km, indicating an eruption duration of at least 6 months. Considering the volume and distribution of the Eldgjá lava, a long duration for the eruption is inevitable, because our measurements only take into account two of many flow lobes within the flow field.

6.2. Atmospheric SO_2 mass-loading and climate effects

Our estimate of ~219 Mt for the atmospheric SO_2

Table 6
Evidence of unusual atmospheric conditions and weather in the period of the Eldgjá eruption. Data is from Stothers (1998), Zielinski et al. (1995) and Miller et al. (1997)

Phenomenon	Year AD	Descriptions
Atmospheric phenomenon	< 936	Saxony: before the death of Saxon King, Henry I the Fowler, in 2 July 936 AD, the sun appeared in a cloudless sky with almost no brightness and of blood-red color. The chronicle also mentions an eruption at unspecified locality
	933	Ireland: blood-red sun for one day in Ireland
	939?	Portugal: sun without brightness for two months
		Spain: pale sun on 15 October. Original sources give the year as either AD 934 or 938
Weather	934–35	Ireland: a long bitterly cold winter
		Belgium: rivers frozen solid from November 934 to March 935
		Constantinople, Turkey: unusual cold spell set in December 934, the Earth was frozen over for 120 days
		Baghdad, Iran: unusual snowfall during the winter 934–935, following June was chilly and rainy.
	935	Egypt: the year marks the initiation of a 30-year span of very low flood discharge from the Nile River. This is one of the lowest deviations ever recorded. Records show that reduction in Nile discharge correlates with cold temperatures in Europe
	939–940	Ireland: great winter frosts, lakes and rivers passable on ice
		Germany: Very harsh winter
		Switzerland: A hard year
		Iran: Unusual floods in Tigris River (winter snow and rain?)
Tree-ring chronologies	933	Significant negative growth signature in European oak chronologies
	935	Significant negative growth signature in European oak chronologies
	936	Strong negative departure in reconstructed summer temperatures from Fennocandian tree chronologies
		Strong negative departure in reconstructed summer temperatures in California conifers chronologies
	939	Significant negative growth signature in European oak chronologies
	940	Strong negative departure in reconstructed summer temperatures from Fennocandian tree chronologies
	942	Significant negative growth signature in European oak chronologies

mass-loading by the Eldgjá eruption is four times higher than the ~55 Mt obtained previously by the petrologic method (Palais and Sigurdsson, 1989). The atmospheric SO_2 loading by the Eldgjá eruption exceeds that of 1783 AD Laki eruption by a factor of 1.8 (Thordarson et al., 1996) and 1815 AD Tambora eruption in Indonesia by factor of 2.0–2.8 (Clausen and Hammer, 1988; Sigurdsson and Carey, 1992). This makes Eldgjá the greatest known volcanic pollutant in the last millennium equivalent to, or perhaps slightly larger than that of the less well-constrained estimates for the 1352–3 AD Kuwae eruption (Witter and Self, 1997).

Assuming that the aerosol particles consisted of 75% H_2SO_4 and 25% H_2O (Thomason and Osborne, 1992), our estimates of 219 Mt for total atmospheric SO_2 mass-loading by the Eldgjá eruption gives a potential H_2SO_4-aerosol yield of ~450 Mt. A yield of this magnitude strongly suggests that Eldgjá was a climatically significant eruption. Laki and Tambora had significant effects on the environment. Both were followed by unusual weather and a short-lived (3–5 years) hemispheric cooling of approximately 0.5–1.0°C, which has been linked to the atmospheric SO_2 mass-loading by these eruptions (e.g. Thordarson, 1995; Angell and Korshover, 1985; Fiacco et al., 1994 and papers in Harington, 1992). Several other eruptions in the last 250 years were followed by surface cooling of the order of 0.1–0.5°C which lasted for a few years (e.g. Rampino and Self, 1984;

Self et al., 1996). The data indicates a positive correlation between the degree of cooling and the SO_2 mass-loading from these eruptions (Sigurdsson, 1990). If we assume instantaneous atmospheric loading of the total SO_2 mass released by the Eldgjá eruption and apply the empirical relationship of Sigurdsson (1990) between the sulfur yield and decline in surface temperature, the anticipated cooling following the Eldgjá eruption is on the order of ~1.2°C. However, the assessment of potential atmospheric and climatic impact of the Eldgjá eruption is not straightforward. The timing of the eruption in the Dark Ages of Europe precluded the detailed documentation of atmospheric and weather-related phenomena that are available for the Laki eruption. In addition, our evidence suggests that the Eldgjá eruption was prolonged, possibly lasting for as much as 6–8 years, and featured up to eight significant eruption episodes spaced at sporadic intervals. We also surmise that the eruption columns were relatively low (<16 km), implying that the aerosol plumes were confined to the upper troposphere and the lower stratosphere and were dispersed from source by the westerly jet stream. Thus, their distribution would have been confined to latitudes above 30° North (Lamb, 1970).

Notwithstanding the poor record keeping endemic to the Dark Ages in Europe, fragmental documentation of atmospheric phenomenon and unusual weather in the 930 AD period exists (Table 6). One outstanding feature of these records is the ambiguity regarding the timing of the inception of these phenomena relative to a single short-lived eruptive event. These records indicate occurrences of volcanic haze (dry fog) in Europe in 934 and 939 AD, which coincide with unusual winter weather in Europe and the Middle East. Detailed records on the effects of the eight-month-long Laki flood lava eruption record a volcanic (sulfuric) haze that hung over the North Atlantic, Europe, North Africa, and Asia for more than 5 months (Thordarson, 1995; Stothers, 1996a). The Laki eruption produced ~250 Mt of H_2SO_4 aerosols which were dispersed at 7–13 km altitude by the polar jet stream to various regions of the Northern Hemisphere. Approximately 30 Mt of H_2SO_4 aerosols remained aloft in the tropopause for atleast 1 year and the remaining ~200 Mt were removed as acid precipitation in the summer and fall of 1783. The high-level altitude haze was the sole contributor to the longer lasting atmospheric perturbations of Laki and resulted in annual cooling on the order of 0.5–1.0°C that lasted for 2–3 years and was most pronounced in during the winters of 1783–84 and 1784–85 (Angell and Korshover, 1985; Thordarson, 1995). Based on these records and our evidence of a similar prolonged eruption and low eruption columns that introduced significantly more sulfuric aerosols into the atmosphere, we conclude that Eldgjá must have had an atmospheric and climatic impact at least equivalent to that of Laki and of longer duration.

7. Conclusions

Our investigation of the 934 AD eruption of Eldgjá has yielded several new interpretations regarding the duration and magnitude of the eruption and its effects on Northern Hemisphere climate. The total volume of erupted magma exceeded ~19.6 km^3, making the Eldgjá eruption the most voluminous basaltic fissure eruption in historic time. Integrating these data with new analyses of sulfur content in the Eldgjá products, we estimate that the amount of sulfur gases released by the eruption was 220 Mt of SO_2, increasing previously published estimates by a factor of 2.6–4.5. This revises the estimate of the potential atmospheric H_2SO_4-aerosol yield to ~450 Mt. A similar large volume basaltic fissure eruption (Laki, 1783) is estimated to have produced less than 60% of the aerosol yield of the Eldgjá event. Laki had a marked but short-lived effect on northern hemisphere climate, and we can only conclude that the climatic impact of the Eldgjá event is likely to have been of similar magnitude. We also resolve the ambiguity in timing of the eruption suggested in ice core data and contemporary accounts. While ongoing detailed studies of the tephra deposits from the Eldgjá eruption will more rigorously define the eruptive history of the Eldgjá event, we suggest that the Eldgjá eruption must have lasted for several years (possibly 6–8 years), and was punctuated by at least two major explosive episodes and high lava output. The first of these major events appears to have occurred at the beginning of the eruption in 934 AD, and the second was in 939 AD.

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