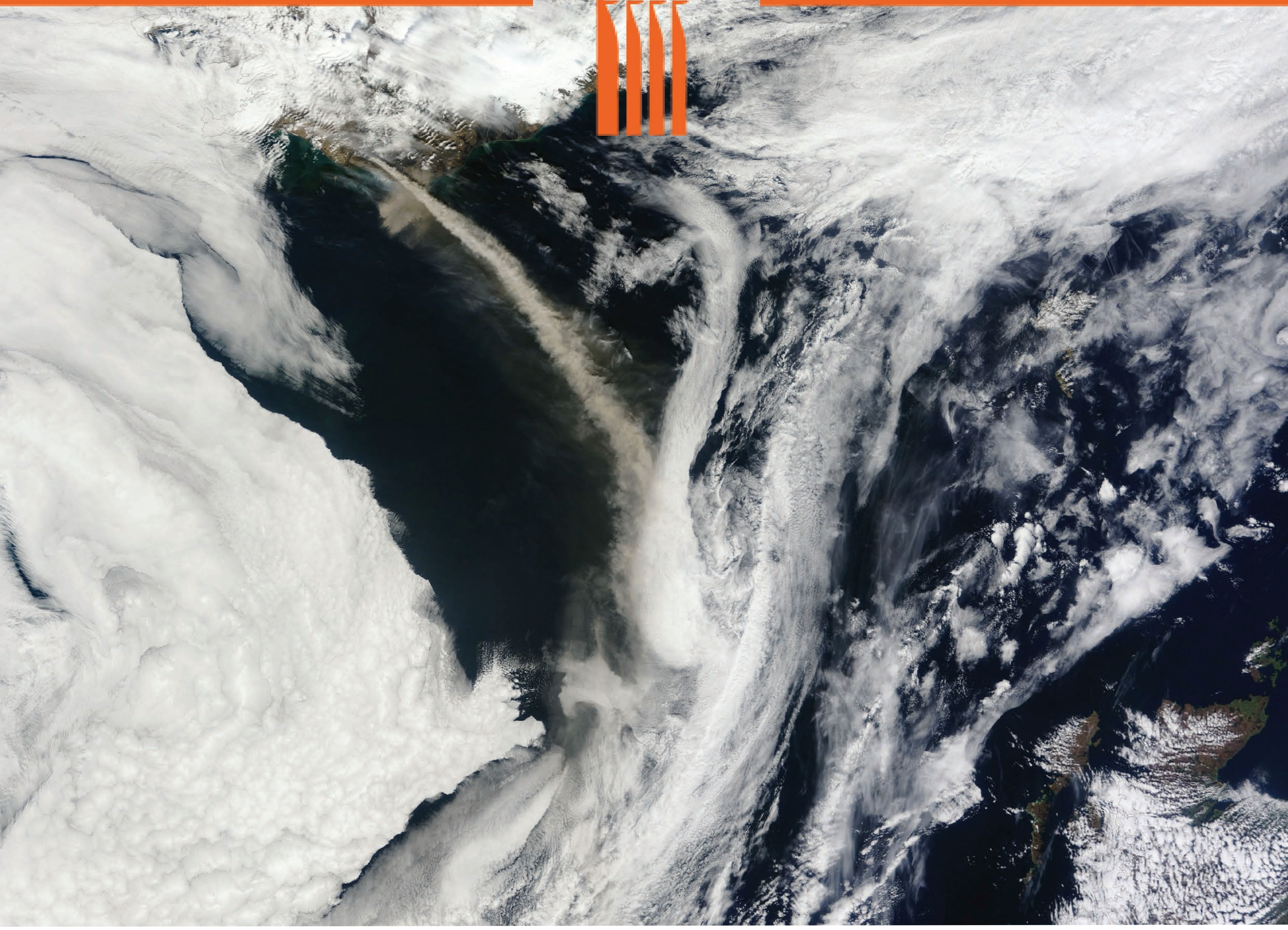

Total Grain Size Distribution in Selected Icelandic Eruptions

Work for the International Civil Aviation Organization (ICAO)
and the Icelandic Meteorological Office

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ICAO

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Abstract

One of the main hazards from explosive eruptions is volcanic ash that is dispersed through the atmosphere. In order to enhance and increase accuracy of models used to forecast volcanic ash distribution in the atmosphere, eruption source parameters (ESP) need to be well defined. One of the most important parameters is the grain-size distribution of all the erupted material (TGSD). Another important parameter is the maximum height of the eruption cloud (Hc), which is a direct consequence of the volumetric eruption rate (VER). The Hc can be obtained during an ongoing eruption, or it can later be derived from the deposits, and thus VER can be obtained. However, the TGSD can not be obtained until the eruption is over.

The TGSD obtained for older eruptions can be used as a benchmark for what can be expected from future eruptions. Constructing a comprehensive database of TGSD for past eruptions is therefore very important. As a first step towards that goal, we here report TGSD for 15 Icelandic eruptions. The 15 eruptions are both historic, before instrumental era, and more recent, observed by modern techniques. From the overview presented her, it is evident that there are significant variations in TGSD not only between eruptions from different volcanoes, but between eruptions from the same volcano.   This further emphasizes the importance of reconstructing TGSD from numerous volcanoes and for eruptions covering a large range in VER and magma composition for each volcano.

Modern day travel is highly dependent on aviation, and the aviation industry is among the most secure industries in the world, due to strict quality control. A more comprehensive dataset of TGSD, and hence greater understanding of the link between TGSD and VER, will aid in minimizing the impacts on aviation from future eruptions, especially in the case of Icelandic eruptions. We hope that this work provides the starting point into the creation of a such a database.

1 Introduction

The aim of this project is to investigate and summarize the size distribution of volcanic tephra associated with selected volcanic eruptions in Iceland. To evaluate an explosive volcanic eruption and the hazards such an event might pose to the environment, infrastructure, transport systems and humanity, it is necessary to quantify the key eruption source parameters (ESPs, for definition see Mastin et al., 2009). One of the most important ESPs is the size distribution of the tephra grains generated in the eruption, referred to as the Total Grain-Size Distribution (TGSD). Once obtained, the TGSD can be used as input data for the simulation of tephra transport in the atmosphere. The mass of individual grains in an eruption column mostly depends on their size, shape, and density. Quantification of the grain-size distribution is therefore fundamental for forecasting quantity and concentration of tephra grains in the atmosphere.

Explosive eruptions are of utmost importance when considering aviation safety. Most modern airplanes are not made to withstand volcanic particles. In explosive eruptions, large amounts of particles (fine ash and gases that turn into aerosols upon reaction with atmospheric vapor) are dispersed throughout the atmosphere. These particles have long residence time in the atmosphere and can be transported for several thousand km. Computer models can be used to predict atmospheric dispersal of volcanic particles. However, the quality of the model outputs depends greatly on how well constrained the input parameters are, such as plume height and TGSD. Most parameters cannot be accurately determined until after an eruption has ended. However, ESP‘s for older eruptions, determined by analysis of the tephra deposits, can be used as a benchmark for what to expect from future eruptions. In this report we present and summarize the available information on TGSD for 14 historic explosive eruptions in Iceland. These eruptions cover a large range in terms of plume height and TGSD distribution. As such, they give an idea on what is to be expected from each of the volcanoes in question. The results in this report also underpin the importance of carrying out a more comprehensive study of the most explosive volcanoes in Iceland, such as Grímsvötn, Katla, and Hekla.

All maps are based on cartographic data from the National Land Survey of Iceland (LMÍ).

2 Explosive volcanism in Iceland

Iceland is the largest and most active volcanic area in Europe. Volcanism in Iceland is due to two main processes; the separation of the American and Eurasian plates and the deep-rooted convection in the mantle manifested as the Icelandic hot spot. Both phenomena lead to magma generation and upwelling in such a quantity that its accumulation in the middle of the North Atlantic forms an island of some 103,000 km2, with crustal thickness of up to 45 km (Thordarson and Höskuldsson, 2008).

Volcanism in Iceland is mainly bound to the active plate boundary that crosses the island from Reykjanes in the SW to Melrakkaslétta in the NE. Complex interplay between the deep mantle convection and the plate boundary cause variation in crustal stresses, expressed on the surface by echelon formation of clusters of fissures and normal faults crowned with central volcanoes. This is referred to in Iceland as volcanic systems, of which there are 30 above sea-level (Figure 1). Normally, oceanic and hot spot volcanism is manifested by effusive (i.e., lava forming) eruptions, but Iceland is an exception. Due to the thick crust, the mantle derived magma has relatively long crustal residence and consequently, it becomes more evolved in composition. Therefore, Icelandic eruptions have the potential of being highly explosive. The geographic location of Iceland and oceanic climate means that surface water is abundant. Interaction of magma and surface water, mainly in the form of glaciers, further enhance the ash-production by quenched granulation in Icelandic eruptions (Lynch, 2015; Moreland, 2017).

During historic time (approximately last 1100 years), a minimum of 217 eruptions have occurred in Iceland and 161 of these were explosive (Thordarson and Larsen, 2007). During the past 113 years (i.e., the time period for which all eruptions in Iceland are accounted for) there have been 50 eruptions, of which 20 were explosive. This implies an eruption recurrence interval of about 2.3 years, and 5.6 years for explosive eruptions in Iceland.

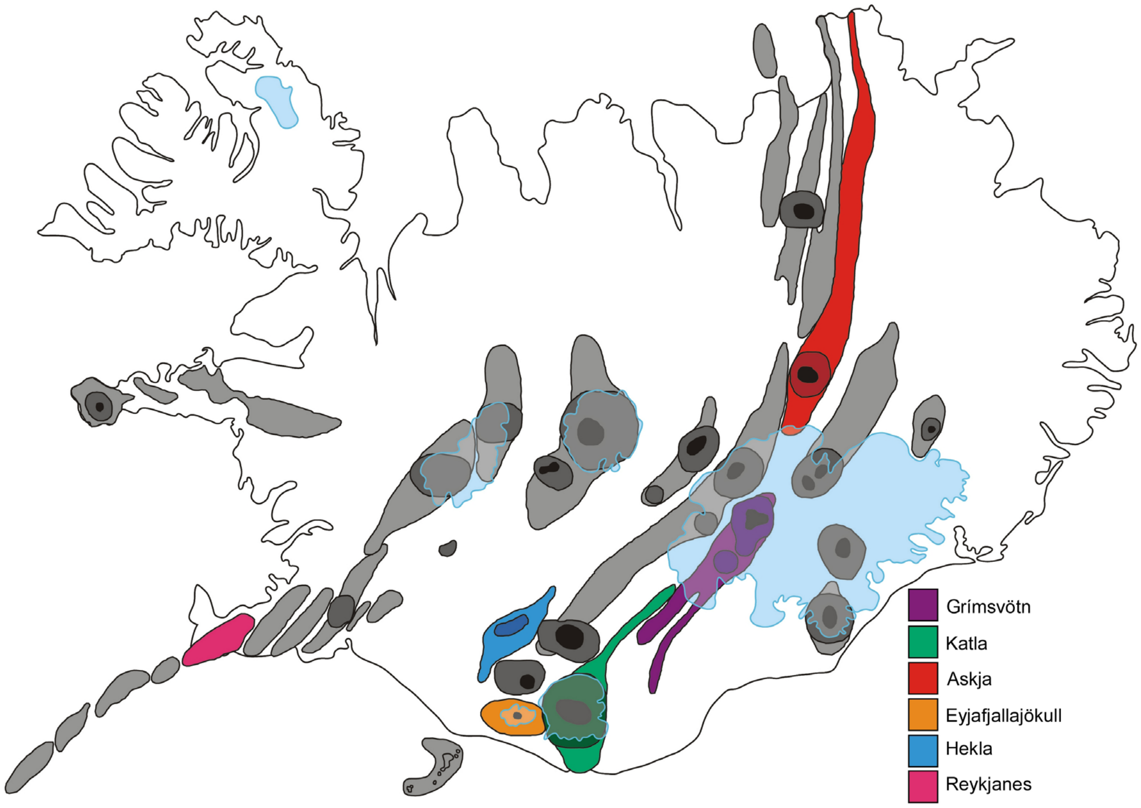

Figure 1. Distribution of volcanic systems in Iceland. Volcanoes focused on in this project are shown in colour: blue Hekla, green Katla, red Askja, purple Grímsvötn, orange Eyjafjallajökill, pink Reykjanes. For all others, central volcanoes are shown in dark grey, summit crater or caldera in black, and associated fissure swarm in light grey. Glaciers are shown in light blue. Modified from Thordarson and Höskuldsson (2008).

A range of hazards are associated with volcanic eruptions. For the aviation industry, the explosive eruptions are of greatest concern, since those eruptions inject a mixture of tephra and gas into the atmosphere. Volcanic particles, the smallest grains (i.e., ash <2 mm, fine ash <0.063 mm = 63 μm), has a long residence time in the atmosphere and thus may cause damage to airplanes that encounter such ash plumes.

In general, highly explosive eruptions are more likely to occur when the eruptive magma is more evolved (i.e., more silica rich) such as andesite, dacite or rhyolite magmas. Less evolved magma (silica poor = basalt) is generally speaking more likely to be erupted as a lava flow or as low intensity explosive eruptions, although studies over the past three decades have shown that these eruptions can feature powerful, but relatively short-lived explosive phases (e.g., Thordarson and Self, 1993, 2003; Coltelli et al., 1996; Sable et al., 2006; Moreland, 2017). Explosive eruptions are divided into two main groups: phreatomagmatic eruptions where the explosivity results from hot magma interacting with external water and magmatic eruptions where the explosivity is driven by exsolution of water and other volatiles in the magma. The former tend to result in plumes reaching 10 to 12 km altitude in case of volatile poor magma, whereas the latter can result in much taller plumes, reaching altitudes of 20 to 40 km. In the past 113 years, two eruptions in Iceland generated a volcanic plume higher than 20 km: the Grímsvötn 2011 eruption with a plume height of 22 km (Petersen et al., 2012) and the Hekla 1947 eruption with a plume height of 30 km (Thorarinsson, 1957. Eruptive plumes from the other 18 explosive eruptions ranged from 8 to16 km in altitude.

3 Selected volcanoes

The overall purpose of this project is to inventory available TGSD data as a first step towards creating a comprehensive inventory for Icelandic volcanoes. It focuses on some of the most explosive volcanoes in Iceland. We consider eruptions of different size and different magma composition, to try to cover vide spectra of Icelandic eruptions. The volcanoes analysed in this report are: Hekla (including the eruptions of 1104, 1300, 1693, 1766, 1845, 1991, and 2000 CE), Katla (the 1625 and 1755 CE events, and the Eldgjá 934–39 CE flood lava event), Grímsvötn (the 2004 and 2011 CE events), Eyjafjallajökull (the April-May 2010 CE summit eruption), Askja (phases B, C and D of the 28–29 March 1875 event), and the 1226 explosive phase of the 1210–40 Reykjanes Fires (Höskuldsson et al., 2007; Guðnason et al., 2018; Janebo et al., 2018; Schmith et al., 2018; Thordarson et al., 2001; Moreland, 2017; Jude-Eton et al., 2012; Lynch, 2015; Bonadonna et al., 2011; Gudmundsson et al., 2012; Carey et al., 2009, 2010; Sigurgeirsson, 1995; Magnúsdóttir, 2015). The eruptions were chosen based on three criteria:

1) High eruptive frequency of individual volcanic systems (i.e., Hekla, Katla, and Grímsvötn systems);

2) The proximity to Keflavik international airport (i.e., Reykjanes 1226 eruption);

3) Eruptions of concern due to their magnitudes and/or intensities (i.e., Askja 1875 and Eldgjá 934).

The reason for focusing on these selected eruptions is that it provides an insight of what to expect from the most active volcanoes and volcanic systems in Iceland as well as a perception of what may happen during the most intense explosive eruptions in Iceland. However, in order to produce a comprehensive database on tephra producing eruptions in Iceland, this work needs to be maintained and continued, at least until we have source parameter estimates for all typical explosive eruptions in Iceland. Only then can we satisfy the minimum requirement to improve the reliability of volcanic cloud dispersal forecast during the next explosive eruption in Iceland. This will, eventually, allow for reduction of uncertainty associated to the forecast maps and, as such, to mitigate the potential impact these event may have on the aviation industry.

4 Total Grain-Size Distribution (TGSD)

Explosive eruptions are typically characterized and classified based on physical parameters associated with eruption dynamics and the deposits formed from the erupted material (e.g., plume height, mass eruption rate, erupted volume, and deposit dispersal). Of all ESPs (see Mastin et al., 2009) one of the most important, but least well characterized, is the size distribution of the erupted material. The material erupted is all particles injected and dispersed through the atmosphere and its size distribution is commonly referred to as TGSD. The TGSD is crucial for real time forecasting (e.g., Folch, 2012) and provides fundamental insights into eruption dynamics (e.g., Kaminski and Jaupart, 1998; Bonadonna and Houghton, 2005; Rust and Cashman, 2011). It controls both the mass distribution of tephra within the eruptive plume and its sedimentation processes. Furthermore, it provides essential information and constraints on the fragmentation mechanisms involved in disintegrating the magma in individual events.

TGSD is typically calculated by integrating the grain-size of the tephra obtained from samples collected at multiple sites. Various methods have been used in previous studies, such as averaging all grain-size data over deposit area (e.g., Walker, 1980) or weighted averaging over sectors (e.g., Murrow et al., 1980; Carey and Sigurdsson, 1982; Sparks et al., 1981). TGSD is sensitive to both the reconstruction method used, and the number and spatial distribution of grain-size data (Bonadonna and Houghton, 2005). TGSDs calculated using different methods are not always compatible, and many TGSDs are only partial distributions due to insufficient sample coverage. The Voronoi-Tessellation technique has been shown to be the most appropriate reconstruction method so far (Bonadonna and Houghton, 2005). The deposit is divided into Voronoi cells, based on the distance between adjacent sample locations, and the TGSD is calculated from the area-weighted average of all the Voronoi cells. The advantage of the Voronoi-Tessellation technique is that it takes the spatial distribution of grain-size samples into account, without introducing bias due to dividing the deposit into arbitrary sectors. It has been used for numerous recent studies (e.g., Bonadonna and Houghton, 2005; Scollo et al., 2007; Andronico et al., 2014; Bonadonna et al., 2015), including all the eruptions covered by this report.

5 The work strategy

The current Research Group took over this project in spring 2016. At that point, a board was nominated for the project, consisting of Sigrún Karlsdóttir (IMO), Thorvaldur Thordarson (UI), Costanza Bonadonna (UG), and Ingvar Kristinsson (IMO). The project leader was Ármann Höskuldsson (UI) and the assistant project leader was Maria Janebo (UI).

From June 2016 to January 2017, eight students participated in the project; Jónas Guðnason, Johanne Schmith, William Moreland, Sarah Tapscott, Alma Gytha Huntingdon-Williams, Fjóla Sif Sigvaldadóttir, Katrín Steinþórsdóttir, Þóra Björg Andrésdóttir, Daníel Þórhallson, Helga Kristín Tómasdóttir and Sophie Paillot.

Fieldwork in Iceland is dominantly done during summertime. During June to September 2016, fieldwork was carried out in southern and north-eastern Iceland. Samples were collected from the eruptions in Askja 1875, Katla 1625 and 1755, and Eldgjá 934. Further fieldwork was carried out in the Hekla and Reykjanes area to fortify the datasets used for TGSD calculations.

Actively participating in the field work were Thorvaldur Thordarson, Costanza Bonadonna, Marco Pistolesi (University of Pisa), Raffaello Cioni (University of Florence), Maria Janebo, and Ármann Höskuldsson.

Table 1. Overview of eruptions included in the project.

Volcano	Year	Magma composition	TGSD page	Volume (km3)	Plume height (km)
Hekla	1104	Rhyolite	15	0.9 - 1	20.1 - 24.5
	1300	Bas-Andesite/ Dacite	16	0.5 - 0.6	21.5 - 24.7
	1693	Andesite	17	0.2 - 0.7	13 - 17.7
	1766	Andesite	18	0.2 - 0.8	17.5 - 17.8
	1845	Andesite	19	0.13 - 0.22	~20
	1991	Basaltic - andesite	20	0.02	11.5
	2000	Basaltic - andesite	21	0.01	~12
Katla	1625	Basaltic	23	1.24	10 – 25
	1755	Basaltic	24	1.34	9 - 25
	934 Eldgjá	Basaltic	25-26	>5	11-18
Askja	1875 B	Dacite - Rhyolite	28-29		8
	1875 C	Dacite - Rhyolite	28-29	1.8 (DRE = 0.32)	22.8
	1875 D	Dacite - Rhyolite	28-29		26
Grímsvötn	2004	Basaltic	31	0.05 (DRE= 0.02)	6 - 10
	2011	Basaltic	32	0.2	20-22
Eyjafjallajökull	2010, May	Basaltic to beinmoritic	34	0.18	4 - 9
Reykjanes	1226 Medieval	Basaltic	36	0.1	9 - 10

6 Summary of the project

An overview of the 15 eruptions included in the project, and the current status of available data for each eruption, is given in Table 1. In addition to TGSD, estimates of eruptive volume and the plume height have also been included. Summaries of the eruptions and preliminary results are given in section 7.

7 Eruption summaries and TGSDs

The following section gives a general introduction to the six volcanic systems analysed in this report, summarizes the selected eruptions from each volcanic systems and presents the available TGSD data

7.1 Hekla

Hekla is a ridge-shaped stratovolcano, located in the East Volcanic Zone (Figure 2, 3) (Catalogue of Icelandic Volcanoes). The central volcano reaches 1490 m a.s.l. and the areal extent of the Hekla-Vatnafjöll volcanic system is 60 by 19 km (Thordarson and Höskuldsson, 2008).

Hekla has erupted at least 18 times in historical times (Table 2), which makes it one of the most active volcanoes in Iceland. Hekla has erupted at least once every hundred years since 1104 (with the exception of the 15th century). From 1970, the frequency increased to one eruption per decade, with the most recent eruption in the year 2000.

Hekla is different from all other volcanoes in Iceland as, in addition to a fissure swarm, it also has a central fissure that cuts across the crest of the volcano. At the start of each eruption, this ~5 km long fissure opens up and activity is then usually focused at one or multiple vents along the fissure. The explosive eruptions from Hekla can be divided into two main types.

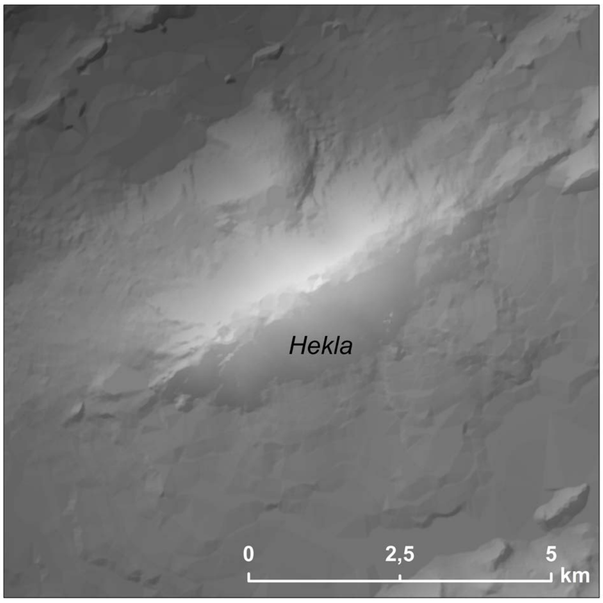

Figure 3. Hekla volcano. DEM and hillshade from LMÍ.

Type 1 are purely explosive, consisting of a short, high intensity explosive phase (Plinian or subplinian).

Type 2 starts with a high intensity explosive phase followed by lower intensity explosive phase and lava flows. Hekla erupts a range of magma types, from mafic to silicic. As a general trend, the magma is more evolved, and the eruption is therefore

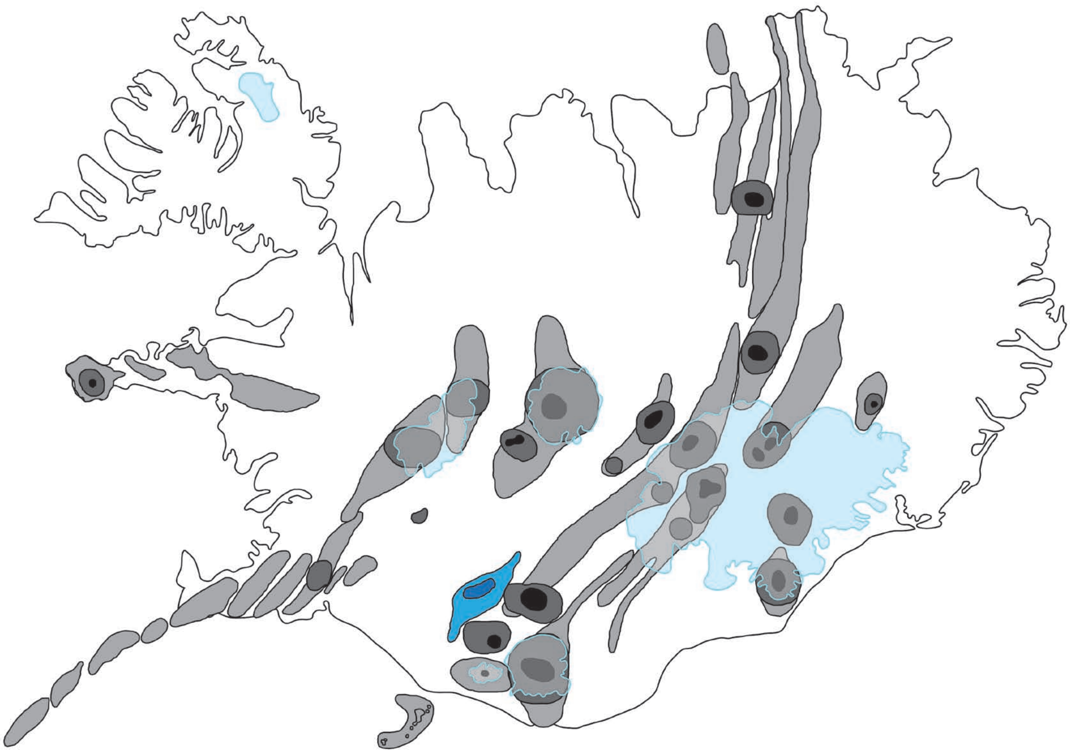

Figure 2. Location of Hekla shown in blue. Other volcanic systems are shown in grey. Glaciers are shown in light blue. Modified from Thordarson and Höskuldsson (2008).

more explosive, the longer time has passed since the previous eruption (e.g., Thorarinsson, 1967; Janebo et al., 2018; Guðnason et al., 2018).

The main hazards associated with eruptions from Hekla is ash fall on the ground and ash in the atmosphere. All of the historical eruptions of Hekla, independent of magma type and eruption size, has formed a well-established ash plume, which poses a threat to aviation. Hekla eruptions are generally preceded by earthquakes, but the warning time is usually very short (often less than one hour) (e.g., Thorarinsson and Sigvaldason, 1972; Grönvold et al., 1983; Soosalu and Einarsson, 2002; Soosalu et al., 2003).

Table 2. Overview of historical eruptions in Hekla

Eruption	VEI	Repose time
2000	3	9
1991	3	10
1980–1981	3/2	10
1970	3	22
1947–48	4	101
1845	4	77
1766–68	4	73
1693	4	56
1636	3	39
1597	4	86
1510	4	120
1389	3	47
1341	3	40
1300	4	78
1222	2	15
1206	3	46
1158	4	53
1104	5	>230

Hekla 1104

Plume height: 20.1 - 24.5 km
Volume: 0.9 - 1 km3

The 1104 eruption (also known as the “H1” eruption) took place in the autumn of 1104 and was the first eruption of Hekla after the settlement of Iceland. There are no direct written accounts for estimates of the duration, but the eruption probably lasted for only a few hours to half a day (Thorarinsson, 1967).

The tephra was rhyolitic (72 wt% SiO2) (Thorarinsson, 1967; Larsen and Thorarinsson, 1977; Larsen et al., 1999) and it was deposited towards the north, covering most of Iceland (Figure 4). The column height is estimated to have been 20.1–24.5 km (Janebo et al., 2016).

The main impact from the Hekla 1104 eruption was destruction of several farms (at least 18) north to northwest of Hekla due to ~7 to >20 cm of tephra fall, although it is likely that some of these farms were at the brink of being abandoned before the eruption (Thorarinsson, 1967).

The TGSD for the Hekla 1104 deposit (Figure 5) is bimodal, with a coarse mode at 8 mm and a finer mode at 0.063 mm. The total ash fraction (<2 mm) amounts to 44% of the tephra mass, and fine ash (<63 µm) accounts for 25% (Janebo et al., 2018).

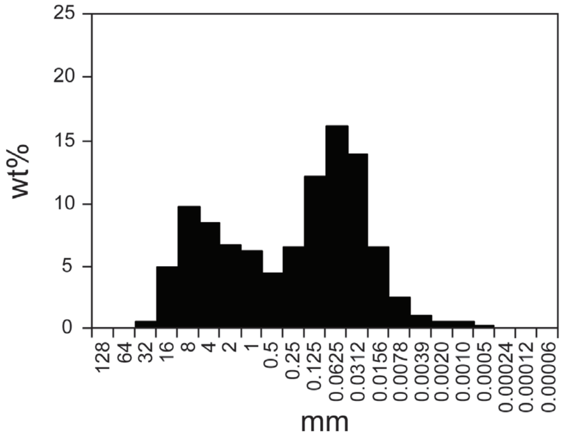

Figure 5. TGSD for the Hekla 1104 eruption (Janebo et al., 2018).

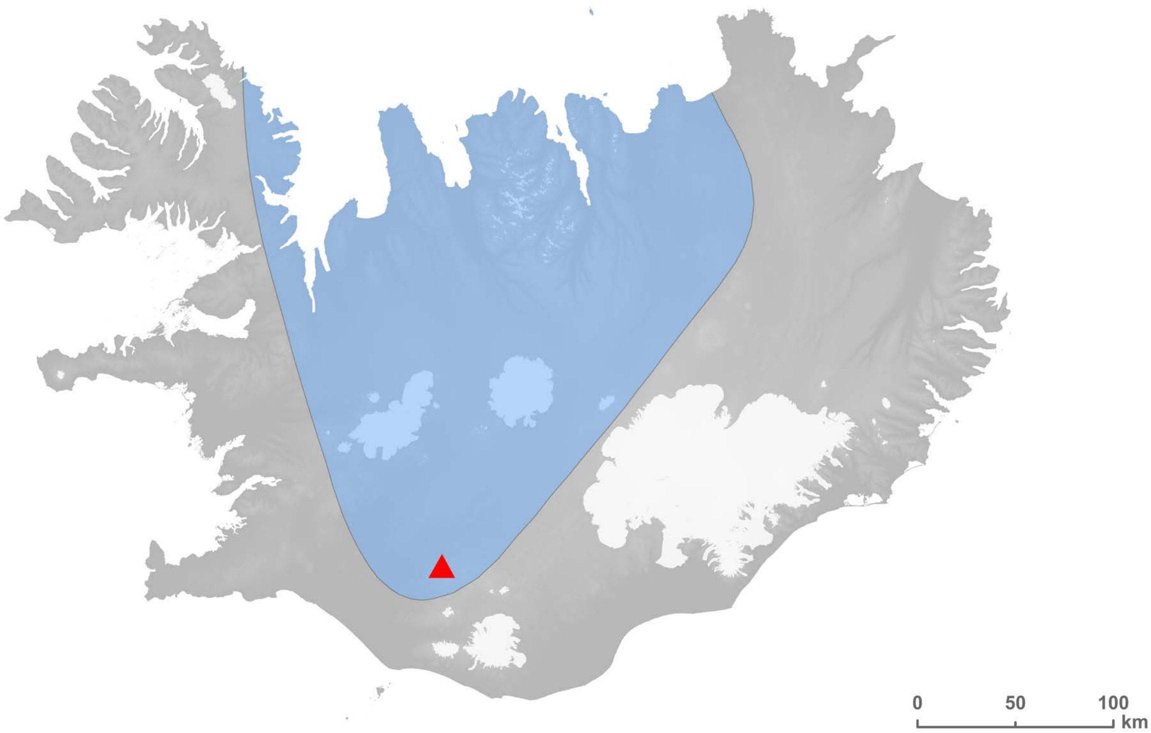

Figure 4. Main area affected by tephra fall from the Hekla 1104 eruption. Location of Hekla shown by red triangle. Adapted from Janebo et al. (2016).

Hekla 1300

Plume height: 21.5 - 24.7 km
Volume: 0.5 - 0.6 km3

The fifth and second largest historical eruption of Hekla started on 11 or 12 July 1300 and lasted for 12 months (Thorarinsson, 1967). The initial explosive phase was likely short (a few hours). The magma composition was basaltic-andesite to dacite (62–72 wt% SiO2). The plume height for the initial phase (referred to as 1300-D) is estimated to have been about 21.5–24.7 km (Janebo et al., 2016). Tephra was dispersed towards the northeast (Figure 6).

The eruption destroyed multiple farms and damaged grasslands in Northern Iceland, and is linked to famine the following year (Thorarinsson, 1967).

The TGSD for the Hekla 1300-D phase is bimodal (Figure 7), with a coarse mode at 2 mm and a finer mode at 0.063 mm. The total ash fraction (<2 mm) amounts to 73% of the tephra mass, and fine ash (<63 µm) accounts for 23% (Janebo et al., 2018).

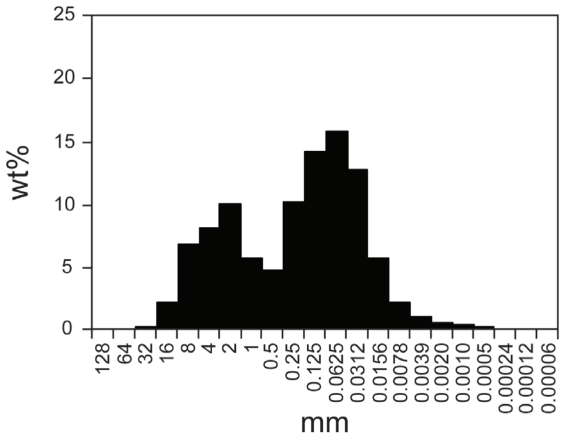

Figure 7. TGSD for the opening phase of the Hekla 1300 eruption (Hekla 1300-D, Janebo et al., 2018).

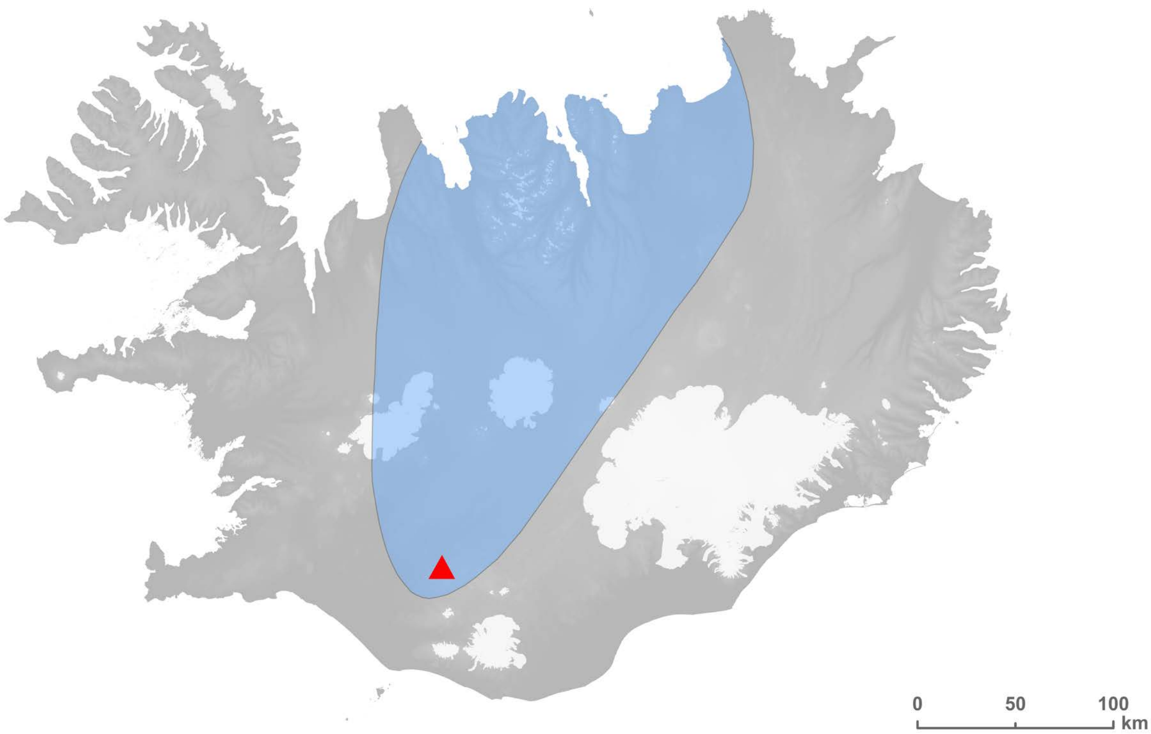

Figure 6. Main area affected by tephra fall from the Hekla 1300 eruption. Location of Hekla shown by red triangle. Adapted from Janebo et al. (2016).

Hekla 1693

Plume height: 13 - 17.7 km
Volume: 0.2 - 0.7 km3

The Hekla eruption in 1693 began in the evening of 13 February and the main, initial phase lasted for about 30 minutes to one hour (Thorarinsson, 1967).

The eruption started at the summit and then migrated down both flanks along the fissure. Weaker activity continued for 7 to 10.5 months, mostly consisting of intermittent explosions and fire fountains, as well as multiple lava flows from both ends of the fissure. Over 90% of the tephra, however, was emitted during the initial phase and deposited northwest of Hekla (Figure 8). The magma composition is andesitic (55–60 wt% SiO2). The plume height is estimated to have been 13–17.7 km (Janebo et al., 2016).

Tephra fall from the eruption damaged or destroyed 55 farms, and caused death of livestock, birds, and fish (Thorarinsson, 1967).

The TGSD (Figure 9) is bimodal, with a coarse mode at 4 mm and a finer mode at 0.063 mm. The total ash fraction (<2 mm) amounts to 59% of the tephra mass, and fine ash (<63 μm) accounts for 15% (Janebo et al., 2018).

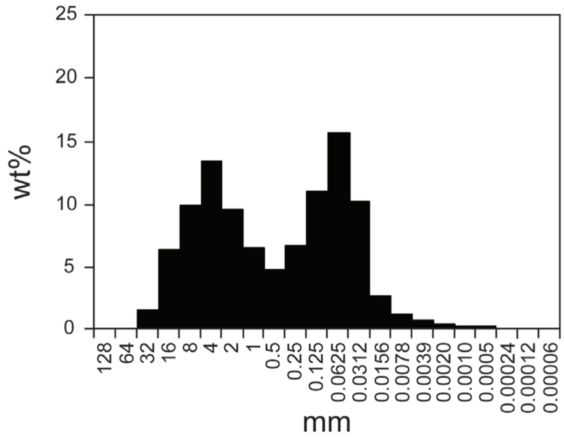

Figure 9. TGSD for the opening phase of the Hekla 1693 eruption (Janebo et al., 2018).

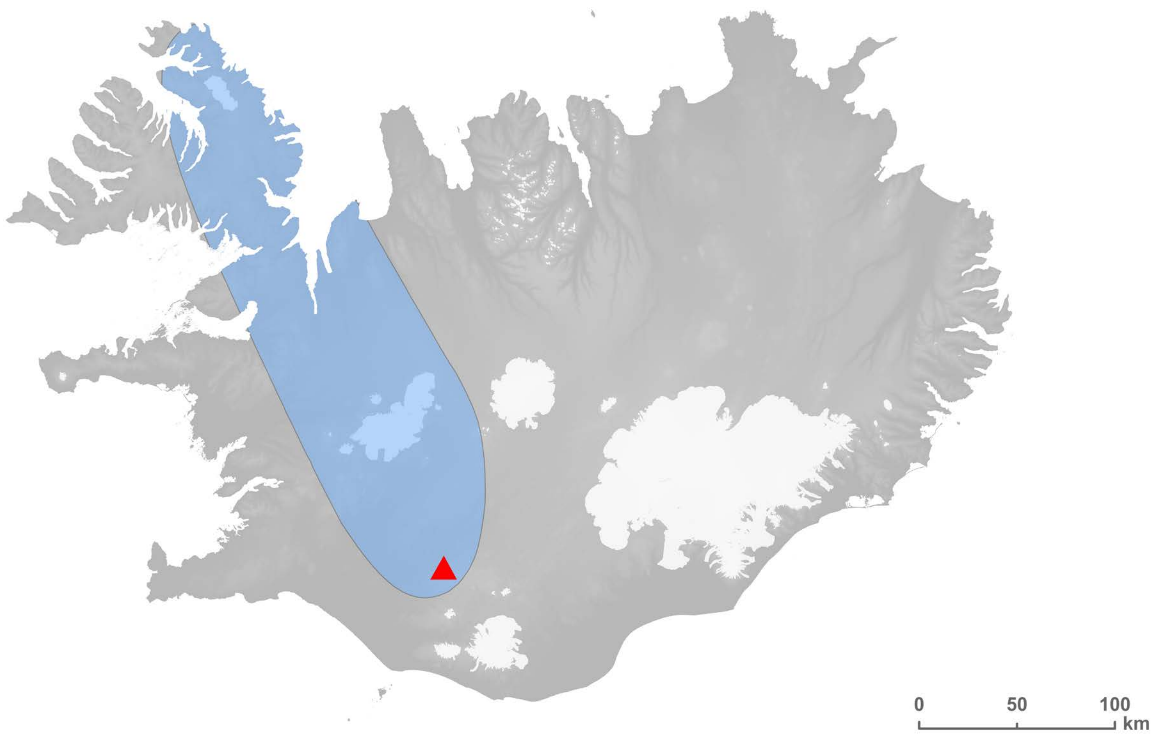

Figure 8. Main area affected by tephra fall from the Hekla 1693 eruption. Location of Hekla shown by red triangle. Adapted from Janebo et al. (2016).

Hekla 1766

Plume height: 17.5 - 17.8 km
Volume: 0.2 - 0.8 km3

The 1766 eruption started in the early morning on 5 April, and the subplinian phase lasted for 5 to 6 hours (Thorarinsson 1967). The eruption continued for almost two years, including a hiatus between August 1766 and March 1768, ending in April 1768. Most of the later activity consisted of weaker transient explosive events, but there were several more violent explosive phases with ash plumes reaching up to 4 km. The initial eruption originated from one summit crater and one crater on the SW ridge, after which a fissure along the SW flank and a third crater on the NE flank opened. As many as nine craters are thought to have been active during the entire eruption.

Over 80% of the tephra was produced during the initial phase of the eruption, during which the wind direction was toward the north. The magma composition was andesitic (55–60 wt% SiO2). The column height is estimated to have been between 17.5 and 17.8 km (Janebo et al., 2016). The tephra dispersal is shown in Figure 10.

Tephra fall from the eruption caused damage to multiple farms, pastures and woodlands, and resulted in death of both livestock and fish (Thorarinsson, 1967).

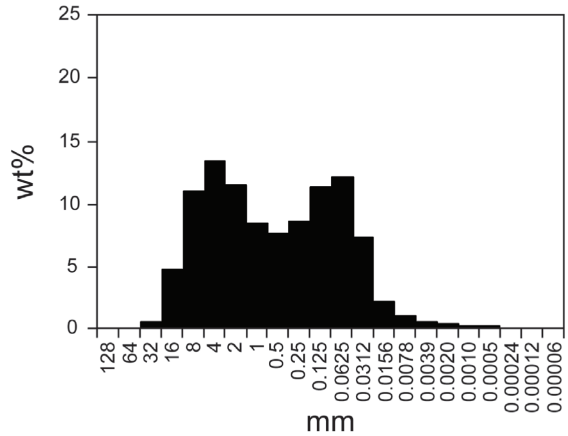

Figure 11. TGSD for the opening phase of the Hekla 1766 eruption (Janebo et al. 2018).

The TGSD for the Hekla 1766 eruption is bimodal (Figure 11), with a coarse mode at 4 mm and a finer mode at 0.063 mm. The total ash fraction <2 mm amounts to 59% of the tephra mass, and fine ash <63 µm accounts for 11% (Janebo et al., 2018).

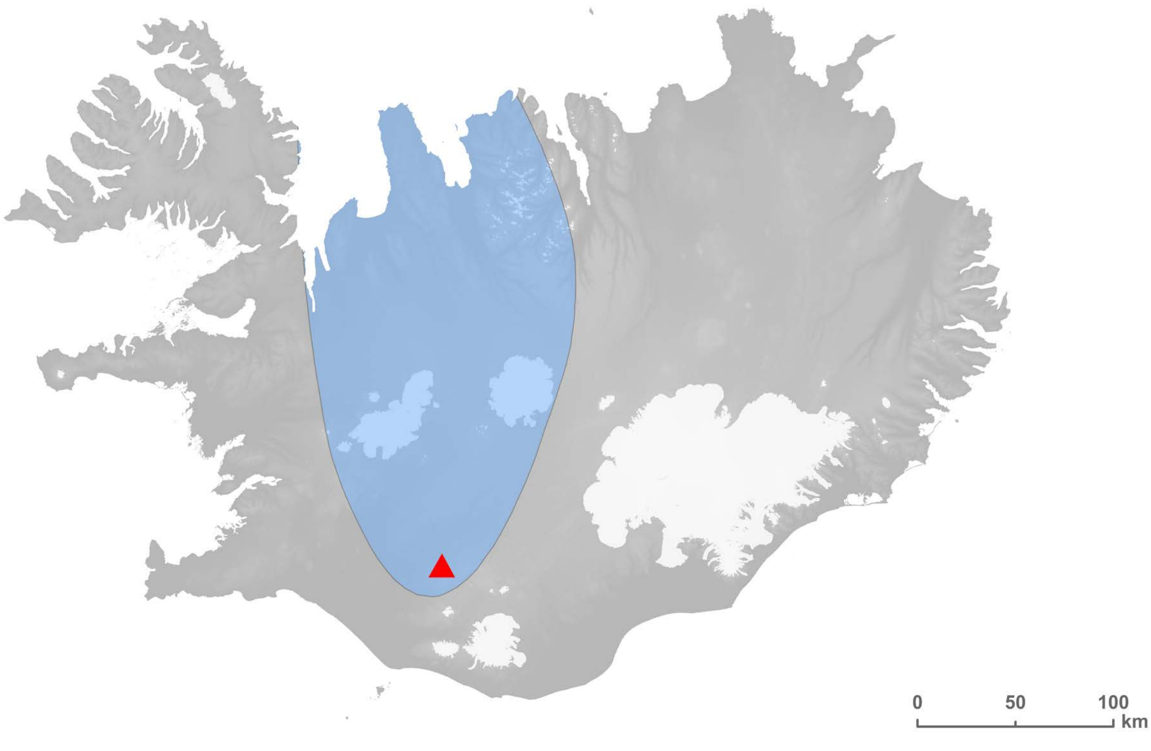

Figure 10. Main area affected by tephra fall from the Hekla 1766 eruption. Location of Hekla shown by red triangle. Adapted from Janebo et al. (2016).

Hekla 1845

The 15th historic Hekla eruption started mid-morning on 2 September 1845. There are descriptions of precursors that can be interpreted like earthquakes and volcanic tremor (Erlendsson, 1847). The eruption plume rose to heights of ~20 km and produced tephra fall to the ESE of Hekla (Figure 12; e.g., Gudnason et al., 2017)

The rising plume was seen from farms up to 100 km away and first reports of tephra fall were around one hour after onset of eruption at distance 80 km downwind from Hekla. Tephra deposition continued for ~6 hours and during peak deposition daylight was blocked (Schythe, 1847).

Deposition of tephra was reported from ships at 800 to 1100 km away from Hekla within 24 hrs from start of the eruption. The reports include information of tephra fall on the Faroe and Shetland Islands are also available (e.g., Gudnason, 2017).

Plume height: ~20 km
Volume: 0.13 - 0.22 km3

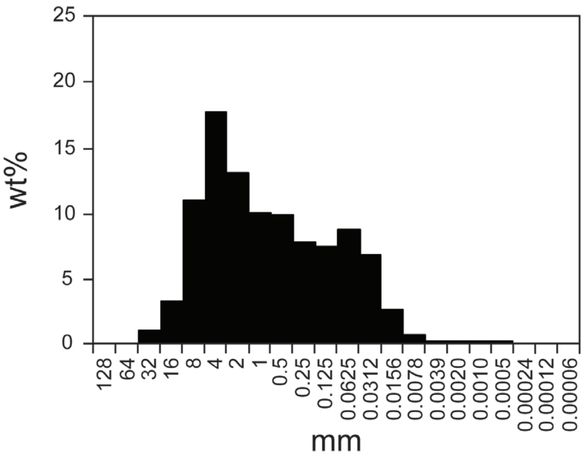

Figure 13. TGSD for the opening phase of the Hekla 1845 eruption (Gudnason et al., 2017).

The TGSD for Hekla 1845 is bimodal (Figure 13) with primary coarse peak at 6 mm and a secondary finer peak at 0.125 to 0.045 mm. The ash fraction (<2 mm) amounts to 54% of the tephra mass, and fine ash (<63 μm) accounts for 11% (Gudnason et al., 2017).

Figure 12. Main area affected by tephra fall from the Hekla 1845 eruption. Location of Hekla shown by red triangle. Adapted from Gudnason et al. (2017).

Hekla 1991

The 17th historic Hekla eruption started on 17 January 1991. The first earthquakes associated with the eruption started 16:32 on 17 January (Gudmundsson et al., 1992; Larsen et al., 1992). The opening phase of the eruption started 17:01 with onset of volcanic tremor (Soosalu et al., 2003), coinciding with rising tephra laden eruption column (Larsen et al., 1992; Gudnason et al., 2017).

The erupted material is basaltic Icelandite (55.5 wt% SiO2). The maximum plume height of 11.5 km a.s.l. was attained in only 10 minutes (Gudmundsson et al., 1992).

The major tephra producing phase lasted 50 minutes and sustained an eruption column around 11.5 km a.s.l. high (e.g. Gudnason et al., 2017). The explosive activity produced a tephra layer to the NNE from Hekla (Figure 14), covering ~21000 km2 (Larsen et al., 1992).

No tephra fall was reported outside of Iceland from the 1991 eruption.

Plume height: 11.5 km
Volume: 0.02 km3

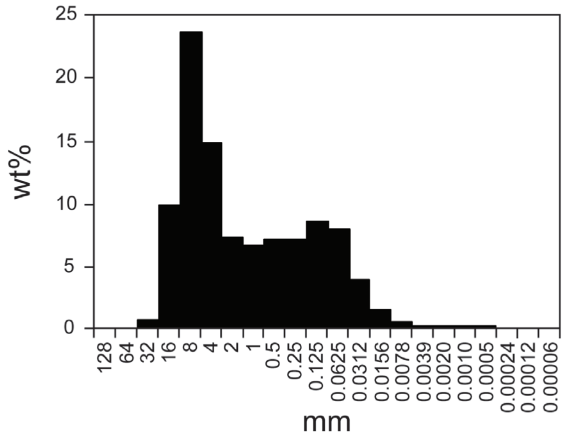

Figure 15. TGSD for the opening phase of the Hekla 1991 eruption (Gudnason et al., 2017).

The TGSD from the Hekla 1991 eruption (Figure 15) is bimodal, with a coarser mode at 11 to 5.6 mm, and a finer mode at 0.18 to 0.09 mm. The total ash fraction (<2 mm) amounts to 44% of the tephra mass, and fine ash (<63 µm) accounts for 6% (Gudnason et al., 2017).

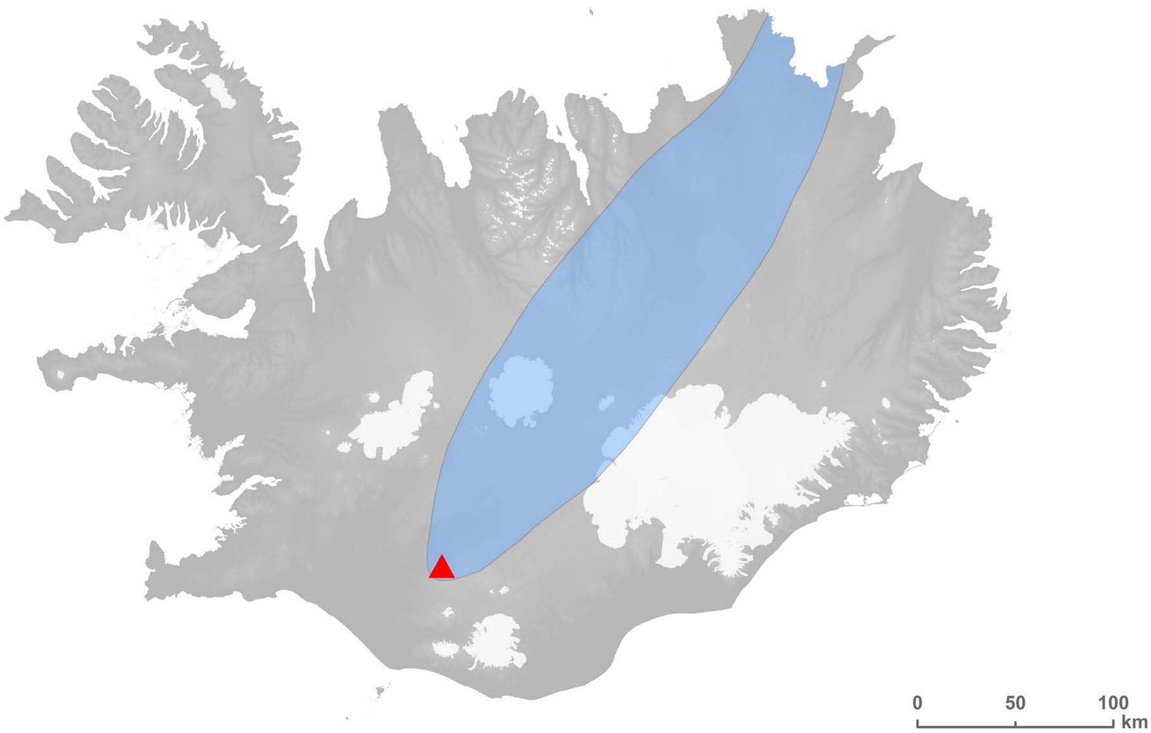

Figure 14. Main area affected by tephra fall from the Hekla 1991 eruption. Location of Hekla shown by red triangle. Adapted from Gudnason et al. (2017).

Hekla 2000

The 18th historic, and most recent, Hekla eruption started on 26 February 2000. The opening phase of the eruption was highly explosive, producing a ~12 km high (a.s.l.) plume in matter of minutes. The total volume of magma erupted in the eruption was 0.2 km3, of which the volume of tephra was 0.01 km3 (Haraldsson, 2001).

The precursors for the 2000 eruption were short. However, a warning was sent out with an hour notice that an eruption was imminent (Höskuldsson et al., 2007). Tephra was deposited to the north of Hekla (Figure 16) and was sampled on snow immediately after the eruption.

The TGSD for Hekla 2000 (Figure 17) is bimodal with modes at 8 mm and 0.125 mm and a minimum at 0.5 mm. The total ash fraction (<2 mm) amounts to 74% of the tephra mass, and fine ash (<63 µm) accounts for 18% (Biass et al., 2014).

Plume height: ~12 km
Volume: 0.01 km3

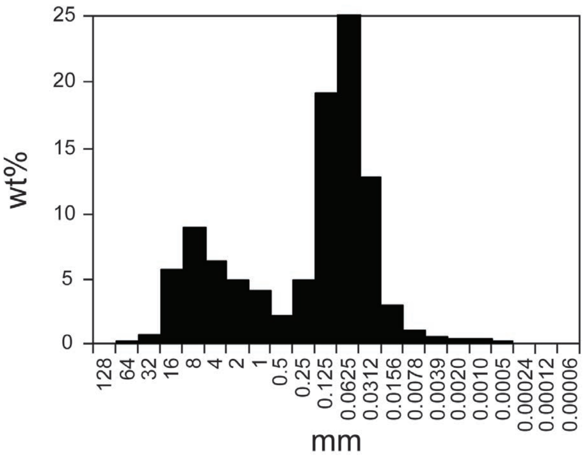

Figure 17. TGSD for the opening phase of the Hekla 2000 eruption (Biass et al., 2014).

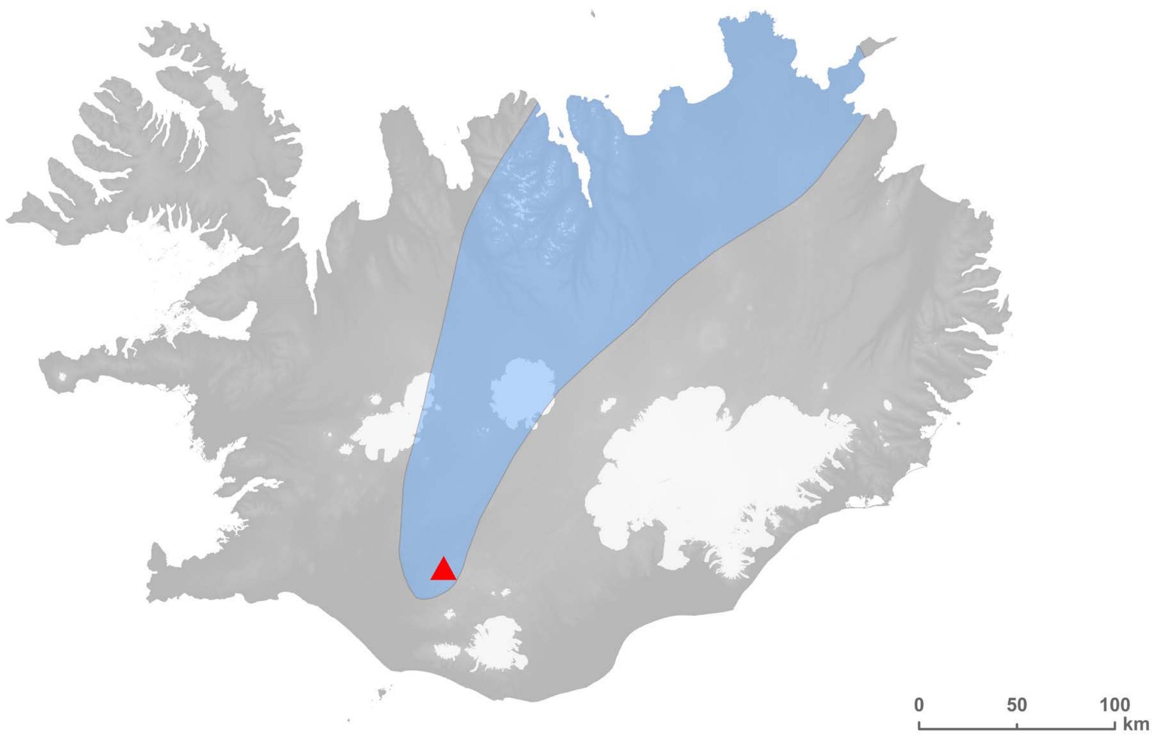

Figure 16. Main area affected by tephra fall from the Hekla 2000 eruption. Location of Hekla shown by red triangle. Adapted from Höskuldsson et al. (2007).

7.2 Katla

Katla central volcano is located below the Mýrdalsjökull and part of the East Volcanic Zone (Figure 18, 19) (Catalogue of Icelandic Volcanoes) with a fissure extending towards the northeast, beyond the glacier. Katla is the second most active volcano in Iceland with more than 20 eruptions in historical time (Table 4)(e.g., Thordarson and Larsen, 2007).

The most recent eruption that broke through the icecap took place in 1918 and lasted for 24 days (Sveinsson, 1919).

Eruptions from Katla are typically highly explosive basaltic events due to high water content of the magma and to lesser extent the interaction with the overlying ice cap, making these events into phreatomagmatic eruptions. Consequently, the eruptions produce widespread tephra fall and large jökulhlaups.

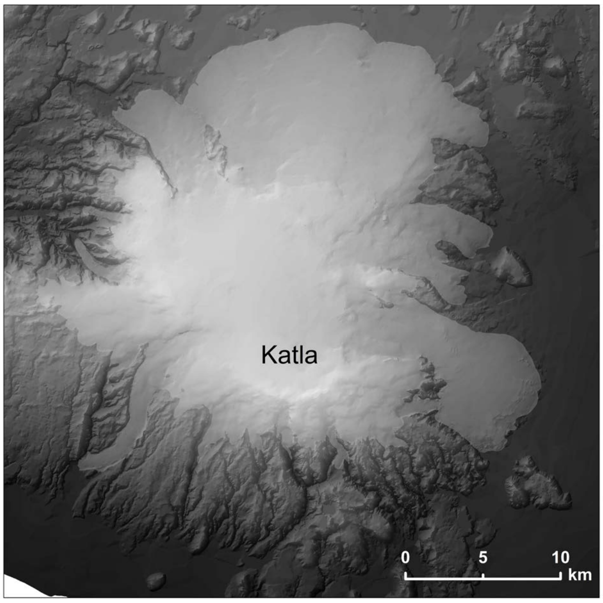

Figure 19. Katla volcano. DEM and hillshade from LMÍ.

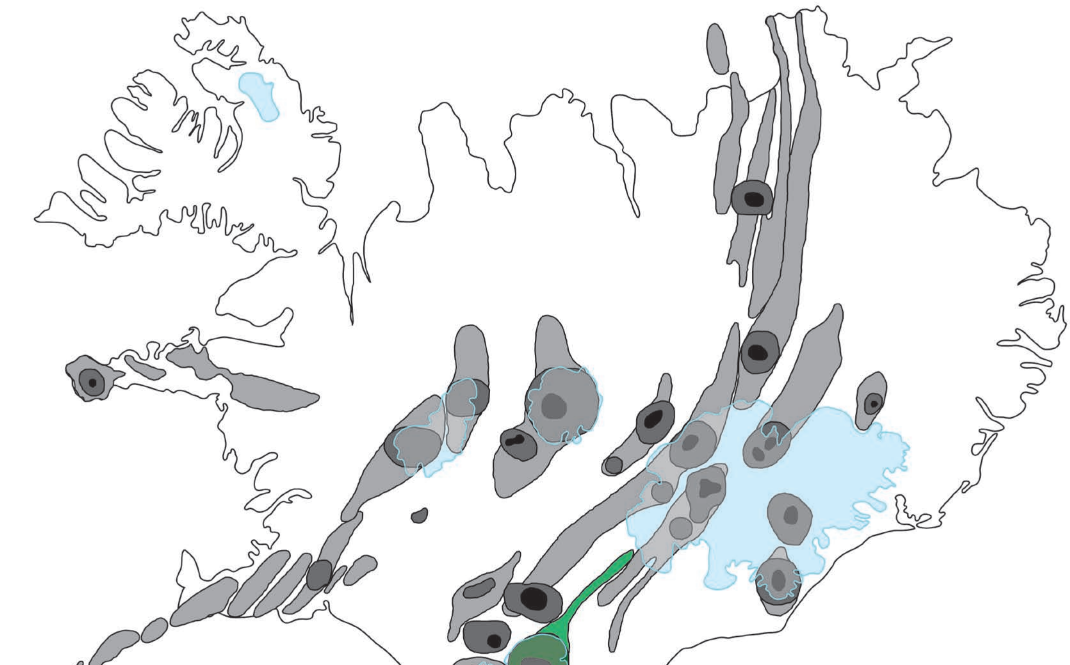

Figure 18. Location of Katla shown in green. Other volcanic systems are shown in grey. Glaciers are shown in light blue. Modified from Thordarson and Höskuldsson (2008).

Katla 1625

The 1625 eruption started with a loud explosion and a jökulhlaup, an eruption column was seen in the sky at 8 AM on the 2nd September 1625 (Magnússon, 1627). The eruption column lasted ~11 days until the evening of the 13th September (Magnússon, 1627; Schmidt, 2017).

The deposits suggest that the activity of the 1625 eruption was characterized by highly varying magma to water mass ratio. Nine distinct phases can be recognized in the near vent deposits (Schmidt et al., 2018).

These distinct phases suggest that explosive activity driven by rapid expansion of magmatic gasses dominated in the first days of the eruption and as the eruption went on the magma gradually interacted with more and more water (Schmidt et al., 2018). The dispersal of the Katla 1625 tephra on land is shown in Figure 20.

Plume height: 10 – 25 km
Volume: 1.24 km3

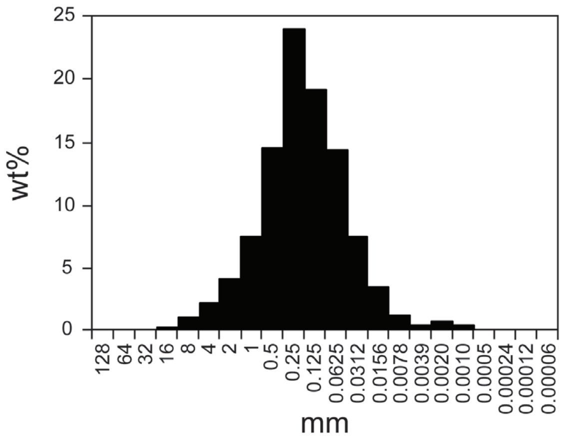

Figure 21. TGSD for Katla 1625 (Schmidt, 2017).

The TGSD is unimodal (Figure 21) with the mode at 0.125 mm. The total ash fraction (<2 mm) amounts to 93% of the tephra mass, and fine ash (<63 μm) accounts for 14% (Schmith et al., 2018).

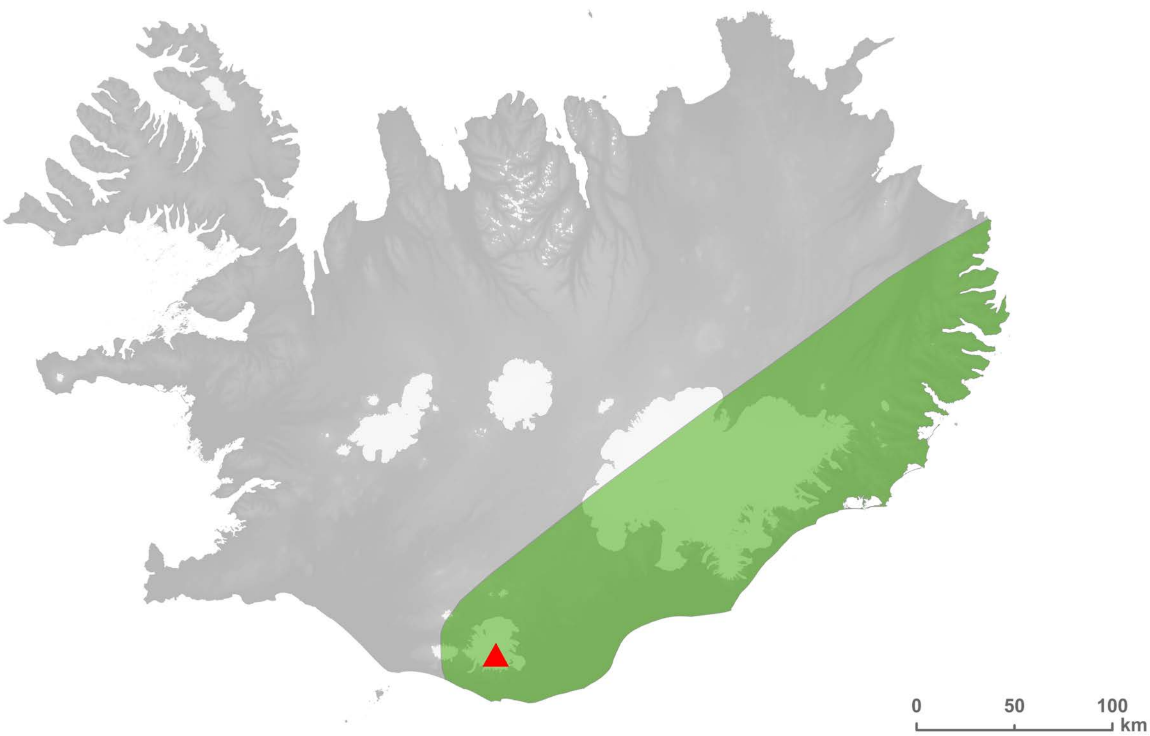

Figure 20. Main area in Iceland affected by tephra fall from the Katla 1625 eruption. Location of Katla shown by red triangle. Adapted from Schmidt et al. (2017, 2018).

Katla 1755

Plume height: 9 - 25 km
Volume: 1.34 km3

The eruption began on 17 October 1755 (e.g., Hallgrímsson 1870; Schmith et al., 2017, 2018; Schmith, 2017). Descriptions of the beginning of the eruptions include earthquake and jökulhlaup (glacial meltwater outburst floods).

Shortly after the earthquakes and the flood an eruption column rose into the atmosphere from the summit region of the central volcano.

The eruption lasted for 17 days or until 3 November. Schmith et al. (2018) showed that the intensity of the activity was uniform from the 17th to the 23rd, although the tephra-laden plume was carried in different directions due to changing wind directions. Between the 24th until the end of the eruption, the intensity waxed and waned a little before going into steadily decreasing mode (Schmith et al., 2018; Schmith, 2017). The dispersal of the Katla 1755 tephra on land is shown in Figure 22.

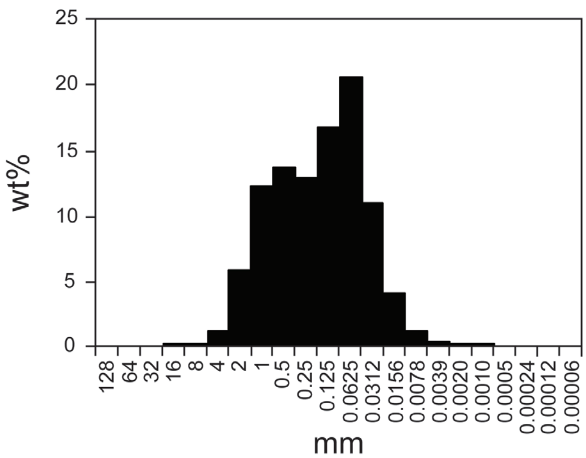

Figure 23. TGSD for Katla 1755 (Schmit et al., 2018; Schmith, 2017).

The TGSD is weakly bimodal (Figure 23) with modes at 0.5 mm and 0.063 mm. The total ash fraction (<2 mm) amounts to 93% of the tephra mass, and fine ash (<63 µm) accounts for 17% (Schmith et al., 2018).

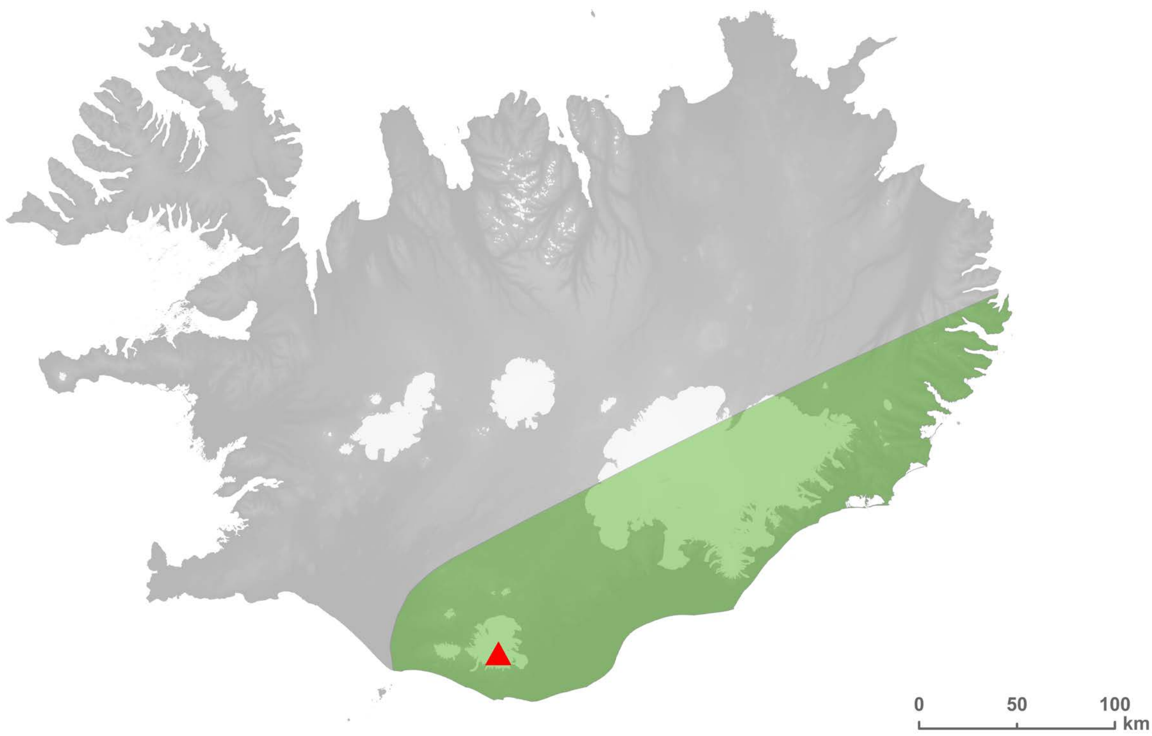

Figure 22. Main area in Iceland affected by tephra fall from the Katla 1755 eruption. Location of Katla shown by red triangle. Adapted from Schmit et al. (2018).

Katla 934 - Eldgjá

Plume height: 11-18 km
Volume: >5 km3

The 10th century Eldgjá flood lava eruption is one of the largest eruptions in Iceland. It originated from a ~75-km discontinuous fissure stretching from Katla caldera beneath Mýrdalsjökull to the western margins of Vatnajökull. In addition to producing two extensive lava fields covering a total area of 780 km2 and a volume of 19.6 km3, it produced the third largest tephra fall deposit in historical time, with a bulk volume > 5 km3 (= 1.2 km3 calculated as dense rock, DRE) and produced in at least 16 explosive phases.

The explosive phases were discrete events from different parts of the fissures. The first 10 explosive phases alternated between subglacial (phreatomagmatic) and subaerial (magmatic) locations, whereas all the latter ones were subaerial (i.e., magmatic).

The thickness of the tephra fall deposit is over 2 m at distance of 10 km from the nearest source vents and eruption column heights are estimated to have been between 11 and 18 km (Moreland, 2017).

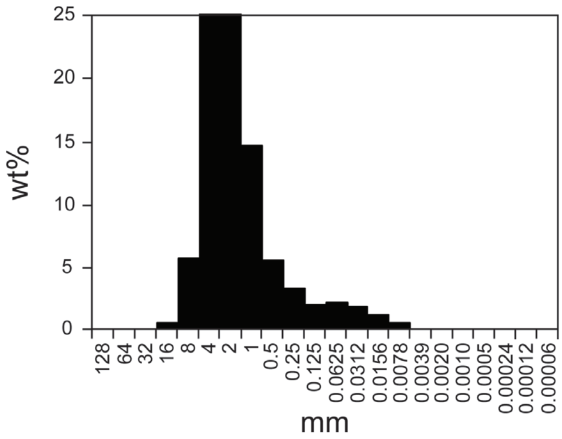

Figure 25. TGSD for Eldgjá unit 7 (Moreland, 2017).

Two units of the Eldgjá eruption have been studied in detail: the magmatic (subaerial) unit 7 and the phreatomagmatic (subglacial) unit 8.

Unit 7 erupted from the SW fissure segment whereas unit 8 was erupted from a short length subglacial fissure. The tephra from the two units were dispersed towards the east (Figure 24) (Moreland, 2017).

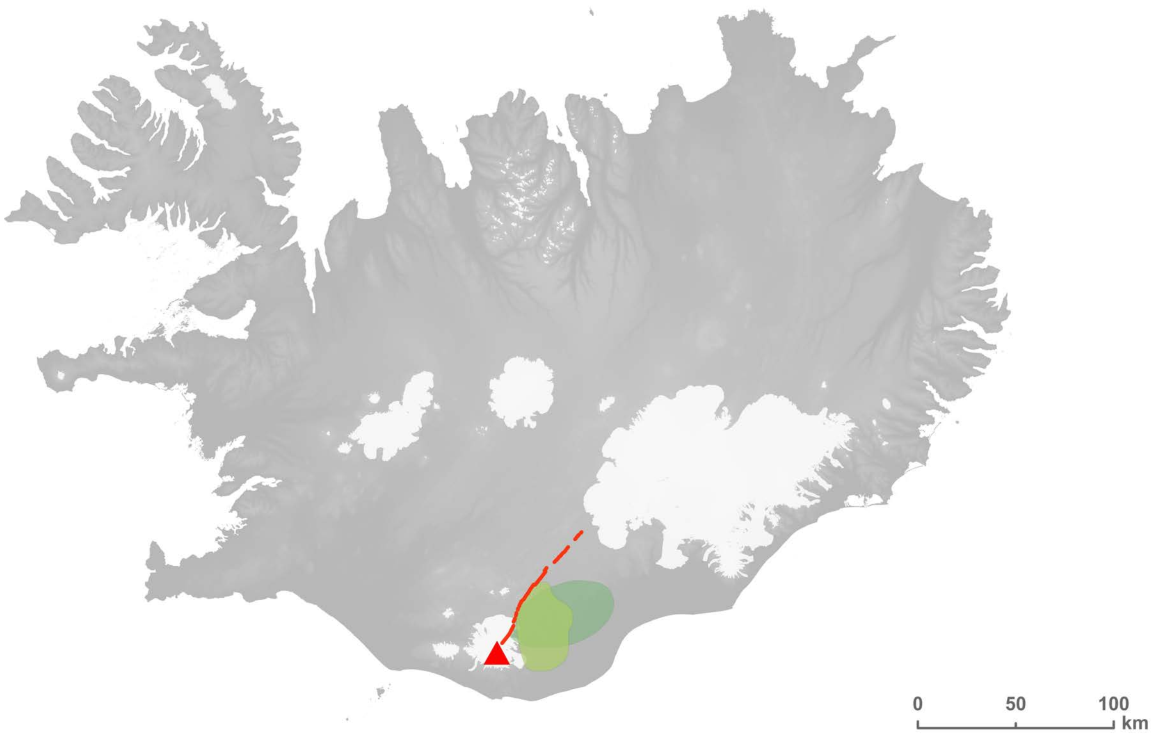

Figure 24. Main area affected by tephra fall from the Eldgjá eruption units 7 and 8. Location of fissure shown by red lines. Adapted from Moreland (2017).

The TGSD for unit 7 is unimodal (Figure 25) with the mode at 4 mm. In contrast, the TGSD for unit 8 is bimodal (Figure 26) with a coarser mode at about 2-0.5 mm and a fine mode at 0.03 mm.

The total ash (<2 mm) is 31% for unit 7 and 82% for unit 8, and the fine ash (<63 μm) accounts for 4% in unit 7 and 27 in unit 8 (Moreland, 2017).

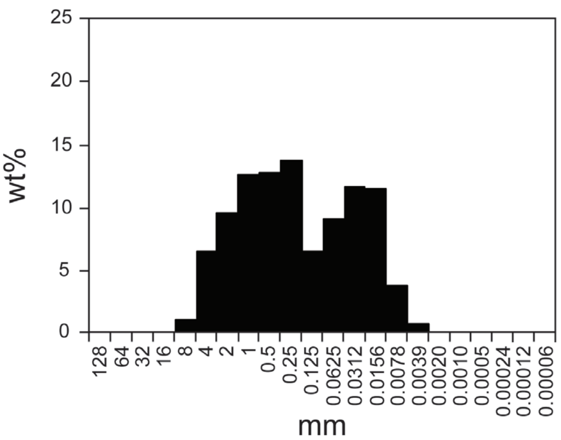

Figure 26. TGSD for Eldgjá unit 8 (Moreland, 2017).

7.3 Askja

Askja central volcano is located in the North Volcanic Zone (Figure 27, 28) (Catalogue of Icelandic Volcanoes). The Askja volcanic system covers an area of 2300 km2, making it the second largest in Iceland (Thordarson and Larsen, 2007; Thordarson and Höskuldsson, 2008).

The central volcano rises 800 m above its surroundings. Askja consists of multiple overlapping calderas, and the youngest one is occupied by Lake Öskjuvatn. In historical time, there have been several primarily lava-producing mafic eruptions along with one Plinian explosive eruption on 28–29 March 1875, featuring three distinct explosive phases: a sub-Plinian phase B, phreatoplinian phase C and a paroxysmal Plinian phase D (Carey et al., 2009a,b; Lupi et al., 2011; Hartley and Thordarson, 2012; Hartley et al., 2016).

The most recent eruption took place in October 1961, forming a lava flow from a fissure north of Öskjuvatn (Thorarinsson and Sigvaldason, 1962).

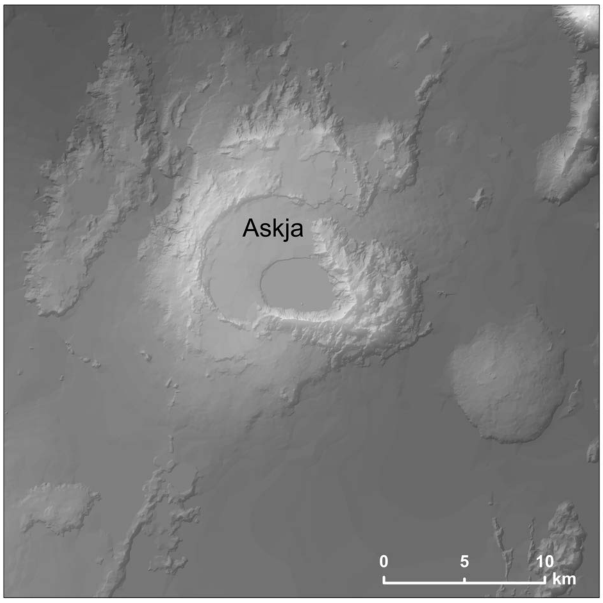

Figure 28. Askja volcano. DEM and hillshade from LMÍ.

The main hazards associated with effusive eruptions from Askja are lava flows and silicic explosive eruption have the potential of producing widespread tephra fall (e.g. Carey et al., 2010). Due to the location of Askja in the highlands, no towns are within close proximity, but the area is a popular tourist attraction.

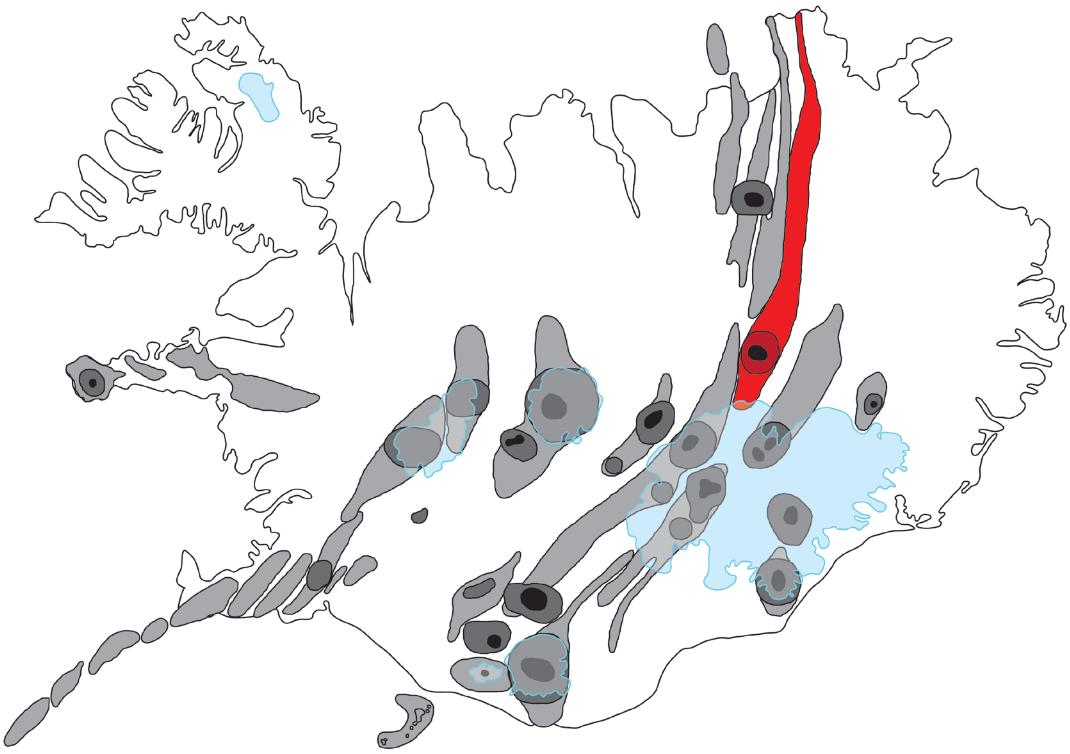

Figure 27. Location of Askja shown in red. Other volcanic systems are shown in grey. Glaciers are shown in light blue. Modified from Thordarson and Höskuldsson (2008).

Askja 1875

The column height:
Phase B = 8 km
phase C = 22.8 km
phase D = 26 km
Volume: 1.8 km3 (DRE = 0.32 km3)

The most recent explosive eruption, and only large explosive eruption of Askja in historical time, took place on 28–29 March 1875. The deposits are inferred to comprise seven phases named A to E, where units A, E and F are correlated with weak phreatic or hydrothermal activity prior to and following the main phases and units B to D represent the deposits produced by the main eruption (Sparks et al., 1981).

The main eruption began in the evening of 28th with a subplinian phase B, which began at 9 pm and lasted for about an hour. This was followed by a 9 hour hiatus, punctuated by onset of phase C, which also approximately lasted for an hour, and followed by a 5–6 hour long Plinian phase D (Carey et al., 2009).

The magma is dacite to rhyolite (67–70 wt% SiO2). Tephra was dispersed towards the east (Figure 29, 33-35). The Askja B deposit is confined to Iceland, but ash from both Askja C and Askja D reached Scandinavia (Figure 18; Carey et al., 2010). Column heights are estimated to have been 8 km for phase B, 22.8 km for phase C, and 26 km for phase D (Carey et al., 2010).

The TGSD for Askja B is unimodal (Figure 30), with the mode at 1 mm. The total ash fraction (<2 mm) amounts to 54% of the tephra mass, and fine ash (<63 µm) accounts for 4% (Janebo, 2016; Janebo et al., in prep).

The TGSD for Askja C (partial TGSD, material deposited in Iceland) is unimodal (Figure 31), with the mode at 0.09 mm (Janebo, 2016; Janebo et al., in prep). The total ash fraction (<2 mm) amounts to 93% of the tephra mass, and fine ash (<63 µm) accounts for 34%.

The TGSD for Askja D (partial TGSD, material deposited in Iceland) is bimodal (Figure 32) with a coarser mode at 16 mm and a finer mode at about 0.5 mm. For the Askja D deposit in Iceland, the total ash fraction (<2 mm) amounts to 44% of the tephra mass, and fine ash (<63 µm) accounts for 3% (Janebo, 2016; Janebo et al., in prep).

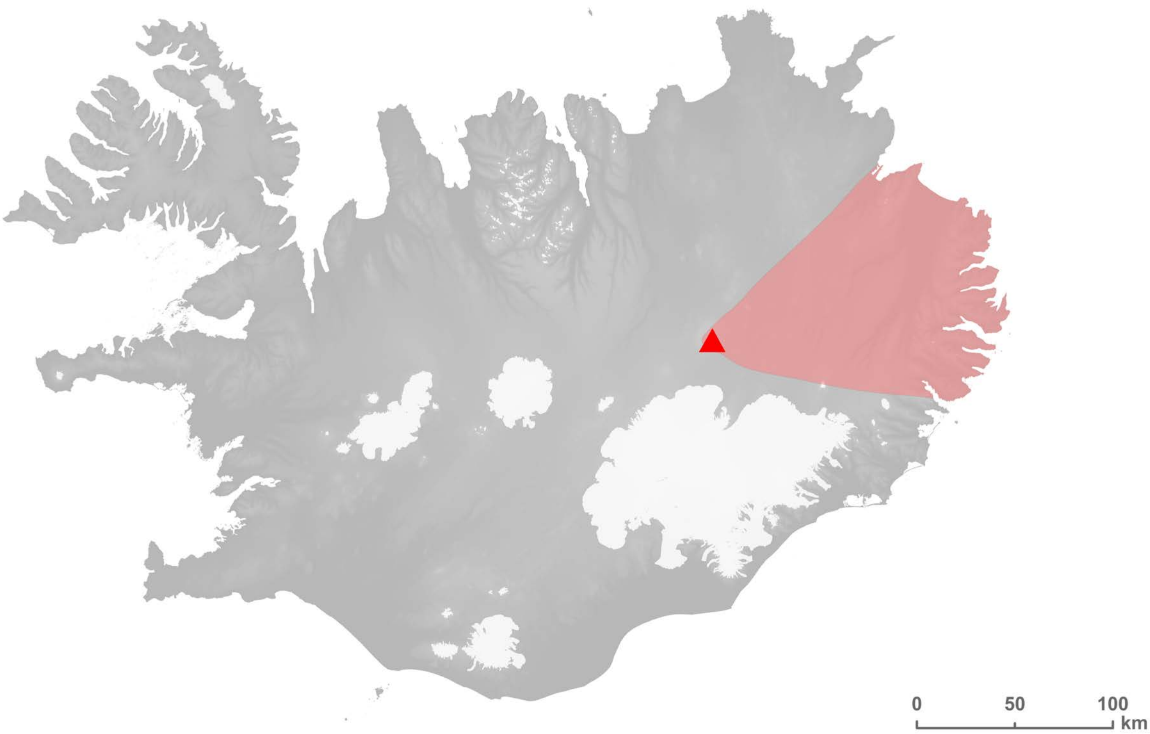

Figure 29. Main area affected by tephra fall from the Askja 1875 eruption. Location of Askja shown by red triangle. Note that the deposit continues outside of the figure area. Adapted from Carey et al. (2010), see individual units in Figures 32-34.

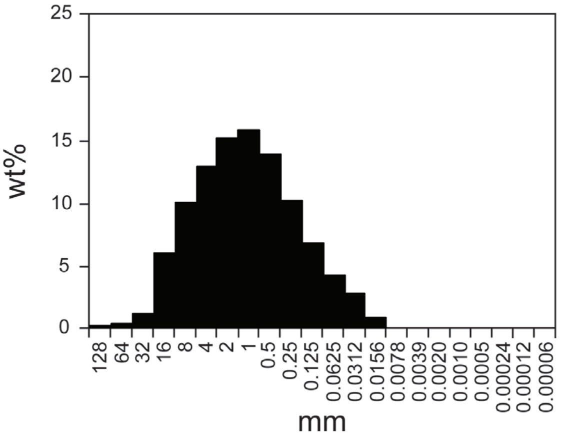

Figure 30. Preliminary TGSD for Askja B (Janebo 2016; Janebo et al., in prep).

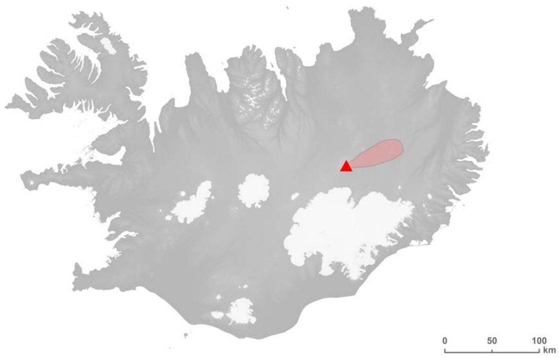

Figure 33. Main area affected by tephra fall from the Askja 1875 eruption unit B.

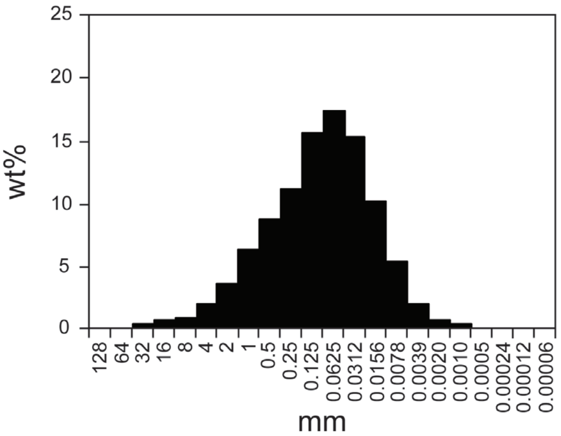

Figure 31. Preliminary TGSD for Askja C (Janebo, 2016; Janebo et al., in prep).

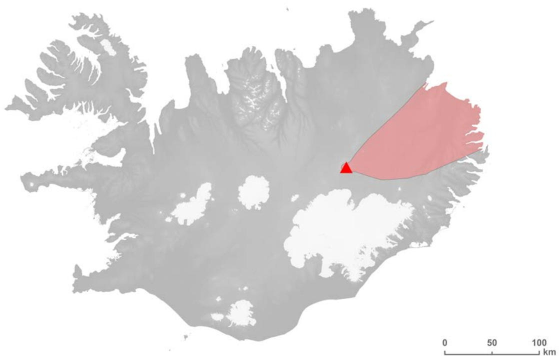

Figure 34. Main area affected by tephra fall from the Askja 1875 eruption unit C.

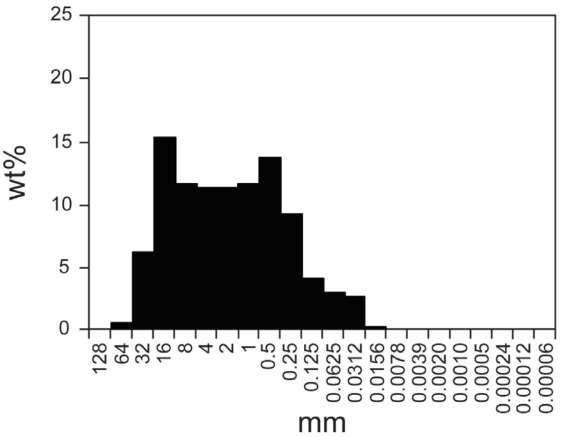

Figure 32. Preliminary TGSD for Askja D (Janebo 2016; Janebo et al., in prep).

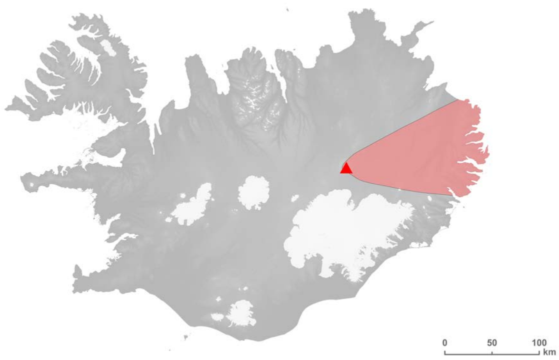

Figure 35. Main area affected by tephra fall from the Askja 1875 eruption unit D.

7.4 Grímsvötn

Grímsvötn central volcano is located within the Vatnajökull ice cap (Figure 36, 37) (Catalogue of Icelandic Volcanoes) with fissures extending towards the southwest, beyond the glacier.

Grímsvötn is the most active volcano in Iceland with more than 70 eruptions in historical time (Thordarson and Larsen, 2007). The most recent eruption that broke through the icecap took place in 2011 and lasted for 7 days (Lynch, 2015).

Eruptions from Grímsvötn are typically highly explosive basaltic events due to high water content of the magma and to lesser extent interaction with the overlying ice cap and thus typically coined as phreatomagmatic eruptions.

Consequently, the eruptions are usually associated with tephra fall and large jökulhlaups.

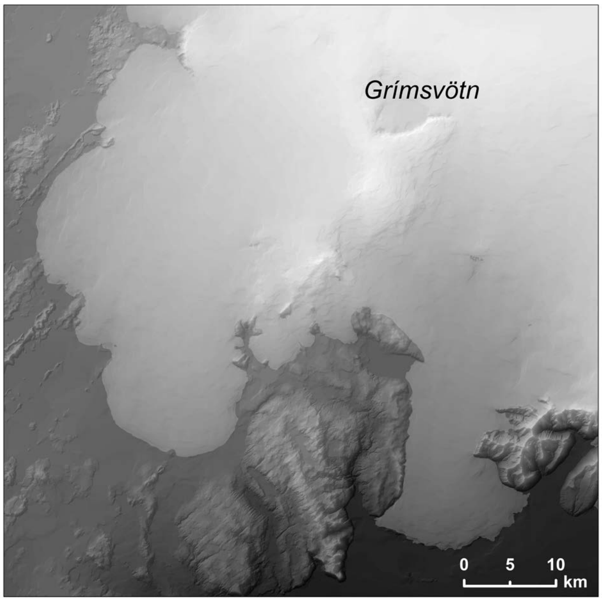

Figure 37. Grímsvötn volcano. DEM and hillshade from LMÍ.

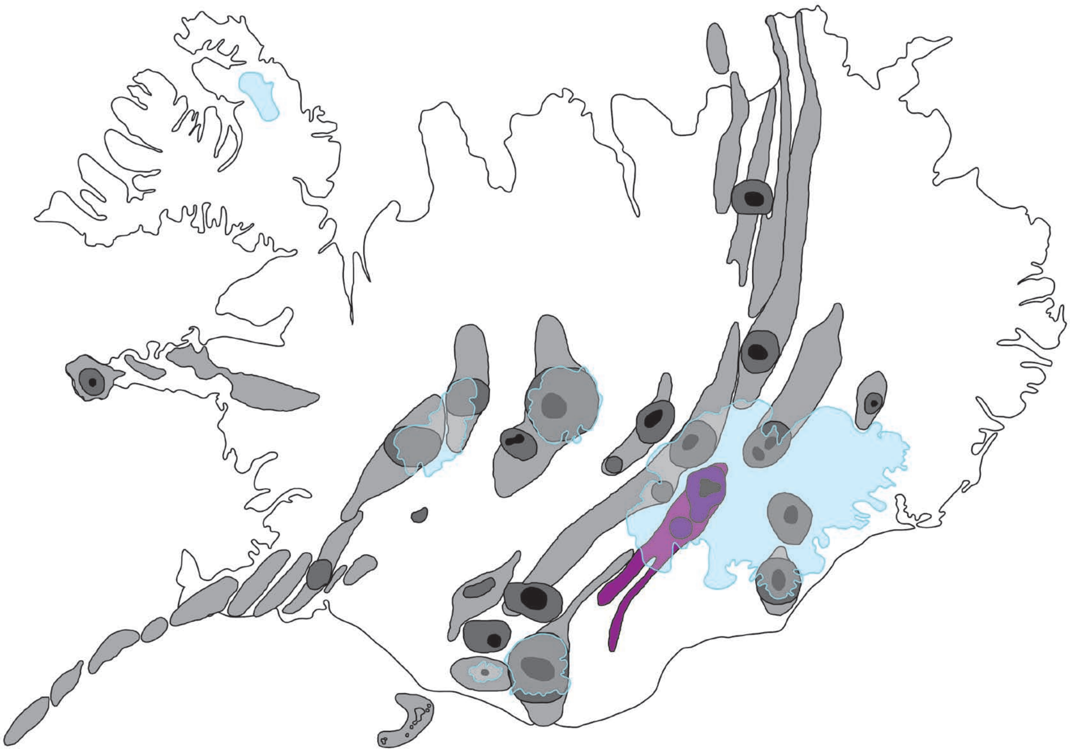

Figure 36. Location of Grímsvötn shown in purple. Other volcanic systems are shown in grey. Glaciers are shown in blue. Modified from Thordarson and Höskuldsson (2008).

Grímsvötn 2004

Plume height: 6 - 10 km
Volume: 0.02 km3

The 2004 phreatomagmatic eruption of Grímsvötn started on 1 November and lasted for 5 days. Two separate vents were active during the eruption. The magma was basaltic.

Significant deposition of tephra occurred in the first 45 hours, forming a fall deposit with a volume of 0.05 km3 (= 0.02 km3 DRE; Jude-Eton et al., 2012).

The deposit has been subdivided into seven units (A–G), of which units C and E account for 80% of the total deposit volume. The bulk of the tephra was deposited to NE (Figure 38) from an inclined 6–10 km high plume (Oddsson, 2007; Jude-Eton et al., 2012).

The Grímsvötn 2004 TGSD is bimodal (Figure 39)(Jude-Eaton, 2011) with coarser modes at 1-0.5 mm and finer modes 0.0625. The total ash fraction (<2 mm) amounts to 85% of the tephra mass, and fine ash (<63 µm) accounts for 20%.

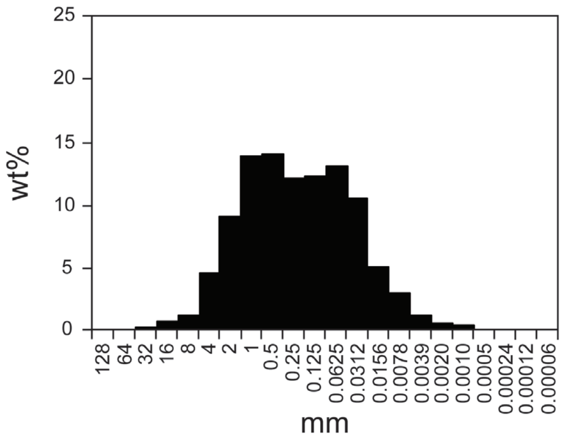

Figure 39. TGSD for Grímsvötn 2004 (Jude-Eaton, 2011).

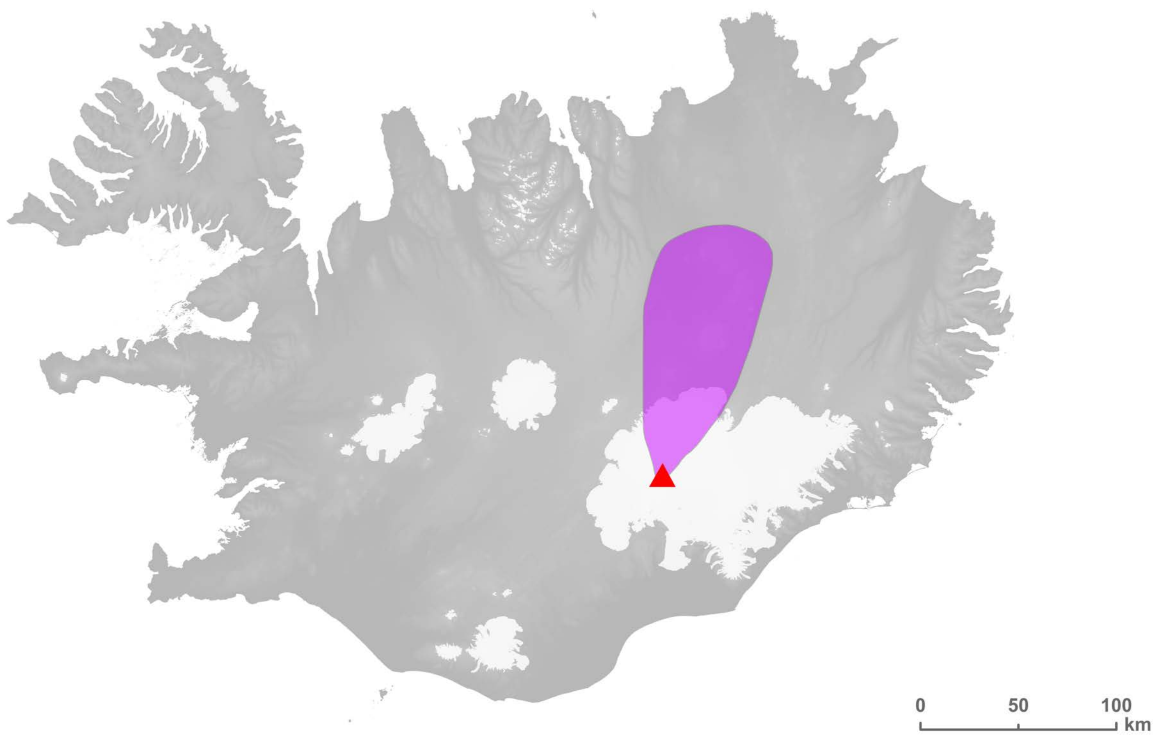

Figure 38. Main area affected by tephra fall from the Grímsvötn 2004 eruption. Location of Grímsvötn shown by red triangle. Adapted from (Jude-Eton et al., 2011).

Grímsvötn 2011

The most recent eruption of Grímsvötn started on 21 May 2011 and lasted until 28 May. The plume height was measured with both direct observations and weather radar and reached a maximum of 25 km on 21 May, decreased to approximately 15–20 km height on 22 May, and to 10 km on 23 May.

The tephra-laden plumes were carried south-southwest with tephra with tephra fallout onto Vatnajökull Glacier and the lowlands of the Fire Districts (Lynch, 2015) and subsequently all the way to the UK and mainland Europe (Stevenson et al., 2013; Figure 40), where 900 passenger flights were cancelled (Hreinsdóttir et al., 2014).

The TGSD for Grímsvötn 2011 only includes the material that was deposited on Vatnajökull and thus is a partial TGSD. It is bimodal with a coarse mode at 2 mm and a fine mode at 0.063 mm (Figure 41). The total ash fraction (<2 mm) amounts to 61% of the tephra mass, and fine ash (<63 µm) accounts for 15%.

Plume height: 20-22 km.
Volume: 0.2 km3

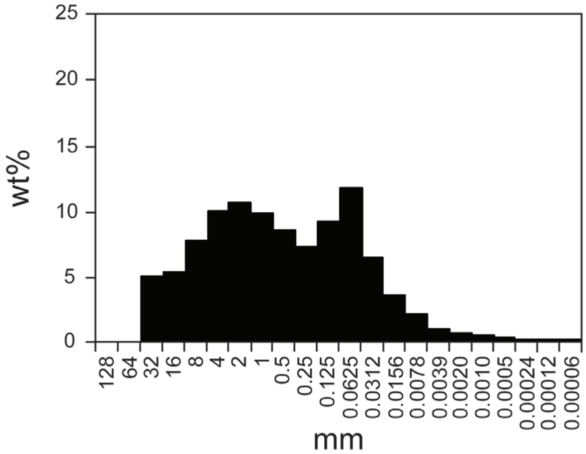

Figure 41. TGSD for Grímsvötn 2011

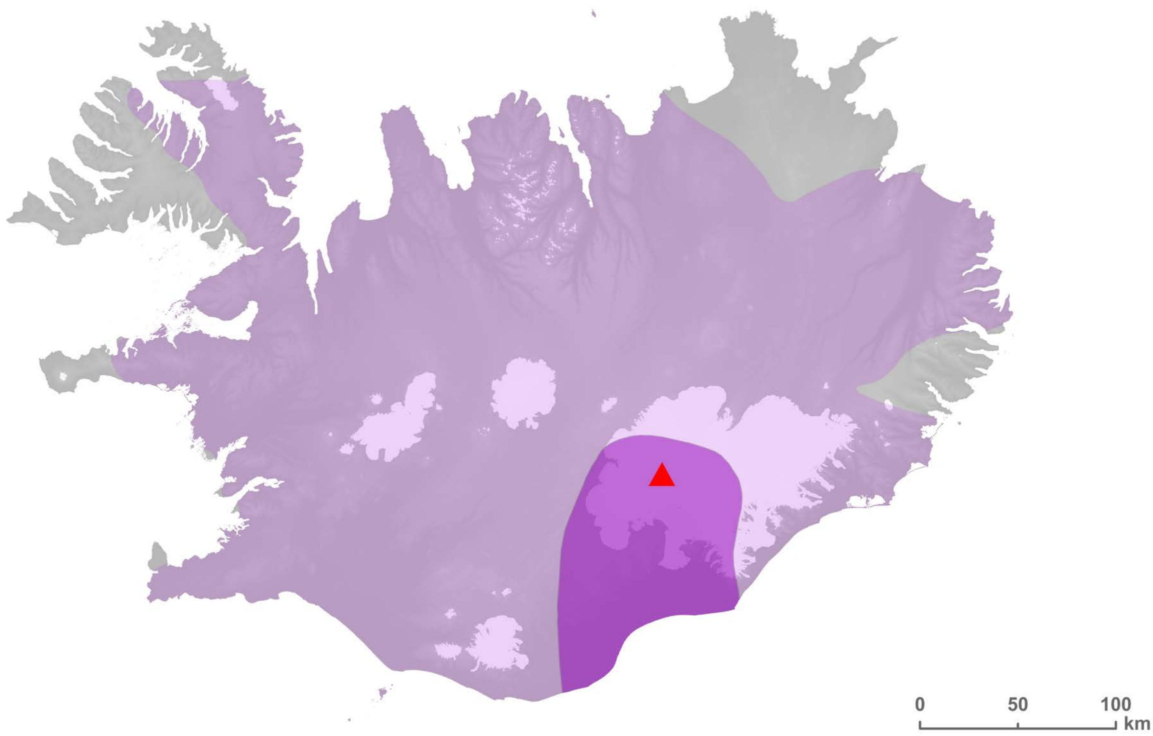

Figure 40. Main area affected by tephra fall from the Grímsvötn 2011 eruption (dark purple), light purple show reported tephra during the eruption. Location of Grímsvötn shown by red triangle. Adapted from Thordarson and Höskuldsson, unpublished data.

7.5 Eyjafjallajökull

Eyjafjallajökull central volcano is located below the Eyjafjallajökull ice cap and forms a part of the Easter Volcanic Zone (Figure 42, 43) (Catalogue of Icelandic Volcanoes).

Eyjafjallajökull is not among the most active volcanoes in Iceland with four confirmed eruptions during historic time. The most recent eruption occurred in 2010 and lasted for about 2 months (Gudmundsson et al., 2012).

Eruptions from Eyjafjallajökull are typically explosive to effusive. Existence of the summit ice-cap enhances mixing of surface water with the magma (phreatomagmatic eruptions).

Consequently, the eruptions are usually associated with tephra fall and jökulhlaups.

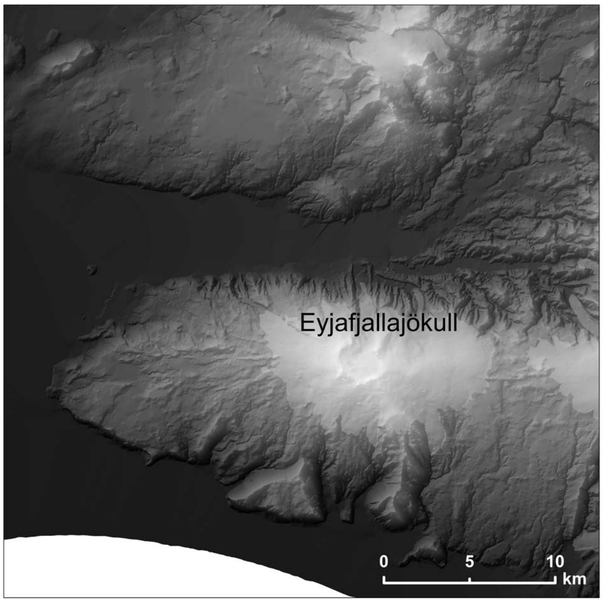

Figure 43. Eyjafjallajökull volcano. DEM and hillshade from LMÍ.

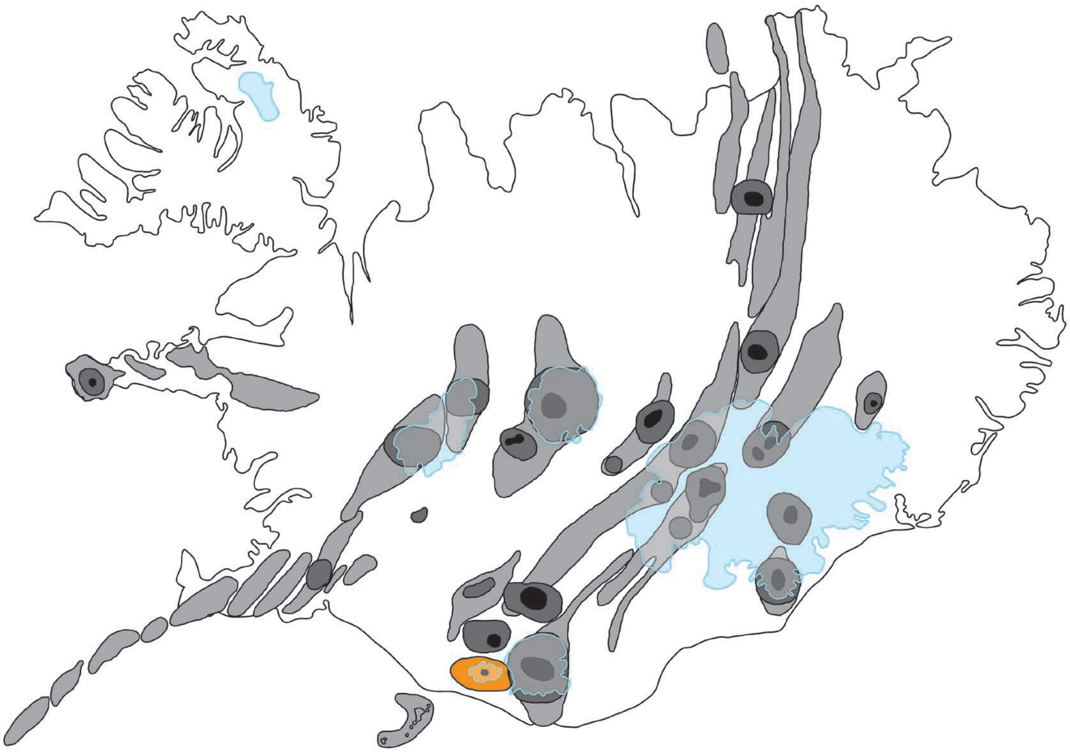

Figure 42. Location of Eyjafjallajökull in orange. Other volcanic systems are shown in grey. Glaciers are shown in blue. Modified from Thordarson and Höskuldsson (2008).

Eyjafjallajökull 2010

The most recent eruption of Eyjafjallajökull started as a flank eruption in April 2010 and was followed by explosive activity at the summit in May 2010.

Tephra produced in the period 4 to 8 May 2010 was dispersed to the SE (Figure 44). Most of the tephra was deposited on Eyjafjallajökull and Fimmvörðuháls, around 1 kg m-2. On the S flanks of Mýrdalsjökull, the mass loading had dropped down to 0.2 kg m2.

The tephra deposited during this time was from a 5 to 10 km a.s.l high eruption plume (The tephra was reported in Europe and caused considerable problems for air traffic).

The TGSD of the May deposits of Eyjafjallajökull 2010 determined using the Voronoi tessellation technique (Figure 45) is unimodal with the mode at 0.5 mm, and a median of 0.25 mm (Bonadonna et al., 2011). The total ash fraction (<2 mm) amounts to 85% of the tephra mass, and fine ash (<63 μm) accounts for 26% (Bonadonna et al., 2011).

Plume height: 4 - 9 km
Volume: 0.18 km3

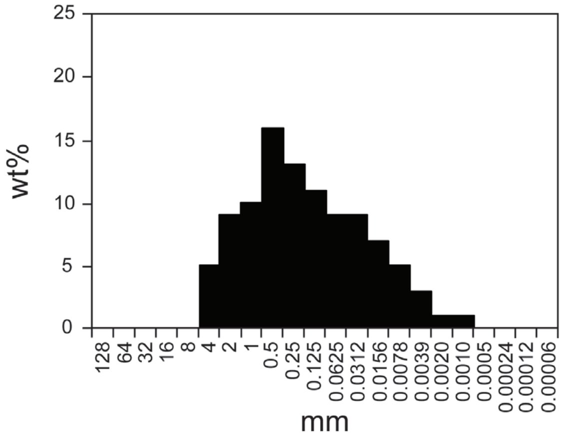

Figure 45. TGSD for Eyjafjallajökull May 2010 (Bonadonna et al., 2011).

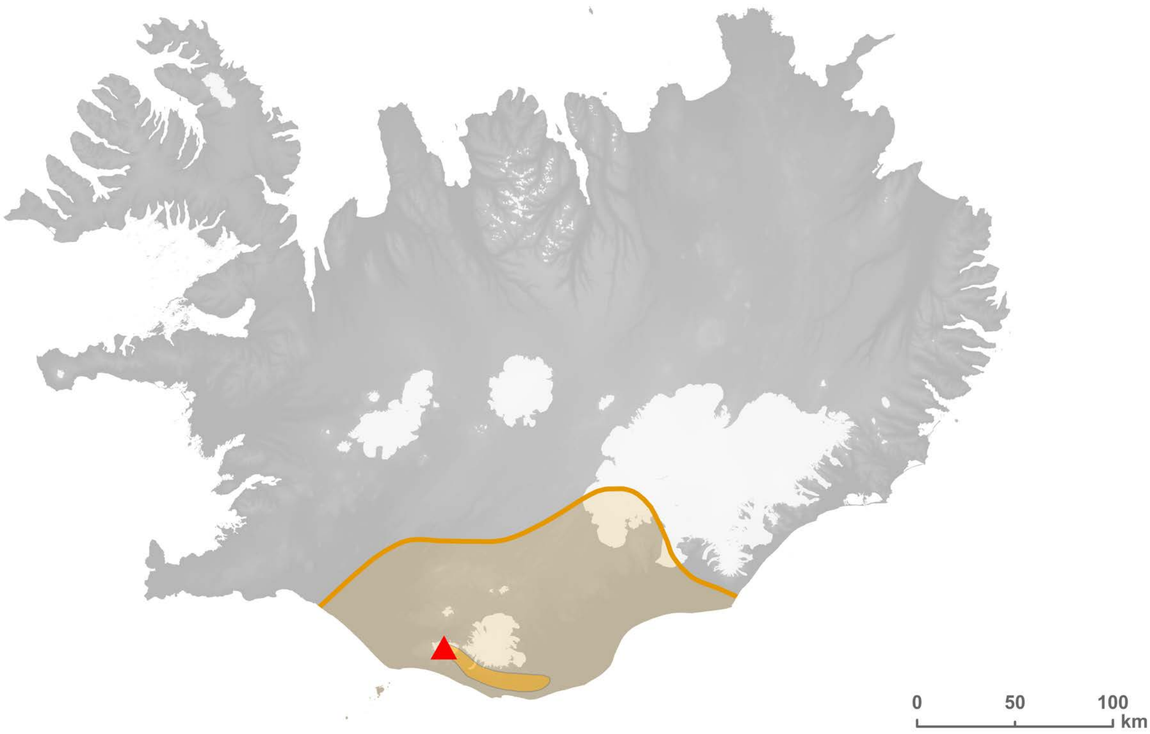

Figure 44. Main area affected by tephra fall from the Eyjafjallajökull 2010 eruption (larger area) and smaller area show tephra fall in the beginning of May, 2010. Location of Eyjafjallajökull shown by red triangle. Adapted from Bonadonna et al. (2011).

7.6 Reykjanes

The Reykjanes volcanic system (Figure 46, 47) (Catalogue of Icelandic Volcanoes) is the westernmost system of the Reykjanes Peninsula and 9 km of its total length is submarine, extending offshore to the SW (Jakobsson et al., 1978).

In contrast to the other volcanic systems discussed herein, the Reykjanes volcanic system has no central volcano and all the eruptions are from fissures oriented SW–NE, belonging to two fissure swarms (Höskuldsson et al., 20076). The magma is basaltic in composition and the majority of eruptions are effusive, forming lava flows.

There have, however, been at least 12 phreatomagmatic eruptions offshore in the past 4000 years producing tephra layers on land (Sigurgeirsson, 1995). The most recent period of activity was in 1211 to 1240, which produced four individual tephra layers known as R-7 to R-10.

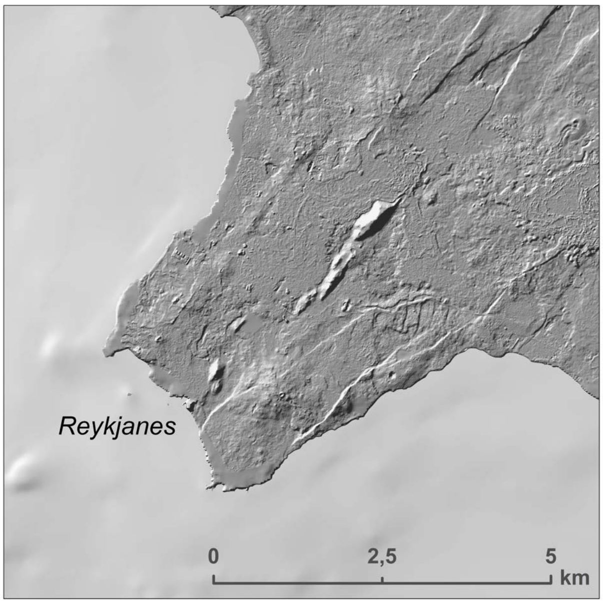

Figure 47. Reykjanes. DEM and hillshade from LMÍ.

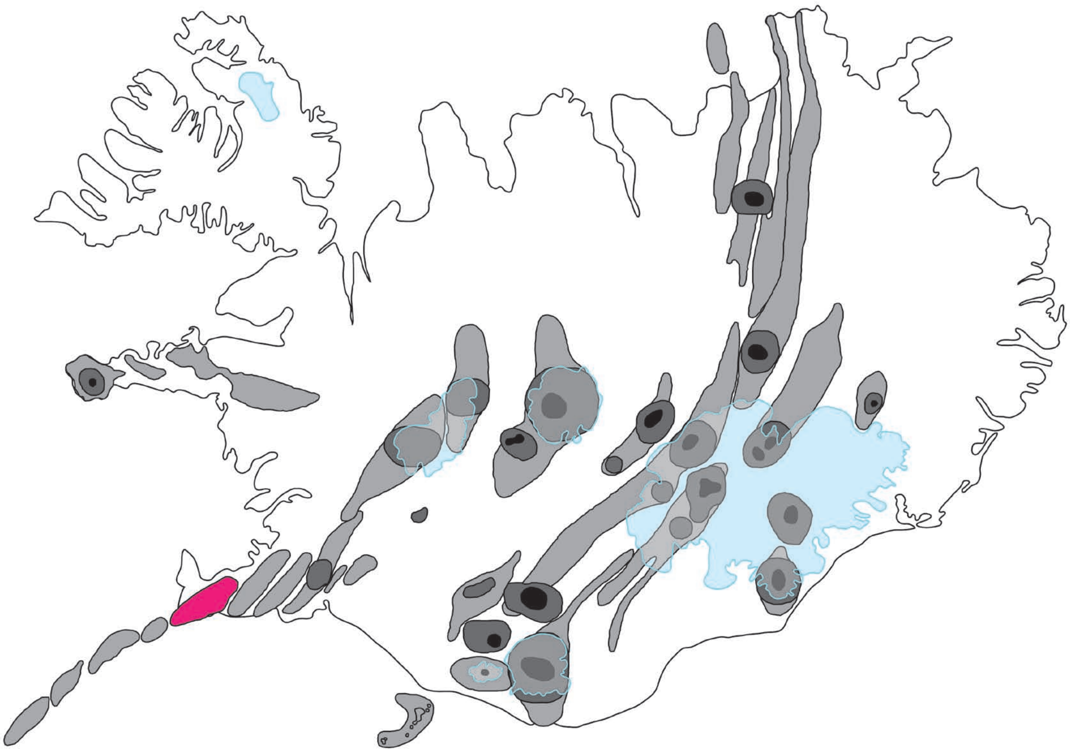

Figure 46. Location of Reykjanes shown in pink. Other volcanic systems are shown in grey. Glaciers are shown in blue. Modified from Thordarson and Höskuldsson (2008).

Reykjanes 1226

The Medieval tephra layer was formed in an eruption within the Reykjanes volcanic system in the year 1226 CE.

It is the largest tephra layer formed in the system and on the Reykjanes peninsula since the settlement of Iceland. The vent was located off the coast and deposited tephra to the northeast on land (Figure 48).

The TGSD for the Medieval tephra layer is unimodal with the mode at 0.125 mm (Figure 49). The total ash fraction (<2 mm) amounts to 99.7% of the tephra mass, and fine ash (<63 µm) accounts for 15%.

Plume height: 9 - 10 km.
Volume: 0.1 km3

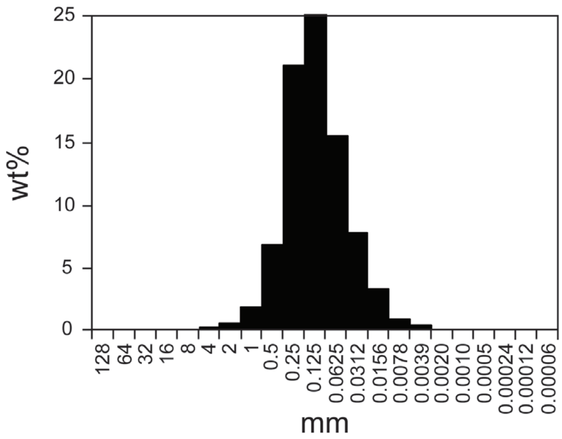

Figure 49. TGSD for Reykjanes 1226 (Magnusdottir, 2015).

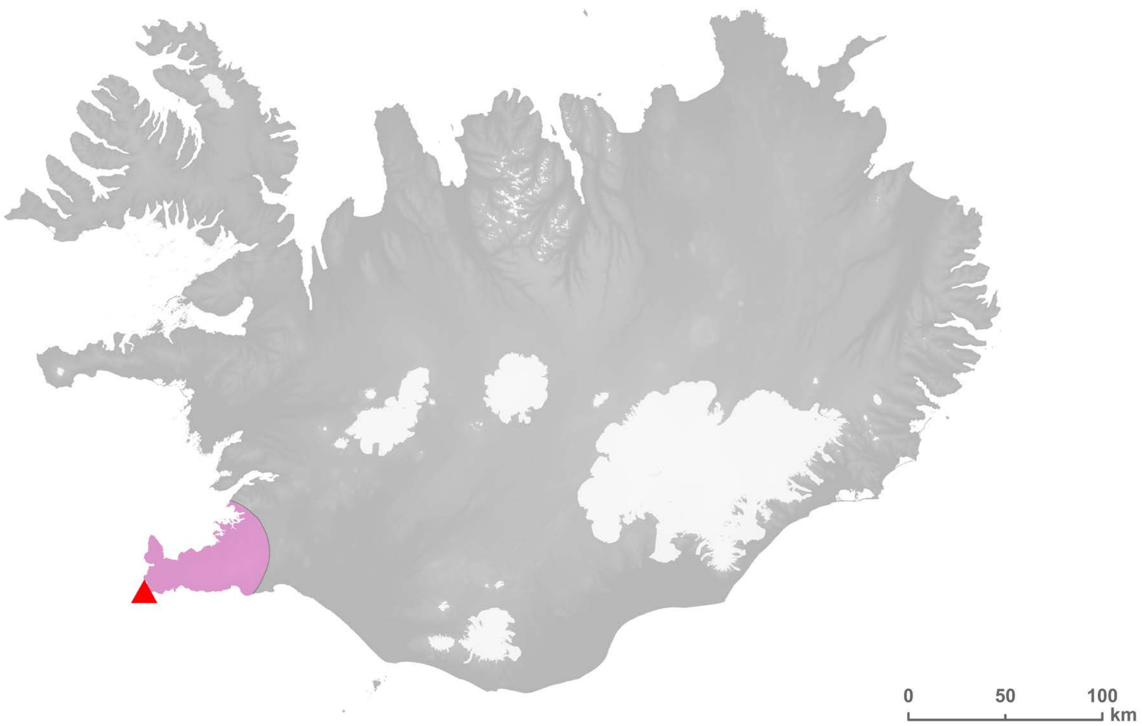

Figure 48. Main area affected by tephra fall from the Reykjanes 1226 eruption. Location of vent shown by red triangle. Adapted from Magnusdottir (2015).

8 Conclusions

In this research project, the focus has been on a selection of 14 explosive volcanic eruptions in Iceland, summarizing the available information concerning their TGSD and other important ESPs. All of the selected eruptions are historical (i.e., took place within the last 1150 years). Although this selection of eruptions covers a significant time period as well as range of events in terms of magma composition (basalt to rhyolite), eruption size, magnitude and style, it represents only a fraction of the explosive eruptions in Iceland in terms of numbers, size, magnitude and style. Hence, the selection reported here only captures a portion of the large range in eruptive behaviour observed among Icelandic volcanoes.

Bulk of the data presented here is from the Hekla volcano, with 7 of the 14 eruptions considered in this report (Table 1 & 4). This represents 40% of all Hekla eruptions in historic time (i.e., last 1150 years) and captures reasonably well the range of eruption sizes, magnitudes and styles in this time period. Historic eruptions at Hekla have consistently begun with a highly explosive phase and then transitioning into effusive lava forming eruptions. During smaller eruptions the explosive phase only last for tens of minutes to an hour, while the larger eruptions can maintain an explosive phase for a day or two. But, it is important to recognize that Hekla´s eruption history extends further back in time. Studies on the deposits from explosive Hekla eruptions in prehistoric time reveal events that are orders of magnitude larger in terms of size and intensity, such that the ash from these events has been identified as layers/distinct horizons on mainland Europe. Furthermore, although the pre-historic eruption frequency is similar to that of historic time, the story unfolding by recent research is that Hekla has featured periods where the eruptions are larger and more intense than we have seen in the past 1000 years (e.g., Larsen and Eiríksson, 2007, 2008; Stevenson et al., 2015). Thus, in order to capture the worst case scenario for Hekla eruptions, further studies are required.

Of 23 historic eruptions within the Katla volcanic system, three are included in this report or 13% of all historic events (Table 3). Two of the events (Katla 1625 and 1755) took place at the Katla volcano, while the third (Eldgjá 934–39) erupted from a linear vent system extending 75 km to the northeast from the Katla volcano. It represents the largest flood lava event on Earth in the last 2000 years and produced the third largest tephra fall deposit since settlement of Iceland (e.g., Larsen 2000; Moreland, 2017). Furthermore, this selection of eruptions includes two of the largest explosive events at the Katla volcano, which erupts explosively regardless of its ice cover due to high water content in its magmas (Moreland, 2017; Schmith, 2017). Consequently, large and small Katla eruptions are always explosive and the individual event can maintain explosive activity for weeks. Therefore, it is paramount to obtain a comprehensive data set for the more common small to intermediate size Katla events. Grímsvötn is Iceland´s most frequently erupting volcano with one event per decade on average.

This report includes data for the two most recent eruptions, the ones in 2004 and 2011 (Table 1), representing <3% of all historic eruptions at Grímsvötn plus span the small to intermediate size and magnitude spectrum of explosive eruptions from Grímsvötn. The Grímsvötn volcanic system was also the site of the second largest flood lava eruption on Earth in the last 2000 years, namely the 1783-4 Laki eruption, which featured 10 explosive subplinian phases producing tephra fall deposit with a volume exceeding the cumulative volume of all explosive eruption in Iceland in the 20th Century (e.g., Thordarson and Self, 1993, 2003; Thordarson et al., 2003). Furthermore, recent studies show that in prehistoric time the system featured explosive eruptions that were 2–3 orders of magnitude larger than the explosive phases at Laki and that of the 2011 event (Jennings et al., 2014; Thordarson, 2014).

A major problem with reconstructing TGSD and other ESPs for older small to intermediate size explosive eruptions from Grímsvötn is that bulk of the tephra fall is deposited on top of the Vatnajökull glacier, and therefore is not easily accessible plus their preservation potential is very low. Therefore, it is paramount to document and sample the tephra fall from the next eruption at Grímsvötn immediately after the the eruption is over in order to improve the current data set. This data set could also be complemented by further research of the tephra fall deposits from the 1783-4 Laki event as well as the very large prehistoric events, as they are not as sensitive to the presence of the Vatnajökull glacier.

For Askja, only one eruption is included. This is due to the nature of Askja volcano, which has dominantly had effusive lava forming activity. The eruption from 1875 resulted in a 25–28 km plume, causing abundant ash fall in Scandinavia. It is of special interest because it consists of three phases of contrasting eruptive intensity, including the only historical phreatoplinian eruption (e.g., Carey et al., 2009, 2010).

Only one eruption is included for the Eyjafjallajökull volcano, namely that of 2010. However, it is one of the more interesting eruptions in recent times because it was small explosive eruption of very long duration (i.e., >40 days), but yet with a huge societal and economic impact in Europe and beyond. Furthermore, is one of best documented eruptions in Iceland. The peculiarities of the Eyjafjallajökull 2010 eruption are its low volume, low plume height, long duration, and extremely fine-grained nature of the erupted material. This combination caused unprecedented problems for aviation. Another issue is that this eruption did not leave behind a substantial tephra layer that was preserved, except in the closest vicinity of the volcano. The same is likely the case for many other older eruptions, and thus provides challenges for investigating this type of eruption and to properly define how many similar eruptions have occurred in Iceland. But it is important that we attempt to figure this out.

Reykjanes Peninsula is of special interest because it is a peninsula on which all main infrastructure in Iceland is located, including the main international airport and the vicinity of Reykjavík, Iceland´s capital. Although eruptive activity is frequent on the peninsula, there has not been an eruption since 1246. The largest historic explosive eruption on Reykjanes Peninsula is the 1226 CE event, which is included in this report. Eruptions such as the one in 1226 can be long-lasting and maintain its explosive activity for weeks due to continuous access to external water. The continuation of the Reykjanes ridge passes from the peninsula into the sea. The part of the ridge that is on the continental shelf of Iceland is known to have an eruption frequency of about two eruptions per century. Eruptions on the shelf all have the potential of being explosive.

9 Future work

The output of this study is a step towards enhancing our understanding the spectrum of explosive eruptions in Iceland and gives us a glimpse of what to expect from future eruptions. Modern society is very vulnerable to all atmospheric pollutants and disturbance of travel between continents. Experience has taught us that even relatively moderate size explosive eruptions, such as Eyjafjallajökull 2010, can affect air traffic over Europe and between Europe and North America. It has also taught us that the potential impact off intermediate to very large explosive eruption is not always a simple linear function of scaling up the small events. Thus, establishing a robust and statistically valid data base on ESPs for the full spectrum of explosive eruptions in Iceland is essential for enabling reliable prediction of tephra dispersal, atmospheric ash mass loading and impact of future explosive eruptions. Modern satellite techniques can provide real-time observations of the densest part of an ash cloud, however, as the clouds are diluted, detection by satellites becomes increasingly difficult.

Model simulations of tephra dispersal is an important tool for monitoring and control of the airspaces. All models, however, are limited by the input parameters used, i.e., the quality of the ESP‘s data set used in the simulations. The plume height can be obtained in real time by land, air or satellite based observations. In contrast, the final TGSD can only be reconstructed once the eruption has ended. In countries, such as Iceland, where explosive eruptions are frequent and of different nature we can obtain TGSD for type example eruption by researching and studying exiting tephra deposits. Improving and extending the available dataset for TGSD, as well as the other ESP‘s, for the full range of explosive activity from Iceland volcanoes is therefore paramount.

Future work need also to focus on assessing the quality of the TGSD datasets based on e.g. deposit exposure. Both number of sample points and spatial distribution of samples across the deposit area need to be evaluated to carefully and systematically in order to provide a robust quality assessment of individual TGSD.

Therefore, we propose to continue this work to ensure comprehensive characterization of the full range of explosive eruptions in Iceland. It cannot be overstated how important it is for modellers to have accurate information on source parameters to constrain uncertainties of the model outputs and thus the reliability of the assessments. In this report results for 14 explosive eruptions in Iceland is presented. This work is very labour intensive and expensive. Therefore, it would not have been possible to achieve the outputs presented in this report without the involvement of 4 PhD and 2 MSc students and the outcome of their thesis research as well as additional financial support from US National Science Foundation (NSF), Iceland science foundation Rannís, Nordvulk, University of Iceland, Vinir Vatnajökuls Research Fund and the Vatnajökull National Park and ICAO.

In historic time (i.e., the last 1150 years), a minimum of 160 explosive eruptions have taken place in Iceland (Thordarson and Larsen, 2007) and about 1900 such events in the last 11000 years (Thordarson and Hoskuldsson, 2008). So, the data set presented in this report only covers a very small fraction (<1%) of the total number of events as well as limited range of the explosive eruption types in Iceland available for ESP parameterization. Each volcano in Iceland can be characterized by its own chemistry, which suggests that EPS parameters are not a simple function of the eruption intensity but also the differences in magma composition between volcanoes. That fact further points out the need to characterize the range of eruption types at as many of the Icelandic volcanoes as possible. We, therefore, strongly suggest continuation of this work.

As this work is time intensive, we propose that it is divided up in two periods of 3 years, or 6 years in total. During the first three-year period we would focus on the volcano Katla which has erupted 23 time during the historic time in Iceland, with special emphasis on small to intermediate size events. Katla has now been dormant for 100 years and we can expect an eruption from that volcano in the near future, especially since it has been showing signs of unrest in recent years (http://icelandicvolcanos.is/#). We propose to characterize five more Katla eruptions in terms of ESPs, two small size events (the Katla 1440 and 1612 eruptions), two moderate size events (Katla 1416 and 1721 eruptions) and one more of the large eruptions (Katla 1262).

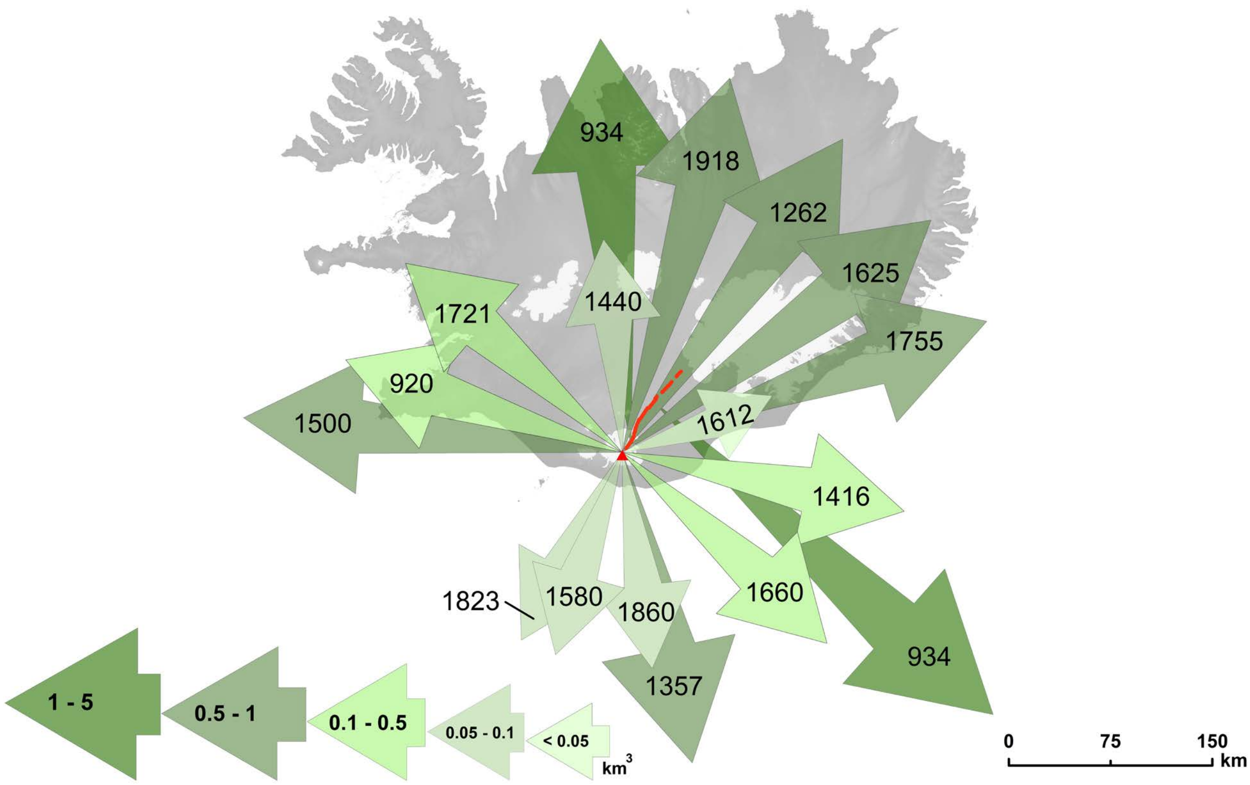

Figure 50. Main direction of tephra dispersal from historical eruptions in Katla

In the second three-year period we propose to focus on volcanoes where the explosive eruption are less frequent, but more powerful, namely the large-volume basaltic phreatoplinian events of Veiðivötn 1477CE, and Vatnaöldur 870 CE, including the 870 CE Plinian rhyolite phase from the Torfajökull volcano, the 1362 CE Plinian eruption at Öræfajökull, the largest explosive eruption in historical time in Iceland, the two largest Plinian eruptions in Iceland the Hekla H3 and H4 events and Snæfellsjökull 200 AD event, because the direct threat an eruption at Snæfellsjökull poses for the Greater Reykjavík area and air traffic out of Reykjavík and Keflavík airports. This work would produce the coverage of Icelandic explosive eruptions required for accurate and robust of model outputs. The data set is surely going to be strengthened but further analysis of EPS from future eruptions and further studies of the rest of historic and prehistoric eruptions in Iceland. However, the urgency of having minimum numbers of accurate ESP parameters should be solved within the next 6 years if continuation of the project is accepted.

Table 3. Overview of historical eruptions in Katla

Volcano	Year	Length days
Katla	1955	
Katla	1918	24
Katla	1860	20
Katla	1823	28
Katla	1755	120
Katla	1721	100
Katla	1660	60
Katla	1625	13
Katla	1612	
Katla	1580	
Katla	1500	
Katla	15th century	
Katla	1440	
Katla	1416	
Katla	1357	
Katla	1262	
Katla	1245	
Katla	1179	
Katla	12th century	
Katla - Eldgjá	934-940	
Katla	920	
Katla	9th century	

Table 4. Overview of TGSD

Eruption	Year	TGSD distribution	Mode/modes (mm)	% ash (<2 mm)	% fine ash (<63 um)
Hekla	1104	bimodal	8 & 0.063	44	25
	1300	bimodal	2 & 0.063	73	23
	1693	bimodal	4 & 0.063	59	15
	1766	bimodal	4 & 0.063	59	11
	1845	bimodal	6 & 0.125-0.045 mm	54	11
	1991	bimodal	11-5.6 & 0.18-0.09	44	6
	2000	bimodal	8-0.125	74	18
Katla	1625	unimodal	0.125	93	14
	1755	weakly bimodal	0.5 & 0.063	93	17
	934 Eldgjá unit 7	unimodal	4	31	4
	934 Eldgjá unit 8	bimodal	2-0.5 & 0.03 mm	82	27
Askja	1875 B	unimodal	1	54	4
	1875 C	unimodal	0.09	93	34
	1875 D	bimodal	16 & 0.5	44	3
Grímsvötn	2004	bimodal	1-0.5 & 0.0625	85	20
	2011	bimodal	2 & 0.063	61	15
Eyjafjallajökull	2010, May	unimodal	0.5	85	26
Reykjanes	1226 Medieval	unimodal	0.125	99.7	15

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