Reviewed research article

Volcanic hazards in Iceland

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Abstract — *Volcanic eruptions are common in Iceland with individual volcanic events occurring on average at a 3–4 year interval, with small eruptions (<0.1 km^3 Dense Rock Equivalent - DRE) happening about once every 4–5 years while the largest flood-basalt eruptions (>10 km^3 DRE) occur at a 500–1000 year interval. Despite the dominance of basalts, explosive eruptions are more common than effusive, since frequent eruptions through glaciers give rise to phreatomagmatic activity. The largest explosive eruptions (Volcanic Explosivity Index - VEI 6) occur once or twice per millennium, while VEI 3 eruptions have recurrence times of 10–20 years. No evidence for VEI 7 or larger eruptions has been found in the geological history of Iceland. Jökulhlaups caused by volcanic or geothermal activity under glaciers are the most frequent volcanically related hazard, while fallout of tephra and fluorine poisoning of crops, leading to decimation of livestock and famine, killed several thousand people prior to 1800 AD. The most severe volcanic events to be expected in Iceland are: (1) major flood basalt eruptions similar to the Laki eruption in 1783, (2) VEI 6 plinian eruptions in large central volcanoes close to inhabited areas, similar to the Öræfajökull eruption in 1362, which wiped out a district with some 30 farms, and (3) large eruptions at Katla leading to catastrophic jökulhlaups towards the west, inundating several hundred square kilometres of inhabited agricultural land in south Iceland. With the exception of the 1362 Öræfajökull eruption, fatalities during eruptions have been surprisingly few. Economic impact of volcanic events can be considerable and some towns in Iceland are vulnerable to lava flows. For instance a large part of the town of Vestmannaeyjar was buried by lava and tephra in a moderate-sized eruption in 1973. The prospect of fatalities in moderate explosive eruptions is increasing as frequently active volcanoes, especially Hekla, have become a popular destination for hikers. Automated warning systems, mainly based on seismometers, have proved effective in warning of imminent eruptions and hold great potential for averting danger in future eruptions.*

INTRODUCTION

During the eleven centuries of settlement in Iceland volcanic activity has repeatedly affected the population, directly and indirectly, and sometimes with extreme severity. Eruptions and events directly related to volcanic and geothermal activity commonly occur and their consequences range from direct impact of incandescent tephra or lava to jökulhlaups and contamination of air, water and crops (Figure 1). For the most part Iceland is sparsely populated with no permanent settlements in the interior highlands. Population clusters mainly occur along the coast, with about 70% of the 300 thousand inhabitants living in the greater Reykjavík area and along the southern shore of Faxaflói Bay in southwest Iceland. The Reykjavík metropolitan area is located just outside the margins of the active volcanic zone and the occurrence of volcanic eruptions inside the Reykjavík area is therefore considered remote although its southern and easternmost parts are susceptible to lava flows from future eruptions.

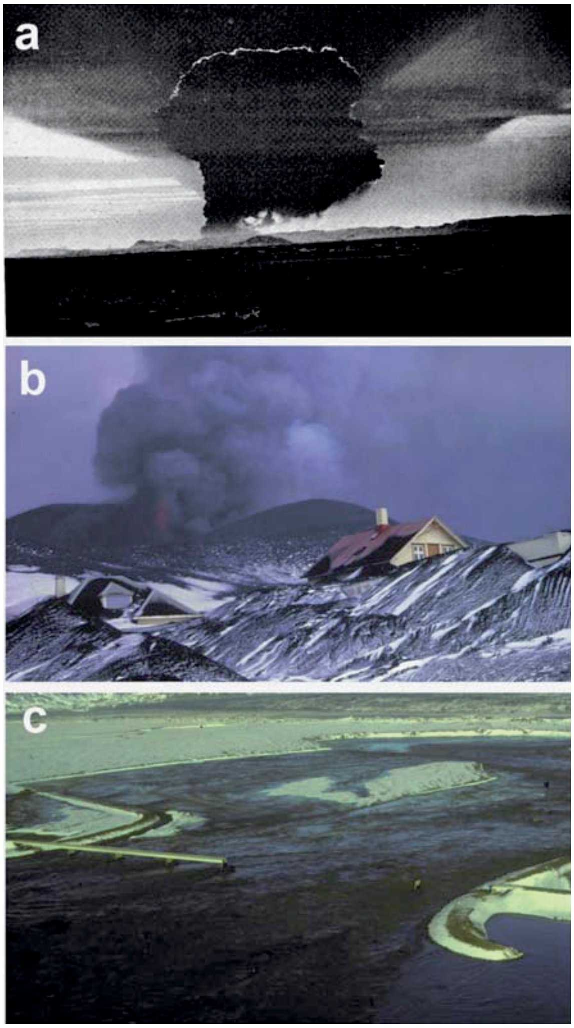

Figure 1. Examples of hazards caused by volcanic activity in Iceland: (a) The 28 km high plinian eruption column of Hekla in 1947. Photo: Sæmundur Þórðarson. (b) Burial of part of the town of Vestmannaeyjar in lava and tephra by the Eldfell eruption in 1973. Photo: Sigurður Thorarinsson. (c) a jökulhlaup caused by the Gjálp eruption in 1996 destroying one of the bridges on Highway 1 on Skeiðarársandur outwash plain. – *(a) Gosmökkur í Heklugosinu 1947, 28 km hár, teygir sig til suðurs í átt að Fljótshlíðinni; (b) Stór hluti húsanna í Vestmannaeyjum grófst í gjósku í gosinu 1973; (c) Grímsvatnahlaup sem kom í kjölfar Gjálpargossins haustið 1996 tók af brúna á Gígjukvísl og skemmdi stóran hluta vegarins yfir Skeiðarársand.*

Moderately populated areas are located close to very active volcanic centres in south, southeast and northeast Iceland. Major eruptions ($\sim$ 2–20 km^3 DRE) occur every few hundred years and have major regional effects which in some cases in the past, as in Laki 1783–84, caused famine in Iceland and had a marked temporal effect on climate in the northern hemisphere (e.g. Thorarinsson, 1974a; Thordarson and Self, 2003). In recent decades, explosive eruptions have posed a threat to aviation traffic in the busy routes between Europe and North America and East Asia.

The aim of this paper is to present a brief overview of the principal types of volcanic hazard in Iceland with special emphasis on the time since settlement (last $\sim$1130 years), the damage and loss due to volcanic activity in recent decades, the present state of hazard awareness and future prospects.

GEOLOGICAL SETTING – CHARACTERISTICS OF VOLCANISM

Volcanic activity in Iceland is confined to the active volcanic zones (Figure 2) The zones are composed of volcanic systems which usually consist of a central volcano and a fissure swarm that may extend tens of kilometres along strike in both directions away from the central volcano. Out of the 30 identified volcanic systems (Thordarson and Larsen, 2007), 16 have been active after 870 AD (Table 1). Most eruptions occur within central volcanoes, with Grímsvötn, Hekla and Katla having the highest eruption frequencies (Table 1) and together with their associated fissure systems they have the highest volcanic productivity (Thordarson and Larsen, 2007). The central volcanoes have often developed calderas that frequently host active geothermal systems, and erupt a range of magma compositions from basalts to rhyolites although basalts or basaltic andesites are usually volumetrically dominant in the their products (e.g. Sæmundsson, 1979; Jakobsson, 1979; Thordarson and Larsen, 2007). In many central volcanoes typical eruptions are small (<0.1 km^3 DRE) although in historical times eruptions in both Hekla and Katla have frequently been considerably larger. Eruptions on the

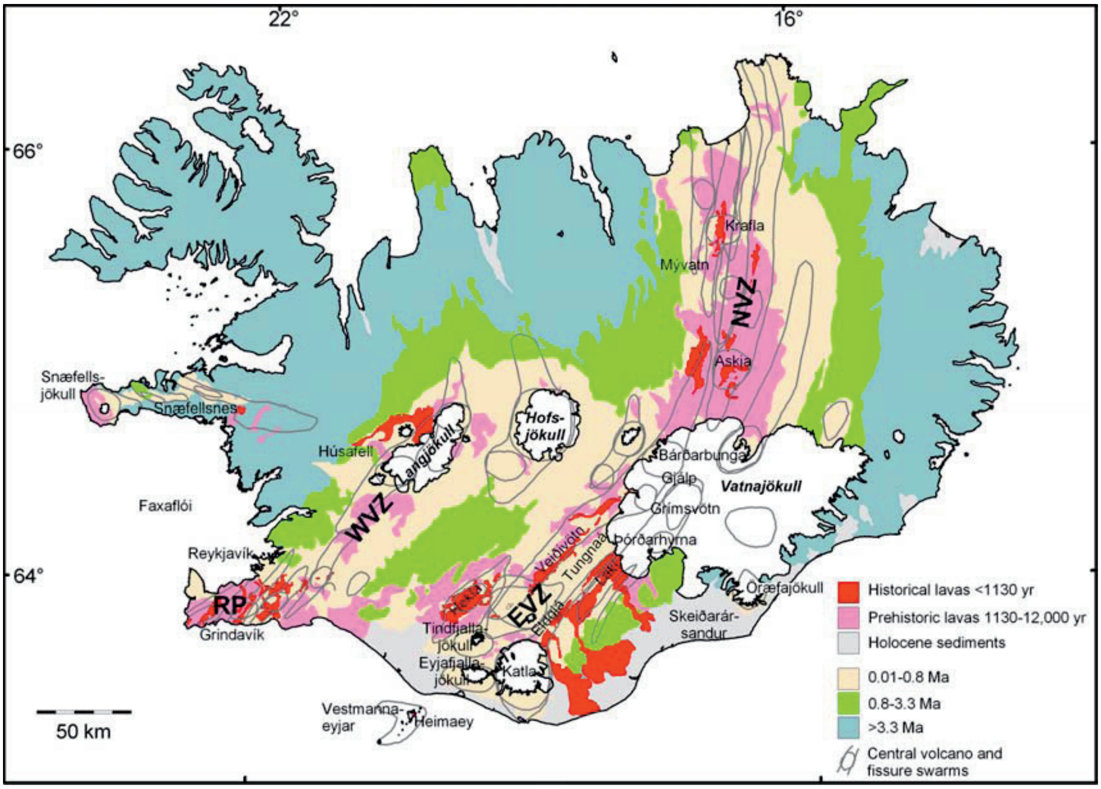

Figure 2. Simplified geological map of Iceland showing historical and Holocene lava flows, glaciers, and the main chronologically-defined units. Modified from Jóhannesson and Saemundsson (1998). – *Einfaldað jarðfræðikort af Íslandi. Á kortinu sjást nýleg hraun (rauð og bleik) og helstu jarðsögulegu einingar landsins.*

fissure swarms produce basalts. They are less frequent but tend to be larger than eruptions confined to the central volcanoes, with volcanic fissures extending up to several tens of kilometres. Some of the largest known eruptions in Iceland are of this type. Examples are the Laki eruption in 1783 and the Eldgjá eruption of 934, both of which erupted well in excess of 10 km^3 DRE (Table 1). It should be noted that the four largest effusive eruptions account for over 50% of the total magma volume emitted in historical time (see Thordarson and Larsen, 2007 and references therein). Many of the largest volcanic events are fires: a series of eruptions occurring along the same fissure over a period of several months or years. Basalts account for 79% of the total of the 87 km^3 DRE erupted in Iceland in the last 1130 years, with intermediate compositions accounting for 16% and silicic eruptions for 5% (Thordarson and Larsen, 2007). Eruptions have occurred in Iceland on average once every 3–4 years over the last 4 centuries (Thordarson and Larsen, 2007). The recurrence time of eruptions of different sizes and severity is summarized in Table 2. The eruption size frequencies are based on published data on eruption sizes (Thordarson and Larsen, 2007 and references therein). The bulk volume of pyroclastic deposits (Thorarinsson, 1958, 1967, 1975; Larsen, 1984, 2000; Thordarson and Larsen, 2007 and references therein) is used as a basis for the the recurrence times of eruptions with different VEI values.

Explosive eruptions and explosive phases of mixed eruptions are basically of two categories, magmatic eruptions where the explosive fragmentation is

Table 1. Volcanic systems in Iceland where eruptions have occurred after ∼870 AD – *Eldstöðvakerfi sem gosið hafa eftir að landið byggðist (eftir ∼870).*

Volcano/ Volcanic system	Conf. eruptions Since ∼870 AD	Most recent eruption	Magma prod. since ∼870 AD DRE (km^3)	Largest explosive eruption	Largest effusive eruption	Principal hazards
Katla (1, 2)	21	1918	25	934 VEI 5	934 18 km^3	Jökulhlaups Tephra fall Lava flows
Grímsvötn Laki (1, 3)	∼70	2004	21	1783 VEI 4	1783 14 km^3	Jökulhlaups Lava flows Tephra fall
Hekla (4, 1)	23	2000	13	1104 VEI 5	1766–68 1.3 km^3	Tephra fall Lava flows Fluorosis
Bárðarbunga-Veiðivötn (1, 5)	23	1910?	10	1477 VEI 5–6	Pre 12th century 5 km^3	Tephra fall Jökulhlaups Lava flows
Öræfajökull (6)	2	1727	2	1362 VEI 6	–	Pyroclastic flows Jökulhlaups/lahars Tephra fall
Askja (7, 1)	>two episodes	1961	>1.5*	1875 VEI 5	uncertain	Tephra fall
Krafla (8, 9)	two episodes	1984	0.5	–	1984 ∼0.1 km^3	Lava flow
Eyjafjallajökull (10)	3	1821–23	<0.1	1821–23 VEI 2	∼920 0.05 km^3	Jökulhlaups/lahars Tephra fall
Vestmannaeyjar (11, 12)	2	1973	$\geq$ 1.2	1963–64 VEI 3	1964–67# 1 km^3	Tephra fall Lava flow
Reykjanes Peninsula (four volc. systems) (13, 14)	four episodes	∼ 1340?	3	–	∼ 1227 0.3 km^3	Lava flow Tephra fall
Prestahnúkur system (1)	1	∼ 950	8	–	∼ 950 8 km^3	Lava flow
Þeistareykir - submarine part (15)	1	1867	?	VEI 2?	–	Tephra fall
Snæfellsnes (16)	1	∼ 900	0.2	–	∼ 900 0.2 km^3	Lava flow Tephra fall

* Values highly uncertain. #: Volume applies to whole Surtsey eruption, both explosive and effusive phases. References: (1) Thordarson and Larsen (2007), (2) Larsen (2000); (3) Larsen (2002); (4) Thorarinsson (1967); (5) Larsen (1984); (6) Thorarinsson (1958); (7) Thorarinsson (1944, 1963); (8) Sæmundsson (1991); (9) Rossi (1997); (10) Gudmundsson *et al.* (2005); (11) Jakobsson (1979), (12) Mattsson and Höskuldsson (2003); (13) Jónsson (1983); (14) Einarsson and Jóhannesson (1989); (15) Thorarinsson (1965); (16) Jóhannesson (1978).

primarily caused by the expansion of magmatic gases and phreatomagmatic eruptions where fragmentation results from magma-water interaction. In Iceland, by far the greatest majority of explosive events are phreatomagmatic explosive basaltic eruptions. These occur in volcanic systems that are partly covered by ice caps such as the Grímsvötn and Katla volcanoes, have high groundwater level (e.g. the Veiðivötn fissure swarm), or are situated on the continental shelf (like Vestmannaeyjar). Plinian, subplinian and phreatoplinian explosive events producing andesitic, dacitic or rhyolitic tephra are less common but constitute 24 of about 150 known explosive or partly explosive eruptions since AD 870. They have, however, generally wider aerial dispersal and more poisonous effects than the phreatomagmatic eruptions; mainly due to halogens adhering to the tephra (Thordarson and Larsen, 2007; Larsen and Eiríksson, this volume).

Table 2. Recurrence times, magnitude and severity of eruptions in Iceland. (a) Recurrence times - eruption magnitude. – *Tíðni og stærð eldgosa á Íslandi.*

V_{DRE} km^3	Recurrence time Years
<0.01	5–10
0.01–0.05	5–10
0.05–0.1	10
0.1–0.5	10–20
0.5–1.0	50
1–5	100
5–10	500
>10	500–1,000

(b) Recurrence times of eruptions of Volcanic Explosivity Index 1–6.

VEI	Recurrence time Years
1	10
2	10
3	10–20
4	30–50
5	100–200
6	500–1,000

The high frequency of eruptions within glaciers in Iceland implies that some common terms used to describe explosive eruptions such as the Volcanic Explosivity Index (VEI) can give misleading information on the true magnitude or impact of events. For example, the Gjálp eruption in 1996 produced only ~ 0.01 km^3 of airborne tephra and no lava. Yet it was the fourth largest eruption in Iceland in the 20th century but with the bulk of the material deposited subglacially (Gudmundsson *et al.*, 1997). A similar argument can be applied to the Katla eruption in 1918 where a large part of the erupted material was water-transported tephra (Larsen, 2000; Tómasson, 1996). Hence, the volume of meltwater (about 4 km^3 for Gjálp) may be a useful indicator of magnitude in subglacial eruptions.

Short term warning of an impeding eruption is at present based on short term seismic precursors. These are usually intense swarms of earthquakes in the hours before the onset of an eruption. The start of an eruption often distinguishes itself on seismic records as a sudden drop in frequency and magnitude of earthquakes and the onset of continuous seismic tremor (e.g. Einarsson, 1991a, 1991b; Soosalu *et al.*, 2005). All confirmed eruptions since 1996 have been predicted on the basis of such seismic activity.

The most severe volcanic eruptions in Iceland are the dominantly effusive flood basalt eruptions reaching a volume of 20 km^3 DRE, and plinian eruptions with a VEI of 6 (bulk volume of tephra $\geq$10 km^3). Evidence for explosive eruptions reaching VEI 7 and VEI 8 has not been discovered in the geological record of Iceland.

MAIN TYPES OF VOLCANIC HAZARDS

Tephra fallout

The factors influencing tephra dispersal can broadly be divided into those governed by the type, intensity and magnitude of the eruption, including height of the eruption column and the duration of the eruption, and those governed by external factors such as wind strength, wind direction and changes in wind direction during an eruption. The location of a volcano relative to inhabited areas is also important with respect to potential hazards from tephra fallout.

Tephra fallout from plinian and subplinian eruption columns, normally lasting an hour to several hours, is most often confined to relatively narrow sectors but tephra thickness within these sectors can reach tens of cm in proximal areas (Figure 3). Phreatomagmatic basaltic eruptions are fissure eruptions that generally last days or weeks and although the tephra is dispersed from lower eruption columns, changing wind directions can increase the area affected by the fallout due to the longevity of the eruptions.

Hekla volcano, located at the northeast margin of the Southern lowlands, is characterised by eruptions having a subplinian to plinian opening phase with tephra volumes ranging from 0.1 to 2 km^3 of

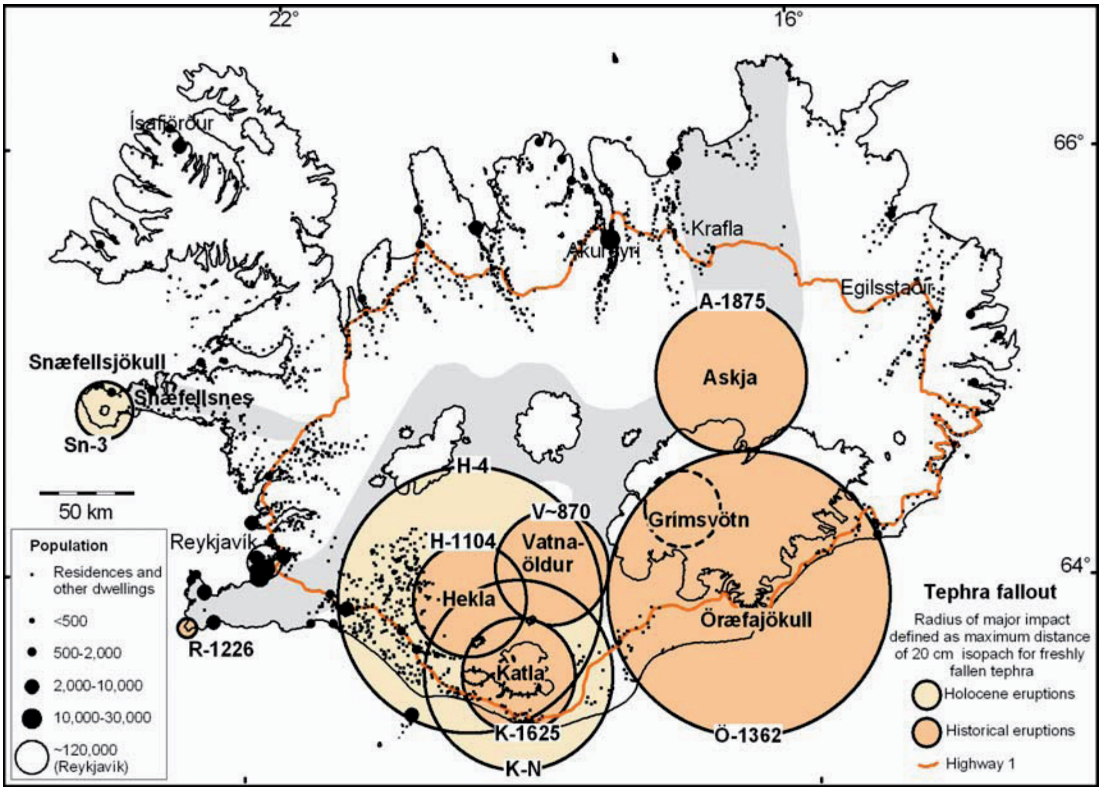

Figure 3. Areas that may receive over 20 cm of tephra fall in major explosive eruptions are indicated with circles around volcanoes or fissure swarms where explosive activity is common or the dominant mode of activity. The radius of each circle is defined as the distance to the 20 cm isopach along the axis of thickness for the largest historical and prehistoric explosive eruptions of each volcano. Also shown are populated areas and the main route, Highway 1. The volcanic zones are shown with a shade of gray. – *1. Svæði þar sem gjóskufall getur orðið 20 cm eða meira í miklum sprengigosum eru sýnd með hringjum utan um eldstöðvarnar. Geisli hvers hrings ákvarðast af mestu fjarlægð til 20 cm jafnþykktarlínu fyrir stærstu þekkt gos í hverri eldstöð á sögulegum og forsögulegum tíma. Á kortinu sjást einnig byggð svæði og þjóðvegur 1.*

uncompacted tephra (VEI indices 3–5). The largest of the 18 Hekla eruptions of the last millennium, in 1104, deposited a 20 cm thick tephra layer 30 km from Hekla and devastated farms up to 70 km from the volcano. The largest plinian eruption of the last millennium (VEI 6) which produced about 10 km^3 of uncompacted tephra, occurred in 1362 at the ice capped Öræfajökull volcano located in the middle of the Öræfi district in South East Iceland (Thorarinsson, 1958). The inhabited area at the base of the volcano and stretching eastward along the coast to Hornafjörður was devastated by tephra fallout. The tephra reached a thickness of $\geq$1 m some $\sim$15 km from source. Furthermore the immediate surroundings of Öræfajökull where affected by jökulhlaups, and pyroclastic flows and surges (see below). The plinian eruption of Askja in 1875, which produced 2 km^3 bulk volume, caused abandonment of farms in the highlands 60–70 km away from the volcano (Thorarinsson, 1944; Sparks *et al.*, 1981).

The majority of the phreatomagmatic eruptions during the last millennium occurred on the ice-covered parts of the Grímsvötn system with the heaviest tephra fall within the ~8000 km^3 Vatnajökull ice cap. Tephra fallout causing problems in farming areas occurred only during the largest events (VEI 4), e.g. the Grímsvötn eruptions of 1619, 1873 and 1903. Eruptions in the subglacial Katla volcano have caused much more damage than those within Vatnajökull. The upper slopes of Katla volcano are covered by the 600 km^3 Mýrdalsjökull ice cap and the lowlands to its west, south and east are partly inhabited. Depending on wind direction during large eruptions (VEI 4) inhabited areas have been subjected to heavy tephra fall, such as up to 20 cm at distances of 30 km (Figure 3). However, the largest phreatomagmatic eruptions (VEI 5) are those occurring on long fissures in areas of high ground water or below ice, such as the ~870 AD Vatnaöldur and ~934 AD Eldgjá eruptions (see Figs. 2 and 3 for location). Although the 20 cm isopachs do not extend significantly farther from source than the those of smaller (VEI 4) eruptions (Figure 3), the area within that isopach is an order of magnitude larger, e.g. 240 km^2 and 1600 km^2 for K–1625 and V~870 tephra layers, respectively (Larsen, 1984, 2000).

The moderate-sized explosive eruptions that have occurred in recent decades have produced eruption plumes rising to 8–15 km. As a result eruption plumes have repeatedly caused temporal disruption to air traffic within Iceland and in parts of the North Atlantic. Over the last 20 years this occurred in 1991, 1996, 1998, 2000 and 2004 (e.g. Höskuldsson *et al.*, 2007; Vogfjörd *et al.*, 2005).

Lightning

Lightning is common in phreatomagmatic eruption columns. In the past lightning has been a threat to livestock and people during Katla eruptions due to the volcano's proximity to populated areas, resulting in two fatalities at a farm 30 km from Katla in 1755 (Safn til sögu Íslands IV; 1907–1915). No reliable numbers exist for loss of livestock although it is often mentioned in accounts of eruptions of Katla. Even though lightning is also common during the more frequent Grímsvötn eruptions, they have posed much less of threat due to the location of Grímsvötn far from populated areas and the moderate size of past eruptions.

Pollution

Chemical compounds adhering to the surface of tephra particles can cause pollution of water supplies and grazing lands in areas remote to the erupting volcanoes. Hekla magma is rich in halogens, in particular fluorine. Fluorosis, poisoning of grazing livestock, has been reported in almost all Hekla eruptions where adequate records exist. Mass death of trout in lakes 110 km from Hekla in 1693 was attributed to tephra fallout. Fluorosis poisoning in livestock and humans was also reported from the Laki eruption in 1783 (D'Alessandro 2006, Steingrímsson 1998). The most pronounced atmospheric pollution from an Icelandic eruption occurred in the large flood basalt eruptions of Eldgjá 934 and Laki 1783. The former released some 220 Mt of SO_2 and the latter about 120 Mt. (Thordarson *et al.*, 1996, 2001). The resulting haze that accompanied the Laki eruption was noted in Europe in the summer of 1783 (Thordarson *et al.*, 1996). In Iceland the poisoning led to ill health of the population, decimation of livestock and a subsequent famine that killed thousands of people (Thorarinsson, 1974a). Studies in Europe suggests that the haze contributed to unusually high mortality in England and France in 1783–1784 (Grattan *et al.*, 2003a, 2003b, 2005; Courtillot, 2005; Witham and Oppenheimer, 2005).

Pyroclastic density currents

Due to the primarily basaltic nature of Icelandic volcanism, pyroclastic density currents are not prominent. However, major ignimbrites and minor pyroclastic flow deposits have formed throughout the geological history of Iceland within central volcanoes erupting evolved magma. Several are found within the Tertiary formations (Walker, 1959, 1962, 1963) notably the Skessa Tuff. In western Iceland the ignimbrite in Húsafell is well known (Sæmundsson and Noll, 1974). Only three examples are known from the Quaternary Period (<1.8 Ma), the Halarauður tuff from Krafla volcano (Sæmundsson, 1991), the ~55,000 year old Þórsmörk ignimbrite from Tindfjallajökull volcano (Lacasse and Garbe-Schönberg,

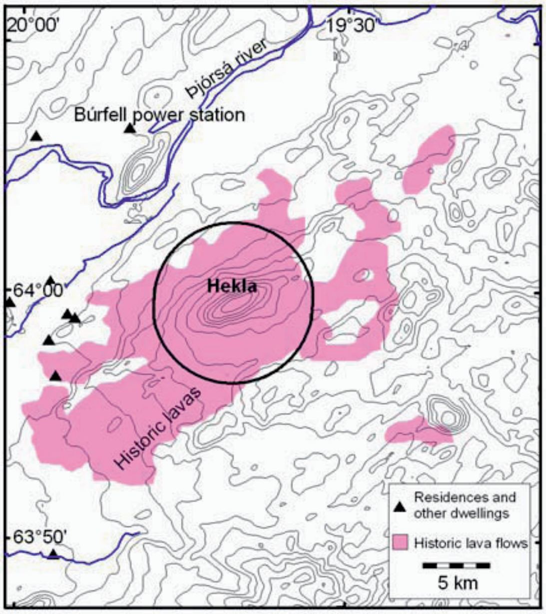

Figure 4. Hekla and surroundings. The extent of historical lavas and the maximum extent of pyroclastic flows during 20th century eruptions is shown (circle). – *Útbreiðsla hrauna frá Heklu á sögulegum tíma og mesta fjarlægð sem gjóskuflóð hafa náð út frá eldstöðinni á 20. öld (sýnd með hring).*

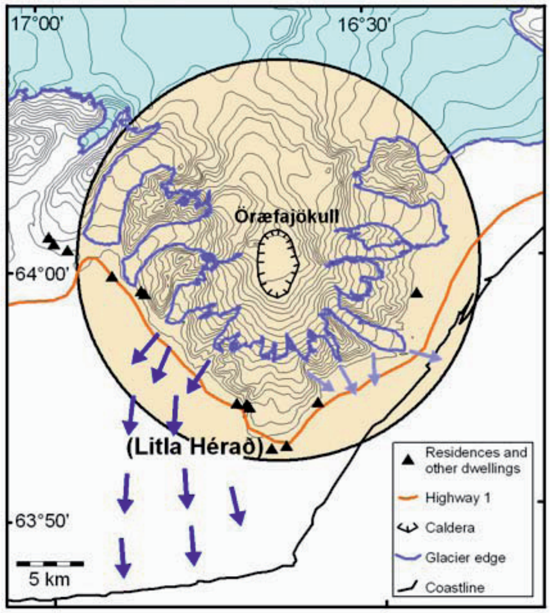

Figure 5. Öræfajökull and surroundings. The circle defines the maximum extent of pyroclastic flows using the observed runout length of such flows towards the south and the west in the 1362 eruption. The dark arrows show confirmed pathways of jökulhlaups in 1362 while the light arrows indicate suspected pathways (Thorarinsson,1958; Höskuldsson and Thordarson, unpublished data). – *Öræfajökull og nágrenni. Geisli hringsins miðast við mestu fjarlægð sem gjóskuflóð runnu út frá fjallinu til suðurs og vesturs í gosinu 1362. Dökku örvarnar sýna staðfestar leiðir jökulhlaupa í gosinu 1362 en þær ljósu líklegar hlaupleiðir.*

2001) and the Sólheimar ignimbrite from Katla volcano (Jónsson, 1987) dated at 12,171±114 ice core years (Rasmussen *et al.*, 2006). The apparent lack of preserved silicic pyroclastic flow deposits during the Quaternary Period in Iceland may be a result of heavy glaciation. Firstly, during glacial periods the pyroclasts may have been deposited on glaciers and therefore not preserved. Secondly, glacial erosion may have removed interglacially-formed pyroclastic deposits.

The opening phase of the subplinian Hekla 2000 eruption generated several small pyroclastic flows that extended up to 5 km from the vent (Höskuldsson *et al.*, 2007). Similarly the subplinian eruption of Hekla in 1980 generated pyroclastic flows (Figure 4). The plinian Hekla eruption in 1947 may have generated several pyroclastic flows and some quite extensive, however, the deposits were first interpreted as being jökulhlaup and mud flow deposits (Kjartansson, 1951; Höskuldsson, 1999). The plinian Askja eruption in 1875 was accompanied by pyroclastic surges that where confined to the main Askja caldera (Sparks *et al.*, 1981). The most violent eruption during historical time in Iceland is that of Öræfajökull in 1362.

Contemporaneous annals simply state that the district as a whole was laid waste but later annals indicate that the entire population of about 30 farms at the foot of the volcano perished in the eruption (Figure 5). Recent re-examination of the deposits has revealed that several pyroclastic flows and surges where generated at the beginning of the eruption (Höskuldsson and Thordarson, 2007), possibly supporting the annals' information that nobody survived. These recent studies have therefore revealed that pyroclastic flow deposits are common in historical plinian and subplinian eruptions in Iceland.

Although pyroclastic flows can be the most devastating and deadly hazard in explosive eruptions, the probability of such events reaching inhabited areas in Iceland is low. The highest probability of this occurring applies to Snæfellsjökull, Eyjafjallajökull and Öræfajökull. Although the Holocene eruption frequency of these volcanoes has been quite low (eruption interval of order 1000 years) this threat cannot be ignored.

Lava flows

Postglacial lava flows cover large parts of the volcanic zones. Many of these are 8000–10000 year old, formed in a surge of activity following the deglaciation at the end of the Weichselian glaciation (e.g. Maclennan *et al.*, 2002). This includes the large lava shields which have volumes ranging from 1 to 20 km^3 (Rossi, 1996; Gudmundsson, 2000). Lava flows formed in historical times (Figure 6) cover 3300 km^2. Small volume lavas are confined to the volcanic systems and central volcanoes, while the larger volume lavas can flow for tens of kilometers away from the source into areas outside the active volcanic zones (Thordarson and Larsen, 2007). The rate of advance of lava is relatively slow except close to vent or for lava formed at very high eruption rate. Risk of fatalities in effusive eruptions is therefore low. Property loss has been frequent in Icelandic effusive eruptions, especially when eruption occurs close to inhabited areas. Examples of loss of property are the Eldgjá eruption in 934, the Hekla eruptions, in particular the eruption of 1389, the Laki eruption in 1783, the Mývatn fires in 1724–29 and the eruption of Heimaey in 1973 (Landnámabók, 1968; Thorarinsson 1967, 1979; Einarsson, 1974). Hazard of future effusive eruptions flowing into populated areas in Iceland is relatively high and increasing considering the growing population of the island; of special concern are the southern suburbs of Reykjavík, Grindavík on the Reykjanes Peninsula, the town of Heimaey, the Mývatn district and the populated lowland around Snæfellsjökull.

Jökulhlaups

The most common hazards related to volcanic and geothermal activity in Iceland are frequent jökulhlaups, the majority coming from the glaciers of Vatnajökull and Mýrdalsjökull (Katla) (Figures 2 and 7). Most of these events are water flows although they may often carry a heavy load of sediments and sometimes ice blocks (e.g. Tómasson, 1996) and unless otherwise stated the term jökulhlaup is here used for such flows. However, occasionally the floods may be lahars (hyperconcentrated or debris flows). In historical times substantial jökulhlaups have originated in the central volcanoes or associated fissure swarms of Grímsvötn, Katla, Öræfajökull, Bárðarbunga, Eyjafjallajökull, Þórðarhyrna and the subglacial geothermal area of Skaftárkatlar in northwest Vatnajökull (e.g. Thorarinsson, 1958, 1974b; Björnsson, 2003; Tómasson, 1996; Larsen, 2000; Ísaksson, 1984; Gudmundsson *et al.*, 2005; Gröndal and Elefsen, 2005). Two main types of volcano-related jökulhlaups occur. Firstly, where the meltwater is produced in volcanic eruptions by release of thermal energy from rapidly cooling volcanic material as in Katla 1918 and Gjálp 1996. Secondly, where subglacial geothermal areas continuously melt the ice, the meltwater accumulates in a subglacial lake and is then drained at semi-regular intervals when lake level exceeds some critical value (Björnsson, 2003). This latter type tends to be smaller and is much more common. Jökulhlaups also occur from ice-dammed lakes without any volcanic involvement. These are usually much smaller than jökulhlaups due to subglacial volcanic eruptions and will not be considered further here.

The Katla jökulhlaups have been preceded by earthquakes 2–10 hours before the floodwater emerges from the glacier (Safn til sögu Íslands, 1907–1915; Gudmundsson *et al.*, 2005). A large Katla jökulhlaup as in 1918 may reach peak discharge of

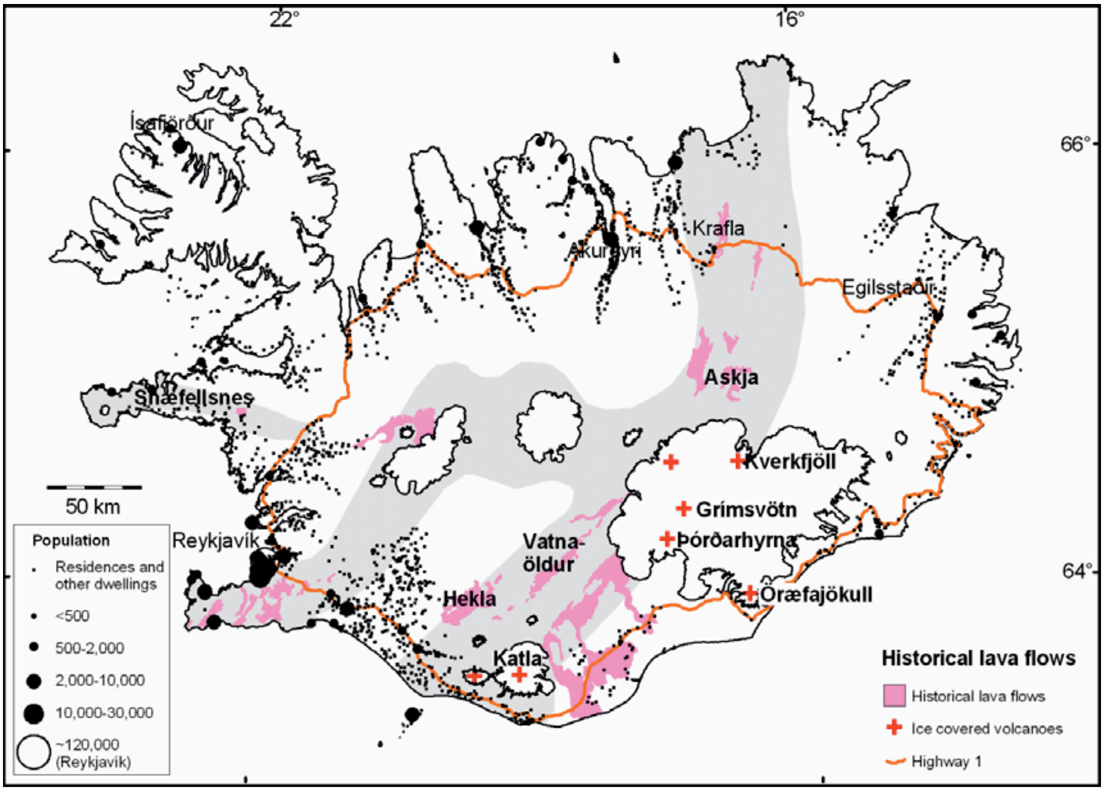

Figure 6. Historical lava flows in Iceland (age less than 1130 years). The volcanic zones are shown with a shade of gray. – *Hraun sem runnið hafa á Íslandi á sögulegum tíma (á síðustu 1130 árum).*

300,000 m^3/s and inundate an area of 600–800 km^2 to the east of the volcano (Tómasson, 1996; Larsen, 2000). The short warning time puts severe strain on civil defence authorities as only about 1–1.5 hours are available to close roads and evacuate areas potentially at risk. Recent studies (Smith, 2004; Larsen *et al.*, 2005) show that during the Holocene, large Katla jökulhlaups have on average flowed towards the west once every 500–800 years. Simulations indicate that a westward flowing jökulhlaup of the same magnitude as the 1918 jökulhlaup would inundate an area of 600 km^2 with a population close to 600 (Elíasson *et al.*, 2007). Water depths exceeding 1 m and flow velocities >1 m/s are predicted over most of the populated part of the inundated area. Jökulhlaups from Katla issued directly towards the south around the time of settlement some 1100 years ago. The onset of a Katla eruption therefore calls for evacuation of a large area on both the west and east side of the volcano, and over a limited area on its south side. Figure 8 shows the results of simulations of propagation times and inundation areas for jökulhlaups towards the west, south and east. The great hazard posed by Katla has led to special monitoring with seismometers, continuously recording GPS, radio-linked river gauges, regular airborne radar profiling and inspection flights of the ice cap (e.g. Gudmundsson *et al.*, 2007). Most of these data can be viewed in real time on the internet through the web-pages of the Icelandic Meteorological Office, the Hydrological Survey and the Institute of Earth Sciences, University of Iceland.

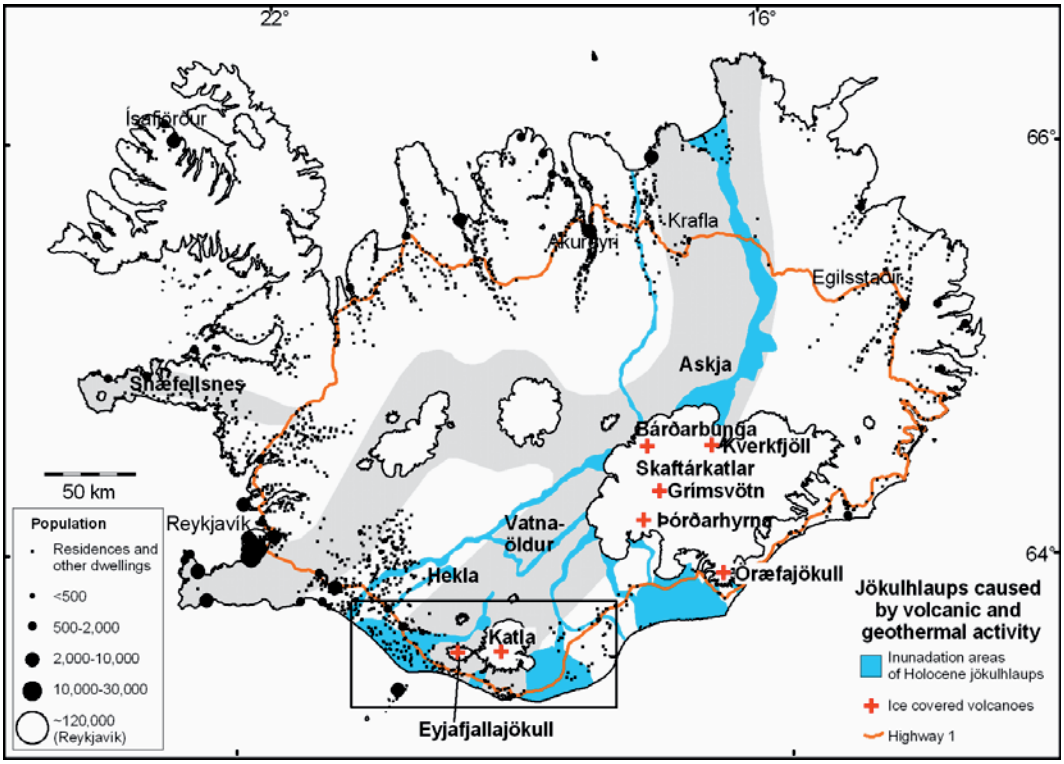

Figure 7. Areas affected by jökulhlaups attributed to volcanic activity in Iceland during the Holocene. Over the last 1130 years the most severely and frequently impacted areas have been Mýrdalssandur east of Katla and Skeiðarársandur, southeast of Vatnajökull. The box indicates the area shown on Figure 8. The volcanic zones are shown with a shade of gray. – *Svæði sem jökulhlaup hafa farið yfir á Íslandi á síðustu 10.000 árum. Síðan land byggðist hafa stór hlaup einkum farið um Skeiðarársand og Mýrdalssand.*

Jökuhlaups from Grímsvötn are either geothermal or eruption-induced, with the latter type usually being much larger but less frequent. A frequent size of geothermal jökulhlaups in the latter half of the 20th century was 1,000–10,000 m^3/s (Gudmundsson *et al.*, 1995) while the jökulhlaup caused by the Gjálp eruption in 1996 reached 45,000 m^3/s (Björnsson, 2003). The high frequency of Grímsvötn jökulhlaups has made Skeiðarársandur, the pathway of the jökulhlaups, uninhabitable. Volcanic jökulhlaups may, however, overflow and damage Highway 1 and in that way block the main transportation route in southeast Iceland. Smaller jökulhlaups caused by geothermal activity can issue from various places in the western part of Vatnajökull and Mýrdalsjökull (Katla) but these are usually relatively minor. The eruptions in Öræfajökull in 1362 and 1727 caused jökulhlaups or lahars that swept down the steep slopes of the volcano and issued from outlet glaciers. The 1727 floods claimed three lives, one of the surprisingly rare recorded fatalities associated with jökulhlaups (Thorarinsson, 1958). In the 1362 eruption, major jökulhlaups occurred, perhaps partly caused by fallout or density currents of hot tephra on glaciers in the steep mountain slopes. These may have played an important role in destroying the district around Öræfajökull volcano, formerly known as Litla Hérað.

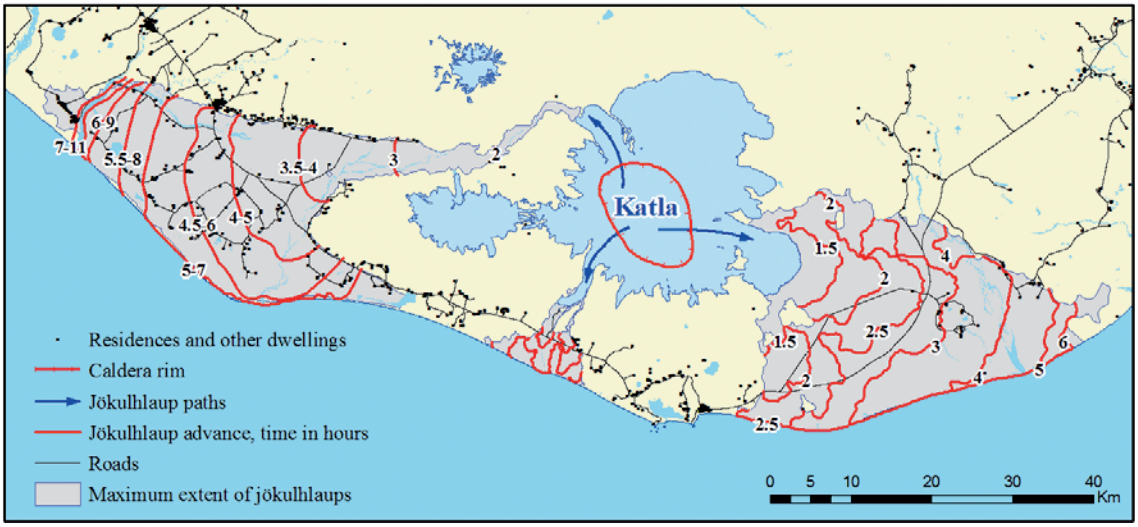

Figure 8. The inundated areas and predicted propagation times for jökulhlaups of peak discharge 250,000–300,000 m^3/s arising from eruptions within the ice-covered Katla caldera. Although jökulhlaups from all three outlets are shown on the map, the probability of major floods issuing during the same eruption down more than one of the three flood routes is small. – *Útbreiðslusvæði og reiknaðir útbreiðslutímar jökulhlaupa vegna eldgosa innan Kötluöskjunnar. Á myndinni eru sýnd þrjú tilfelli (hlaup um Kötlujökul, Entujökul og Sólheimajökul). Gert er ráð fyrir hámarksrennslinu 250.000–300.000 m^3/s í hverju tilfelli. Líkur á að hlaup af þessu tagi komi fram á fleiri en einum stað á sama tíma eru hverfandi.*

Other hazards

Hazards not listed above include earthquakes, faulting, damming of rivers by lava flows or tephra, and tsunamis. These events can be regarded as infrequent or minor compared to those discussed earlier. Seismic activity associated with eruptions is usually not of sufficient magnitude to be the cause of major damage although the seismic precursors are one of the most important warning signs of an imminent eruption (e.g. Einarsson, 1991b; Gudmundsson *et al.*, 2005). Since eruptions sometimes occur during major rifting episodes, faulting may damage roads and buildings. The large fissure eruptions of Vatnaöldur in 870 AD and Veiðivötn in 1477 AD caused damming of the river Tungnaá and subsequent flooding (Larsen, 1984). Minor tsunamis have occurred, related to jökulhlaups from Katla and Grímsvötn (e.g. Thorarinsson, 1975). These events were somewhat delayed in relation to the floods, suggesting that they resulted from submarine slumping of unstable sediments carried to the ocean by the floods.

DAMAGE AND LOSS DUE TO VOLCANIC HAZARD

There is evidence to suggest that weather-related events (storms, blizzards, heavy seas, snow avalanches etc.) have claimed the largest number of lives of any hazards in Iceland (Jóhannesson, 2001). In comparison, the volcanic death toll is considerably smaller. However, when it comes to the potential severity of single events, the largest volcanic eruptions (e.g. Laki 1783, Öræfajökull 1362) dwarf events caused by other natural hazards. The prospects for fatalities in volcanic eruptions have, however, changed considerably over the last 100 years or so. The main reason for fatalities in conjunction with volcanic eruptions in Iceland has been famine caused by crop failure or loss of livestock as a result of tephra fallout and fluorine poisoning (Table 3). By far the most severe recorded event was the famine in 1784–1785 following the Laki eruption. Records are incomplete but other eruptions where contemporary sources indicate famine include the Hekla eruptions of 1104 and 1300, and famine is also suspected for the Eldgjá eruption in 934. Major loss of livestock is recorded for eruptions from Hekla in 1510, 1693 and 1766–68 (Thorarinsson, 1974a). The total loss of life cannot be estimated with any accuracy from pre-18th century records, but the number of fatalities is probably well over 10,000. Major loss of life is suspected for the Öræfajökull 1362 eruption. However, confirmed fatalities from reasons other than post-eruption famine are surprisingly few. Only two fatalities occurred in the 20th century (Jóhannesson, 2001) despite the Heimaey eruption in January 1973 when the volcanic fissure was located just 200 m east of the town with over 5000 inhabitants. Had the fissure opened up 500 m further to the west, considerable loss of life would have been unavoidable.

Although post-eruption famine is a remote prospect today, damage to infrastructure and the economical consequences of eruptions can be severe for a nation of only 300,000 people. Roads, communication and power lines cross known floodpaths of major jökulhlaups from Grímsvötn and Katla and geothermal power plants can by necessity be located on or immediately adjacent to central volcanoes. Some losses are therefore inevitable in the future as in the past. The economic losses resulting from volcanic eruptions since 1970 are outlined in Table 4. These are minimum estimates since any loss to private and public businesses due to inconveniences caused by these events are not listed and neither are costs due to rerouting of aircraft during eruptions. The total loss due to volcanic events over the last 37 years amounts to approximately 180 million euro or about 5 million euro on average per year. Two events stand out, the Heimaey eruption in 1973 and the accumulated loss in production in the Krafla power plant.

DISCUSSION

During medieval times and the Little Ice Age, the community in Iceland was poor and relied mostly on subsistence farming. Hence, loss of life due to famine as a result of volcanic eruptions could be very severe as outlined above. Considering the technological and economical advancement over the last 100 years, such fatalities are extremely unlikely in present-day Iceland. Moreover, the increasingly sophisticated warning systems, notably the real time seismic network, hold great prospects of advance warning for most volcanic eruptions. Infrequent, high magnitude events, such as the Öræfajökull eruption of 1362 could today, as in 1362, nevertheless cause major damage and loss of life if affected areas could not be evacuated in time. The opening of a volcanic fissure within a town, as almost happened in Vestmannaeyjar in 1973, could have catastrophic consequences. With increased tourism, active volcanoes that often have erupted explosively in the past have become popular destinations for hikers and other travellers. Hekla in particular, has erupted every 10 years over the last 40 years and is infamous for the very short duration of seismic precursors prior to eruptions. Therefore the prospect of fatalities in the beginning subplinian phase of a future Hekla eruption are rising.

The prospects for severe loss of property and other economic damage are considerable. Moderate effusive eruptions on the Reykjanes peninsula, as occurred several times in the 10th–13th century AD (Table 1) can in future produce lava flows that can reach the shore on either side of the peninsula. Hundreds of residential homes, key transportation routes and important industrial estates could be lost as a result. Awareness of this potent threat, together with appropriate planning and location of future residential and industrial areas is essential to minimise this risk. Similar arguments apply to pathways of past catastrophic jökulhlaups west of Katla. Sensible planning of areas close to the Katla volcano is the key issue to minimize risk to life and limit economic damage. In the case of future eruptions of Katla the loss of parts of Highway 1 is anticipated as well as possible damage to components of communication and power transmission systems from lightning.

Table 3. Fatalities due to eruptions in Iceland – *Dauðsföll vegna eldgosa á Íslandi.*

Volcano	Year	Fatalities during eruption	Fatalities after eruption	Comments
1500 AD – present				
Eldfell	1973	**1**	–	Gas poisoning - drowning in CO_2 filled cellar (1)
Hekla	1947	**1**	–	Scientist killed by collapsing front of advancing lava (2)
Grímsvötn	1860	**1**	–	Drowning in water filled kettle hole after a jökulhlaup (3)
Laki	1783	–	<8700*	Famine after decimation of livestock. Population reduction of 10,500 in 1783–86, partly due to epidemics and reduced birth rate
Katla	1755	**1**	–	Struck by lightning 35 km from volcano (4)
Öræfajökull	1727	**3**	–	Drowning in lahar/jökulhlaup (5)
Grímsvötn	1684	**1**	–	Drowning in jökulhlaup (3)
Grímsvötn	1629	**4+**	–	Drowning in jökulhlaup (3)
Hekla	1510	**1**	–	Probably caused by impact injuries during tephra fall (2)
Pre–1500 AD record highly uncertain				
Öræfajökull	1362	50–300?	?	Pyroclastic flows, jökulhlaups, tephra fallout. Death toll not mentioned in contemporary annals – later records indicate total annihilation of 30 farms (5)
Hekla	1300	–	>500	Famine after decimation of livestock in parts of N-Iceland according to annals (6)
Hekla	1104	?	?	Largest eruption of Hekla - destruction of farmland – no confirmed fatalities – likely cause of famine in parts of N-Iceland (6)
Eldgjá	934	?	?	Largest eruption in last 1130 years. No contemporary records - infighting and slaying among chieftains deprived of land by consequences of the eruption (7)
Total	1500 – present 900 – 1500	**14** (100–300)	<8700 > 500	Reliable record Indirect evidence and annals - no contemporary records exist of the effects of the Eldgjá 934 and Hekla 1104 eruptions

*During the years 1780–1783 about 1500 people died annually by natural causes (Hálfdánarson, 1984) while in 1785–1787 about 8700 more people died than the 1780–1783 average annual death rate predicts. Part of the 1785–1787 death toll was due to epidemics. (1) Einarsson (1974); (2) Thorarinsson (1967); (3) Thorarinsson (1974b), (4) Thorarinsson (1975); (5) Thorarinsson (1958); (6) Thorarinsson (1974a); (7) Landnámabók (Book of settlement) (1968).

In the case of a major flood basalt eruption such as Laki 1783, severe economic impact could result, in Iceland and Northern Europe, since air traffic could be halted for months in Northern Europe and over the North Atlantic (Thordarson *et al.*, 1996) due to high concentration of sulphur in the atmosphere. Further, the high concentration of sulphuric acid in the air could have severe effects on modern society. In 1783 paintings changed colours and today various delicate electrical instruments might be affected, decreasing the effectiveness of modern societies. In 1783 problems due to inhaling the sulphuric polluted air caused premature deaths. Today's societies have much higher population densities and illness and fatalities might arise from the pollution caused by such an eruption, putting severe strain on healthcare systems in both Iceland and elsewhere in Northern Europe.

Major explosive eruptions, similar to the VEI 6 eruption of Öræfajökull in 1362 AD, are likely to deposit tephra over large parts of Iceland. In such a case

Table 4. Major damages and financial losses (2007 prices) due to volcanic activity in Iceland 1970–2007. – *Tjón vegna eldgosa á árunum 1970–2007 í evrum á verðlagi ársins 2007.*

Eruption	**Type**	**Damage**	**Cost** Million euros
Hekla 1970	Tephra fallout/ fluorine poisoning	Up to 8000 sheep killed by fluorine poisoning in NW-Iceland (1)	1–2
Heimaey 1973 (Eldfell)	Lava flow-tephra fallout	Approximately 400 buildings destroyed (buried in lava and tephra) in the town of Vestmannaeyjar. (2)	80
Krafla 1975–84	9 small effusive eruptions	Disrupted construction of a geothermal power plant. Full production delayed by two decades (3)	70
Gjálp 1996	Volcanically induced jökulhlaup	Destruction of bridges, power lines and sections of the main road between south and east Iceland (4)	25

(1) Thorarinsson (1970); (2) Björnsson (1977); (3) Electricity price of 0.02 USD/kWh is used to calculate lost revenue due to loss of production of 240 GWh/year over a 20 year period; (4) Icelandic Road Authority.

the greatest damage to manmade structures, crops and vegetation would presumably occur within 70–80 km from the volcano, within the 20 cm isopach. However, the consequences of such tephra fall could be widespread and long-lasting due to the presence of glassy ash particles in the environment, ranging from health problems due to contamination of air and water to problems related to mechanical abrasion.

Global warming over the next several decades may over the next 100–200 years lead to rapid retreat and removal of most of the ice mass presently stored in glaciers in Iceland. Such rapid changes give rise to isostatic rebound and the reduction in ice load on the presently ice-covered volcanoes may lead to instabilities in underlying magma chambers and give rise to increased volcanic activity in Iceland (Pagli and Sigmundsson, 2008). Both theoretical models of lava production and the eruption history of the Holocene indicate that de-loading caused a major peak in volcanism and lava production in Iceland at the end of the last glaciation (e.g. Maclennan, 2002). It is possible that similar events but at a smaller scale may happen as a result of the anticipated shrinkage of Vatnajökull. As a consequence, temporal increase in volcanic hazard may result. On the other hand, if this scenario of rapidly disappearing ice cover comes to reality, in the long run it should lead to fewer eruptions under glaciers and reduced jökulhlaup hazard.

SUMMARY AND CONCLUSIONS

1. Volcanism has claimed thousands of lives in Iceland over the last 1130 years. The most common cause of fatalities has been famine caused by poisoning and decimation of crops and livestock.
2. Volcanic eruptions are common, occurring every 3–4 years. Eruptions of volume 1 km^3 DRE occur on average once every 50–100 years, and of volume >10 km^3 once every 500–1000 years.
3. Explosive eruptions are more common than effusive, mainly due to the large number of phreatomagmatic eruptions. VEI 5 eruptions occur once every 100–200 years and VEI 6 eruptions once every 500–1000 years.
4. Jökulhlaups are the most common hazard related to volcanism, but tephra fallout and lava flows are also significant and frequent. Pyroclastic flows and lightning may pose a threat in some eruptions.
5. The most serious volcanic events to be expected in Iceland are (i) major flood basalt eruptions such as the Laki eruption of 1783 causing widespread pollution and disruption to transport in a large region around the North-Atlantic; (ii) VEI 6 plinian eruptions with major pyroclastic flows and fallout of tephra, and (iii) an eruption at Katla causing a catastrophic jökulh-

laup towards west, over a large populated area. All these events have recurrence times of 500–1000 years.

6. Prospects for fatalities in moderate-sized explosive eruptions are increasing due to increasing numbers of hikers and tourists on the slopes of volcanoes.

Acknowledgements

T. Högnadóttir prepared the figures. Research on jökulhlaups from Katla was supported by a special grant from the Icelandic Government, and research on the Öræfajökull 1362 eruption has been supported by the Kvísker Fund. This paper benefitted from reviews by Jennie Gilbert and an anonymous reviewer.

ÁGRIP

Vá vegna eldgosa á Íslandi

Í greininni er fjallað um vá af völdum eldgosa á Íslandi en þau verða að meðaltali á þriggja til fjögurra ára fresti. Tiltölulega lítil eldgos þar sem heildarmagn gosefna (mælt sem fast berg) er minna en 0,1 km^3 verða að jafnaði með 4–5 ára millibili en stærstu flæðigos eins og Skaftáreldar 1783 eða Eldgjá 934 (magn gosefna meira en 10 km^3) verða á 500–1000 ára fresti. Basísk eldgos eru lang-algengust en þrátt fyrir það eru sprengigos fleiri en flæðigos. Ástæðan er fjöldi gosa í jöklum þar sem utanaðkomandi vatn veldur myndun gjósku við tætingu kvikunnar. Í stærstu sprengigosum sem þekkt eru á Íslandi (t.d. Öræfajökulsgos 1362 og Veiðivatnagos um 1477) hafa komið upp um og yfir 10 km^3 af gjósku en slík gos verða einu sinni til tvisvar á hverju árþúsundi. Þegar borin er saman tíðni hættulegra atburða af ýmsu tagi sem eldgos valda á Íslandi, kemur í ljós að jökulhlaup eru langtíðust. Hinsvegar hafa gjóskufall og flúoreitrun hvað eftir annað valdið skepnufelli og hungursneyð komið í kjölfarið. Allt að 8500 manns fórust í hungursneyðinni eftir Skaftárelda, nokkur hundruð dóu af sömu orsökum eftir Heklugos árið 1300 og talið er sennilegt að svipað hafi gerst í fleiri gosum, t.d. eftir Heklugosið 1104 og Eldgjárgosið 934, þó heimildir séu fáorðar. Þeir atburðir sem talið er að geti valdið mestu tjóni hér á landi eru: (1) Stórt hraungos svipað Skaftáreldum 1783, (2) stórt sprengigos eins og Öræfajökulsgosið 1362 sem talið er að hafi eytt Litla Héraði, sveit þar sem voru um 30 bæir fyrir gosið, og (3) stórt gos í Kötlu sem ylli hamfarahlaupi niður Markarfljót og Landeyjar. Endurkomutími allra þessara atburða er svipaður, um 500–1000 ár. Ef frá er talið Öræfajökulsgosið 1362, þar sem sterkar líkur eru á að fjöldi manns hafi farist þegar heit gjóskuflóð flæddu yfir byggðina, hafa tiltölulega fáir farist í sjálfum eldgosunum. Efnahagsleg áhrif eldgosa geta verið veruleg. Þó svo engin stórgos hafi orðið á síðustu fjórum áratugum má meta fjárhagslegt tjón vegna eldvirkni á þessu tímabili á um 15–20 milljarða króna á verðgildi ársins 2007. Sumir þéttbýlisstaðir innan virka gosbeltisins eru berskjaldaðir fyrir hraunrennsli ef gos kæmi upp í nágrenni þeirra. Þannig hagaði til á Heimaey 1973 þegar meðalstórt eldgos kaffærði stóran hluta Vestmannaeyjarbæjar í gjósku og hrauni. Telja verður að líkur á manntjóni í litlum og meðalstórum sprengigosum fari vaxandi vegna aukinna vinsælda gönguferða á eldfjöll sem gosið geta með skömmum fyrirvara, einkum Heklu. Sjálfvirk eftirlitskerfi sem einkum byggjast á jarðskjálftamælum hafa á síðustu árum sannað gildi sitt með því að nema skammtímaforboða og vara þannig við eldgosum skömmu áður en þau hefjast. Slík eftirlitskerfi mun án efa gegna lykilhlutverki í að draga úr hættu á slysum í eldgosum í framtíðinni.

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