ANNAL OF MAGMATIC EVENTS IN ICELAND 1900-2010

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Introduction

This annal is compiled in order to facilitate the use of the Icelandic Analog Seismograph Archive (seismis.hi.is) for the studies of magmatic events in the crust of Iceland. Both confirmed eruptions and unconfirmed events are listed, but in separate chapters. A large part of the information on the activity of Icelandic volcanoes is difficult to access. A good part of it is assembled in the books and publications of Sigurður Þórarinsson, notably his treatises of Hekla (Þórarinsson 1967), the Vatnajökull region (Þórarinsson 1974) and Katla (Þórarinsson 1975). The rest is scattered throughout the literature, to a large extent in Icelandic, and inaccessible to researchers elsewhere. Recent overviews are provided in the book „Náttúruvá" (Sólnes et al., 2013) and on the webpage of the Catalog of Icelandic Volcanoes (icelandicvolcanos.is). An overview of short-term seismic precursors of Icelandic eruptions is given by Einarsson (2018).

Terms and definitions

Volcanological terms used in Iceland may in some instances deviate from the ones used in other areas. This results from the somewhat special circumstances of a subaerial divergent plate boundary. Volcanic structures are exposed on the surface that are usually submerged by ocean and the volcanism often is of areal extent. Walker (1993) used the term central volcano to describe areas of intense volcanism in the Tertiary lavas of Eastern Iceland and found them to be associated with dyke swarms. He used the term volcanic system for the structural unit consisting of a central volcano and associated dyke swarms. Saemundsson (1974) pointed out that the present-day equivalents of the dyke swarms were the fissure swarms commonly found in the neovolcanic zones and defined the active volcanic systems of the volcanic rift zone in Northern Iceland accordingly. Later, using the same criteria, he defined the volcanic systems of the whole neovolcanic zone of Iceland (Saemundsson, 1978). Jakobsson (1979a) established petrological characterisics of most of the systems of South and Central Iceland and showed that they could be distinguished by the chemical composition of their products. Johnson and Jakobsson (1985) defined the systems offshore Reykjanes.

For clarification we define these terms as follows:
Central volcano is an area of high volcanic productivity, often of basaltic composistion. Central volcanoes are also often associated with the production of rocks with high silca content such as rhyolite and dacite. A central volcano may have one or more calderas and geothermal systems. *A fissure swarm* is a collection of many similar, parallel or subparallel fissures and normal faults occurring in a limited area. A *volcanic system* is a structural and petrological unit consisting of a central volcano and associated fissure swarms.

We note that there is overlap between these terms and terms used elsewhere. The Hawaiian term *rift zone*, e.g. is almost synonymous with our term *fissure swarm*. Also, our term *volcanic system* is in some cases similar to the term *ridge segment* used for structural units on the mid-ocean ridges.

Different authors have used different definitions for volcanic systems of Iceland and there is considerable confusion in the literature regarding names. In this paper we follow the classification of Einarsson and Saemundsson (1987) which is widely referenced.

Holocene volcanic systems in Iceland

Most of the volcanic systems in the Iceland area are directly related to the mid-Atlantic plate boundary that crosses the area (Fig. 1). The boundary is segmented. Off shore the two segments approaching from the south and north are the Reykjanes Ridge and the Kolbeinsey Ridge, respectively. The are linked to the main divergents segments on land by two oblique rifts, The Grímsey and Reykjanes Peninsula Oblique Rifts. The main divergent segments on land are the Northern Volcanic Zone in North Iceland and the sub-parallel Eastern and Western Rift Zones in the south. Off-rift or volcanic flank zones are the Snæfellsnes Flank Zone in West Iceland, the Öræfajökull-Snæfell Flank Zone in Eastern Iceland, and the South Iceland Flank Zone. All together these zones contain about 45 volcanic systems, see following table.

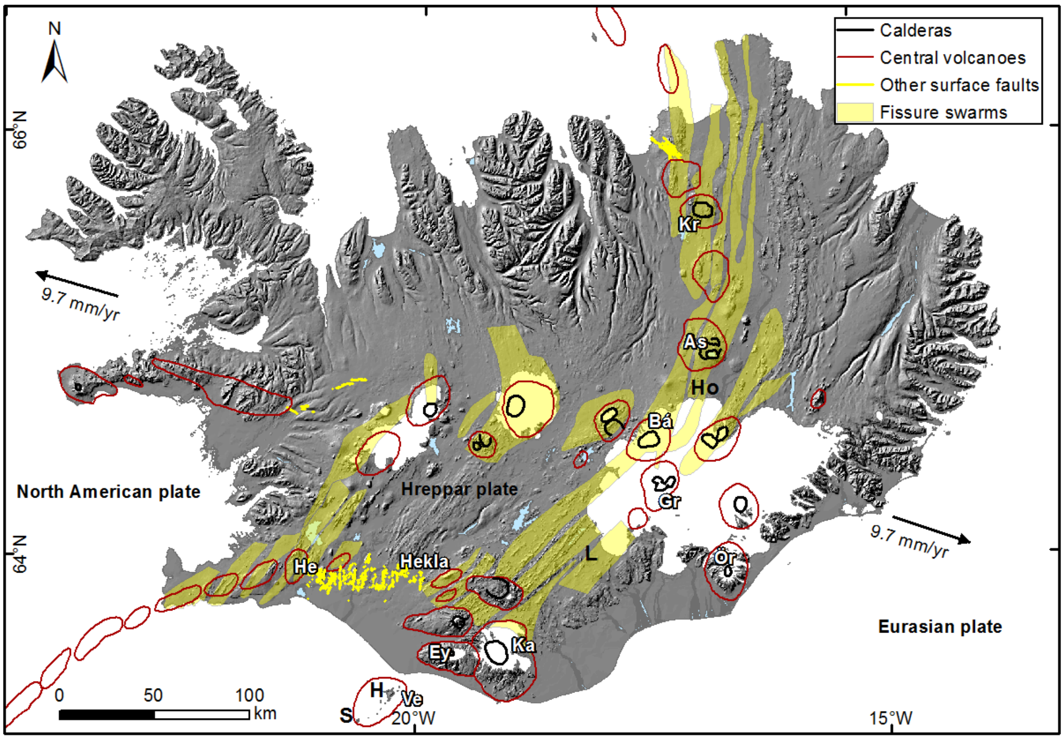

*Fig. 1. A map showing the neo-volcanic zones of Iceland and the active volcanic systems: **Kr** Krafla, **As** Askja, **Bá** Bárðarbunga, **Gr** Grímsvötn, **Ör** Öræfajökull, **Hekla**, **Ka** Katla, **Ey** Eyjafjallajökull, **Ve** Vestmannaeyjar, **He** Hengill. Eruption sites are also shown: **Ho** Holuhraun, **H** Heimaey, **S** Surtsey. From Einarsson (2018).*

		Characteristics	Last eruptions
Reykjanes Ridge			
Eldey	**63°44´**	Tholeiite, picrite	(1926)
Geirfuglasker	**63°42´**	Tholeiite, olivine tholeiite	1879, (1884)
(No name)	**63°38´**	Tholeiite	
(No name)	**63°32´**	Tholeiite	1830
Eldeyjarboði	**63°28´**	Tholeiite	(1970)
Brandur	**63°21´**	Tholeiite	
Hraunhóll	**63°16´**	Tholeiite	1783
Steinahóll	**63°05´**	Tholeiite	
Reykjanes Peninsula Oblique Rift			
Reykjanes		Tholeiite, olivine tholeiite, picrite	about 1226
Krísuvík			1151
Brennisteinsfjöll			1240
Hengill			2 ky. ago
Hrómundartindur			early Holoc.
Western Rift Zone			
Laugarvatn - Tindaskagi		(not well defined)	early Holoc.
Prestahnúkur			Holocene
Langjökull			?2 ky ago
Hofsjökull			Holocene
Eastern Rift Zone			
Bárðarbunga-Veiðivötn			1996, 2014-15
Grímsvötn-Laki			1998, 2004, 2011
Loki-Fögrufjöll			(2000, 2014)
Tungnafellsjökull			Holocene
(Hágöngur)			
Hamarinn			(2011)
Northern Rift Zone			
Kverkfjöll			
Askja			1961
Fremrinámar			
Krafla			1975-84
Þeistareykir			
Grímsey Oblique Rift			
Mánáreyjar			1867
Nafir			
Hóll			

Stóragrunn
Kolbeinsey

South Iceland Flank Zone

Hekla	andes., bas. andesite, acidic, trans. alk. bas.	1991, 2000
Vatnafjöll	trans. alk. basalt	1 ky ago
Torfajökull	rhyolite	about 1480
Tindfjöll	trans. basalt, interm.- rhyolite	early Holoc.
Katla	trans. alk. basalt, interm.- rhyolite, high Ti	1918, (2011)
Eyjafjöll	basalt - basaltic andesite - acidic	1821-23, 2010
Vestmannaeyjar	alk. ol. basalt, bas. andes. (hawaiites)	1963-67, 1973

Snæfellsnes Flank Zone

Snæfellsjökull		about 200 CE
Lýsuhóll		
Ljósufjöll		about 900 CE

Öræfajökull-Snæfell Flank Zone

Öræfajökull		1362, 1727
Esjufjöll		(1927)
Snæfell		early Holoc.

Monitoring ways and means

Great change in the possibilities during the century, the threshold of detection is lowered throughout the period.
1920ies, first seismographs, although insensitive, gave an indication of the activity.
1940ies, availabilty of aircraft, flying over the inaccessable interior parts of the country.
1970ies, great increase in the number of sensitive seismographs.
1985, installation of the telemetered seismograph network in the interior.
1990, installation and growth of the sophisticated, digital seismic network.
2010, seismographs entirely digital.
More details are given by Einarsson and Björnsson (1987) and Einarsson (2018).

Annal of activity 1900-2010

CONFIRMED ERUPTIONS

1902 **Dyngjuháls** (probable location). About the middle of December fire was seen from North Iceland in the direction of western Vatnajökull (Þórarinsson 1974). During the same days floods occurred in the rivers Skjálfandafljót and Jökulsá á Fjöllum and ferries on both rivers were destroyed. Ash was detected in the wool of sheep in Eastern and Southern Iceland. This evidence points to an eruption and its most probable location is in and near a glacier and on the water divide between the two rivers. This strongly suggests the Dyngjuháls area of the Bárðarbunga volcanic system. Many short eruptive fissures are known in this area but it is not known which one was active in this eruption, which was probably rather insignificant.

1903 **Þórðarhyrna.** A jökulhlaup in the river Skeiðará began on May 25 and increased rapidly over the next few days. The increase was particularly rapid on May 28 and was then accompanied by thumps and cracking noises which is rather unusual for floods in Skeiðará. Rivers on the western part of the Skeiðarársandur plain also flooded on May 28. The flood was mostly over by May 31. An eruption was detected on May 28. Its origin appeared to be near Þórðarhyrna. It was accompanied by considerable tephra airfall, most on May 28 and 29, that was carried to the NE. Þórarinsson (1974) estimates the volume of ash as 100 Mm^3. Activity was noticed for at least 7 ½ months. Some of it may have occured in the Grímsvötn area as well (Jóhannesson 1983).

1910 **Loki Ridge, E Cauldron.** An eruption in W Vatnajökull was most likely located on the Loki Ridge. Ash fell in several places around the country, first on June 18 in S-Iceland, in August in S-Iceland, in particular on the 15th, on September 21-22 in E-Iceland, and during the 12 last days of October in S- and W-Iceland. No jökulhlaups were documented this year. Þórarinsson (1974) concluded that the eruption place was west of Grímsvötn, near Hamarinn. A painting showing an eruption column indicates that the eruptive activity took place at the Eastern Skaftá Cauldron on the Loki Ridge (Jónsson 1986).

1913 **Hekla system.** An eruption began on a 2 km long fissure at Mundafell, some 6 km east of Hekla on April 25, preceded by vigorous earthquake activity. About 10 hours later another eruptive fissure, about 4 km long, opened up at Lambafit, 12 km NE of the first one. Both fissures produced basaltic lava with only minor ash. The first fissure ceased erupting on May 4, the second one a fortnight later (Thorarinsson 1970). The lavas were 3.8 and 6.3 km^2 in area, respectively.

1918 **Katla.** A large, explosive, basaltic eruption began on October 12 and lasted for about three weeks (Sveinsson, 1919, Jóhannsson, 1919).The eruption site was near the SE rim of the caldera, beneath about 400 m of ice. The eruption was preceded by felt earthquakes that began about 13 h. An eruption column was seen from the nearby village Vík about 2 hours later and at about the same time a flood wave of meltwater mixed with ice, ash and debris was seen emanating from the glacier and crossing the alluvial plain SE of the volcano and flowing towards the sea at a speed of about 10 m/s (Tómasson, 1996). A small tsunami was generated when the flood entered the ocean. It propagated along the coast to the west but did not cause damage. The initial eruption column height was estimated 14 km. The ash was carried to the NE during this initial phase (Þórarinsson, 1975, Larsen, 2000). The eruption intensity diminished significantly and the flood was almost over after the first day. The intensity of the eruption again increased on October 22, remained high for a couple of days and then gradually diminished until the eruption faded away on November 3-4. Ash was carried mainly to the NE and S during this time and was coarser than during the first day. Intense lightning was associated with the eruption column during the whole eruption. The flow rate of the intial flood has been estimated to be 100-300.000 m^3/s and the total water volume as high as 8 km^3 (Tómasson, 1996). The flood vained after the first day but increased again a few days later. Several minor bursts of floods were seen. A particularly large burst occurred on November 26, three weeks after the eruption ended. The floods carried enormous amount of volcanic ash into the sea and advanced the coastline by more than 4 km. This distance was reduced to 2 km when measured in the middle of the winter (Sveinsson, 1919). The Katla 1918 eruption was a large eruption but estimates of the total volume of erupted material vary. Water transported material is estimated between 0.7 and 1.6 km^3 (Larsen, 2000) and airborne tephra at 0.7 km^3 (Larsen, 1993).

1919 **Grímsvötn.** A tephra layer from this year with the chemical signatures of Grímsvötn has been found in the Vatnajökull glacier (Larsen et al. 1998).

1921 **Askja.** A series of small basaltic lava eruptions occurred within the caldera and on the south flank of Askja during the time period 1921-1929. There is some uncertainty regarding the dates of individual eruptions. We adopt the version of Thorarinsson and Sigvaldason (1962) and Þórarinsson (1963) that is similar to Einarsson (1962). The series began with a small eruption in March 1921 on the eastern caldera wall of Öskjuvatn. The lava, Bátshraun, was of insignificant volume and flowed into the caldera lake formed in the large eruption of 1875. An eruption in November 1922 west of the caldera lake produced a flow of 2.2 km^2 area, Mývetningahraun, that flowed into the lake. Assuming a thickness of 5 m we estimate a volume of 10 Mm^3. In 1922-23 two small and insignificant lava flows were formed at the SE caldera wall of Öskjuvatn. In 1926 an island of scoria, Hornfirðingahólmi, formed in the Öskjuvatn caldera lake. The volume is estimated 50 Mm^3. A lava eruption occurred on a 6 km long fissure on the S flank of the volcano, most likely in 1924 or 1929, or both. The area of the flow is 16 km^2 and the volume is estimated 100 Mm^3 (Thorarinsson and Sigvaldason, 1962). Total volume of the 1921-1929 activity is estimated 150 Mm^3.

1922 **Grímsvötn.** An eruption in the SW-corner of the caldera was accompanied by considerable ashfall. The visible eruption was preceded by a jökulhlaup that was noticed first on September 22. The flood water increased slowly for several days and culminated on October 4-5. The eruption was in progress on

October 4, but may have begun earlier, possibly as early as September 29 (Þórarinsson 1974). The eruptive activity was at its peak on October 6, then it decreased and was not detected after October 23. The ash produced in this eruption did not cause damage.

1926 **Eldey.** Submarine eruption on the Reykjanes Ridge, about 10 km off shore, was witnessed by fishermen in early June (Þórarinsson 1965). The sea boiled and dead fish was seen.

1933 **Vatnajökull.** Eruptive activity in the Vatnajökull area. Flashes and fires were seen during a 10 days period in November and December. The eruption site was most likely N of Grímsvötn and no flood water was detected (Jóhannesson 1983).

1934 **Grímsvötn.** A basaltic eruption near the SW caldera wall was preceded by a jökulhlaup and accompanied by ashfall. Three craters were active. The beginning of the eruption was accompanied by 5 earthquakes in the magnitude range 3.5-4.5 (Tryggvason, 1960, Brandsdóttir, 1984). The jökulhlaup was first detected in Skeiðará River on March 22 but in the Súla River on March 28. The flood increased slowly, culminated on March 31 and then stopped rather abruptly. A 7-8 km long section of the main telephone line across the flood plain was washed away. The Grímsvötn caldera ice shelf subsided about 150 m, water volume was estimated 7 km^3 and the peak discharge rate 40000 m^3/s (Þórarinsson 1974). The eruption was detected on March 30 (Áskelsson 1936) and appears to have had a maximum during the following night and day. Eruptive activity was seen from the inhabited areas until April 7, but was not completely over until the middle of April. Estimated ash fall is 10-20 Mm^3 (Þórarinsson 1974) and the total volume is 30- 40 Mm^3 (Guðmundsson and Björnsson, 1991)

1938 **Gjálp area.** A concealed subglacial eruption occurred north of Grímsvötn breaching the glacier surface shortly at the very end of the eruption [Björnsson, 1988; Gudmundsson and Björnsson, 1991]. A subglacial ridge, 0.3-0.5 km^3 in volume, was formed. The melting left a large depression in the ice surface. The meltwater was collected in the neighboring Grímsvötn caldera and released in a large jökulhlaup, first detected on May 23. The flood increased rather rapidly and culminated on May 26. It was considered over by June 6. A 7 km long section of the telephone line was swept away (Þórarinsson 1974). The peak discharge of some 30,000 m^3/s was reached in about 3 days, and the total water volume released in the flood was estimated 4.7 km^3 [Björnsson, 1992, Gudmundsson et al., 1995].

1947 **Hekla.** An eruption began on March 29 at 06:41 slightly north of the summit (Þórarinsson 1967, 1970). At 06:50 an earthquake of magnitude about 5 occurred. About the same time the eruption vigour greatly increased and a few minutes later the eruptive fissure had reached a length of 4 km along the crest of the main Hekla ridge. A Plinian eruption column soon reached a height of 30 km. The main tephra fallaout lasted for an hour, an estimated tephra volume of 75000 m^3/s the first half hour and 22000 m^3/s the second half hour. The total estimated tephra volum during this first phase of the eruption is 180

Mm^3. The tephra was carried to the south and was detected as far as Finland. A flood of meltwater was issued into the Rangá river following the initial Plinian phase. Many craters were active along the crest of the mountain during the first few days of the eruption, but soon thereafter most of the activity was limited to two main craters, one at the summit, the other on the western shoulder. Several small craters were also active at the western shoulder, one of them oosing out lava mostly without spattering. Lava production began during the first half hour of the eruption and after September 1947 only lava was produced. The eruption ended on April 21, 1948. The total area of new lava was 40 km^2 and the volume is estimated 800 Mm^3. The total volume of tephra is estimated 210 Mm^3. The very first lava produced was dacite (silica content 63-61%), soon changing to andesite. Towards the end of the eruption the composition had gradually changed towards that of basalt (silica content 55-54%). Large amounts of CO_2 issued from the ground west of Hekla in the spring and summer of 1948 killing sheep and birds.

1961 **Askja.** A basaltic lava eruption began on October 26, in the afternoon, from a short E-W striking fissure near the E caldera wall. Precursors to the eruptions were noticed. Geothermal activity increased in early October following a small earthquake swarm (Þórarinsson 1963, Þórarinsson and Sigvaldason, 1962, Einarsson, 1962). Steam explosions occurred on October 17 and 19. The average lava production during the first few hours was estimated 600 m^3/s and the lava flowed to the north and east, out of the caldera opening. The total volume is estimated 150 Mm^3

1963 **Surtsey.** An eruption was detected on November 14 on the ocean bottom at the southern tip of the Eastern Volcanic Zone but may have started a few days earlier (e.g. Thorarinsson et al., 1964, Thorarinsson, 1964, 1965, 1966, 1967, 1968, Einarsson, 1966). The water depth was 130 m but a new island, Surtsey, was formed the following day. Four craters were active on a 500 m long, SW-NE striking fissure. The activity gradually concentrated on one crater, Surtur I, and phreato-magmatic activity continued with little changes until the end of January 1964 when it stopped temporarily. A second eruption site was active during this first phase of the eruption, about 2.5 km ENE of Surtsey, producing a submarine ridge, Surtla, almost extending to sealevel. On February 1 a new crater, Surtur II, began erupting. Phreato-magmatic activity continued until April 4, 1964. Then the magma conduit got isolated from the sea water and the activity changed into lava effusion. A lava shield was formed during a period of lava effusion that ended in the middle of May 1965. On May 23 1965 a new submarine eruption site became active 0.6 km east of Surtsey, building an island in 5 days. The new island, Syrtlingur, had attained a an area of 0.15 km^2 and height of 70 m by September 1965. This eruption site became inactive in the middle of October and the island was eroded away in a week. No eruptive activity was spotted for 2 months, but in late December 1965 an eruption began on the ocean bottom 0.8 km SW of Surtsey. The eruption built an island, Jólnir, in about a week. By July 1966 the new island had an area of 0.4 km^2 and a maximum height of 70 m. This eruption ended on August 10, 1966 and by September 20 this new island had also disappeared. On August 19, 1966 a new eruptive fissure opened up within the crater Surtur I (see seismogram in Fig. 2). Three craters were active in the beginning but a few days later only one remained. Lava was erupted from this crater until June 5, 1967, building up a flat lava shield and extending the Surtsey island to the east. The eruptive fissure was temporarily extended to the north side of the island on January 1, 1967, producing a small patch of lava. The total volume of erupted material is estimated ~ 1000 Mm^3, all of it basaltic.

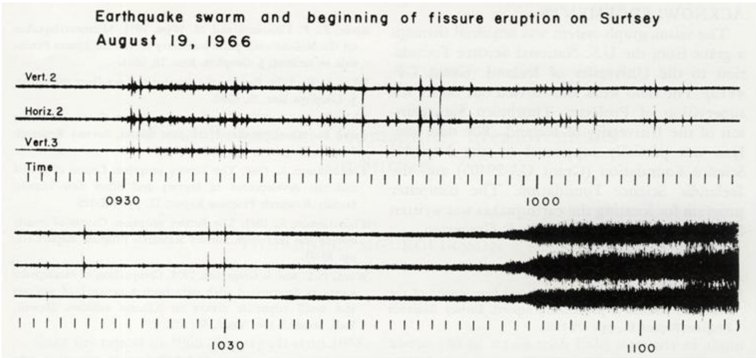

Fig. 2. Seismograms from three components of a small array operated on Surtsey island in 1966, showing the time interval 09:22 – 11:07 on August 19, when a new lava eruption broke out on the island (from Einarsson, 1974).

1970 **Hekla.** An eruption began on May 5 at 21:23, apparently simultaneously on two fissures on the S and SW flanks (Thorarinsson 1970, Þórarinsson and Sigvaldason 1972). About an hour later the third eruption site became active when a fissure opened up at Skjólkvíar on the NNE flank. The initial outbreak was preceded by a swarm of small earthquakes (M ≤ 4) that began at 20:58 (Fig. 3). The eruption column reached a height of 15 000 m during the initial phase. The tephra was carried to the NNW and caused considerable damage to lifestock in N-Iceland due to its fluorine content. Eruptive activiy ceases on the S and SW flank on May 10 and at Skjólkvíar on May 20. But later that day a new fissure opened up about 1 km farther north. This fissure was active until July 5. The 1970 lavas have an area of 18.5 km2 and volume of 200 Mm^3 (Thorarinsson 1970). The total volume of tephra is estimated 70 Mm^3. The chemical composition of the products was rather homogeneous and similar to that of the last products of the 1947 eruption.

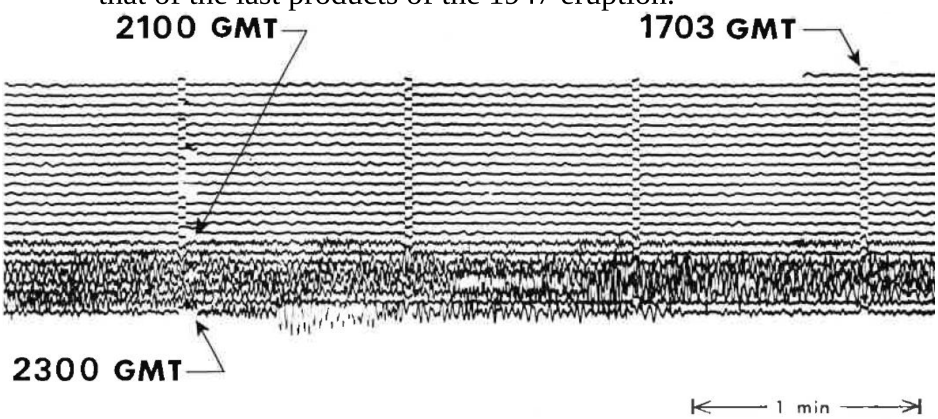

Fig. 3. Seismogram of May 5, 1970 from the vertical, short-period seismograph at the WWSNN-station at Akureyri, 200 km N orth of Hekla, showing the seismic activity associated with the beginning of the eruption of the volcano. From Einarsson and Björnsson (1976).

1973 **Vestmannaeyjar - Heimaey.** An eruption started on January 23 between 0150 and 0155 on the island Heimaey in the Vestmannaeyjar volcanic system, only 200-300 m east of the town of 5300 inhabitants (Thorarinsson et al. 1973). The eruption was preceded by an earthquakes swarm 28-14 hours before the outbreak (Björnsson and Einarsson, 1974). A few events immediately before the outbrak were felt in the town. Other precursors were not reported. Within a few minutes the NNE-striking eruptive fissure was 300-400 m long. A length of about 3 km was attained on January 25 and was extended to the north an additional half kilometer on February 6. Most of the inhabitants were evacuated from the island within 4 hours by the fishing fleet and aircraft. Lava was mainly flowing towards the east during the first few weeks, but later lava also flowed towards the town. A great number of houses were burned down by flying cinders and covered by ash, later also covered by lava flows. The average flow over the first 5 days was estimated 80 m^3s^{-1}. The eruption column occasionally rose to 9000 m. The eruption culminated in vigour during the first day and then gradually diminished and was then concentrated on one crater on the middle of the fissure. A 215 m high cinder cone, Eldfell, was built around the crater. A temporary increase in the eruption was noted in the middle of March, and small submarine eruption was detected about 6.5 km NE of Heimaey on May 26 (Thorarinsson, 1977). Thus the total length of the active fissure system was 10 km. The eruption was accompanied by moderate earthquake activity at 15-25 km depth beneath Heimaey (Björnsson and Einarsson 1974, Einarsson 1991a). The eruption ended on June 26-28 (Þ. Einarsson 1974). The total volume erupted is estimated at 250 Mm^3. The products are classified as hawaiite to mugearite and belong to the alkali basalt-trachyte suite (Thorarinsson et al. 1973). The thick lava flow was used as a heat source for a central heating system for the town for the following 20 years (Björnsson 1987).

1975 **Krafla.** A large sequence of magmatic and tectonic events occurred along the plate boundaries in N-Iceland, beginning in 1974 and lasting until 1989 (e.g., Einarsson, 1991b; Tryggvason, 1984; Björnsson et al., 1977, 1979; Wright et al., 2012). The activity was mainly concentrated on the Krafla volcanic system but also extended into the adjacent Grímsey oblique rift, a part of the Tjörnes Fracture Zone. Most of this time magma apparently ascended from depth and accumulated in a magma chamber at about 3 km depth beneath the Krafla volcano. The inflation periods were punctuated by sudden deflation events lasting from several hours to 3 months when the walls of the chamber were breeched and magma was injected into the adjacent fissure swarm. Twenty deflation events were documented. Large scale rifting was observed in the fissure swarm during these deflation events and in nine of them magma reached the surface in basaltic fissure eruptions lasting from a half hour to 14 days. Several sub-sequences may be identified within the magmatic episode (Buck et al., 2006):

1. The initial event began on December 20 1975 with a small eruption at Leirhnjúkur in the Krafla caldera, accompanied by rapid deflation, rifting and lateral magma injection into the adjacent fissure swarm both to the south and north. This event followed a period of over a year of elevated earthquake

activity in the caldera. The largest rifting occurred at the northern end of the fissure swarm, near its intersection with the Grímsey oblique rift, and triggered a magnitude 6.5 (M_S) strike-slip earthquake on that zone on January 13. The deflation lasted until the middle of March 1976 when inflation resumed at Krafla.

2. A period of rifting events in the northern fissure swarm followed. The first of them was a small and slow event, 29 September to 4 October 1976. No surface rifting was identified but small earthquakes were located 10 km north of the caldera. More rapid and dramatic events occurred on October 31 1976 and January 20 1977 when large scale rifting was witnessed 10-22 km and 5-10 km north of the caldera.

3. Two events followed in the southern fissure swarm, beginning on April 27 and September 8, 1977. Both events began with small eruptions near the northern caldera rim that quickly ended when earthquakes propagated to the south, out of the caldera. The April event was accompanied by rifting 0-13 km south of the caldera, the September event 0-10 km south of the caldera (Brandsdóttir and Einarsson, 1979). Small amount of basaltic pumice was thrown out of a geothermal drill hole in the southern fissure swarm during the rifting on September 8. A third event was a very small one, on December 2, 1977, probably associated with dyking near the southern caldera wall.

4. A period of rifting events in the northern fissure swarm came next. The first four were large, beginning on January 8, July 10 (Einarsson and Brandsdóttir, 1980), and November 10, 1978, and May 13, 1979. Rifting was concentrated at 20-44 km, 20-30 km, 17-27 km and 11-23 km north of the caldera, respectively. The fifth one was in December 1979. It was small and slow, with a flurry of small earthquakes recorded in the southernmost part of the northern fissure swarm.

5. Two deflation events in 1980 were associated with earthquakes and rifting in the southern fissure swarm. A relatively small event began on February 10 and was accompanied by earthquakes at 7-9 km depth, 0-10 km south of the caldera, almost in the same section as the September event of 1977, that was shallower. A rapid deflation event on March 17, 1980 resulted in a small eruption on a 6 km long and intermittent fissure extending from the center of the caldera northwards. The eruption stopped when rifting propagated out of the caldera to the south.

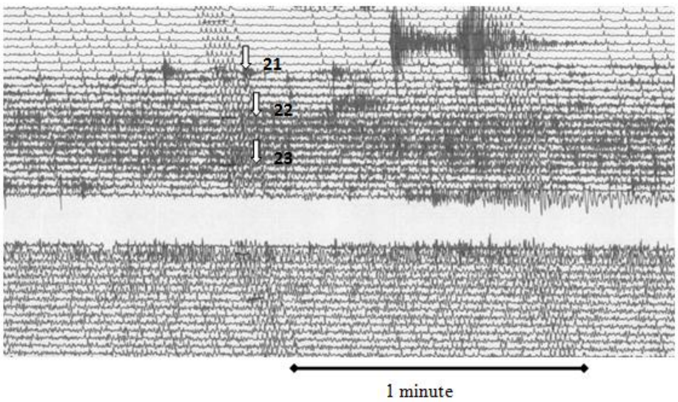

Fig. 4. The beginning of the September 1984 Krafla eruption seen at Skinnastaður, 40 km north of the eruption site. Only a section of the seismogram is shown. The earthquake near the top of the seismogram was a magnitude 2.9 (M_τ) event in the Tjörnes fracture zone in Fljót, unrelated to the eruption. At this station high-

frequency tremor mixed with earthquakes is seen at 22:50. The beginning of the eruption at 23:49 is not accompanied by a significant seismic event. The eruption was accompanied by low-frequency tremor, but very few earthquakes.

6. The episode ended with a sequence of fissure eruptions, each of which was associated with deflation of the caldera region and began in the same fashion as the rifting events had done previously. They all occurred in the same general area, extending from the center of the caldera and about 9 km to the north (Sæmundsson, 1991). They occurred on July 10-18, 1980 (20-30 Mm^3), October 18-23, 1980 (30-40 Mm^3), January 30 – February 4, 1981 (about 32 Mm^3), November 18-22, 1981 (>40 Mm^3), and September 4-18, 1984 (>50 Mm^3).

The caldera region inflated after the last eruption until the pre-eruption level was approached. Then the inflation became intermittent. The last inflation period occurred in the summer of 1989. After that the caldera region has been slowly subsiding (Sigmundsson et al., 1997b), a few centimeters per year. A total of ~ 350 Mm^3 of basaltic lava were erupted during the Krafla episode but a substantially larger volume was emplaced in the crust.

1980 **Hekla.** Eruption began on August 17 at 13:27 preceded by a swarm of earthquakes that began at 13:04 (Grönvold et al. 1983; Brandsdóttir and Einarsson 1992). The eruptive fissure followed the crest of the Hekla ridge to the NE and SW shoulders and from there it extended with bends down to the lower flanks, a total length of about 8 km. The vigor of the eruption reached a maximum during the first hour and the started declining at 16 h. And continued doing so until the end of the eruptive activity on August 20. The tephra during the initial phase was carried to the north. Lava flows were deposited on the flanks, NE, S, W and SW of the summit. The total volume is estimated as 150 Mm^3.

Activity at Hekla resumed in April 1981. Volcanic tremor similar to the August tremor was noticeable on a seismometer shortly after 22:00 on April 8. The tremor amplitude increased rapidly between 02:00 and 05:00 in the morning of April 9 when the first tephra fall was noted. However, the weather conditions prevented direct observations of the eruption site. The tremor started to decrease slowly in the morning of April 10 and finally disappeared below the detection level on April 16 with the last signs of the eruption (Grönvold et al. 1983). Small lava flows issued from the summit and radial fissures extending down the upper N flank from the summit.

1983 **Grímsvötn.** A small eruption broke out from a short fissure near the S caldera wall near Svíahnúkur Vestri on May 28 (Grönvold and Jóhannesson 1984, Einarsson and Brandsdóttir 1984). The products were basaltic and the eruption was entirely phreato-magmatic due to its location under ice and water. The eruption was preceded by a 6-month period of enhanced earthquake activity under the southern part of Grímsvötn, and a sharp earthquake swarm accompanied its outbreak (Fig. 5). The earthquake activity was replaced by tremor as soon as the eruption began. Tremor bursts were recorded throughout

the eruption which ended on June 2. The erupted volume was estimated <10 Mm^3 (Guðmundsson and Björnsson, 1991).
Another and smaller eruption may have occurred on August 21, 1984 as indicated by seismic data alone (Björnsson and Einarsson, 1990), see below.

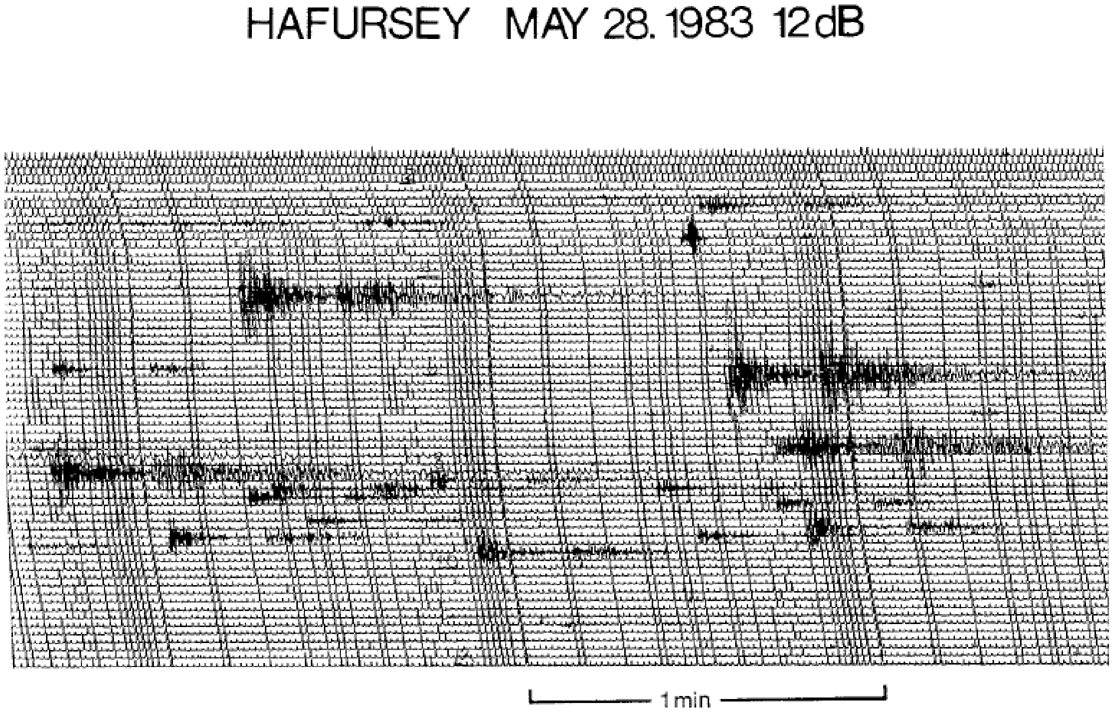

Fig. 5. Seismogram from the beginning of the Grímsvötn eruption of 1983 recorded at Hafursey, at a distance of 120 km from the eruption site. Note the variable appearance of the different earthquakes. From Einarsson and Brandsdóttir (1984).

1991 **Hekla.** An eruption began in Hekla on January 17 at 17 h and was first noticed at 17:05 at a nearby farm (Guðmundsson et al. 1992), about at the same time as vigorous volcanic tremor was detected by the local seismic network. A swarm of small earthquakes began at 16:30 (Soosalu and Einarsson 2002) preceding the outbreak by only 30 minutes. Borehole strainmeters located 14-45 km from the summit recorded a strain pulse beginning at 16:36 (Linde t al. 1993). The column attained a height of 11.5 km in 10 minutes. The tephra of the initial phase, lasting only 2 hours, was carried to the north. In addition to the southern part of the main Hekla fissure, several small fissures were active on the lower flanks of the volcano. The activity peaked in the first hour and then gradually diminshed. This behaviour was generally consistent with the amplitude of volcanic tremor recorded by the local seismographs (Soosalu, et al., 2003). Effusion rate of lava was estimated at 800 m^3s^{-1} during the first day (Guðmundsson et al. 1992), and then declining to a temporary minimum of 1 m^3s^{-1} in early February, then ranging between 1 and 12 m^3s^{-1} until its end on March 11. The activity was concentrated on one short fissure on the lower east flank after the first days, and built up a cinder cone there. The total area of lava was 23 km2 and its volume is estimated as 150 Mm^3. The products are basaltic andesite, very similar to that of 1970 and 1980-81 (Guðmundsson et al. 1992). The Hekla volcano deflated during the eruption, as measured by GPS-geodesy (Sigmundsson et al. 1992).

1996 **Gjálp.** A volcanic eruption began beneath the Vatnajökull ice cap in Central Iceland in the late evening of September 30, on a 4 km long fissure located between the volcanoes Bárðarbunga and Grímsvötn (Einarsson et al. 1997, Guðmundsson et al. 1997, 2004). Meltwater from the eruption site flowed into the caldera lake of the Grímsvötn volcano, where it accumulated beneath a floating ice shelf. The lake´s ice dam was lifted off the glacier bed on November 4, and in the next two days the water drained out beneath the glacier and flushed down to the south coast´s alluvial plain, causing extensive damage to transportation and communication systems. The eruption was preceded by an unusual sequence of earthquakes, beginning on September 29 at 10:48 with a magnitude 5.4 (M_s) event at the northern rim of the Bárðarbunga caldera (Einarsson and Brandsdóttit, 1997). Many similar earthquakes occurred beneath the Bárðarbunga volcano during 22 years prior to the eruption , but none had significant aftershocks, nor were they followed by magmatic activity. This time the earthquake was followed by an intense earthquake swarm. The Civil Defense authorities as well as the scientific community were warned of this unusual seismic activity and the possibility of eruptive activity. The earthquakes were initially located below the northwestern rim of the Bárðarbunga caldera, and then, over 24 hours, migrated 20 km southward toward Grímsvötn, accompanied by continuous tremor. In the evening of September 30 the earthquake activity near Grímsvötn decreased markedly, and instead the seismograph at Grímsvötn began recording continuous, low-amplitude eruption tremor. This may be taken as evidence that the predicted eruption had begun. The eruption site was discovered early the following morning from an aircraft. By that time two elongate, 1-2 km wide and NNE trending subsidence cauldrons had formed on the ice surface SSE of Bárðarbunga, on the northern flank of the Grímsvötn volcano. The fissure was located within the drainage basin of the Grímsvötn caldera causing the meltwater from the eruption to drain into the caldera lake. The eruption was most powerful during the first 4 days. Most of the activity was subglacial, but in the morning of October 2 an opening formed in the glacier surface, through which an eruptive column rose to 4-5 km altitude. Later that day the eruptive fissure extended some 3 km farther to the north. Ash dispersed to the north and colored the glacier surface. The opening in the glacier grew larger in the following days and the subsidence area grew to 9 km long and 3-4 km wide. An ice canyon melted along the central axis of the depression. Water flowed southward along the canyon toward the Grímsvötn caldera. The volcanic tremor stopped on October 13, indicating that magma transport to the eruption site had ceased. The eruption produced on the order of 500 Mm^3 of basaltic andesite. The composition varies significantly, SiO_2 is in the range 51.8 - 54.2 % and MgO in the range 2.5 - 3.7 %. The eruptive products are different from those of Grímsvötn, as defined by the products of the most recent eruptions. They are also different from typical Bárðarbunga products, that generally contain MgO in the range 7.2 - 8.8 %.

The rate of meltwater flow into the neighbouring Grímsvötn caldera during the first few days of the 1996 eruption was about 5000 m^3/s and the ice shelf on the caldera lake rose 15 - 20 m per day. By the end of October the lake level was approaching the point where ice closing the outlet of the lake would be lifted off the glacier bed. On November 4 the sudden appearance of a continuous, high-frequency (> 3 Hz) tremor on the Grímsfjall seismograph indicated that the ice barrier holding the lake was failing. The water emerged at the glacier edge as a flood wave 10 1/2 hours later, initially in the easternmost river, Skeiðará. Several hours later the rivers farther west on the Skeiðarársandur alluvial plain were also flooding. The maximum discharge rate was the highest ever recorded, about 45 000 m^3/s on November 5. The flood ended on the morning of November 7. The total volume of water released from the glacier is estimated at 3.5 km^3. The water brought with it dissolved volatiles from the eruption enabling measurements of 50 elements (Gíslason et al, 2002). A total of 0.6 million tonnes of CO_2 were dissolved.

1998 **Grímsvötn.** An eruption began on December 18 and lasted 10 days. It took place on a 1.3 km long fissure under the SW caldera wall at Svíahnúkur Vestri, in the same area as the 1934 and 1983 eruptions (Guðmundsson et al., 1999). The eruptive activity very soon concentrated on one crater in the middle of the fissure. The eruptive products were basaltic and the activity was phreato-magmatic. The volume of erupted magma is estimated 60-80 Mm^3 (Guðmundsson et al., 2000). The eruption was preceded by a period of agitated earthquake activity for several months. Bryndís Brandsdóttir and others (in Alfaro, 2001) operated a local seismograph array in the summers both before and after the eruption and noted a a change consistent with inflation-related activity before, vs relaxed state after the eruption. Geothermal activity greatly increased along the S caldera wall after the eruption, generally assumed to be due to a dyke injected into the caldera fault in association with the beginning of the eruption (Guðmundsson et al., 1999). Sturkell et al. (2003a) measured displacement of a geodetic point on Grímsfjall 1992-2001 and found movements consistent with a deflation of the Grímsvötn volcano associated with the 1998 eruption and a subsequent reinflation.

2000 **Hekla.** An eruption began at 18:19 on February 26. The outbreak was preceded by a swarm of small earthquakes beginning at 17:00, which was immediately noticed (Soosalu et al. 2005). A strain signal was detected confirming the conclusion that an eruption was highly probable (Ágústsson et al. 2000). An announcement of an impending eruption of Hekla was made on the public radio at about 18:00. The eruption broke out on the main fissure of Hekla and several small fissures on the flanks. The eruption column during the initial phase reached a hight of 11 km (Lacassse et al 2003). Pyroclastic flow deposits were found from this initial phase of the eruption (Ólafsdóttir et al. 2002). Lava flows issued down the northern and southern flanks. The eruption soon concentrated on the SW-shoulder of the volcano and continued there. The last eruptive tremor was detected on seismometers in the morning of March 8 at 8:44. By this definition of detection of tremor, and as no signs of eruptive production was observed since March 5, the eruption lasted 11 days. The products were basaltic andesite, mainly lava. The lava covers approximately 17 km^2 and estimated total lava production is 170 Mm^3 , most of it erupted during the first two days (Ólafsdóttir et al. 2002; Höskuldsson et al., 2007).

2004 **Grímsvötn.** The eruption that began on November 1 was forecast on several different timescales. Inflation of the volcano began immediately after the 1998 eruption and was monitored by GPS measurements on the caldera rim. Seismic activity began increasing in July 2003 and by September 2004 the inflation level of the volcano had reached the 1998 pre-eruption level (Vogfjord et al., 2005; Sturkell et al., 2006). It became public knowledge that a Grímsvötn eruption was imminent. At this time it also became known that the lake level in the Grímsvötn caldera was rising beyond the critical level for a jökulhlaup, a situation that could possibly trigger an eruption by sudden release of pressure on the magma system. The beginning of a jökulhlaup was detected on October 27 by high-frequency tremor on regional seismographs. The flood was detected on the lowland two days later. An announcement was given for increased probability of an eruption within a few days. A dense swarm of small earthquakes began in the early hours of November 1 signifying magma propagating towards the surface. The swarm intensified at 19:30 and by 20 h the activity was dominated by volcanic tremor, indicating the beginning of an eruption. This was a relatively small eruption. The maximum plume height of 12 km was measured a few hours after the beginning, and by November 3 the plume disappeared from radar. The eruption appears to have ended on November 6.

2010 **Eyjafjallajökull**. Following 18 years period of unrest, including 3 intrusions in 1994, 1999, and 2009 of several months´ duration each (Pedersen and Sigmundsson, 2004, 2006), a small lava eruption broke out on the eastern flank of the volcano, at Fimmvörðuháls on March 20 (Sigmundsson et al., 2010). The eruption immediately followed the fourth intrusion that began in early January 2010 accompanied by escalating seismicity, more intense than in any of the previous episodes. An eruption was anticipated but the time scale was uncertain. Earthquake hypocenters were propagating towards the eastern flank but the premontory seismic signal was rather weak. When the eruption finally broke out it was first spotted visually by local inhabitants. The eruption continued with low-level fire fountains for three weeks, and produced a small lava field extending into the gullies on the NE flank. The eruption ended rather abruptly on April 12. The volcano did not deflate during the eruption, indicating that it was fed by magma directly from deep sources.

2010 **Eyjafjallajökull**. The sudden end of the flank eruption suggested that the magma feeding channel had been blocked or breached, and further activity might be expected. This came sooner than anticipated. A new eruption broke out shortly after midnight on April 14 and this time in the summit region of the volcano [e.g. Guðmundsson et al., 2010]. It was preceded by a distinct increase in earthquake activity beneath the summit caldera. The beginning of the eruption appears to have been very subtle and was only detected by low-amplitude volcanic tremor at 01:15. No further signs of the eruption were seen until 06:50. Then a pulse of tremor was recorded, a considerable body of water was released from the summit caldera and the eruption broke through the glacial cover. The eruptive column reached a height of 10 km in the first day.

This summit eruption lasted 39 days (Gudmundsson et al., 2012) and spread ash widely, including the European continent where it blocked air traffic for several days.

OTHER MAGMATIC EVENTS AND SUSPECTED ERUPTIONS

1927 **Esjufjöll.** A jökulhlaup in the river Jökulsá á Breiðamerkursandi on September 7-8 was accompanied by sulphuric smell and minor ashfall. These were taken to indicate eruptive activity (Björnsson 1977) and the most likely volcano to produce a flood in Jökulsá á Breiðamerkursandi is Esjufjöll (Björnsson and Einarsson 1990). One person lost his life in the flood.

1939 **Grímsvötn.** A small jökulhlaup culminated on July 15. Jóhannesson (1983) suggests that it was caused by eruptive activity, but Guðmundsson and Björnsson (1991) explain increased jökulhlaup frequency by delayed melting of ice by the 1938 eruptive products at Gjálp.

1941 **Grímsvötn.** A small jökulhlaup culminated on May 16. Jóhannesson (1983) suggests an eruption as the cause, but Guðmundsson and Björnsson (1991) seek an alteranative explanation, see above.

1945 **Grímsvötn.** A jökulhlaup draining Grímsvötn occurred, beginning on September 16 and ending on September 27. The ice shelf subsided about 80 m and the western and north-western part of it were broken up. Inspection revealed apparent ashfall in the caldera, believed to be from a steam explosion or a small eruption (Áskelsson 1959, Þórarinsson 1974). This ash was later shown to be remanents of the 1934 ash layer by Guðmundsson and Björnsson (1991).

1948 **Grímsvötn.** A jökulhlaup culminated on February 23. Jóhannesson (1983) suggests an eruption, but Guðmundsson and Björnsson (1991) consider it unlikely, see above.

1954 **Grímsvötn.** A jökulhlaup was first detected on July 7, slowly increasing and reaching a maximum on July 18. The discharge rate was then estimated 10 500 m^3/s (Þórarinsson 1974). The flood ended on July 21. The total volume was estimated 3.5 km^3. The contamination of H_2S was particularly severe, killing birds and trout. Leaves fell off trees. The Grímsvötn ice shelf subsided 100 m and ice cauldrons were formed, presumably because of explosions, steam explosion or a small eruption. Ash was found around this area and was taken as evidence for an eruption (Þórarinsson, 1974, Jóhannesson, 1983). It was shown by Guðmundsson and Björnsson (1991) to be remanent of the 1934 ash.

1955 **Katla.** A probable small, subglacial eruption occurred on the eastern rim of the caldera. No tephra erupted through the glacier, but two collapse cauldrons formed in the glacier surface and a relatively small jökulhlaup occurred on Mýrdalssandur on June 25 (Þórarinsson 1975). These events were accompanied by earthquakes (Tryggvason, 1960).

1962 **Askja.** Earthquake swarms on January 30 and June 12 indicates intrusive activity following the 1961 eruption (Brandsdóttir, 1992).

1970 **Eldeyjarboði, Reykjanes Ridge.** A submarine eruption in 1970-1971 is suspected from very fresh basalt dredged in 1971 (Jakobsson 1974). The probable eruption site is near 63° 26' N and 23° 50' W, about – km SW of the tip of the Reykjanes Peninsula.

1984 **Grímsvötn.** A small, subglacial eruption may have occurred on August 21, when a sudden burst of contiuous tremor occurred, lasting about one hour. This burst put an end to a period of enhanced earthquake activity that probably accompanied re-inflation of Grímsvötn following the 1983 eruption. In a reconnaissance flight on August 22 an unusual number of depressions were discovered in the ice, due to melting from below (Björnsson and Einarsson 1990) but no fresh eruptive products were detected (Guðmundsson and Björnsson, 1991).

1986 **Loki Ridge, E Cauldron.** A flood that began in the river Skaftá on November 29 was followed by bursts of continuous tremor recorded by several seismographs around Vatnajökull on Nov. 30 and Dec. 1. The flood issued from underneath the Eastern Skaftá Cauldron, NW of Grímsvötn which collapsed during the flood. The tremor occurred after the peak of the water flow had passed and was interpreted by Björnsson and Einarsson (1990) to be due to a small, subglacial eruption triggered by the pressure release when the water was drained away.

1991 **Loki Ridge, E Cauldron.** Probable small, subglacial eruption associated with flood in Skaftá in August 9-16 (Einarsson et al. 1997; Zóphoníasson and Pálsson, 1996).

1994 **Eyjafjallajökull.** Earthquake swarm beneath the NE flank indicates intrusive activity (Dahm and Brandsdóttir 1997). Increased earthquake activity was noted already in 1991 and sporadic seismic activity occurred in the following years. Ground deformation indicating inflation was confirmed by tilt and GPS-geodesy and appears to have been mostly in 1994, during the peak of the seismic activity (Sturkell et al. 2003). Inflation was further confirmed by SAR, with a center beneath the S-flank at 3 km depth (Pedersen and Sigmundsson. 2004).

1994 **Hrómundartindur.** Increased seismic activity and slow land uplift indicates magma flow into the roots of the volcanic system at 6 km depth (Sigmundsson et al., 1997, Feigl et al. 2000, Clifton et al. 2002, Pedersen et al., 2007). Slow uplift continued for more than 4 years, reaching 8 cm at the apex. The volume of injected magma is roughly estimated 15 Mm^3 (Feigl et al. 2000; Einarsson, submitted 2018). Earthquakes of magnitude 5 occurred at the perifery of the uplifted area in June 1998 and 10 km farther south in November 1998 (Rögnvaldsson et al., 1998).

1995 **Loki Ridge, E Cauldron.** A small, subglacial eruption beneath the Eastern Cauldron may have been associated with flood in Skaftá that began on July 25 (Einarsson et al. 1997, Zóphoníasson and Pálsson 1996). Tremor bursts were recorded on seismographs around the Vatnajökull glacier, and temporary seismographs on the glacier showed that small-amplitude tremor began before the flood was released. This indicates that the flood may have been triggered by eruptive activity (Þorbjarnardóttir et al. 1997).

1996 **Hamarinn.** An earthquake swarm in February 9-14 had some of the characteristics of volcanically induced earthquakes and may indicate intrusive activity. Its source area was on the Hamarinn volcano and western part of the Loki Ridge. It began gradually and increased in intensity for 4 days. It was over in a week.

1996 **Loki Ridge, W Cauldron.** A flood in Skaftá originating in the Western Cauldron on the Loki Ridge was accompanied by tremor bursts (Einarsson et al. 1997, Zóphoníasson and Pálsson 1996). The tremor began after most of the water left the cauldron. If the tremor indicates eruptive activity, it looks as if this time the flood triggered the eruption (Þorbjarnardóttir et al. 1997). The flood began on August 9 and was over by August 17. This event was followed by increased local seismicity during the next few weeks.

1997 **Loki Ridge, E Cauldron.** A small, subglacial eruption may have occured associated with a flood in Skaftá. The flood began on August 15 and tremor amplitude as measured on nearby seismographs starts increasing on August 16. The flood discharge peaked on August 17 and bursts of high amplitude tremor were recorded that day and the next. The flood was over by August 22 (Zóphoníasson, 2002).

1999 **Katla.** A small, subglacial eruption may have occurred on July 18 on the SW caldera fault. A flash-flood occurred in Jökulsá á Sólheimasandi, almost destroying the bridge on Route 1 (Sigurðsson et al. 2000), following a burst of volcanic tremor recorded on many seismographs in S-Iceland (Einarsson 2000). A new ice cauldron was formed. Increased geothermal activity was detected along the caldera rim in the following weeks as seen by the deepening of pre-existing ice cauldrons (Guðmundsson et al. 2000). Inflation centered on the caldera of the Katla vocano and increase in seismic activity of the area was detected in the following years (Sturkell et al. 2003a,b). It has been suggested that increased seismicity in a tight cluster west of the caldera is the expression of an ascending cryptodome (Soosalu et al., 2006).

1999 **Eyjafjallajökull.** Seismicity and surface deformation indicate intrusive activity. Following a M=3.6 earthquake under the N-flank in April surface deformation seems to have set in in July accompanied by swarm activity beneath the S-flank.. Tilt measurements and GPS-geodesy indicate a center of inflation at 3.5 km depth beneath the S-flank (Sturkell et al. 2003) and InSAR data show that the inflation bulge is displaced slightly with respect to the 1994 inflation bulge (Pedersen and Sigmundsson, 2006) in the same general area. Estimated volume of intruded magma is 18 Mm^3.

2000 **E and W Skaftárketill.** Probable small, subglacial eruptions associated with two floods in Skaftá, in August 5-17.

2002 **W and E Skaftárketill.** Probable small, subglacial eruptions associated with floods in Skaftá, in the W-cauldron in July 7-15, and in the E-cauldron in September 17-25.

2005 **W Skaftárketill.** Eruption tremor suggests a small, subglacial eruption at the end of a flood in Skaftá in July 31-August 9.

2006 **E Skaftárketill.** A flood in April 21-26 was followed by bursts of eruption tremor, suggesting a small eruption.

2007 **Upptyppingar – Álftadalsdyngja.** A swarm of small earthquakes originated in the lower crust, 12-20 km depth (Jakobsdóttir et al., 2008; Soosalu et al. 2010), and suggested magma movements. The swarm began in February 2007 and ended in May 2008. Both the geometry of the hypocentral zone and the surface displacement field suggest intrusion of magma along a dipping surface (e.g., Hooper et al. 2011; White et al. 2011). The activity is located beneath the Kverkfjöll fissure swarm of the Northern Volcanic Rift Zone (Hjartardóttir and Einarsson, 2012).

2008 **W and E Skaftárketill.** Eruption tremor suggests small, subglacial eruptions associated with floods in Skaftá, in the W-cauldron in August 9-17 and in the E-cauldron on October 11-16.

2009 **Eyjafjallajökull**. An intrusion event began at the end of December and continues into the new year, indicated by increased seismicity and inflation seen on CGPS-station at Þorvaldseyri and temporary GPS-station at Steinsholt. A shot of increased acidity was detected in the springs at Syðsta-Mörk on January 29. Precursory activity to the eruptions of March and April.

Discussion: *Frequency of Icelandic eruptions.*

A frequently quoted number for the rate of volcanic eruptions in Iceland is one eruption per 5 years. This rate is certainly too low, and for at least two reasons. The rate was found from only known and confirmed eruptions. Experience from the last decades indicates that small eruptions in the remote interior may easily go undetected in the inhabited regions. Thus numerous small eruptions in the interior may have been missed in the historical record. Also the period of observations includes the middle part of the 20th century which seems to be one of the quietest period of the whole Historical time in Iceland. The frequeency of eruptions also depends on the definition of an eruption, whether for example the Krafla magmatic episode is taken as one eruption or nine, the Hekla 1980-81 activity is counted as one or two eruptions etc. In the case of Krafla, magma was probably flowing continuously from the mantle into the shallow magma chamber during the whole period 1974-1985 even though extrusion to the surface took place in 9 well defined events. Similarly the Surtsey eruption was divided into at least 6 phases where activity shifted from one eruptive site to another with longer or shorter intermissions of no visible surface activity. Taking a very conservative view and defining events close to each other in time and space as one event we come up with 23 confirmed events in 100 years, or one event per 4.3 years. Taking the other extreme and defining an eruption as an event of magma delivery to the surface after a period of no visible activity, the rate becomes much higher. We would then separate the Krafla active period into 9 different eruptions, the Askja activity of the 1920´ies into 5 eruptions, the Surtsey activity into 6 eruptions (Surtur I, Surtur II, Surtla, Syrtlingur, Jólnir, back to Surtur I), and Hekla 1980-81 into two eruptions. The total number of eruptions thus becomes 42, i.e. one eruption in 2.4 years. Also, counting the unconfirmed but suspected eruptions we get 15 more events, or 57 events in 100 years, i.e. one eruption every 1.8 years.

The question arises to what extent the twentieth century can be taken as a typical century with regard to volcanic activity. Björnsson and Einarsson (1990) point out that the most active volcanic systems of the Vatnajökull region, Bárðarbunga and Grímsvötn, were conspicuously quiet in the last decades of the century, and Larsen et al. (1998) confirm from the study of tephra layers in the icecap that this period is one of the quietest in Historic times. Since not much else was going on elsewhere, this conclusion can probably be extended to the whole country.

There are remarkable fluctuations in the activity when the whole century is considered. Three periods can be distinguished.

1. 1900-1938. This period is characterised by activity in the central area of the hotspot, Grímsvötn, Askja, Bárðarbunga, also Hekla system 1913 and Katla 1918.
2. 1938-1961, the quiet period. The only documented eruption is the Hekla eruption of 1947, a very large eruption.
3. 1961-2014, the active period. Many and widespread significant events, Vestmannaeyjar (Surtsey and Heimaey), Krafla, Gjálp and Bárðarbunga, Grímsvötn, Eyjafjallajökull, Hekla changes its pattern to fequent moderate eruptions, Askja.

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