Millennium
European Climate

SG4

Explosive and partly explosive eruptions during the last millennium: Dispersal of air-fall tephra from volcanic eruptions 1901-2005

Millennium SG4: Marine Proxies for the Last Century

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Reykjavík 2007
July 2007 / RH-17-2007

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Introduction

This report is part of Workpackage WP4 (Deliverable D18) of Subgroup 4 of the Millennium project. Workpackage WP4 concerns the last 100 years cf. p. 136 in Annex I - Description of Work. The report provides background data for tephrochronological dating of the marine sediments on the north Icelandic shelf (SG4) where multicores, box cores, and gravity cores were collected as well as for lake sediments in West Iceland (SG3).

Sources of Information

Sources of information about explosive and partly explosive eruptions in Iceland are of several kinds.

1) Written descriptions of volcanic eruptions or phenomena that could be caused by volcanic eruptions. These may include date of the eruption (year, month, day, hour) location of the volcano, description of the type of activity and course of events, duration of the activity, type of products, direction or area of tephra fall, areas of damage. This is the case for many eruptions of the Hekla and Katla volcanoes which lie close to farming areas in S-Iceland.

However, for eruptions in more remote areas such as the central highlands or Vatnajökull ice cap the information may consist only of the eruption year and a few words about eruption cloud or fire, glow in the sky, tephra fall, darkness, flood, or other phenomena that people thought were signs of volcanic activity. Location of the eruption site may be vague or attributed to the wrong volcano. Also, names that differ from the present ones may have been used for mountains, ice caps and districts at the time of writing.

In genereal, however, the date of an eruption is likely to be more accurate than the location of the volcano because the calendar was a common knowledge although the geographical knowledge was often poor. Volcanic eruptions were as much news then as they are today and were definitely worth mentioning.

Volcanic eruptions or phenomena that could be caused by volcanic activity are mentioned or described in various documents from the 12th century onwards.

2) The volcanic products, in this case the tephra layers, their identification, mapping and chemical fingerprinting. Tephra layers have many macroscopic and microscopic characteristics that can be used to identify, correlate, map and trace tephra layers to source - and build a local or regional tephra stratigraphy. Many volcanic systems in Iceland have chemical characteristics that make it possible to correlate tephra layers to source - and build or verify correlations in the field.

Many descriptions of eruptions and tephra fall are detailed enough to allow correlation of certain tephra layers to definite dated eruptions, thereby providing securely dated tephra horizons within the local or regional tephra stratigraphy. This allow further correlation of tephra layers to dated eruptions, verified by chemical characteristics when needed for solid tephra stratigraphy. Dated pairs or series of tephra layers are more secure that single tephra layers and the first such series in the Icelandic tephrochronology consisted of the H-1766, K-1721 and H-1693 tephra layers (Thorarinsson 1944).

Not all tephra layers can be correlated to a documentary date - there are more tephra layers than dates. Moreover, not all eruptions mentioned in documents can be fitted to a tephra layer, even in the last century there are several eruptions that are classified as reported only because no corresponding volcanic products have been found.

Figure 1 summarizes the current knowledge on frequency of explosive and partly explosive eruptions in Iceland for the period under consideration in the Millennium project. Because of low frequency of explosive eruptions at the beginning of the last millennium the base line is set at AD 870 where the Settlement tephra layer (Vatnaöldur eruption) provides a well documented isochron (Thorarinsson 1944; Larsen 1984, Grönvold et al 1995). Those tephra layers that cannot be correlated to an eruption year are assigned a date calculated using soil or sediment accumulation rate (SAR) between securely dated tephra horizons. These are often accurate to ±5 years or ±10 years, which is why binning to 20 years is used in Figure 1.

Some sightings of phenomena that were interpreted as signs of volcanic eruptions may - or may not - be caused by volcanic activity. Some accounts of tephra fall may also be false - as late as in the 2004 Grímsvötn eruption reports of tephra fall were spurred by dust storms. In Iceland such dust is mostly volcanic glass dust but differs from fresh tephra being inhomogenous both in grain morpology and composition.

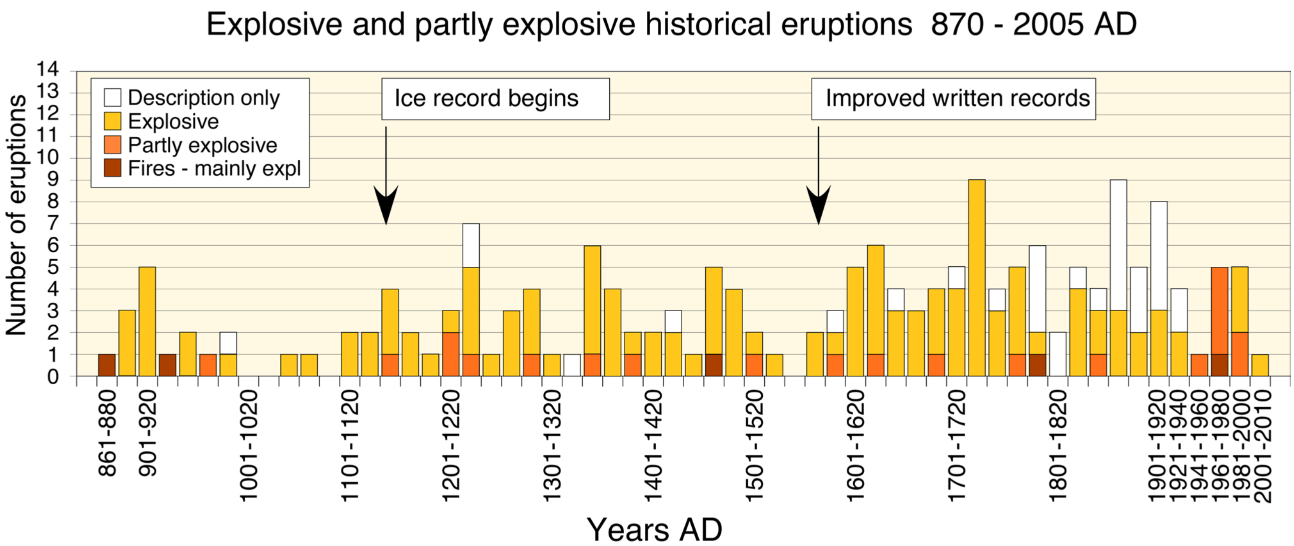

Figure 1: Frequency of explosive and partly explosive eruptions - i.e. tephra-producing eruptions - per 20 years (after Larsen and Eiríksson in press). Roughly 180 tephra-producing eruptions are known since late 9th century, of them about 30 are "reported only" eruptions within Vatnajökull ice cap. The frequency per 20 years varies from 0 to 9 eruptions, with peaks spaced 120-160 years apart. An apparent general increase in eruption frequency with time is probably an artifact, reflecting improved knowledge. Tephra layers in Vatnajökull ice go back to the 12th century, greatly adding to the knowledge of volcanic eruptions within the Vatnajökull ice cap (first arrow). Written descriptions, including those of volcanic eruptions, improve in the 17th century (second arrow).

Tephra producing eruptions of the 20th century

The documentation of volcanic events in the 20th century is very good for the latter half and reasonable for the first half. Below only the essential informations on each eruptions is presented but more complete bibliography is in the list of references. The dispersal maps provided in this report do not necessarily show the complete dispersal of each tephra layers on land as the emphasis is on the North Iceland shelf and W-Iceland. The maps are based on comtemporary descriptions in all cases and also on ground data (thickness measurements or mass per utit area) in many cases. Areas of documented tephra fall are shown and potential dispersal off N-Iceland is indicated. At least 24 explosive or partly explosive eruptions have been reported between 1901 and 2005. Of those 17 are verified by detailed descriptions and volcanic products but seven eruptions are reported only (Fig. 1) which means that the tephra deposits have not been found. The latter are shown in red in the list of eruptions (Table 1).

Table 1.	Explosive and partly explosive eruptions 1901-2005				
Year	Eruption site	Volc. System	Year	Eruption site	Volc. System
2004	Grímsvötn	Grímsvötn	1938	Grímsvötn	Grímsvötn
2000	Hekla	Hekla	1934	Grímsvötn	Grímsvötn
1998	Grímsvötn	Grímsvötn	1933	Grímsvötn	Grímsvötn
1996	Gjálp	Grímsvötn	1922	Grímsvötn	Grímsvötn
1991	Hekla	Hekla	1919	Grímsvötn	Grímsvötn
1983	Grímsvötn	Grímsvötn	1918	Katla	Katla
1980	Hekla	Hekla	1910	Vatnaj	Not known
1973	Heimaey	Vestam.eyjar	1908	Vatnaj	Not known
1970	Hekla	Hekla	1906	Vatnaj	Not known
1963-67	Surtsey	Vestam.eyjar	1904	Vatnaj	Not known
1961	Askja	Askja	1903	Thordarhyrna	Grímsvötn
1947	Hekla	Hekla	1902	Vatnaj	Not known
Black:	17 verified eruptions, chemically analysed tephra				
Red:	7 reported eruptions, tephra has not been found				

Short descriptions of relevant 20th century explosive and partly explosive eruptions

In this chapter semi-standardized information on 15 explosive and partly explosive erupions is compiled, including location, time and length of eruption, type of explosive activity, dispersal and volume of the tephra together with selected references.

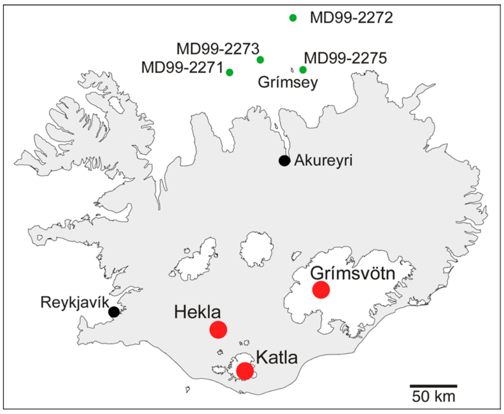

Figure 2: Eruption sites for the 20th century tephra layers of Grímsvötn, Hekla, Katla. Also shown are locations of the cores MD99-2271, MD99-2272, MD99-2273, MD99-2275.

Note that the references for each eruption are limited to those containing information relevant to this report. Figure 2 shows the location of the eruption sites that produced most of the tephra layers. Figure 3 shows the dispersal of the 15 tephra layers. Note that the dispersal maps do not necessarily include all known areas of tephra deposition. Examples of the chemical composition are presented in Table 2 together with the relevant references.

Grímsvötn 2004

Eruption site: Grímsvötn caldera, Grímvötn volcanic system. Eruption began around 22 o'clock on Nov. 1, 2004 and lasted for a week.

Subglacial opening stage was followed by surtseyan activity and the only product was basaltic tephra. Maximum height of eruption cloud was 12-13 km according to the weather radar of the Icelandic Meterorological Office (IMO). Tephra dispersal was towards NNE, N, NNW and minor tephra fall reached the coast of NE Iceland. The tephra layer was a small one, with the mass of tephra close to 25 million tons.

(Sigmundsson and Gudmundsson 2004; Oddson et al. 2007).

Hekla 2000

Eruption site Hekla central volcano, Hekla volcanic system. Eruption began at 18:19 on Feb. 26, 2000 and lasted 12 days.

Subplinian opening stage emitted basaltic-andesitic tephra, followed by mixed explosive and effusive activity. Maximum height of the eruption cloud was 11-12 km according to the weather radar of the IMO. The main tephra producing phase lasted a few hours, tephra was carried NNE onto the shelf off North Iceland along a narrow sector crossing Grímsey Island, where 10-15 g/m^2 was deposited. The tephra layer was a small* one, calculated volume is 10 million m^3. *(small 0,01-0,05; moderate 0,05-0,1; average 0,1-0,5; fairly large 0,5-1 km^3 as freshly fallen).

(Haraldsson 2001; Árnason 2002; Haraldsson et al 2002; Lacasse et al 2004; Soosalu and Einarsson 2005).

Grímsvötn 1998

Eruption site: Grímsvötn caldera, Grímvötn volcanic system. Eruption began around 09:30 o'clock on Dec. 18, 1998 and lasted until the Dec. 28.

Surtseyan explosive activity, apparently without a preceding subglacial stage, only product basaltic tephra. Maximum observed height of eruption cloud was about

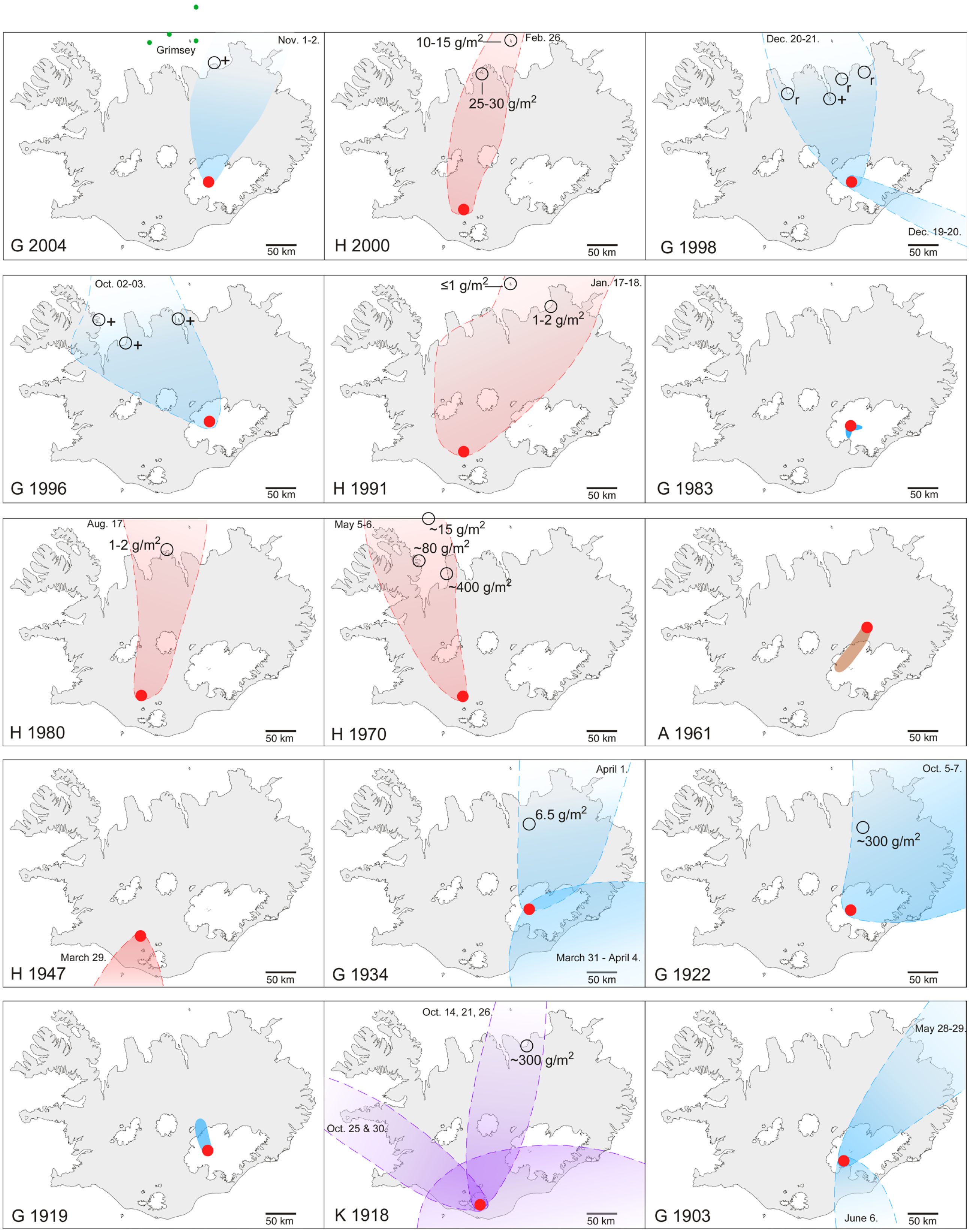

Figure 3. Dispersal of tephra from 15 eruptions in the period 1901-2005. Red: Hekla. Blue: Grímsvötn. Violet: Katla. Brown: Askja. Small cirles with numbers indicate locations where mass of deposited tephra is known near or off the north coast, "+" and "r" indicate confirmed and reported traces of tephra, respectively. Estimated mass of ~300 g/m² is assigned to localities where footprints were traceable after light tephra fall, in accordance with Thorarinsson (1955).

10 km asl. Main tephra dispersal was towards ESE but minor tephra fall reached the coast of North Iceland. The volume of the north trending tephra sector is not known.

(Gudmundsson et al. 1999, 2000; Óskarson et al. 1999; Sigmarsson et al 2000).

Gjálp 1996

Eruption site: Gjálp in Vatnajökull, Grímvötn volcanic system. Eruption began around 22 o'clock on Sept. 30, 1996 and lasted until the Oct 13/14.

Subglacial opening stage was followed by surtseyan activity, only product was basaltic-andesitic tephra. Maximum observed height of eruption cloud was about 9 km asl. Main tephra dispersal was towards NW and minor tephra fall reached the coast of North and Northwest Iceland. The volume of the tephra layer was small.

(Gudmundsson et al. 1997, 2004; Sigmarsson et al. 2000; Steinthorsson et al. 2001)

Hekla 1991

Eruption site Hekla central volcano, Hekla volcanic system. Eruption began at 17 o'clock on Jan. 17, 1991 and lasted until March 11.

Plinian opening stage emitted basaltic-andesitic tephra and was followed by mixed explosive and effusive activity. Maximum observed height of the eruption cloud was 12 km asl.. The main tephra producing phase lasted a few hours, tephra was carried NNE onto the shelf off North Iceland along a sector east of Grímsey Island, where about 1 g/m^2 was deposited. The tephra layer was a small one, calculated volume is 20 million m^3.

(Gudmundsson et al. 1992; Larsen et al. 1992).

Grímsvötn 1983

Eruption site: Grímsvötn caldera, Grímvötn volcanic system. A minor eruption began probably around noon on May 28 but was first observed in the morning of May 29 and last seen on June 1.

Subglacial opening stage was followed by surtseyan activity, only product was basaltic tephra. Maximum observed height of eruption cloud was about 5 km asl. Tephra dispersal was towards S and E but the tephra layer was a minor one and no tephra deposition was recorded outside Vatnajökull ice cap.

(Einarsson and Brandsdóttir 1984; Grönvold and Jóhannesson 1984).

Hekla 1980

Eruption site Hekla central volcano, Hekla volcanic system. Eruption began at ca 13:27 on August 17 and ended on August 20.

Plinian opening phase emitted basaltic-andesitic tephra and was followed by mixed explosive and effusive activity. Maximum observed height of the eruption cloud was 15 km asl. The main tephra producing phase lasted 4-5 hours. The tephra was carried due N to the coast where 1-2 g/m^2 were deposited and onto the shelf off North Iceland along a sector mainly west of Grímsey Island. The tephra layer was a moderate one, calculated volume is about 60 million m^3.

Activity was resumed in April 1981 and lasted 7 days. Weak explosive activity in several shortlived phases dispersed tephra up to 40 km from source. Maximum cloud height was only 6.6 km asl as observed by radar.

(Sverrisdóttir 1982; Grönvold et al. 1983).

Hekla 1970

Eruption site flanks of Hekla central volcano, Hekla volcanic system. Eruption began between 21:20 and 21:25 on May 5 and lasted 2 months.

Plinian/subplinian opening phase emitted basaltic-andesitic tephra from two separate fissures and was followed by mixed explosive and effusive activity. Maximum observed height of the eruption cloud was about 16 km asl. The main tephra producing phase lasted 4-5 hours. The tephra was carried NNW to the coast where up to 160 g/m^2 were deposited and onto the shelf off North and Northwest Iceland where up to 15 g/m^2 were deposited at ca N66°50'. The tephra layer was a moderate one, calculated volume is about 70 million m^3.

Rafts of pumice were observed along the Northwest coast (Raudisandur) in May 1970 and off and along the North coast in late June and July 1970 (Strandir to Skjálfandaflói). This was assumed to be Hekla tephra that was transported down to the sea by rivers in South Iceland during and after the Hekla eruption.

(Thorarinsson 1970, Thorarinsson and Sigvaldason 1972).

Askja 1961

Eruption site Askja caldera, Askja volcanic system. Eruption began between in the afternoon of October 26 and ended in early December.

Strombolian opening phase emitted basaltic tephra from a short fissure and was followed by effusive activity. Maximum observed height of the eruption cloud was about 10 km asl. The tephra from the opening phase was carried SSW onto Vatnajökull ice cap and is not thought to have anywhere reached the coast. The tephra layer was a minor one, estimated volume is about 2 million m^3.

(Einarsson 1962; Thorarinsson and Sigvaldason 1962; Thorarinsson 1963).

Hekla 1947

Eruption site Hekla central volcano, Hekla volcanic system. Eruption began around 06:40 on March 29 and lasted 13 months.

Plinian opening phase emitted andesitic to basaltic-andesitic and was followed by mixed explosive and effusive activity. Maximum observed height of the eruption cloud during the opening phase was about 30 km asl. The main tephra producing phase lasted about an hour but strong explosive activity continued into the afternoon and was significant during the next two days. The tephra produced during these first days was carried due S and to the European mainland. Currents carried some of the tephra that was deposited into the sea westwards along the coast. The tephra layer was an average one, calculated volume is about 180 million m^3.

Weaker explosive activity continued intermittently during the next 2-3 months and tephra was carried towards west and north on several occasions but so far no information exists on tephra fall in West or North Iceland or off the north coast. However, rafts of pumice and ash that resembled shoals of herring as seen from a distance were observed off North Iceland in June 1947. This was assumed to be part of the tephra that fell offshore on March 29.

(Thorarinsson 1954, 1968; Morgunbladid 1947, June 14, p. 12).

Grímsvötn 1934

Eruption site: Grímsvötn caldera, Grímvötn volcanic system. The eruption was first observed on March 30 and lasted until middle of April.

Presumably the eruption had a subglacial opening stage that was followed by surtseyan activity. The only known product was basaltic tephra. Maximum observed height of eruption cloud was about 12.8 km asl. Tephra dispersal was towards SE, E and N. In North Iceland 6 g/m^3 to perhaps 300 g/m^3 of tephra were deposited 30 to 60 km inland. Tephra fall in the coastal areas and offshore must have been considerably less. Estimated volume of tephra is 10-20 million m^3.

(Áskelsson 1936; Thorarinsson 1974)

Grímsvötn 1922

Eruption site: Grímsvötn caldera, Grímvötn volcanic system. The eruption began on October 2 and lasted at least until October 23.

Presumably the eruption had a subglacial opening stage that was followed by surtseyan activity. The only known product was basaltic tephra. Tephra dispersal was was mainly towards N, NE and E between October 5-7 across North and Northeast Iceland and off the coast. Minor tephra fall (dust) was reported in Northwest Iceland. The tephra volume erupted in October was at least 15-20 million m^3.

A predominantly effusive eruption that began in November on the Askja volcanic system may have contributed slightly to the tephra deposits in Northeast Iceland later on.

(Thorkelsson 1923; Thorarinsson 1974).

Grímsvötn 1919

Eruption site: Probably Grímsvötn caldera, Grímvötn volcanic system. The eruption left a tephra layer in the Vatnajökull ice.

No observations of the eruption are known . A brief description mentioning volcanic mist and tephra fall in South Iceland could indicate that the eruption took place in early July. The tephra layer was previously attributed to an Askja eruption. (Steinthorsson 1978; Larsen and Gudmundsson 1997; Morgunbladid 1919, July 16)

Katla 1918

Eruption site: Katla caldera in Mýrdalsjökull, Katla volcanic system. The eruption began on October 12 and lasted for three weeks.

Presumably the eruption had a short subglacial opening stage that was soon followed by strong phreatomagmatic explosive activity producing basaltic tephra. Explosive activity was most intense during the first days and continued intermittently throughout the eruption. The tephra was dispersed widely and tephra fall reached North Iceland on October 14 and also later during the eruption. On October 26 tephra deposition in Akureyri and Húsavík village on the north coast of Iceland may have exeeded 300 g/m^3 (footprints traceable). The tephra layer was fairly large, estimated volume was about 700 million m^3.

(Morgunbladid 1918, October 15, p. 1, October 27, p. 1; Sveinsson 1919; Eggertsson 1919; Thorarinsson 1955, 1975; Larsen 2000).

Grímsvötn 1903

Eruption site: Thordarhyrna, Grímvötn volcanic system. The eruption was first observed on May 28 and continued intermittently for over 7 months.

Presumably the eruption had a subglacial opening stage that was followed by surtseyan activity. The only known product was basaltic tephra. Maximum height of eruption cloud is not known. Tephra production was most intense during the first two days and the tephra was carried towards NE over Northeast and East Iceland and off the coast. Tephra fall was reported by a ship 30 miles east of the coast, off Langanes. Tephra was also dispersed towards SSE. The tephra layer was an average one, estimated volume on land was about 100 million m^3.

(Thoroddsen 1924; Mouritzen and Nygaard 1950; Thorarinsson 1974).

Main element glass composition

Table 2 shows EMPA glass analyses of 12 tephra layers, selected to show range of

Table 2 EPMA glass analyses of tephra from the Grímsvötn, Katla and Hekla volcanic systems

Grímsvötn eruptions*

Element	2004 1)	2004	1998 2)	1998	1996 3)	1996	1934 4)	1934	1922 4)	1922	1903 4)
SiO_2	50,57	49,70	51,15	50,30	54,78	49,44	50,30	50,00	50,30	49,80	49,80
TiO_2	2,73	3,14	2,59	2,56	2,69	2,33	2,80	3,14	3,14	2,98	2,92
Al_2O_3	13,29	13,17	13,41	12,94	12,26	13,08	12,50	12,90	12,90	12,70	13,10
FeO	13,24	14,28	12,24	12,32	14,82	13,49	13,70	14,30	14,10	13,80	13,60
MnO	0,20	0,20	0,19	0,19	0,07	0,27	0,21	0,27	0,20	0,20	0,20
MgO	5,30	5,01	5,64	5,54	2,64	4,50	5,04	5,12	5,22	5,25	5,45
CaO	9,50	9,28	9,75	11,12	8,32	9,74	9,91	9,83	10,20	10,30	10,30
Na_2O	2,80	2,85	3,11	3,02	1,41	2,41	2,56	2,64	2,55	2,39	2,53
K_2O	0,42	0,54	0,59	0,60	0,62	0,49	0,42	0,53	0,40	0,41	0,38
P_2O_5	n.d.	n.d.	0,46	0,50	0,31	0,71	0,34	0,38	0,30	0,31	0,27

Katla eruption*

Element	1918 5)	1918
SiO_2	47,58	47,01
TiO_2	4,70	4,59
Al_2O_3	12,93	12,84
FeO	14,35	14,48
MnO	0,20	0,22
MgO	4,72	4,75
CaO	8,94	9,01
Na_2O	3,26	3,18
K_2O	0,76	0,75
P_2O_5	0,79	0,86

Hekla eruptions*

Element	2000 1)	2000	1991 1)	1991	1980 1)	1980	1970 1)	1970	1947 6)	1947
SiO_2	56,90	56,15	56,03	55,42	56,17	55,87	57,47	55,93	63,61	59,09
TiO_2	2,16	1,96	2,06	2,17	1,92	1,96	1,91	2,20	1,07	1,15
Al_2O_3	13,90	14,49	14,02	13,47	15,02	14,73	14,78	14,34	15,56	15,90
FeO	11,64	11,89	12,14	12,52	10,91	11,73	11,04	12,29	7,65	8,98
MnO	n.d.	n.d.	n.d.	n.d.	0,26	0,28	0,27	n.d	0,23	0,24
MgO	2,95	2,85	2,93	3,02	2,71	3,02	2,76	2,81	1,19	1,71
CaO	6,45	6,63	6,53	6,59	6,31	6,26	5,68	6,97	4,21	4,99
Na_2O	3,84	3,59	3,64	3,58	4,06	3,75	4,36	3,85	4,48	4,52
K_2O	1,19	1,43	1,24	1,59	1,37	1,34	1,43	1,29	1,83	1,69
P_2O_5	0,82	0,90	0,96	0,90	1,11	1,03	1,26	0,99	n.d.	n.d.

Hekla-outliers*

Element	2000 1)	2000	2000
SiO_2	75,97	72,53	70,36
TiO_2	1,05	0,45	0,72
Al_2O_3	13,21	12,85	15,42
FeO	1,31	3,00	0,93
MnO	n.d	n.d.	n.d.
MgO	0,53	0,48	0,31
CaO	1,81	1,43	3,11
Na_2O	4,43	3,97	5,19
K_2O	2,75	4,44	1,92
P_2O_5	0,01	0,15	0,10

***EPMA analyses of single grains indicating range of compositions (not average compositions)**

1) Larsen unpublished data
2) Óskarsson et al. 1999
3) Steinthorsson et al. 2000
4) Grönvold & Jóhannesson 1984
5) Óladóttir et al. in press
6) Larsen et al. 1999

composition where appropriate. The main element composition of the Hekla 1970, 1980, 1991 and 2000 tephra is similar and glass from these layers will be difficult to tell apart. Note the highly silicic Hekla 2000 grains (outliers). Of the tephra from the Grímsvötn system, the 1996 Gjálp tephra is easily disinguished while the 1998 and 2004 tephras are more difficult to tell apart. Also shown is the Katla 1918 glass composition.

Summary

Tephra from 11 eruptions was carried northwards across Iceland and onto the shelf off North Iceland in the period 1900-2005 (Figure 4).

All the northbound Hekla tephra layers are small, between 10 and 70 million m^3. Where data exists on tephra deposition offshore in the Hekla eruptions the mass is 1-15 g/m^2, and at the shoreline north of 66°N the range is 1-80 g/m^2.

Tephra from Grímsvötn eruptions forms thinner “tephra veils” in north Iceland than the tephra from Hekla eruptions, partly because of different type of explosive activity and in some cases because the main tephra dispersal was towards other directions.

In the 1918 Katla eruption tephra fall in North Iceland may have exceeded 300 g/m^2 in Húsavík (footprints traceable) at 66°N. This eruption was the largest eruption of the 20th century.

In nine eruptions airfall may have reached the area of cores MD99-2271, MD99-2272, MD99-2273 and MD99-2275. These were the Katla 1918, Grímvötn 1934, Hekla 1970, 1980, 1991, Gjálp 1996, Grímsvötn 1998, Hekla 2000 and Grímsvötn 2004 eruptions. Known tephra deposition off the north coast was minor, ranging from less than 1 g/m^2 to ~15g g/m^2.

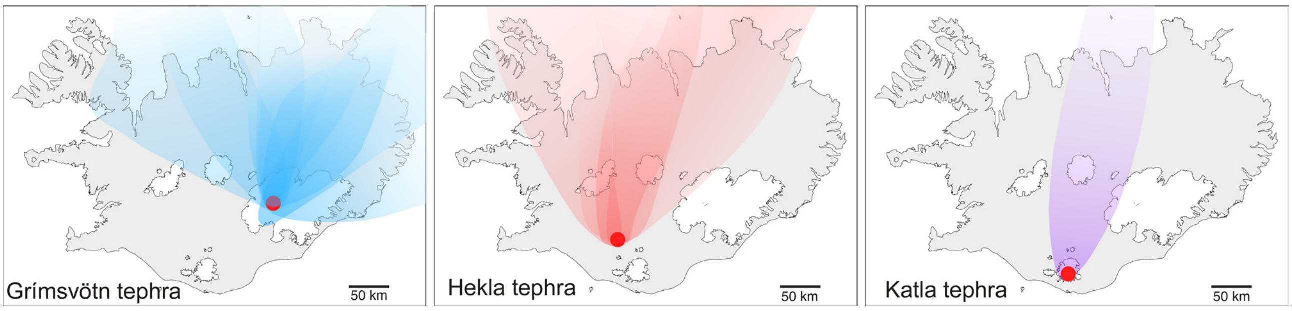

Figure 4: Tephra dispersal towards northerly directions in the period 1901-2005: Grímsvötn 1903, 1922, 1934, 1998, 2004, Gjálp 1996, Hekla 1970, 1980, 1991, 2000 and Katla 1918.

The best candidates for 20th century isochrones in the area where the cores MD99-2271, MD99-2272, MD99-2273 and MD99-2275 were collected are probably the Hekla 2000 and Katla 1918 tephras.

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