Eruptions in Grímsvötn, Vatnajökull, Iceland, 1934-1991

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ABSTRACT
During the period 1934 to 1991 evidence has only been found for three or four volcanic eruptions within the Grímsvötn volcanic centre, i.e. the directly observed eruptions in 1934, 1938, 1983, and probably a small eruption in 1984, deduced from seismic tremors. Tephra layers observed by visitors in the northwestern part of the Grímsvötn depression in the period 1934 to the 1960's have been misinterpreted as signs of eruptions; the very same ash cover was observed throughout the period. This ash cover dates back to the eruption of 1934, but earlier Grímsvötn eruptions may have contributed to its formation. Reported openings in the ice shelf (1945, 1954, 1960) are considered not to be signs of eruptions but could be explained by either steam explosions of hydrothermal reservoirs sealed by impermeable caprock or by increased upwelling of hydrothermal fluid in reservoirs of high permeability due to pressure release during lowering of the Grímsvötn lake level in jökulhlaups. Frequent jökulhlaups in the period 1938-1948 can be adequately explained by high melting rate at the site of the eruption of 1938.

The eruptions of 1934 and 1983 produced hyaloclastites of volume $30-40 \times 10^6$ m$^3$ and $10-10^6$ m$^3$, respectively. The eruption of 1938, on the other hand, produced volcanic material of the order of $400-10^6$ m$^3$ and may have been the third largest eruption in Iceland this century, after Hekla in 1947 and Surtsey in 1963-1967. The volume of material erupted in Grímsvötn since 1600 AD has been estimated of the order of 2.3 km$^3$ and the total production may have been 3-5 km$^3$ in historical times.

INTRODUCTION
The history of recent volcanism within the Vatnajökull ice cap, SE-Iceland, has been studied by several authors (Þórarinsson, 1974; Steinþórsson, 1977; Larsen, 1982; Jóhannesson, 1983; 1984; Grönvold and Jóhannesson, 1984; Björnsson, 1988; Björnsson and Einarsdóttir, 1990; Guðmundsson, 1992). About 80 eruptions have been attributed to the volcanoes beneath Vatnajökull in historical times of which 63 are considered certain. Over the last several hundred years, Grímsvötn (Fig. 1) has been the most active of the volcanoes located within Vatnajökull. This volcanic centre has developed three calderas (Sæmundsson, 1982; Guðmundsson, 1992). The number of eruptions in Grímsvötn over the last 1100 years has been estimated to be between forty and fifty (Þórarinsson, 1967). Björnsson and Einarsson (1990) list 36 eruptions within or near Grímsvötn in their compilation of known eruptions in historical times.

The volcanic history of the 20th century has been a subject of some discussion in recent years. Three eruptions are known for sure, in 1922, 1934 and 1983 (Þórarinsson, 1974). There is also a general agreement that an eruption took place to the north of Grímsvötn in 1938, causing a large jökulhlaup (Þórarinsson, 1974; Björnsson, 1988).

Jóhannesson (1983; 1984) reexamined records on eruptions in Grímsvötn in this century and concluded that eruptions had taken place in Grímsvötn in 1902-1905, 1922, 1933, 1934, 1938, 1945, 1954 and 1983. Moreover, he considered it possible that small eruptions had occurred in 1939, 1941 and 1948. His conclusions are based on reinterpretation of field observations in Grímsvötn, irregularities in the period
between jökulhlaups from the Grímsvötn lake, and in the case of the inferred eruption in 1933, on the sighting of an eruption column.

Brandsdóttir (1984), analysing existing seismic records for the period 1900-1982 concluded that seismic activity similar to that observed during the eruptions in 1934 and 1983 did not occur in the period between the eruptions. A burst of volcanic tremor observed for about 1 hour on August 21, 1984 has been interpreted as a small eruption that did not reach the surface of the ice (Björnsson and Einarsson, 1990).

Due to the remoteness of Grímsvötn only the eruptions of 1934 and 1983 have actually been observed in the field (Áskelsson, 1936; Grönvold and Jóhannesson, 1984). The majority of eruptions in Grímsvötn have been inferred from the sighting of eruption columns and tephra falling on the lowlands surrounding the glacier.

The first known visit to Grímsvötn was that of two Swedish geologists, H. Wadell and E. Ygberg in the summer of 1919 (Wadell, 1920). The next visit took place during the eruption in 1934. Between 1934 and 1953 the area was inspected from the air or visited by expeditions on the ground every one or two years (Pórarinsson and Sigurðsson, 1947; Pórarinsson,
1974). Since 1953, annual expeditions have visited the area and Grímsvötn has been inspected from the air during every jökulhlaup since 1941 (Bórarinsson and Sigurðsson, 1947; Pórarinsson, 1974; Björnsson, 1988).

In order to study further the volcanic history of Grímsvötn in this century we have examined data acquired within the Grímsvötn area since 1934. These data are written accounts from expeditions, air photos, old maps of ice surface topography and photographs. Further, the bedrock topography in the area (Fig. 2) has now been defined in considerable detail (Björnsson, 1988; Guðmundsson, 1989). Potential eruption sites can therefore be inspected for evidence of eruptive vents.

EFFECTS OF ERUPTIONS IN GRÍMSVÖTN; DIRECT OBSERVATIONS

THE ERUPTIONS IN 1934 AND 1983

The eruption in March-April 1934 lasted for at least 2 weeks and three craters were active during the eruption (Áskelsson, 1936; Nielsen, 1937; Pórarinsson, 1974). The craters were all located near the southern caldera rim and the largest crater was under the southern caldera wall to the north of the nunatak Svíahnúkur Vestri (Figs. 2 and 3). The eruption formed an opening in the ice shelf, 500-600 m in diameter with vertical ice walls, a few tens of metres high. A semicircular island had formed in the centre but fans of dark sand or tephra could be seen under the ice walls to the north and the west. The two other craters were much smaller, located in the southwest corner of the caldera. A
layer of tephra was spread over the area but the flat interior parts of the ice shelf were apparently covered with new snow, masking the tephra layer shortly after the eruption (Áskelsson, 1936; Nielsen, 1937).

Five earthquakes with epicentral distance fitting with Grímsvötn, were recorded in Reykjavík at the start of the eruption, ranging in magnitude from 3.5 to 4.5 (Tryggvason, 1960). Traces of smaller earthquakes with similar appearance can also be seen on the seismic records (Brandsdóttir, 1984).

Expeditions to Grímsvötn in the summer of 1935 (Áskelsson, 1936; Nusser, 1948) reported that the craters were still visible, as were the ice walls surrounding the large crater. The island and the fans of tephra below the ice walls were no longer visible as the rise in the water level since April 1934 was of the order of 40 m (Guðmundsson and Björnsson, in prep.). In the spring of 1936 the craters were still visible but no water was detected (Nielsen, 1937). No expeditions visited Grímsvötn in 1937. Air photos by P. Hannesson from May 28, 1938 (Table A2 in Appendix) indicate that no open water existed in the craters at that time.

The eruption site of 1983 was at a similar location as the large crater of 1934 (Figs. 2 and 3). A similar opening in the ice shelf was formed (Fig. 4), about 500 m in diameter (Grönvold and Jóhannesson, 1984). The eruption lasted a few days, started on May 28 and was probably over on June 2. An island, semicircular in form and with a diameter of about 80 m, was formed in the lake. On the ice shelf, an ash and debris fan radiated 0.5-1 km to the north from the crater. Ash
fans towards south and east were also seen. The eruption was detected by seismometers (Einarsson and Brandsdóttir, 1984) but was not seen from the inhabited areas to the south of the glacier. The 1983 eruption was much smaller than that of 1934.

Since 1983, conditions at the eruption site have been observed during the annual expeditions of the Iceland Glaciological Society and other expeditions to Grímsvötn (Björnsson and Guðmundsson, unpublished data). The opening in the ice shelf around the crater remained open through 1984 but open water was not observed in the crater in 1985 and 1986. However, it is evident from the crevasse pattern on air photos taken on September 12, 1986 (Table A1 in Appendix), at the end of a jökulhlaup, that the ice shelf in the crater area was very thin. During the summer of 1987 the mound formed in 1983 was clearly visible and the opening in the ice shelf reappeared. A much smaller opening was observed in 1988. By 1989 the mound had disappeared under the rising water level and open water was not detected. Inspection of the crevasse pattern formed at the end of the 1991 jökulhlaup shows that a substantially thicker ice shelf covered the crater of 1983 than at the end of the jökulhlaup in 1986.

Fig. 5 shows a cross section through the southern caldera rim, including the two eruption sites. It is based on the results of recent radio-echo soundings, air photos and seismic reflection (Guðmundsson, 1989). The mounds formed during the eruptions of 1934 and 1983 can be seen. The mounds rise slightly above the lake level at the time of the eruptions. The mounds are presumably the rims of the craters active during the eruptions and Fig. 6 is a schematic cross section showing conditions during an eruption like the two described above. The dashed lines show the form of the ice shelf before the eruption.

The volume of the material erupted in 1934 and
1983 can be estimated from the size of the mounds formed and the tephra that was spread over the glacier surface. It may, however, be an underestimate as some of the erupted material may have been deposited on the lakefloor as lahars beds. Moreover, reflection seismics and magnetics indicate that parts of the lake floor are covered with lava flows which must have formed under water (Guðmundsson, 1989). The volume of the mound of the main cather in 1934 is $15-20 \times 10^6$ m$^3$ while the volume of material deposited at the other two sites was less, probably no greater than $5 \times 10^6$ m$^3$. Þórarinsson (1974) estimated the total volume of tephra in 1934 as $10-20 \times 10^6$ m$^3$. Therefore, the minimum estimate of the volume produced in the eruption of 1934 is $30-40 \times 10^6$ m$^3$.

The hillock formed in 1983 has a volume of $6-8 \times 10^6$ m$^3$ and the amount of ash erupted was minute compared to 1934 (Grönvold and Jóhannesson, 1984). Hence, the total volume produced by the eruption of 1983 was not greater than $10-10^6$ m$^3$.

**THE ERUPTION IN 1938**

A large unexpected jökulhlaup occurred on May 23 - June 6, 1938, only 4 years after the large jökulhlaup in 1934 (Þórarinsson, 1974; Björnsson, 1988). Usually the Grímsvötn jökulhaups rise for 7-15 days and then recede in 1-3 days (Björnsson, 1988). The 1938 jökulhlaup reached a maximum in 3 days and receded slowly for two weeks. The reason for this was that a large area to the north of Grímsvötn subsided and a large volume of water was drained into Grímsvötn causing a sudden rise in the lake level, sparking off the jökulhlaup (Björnsson, 1988) (Figs. 1, 7 and 9a). In a reconnaissance flight on May 28, 1938, no tephra was seen on the surface of the glacier within or near the subsided area. The depression trended towards the north for 9 km from the northwest corner of Grímsvötn. The area could be divided into two parts. The southern part was linear while the northern part, which was the wider of the two, was elliptic with the long axis striking NNE. The border area between the two was narrower and the sub-
dence of the ice surface was somewhat less than elsewhere (Fig. 7); suggesting reduced basal melting at the border area. According to a map drawn by G. Gestsson (Dórarinsson, 1974) (Fig. 9a) on the basis of the photos from May 28, 1938, the volume contained within the subsided area is 2 km³. Dórarinsson (1953a; 1974) used the same data together with rough mass balance estimates for the Grímsvötn basin and obtained a value of the order of 3 km³.

Oblique air photos were used to draw the surface contours of Vatnajökull on the maps of the Danish Geodetic Institute (Nørlund, 1944). These photos were taken in 1937 and 1938. A photo taken over Dyngjuháls (50 km to the north of Grímsvötn) on August 28, 1937 shows that the depression to the north of Grímsvötn observed in 1938 did not exist at that time. Three sets of photos exist from 1938 that show Grímsvötn, the depression and the cauldrons. The first set was taken on June 23 from a plane over Köldukviðarljökull, about 25 km to the northwest of Grímsvötn (Fig. 8a). The second set of photos was taken on July 1, at a point 40 km to the southwest of Grímsvötn. The third set is taken from a point about 25 km to the northeast on August 30 (Fig. 8b). The northern part of the subsided area is covered with a dark layer on the July and August photos while it cannot be decided with certainty whether such a layer existed on June 28.

Dórarinsson (1974) considered it likely that a subglacial eruption had occurred to the north of Grímsvötn causing rapid melting of ice, forming the depression and the cauldrons. Björnsson (1988) car-
ried out radio-echo soundings in the area in 1987 and 1991 and found that the location of a north trending subglacial ridge coincides with that of the subsided area of 1938. Further, he suggested that the ridge may have been formed in an eruption in 1938.

The dark ash layer observed in the northernmost part of the subsided area in July and August 1938, suggests that an eruption broke through the surface after May 28. Hence, volcanic activity may have persisted for some weeks. However, its vigour was probably not great after May 28, as the extent of the subsided area does not seem to have increased significantly during the summer.

The course of events in 1938 may have been as follows: An eruption started on a several km long N-S trending fissure to the north of the northwest corner of Grímsvötn, probably several days prior to the onset of the jökulhlaup. By May 28 the eruption had melted at least 2 km$^3$ of ice. The meltwater drained to Grímsvötn and caused a sudden rise in water level and rapid opening and draining of the lake. Before May 28 anyway, the eruption was entirely subglacial but later renewed or continued activity broke the surface of the glacier and a small ash layer was spread over the northern part of the subsided area.

The bedrock in the area of the subsidence is fairly
Fig. 9.

a) Grímsvötn and the subsided area in 1938. The contours are from G. Gestsson’s map and the solid lines show the radio-echo sounding lines that cover the area. Grímsvötn og sigdældin norðan þeirra 1938 samkvæmt korti Gísla Gestssonar. Íssjárlnir yfir svæðið þar sem sigdældin var 1938 eru merktar inn á kortið.

b) Cross sections showing the ice surface in 1938 and the bedrock as measured in 1987 and 1991. The ridge considered to have been formed in the eruption is shaded. Sníð yfir sigdældina frá 1938 samkvæmt íssjármælingum 1987 og 1991. Hryggurinn sem talinn er hafa myndast í gosinu er skyggður.

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complicated with several ridges and mounds. Figure 9 shows six east-west profiles across the area. A 70-200 m high ridge is located beneath the subsided area. The volume of the ridge is greatest in the northernmost part where the width and depth of the subsided area was greatest. The total volume of the ridge is of the order of 0.4 km³. The form and size of the ridge conforms reasonably well with that of the depression and its volume is sufficient to account for the ice melted by the eruption. This supports the suggestion that this ridge was formed in the subglacial 1938 eruption.

A depression like the one formed in 1938 would be eliminated by ice flow within a few years if it were not maintained by melting by a subglacial heat source. Apparently, by 1942 the larger part of the depression had been eliminated by ice flow (Sigrúnsson, 1942; 1984). However, a slight depression was visible in 1945 (Fig. 10), and on vertical air photos from September 1946, the northern margin of the depression was marked by crevasses, indicating that melting of ice at the bedrock was still taking place eight years after the eruption.

COMMON EFFECTS OF ERUPTIONS IN GRÍMSVÖTN

Before reviewing the various reports of observations in Grímsvötn and their significance as indicators of recent eruptions we summarize the effects of the three eruptions in 1934, 1938 and 1983 which were all thoroughly described.

1. Layers of tephra were spread on the ice surface.
2. Openings were formed in the ice shelf or the glacier directly above the crater, often containing water bordered by vertical ice walls.
3. Open water or a depression in the ice at the eruption site may persist for years, indicating locally increased heat flux.
4. A pile (a mound or a ridge) of hyaloclastites is formed in the bedrock at the eruption site.
ASSESSING ERUPTIONS IN GRÍMSVÖTN FROM INDIRECT EVIDENCE

TEPHRA LAYERS IN GRÍMSVÖTN

Several visitors to Grímsvötn in the period 1934 to the early 1960’s reported ash layers on the glacier surface which later have been taken as signs of continued volcanic activity during this period. Photos taken at the end of the eruption in 1934 (Áskelsson, 1936; Nielsen, 1937) show that the Grímsvötn area is covered by tephra except for depressions where the tephra is apparently hidden with new snow. The
photos from the early summer of 1935 (Áskelsson, 1936; Nusser, 1948) show that the crevassed slope at the northern margin of Grímsvötn is covered with tephra while fresh snow and firn cover the lowstanding areas and the glacier surrounding Grímsvötn. The photos from the summer of 1938 (Figs. 7-8) show little tephra in May, in June the area had a light grayish colour and in late August the surface of the depression was covered with dark ash.

In August 1942 the western part of Grímsvötn was covered by dark ash and the snow in the eastern part was coarse and dirty (Sigurðsson, 1942; 1984). Vertical air photos have been taken several times in Grímsvötn. The first set of photos were taken on August 30, 1945, one month prior to a jökulhlaup (Dórarinsson, 1974). The northwestern part of Grímsvötn was covered with dark ash and the firm in the southern and eastern parts has a grayish colour. The photos from September 19, 1946 (Fig. 11), show the area to be covered with the same ash layer as in August 1945. This can be seen by comparing the margins and the surface pattern of the ash layer (Fig 12). On both sets of photos the margins of the ash layer are clear, shifting from dirty firm to continuous ash cover. Apparently the ash layer is overlain by firm.

The northwestern corner of Grímsvötn was covered with ash on July 22, 1947 and August 28, 1950 as well as the edge of the northern slopes (Figs. 13a and 13d). In contrast, no ash layers could be seen on February 22, 1948 (Figs. 13b, c). However, the surface in the northwestern part of the depression is uneven (Fig. 13c) because dirt cones are only partly covered with the winter snow.
Fig. 13. Grímsvötn from the air (photos Sigurður Þórarinsson). *Grímsvötn úr lofti*


c) February 22, 1948. View from the north showing the western part of the depression. Crevasses in the foreground but the small undulations on the surface in the northern part of the depression are partly covered dirt cones and ridges. 22. febrúar 1948. *Horfi úr norðri.* *Fremst á myndinni er sprungusveðri í Svartabunka en ójófurnar í norðurhluta vatnanna eru aurkeillur og hryggir sem ná upp úr vetrarsnjónum.*

Figure 12 shows the distribution of ash in Grímsvötn according to the vertical air photos. Two months after a jökulhlaup, in September 15, 1954, patches of ash were located in the northwestern part of Grímsvötn. In August 9, 1960, seven months after a jökulhlaup, isolated patches of ash could be seen in the northwestern part, located at the same places as in 1954. No similar ash layers could be detected on air photos from August 10, 1972. However, the firm was dirty with ash near Nagur and at one location in Svatibunki (Fig. 1). In August 22, 1984 the ash layer seen on earlier photos could no longer be detected but ash was spread over parts of Grímsfjall and around the 1983 crater. This ash layer is from the 1983 eruption and has not been observed after 1984.

During the period from 1934 to 1960 at least, it depended on the time of the year whether tephra was observed in Grímsvötn. With the exception of 1934 and 1935, very little or no tephra was detected in Grímsvötn in winter and spring. In contrast, all observations in late summer and autumn show sizable parts of the northwestern corner of the area covered in tephra. Moreover, photos show that the surface of the ash-covered area was uneven and rough in late summer, similar to ablation areas of some outlet glaciers.

These observations raise the question whether the very same ash layer was being observed throughout this period (1934-1960). That would imply the whole winter accumulation in the northwest part of Grímsvötn being melted during the summer and that the area was an ablation area indeed. For such an ablation area to exist, surface melting would have to be considerably greater than typically at the elevation of 1400 m a.s.l. in Vatnajökull (Björnsson, 1988). The mean winter balance in Grímsvötn is about 4.5 m of snow, equal to 2450 mm of water (Björnsson, 1985) whereas the summer balance under normal snow conditions with albedo of 0.6 is of the order of -500 mm.

Dispersal of ash over the glacier surface, decreasing the albedo, may explain melting of the entire winter accumulation. An average solar radiation flux of 200 W/m² (as measured by Björnsson (1972) on Bægisárjökull, North Iceland during July and August; 1100 m a.s.l.) could melt the whole winter accumulation in 70 days if the albedo were 0.2.

From 1934 to the 1960’s low albedo values were maintained in the western part of Grímsvötn during summer. Wind-blown ash and loose material were dispersed from nunataks and ash cones and ridges which became free of snow early in the summer. On these nunataks the geothermal heat flux was high and the winter accumulation was reduced by snowdrift on the uneven surfaces (see Figs. 7-8 and 13). This is e.g. confirmed by photogrammetric measurements of vertical air photos (H. Kristinsson, Hnit engineering consultants) which show that the surface of the ash covered area in the northwestern part of Grímsvötn was uneven with a relief of a few metres on September 19, 1946.

Figure 12 shows a gradual decrease of the ash covered areas between 1946 and 1972. Photos from the area show that a gradual decrease in the extent of the ice-free areas was also apparent by the early 1950’s. That decrease was accelerated in the late 1960’s and 1970’s (Björnsson, 1988). Apparently increased albedo retarded the melting of the winter accumulation and the ash layers finally became buried by snow. Further, the trend towards cooler summers in Iceland since 1946 (Einarsson, 1989) and reduced ablation may have accelerated the burying of the ash layer.

On the basis of these considerations we suggest that the northwestern part of the Grímsvötn depression was an ablation area, at least over the period 1934-1960 and the very same ash layer was observed by expeditions to the area throughout this period. This ash cover dates back to the eruption of 1934 but it may contain ash dispersed in earlier eruptions, especially that of 1922. According to Fig. 12 the size of this ablation area was about 20 km² in 1945 and 1946. By 1972 the ablation area no longer existed.

**Effects of tephra layers on glacier mass balance**

The existence of an ablation area within Grímsvötn in the period 1934 to 1960 calls for an explanation of greater surface melting than at present. As the data on surface ablation within the Grímsvötn depression are limited and sporadic, estimates of total ablation have been fairly rough. Björnsson (1988) used available data to estimate the mean ablation at present as being
of the order of 500 mm/yr within the 160 km² Grímsvötn basin. In order to estimate the surface ablation in Grímsvötn in the period 1934-1960, we have divided the drainage basin into three areas. First, the 20 km² ablation area where we estimate the surface ablation to have been 2500-3000 mm/yr (elevation 1350-1450 m a.s.l.). Second, we use a value of 1500 mm/yr in a 20 km² surrounding area (elevation 1350-1500 m) and third, a 120 km² area (elevation 1500-1700 m) with an ablation of 200 mm/yr, similar to present conditions. The mean ablation within the basin according to this model is estimated as 650-710 mm/yr or 30-40% greater than the present value.

**OPENINGS IN THE ICE SHELF**

Volcanic eruptions can create openings or sinkholes in the glacier but it has been a matter of some discussion whether reports of such holes can be taken as sure signs of volcanic activity. Depressions or cauldrons in the ice surface are scattered over the area surrounding the Grímsvötn lake (Fig. 1). These cauldrons are created by subglacial geothermal activity. Over the period of observations, these cauldrons have varied in number, size and shape. Inspection of the vertical air photos (from 1945, 1946, 1954, 1960, 1972, 1984 and 1986, Table A1) shows, however, that most of the cauldrons are observed over the whole period. Several cauldrons are located under the southern caldera wall and in the Svartibunki area, the former northern margin of the subglacial lake in the northwest corner of the depression (Fig. 1). Judging from the size of the cauldrons, geothermal activity under the southern caldera wall does not seem to have decreased. On the other hand the cauldrons located a few km north of Svíahálmur Eystrí have decreased in size since 1960 and the same seems to apply to the cauldrons in the Svartibunki area.

According to air photos and field observations (Sigurðsson, 1942; 1984; Þórarinsson, 1953b) a large patch of open water existed in summer along the western slopes of the caldera in the forties and early fifties. This patch was 50-100 m wide and several hundred metres long. This indicates intense heat

Fig. 14. The sinkhole that formed in Svartibunki near the end of the jökulhlaup in 1954 viewed from the northwest (photo Sigurður Þórarinsson, August 28, 1954).

*Strokkurinn sem myndaðist í Svartabunka í lok hlaupsins 1954. Horfi úr norðvestri.*
flow in this area at the time. After 1960 the patch decreased in size and it disappeared in the early eighties. No holes or openings similar to the ones formed during the eruptions in 1934 and 1983 have been observed in this area.

An expedition that visited Grímsvötn on October 5, 1945, reported a circular sinkhole in the “eastern part of the northwest corner of the depression” (Áskelsson, 1959). The walls were vertical, the depth close to 100 m while the diameter was smaller. Strong smell of sulphur was found in the vicinity of the crater. Áskelsson (1959) considered that the crater was created a few days earlier by a small eruption producing mostly steam but also an ash layer covering the northwestern part of the Grímsvötn depression. No eruption column was ever seen during the course of the jökulhlaup that started on September 16, 1945, culminating around September 27, and no indications of an eruption were seen during inspections from the air on September 22, 26 and October 4 (Hannesson, 1958).

Was the sink crater observed by Áskelsson in 1945 created by a volcanic eruption? The question whether a subglacial mound is situated at the site of the sinkhole cannot be answered, as its exact location is unknown. The ash layer which Áskelsson (1959) considered to have been formed in an eruption shortly before October 5 existed on August 30 and had probably done so for some years. Moreover, no signs of locally increased heat flow in this area can be seen from the air photos of 1946. Hence, we find no support for Áskelsson’s (1959) suggestion.

A sinkhole with about 50 m high vertical walls and a diameter of about 200 m was observed in the eastern part of Svatibunki at the culmination of the jökulhlaup in 1954 (Pórarinsson, 1974). Small ice blocks floated on the water covering the bottom of the hole (Fig. 14). The hole apparently maintained its shape for at least seven weeks (July 21 - September 7) but the vertical air photos (Table A1) show that it had collapsed by September 15. A smaller sinkhole was formed in the southwest corner of Grímsvötn at the culmination of the 1954 jökulhlaup. The firm surface surrounding the smaller hole was crevassed but not stained by ash or tephra. This hole was still visible on September 15. No eruption column was observed in 1954 and Pórarinsson (1974) suggested that the large sinkhole was created by a steam explosion. Jóhannesson (1983) has suggested that a small eruption took place near the end of the jökulhlaup in 1954.

Air photos from 1945 onwards, show that a cauldron has existed in Svatibunki where the sinkhole formed, at least since 1945. This indicates that the hole formed above a local geothermal upflow zone. Furthermore, according to Pórarinsson (1955) and Eyþórsson (1960), a sinkhole with a powerful fumarole was observed at the same location in June 1955 and 1960. On both occasions the sinkhole had vertical walls and a diameter of about 30 m.

The area surrounding the cauldron has been covered with a dense network of radio-echo soundings and the site of the sinkhole of 1954 is shown on the bedrock map on Fig. 2. There are no signs of a mound indicating the eruption of magma onto the base of the glacier under the sinkhole. Hence, the suggestion that a volcanic eruption occurred at this site in 1954 should be discarded.

Pórarinsson (1974) suggested that the sinkholes in Grímsvötn were created by steam explosions. A steam explosion may occur where a hydrothermal reservoir is sealed by poorly or impermeable caprock (Williams and McBriney, 1979). Boiling in the reservoir leads to increased fluid pressure which may exceed the lithostatic load. Fracturing in the caprock may open a channel for the fluid to the surface and a sudden release of pressure will cause rapid boiling and catastrophic expansion of the fluid. In Grímsvötn a steam explosion may take place because a sudden pressure release occurs during a jökulhlaup, about 10 bars in a fortnight.

The sinkholes may also be created by locally enhanced melting of ice after increased upwelling of hydrothermal fluid in reservoirs of high permeability due to the pressure release during the jökulhlaups. Within zones of upwelling of hydrothermal fluids in high temperature geothermal areas, the temperature gradient in the vertical fluid column follows the boiling point curve and the ratio of steam and liquid is presumably stable. A sudden pressure release reduces the boiling point below the actual temperature, throughout the column, and leads to vigorous
boiling and increased buoyancy of the fluid (Fig. 15). Alternatively, vigorous upwelling of the hydrothermal fluid may be caused by magmatic intrusion into the hydrothermal reservoir. This may have been the case when the sinkhole, observed northeast of Sviðnúkur Eystri on December 8, 1983 (Björnsson and Kristmannsdóttir, 1984), was formed by the collapse of an ice cauldron during a period of high seismic activity in Grímsvötn after the eruption of 1983 (Björnsson and Einarsson, 1990).

**SEISMIC TREMORS**

Björnsson and Einarsson (1990) suggest that a small subglacial eruption occurred in Grímsvötn on August 21, 1984. Continuous tremors were observed on seismographs for about one hour, and based on the relative amplitudes on different seismographs a source could be located in the Vatnajökull area. After this event seismic activity in the Grímsvötn volcano ceased, having been high for some months. Aerial photos from August 22 (Table A1) indicate that surface melting was high but no signs of a recent eruption were apparent. If a subglacial eruption occurred on August 21 the volume of erupted material was small compared to the 1934 and 1983 eruptions.

**HIGH SEDIMENT LOAD IN JÖKULHLAUPS**

An unexpected peak in the sediment concentration occurred near the end of the jökulhlaup in 1972 (Tómasson, 1974). No eruption was observed in Grímsvötn (Björnsson and Hallgrímssson, 1976). Air photos taken on August 10, 1972, 4 months after the jökulhlaup show no signs of a recent eruption or unusually high heat flow. Moreover, Einarsson and Brandsdóttir (1984) consider an eruption at this time very unlikely, as it would have been detected by seismometers. A different explanation should therefore be sought for the observed peak in the sediment load.

**DARK LAYERS IN SNOWPITS**

A thin brown layer was observed in snowpits at 1.5-2 m depth in Grímsvötn in the summer of 1954.
(Pórarinsson, 1955). The thickness of the winter accumulation was of the order of 4 m, suggesting that the layer was dispersed over the area in mid winter. Fresh ash layers within Grímsvötn have a black colour when observed in snow pits and crevasses. Hence, the brown colour indicates that the layer was created when fragments of hyaloclastite tuffs where dispersed by a steam explosion.

SHORT INTERVALS BETWEEN JÖKULHLAUPS

The unusually short time interval between the jökulhlaups of 1939, 1941, 1945 and 1948 has been cited as indirect evidence for eruptions in the Grímsvötn area (Jóhannesson, 1983; 1984; Grönvold and Jóhannesson, 1984). As far as we are aware, no observations were made in Grímsvötn in 1939. During the jökulhlaup in 1941, however, Grímsvötn were inspected from air by P. Hannesson (Pórarinsson, 1974). He recorded no unusual activity in Grímsvötn, only crevasses around the periphery of the depression indicating that the central ice shelf was subsiding. The jökulhlaup in 1948 reached a maximum on February 23 about a month after its start. On the morning of February 20 a fallout of gray-brown ash was recorded on a fishing boat off the SE coast, about 120 km to the SE of Grímsvötn but ash was not detected elsewhere (Pórarinsson, 1974). Grímsvötn were inspected from the air on February 22, 1948, (Figs. 13b, c) but no signs of volcanic activity were observed (Pórarinsson, 1974). Whatever the nature of the gray-brown ash detected off the SE coast, its origin was not in Grímsvötn. Björnsson, (1988, p. 84), however, suggested that increased geothermal activity following the eruption of 1938 caused the frequent jökulhlaups in the 1940’s.

Effects of the 1938 eruption on jökulhlaup frequency

The main volcanic event in Grímsvötn since 1934 was the fissure eruption in 1938 and the high frequency of jökulhlaups in the period 1938-1948 may be explained by melting of ice at the eruption site. The volume of the ridge created in the eruption is of the order of 0.4 km³ and assuming that it is made of hyaloclastites, its mean density may be close to 2000 kg/m³ which puts the total mass of the erupted material to 8.0·10¹¹ kg. The maximum amount of melting during the eruption would occur if all the magma were quenched as basaltic glass. The heat released during the eruption would then be given by E=mC(T₀-T₁) where m is the total mass of the erupted material, C is the specific heat capacity of the glass, T₀ is the initial temperature of the magma and T₁ is the ambient temperature at the eruption site (T₁=0°C). By using T₀=1150°C (typical for tholeiitic magma, Williams and Mc Birney, 1979) and C=1000 J/kg°C (Allen, 1980), the total heat released would be 9.2·10¹⁷ J. Using the latent heat of fusion for water, Lₑ=3.35·10⁸ J/kg, the total mass of ice melted during the eruption is 2.7·10¹² kg or 2.7 km³ of water, which is similar to the volume of the depression formed in the glacier surface in 1938 (Fig. 9). If pillows make up a significant part of the rock volume the rate of melting during the eruption would be somewhat less as the heat would be released over a longer period of time.

The quenching of the magma and the formation of glass results in the latent heat of fusion of the magma not being released upon cooling but gradually during the alteration of the glass to palagonite. According to experience from Surtsey, the palagonitization was well advanced in a large fraction of the rock volume 12 years after the eruption that formed the hyaloclastites (Jakobsson and Moore, 1982). Steinþórsson and Óskarsson (1986) estimated that the heat released during palagonitization of basaltic glass is about 4.2·10³ J/kg. Thus, the total energy released in the palagonitization of a mass of 8.0·10¹¹ kg is 3.4·10¹⁷ J which would melt 1.0·10¹² kg of ice which is equivalent to a water volume of 1.0 km³. The total volume of meltwater would therefore be 2.7+1.0 km³ = 3.7 km³. Crystallization and cooling of the feeder dyke will also cause melting. For example, a feeder that is 2 km high, 8 km long and 2 m wide (i.e. 0.032 km³) would give away heat that melts about 0.4 km³ of water. The total volume of water melted gradually over several years is therefore of the order of 1.4 km³.

The meltwater formed above the ridge after the eruption of 1938 either drained continuously to
<table>
<thead>
<tr>
<th>YEAR</th>
<th>DURATION</th>
<th>TYPE AND NUMBER OF CRATERS</th>
<th>MOUND/ RIDGE VOLUME</th>
<th>TEPHRA VOLUME</th>
<th>TOTAL VOLUME</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ár</td>
<td>fjiði giga</td>
<td>rúmmál hryggs km³</td>
<td>rúmmál gjósku km³</td>
<td>heildarrúmmál km³</td>
</tr>
<tr>
<td>1934</td>
<td>&gt;2 weeks</td>
<td>3</td>
<td>0.02</td>
<td>0.01–0.02</td>
<td>0.03–0.04</td>
</tr>
<tr>
<td></td>
<td>&gt;2 vikur</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1938</td>
<td>1–5 weeks</td>
<td>7–8 km fissure sprunga</td>
<td>0.3–0.5</td>
<td>minute örlitöd</td>
<td>0.3–0.5</td>
</tr>
<tr>
<td></td>
<td>1–5 vikur</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>5–6 days</td>
<td>1</td>
<td>0.01</td>
<td>minute örlitöd</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>5–6 dagar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 klst?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Grímsvötn or accumulated above the fissure in subglacial vaults. The water filled vaults may have drained periodically to Grímsvötn, increasing suddenly the lake level, perhaps by an order of a few metres at a time. This meltwater was an addition to the volumes melted within Grímsvötn, causing exceptionally fast rise in lake level. Moreover, during periods of increased geothermal heat flow, the temperature of the lake water may be somewhat higher than usual. That may lead to jökulhlaups at a lower lake level than during periods of lower geothermal heat flow. Thus, the frequent jökulhlaups from Grímsvötn in the first ten years after 1938 may have been a consequence of a single large fissure eruption in 1938. There is no need to claim that several eruptions took place in the period.

**DISCUSSION**

The eruption of 1938 is one of largest in Iceland this century, in terms of volume erupted. Only two eruptions are known to have been more voluminous, i.e. Hekla in 1947 and Surtsey in 1963-1967 both of which produced around 1 km³ (Dórarinsson, 1967). This large fissure eruption in 1938 was almost entirely subglacial while the two fairly small eruptions of 1934 and 1983 broke through the surface of the ice soon after their start. This is probably due to the great ice thickness at the site of the 1938 fissure, 400-700 m, requiring larger buildup of hyaloclastites, while the water depth at the sites of the 1934 and 1983 eruptions was of the order of 100 m. This shows that fairly large subglacial fissure eruptions may have occurred beneath Vatnajökull in past centuries without being observed from the lowlands surrounding the glacier. Large jökulhlaups, however, would witness to the event.

Dórarinsson (1967) estimated the total volume erupted in Grímsvötn in historical times (1100 years) as 1.5 km³. We have shown here that the magma production was about 0.35 km³ (magma density 2650 kg m⁻³) in the last 57 years, a period with relatively few eruptions. Large eruptions, similar to the event in 1938, have occurred earlier, i.e. in 1867 and probably also in 1892 (Björnsson, 1988). The production rate observed in 1934–1991, of 6·10⁻⁶ m³ a⁻¹, may therefore be representative for the period after 1600 AD, yielding a total volume of 2.3 km³. If this high production rate has prevailed over the last 1100 years the total volume erupted would be 6–7 km³. A total of 29 eruptions have been attributed to Grímsvötn in the period after 1600 but only 7 in the period 900–1600.
Although this apparent difference in eruption frequency may, at least partly, be due to incomplete records, it suggests that a more conservative estimate of the total volume erupted should be made. If the production rate prior to 1600 was, say, one fourth to half that observed at present, the estimate of the total volume erupted in historical times would be 3–5 km$^3$.

The conclusions reached in this paper are consistent with the interpretation of internal reflections acquired with a multiband synthetic pulse radio-echo sounder in the Grímsvötn area in 1991 (Björnsson et al., in preparation). The internal reflectors are interpreted as being tephra layers within the ice. Sounding profiles in the eastern part of the Grímsvötn area show four tephra layers above the depth of 200 metres. The two uppermost layers are considered to be from the eruptions of 1934 and 1922, on the ice divide to the east of Grímsvötn, the depth to these layers is 130 m and 150 m, respectively. In the central part of the Grímsvötn ice shelf the depth to the layer of 1934 is reduced to 80 m. No tephra layers were detected above the layer of 1934, supporting our conclusion that no eruptions occurred within Grímsvötn between 1934 and 1983.

Temporary existence of an ablation area in the Grímsvötn depression would complicate the use of tephra layers for estimating glacier mass balance from ice cores and radio-echo soundings. Conditions similar to those observed during the period from 1934 to the 1950’s may have been frequent in Grímsvötn in previous centuries. Such conditions may also be expected in the neighbourhood of the most active subglacial volcanoes in Iceland, like Kverkfjöll and Bárðarbunga in Vatnajökull, and Katla in Mýrdalsjökull. However, the size of ablation areas of this type is probably always very limited. In most parts of the accumulation areas of the ice caps the dispersed ash layers only affect the mass balance of one year as they are buried permanently by the snowfall of the next winter (cfr. results of radio-echo soundings discussed above). Such conditions have existed, at least over the last few hundred years, south of Bárðarbunga, NW-Vatnajökull, where a 415 m long ice core was recovered in 1972 (Steinþórsson, 1977). No evidence was found for a discontinuity in the tephrachronological record.

CONCLUSIONS

Firm evidence can only be found for three eruptions within or near Grímsvötn in the period 1934-1991, i.e. in 1934, 1938 and 1983. In addition, seismic data alone indicate a small subglacial eruption in 1984. Data on these events are summarized in Table 1. An eruption at the end of the jökulhlaup of 1954 can be discarded as no crater is situated at the proposed eruption site. Further, aerial observations indicate that eruptions did not occur during the jökulhlaups of 1941 and 1948. The exact location of the sinkhole formed in 1945 is not known and consequently the existence or absence of a crater in the bedrock cannot be established. However, we consider a steam explosion or increased upwelling in a geothermal upflow zone the most likely explanation for the sinkhole of 1945.

An ash cover that was observed in the northwestern part of Grímsvötn in the period 1934-1960 dates back to the eruption of 1934 but may contain ash dispersed in earlier eruptions. During this period (since 1934 and possibly longer) the ash cover was exposed every year in late summer as the winter accumulation was melted, and this part of the Grímsvötn depression was an ablation area. Moreover, the frequent small jökulhlaups from Grímsvötn in the period 1938-1948 are considered to have been caused by melting at the site of the eruption of 1938, north of Grímsvötn. Consequently, both the ash layer and the jökulhlaups in the 1940’s can be adequately explained without assuming eruptions after 1938.

ACKNOWLEDGEMENTS

We would like to thank Haukur Jóhannesson and an anonymous reviewer for constructive criticism of the manuscript. Assistance from the Iceland Geodetic Survey in locating air photos from Grímsvötn is gratefully acknowledged as well as grants from the Research Fund of the University of Iceland and the Icelandic Road Authority. Members of the Iceland Glaciological Society assisted in the fieldwork.
APPENDIX. AIR PHOTOS USED IN THIS STUDY

Table A1 lists all known vertical air photos which show Grímsvötn while Table A2 lists the oblique air photos that have been used in this study. It is far from being a complete list of aerial observations of the area. We have not been able to find photos from flights by Pálmi Hannesson on May 13, 1941 during a jökulhlaup nor flights on February 22, 1946 and February 10, 1947 by Steinþór Sigurðsson and Sigurður Pórarinsson (Pórarinsson and Sigurðsson, 1947).

Table A1. Vertical air photos from the Grímsvötn area/loftmyndir af Grímsvötnum

<table>
<thead>
<tr>
<th>Date of flight/ hvenær flögð</th>
<th>Flight elevation/ flughæð m a.s.l.</th>
<th>Flown by Myndataka</th>
<th>Notes/ Athugasemdir</th>
</tr>
</thead>
<tbody>
<tr>
<td>1945, August 30</td>
<td>6900</td>
<td>AMS</td>
<td></td>
</tr>
<tr>
<td>1946, September 19</td>
<td>7000</td>
<td>AMS</td>
<td></td>
</tr>
<tr>
<td>1954, September 15</td>
<td>4600</td>
<td>IGS</td>
<td></td>
</tr>
<tr>
<td>1960, August 10</td>
<td>5500</td>
<td>AMS</td>
<td></td>
</tr>
<tr>
<td>1961, June 21</td>
<td>9200</td>
<td>AMS</td>
<td>Area partly covered with clouds / hluti svæðisins hulínn skýjum</td>
</tr>
<tr>
<td>1972, August 10</td>
<td>4000</td>
<td>IGS</td>
<td>Shows only extreme W- part / sýnir eingöngu vestasta hlutann</td>
</tr>
<tr>
<td>1980, August 28</td>
<td>3400</td>
<td>IGS</td>
<td></td>
</tr>
<tr>
<td>1984, August 22</td>
<td>5500</td>
<td>IGS</td>
<td></td>
</tr>
<tr>
<td>1986, August 29</td>
<td>5500</td>
<td>IGS</td>
<td></td>
</tr>
<tr>
<td>1986, September 12</td>
<td>7600</td>
<td>IGS</td>
<td>Clouds cover extreme N-part / Nyrsti hlutinn hulínn skýjum</td>
</tr>
<tr>
<td>1990, August 30</td>
<td>6700</td>
<td>IGS</td>
<td></td>
</tr>
</tbody>
</table>

AMS: US Army Map Service; IGS: Iceland Geodetic Survey
<table>
<thead>
<tr>
<th>Date of flight</th>
<th>Photos by ljósmyndari</th>
<th>Location/prev. publ. (Fig. no. in this paper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hvenær tekmar</td>
<td></td>
<td>Staðs./fyrri birting(myndnúmer í þessari grein)</td>
</tr>
<tr>
<td>1937, August 28</td>
<td>Danish Geod. Inst.</td>
<td>Iceland Geodetic Survey</td>
</tr>
<tr>
<td>1938, May 28</td>
<td>Pálmí Hannesson</td>
<td>Hannesson, 1939, Fig. 133; Hannesson, 1958, p. 256; Þórarinsson, 1974, p. 166. (Fig. 7)</td>
</tr>
<tr>
<td>1938, June 23</td>
<td>Danish Geod. Inst.</td>
<td>Iceland Geodetic Survey (Fig. 8a)</td>
</tr>
<tr>
<td>1938, July 1</td>
<td>Danish Geod. Inst.</td>
<td>Iceland Geodetic Survey</td>
</tr>
<tr>
<td>1938, August 30</td>
<td>Danish Geod. Inst.</td>
<td>Iceland Geodetic Survey (Fig. 8b)</td>
</tr>
<tr>
<td>1945, September 22</td>
<td>Steinþór Sigurðsson</td>
<td>Þórarinsson and Sigurðsson, 1947, p. 64. (Fig. 10)</td>
</tr>
<tr>
<td>1945, October 4</td>
<td>Pálmí Hannesson</td>
<td></td>
</tr>
<tr>
<td>1947, July 22</td>
<td>Sigurður Þórarinsson</td>
<td>Þórarinsson, 1974, p. 34. (Fig. 13a)</td>
</tr>
<tr>
<td>1948, February 22</td>
<td>Sigurður Þórarinsson</td>
<td>Science Institute, University of Iceland (SIUI), slide collection (Fig. 13b, c)</td>
</tr>
<tr>
<td>1950, August 28</td>
<td>Sigurður Þórarinsson</td>
<td>ÞóRARINSSON, 1953a, p. 274; 1953b, p. 16; SIUI slide collection. (Fig. 13d)</td>
</tr>
<tr>
<td>1953, August 18</td>
<td>Sigurður Þórarinsson</td>
<td>ÞóRARINSSON, 1953a, p. 274; 1953b, p. 17; SIUI slide collection</td>
</tr>
<tr>
<td>1954, July 14</td>
<td>Sigurður Þórarinsson</td>
<td>ÞóRARINSSON, 1974, p. 188; SIUI, slide collection</td>
</tr>
<tr>
<td>1954, July 21</td>
<td>Sigurður Þórarinsson</td>
<td>SIUI, slide collection</td>
</tr>
<tr>
<td>1954, August 28</td>
<td>Sigurður Þórarinsson</td>
<td>ÞóRARINSSON, 1974, p. 188; SIUI, slide collection</td>
</tr>
<tr>
<td>1954, September 7</td>
<td>Sigurður Þórarinsson</td>
<td>ÞóRARINSSON, 1974, p. 191; SIUI, slide collection. (Fig. 14)</td>
</tr>
<tr>
<td>1955, August 27</td>
<td>Sigurður Þórarinsson</td>
<td>SIUI, slide collection</td>
</tr>
<tr>
<td>1955, September 7</td>
<td>Sigurður Þórarinsson</td>
<td>SIUI, slide collection</td>
</tr>
<tr>
<td>1961, August 24</td>
<td>Sigurður Þórarinsson</td>
<td>SIUI, slide collection</td>
</tr>
<tr>
<td>1983, May 29</td>
<td>Helgi Björnsson</td>
<td>Björnsson, 1988, p. 15. (Fig. 4)</td>
</tr>
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**Ágrip**

**GOS Í GRÍMSVÖTNUM 1934-1991**


Í maí 1938 kom övern tórhlaupa í Skeiðará, aðeins fjórur árum frá hlaupinu 1934. Mikil sigdæld hafði myndast norðan Grímsvatna (7. mynd) og vatn runnið þaðan niður í Grímsvötn og komið af stað

Ljóst er af þeim gögnum sem til eru (frá 1934, 1938 og 1983) að við gos dreifist aska yfir jökulinn, vök eða sigðæld myndast yfir gosstjóðvunum og er hvín sýnileg í nokkur ár eftir gosið kælingar gosenanna. Þa myndast í gosinu hryggur eða gíg-hrúggald. Þessar staðreyndir þarf að hafa til hlíðsjónar þegar líkur á gosi í tilteknum tíma eru metnar.


