The Grímsvötn Geothermal Area, Vatnajökull, Iceland

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ABSTRACT

Melting of ice at the Grímsvötn geothermal area has created a depression in the surface of the ice cap Vatnajökull and produced a subglacial lake from which jökulhlaups drain to Skeidarársandur. The geothermal activity is also expressed by small cauldrons on the surface of the ice as well as by fumaroles on two nunataks that rise 300 m above the lake level. Vapour from the fumaroles yields little information about the deep reservoir fluid. The vapour seeps upwards from the water table and repeatedly condenses and evaporates on the way to the surface. The chemistry of the water in jökulhlaups, however, provides information about the fluid in the geothermal system. This information is not easy to interpret because of water-rock interaction in the lake. Silica solubility data and assumptions about the likely reservoir temperature, however, indicate that about 15% of the total mass in the lake is fluid discharged from the geothermal reservoir. This information about the geothermal mass fraction together with mass and energy balances for the lake enables one to calculate the masses of water and steam discharged from the geothermal reservoir as well as the mass of ice melted in the lake. The steam mass fraction is estimated to be 20-35% when the fluid enters the lake. From this, new estimates of the thermal power of the geothermal system are obtained. The total thermal power of the system is 4700–4900 MW, of which 2100-3000 MW are transported by steam and the rest by water.

Grímsvötn is one of few geothermal areas where active volcanism is observed and where there is a direct interaction between magma and geothermal water. Evidence of volcanic activity was found in the water chemistry of the jökulhlaup in December 1983. The high content of sulphate and the presence of iron indicated eruption of magma into the geothermal fluid.

Since the nineteen-fifties jökulhlaups have occurred regularly at 4-6 year intervals when the lake level has risen up to a critical level required for draining water from the bottom of the lake. However, jökulhlaups may occur at lower water levels. In 1983 a jökulhlaup was triggered at a water level 20-30 m lower than the critical level. This jökulhlaup may have been triggered by the opening of waterways into the lake along the slopes of Grímsfjall, where increased geothermal or volcanic activity has melted ice in places. An odour of hydrogen sulphide was detected for two months on Skeidarársandur before the jökulhlaup commenced. Sulphurous odour for long periods may warrant a forecast of such premature jökulhlaups.

INTRODUCTION

The Grímsvötn geothermal area is located in the interior of the Vatnajökull ice cap at the most active caldera volcano in Iceland. The volcano, the thermal area and the caldera lake Grímsvötn are almost completely covered with ice. Periodic bursts of water (jökulhlaups) drain the lake subglacially down to the rivers on the Skeidarársandur outwash plain : Skeiðará, Sandgígjukvísl and Súla. (Fig.1). The volcanological and geothermal activity in the area has been studied by many authors. This includes the history of eruptions and jökulhlaups, the mass balance of the lake,

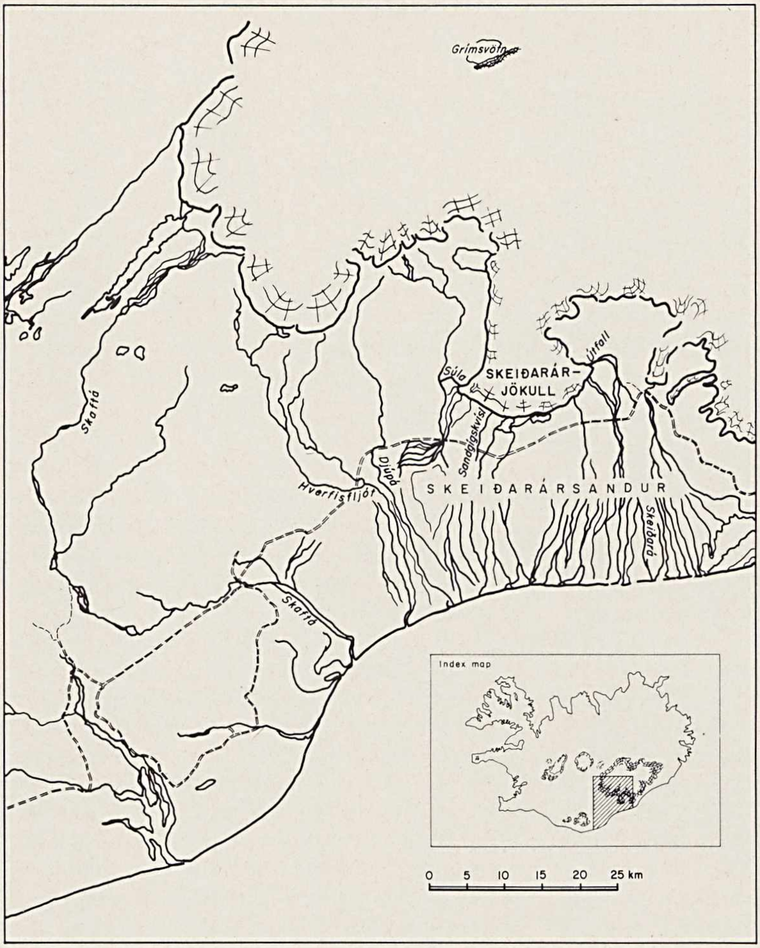

Fig. 1. SW-Vatnajökull, Skeidarársandur and rivers that drain Vatnajökull.
1 .mynd. Suðvesturhluti Vatnajökuls, Skeiðarársandur og ár sem falla frá Vatnajökli.

the triggering of jökulhlaups, estimates of the total output of heat from the geothermal system and the mechanism of heat extraction, the chemical composition of the water in the jökulhlaups and the possibilities of predicting the floods by chemical monitoring of river water. This paper adds new information about the geothermal activity and recent volcanic events, the heat flux transported by the geothermal fluid and the triggering mechanism of jökulhlaups. The work is based on various field studies but most of the information is gained from geochemical studies in the Grímsvötn area and from chemical studies of water in jökulhlaups.

Field studies in the Grímsvötn area date back to the year 1919 (*Wadell* 1920). The next studies in the area were done by expeditions during the volcanic eruption in 1934. (*Einarsson* 1946, *Áskelsson* 1936, *Nielsen* 1937). During the jökulhlaup in 1938 the area was studied from the air. *Thorarinsson and Sigurdsson* (1947) summarize all expeditions to the area from 1934 to 1947. Later expeditions are described by *Thorarinsson (1953a, 1953b, 1954, 1955, 1956, 1957, 1958, 1965, 1974)*, *Eythorsson* (1957,1960), *Áskelsson* (1959), and *Björnsson* (1974, 1977). Recent observations of the Grímsvötn area have been carried out in the annual expeditions of the Iceland Glaciological Society, in which the Science Institute and the National Energy Authority (NEA) have participated.

Thorarinsson (1974) has compiled a history of jökulhlaups from Grímsvötn. The first report of a jökulhlaup dates back to A.D. 1332. From 1600 until 1934 there occurred about one jökulhlaup per decade with an estimated discharge of 6-7 km^3 of water and a maximum discharge rate of approximately 40 000 m^3/s (for example in 1903, 1913, 1922, 1934). But since 1934 there have been two, even three, bursts per decade with correspondingly smaller volumes (except for 1938), 1-3.5 km^3, and maximum discharge rates of 5-8000 m^3/s (1938,1939,1941,1945,1948,1954, 1960,1965,1972,1976,1982 and 1983; *Thorarinsson* 1974, *Rist* 1955,1973,1976, *Björnsson* 1983). In December 1983 the smallest jökulhlaup ever was observed with a total volume of 0.5 km^3 (*Sigurjón Rist,* pers. comm.).

The Grímsvötn lake owes its existence to the geothermal area. Melting due to the geothermal activity creates a depression in the surface of the Vatnajökull ice cap. Ice and water are diverted towards the depression from a 300 km^2 drainage basin (Fig.1). The meltwater accumulates in a 25 km^2 subglacial lake, which is covered by a 200 m thick floating ice shelf (*Thorarinsson* 1953b, 1974, *Björnsson* 1974). The lake is sealed and no water drains out of it between the jökulhlaups. Water accumulates in the lake and when the water level has risen to a critical level, water is forced out of the lake beneath a barrier east of the lake (Fig.2). The subglacial waterways are enlarged by frictional melting and the lake is drained in a fortnight by a catastrophic flood. Eventually, the ice overburden pressure is able to close the water tunnels and the flood stops abruptly before the lake is empty (*Björnsson* 1974, *Nye* 1976). The water-level change in the larger jökulhlaups has been estimated to be about 150 m, but is observed to be 80-100 m during the last three decades (Fig.3). The frequency and water volume are believed to depend on the thickness of the glacier. This model is considered to explain most of the jökulhlaups. The jökulhlaup in December 1983, however, occurred at a water level that was 20-30 m below the present critical level for triggering jökulhlaups. Explanation of this will be discussed in the paper.

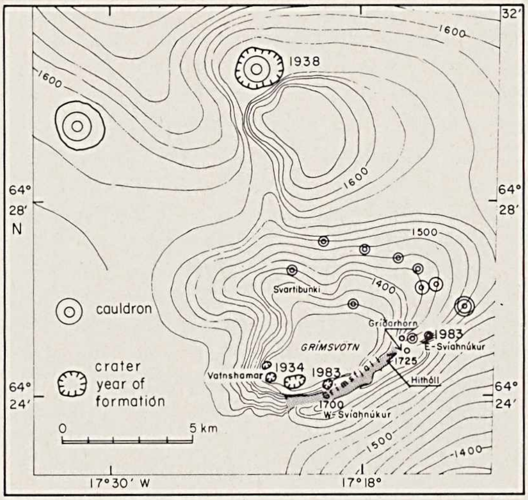

Fig. 2. The Grímsvötn area. Contour map of the Icelandic Geodetic Survey from 1946 on which we have marked the position of craters in 1934 and 1983, the depression north of Svartibunki from 1938, and ice cauldrons. The cauldron that formed during the jökulhlaup in 1983 is marked on the map. The cauldron northwest of Grímsvötn drains to the river Skaftá.

2. mynd. Grímsvatnasvæðið. Kortið sýnir hæðarlínur frá 1946, en á það eru merktir sigkatlar og gígarnir frá gosunum 1934 og 1983. Rennan norðan við Svartabunka myndaðist 1938 og sést enn árið 1946. Sigketillinn, sem myndaðist við hlaupið í desember 1983 er merktur á kortið. Sigketillinn norðvestan við Grímsvötn hleypir vatni í Skaftá.

The heat output of the subglacial geothermal area has been estimated by using the Grímsvötn lake as a natural calorimeter. A long term mass balance of the drainage basin has been given by *Björnsson* (1974). The average accumulation in the form of ice is equivalent to 2200 mm /yr of water and the surface ablation amounts to 500 mm /yr. A long-term steady-state model for the drainage basin proves to be a valid approximation (*Björnsson* 1974). The water added to the lake is $6.6 \cdot 10^{11}$ kg/yr. About $1.5 \cdot 10^{11}$ kg/yr are melted at the surface of the glacier by meteorological processes, but the difference, about $5 \cdot 10^{11}$ kg/yr is melted by the geothermal heat within the drainage basin. The heat flux required to melt this ice is about 5000 MW (thermal). In the present work we estimate the geothermal mass fraction in the lake and present new estimates of the thermal power of the geothermal system.

Shallow intrusions of magma are the source of heat for the geothermal area. Meltwater percolates down towards the magma intrusions and heat is transferred upwards by hydrothermal convection. *Björnsson et al.* (1982) have suggested that this heat flux can be explained by penetration of water into hot boundaries of magma at shallow depths. Assuming an upper surface area of 10 km^2 for a magma body under Grímsvötn, water penetrating into that body would have to propagate at an average rate of 5 m/yr to yield the observed flux of 5000 MW. The geothermal activity, however, is not limited to the lake but scattered over a larger area, estimated to be up to 100 km^2.

The Grímsvötn area is one of the most (if not the most) powerful geothermal systems in Iceland. So far the heat transfer in the geothermal system upwards to the lake has not been studied. The circulating fluid is probably liquid dominated. As the system is situated within the active volcanic area the fluid probably attains a base temperature of 300 to 340 °C and is presumably at the boiling point when it flows as water and steam through vents into the lake. The bottom of the Grímsvötn lake is situated at about 1000 m a.s.l. (*Björnsson* 1974). The pressure at the lake floor varies from 30 bar at the end of jökulhlaups to 40 bar when the water level has risen to the critical level. Hence, the boiling temperature at the lake floor varies from 235 to 250 °C. The transfer of heat to the lake by steam and water is discussed in the paper.

The heat transfer within the lake has not been studied either. Boiling water and steam would be injected into the lake through hydrothermal vents and thermal plumes ascend into the lake. Convection in the lake brings heat up from the floor to a level where the temperature is 4 °C. From that level heat is conducted in a thin layer to the melting ice cover. Meltwater at 0 °C is continuously added to the top of the lake from the ice cover and mixed with warmer water. The conducting layer can hardly remain stable. The hydrothermal vents that inject boiling water to Grímsvötn are located on fissures and scattered spots, which are believed to cover only a small part of the lake floor. The floor between the vents is heated by conduction and is much cooler. Chemical analyses, presented in the paper, show that the concentration of magnesium in water from Grímsvötn is similar to that of cold ground water. The magnesium was leached out of hyaloclastites at the lake floor. The leaching cannot have occurred at temperatures exceeding 30-40 °C and the water has not been exposed to higher

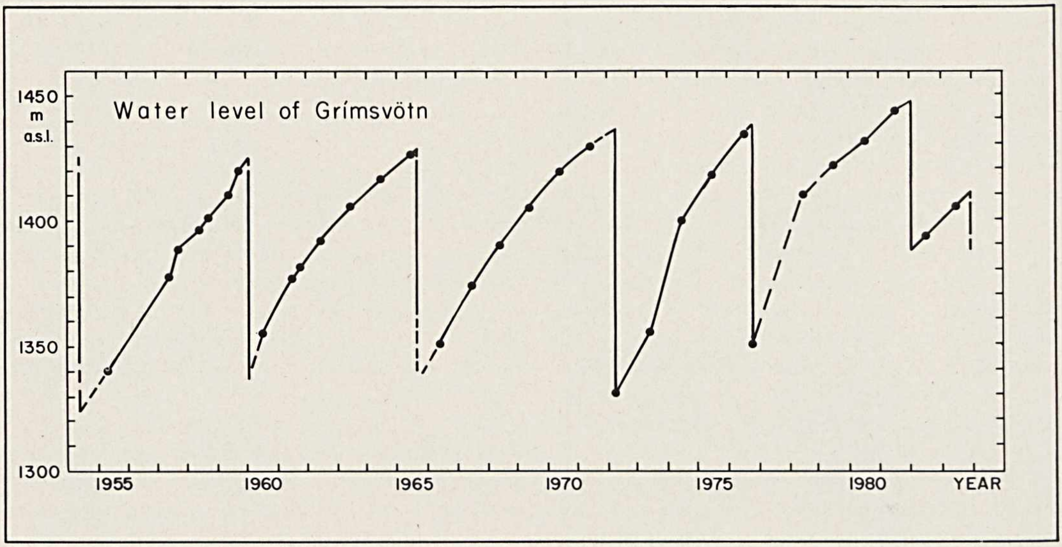

Fig. 3. Variations of water level in Grímsvötn.
2. mynd. Vatnshæð í Grímsvötnum frá 1954.

temperatures for any length of time. Furthermore, we may add, as the water emerges on Skeidarársandur during jökulhlaups, the temperature has been measured 0 °C (*Rist* 1955). The temperature of the lake has neither been measured nor estimated by theoretical models but we believe the average temperature is close to the melting point.

Water in the Grímsvötn lake is a mixture of meltwater from the glacier and fluid discharged from the geothermal system. The chemical composition of the two components is rather different. The circulating geothermal fluid attains a base temperature of around 300 °C and obtains its chemical composition by interaction with the ambient rocks. When water from the geothermal area in Grímsvötn has reached Skeidarársandur in jökulhlaups, the chemical composition of the rivers changes drasically. The first sign of a jökulhlaup is a strong sulphurous (H_2S) odour from the river Skeidará that can be noticed some days before the discharge begins to increase. The colour of the river changes, sometimes even before the jökulhlaup commences. All jökulhlaups on Skeidarársandur start in Skeidará, and as they proceed the flood may emerge in Sandgígjukvísl and finally in Súla in the largest burst.

Considerable information about the Grímsvötn area has been obtained by studies of the jökulhlaups on Skeidarársandur. The discharge rate and total volume of the jökulhlaups have been estimated (*Rist* 1955,1973,1976, see *Thorarinsson* 1974). The sediment transport has also been estimated, both the total load and chemical composition (see *Thorarinsson* 1939,1974, p.165, *Rist* 1955, *Tómasson* 1974, *Tómasson et al.* 1982). Furthermore, chemical studies of water from the river Skeidará have been presented by *Rist* (1955), *Sigvaldason* (1965) and by *Steinthórsson and Óskarsson* (1983).

The present work presents chemical data (collected by the National Energy Authority and the Science Institute) for the rivers on Skeidarársandur during jökulhlaups in 1976,1982 and 1983 and in the period between the last two jökulhlaups. The data show the normal chemical concentrations in the rivers in 1982/83 when they are not influenced by jökulhlaups. With this background we can distinguish the various changes in the chemical composition that appear in the rivers during jökulhlaups. In addition, we can distinguish certain chemical changes in jökulhlaups from Grímsvötn when the geothermal area is influenced by volcanic activity. On the basis of general knowledge about high temperature geothermal areas we can explain the chemical composition of water in Grímsvötn in terms of interaction with highly reactive basaltic glass in the lake. However, the concentration of some substances like silica is not changed by water-rock interaction and by using data for those we estimate the fraction of the geothermal fluid in the water mixture from Grímsvötn.

The heat flux in Grímsvötn shows sporadic increases, which may be of the order of 2 to 3 times the base flux of 4000 to 5000 MW (*Björnsson* 1983). During the last 120 years these peaks constitute about 10% of the total heat flux. They are believed to be caused by intrusions of magma to the base of the glacier. Altogether the inflow of magma into the Grímsvötn area is estimated to be about $50 \cdot 10^6$ m^3/yr of which 10% is erupted to the surface and 90% is solidified in the upper crust and cooled down by the hydrothermal convection (*Björnsson et al.* 1982, *Björnsson* 1983).

No volcano in Iceland has shown a higher eruption frequency than the Grímsvötn volcano. *Thorarinsson* (1974) attributed at least 50 eruptions to the volcano in historical times and *Jóhannesson's* (1983) recent studies of historical documents add still more eruptions to the list. The latest eruption in Grímsvötn occurred in May-June 1983. *Grönvold and Jóhannesson* (1984) describe the course of events and chemical studies of the tephra and *Einarsson and Brandsdóttir* (1984) analysed the seismic activity leading up to the eruption. The present paper adds information about the recent volcanic activity based on geochemical studies of water in the jökulhlaups.

DESCRIPTION OF GEOTHERMAL ACTIVITY

The mountain Grímsfjall marks the southern rim of the Grímsvötn caldera (Fig.2). The two highest peaks of the mountain form nunataks where hyaloclastic rocks are exposed to the surface: W- Svíahnúkur (1700 m) and E-Svíahnúkur (1725m). The northern face of the mountain beneath the two nunataks forms almost vertical cliffs, 300 to 400 m high. There hyaloclastic rocks with intermediate basalt layers are exposed. Glacier tongues flow from the mountain between the nunataks down to the caldera lake. The western rim of the caldera is formed of gently sloping hyaloclastic hills which are covered by ice. The main hill, Vatnshamar, rises about 100-200 m above the ice cover of the lake. Rocks are visible at some places on the eastern slopes of the hills. The northern and eastern borders of the caldera are covered with thick glaciers. However, the glacier surface topography indicates an extension of the depression towards Svartibunki in the northwestern area. Further east, the northern border is located south of Svartibunki.

Three craters were active during the eruption in 1934. The largest crater, 600 m in diameter was located northwest of the foot of W-Svíahnúkur. Two smaller craters were situated in the SW corner of the Grímsvötn depression (Fig.2). In May 1935, more than one year after the eruption was over, the largest crater still issued gas and smoke at intervals.

Signs of geothermal activity in the Grímsvötn depression.

Indications of geothermal activity can be observed along the northern walls of the mountain Grímsfjall and at the eastern slopes of Vatnshamar. *Wadell* (1920, fig. 4 and 6, p. 309-312) described open water at several places along the walls of the caldera. Almost every expedition has reported a waterpool at Vatnshamar and frequently along the slopes of Grímsfjall beneath the two nunataks. The water level is at the same height in all the waterpools (*Thorarinsson* 1953a, p.15; 1957, p. 46; 1958, p. 3; 1974). The water is usually cold (near to 0 °C) but when the surface of the lake is at low levels warm springs have been observed at Vatnshamar. *Thorarinsson* (1953a) observed seven hot springs situated between basalt dykes 1 to 15 m above the lake level at about 1350 m a.s.l. Their total discharge was 5 to 10 l/s and the largest one gushed water at 87.5 °C continuously up to about 40 cm height. Samples from the largest spring contained 52 mg/kg of SiO_2, and 91 mg/kg of total carbonate as $CaCO_3$ and had a pH of 7.3. The ground beneath this spring was covered by a 5 mm thick layer of calcium carbonate. In 1942 an expedition reported open water in a 30-100 m wide strip at the foot of W-Svíahnúkur. Hot springs were situated along the cliff and emerged both from underneath the water and the glacier tongues (*Steinthór Sigurdsson,* this issue). Further, in 1954 luke-warm water was observed in a depression beneath the walls northeast of Grídarhorn (*Holtzscherer* 1954, fig.21, p. 25). In 1957 this pool was covered by ice but with a small opening (*Thorarinsson* 1957, p.46). Sulphurous odour is usually not noticable in the Grímsvötn depression. However, *Thorarinsson* (1953a) reported a distinct odour of sulphur in the area and a faint odour could be detected from open water near Grídarhorn.

A number of ice cauldrons or circular depressions in the surface of the glacier bear witness to subglacial geothermal activity on the northern slopes of Grímsvötn (Fig.2). The main cauldrons north and northeast of E-Svíahnúkur are always visible but others appear just after jökulhlaups when water has been discharged from them. The largest ice cauldrons are up to 100 m deep and 1 km in diameter.

Considerable changes in the thermal activity have been reported by several expeditions. Some of the changes may even be considered as volcanic. During the jökulhlaup in May 1938 drastic changes occurred in the Grímsvötn area, which may be interpreted as caused by volcanic activity that did not break through the glacier. A reconnaissance flight revealed that a large area of the ice surface to the north of the Grímsvötn depression had subsided (shown by *Pálmi Hannesson's* (1958) photos, see for example *Thorarinsson* 1974, fig. 41, p. 166 or *Björnsson* 1983, fig.3 p.16, and *Gísli Gestsson's* map, see *Thorarinsson* 1974, fig. 43, p.168). Water was released to the caldera lake. A jökulhlaup resulted. The effects of the events in 1938 could be observed for more than 10 years as a depression in the glacier surface north of Grímsvötn (Fig.2). In the summer of 1945 an expedition led by Skarphédinn Jóhannsson reported increased fumarolic activity along the foot of Grímsfjall where no such activity had been observed in 1944 (*Thorarinsson* and *Sigurdsson* 1947, *Áskelsson* 1959). In late September of 1945 a jökulhlaup occurred from Grímsvötn. A reconnaissance flight reported steam rising up above the slopes of Vatnshamar and ash spreading over the western part of Grímsvötn (*Hannesson* 1958). An expedition led by *Áskelsson* (1959) in October observed an explosion-like crater or a sink hole, maybe 100 m deep, near Svartibunki in the northwestern part of the Grímsvötn area. A strong sulphurous

Fig. 4. An ice cauldron NE of Grídarhorn that has collapsed and changed into a circular cylinder about 100-200 m in diameter. Photo: Helgi Björnsson, December 1983.
4. mynd. Sigketill norðaustan við Gríðarhorn sem breyst hefur í sívalningslaga pytt, 100-200 m í þvermál. Myndina tók Helgi Björnsson meðan hljóp úr Grímsvötnum í desember 1983.

odour emanated from the hole. *Áskelsson* suggested that a small eruption had occurred at the end of the jökulhlaup in late September covering a large area in the western part of Grímsvötn with ash. Further, in 1945 *Áskelsson* (1959) observed a cauldron close to the western crater of the eruption of 1934. During the jökulhlaup 4-22 July 1954 *Thorarinsson* (1974, p.188-191) observed from the air a crater at the southern slopes of Svartibunki. The diameter was about 200 m and loose materials had been thrown around by an explosion. In June of 1955 *Thorarinsson* (1955) described the sink hole in an expedition to the area. He also reported a dark layer at 1.5-2 m depth in snowpits. This layer was presumably spread by an explosion when the sink hole was formed during the jökulhlaup in July of 1954. *Thorarinsson* (1956) reported a circular depression of 200 m diameter in the SW corner of Grímsvötn that was not there in 1955. *Eythórsson* (1960) observed a hole 2-3 km northeast of Vatnshamar 5 months after the jökulhlaup during 8-25 January. The opening was circular, 25-30 m in diameter. Steam and sulphurous odour arose from the hole. *Thorarinsson* (1974) suggested that all the sink holes were formed in steam explosions as the overburden pressure was released during the jökulhlaups. He suggested that the dispersed loose material might have been sand rather than new volcanic products. An explosion of that kind had been reported from the Kverkfjöll area in 1959 (*Jóhannsson* 1959). However, *Tryggvason* (1960) reported earthquakes of magnitude about 3 in the Grímsvötn area on 17th and 21 July 1954 and 21, 22 and 24 January 1960 that may indicate volcanic activity.

Since 1960 sudden changes of the thermal activity have not been reported in Grímsvötn until the eruption in late May 1983 from a crater beneath W-Svíahnúkur (Fig.2). During the jökulhlaup in Dec. 1983 an ice cauldron east of Grídarhorn collapsed and changed into a circular cylinder some hundred metres deep and about 100-200 m in diameter (Figs. 2 and 4). So far (February 1984) this sink hole has only been studied from the air. No signs of explosions were observed. We refer later to this cauldron in the discussion of the triggering of the jökulhlaup in December 1983.

Geothermal activity on the Grímsfjall mountain ridge

On the Grímsfjall mountain, direct surface expressions of geothermal activity can be

TABLE 1. Comparison of gas in steam from Grímsfjall. Numbers show volume %.
TAFLA 1. Samanburður gastegunda í gufu frá Grímsfjalli.

Sample	1	2	3	4	5
CO_2	21.36	27.31	29.80	7.26	6.82
H_2S	0.00	0.00	0.00	0.00	0.00
H_2	0.01	0.00	0.00	0.01	0.01
O_2	13.59	10.90	10.04	4.26	5.00
CH_4	0.01	0.00	0.01	0.01	0.01
N_2	63.75	60.66	59.01	87.22	87.54
Ar	1.25	1.11	1.14	1.26	0.61

1. Fumarole on Grímsfjall. Sampled in June 1982 by HB.
2. „ „ „ „ „ „ „ „
3. Fumarole on Grímsfjall. Sampled in June 1983 by HK.
4. Drillhole no. 3 on Grímsfjall. Sampled in June 1983 by HK.
5. „ „ „ „ „ „ „

observed on the two nunataks at about 1700 m a.s.l. (East- and West-Svínahnúkur, Fig. 2). The exposed rock surface is crossed by SW-NE striking fractures through which steam emanates. Fumaroles with temperatures of up to 92.5 °C are found at Hithóll on the western slopes of E-Svínahnúkur (Fig. 2). The subglacial steam outlets have formed extensive ice caves on the slopes of the mountain. The floor of the caves is composed of fresh loose lapilli. White calcite precipitates have heaped up around steam outlets. Outside the caves, where the slopes are exposed to open air, the surface is cemented and much more altered than the floor of the caves. The lapilli have become brown to rust coloured due to oxidation of iron. The evidence of geothermal activity is less significant on the eastern part of E-Svínahnúkur. There, a maximum temperature of 32°C has been measured in a fracture at a depth of about 1 m. In 1983 two holes were drilled into the hill, 15 m and 27 m deep. They yielded saturated steam at low pressure.

No sulphurous odour can be dected on the Grímsfjall mountain, neither from the fumaroles nor in the steam from the drillholes. The low pressure of the steam and the absence of sulphurous odour indicates repeated boiling and washing out of the most soluble gases before the steam leaks out at the surface of the nunatak. There are probably two to three hundred metres down to the boiling water surface, from which vapour seeps upwards and repeatedly condenses and evaporates on the way to the surface. The measured $\delta\ ^{18}O$ = -22‰ for the condensate fits this model as the $\delta\ ^{18}O$ values for the water in the jökulhlaups ranged form -11‰ to -13‰, which are representative for the precipitation in the Grímsvötn area. The gas in the steam is mostly atmospheric with an admixture of carbon dioxide (see Table 1). The precipitates on the rock surface were found to be carbonates with no traces of sulphurous materials. But pyrite (FeS_2) was found in varying amounts in drill cuttings from 6 m depth. The drillholes cut through hyaloclastites to the bottom. The alteration of the basaltic glass is extensive in certain horizons. The hot acid condensate of the ascending vapour readily transforms the reactive basaltic glass and a complete recrystallization has occurred in places.

Surface expressions of geothermal activity have been less significant on W-Svíahnúkur than on the eastern nunatak (during the last decade anyway). Steam emanations are seldom observed

TABLE 2. Concentration of dissolved solids in water from Skeidará sampled at the peak of jökulhlaups.
TAFLA 2. Styrkur uppleystra efna í hámarki jökulhlaupa.

Jökul-hlaups	pH / °C	SiO_2	Na	K	Ca	Mg	CO_2 tot	SO_4	H_2S	Cl	F	Tot. dis.
1954"		57			60.9	15.6		18.1	0.0	8.7	0.3	388
1965+	7.0 /	56	63.5	19.0	59.5	10.4	680	38.7		42.7	0.5	416
1972★	7.5 /	44	89.0	3.0	28.0	10.0	480	13.0		11.0		
1976#		50.5	43.0	3.8	45.6	9.9		23.5		13.5		
1982#	6.02 / 22	60.0	53.1	4.2	50.4	10.8	595	19.2	0.3	13.2	0.17	369
1983#	6.45 / 21	56.5	50.3	4.8	38.9	11.8	343	48.8	0.0	7.6 0	0.31	359

" *Rist* (1955)
NEA data
+ *Sigvaldason* (1965)
★ *Steinthórsson and Óskarsson* (1983)

and the measured maximum ground temperature is 72°C (in 1981).

Marked changes have not been observed in the the geothermal activity on the mountain. However, one of the ice cauldrons on the E-Svíahnúkur collapsed in 1983-84 and a 500 m long, 200 m wide and 50 m deep depression was formed just west of Hithóll (Fig.2). This may have been caused by increased thermal activity. Increased thermal activity was observed at W- Svíahnúkur after the eruption in Grímsvötn in May-June 1983. Ice caves were formed on the slopes similar to those that are usually observed at the eastern nunatak.

INFLUENCE OF JÖKULHLAUPS ON RIVER WATER CHEMISTRY

During jökulhlaups the chemical composition of water in the rivers on Skeidarársandur is influenced by geothermal water from Grímsvötn. Results of chemical analyses of river water have been reported by *Rist* (1955), *Sigvaldason* (1965), *Steinthórsson and Óskarsson* (1983). The present paper adds further data from the jökulhlaups in 1976, 1982 and 1983, together with data for the rivers Skeidará, Sandgígjukvísl and Súla when they are not influenced by jökulhlaups. In addition, data are presented for other glacier rivers (Djúpá, Hverfisfljót and Skaftá) which drain Vatnajökull (Fig.1). Jökulhlaups are not discharged regularly into the rivers Djúpá and Hverfisfljót but periodic jökulhlaups occur in Skaftá from ice cauldrons 10 km northwest of Grímsvötn (Fig. 2, *Thorarinsson and Rist* 1955, *Björnsson* 1977, 1983).

Analyses of river water

Water from Skeidará has been sampled and analyzed during the jökulhlaups in 1965 (*Sigvaldason* 1965), 1972 (*Steinthórsson and Óskarsson* 1983), 1976 (National Energy Authority (NEA) data), 1982 (NEA data and *Steinthórsson and Óskarsson* 1983), and 1983 (NEA data). Up to the year 1982 very little was known about the normal seasonal changes in the chemistry of the water. Since the jökulhlaup in February 1982 water from Skeidará has been sampled and analyzed regularly. Results of the analyses are presented in Figs.5-8 and Table 2. Fig. 5 shows the concentration of Na, SiO_2 and SO_4 during the whole period. The data are believed to represent normal concentrations. They may also show seasonal variation. There appears to be a maximum concentration of most components during the early spring (1983) and a minimum in the late summer (1982 and 1983). However, during the

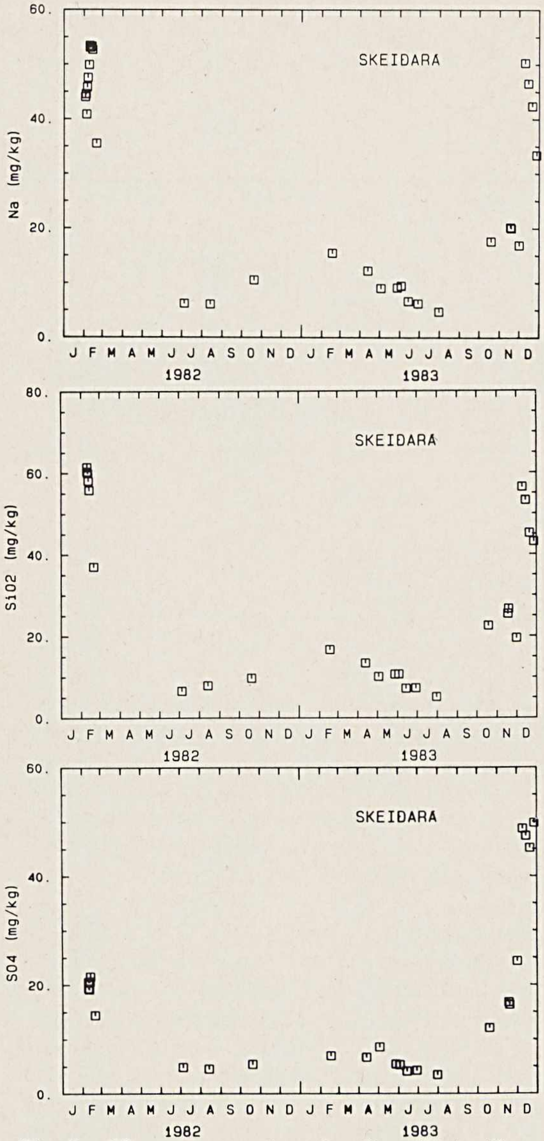

Fig. 5. The concentration of sodium (Na), silica (SiO_2) and sulphate (SO_4) in Skeidará during 1982 and 1983.

5. mynd. Styrkur uppleystra efna í vatni frá Skeidará árin 1982 og 1983; natríum, kísill og súlfat.

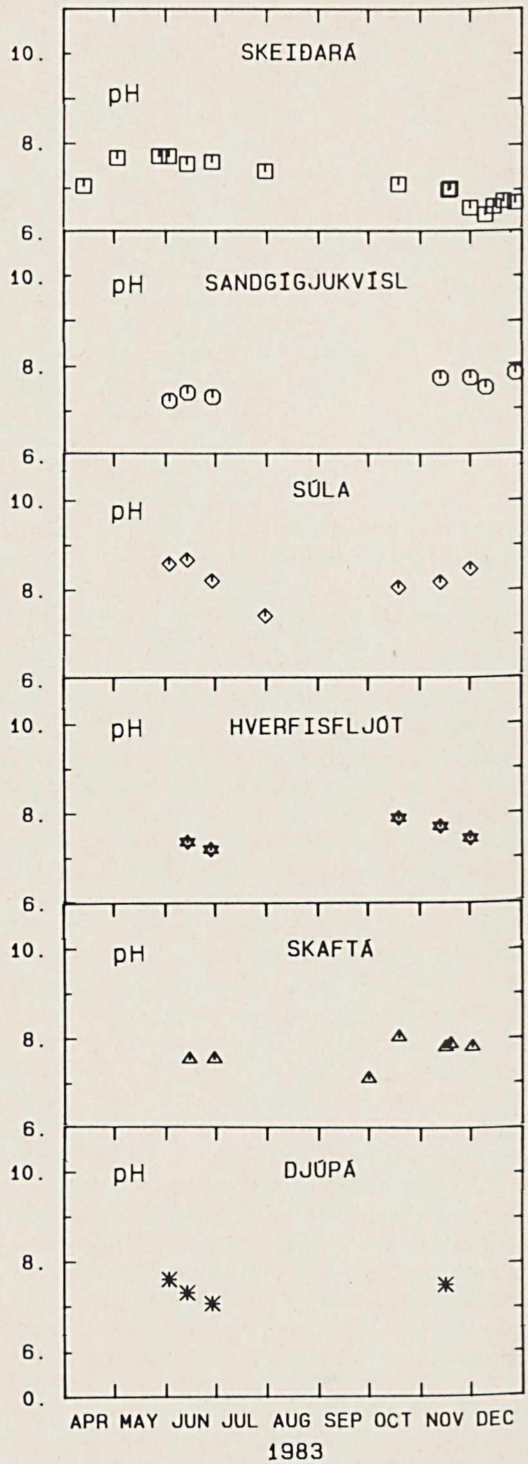

Fig. 6. The pH of water in the glacial rivers Skeiðará, Sandgígjukvísl, Skaftá and Djúpá (see Fig. 1).

6. mynd. Sýrustig vatns í jökulánum Skeiðará, Sandgígjukvísl, Súlu, Hverfisfljóti, Skaftá og Djúpá.

autumn of 1983 increased concentrations of dissolved solids showed geothermal influence in the rivers. This raised the question of leakage out of Grímsvötn two months before the jökulhlaup in December. At the beginning and the end of the period the normal variations were obscured by the influence of jökulhlaups.

Data for the concentration of total dissolved solids (dry residue) exist for Skeidará over a period of twenty years (*Tómasson et al.* 1982). The two years 1982/83 show a seasonal variation that appears to be present for the whole period. However, we should note that sampling was less frequent in the years before 1980 than later.

At the time of the Grímsvötn eruption in 1983 almost no analyses existed for other rivers that drain Vatnajökull. Since then several samples have been collected from the rivers Sandgígjukvísl, Súla, Djúpá, Hverfisfljót and Skaftá (see Fig. 6-8). The concentration of dissolved solids shows considerable variation but the time is too short to give seasonal variations. In September 1983 a jökulhlaup occurred in the river Skaftá.

The water in the rivers has a pH value of 7 to 7.7 but drops down to 6 during jökulhlaups in the rivers Skeidará, Sandgígjukvísl, Súla and Skaftá (Fig. 6, Table 2).

The normal concentration of silica (SiO_2) in Skeidará is about 10-20 mg/kg and during the jökulhlaups it rises up to 50-60 mg/kg (Fig.7, Table 2). In the jökulhlaup in 1972 a lower concentration, 44 mg/kg, was reported by *Steinthórsson and Óskarsson* (1983). The normal concentration of silica in the river Skaftá is similar to that of Skeidará but appears to be somewhat lower, 5-10 mg/kg, for the other rivers. The mean concentration of SiO_2 for Icelandic rivers is 5-15 mg/kg (NEA data).

The concentration of carbonate (as CO_2) is shown in Fig. 8. The normal concentration is around 30 mg/kg in Skeidará but up to 20 times higher during jökulhlaups. Concentrations between 10 and 30 mg/kg are observed in the other rivers.

The sodium (Na) concentration varies normally from 4 to 15 mg/kg in Skeidará but increases to around 60 mg/kg in the jökulhlaups (Fig. 8). In the other rivers the concentration of sodium is 2-15 mg/kg and the seasonal variation appears to be large.

The potassium (K) concentration in Skeidará is normally 0.3-1.2 mg/kg and exceeds 4 mg/kg in water samples from jökulhlaups (Fig. 7). The concentration of potassium in the five other rivers is similar to that of normal water in Skeidará.

The concentration of calcium (Ca) varies between 6 and 19 mg/kg in Skeidará and other rivers have somewhat lower concentrations (Fig.7). During the jökulhlaups the calcium concentration has reached 50 mg/kg in water from Skeidará.

The magnesium (Mg) concentration varies normally between 1.5 and 6 mg/kg and reaches 12 mg/kg in the jökulhlaups in Skeidará. The magnesium concentration is generally lower in the other rivers.

The concentration of sulphate (SO_4) varies normally from 3.5 to 9 mg/kg in Skeidará but reached about 20 mg/kg in the jökulhlaups in 1976 and 1982, around 40 mg/kg in the jökulhlaup in 1965 and nearly 50 mg/kg in 1983. Normal concentrations in the other rivers were observed as 1.5-12 mg/kg during the period June to December of 1983.

During jökulhlaups the river Skeidará reeks of sulphur. However, the concentration of hydrogen sulphide (H_2S) was below the detection limit (0.04 mg/kg) in all water samples taken more than 100 m from the glacier snout.

The concentration of chloride (Cl) in Skeidará is normally 1 to 8 mg/kg and has been observed to increase up to about 13.5 mg/kg during jökulhlaups. *Sigvaldason* (1965) reported maximum values of 43 mg/kg. The normal concentration of chloride in the five other rivers mentioned above varies from 2 to 15 mg/kg.

The concentration of fluoride (F) in Skeidará is normally 0.05 to 0.15 mg/kg and increases up to 0.3 mg/kg during jökulhlaups. The other rivers have a similar normal concentration of fluoride as Skeidará.

Dissolved iron , in concentrations up to 5 mg/kg , was measured in samples of water from the jökulhlaup in Skeidará in Dec. 1983. The samples were filtered one to three days after collection and a part of each acidified. In the fraction of the samples that was not acidified a rust red precipitate of iron oxide appeared the day after filtration. The iron concentration was measured in both parts of the samples. The concentration in the untreated samples was in all cases below detection limit, but 2-5 mg/kg in the acidified samples. In February 1982 samples from the jökulhlaup were filtered a few days after collec-

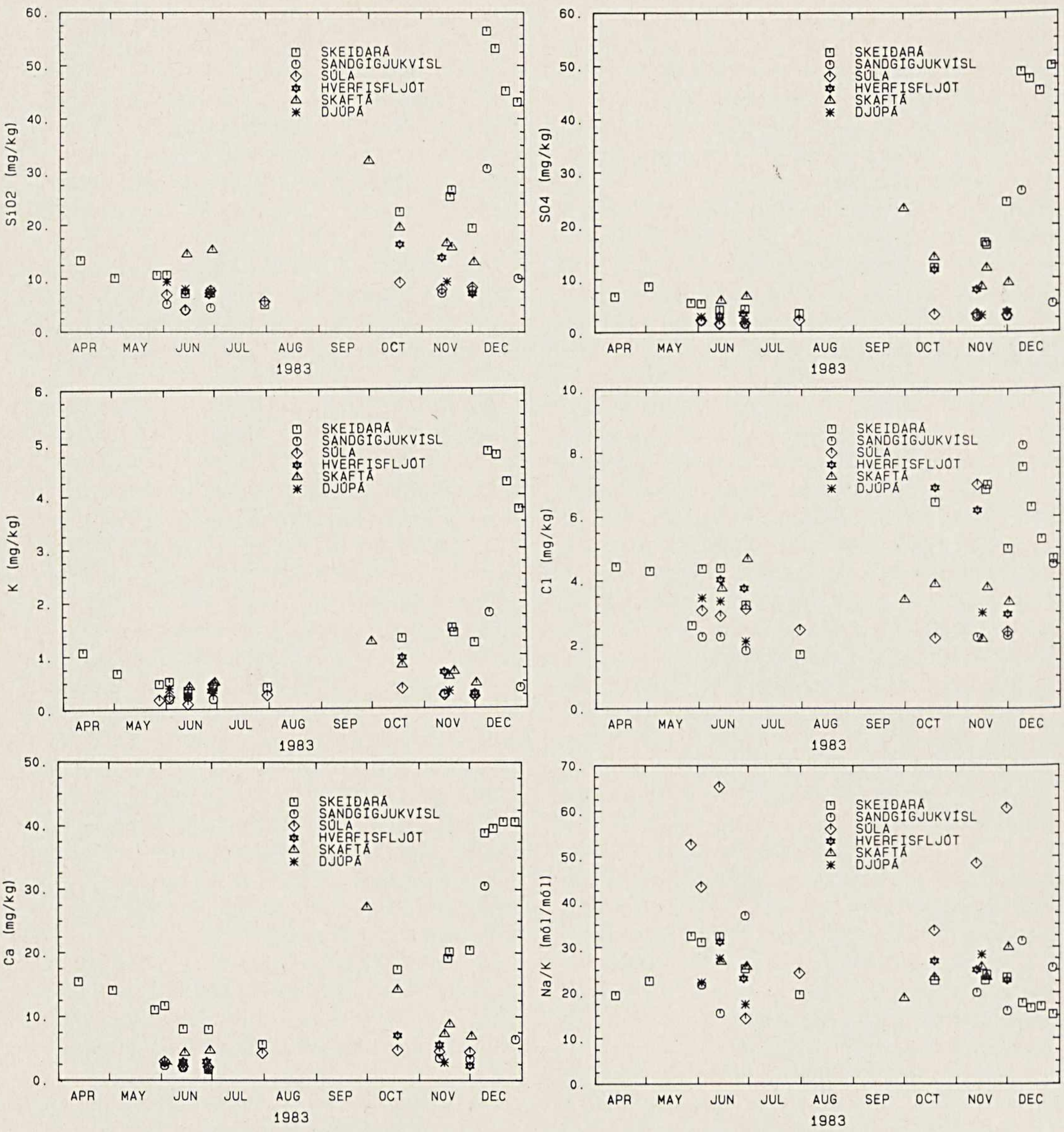

Fig. 7. The concentration of silica (SiO_2), potassium (K), calcium (Ca), sulphate (SO_4) and chloride (Cl) in the glacial rivers Skeiðará, Sandgígjukvísl, Skaftá and Djúpá. Also shown is the molar ratio of Na/K in the water.

7. mynd. Styrkur uppleystra efna í jökulánum Skeidará, Sandgígjukvísl, Súlu, Hverfisfljóti, Skaftá og Djúpá; kísill, kalíum, kalsíum, súlfat og klóríð. Einnig er sýnt hlutfall Na/K.

tion and no precipitation occurred. Hence, the iron concentration in the jökulhlaup of 1983 must have differed from that of 1982. Iron in water from previous jökulhlaups would probably not have been detected due to different handling and storage of the samples. However, 9.5 mg/kg of iron were reported in water from the jökulhlaup in 1954 (*Rist* 1955) but the reliability of the

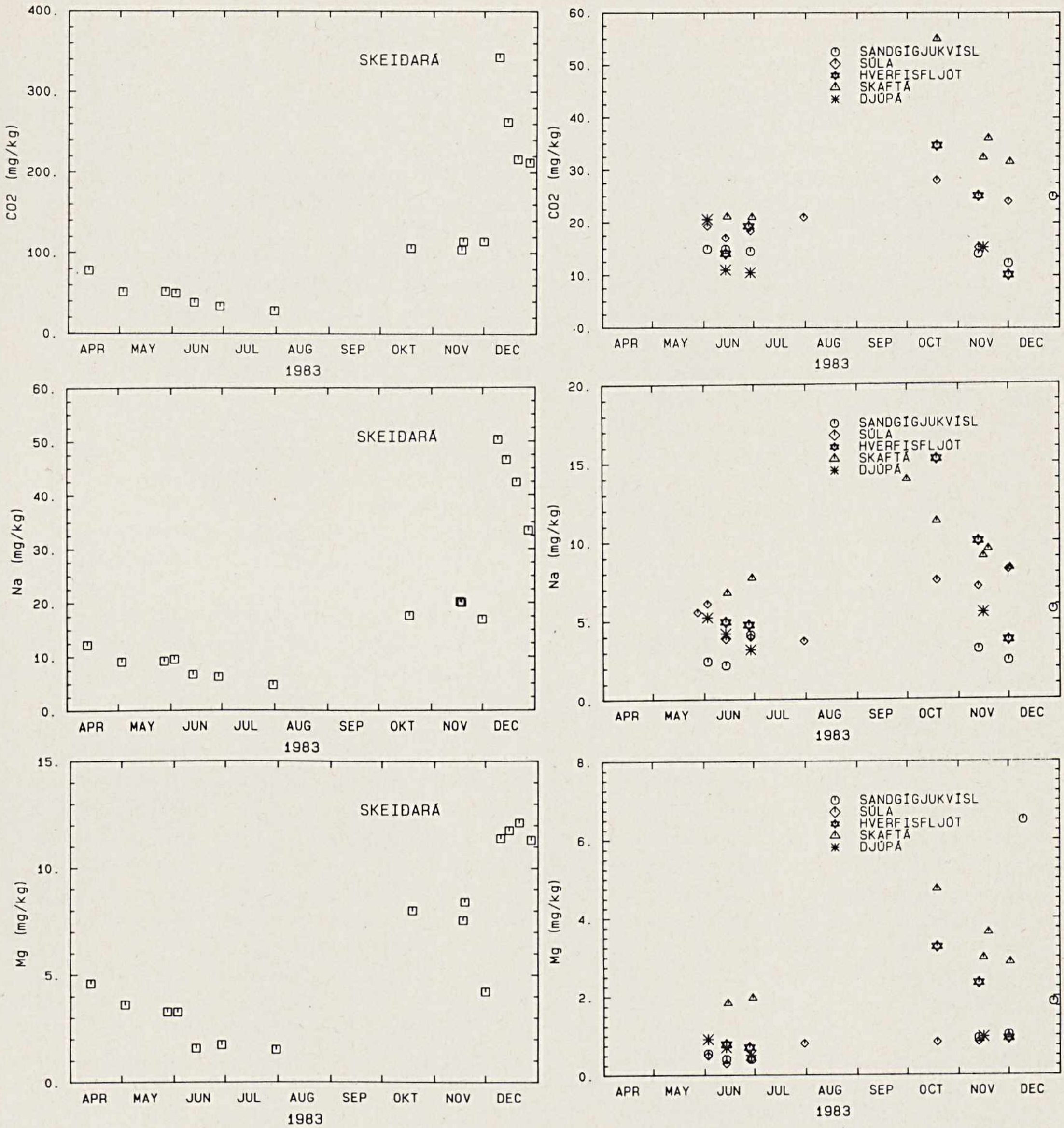

Fig. 8. The concentration of total carbonate (as CO_2), sodium (Na) and magnesium (Mg) in water from the glacial rivers Skeidará, Sandgígjukvísl, Súla, Hverfisfljót, Skaftá, and Djúpá.
8. mynd. Styrkur uppleystra efna í jökulánum Skeiðará, Sandgígjukvísl, Súlu, Hverfisfljóti, Skaftá og Djúpá; karbonat (sem CO_2), natríum og magnesíum.

analysis cannot be evaluated as information is not available about the preparation of the samples and the method of analyses.

Analyses of stable isotopes in the river water are in progress. *Árnason* (1976) reported variations in the deuterium concentrations (δD) in Skeidará from -96 to -59 ‰. The lowest value corresponds to precipitation in the Grímsvötn area whereas the highest value corresponds to precipitation in the lower altitudes where the river emerges from the glacier. The data show large scattering during the year but there may be seasonal variations with the lowest δD values towards the end of the year. During the jökulhlaup in 1972 low and high values were both recorded. Preliminary results of $\delta\ ^{18}O$ values indicate a similar scattering (*Sigfús J. Johnsen,* pers. comm.). Samples taken at various times during the years 1982- 1983 varied from $\delta\ ^{18}O$ = -13.5 to -11 ‰. The variation seems to be irregular and neither seasonal nor showing a systematic change from normal flow to jökulhlaups. During the jökulhlaup in 1982 samples collected on the same day during the maximum discharge of the flood showed -13.5 to -12 ‰. The scattering of the isotopic ratios may to some extent be due to inhomogeneity of the water mixture in the rivers during jökulhlaups. In 1972 estimates of discharge by the method of dilution of radioactive materials proved to be unsuccessful. The radioactive material did not mix completely in the river course (*Páll Theodórsson* pers. comm.).

CHEMISTRY OF WATER IN THE GRÍMSVÖTN LAKE.

The water that drains the Grímsvötn lake has obtained its original chemical composition from four components (with concentrations (C) and the flow of mass per unit time (M) given in parenthesis): geothermal water (C_{gw}, M_{gw}), geothermal vapour (C_{gv}, M_{gv}), ablation from the surface of the glacier (C_a, M_a), and ice melted inside the geothermal area (C_i, M_i). Later this composition may have been modified by chemical reactions in the lake and on the way to Skeidarársandur. The river water in jökulhlaups on Skeidarársandur is a mixture of water from the lake and river water from the normal drainage basin outside the lake (with C_r and M_r). The concentration in jökulhlaups of substances that do not undergo chemical reaction in the lake can be expressed as

$$C_j = k(C_{gw}M_{gw}+C_{gv}M_{gv})/(M_{gw}+M_{gv})+ (1\text{-}k)(C_a M_a+C_i M_i+C_r M_r)/(M_a+M_i+M_r), \quad (1)$$

where k is a geothermal mass fraction defined as the ratio

$$k=(M_{gw}+M_{gv})/(M_{gw}+M_{gv}+M_a+M_i+M_r). \quad (2)$$

The geothermal fraction k could be calculated if we knew the original chemical concentrations and the masses of the components. Not all of this information is available but the model is nevertheless useful as a guide in the discussion of the chemical analyses. For some substances we are able to conclude that the model does not apply and chemical changes must have occurred in the lake. For others the model is applicable and for one of them, silica, reasonable estimates can be made and k evaluated.

Substances whose concentrations are changed by reactions in the Grímsvötn lake

The observed concentrations of sodium, potassium, calcium and magnesium in jökulhlaups are not consistent with a mixture of meltwater and high-temperature geothermal water. They demonstrate that chemical changes have taken place within the lake. The model described by equation (1) does not apply for those substances. That such is the case is clear from comparison with known concentrations in deep water from other geothermal areas like Námafjall, Krafla and Nesjavellir (see Table 3). In those areas the concentration of sodium is much too low to account for the concentration in the jökulhlaups from Grímsvötn. The same applies for potassium although not as conclusively as for sodium. Sodium and potassium are the most soluble of the cations and their rates of leaching out of basaltic glass will be enhanced by the low pH in the lake. The pH of the lake water must be considerably lower than that of the melted ice. This is due to dissolution of acid gases from the geothermal fluid.

Calcium does not exceed about 3 ppm in deep water at non-saline geothermal areas in Iceland (see Table 3) and that is considerably lower than in the normal discharge of the glacial rivers. Dissolution of Ca must have occurred in the highly carbonated water of the Grímsvötn lake.

The magnesium concentration of water from the Grímsvötn jökulhlaups, (10-15 mg/kg), is similar to those of cold groundwater (3-12 mg/kg, NEA data). Experimental data (see *Mottl and Seyfried* 1980) and field data (*Kristmannsdóttir* 1980, *Tómasson et al.* 1977) show that Mg is precipitated at temperatures above 40 °C. The magnesium concentration of non-saline geothermal water is generally in the range of 0.001-0.1

TABLE 3. Composition of geothermal fluids in some high-temperature geothermal areas.
Tafla 3. Efnasamsetning jarðhitavökva í nokkrum jarðhitasvæðum.

Geothermal area		Entalphy Ho	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F	Tot dissolved solids	CO_2	H_2S	H_2	CH_4	N_2	Collection pressure, P_o
		kJ/kg					mg/kg										bars
1 Námafjall	a	2248	162	35.0	5.0	0.1	0.0	1.7	9.0	.19	226	815	975	61.6	1.38	12.25	19.2
Drillhole	b		508	110.9	15.6	0.3	0.010	5.4	27.7	.60	707	153	255	8.6			
BJ-12	c		523	114.1	16.1	0.3	0.010	5.5	28.5	.62	728	22	123	0.1			
2 Krafla	a	1973	113	83.0	14.2	1.4	0.05	55.4	38.0	.31	489	48597	478	40.4	41.7	0.0	12.4
Drillhole	b		607	160.	27.6	2.7	0.103	107.5	73.6	.60	948	1256	42	0.3			
KJ-7.	c		683	181.1	31.1	3.0	0.116	121.0	82.9	.68	1067	573	19	0.1			
3 Nesjavellir	a	2062	226	36.5	7.3	0.08	0.001	2.38	3.3	.15		2598	1288	62.3	1.42	60.3	9.6
Drillhole	b		646	104.3	20.8	0.22	0.004	6.8	9.5			83	155	0.4			
NG-6	c		741	119.9	24.0	0.25	0.004	7.8	10.9	.51		39	88	0.1			
4 Reykjanes	a	1317	584	9120	1386.6	1475.3	0.87	17.8	17634	.15	30272	1842	58	0.19	0.9	7.29	41.7
Drillhole	b		708	10970	1677.1	1843.9	1.118	19.5	21442	.19	37366	50	4	0.0			
Rn-9																	
5 Svartsengi	a	1036	412	6493	1070.9	981.5	1.04	59.7	12990	.07	21773	336	0.06	0.00	0.02	0.32	5.5
Drillhole	b		424	6680	1101.7	1009.8	1.07	61.4	13364	.07	22401	100	0.0	0.00			
SG-11																	

1) Námafjall, drillhole BJ-12. NEA-data. a: total flow, b: deep water (Tquartz 250 °C), c: water boiled at 235 °C.
2) Krafla, drillhole KJ-7. NEA-data. a: total flow, b: deep water (Tquartz 280 °C), c: water boiled at 235 °C.
3) Nesjavellir, drillhole NG-6. *Stefánsson et al.* (1983). a: total flow, b: deep water (Tquartz 290 °C). c: water boiled at 235 °C.
4) Reykjanes, drillhole RN-9. a: water at 295 °C (*Bjarnason* 1984). b: water boiled at 235 °C.
5) Svartsengi, drillhole SG-11. a: water at 240 °C (*Bjarnason* 1983). b: water boiled at 235 °C.

ppm (see *Ellis and Mahon* 1977) and in Icelandic geothermal waters (NEA data and Table 3) only saline or CO_2- waters have magnesium concentrations exceeding 0.1 ppm. We consider the comparison with low-temperature CO_2-water from Lýsuhóll (40-60 °C, 20 ppm Mg) as done by *Steinthórsson and Óskarsson* (1983) to be misleading. Even carbonate-water from high temperature areas would have considerably lower Mg content as the solubility of Mg minerals increases with lower temperatures. Therefore, we do not believe that mixing of meltwater and geothermal water can explain the observed magnesium concentration in jökulhlaups. We suggest instead the interaction between water and highly reactive volcanic glass to be a more likely explanation of the observed Mg concentrations in the water from Skeidará during jökulhlaups. The magnesium was leached from the volcanic glass at temperatures not exceeding 40 °C, and the water has not been exposed to higher temperatures in the lake for any length of time.

The Na/K ratio has been successfully used as a thermometer of geothermal water by many geochemists (*Ellis* 1979, *Fournier* 1981, *Arnórsson et al.* 1983). However, the use of the Na/K geothermometer for highly diluted geothermal water is generally considered questionable (see *Ellis* 1979, *Fournier* 1981, and *Benjamin et al.* 1983). For waters originally at temperatures below 100 °C it is applicable only in special cases (*Kristmannsdóttir and Johnsen* 1982, *Kristmannsdóttir* 1983). *Steinthórsson and Óskarsson* (1983) suggested that the Na/K ratio of water from jökulhlaups could be used to calculate the reservoir temperature in the Grímsvötn geothermal system. The mean value of the Na/K ratio in samples from the jökulhlaup in February 1982 was 24 ± 2 (standard deviation), in December 1983 24 ± 6 and in 1976 the ratio was 19 ± 4. Samples of normal water in Skeidará in 1982 and 1983 show a mean value of 24 ± 6 for the Na/K ratio. The variations of this ratio are greater from one month to another in 1982 and 1983 than between the jökulhlaups in 1976 and 1983. According to *Steinthórsson and Óskarsson* (1983) this ratio was 20 in samples from the jökulhlaup in 1982, 50 in samples from the jökulhlaup in 1972 but it was 40 in their „normal" water (see their table 3, p. 78). For comparison, the average ratio of Na/K in the rivers in SW-Iceland ranged from 17 to 40 in the years 1972/1973 (*Ármannsson et al.* 1972, *Rist* 1974) and the variation in samples from a single river was in the same range. In the river Súla the Na/K ratio in normal water varies from 14 to 65 and from 17 to 45 in the river Djúpá. In light of the described circumstances the use of a Na/K geothermometer on water in the jökulhlaups from Grímsvötn (*Steinthórsson and Óskarsson* 1983) appears questionable.

Substances whose concentrations are not changed by reactions in the lake.

Some substances are not expected to have leached out of basaltic glass in the Grímsvötn lake. First because the glass does not contain the substances in appreciable quantities. This applies for carbonate, fluoride and chloride. Secondly, the substances are poorly soluble in cold water. That applies for silica.

Carbonate is not a major component of basaltic glass and thus would not be leached in the lake. The concentration of total carbonate in the jökulhlaups is the result of plain mixing of the geothermal component and the meltwater. The concentration of carbonate (as CO_2) in normal river water is 10-30 mg/kg as shown in Fig. 8. The concentration for the meltwater component in Grímsvötn is probably lower and an estimate of 20 mg/kg (as CO_2) seems to be an upper limit. It is difficult to estimate the carbonate concentration of the geothermal component. This concentration is variable from one high-temperature geothermal area to another as shown in Table 3.

The concentration of Cl and F cannot be significantly affected by water/rock interaction in the lake but may be slightly changed by increased volcanic activity as HCl and HF are components in volcanic gases.

Silica is poorly soluble in cold water. Hence, no significant leaching is expected in the lake. Therefore, the observed silica concentration of the jökulhlaups reflects the original concentration of the fluid that enters the lake. The discussion of silica will be continued separately in the next section.

GEOTHERMAL MASS FRACTION AND THE BALANCES OF MASS AND ENERGY.

Energy and mass balance equations have so far been used to describe the heat and mass flow in the Grímsvötn area (*Björnsson* 1974, 1983). Now we have obtained new information that allows a more detailed description of the heat flow from the geothermal system. The separation of the geothermal component from the total mass as expressed by the geothermal mass fraction k has now added the third equation (Eq.(2) above).

The flow of mass to the Grímsvötn lake is the sum of four components:

$$M_t = M_i + M_{gw} + M_{gv} + M_a \qquad (3)$$

where

M_i is the mass flow of ice that is melted by geothermal heat in the lake.

M_{gw} is the mass flow of geothermal water.

M_{gv} is the flow of mass in the form of vapour into the lake.

M_a is the flow of water that is melted on the surface of the glacier.

Heat is brought into the lake by the mass flow of geothermal water (M_{gw}) and vapour (M_{gv}) and some heat is conducted through the lake floor. This heat melts a certain mass of ice (M_i) and warms up this mass inside the lake together with water that drains into the lake as surface ablation (M_a). If we neglect the heat flow by conduction, the energy equation can be written

$$M_{gw}\, c_2(T_3-T_2)+M_{gv}(L_v+c_2(T_3-T_2)) = M_i(L_i+c_1(T_2-T_1))+ M_a\, c_1(T_2-T_1) \qquad (4)$$

where

T_1 is the melting point of ice.

T_2 is the temperature of the lake.

T_3 is the temperature of the geothermal fluid when it flows into the lake.

c_1 and c_2 represent the specific heat of water in the respective temperature intervals.

L_i is the latent heat of fusion for water.

L_v is the latent heat of vaporization of water.

We include the equation (2) from the discussion of the chemical analyses.

$$M_{gw} + M_{gv} = k\,(M_a+M_i+M_r+M_{gw}+M_{gv}) \qquad (2)$$

in which k is the geothermal fraction and M_r is the normal mass flow in the river Skeidará that does not originate from Grímsvötn.

As we know M_t and M_a and M_r these three equations can be used to estimate the mass of ice,

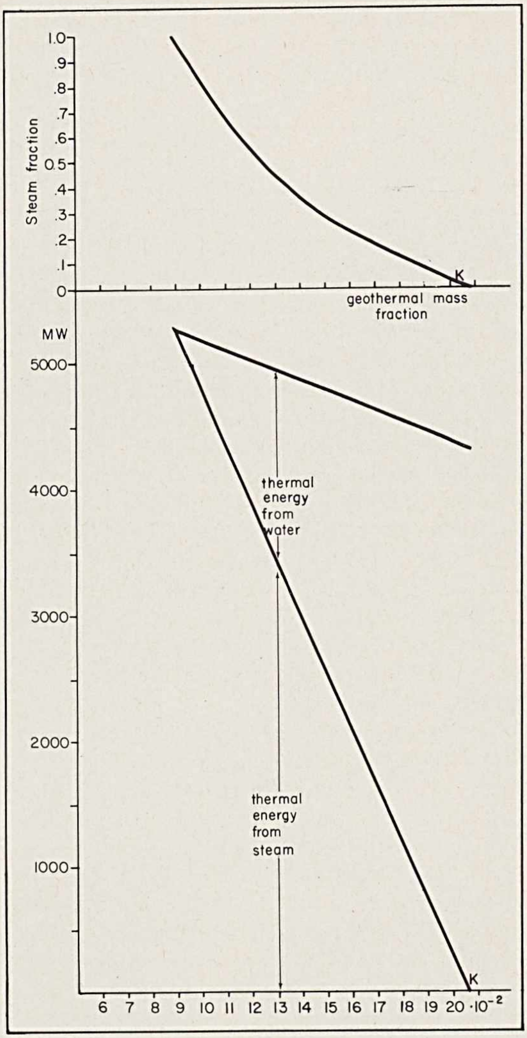

Fig. 9. Thermal power and steam ratio as functions of the geothermal mass fraction. Results of calculations.

9. mynd. Reiknað varmaafl jarðhitasvæðisins í Grímsvötnum (lóðréttur ás) miðað við hlut jarðhitavökva í heildarmassa vatns í Grímsvötnum (láréttur ás). Aðskilinn er varmi frá vatni og gufu. Efsti hluti myndarinnar sýnir hvernig gufuhluti í jarðhitavökvanum breytist eftir því sem heildarmassi jarðhitavökva vex.

geothermal water and vapour. The solution is

$$M_i = (1-k)M_t - kM_r - M_a \qquad (5)$$

$$M_{gv} = (eM_a - a(M_t - M_a) + (L_i + e + a)M_i) / L_v \quad (6)$$

$$M_{gv} = M_t - M_a - M_i - M_{gv} \quad (3)$$

where

$a = c_2(T_3 - T_2)$ and $e = c_1(T_2 - T_1)$.

The equations above have been used to calculate the unknown masses, the steam fraction $x = M_{gv} / (M_{gv} + M_{gw})$, and the terms in the energy equation. Fig. 9 shows how the results vary with the geothermal mass fraction k. These computations were done for the temperature at the bottom of the lake equal to the boiling temperature at 30 bar overburden pressure, that is $T_3 = 235$ °C. The average temperature of the lake was assumed to be $T_2 = 6$°C. (The choice of T_2 is not critical for the results, in the possible range from 0°C to, say 10°C). Other values used in the computations were: $M_t = 6.6 \cdot 10^{11}$ kg/yr, $M_a = 1.5 \cdot 10^{11}$ kg/yr, $T_1 = 0$°C, $L_i = 335$ kJ/kg, $c_1 = 4.218$ kJ/kg K, $c_2 = 4.245$ kJ/kg and $M_r = 0.1 \cdot 10^{11}$ kg/yr (NEA data, *Sigurjón Rist* pers. comm.), and, $L_v = 1770$ kJ/kg.

The results in Fig. 9 show that the energy balance limits k to the range from 0.09 to 0.21. For k=0.09 the entire discharge to the lake must be steam if the required energy is to be provided. For k = 0.21 no steam could be present as heat from the geothermal water provides all the required energy. As k increases the mass of geothermal water is increased but the mass of steam is decreased. But when the mass of steam is reduced by a certain amount the mass of water is increased by $(1+L_v/a)$ times (typically three times) this amount. Therefore, the mass of ice (M_i) required for melting is reduced as k increases and the total thermal power of the geothermal area is reduced from 5300 MW to 4300 MW (see Fig. 9).

Estimates of geothermal mass fraction.

Further interpretation of the calculations, illustrated in Fig. 9, depends on the estimate of the mass fraction k for the Grímsvötn geothermal system. This estimate can be done with the aid of equation (1) which applies for a substance whose concentration is neither changed during storage in the Grímsvötn lake nor when the water runs subglacially to Skeidarársandur. The geothermal mass fraction could be estimated if we knew the original concentration of all five components.

Consider a non-volatile substance whose concentration in the geothermal vapour (C_{gv}) is negligible compared to that of the water phase. Further the concentration in the meltwater component at Grímsvötn is equal to the normal concentration in the rivers on Skeidarársandur. From equations (1), (2), (5), (6) and (7) we obtain for $C_{gv}=0$ and $C_a=C_i=C_r$ the estimate

$$k=(A+S)/(R+B) \quad (8)$$

where

$$A=(e\,M_a + (L_i + e)(M_t - M_a))/L_v \quad (9)$$

$$B=(L_i + e + a)(M_t + M_r)/L_v \quad (10)$$

$$R=(M_t + M_r)(C_{gw} - C_r)/C_{gw} \quad (11)$$

$$S=(M_t + M_r)(C_j - C_r)/C_{gw} \quad (12)$$

and $e=c_1(T_2-T_1)$ and $a=c_2(T_3-T_2)$. All parameters and numerical values are the same as in the section above.

We believe this model applies for the poorly soluble silica. Ice melted in the geothermal area is originally precipitation and contains small amounts of dissolved silica (<1 mg/kg). However, meltwater from the surface as well as the bed may have reacted with rocks on the way to the lake in a similar way as has water discharged into the glacier rivers. For Skeidará the normal concentration of silica is C_r=10-20 mg/kg (see Fig.5) when the river is not influenced by jökulhlaups. The mean concentration of silica is 13± -5 mg/kg for rivers in Iceland (NEA data). The measured concentration of silica is C_j=44-60 mg/kg in water from jökulhlaups (Table 2). In most jökulhlaups the silica concentration has been near 60 mg/kg; this value C_j=60 mg/kg and C_r= 13 mg/kg is used in our calculations. The computations show that the geothermal mass fraction k increases from 0.12 to 0.18 as the concentration C_{gw} in the geothermal water entering the lake decreases from 800 to 300 mg/kg.

The concentration of silica in the geothermal fluid can be estimated on the basis of assumptions about the likely reservoir properties at Grímsvötn. The silica concentration in high-temperature areas is controlled by the reservoir temperature, and its concentration is used as a geothermometer (see *Ellis* 1979, *Fournier* 1981, *Arnórsson et al.* 1983). When water is close to magma, self-sealing due to precipitation of silica puts an upper limit of 330 to 350 °C to the temperature of the fluid (*Fournier* 1983). With increasing temperature, quartz has a solubility maximum at constant pressure. When this maximum is reached (at about 340 °C) precipitation of quartz deep in hydrothermal systems may decrease the permeability to such an extent that convecting meteoric water no longer can attain temperatures higher than that given by the quartz solubility maximum. Known reservoir temperatures in Icelandic high- temperature geothermal areas range from 240 to 350 °C. Table 3 shows chemical concentrations of well discharges for five liquid dominated geothermal areas in Iceland. The first three areas have boiling reservoirs with dilute fluid of meteoric origin. The table shows concentrations for both total discharge and deep water. The two other areas have saline reservoir water. The table shows the deep water concentrations. Further, calculated concentrations are given for water boiled at 235 °C for all the areas. Grímsvötn is a high-temperature geothermal system and the reservoir temperature is presumably above 300 °C. The fluid is dilute and probably liquid dominated. Boiling would occur at 235-250 °C on the lake floor, depending on the height of the lake level.

The concentration of silica in the deep reservoir water may be C_{gw} = 700 mg/kg. If fluid of that concentration were discharged into Grímsvötn, we would estimate the geothermal mass fraction k=0.13 from equation (8). According to the calculations, illustrated in Fig. 9, the mass and energy balances would require the steam mass fraction to be x= 0.45 when the fluid enters the lake. During upflow, however, deep water as well as condensed steam would equilibrate with the formation rocks at or above 235 °C (given a few hours or days, see *Rimstidt and Barnes* 1980). Hence, we estimate the silica concentration C_{gw}= 400-600 mg/kg in the water entering the Grímsvötn lake (see Table 3 for comparison). Further, we estimate the geothermal mass fraction k= 0.14-0.16 and the energy balance requires steam mass fraction x=0.20-0.35 for the fluid discharged to the lake; the mass flow of geothermal water M_{gw}= $0.60\text{-}0.83 \cdot 10^{11}$ kg/yr and M_{gv}= $0.24\text{-}0.34 \cdot 10^{11}$ kg/yr of steam. The mass of ice melted in the lake is estimated to be M_i= $4.0\text{-}4.2 \cdot 10^{11}$ kg/yr. Furthermore, we expect the total thermal power of the Grímsvötn system to be 4700-4900 MW, of which 2100-3000 MW are transported by steam and 1900-2600 MW by water (see Fig. 9).

Calculations similar to those for silica are difficult for carbonate. A plausible estimate is not available for the carbonate concentration of the geothermal component as it varies from one high-temperature area (>300 °C) to another (see Table 3). But if we assume k=0.15 and if the meltwater component contains 20 mg/kg carbonate (as CO_2), (and C_r=C_a=C_i), we can calculate the concentration for the geothermal component that would be consistent with the measured concentrations in the jökulhlaups. The calculations show variations from C=2000 to 4500 mg/kg (as CO_2) for the geothermal component. This is high but not unlikely in an active volcanic area. Direct interaction with magma has been observed in the geothermal systems in Krafla and Námafjall (*Björnsson et al.* 1979). The concentration of CO_2 in geothermal fluids in the Krafla area increased considerably during the recent volcanic events (*Ármannsson et al.* 1982).

The concentrations of fluoride and chloride may well be consistent with a geothermal mass fraction k=0.15 (see Table 3).

VOLCANIC ACTIVITY DEDUCED FROM WATER CHEMISTRY

The high concentrations of sulphate and iron (as well as carbonate) during the jökulhlaup in December 1983 suggest direct contact between magma and geothermal fluid.

Sulphate (SO_4) in the Grímsvötn lake originates from oxidation of H_2S as well as from the SO_4 in the geothermal discharge. The contribution from the meltwater is small as is evidenced by the glacier rivers when not influenced by jökulhlaups (Fig. 8). The concentration of sulphate will be influenced by volcanic activity. We may even expect a sharper increase in sulphate than carbonate shortly after volcanic activity because H_2S (and SO_2) is more soluble in water than CO_2. This may explain the very high concentration of sulphate in the jökulhlaup of December 1983 as compared to those of 1972, 1976 and 1982. The reported concentration of sulfate in the jökulhlaup in 1965 was also very high (*Sigvaldason* 1965).

Geothermal water from high temperature areas in Iceland normally contains less than 0.1 mg/kg of iron. Exceptions are highly saline waters as on the Reykjanes peninsula (2-3 mg/kg) and waters strongly influenced (acidified) by volcanic activity like in the Krafla geothermal area. During volcanic activity in Krafla very high concentrations of dissolved iron (up to 60 mg/kg) were observed in well discharges. Precipitation of iron silicates and sulphides or oxides was observed, either within the wells or in surface pipes (*Kristmannsdóttir* 1984). The normal concentration is only a fraction of those values, i.e. 0.1 mg/kg. In water from Reykjanes the concentration is up to 0.5 mg/kg.

We suggest the following explanation of the iron concentration in the water from the jökulhlaup in 1983. Very acid water has leached iron either from formation rocks or basaltic glass on the lake floor. The high acidity must have been caused by input of acid magmatic gases to the geothermal water. Ferrous iron may remain in solution as long as the water is reducing and the pH is low. High acidity is more likely to remain within the formation rock than on the lake floor where mixing occurs with meltwater. Precipitation of iron is expected due to reactions during storing and oxidation in the lake and the magmatic effects will be masked out. Oxygen in the freshwater will cause oxidation of H_2S to sulphate and ferrous iron to ferric iron. We do not know the time scale for this process.

PREMATURE TRIGGERING OF JÖKULHLAUPS

In general, jökulhlaups from Grímsvötn occur when the water has risen up to a critical level and a pressure barrier has been eliminated. Then water from Grímsvötn escapes beneath the ice east of the lake, 1-2 km to the north of the roots of Grímsfjall. This was discussed by *Björnsson* (1974) and seems to have applied to the triggering of jökulhlaups in 1976 and 1982.

The triggering of the jökulhlaup in 1983.

The jökulhlaup in December 1983 occurred at a water level 20-30 m below the critical level for triggering jökulhlaups (Fig.3). Therefore, water was not able to penetrate out from the bottom of the lake. We suggest that this jökulhlaup was triggered by the opening of waterways along the slopes of Grímsfjall where the collapsed ice cauldron was observed northeast of Grídarhorn (see Figs. 2 and 4). There increased geothermal or volcanic activity had melted ice in places and for two months meltwater with a sulphurous odour had drained from this area down to Skeidarársandur. Finally, this melting managed to open the channels into the lake and the jökulhlaup started. The leakage out of the lake took place at the slopes of the mountain where the water pressure was far from being high enough to open subglacial waterways. This may also explain why the surface of the lake did not fall down to the same level as is usual for jökulhlaups that are triggered at the critical water level.

The small jökulhlaups in 1939, 1941, 1945 and 1948 may all have been triggered through opening of waterways by melting of ice when geothermal activity increased at the northeastern slopes of Grímsfjall. These jökulhlaups are exceptions to the rule that the odour of hydrogen sulphide on Skeidarársandur is detected only a few days before the water discharge increases. (*Thorarinsson* 1974, *Ragnar Stefánsson,* pers. comm.). In 1941 the beginning of a jökulhlaup was noticed in early April but the main flood was in mid-May. In 1945 the jökulhlaup was at maximum in late September but geothermal odour was first noticed in June. The jökulhlaup in 1948 peaked in late February but the sulphurous odour had been perceptible since early January.

In addition to this, we may add that the explorers of Grímsvötn in the fifties seem to have believed that the outlet from Grímsvötn was along the eastern slopes of Grímsfjall. There they described a trench in the glacier surface that has not been observed in recent years (information from Sigurdur Thorarinsson's diaries, kindly provided by his son Sven Th. Sigurdsson 1983).

Increased thermal activity, frequency and volume of jökulhlaups.

The effect of increased geothermal or volcanic activity on the frequency and volume of jökulhlaups from Grímsvötn is an important problem. Subglacial melting at the threshold east of the lake may open waterways into the lake and trigger jökulhlaups. If this takes place on the slopes of Grímsfjall, the occurrence of a jökulhlaup is hastened. Such a triggering mechanism might increase the frequency of jökulhlaups and reduce their volume. Volcanic activity at the threshold east of the lake may trigger jökulhlaups whose behaviour cannot be predicted. They might become catastrophic if the activity prevented the ice overburden from closing the tunnels out of the lake. A volcanic eruption within the lake would melt the floating ice cover but would not cause a rapid rise in the lake level because of the lag in flow of ice into the lake from the surrounding glacier. We would not expect such an eruption to spark off a jökulhlaup immediately if the lake was somewhat below the critical level (assuming, of course, that the activity did not change the triggering mechanism and the critical level remained the same; see *Björnsson* 1974). The eruption in Grímsvötn in May 1983 is an example of such an event. Increased melting in the lake, however, may accelerate the rise of the water level (especially if an opening is formed in the ice cover along Grímsfjall and the ice can flow freely into the lake unimpeded by the mountain). That would hasten the occurrence of a jökulhlaup if the area of the lake increased only slowly in response; the resulting jökulhlaup would have no substantial increase in volume compared to jökulhlaups before the melting increased. But the increased inflow of ice to the lake would only be temporary as it is limited by the mass balance of the drainage basin. The floating line of the ice cover would then move outwards as the ice cover and the surrounding glacier became thinner. The area of the lake would increase and we would expect less frequent and more voluminous jökulhlaups.

An eruption north of the lake would immediately drain meltwater to the lake and cause a rise in the lake level that might trigger a jökulhlaup (*Björnsson* 1974). This happened in 1938.

Steinthórsson and Óskarsson (1983) discussed the effect of increased geothermal activity and suggested that the volume of jökulhlaups would increase but their frequency remain constant. We can agree to the suggestion of increased volume but not to that of constant frequency. Their suggestion of constant frequency seems to be based on a model of a steady state flow of ice into a lake of constant area. The steady state assumption is a valid approximation in the long run but it is questionable whether the area of the lake would remain constant if the geothermal activity increased. Their suggestion of increased volume is based on the observation that more water would be drained out of the lake if the ice cover was thinner. We could agree if it implied that the area of the lake was larger, thus increasing the volume discharged from the lake. But if the area of the lake is to be constant, the drained water volume is the same whether the floating ice cover is thick or thin. Therefore their model seems to imply that the lake is drained empty in the jökulhlaups. But that is not suggested by the authors and all observations indicate that the ice cover on the lake is floating at the end of jökulhlaups.

CONCLUSION

Geothermal activity in the Grímsvötn area is expressed by depressions in the surface of the ice cap; a number of small depressions are superimposed on the main Grímsvötn depression. Ice is diverted to the depression where it melts and water accumulates in the Grímsvötn lake. The lake is covered by a floating ice shelf. Waterpools are observed along the slopes of Grímsfjall and occasionally hot springs have been reported when the surface of the lake is at low levels. The geothermal activity observed on Grímsfjall is minimal in terms of steam outlets and alteration of ground. The water level is 200-300 m below the observed steam outlets on the mountain and by condensation and evaporation of local water all H_2S has been washed out of the steam that escapes from Grímsfjall. The oxygen isotope data are in agreement with the chemical data and show extensive fractioning and depletion of ^{18}O relative to ^{16}O. Chemical studies of the vapour from the fumaroles yield little information about the deep reservoir fluid.

Information about the geothermal fluid at Grímsvötn is obtained from the rivers on Skeidarársandur during jökulhlaups. This information is not easy to interpret because of complications involving water-rock interaction in the lake; this applies to the soluble cations (and Na/K thermometers are not applicable) but to a lesser extent to other elements like silica, carbonate, chloride, fluoride and sulphate as well. Silica solubility data and assumptions about the likely temperature in the geothermal reservoir, however, enables one to estimate the mass of the geothermal fluid discharged into the lake. The geothermal mass fraction is estimated 14-16% of the total mass in the jökulhlaups. The mass and energy balances require that steam is 20-35% (by mass) of the geothermal fluid that enters the lake. The mass flow of geothermal water to the

Grímsvötn lake is estimated to be 0.60-0.83 10^{11} kg/yr, and 0.24-0.34·10^{11} kg/yr of steam. The mass of ice melted in the lake is estimated as 4.0-4.2·10^{11} kg/yr. The total thermal power of the Grímsvötn area is estimated 4700-4900 MW, of which 2100-3000 MW are derived from steam and 1900-2600 MW from water. No marked changes have ever been observed in the geothermal activity on the mountain ridge. Inside the depression, however, the activity has been reduced since 1960 as expressed by ice cauldrons and fumaroles. But in the autumn of 1983 melting of ice in places due to increased thermal activity on the northeastern slopes of Grímsfjall may have opened waterways into the lake and triggered a jökulhlaup. An odour of hydrogen sulphide was detected from the river Skeidará for weeks before the jökulhlaup commenced. The jökulhlaup occurred at a water level 20-30 m lower than the critical level required for triggering the jökulhlaups that are discharged from the bottom of the Grímsvötn lake. Such a mechanism may have triggered the small jökulhlaups in 1939,1941,1945 and 1948. Sulphurous odour for long periods may warrant a forecast of such premature jökulhlaups.

Grímsvötn is one of the few geothermal systems where active volcanism is observed and where there is a direct interaction between magma and geothermal water. Evidence of volcanic activity was found by the high content of sulphate and the presence of iron in the jökulhlaup of December 1983. Volcanic activity in 1983 has increased the SO_4 concentration in the Grímsvötn lake. The high SO_4 content in the jökulhlaup in 1965 may suggest volcanic activity in Grímsvötn at that time. The iron content in the jökulhlaup in December 1983 indicates eruption of magma into the geothermal fluid.

A NOTE ADDED IN PROOF.

In June 1984 the authors visited Grímsvötn. Then, a water pool was observed at the foot of W-Svíahnúkur, in the crater of the 1983 eruption. The pool was 40–50 m wide and 300–400 m long. The water level was at 1385 m a. s. l. Hot springs with temperature up to 80°C were located along the entire southern bank of the lake and vigorous emanation of gas was observed at the lake floor. The temperature at the lake surface was 4–6°C.

Steam emanated from loose tephra south of the pool and sulphur was precipitated at the surface. Sulphurous odour arose from the crater as well as from an open crevasse east of E-Svíahnúkur. A 30–50 m deep trench in the ice surface was observed along the eastern slopes of Grímsfjall. The ice cauldron that collapsed in December 1983 (Fig. 4) was situated in this trench.

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ÁGRIP
JARÐHITASVÆÐIÐ Í GRÍMSVÖTNUM

Helgi Björnsson, Raunvísindastofnun
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Þótt jarðhitasvæðið í Grímsvötnum sé eitt stærsta (ef ekki stærsta) jarðhitasvæði á Íslandi, sjást þar ekki mikil bein ummerki um jarðhita eins og við eigum að venjast á öðrum jarðhitasvæðum. Jarðhitasvæðið er að mestu leyti hulið jökli. Ummerki jarðhitans eru því óvenjuleg. Öldum saman hefur hann brætt ís og myndað mikla lægð inni á miðjum Vatnajökli, Grímsvatnalægðina. Að sunnan afmarkast hún af Grímsfjalli, 300 m háu þverhníptu stáli, að vestan

af Vatnshamri, 100-200 m háum og kollóttum. Að norðan hylur ís öll fjöll og þar hallar jöklinum alla leið upp að Bárðarbungu. Undir ísnum syðst í lægðinni leynast Grímsvötn, hulin 200 m þykkri íshellu. Austur úr þeim falla jökulhlaup á nokkurra ára fresti niður á Skeiðarársand. Allt eru þetta merki um jarðhita undir jökli. Af öðrum ummerkjum niðri í Grímsvatnalægðinni má nefna, vatnsborð við rætur Grímsfjalls og Vatnshamars og stöku sinnum hafa sést þar volgar laugar þegar lágt er í Vötnunum. Uppi á Grímsfjalli sjást íshellar og gufuaugu við báða Svíahnúkana, tvö jökulsker sem rísa upp úr ís.

Gufa sem stígur upp frá Grímsfjalli ber lítil merki jarðhitavökvans undir botni Grímsvatna. Þessi gufa er eimur sem hefur stigið upp af vatnsborði 300 m neðar í fjallinu. Á leið þaðan hefur gufan þést hvað eftir annað og gufað upp á ný og þau efni fallið út sem minna á jarðhita, t.d. finnst örsjaldan brennisteinslykt við Grímsvötn og efnagreiningar frá gufuaugum á Grímsfjalli sýna að flest önnur efni tengd jarðhita eru horfin. Um hlaupvatnið úr Grímsvötnum gildir hins vegar allt annað. Af því leggur hinn versta fnyk og uppruni þess leynir sér ekki. Því hefur vatn verið efnagreint í hlaupunum 1954, 1965, 1972, 1976, 1982 og 1983. Auk þess hefur verið könnuð efnasamsetning í jökulánum utan hlaupa til þess að fá fram hvernig efnasamsetning árvatnsins raunverulega breytist við hlaupin.

Vatn í Skeiðarárhlaupum er blanda af hreinu bræðsluvatni frá jöklinum og jarðhitavatni sem safnast hefur fyrir í Grímsvötnum. Þar verða hins vegar efnabreytingar við geymsluna milli hlaupa og því er ekki vandalaust að fá fram upplýsingar um jarðhitavökvann út frá hlaupvatninu. Súrt vatn skolar út alkalímálma (Na og K) og alkalíjarðmálma (Mg og Ca) úr hvarfgjörnu basaltgleri á botni Grímsvatna. Þess vegna breytist samsetning auðleystra efna svo sem kalíum, kalsíum, magnesíum og natríum. Hvað varðar þessi efni er því samsetning í hlaupvatni engin vísbending um gerð jarðhitavökvans. Af þeim sökum er útilokað að nota efnahitamæla byggða á hlutfallinu Na/K í hlaupvatni til þess að reikna hitastig í jarðhitakerfinu í Grímsvötnum (eins og *Sigurður Steinþórsson og Niels Óskarsson* (1983) reyndu). Því má bæta við að þessar efnabreytingar hafa orðið við hitastig sem hlýtur að vera lægra en 30-40 °C. Styrkur efna eins og magnesíums minnkar með hita og er nær enginn í jarðhitavatni. Svo mikið af magnesíum mælist í jökulhlaupvatni, að efnabreytingarnar í Vötnunum hafa orðið við hitastig undir fyrrgreindum mörkum og hiti getur heldur ekki til lengdar hafa farið yfir þau, því að þá hefði efnið fallið úr vatninu.

Breytingar verða þó ekki á öllum efnum við geymsluna í Vötnunum. Kísill er svo torleystur að hann breytist lítið í köldu vatni og því geymir styrkur hans upplýsingar um jarðhitavökvann sem borist hefur inn í Grímsvötn. Þennan kísilstyrk má meta þar sem náin tengsl eru milli magns af kísli og hitastigs í jarðhitakerfum. (Grímsvötn eru háhitasvæði og hliðsjón er höfð af þekktum jarðhitasvæðum). Jarðhitavatnið hefur síðan blandast kísilsnauðu bræðsluvatni og í hlaupunum berst því þynnt jarðhitavatn niður á Skeiðarársand. Kísilstyrkur þess er mældur og því má reikna með hve miklu kísilsnauðu bræðsluvatni jarðhitavatnið var þynnt. Einnig er unnt að finna hve mikið jarðhitavatn hefur borist í Vötnin; það er vatnið sem á vantar til þess að fá heildarvatnsmagnið í Vötnunum. En þá er ennfremur unnt að finna hvernig jarðhitavökvinn skiptist milli vatns og gufu. Jarðhitagufan er þrefalt orkuríkari á massaeiningu en vatnið og ákveðnum heildarmassa verður aðeins skipt á einn veg milli vatns og gufu ef samanlögð varmaorkan frá þeim á að bræða ákveðinn massa af ís.

Niðurstöður benda til þess að um 15% af heildarmassa vatns í Grímsvötnum sé kominn frá jarðhitavökva. Hér er um að ræða nýjar upplýsingar sem ásamt fyrri gögnum um massa og orkubúskap Grímsvatna gera mögulegt að fá fram nýtt mat á heildarorku jarðhitakerfisins og skilja að þátt vatns og gufu bæði hvað varðar massa og orku sem berst inn í Grímsvötn. Gufa er á bilinu 20-35% af massa alls jarðhitavökvans. Heildarvarmaafl jarðhitans samsvarar 4700-4900 MW og þar af ber gufa upp 2100-3000 MW en vatn 1900-2600 MW.

Grímsvötn eru eitt fárra jarðhitasvæða þar sem eldvirkni gætir og merki sjást um bein tengsl kviku við jarðhitavökva. Þannig sást hátt magn af súlfati og járni af efnagreiningum á hlaupvatni í desember 1983. Það bendir til þess að kvika hafi borist inn í jarðhitakerfið. Efnamælingar benda til þess að svo hafi etv. einnig verið 1954 og 1965.

Síðastliðin þrjú ár hafa hlaup frá Grímsvötnum verið með öðrum hætti en þrjá áratugina á undan. Frá því um 1950 fram að 1976 hljóp reglulega á 4 til 6 ára fresti þegar vatnsborð í Vötnunum hafði risið svo hátt að þrýstingur á botni þeirra nægði til þess að vatn gæti þrengt sér út við botninn austanverðan. En í desember 1983 hljóp við vatnshæð sem var 20-30 m lægri en þurft hefur undanfarna áratugi til þess að hlypi úr Vötnunum. Tvo mánuði fyrir þetta hlaup fannst oft brennisteinslykt af Skeiðará og ræddu menn hvort það gæti bent til þess að leki væri hafinn úr Grímsvötnum. Við teljum hins vegar að hér hafi verið um að ræða afrennsli vatns frá svæði austan í hlíðum Grímsfjalls. Þar hafði myndast mikill hringlaga ketill sem sást úr flugi meðan á hlaupinu stóð (4. mynd). Við teljum aukinn jarðhita á þessu svæði (eða eldvirkni) hafa veitt bræðsluvatni niður á Skeiðarársand um haustið en svo hafi loks farið að bráðnunin hafi opnað vatnsrásir alla leið inn í Grímsvötn. Þá hafi hlaup farið af stað. Þetta gæti einnig hafa gerst við hlaupin 1939, 1941, 1945 og 1948. Á undan þessum hlaupum fannst lykt af Skeiðará svo vikum skipti. Það verður því að telja vissar líkur á Grímsvatnahlaupi ef brennisteinslykt finnst af Skeiðará svo vikum skiptir þótt vatn standi ekki nægilega hátt í Grímsvötnum til þess að það geti þrengt sér út undir jökulinn við botn þeirra.

Hot springs discharged into the crater lake that was formed in the 1983 Grímsvötn eruption. Photo. Helgi Björnsson, 22nd June 1984.
Heitar laugar við vök í gígnum sem myndaðist við Grímsvatnagosið 1983. Ljósm. Helgi Björnsson, 22. júní 1984.