With regard to the small recent moraine lying at the back of Acorrymore which is considered to be Late-glacial in date, it is not possible to say more than that the snow line must have been below the summit of Croaghaun (2192 ft.) and was probably below 1750 ft. O.D. The fact that the moraine lies as low as 750 ft. O.D. (228 m.) has little meaning, for the deep sheltered hollow with a very steep slope left by the previous glacier was an ideal place for the accumulation and preservation of a small glacier at a level somewhat below the natural snow line. The level of the Late-glacial snow line on Mount Leinster in Co. Carlow was formerly estimated at 1650 ft. (503 m.),[3] but with the more cautious approach employed above it would not be possible to say more than that the level must have been below 2000 ft. (610 m.).

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SOME NEW ASPECTS OF THE GRÍMSVÖTN PROBLEM

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Report of a lecture given to the British Glaciological Society at Cambridge on 6 *March* 1952

ABSTRACT. Grímsvötn (The Lakes of Grímur) is the name of a volcanic centre in Vatnajökull, the eruptions of which accompany the gigantic glacier bursts on Skeidarársandur which occur normally about every tenth year. Recent expeditions to Grímsvötn and reconnoitring flights have led to the view that between glacier bursts the Grímsvötn depression is gradually filled with water, forming a lake with a maximum area of about 35–40 sq. km. This accumulation of water is partly due to ablation and partly to continuous solfatara and fumarolic activity.

The close resemblance between the discharge graphs of glacier bursts from Grímsvötn and graphs of drainage of normal ice-dammed lakes such as Lake Graenalón is stressed. It is also pointed out that ten years' accumulation, about 7 cu. km., in the area drained into the Grímsvötn depression, corresponds roughly with the total discharge of a normal glacier burst from Grímsvötn. It is suggested that the glacier bursts determine the moment of eruption and not *vice versa*. This might explain the usually very regular intervals between these eruptions. The irregularities occurring since 1934 might be due to the present climatic amelioration.

ZUSAMMENFASSUNG. Grímsvötn (die Seen von Grímur) ist der Name eines vulkanischen Zentrums in Vatnajökull dessen Eruptionen die riesenhaften Gletscher-Ausbrüche am Skeidarársandur, die sich gewöhnlich ungefähr alle zehn Jahre ereignen, begleiten. Jüngst ausgeführte Expeditionen nach Grímsvötn und Auskundschaftsflüge haben zu der Ansicht geführt, dass die Grímsvötn Senkung sich zwischen den Gletscher-Ausbrüchen allmählich mit Wasser füllt und so einen See mit einer maximalen Fläche von ungefähr 35–40 km.[2] bildet. Diese Wasseransammlung ist teilweise durch Ablation herbeigeführt, teilweise durch ununterbrochenes subglaziales Schmelzen, das auf der Aktivität von Solfataren usw. herrührt.

Die grosse Ähnlichkeit zwischen den Ausströmungs-Diagrammen von Gletscher-Ausbrüchen des Grímsvötn und Ablauf-Diagrammen normaler eisgedämmter Seen wie z.B. des Sees Graenalón wird betont. Es wird ferner darauf hingewiesen, dass das Anfüllen der Fläche des in die Grímsvötn Senkung abgelaufenen Wassers innerhalb zehn Jahren, *ca.* 7 km.[3], ungefähr der Total-Ausströmung eines normalen Gletscher-Ausbruches des Grímsvötn entspricht. Es wird angenommen, dass die Gletscher-Ausbrüche den Augenblick der Eruption bestimmen und nicht umgekehrt. Es könnte dies eine Erklärung für die gewöhnlich sehr regelmässigen Intervalle zwischen diesen Eruptionen sein. Die seit 1934 vorkommenden Unregelmässigkeiten mögen dem sich gegenwärtig verbessernden Klima zuzuschreiben sein.

THE lecture commenced with the early history of the eruptions in the centre of Vatnajökull, the situation of which was already known to the Icelanders before A.D. 1600. The probable routes used by fishermen crossing Vatnajökull in the fifteenth and sixteenth centuries are given in Fig. 1 (p. 269). In 1919 two young Swedish geologists, Erik Ygberg and Hakon Wadell,[13] rediscovered the volcanic centre of Vatnajökull, the eruptions of which are accompanied by great glacier bursts on Skeidarársandur. They named this volcanic centre Svíagígur, or Swede's Crater.

The lecturer's outline of the history of the earlier explorations and the records of previous volcanic eruptions and glacier bursts gave solid historical facts for the rejection of this name in favour of Grímsvötn (The Lakes of Grímur), from which Vatnajökull itself has probably derived its name. When first mentioned by name in the literature it is called Grímsvatnajökull (The Glacier of Grímur's Lakes).[1] The lecturer begged that future expeditions to Iceland would accept the old Icelandic name and not attempt to introduce new names.

The lecturer continued :—

The eruption in Grímsvötn (see Fig. 2, p. 275) in April 1934 was the first to be the object of real investigation. This was quite a normal Grímsvötn eruption. The river Skeidará, which in March and April normally has its smallest discharge, started to rise on *March 22nd*. The rise was slow at first, but on the *24th* it had reached approximately the normal summer high-water level. On the *28th* the water started forcing its way out from under the glacier at several places, breaking up its border. On the morning of *March 31st* the glacier burst reached its climax. Forty to fifty thousand cubic metres of muddy, grey water plunged forth every second from under the glacier border bringing with it icebergs as big as three-storeyed houses. Almost the whole of the *sandur* or outwash plain, some 1000 sq. km. in area, was flooded. At 17.30 hr. the same day the burst suddenly started to abate, and by the following morning the discharge of the Skeidará was normal. On the evening of *March 30th*, that is eight days after the river started rising and on the day previous to the culmination of the glacier burst, the first signs of a volcanic eruption were visible. This culminated during the following days when the column of ash and vapour reached a height of some 13,000 m., with ashes spreading over large areas of the eastern and north-eastern districts.

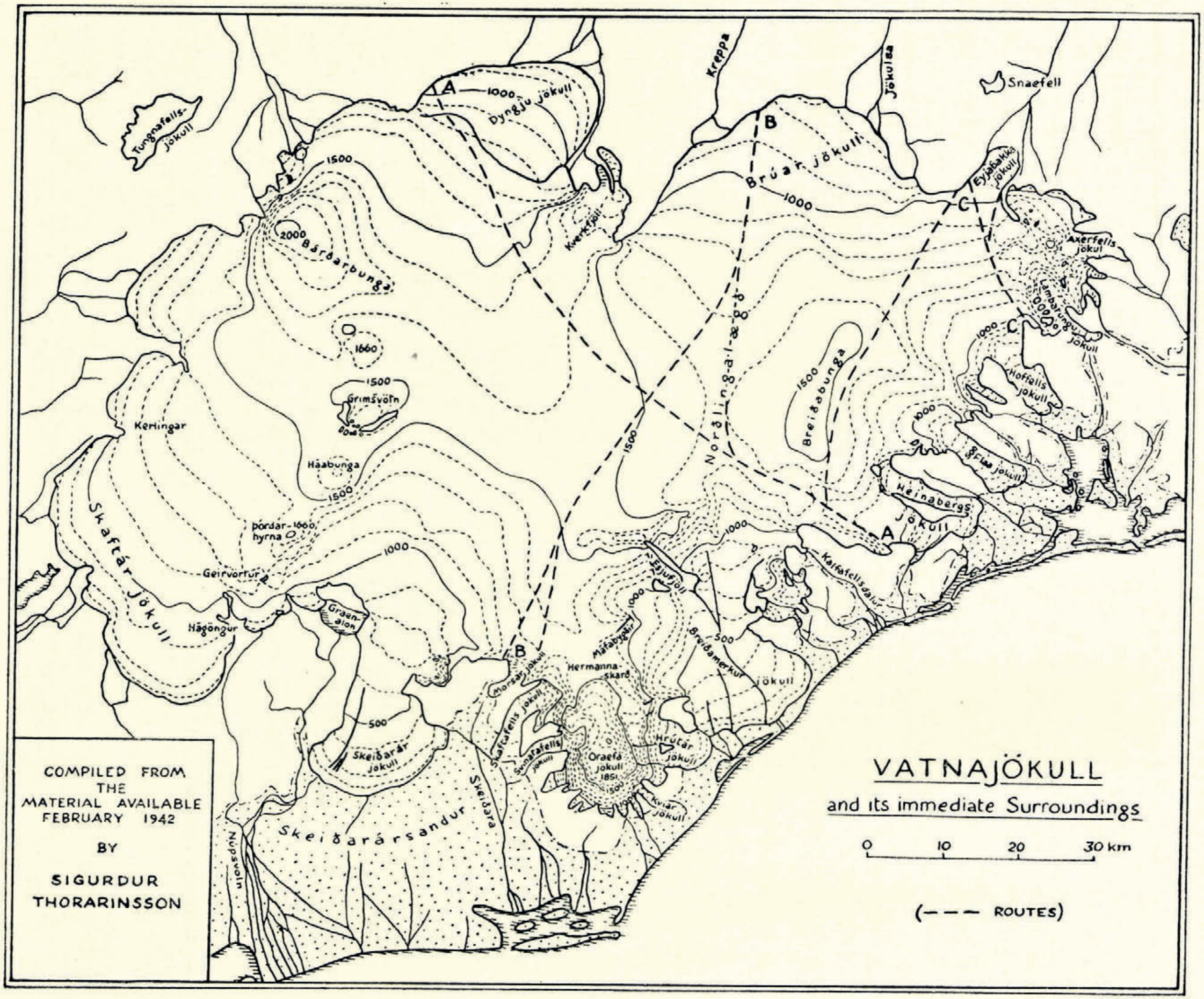
When Icelandic and Danish expeditions reached the Grímsvötn area after the eruption, they found that the precipice which formed the southern limit of the depression was at least 200 m. higher than when the Swedes had seen it in 1919. The ice cover had, in other words, sunk more than 200 m. At the foot of the precipice in the south-western part of the depression, two main craters had formed. The further east of the two was about 500 m. in diameter. Photographs taken by Nielsen [5, 6] and Áskelsson [1] show that the crater was bounded on three sides by a 50 m. high ice wall. Here one can justly say that fire and ice met.

In April 1938 another glacier burst of approximately the same magnitude took place on the Skeidarársandur. Fig. 3 (p. 275) is an aerial photograph of this burst. In it we see the whole outwash plain, about 50 km. broad, flooded, with the exception of some stretches of the coastal bar. In the background we catch a glimpse of the promontory of Ingólfshöfdi (in the most remote part of the bar) washed all around by the flood. This burst was not followed by a volcanic eruption. However, some remarkable changes in the Grímsvötn area could be noted from the air after this burst. About 10 km. north of the Grímsvötn depression there had developed a circular cauldron in the ice, approximately 2 km. in diameter and 150 m. deep in the centre. From it, a valley-shaped depression, 100 to 150 m. deep and 1 to 2 km. wide, led down to Grímsvötn (Fig. 4, p. 271).

The members of the Icelandic and Danish–Icelandic expeditions which visited the Grímsvötn area after the 1934 eruption added considerably to our knowledge of this region, particularly through the unique photographic material which they obtained. They did not, however, provide any final solution of the problem. Indeed, as I shall show later, some of their explanations of the relationship between the volcanic eruptions and the glacier bursts hardly proved tenable. It gradually became clear that more knowledge was needed before the problem could be solved. Information had to be obtained not only about the Grímsvötn depression but also about the regime of the glacier which drains into it.

Since 1938, Icelandic scientists have flown to this region once or twice a year for reconnaissance and photographic purposes. I have taken part in these flights since 1945. In addition, Icelandic expeditions have visited the region. Among these should be mentioned an expedition in August 1942 led by the late Steinthór Sigurdsson, at that time the director of the Icelandic State Research Council; an expedition in August 1946 led by Sigurdsson and myself; and the French-Icelandic

Fig. 1. Map showing the positions of Grímsvötn and Skeidarársandur, and the probable routes across Vatnajökull in the 15th and 16th centuries



expedition in March–April, 1950, led by J. Eythórsson and A. Joset. (The aerial reconnaissances and expeditions from 1934 to 1946 are recorded in the *Polar Record*, Vol. 5, No. 33–34, 1947, p. 60–66.)

The purpose of the 1942 expedition was reconnaissance and survey of the Grímsvötn depression (Fig. 5, p. 271). The aim of the 1946 expedition was: (1) partially to correct the map of the western region of Vatnajökull, mainly to determine the size of the area draining into the Grímsvötn depression; (2) to dig pits for study of accumulation in this area; (3) to determine the height of Bárdarbunga, the cupola of the westernmost Vatnajökull (found to be 1988 m. high, the second highest mountain in Iceland); and (4) to visit Kverkfjöll, the third highest mountain range in Iceland situated on the northern border of Vatnajökull. One of the largest solfatara areas in Iceland lies in a valley which intersects the western part of this mountain range at about 1600 m. elevation. Since this area is partly covered by ice, we expected to obtain an interesting comparison with the Grímsvötn area.

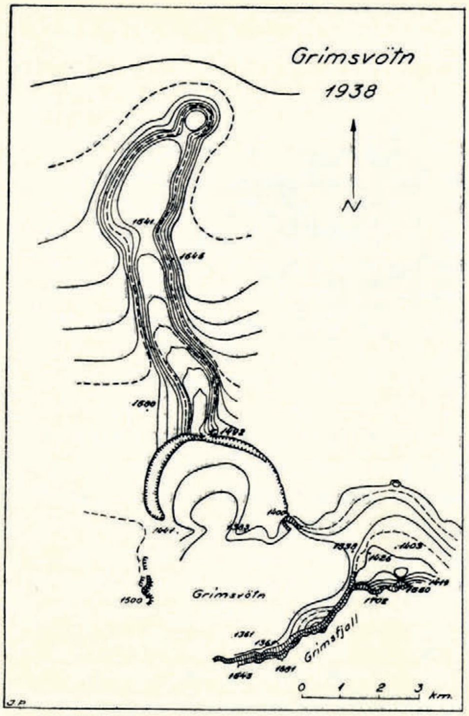
The 1946 expedition was the first motorized Vatnajökull expedition. By using jeeps, it was possible to reach the temporary snow line of Dyngjujökull, 16 km. south of the glacier margin.* From there, trips to Grímsvötn, Kverkfjöll and Bárdarbunga were made with a Canadian, model Eliasson, 25 h.p. motor sledge. Although this sledge is designed only for two persons, six of us used it, as four members of the expedition on ski were pulled along by holding on to a rope fastened to it. Because of this motorization, it was possible to complete the programme in 14 days in spite of a four-day snowstorm. Included in this two-week period was travel time to and from Reykjavík.

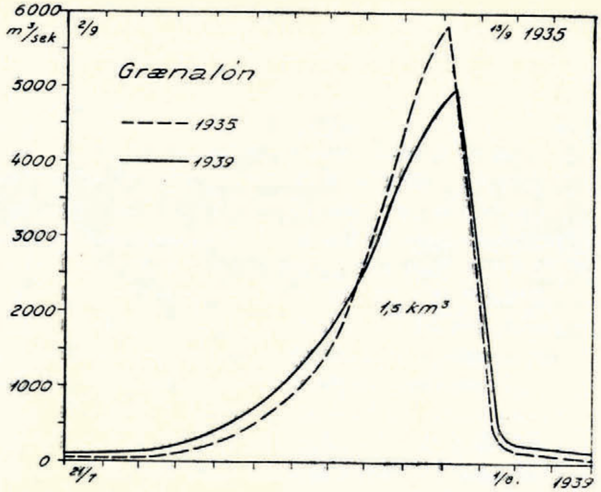
The French–Icelandic Expedition,[3] the most recent expedition to Vatnajökull to date, was even more motorized. Two weasels were used, thus making it possible to cross the glacier and to carry out some important surveys in less than a month's time. This, too, was done in spite of the most severe weather conditions. The main task of this expedition was to measure the thickness of the glacier by seismic soundings. Although fewer measurements were obtained than originally intended, the results were most remarkable. They showed that the ice was much thicker than had previously been thought, the maximum thickness measured being a little more than 1000 m.[4] According to these measurements, the subglacial topography of southern Vatnajökull is very broken and is, in fact, a direct continuation of the eastern Iceland fjord landscape. The largest outlet glaciers, such as Skeidarárjökull, seem to fill deep valleys which reach far in under the central ice plateau. Unfortunately, owing to bad weather conditions, it was not possible to make any reliable measurements of places within the actual Grímsvötn area. However, some pits were dug there by S. Rist [7] in order to measure accumulation.

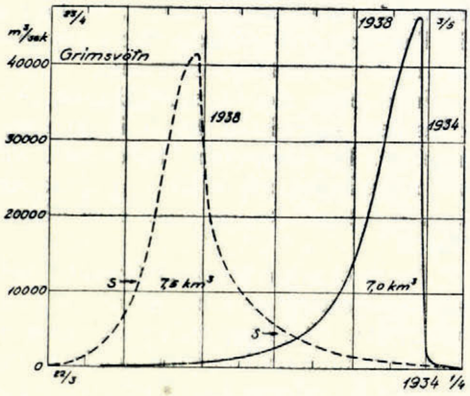
The map of the Grímsvötn depression, drawn by Sigurdsson and based on the trigonometric measurements obtained by the 1942 expedition, shows that the area of the depression below the level of the highest strand lines of the impounded lakes is 35 to 40 sq. km. The area which drains into this depression cannot be determined exactly since we still know too little about the subglacial topography. It is approximately 260 sq. km. and thus the total Grímsvötn area is about 300 sq. km. Although the annual precipitation in this area cannot yet be calculated exactly from the pits dug to date by Rist and myself, the probable annual value is about 2500 mm. of water per unit area.

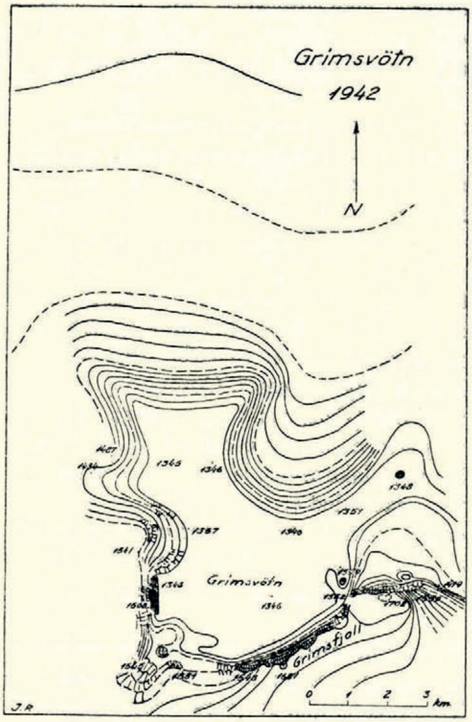
The current interpretation of the Grímsvötn eruptions and their connection with the glacier bursts is the one advanced by the Danish geographer and vulcanologist Niels Nielsen [5, 6] in his papers on Vatnajökull. According to his interpretation, the depression becomes almost filled with ice between eruptions. This quantity of ice, some 10 cu. km., is then melted by the eruptions themselves during a maximum period of 20 days, thus causing the glacier bursts on Skeidarársandur. In my opinion this is an entirely unacceptable assumption—and this was also the opinion of the late Steinthór Sigurdsson.[11]

* Earlier that same summer a reconnaissance of the route across Dyngjujökull had been made by J. Áskelsson in a jeep driven by Á. Stefánsson, who also took part in our expedition in August.









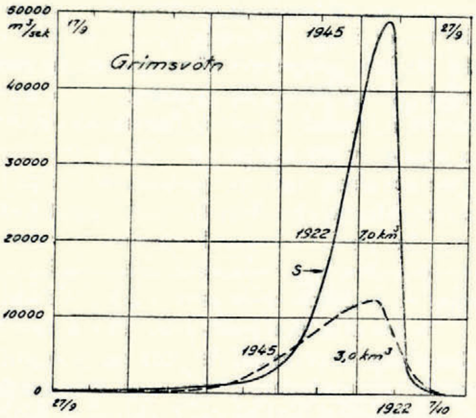


Fig. 4 (top left). The Grímsvötn depression and the area north of it after the glacier burst in 1938. The map was drawn by G. Gestsson and is mainly based on aerial photographs. The semi-circular feature below Pt. 1492 is a nearly vertical ice-cliff. The features by Pts. 1500 and 1543 are ice-free areas. Heights in metres. Contours at 20 m. intervals

Fig. 5 (bottom left). Grímsvötn in 1942. The map was drawn by S. Sigurdsson based on trigonometric measurements in August 1942. The black oblong and the circular areas indicate open water. The cross surrounded by a circle shows the site of the south-westernmost crater of 1934

Fig. 8 (top right). Approximate discharge graphs of the glacier bursts from Grænalón in 1935 and 1939

Fig. 9 (centre right). Approximate discharge graphs of the glacier bursts from Grímsvötn in 1934 and from Grímsvötn and an area 10 km. north of Grímsvötn in 1938

Fig. 10 (bottom right). Approximate discharge graphs of the glacier bursts from Grímsvötn in 1922 and 1945

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Let us consider the following facts: 8×10^{14} kg. cal. are required to melt 10 cu. km. of ice. Assuming a subglacial eruption period of about twenty days, as does Nielsen, the average daily supply of energy required would be 4×10^{13} kg. cal. This is one thousand times more heat than is produced daily by the lava lake Halemaumau (calculated at $3\cdot2\times10^{10}$ kg. cal./day, *cf.* Wolff [14]). The total heat energy produced by the last Hekla eruption, which lasted 13 months, may be calculated at 0·5 to $1\cdot0\times10^{15}$ kg. cal., or about the same amount of energy as is needed to melt 10 cu. km. of ice. Thus, it may be regarded as nearly certain that the Grímsvötn eruption was not as rich in heat energy as assumed by Nielsen. Even if it were, it is not possible that this heat could contribute to the melting except in a very limited degree. This heat can reach the surface of the earth in two ways, either through lava or gases, mostly water vapour. It has been established that lava does not form in any considerable quantity during the Grímsvötn eruptions. One cubic kilometre of dense lava would be necessary to melt 10 cu. km. of ice. This is considerably more lava than was produced by the last Hekla eruption. Furthermore, the escaping gases from the craters, which are very small in proportion to the Grímsvötn depression area as a whole, would certainly melt a funnel-shaped hole through the ice before they could melt more than a fraction of ice in the depression. In this case, most of the heat produced would escape into the air. The photographs taken immediately after the eruption also show perpendicular ice walls 50 m. high on the edge of the east crater.

From the numerous reconnaissance air trips and from the ground expeditions of the 1940's, it has been established that it is primarily water that accumulates in the depression between eruptions. The Grímsvötn basin's level surface is an ice-covered lake surface (*cf.* Fig. 6, p. 275) with a maximum area of some 35–40 sq. km. Particularly to the south-west (Figs. 5, p. 271 and 7, p. 275) small ice-free areas exist which are kept open the year round by the subterranean heat.

The mechanism of the Grímsvötn glacier bursts is most easily understood by comparing it with the catastrophic drainage of the numerous ice-dammed lakes along Vatnajökull's largest outlet glaciers.[8] There, melt water accumulates until the water behind the ice barrier reaches more than nine-tenths of the height of the barrier. The water can then raise the barrier and force its way underneath so that the lake drains with catastrophic results. The largest of Vatnajökull's ice lakes is Graenalón (The Green Lake) which is dammed by Skeidarárjökull. This lake attains an area of 18 sq. km., a depth of more than 150 m. and contains some 1500 million cu. m. or 1·5 cu. km. of water. It is emptied approximately every four years. Fig. 8 (p. 271) shows graphically the drainage discharge pattern in 1935 and 1939. From this we can see that the drainage is slow at first, accelerates to an ephemeral maximum and then rapidly decreases. Comparing these graphs with those of the 1934 and 1922 outbreaks from Grímsvötn (Figs. 9 and 10, p. 271), which may be regarded as normal bursts, we see that the discharge patterns are almost identical. This is explained by the fact that the Grímsvötn is a type of ice-dammed lake which is drained when the water has risen high enough to raise the ice barrier. The more extended course of the 1938 graph is probably explained by the fact that at that time a greater proportion of the water came farther from the north and thus the drainage proceeded more slowly. Based on these graphs, we find that the total drainage volume of these glacier bursts is about 7 cu. km. The maximum discharge is approximately the same as noted by Nielsen.

We are now in a position to estimate the bulk of that part of Vatnajökull which drains into the Grímsvötn depression. As previously noted, the total area is about 300 sq. km. with a probable annual accumulation of 2500 mm. of water per unit area. This means that 10 years' accumulation in the area drained to the Grímsvötn depression is equivalent to about 7·5 cu. km. of water. This figure corresponds roughly to the total discharge of a normal glacier burst from Grímsvötn, which normally occurs about every 10 years. Here we have, in my opinion, the most plausible explanation of the regularity of the glacier bursts during the past centuries. Glacier bursts have occurred in 1934, 1922, 1913, 1903, 1897 (no visible eruption), 1892, 1883, 1873, 1861, and so forth.[12] Accumulation in the area over a period of 10 years is capable of filling the depression with enough water to raise the damming ice barrier. But how does this accumulation, which originates mainly as snow, change into water? Three conditions probably contribute to this: (1) the considerable ablation especially in the depression itself (*cf.* Fig. 7); (2) the actual volcanic eruptions and (3) the continuous subglacial melting because of continuous subglacial solfatara activity of the same type as in Kverkfjöll where in 1946 we found large ice cauldrons due to subglacial melting.[10] Such cauldrons are also commonly formed in the Grímsvötn depression between glacier bursts.[11] Thus, it may be regarded as certain, as already maintained by Áskelsson in 1946,[1] that there is a large permanent centre of subterranean heat at Grímsvötn. It is not possible to calculate exactly how much ice can be melted by this subglacial solfatara activity. However, in the Torfajökull area, the biggest solfatara area in Iceland with the exception of Vatnajökull, the transport of heat to the surface is calculated to be about $1{\cdot}5 \times 10^9$ kg. cal./hour,[2] which would be sufficient to melt about 1·6 cu. km. of ice in 10 years.

We may thus consider the Grímsvötn as an area characterized by a very specific glacial regime where ablation primarily takes place from below and where the discharge on a large scale is limited to a period of only a few days approximately every ten years. Actually, this hypothesis gains credence from the situation within the Grímsvötn area during the 1940's. During this period, instead of one glacier burst of normal magnitude, there were three smaller ones. These occurred in May 1949 (some 2 cu. km.); in September 1945 (some 3 cu. km.) and in February 1948 (some 2 cu. km.). In other words, approximately the same total quantity of water was discharged from three glacier bursts instead of from one. This same tendency appears also in the normal ice-dammed lakes, which at the present time are drained much more frequently than before. The Vatnsdalur Lake, which during the first decades of this century was drained once a year, is now drained two or even three times a year. Formerly Graenalón drained every four years, but recently there were only two years between bursts. The reason for this is the catastrophic thinning of the damming glaciers with the resultant incapacity to dam the lakes to the same height as before. It would appear to be possible that the same might be the case with Skeidarárjökull and Grímsvötn.

Another remarkable fact is that the eastern part of Skeidarársandur, north of Ingólfshöfdi, was inhabited from the time of the colonization of Iceland until the fourteenth century. Such habitation could not have been possible if glacier bursts of the magnitude of recent centuries had taken place. As will be seen from the photograph in Fig. 3, the whole marginal part of the *sandur* becomes flooded when these bursts occur. We know that the Icelandic glaciers were considerably smaller during the early settlement of Iceland than they have been during recent times. Only now are they beginning to shrink to their previous size. May not then the explanation of human habitation of the *sandur* be that the Skeidarárjökull in those days was not capable of damming any major quantity of water in Grímsvötn? In other words, I suggest that a similar situation existed then as in the 1940's with small and frequent glacier bursts instead of large, devastating ones. It is also of interest that no visible volcanic eruptions were connected with the four most recent glacier bursts, whereas almost every glacier burst of the past centuries has been followed by volcanic eruptions.

Volcanic eruptions have always been considered as primary and glacier bursts as secondary phenomena. But we have already established the fact that glacier bursts have taken place without any visible volcanic eruptions. We also know that the eruptions first become apparent when the glacier bursts are about to reach a maximum. It is therefore rather tempting to suggest that the glacier bursts are primary and that it is they that determine the moment of the eruptions and not *vice versa.* The great release in pressure caused by the emptying of the lake might be sufficient to start an eruption. The absence of eruptions in connection with the most recent bursts could perhaps be accounted for by the fact that these were so small that the consequent release in pressure was not great enough to cause an eruption. This, of course, does not rule out the probability that eruptions may again occur when the magmatic tension underneath the Grímsvötn has become sufficiently great.

From this it might be concluded that the change in behaviour of the Grímsvötn in the 1940's was one of the consequences of the climatic amelioration during the past few decades. This, of course, is only an hypothesis which may be disproved by the next glacier burst or eruption, nor am I able to tell if it can explain the behaviour of another subglacial volcano, the Katla volcano in Mýrdalsjökull. Subglacial volcanism in Iceland is still an interesting problem with many unsolved aspects.

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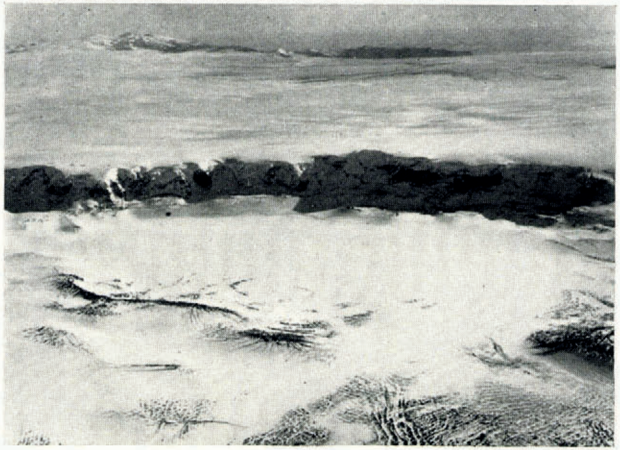
Author's Note

Since I gave the lecture reported above J. Eythórsson has published a map of the subglacial topography of Vatnajökull based on the seismic soundings of the French–Icelandic Expedition 1951 (Landid undir Vatnajökli: *Jökull*, 2. ár. Reykjavík 1952, p. 1–4). According to this map the total subglacial area of Grímsvötn is about 305 sq. km. or practically the same as I had calculated and gave in my lecture. The map shows one sounding within the Grímsvötn depression according to which the bottom of the depression is 780 m. above sea level, but Eythórsson has informed me that this sounding cannot be regarded as reliable. However, it seems probable that the depression is somewhat deeper than has been assumed hitherto.

Further, I want to mention that Eysteinn Tryggvason, seismologist in charge of the seismological station in Reykjavík, has now kindly informed me that on 30 March 1934 the seismographs in Reykjavík registered an earthquake shock at 21.04.46 hr. G.M.T. which was followed by four minor shocks within the next two hours. The epicentre of these shocks was in the Grímsvötn depression. These were the only shocks originating beneath that area registered during the 1934 eruption. It is most likely that these shocks were volcanic. As they coincide with the beginning of the visible eruption it seems probable that the eruption really started on the same day as it became visible and not many days earlier as must be assumed if the eruption is supposed to have caused the melting and started the glacier burst.

Sigurdur Thorarinsson



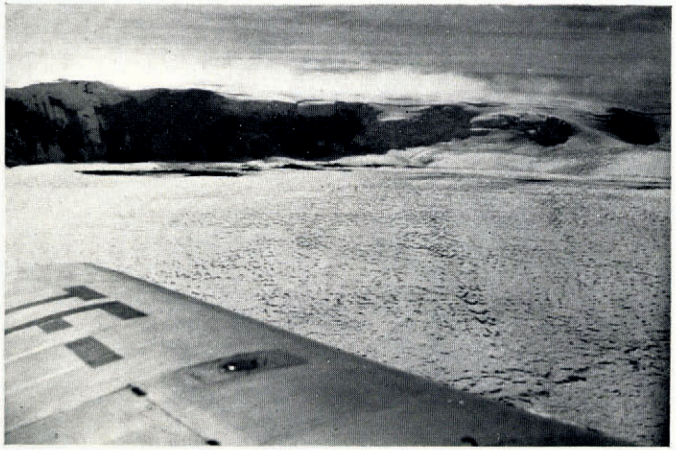


Fig. 2 (top left). The Grímsvötn depression and Mt. Grímsfjall. Aerial view on 20 September, 1945, from the north. In the background the summit of Öræfajökull (2119 m.) is seen

Fig. 3 (bottom left). The glacier bursts on Skeidarársandur on 27 May, 1938. View from the south-westernmost part of the sandur *to the east. The further part of the* sandur *plain is totally flooded except for the 50 km. long coastal bar*

Fig. 6 (top right). The southern part of the Grímsvötn depression on 28 August, 1950. View to the south-west. The black precipice is the north side of Mt. Grímsfjall. Note the ice covered lake surface

Fig. 7 (bottom right). The south-western edge of the Grímsvötn depression on 28 August, 1950. Open water with floating icebergs is seen along the escarpment

Aerial photographs by S. Sigurdsson (Figs. 2 and 3) and by S. Thorarinsson (Figs. 6 and 7)