Volcanoes beneath Vatnajökull, Iceland: Evidence from radio echo-sounding, earthquakes and jökulhlaups

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ABSTRACT

Integration of knowledge of subglacial topography, earthquake activity and jökulhlaups has contributed to more precise locations of the volcanic systems beneath Vatnajökull. Bárðarbunga is the centre of a volcanic system which includes the fissure swarms of Veiðivötn to the SW and Dyngjuháls to the NE. The Grímsvötn volcano is the centre of a volcanic system that comprises the Laki fissure swarm in the SW and extends for an unknown distance to the NE of the volcano. Þórðarhyrna is probably a separate central volcano within this system. The Kverkfjöll system can be traced 10 km to the SW of the Kverkfjöll volcano. It appears to be separated from the Grímsvötn volcano. The Askja fissure swarm extends beneath Dyngjujökull and can possibly be traced to the Grímsvötn volcano. Hamarinn and the ridge striking eastward from Hamarinn (Loki Ridge) are central volcanoes which together with the Fögrufjöll fissure swarm form a volcanic system. No support can be found in the topographic data for the existence of a central volcano near Breiðabunga. Volcanic activity in historical times has mainly been limited to the Grímsvötn and Bárðarbunga systems. Major rifting events have affected large sections of these volcanic systems but both have been remarkably quiet for the past decades. A few volcanic events are presumed to have occurred on the Hamarinn - Loki system and on the Askja fissure swarm beneath Dyngjujökull, but no event is known with certainty on the Kverkfjöll system.

The rivers Skeiðará and Súla have the most frequent eruption-related jökulhlaups. They receive meltwater from the Grímsvötn caldera and the area to the SW of it, including Þórðarhyrna. Núpsvötn, Djúpá and Hverfisfljót drain the southwestern part of the Grímsvötn system, an area bounded by Þórðarhyrna, Geirvörtur, Hágöngur and Pálsfjall. Skaftá drains the Loki Ridge and the area west of Grímsvötn. Jökulhlaups in Kaldakvísl, and ultimately Þjórsá, must originate in the Bárðarbunga or the Hamarinn - Loki systems, and the only possible source for volcanic jökulhlaups in Skjálfandafljót is the northern part of the Bárðarbunga system. Jökulsá á Fjöllum may drain meltwater from activity in all the volcanic systems in northern Vatnajökull: Bárðarbunga, the Askja fissure swarm and Kverkfjöll. This includes the voluminous, ice-filled calderas of Bárðarbunga and Kverkfjöll. Activity in the northern part of the Grímsvötn system may cause floods in Jökulsá á Fjöllum. Meltwater from volcanic activity on the SE flank of a ridge that strikes south from Kverkfjöll may drain to Jökulsá á Brú. Volcanic activity farther north on the E flanks of this ridge would cause floods in Kreppa.

INTRODUCTION

The volcanic rift zones of Iceland radiate from the centre of the Iceland hot spot, considered to be located in the eastern part of the central highland. The volcanic production rate has a maximum in this area (Jakobsson, 1980) and here the volcanic products display the

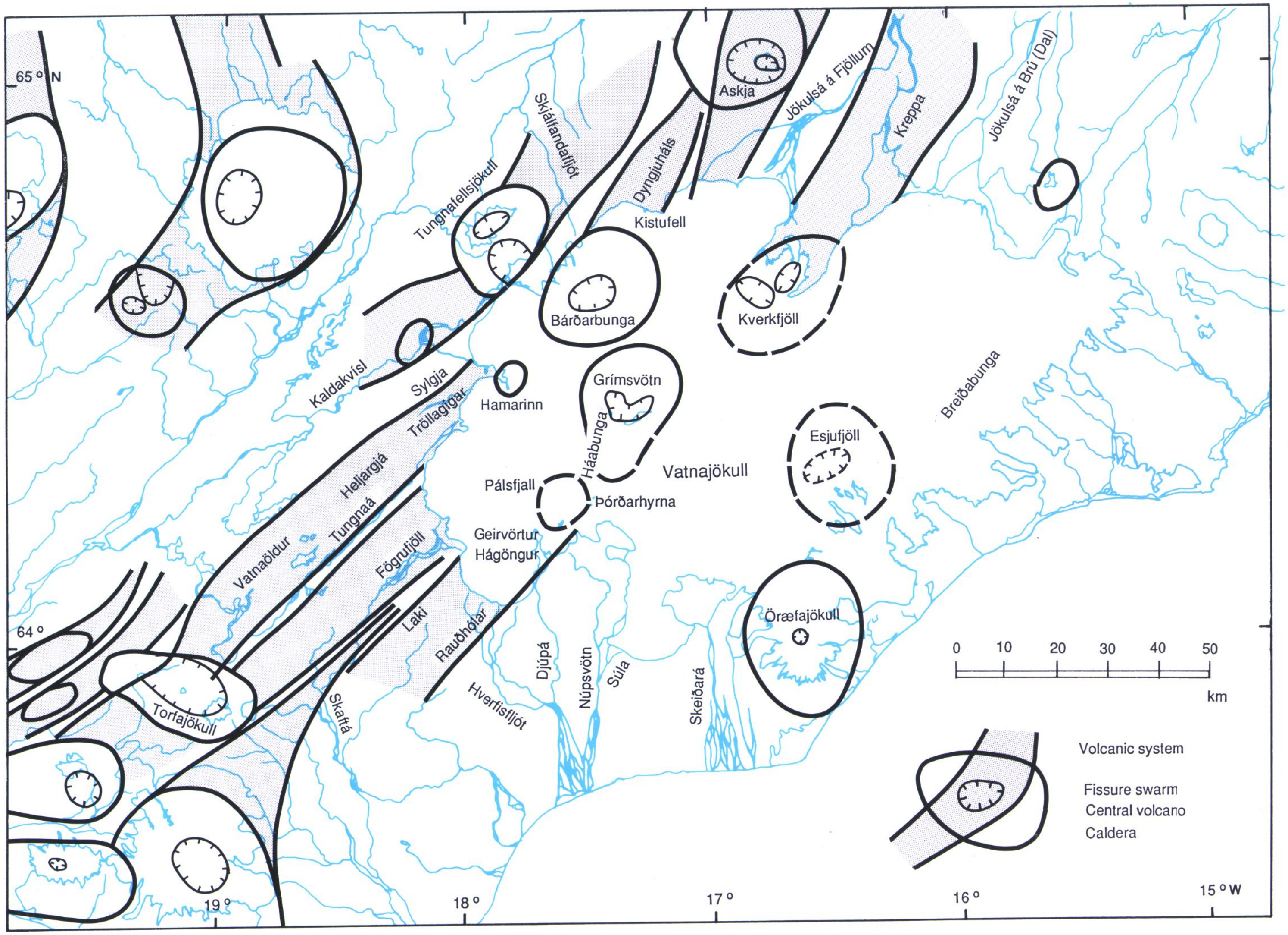

Figure 1. Index map of East-Central Iceland showing the principal central volcanoes and fissure swarms of the neovolcanic zone, the ice cap Vatnajökull and its main glacial rivers (after Einarsson and Sæmundsson, 1987). —*Megineldstöðvar og sprungusveimar í hinu virka gosbelti á suðausturhluta Íslands, Vatnajökull og helstu ár, sem falla frá honum (gert eftir korti Páls Einarssonar og Kristjáns Sæmundssonar, 1987).*

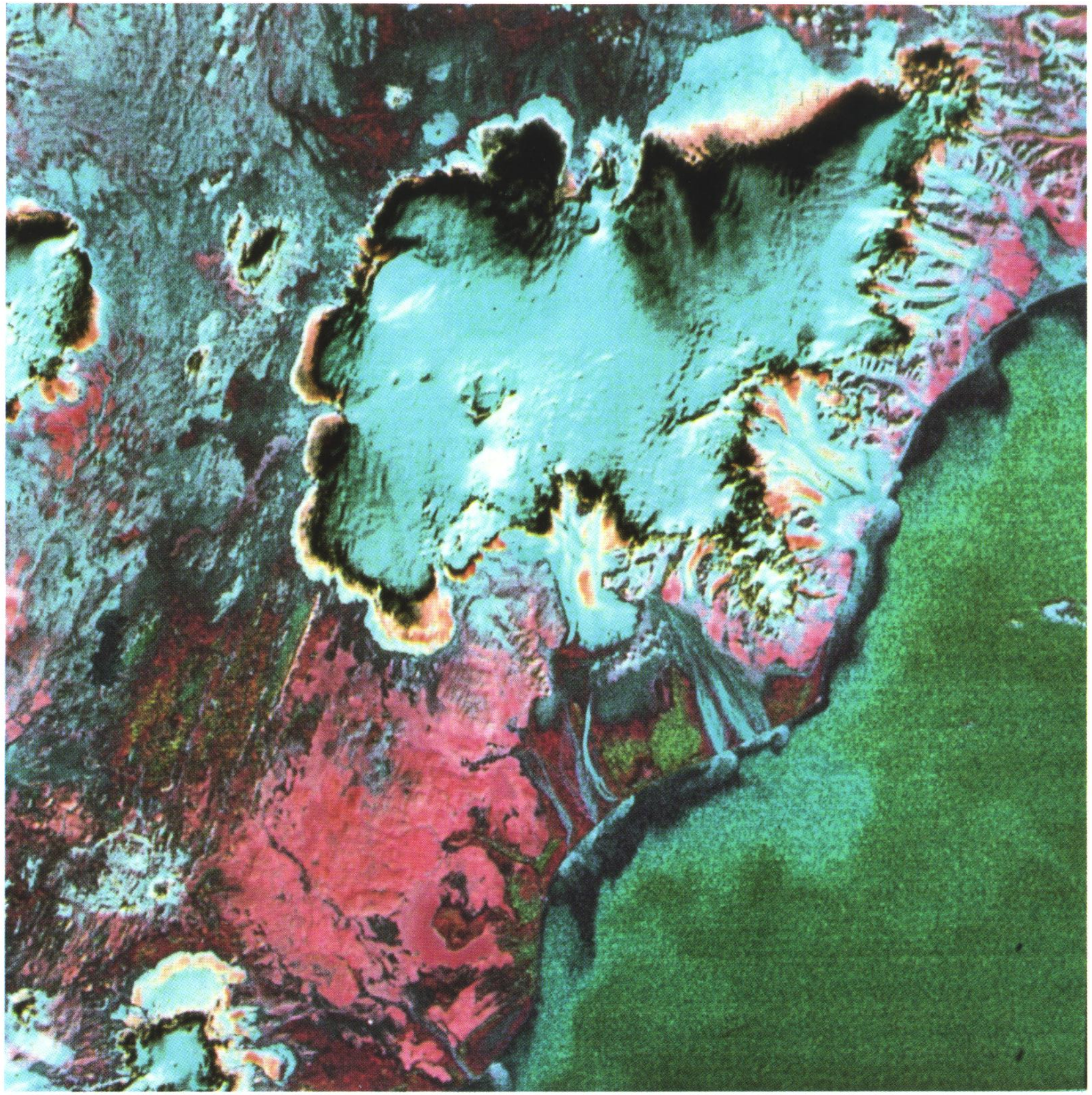

Figure 2. LANDSAT image of the Vatnajökull region. This low sun angle image shows well the calderas of Kverkfjöll, Bárðarbunga and Grímsvötn, also the two ice cauldrons NW of Grímsvötn associated with jökulhlaups in Skaftá river. — *Gervitunglamynd af Vatnajökli, tekin við lága sólarhæð svo að öskjurnar í Kverkfjöllum, Bárðarbungu og Grímsvötnum koma vel fram. Einnig sjást sigkatlarnir norðvestan við Grímsvötn, sem myndast hafa vegna jarðhita undir jöklinum. Undan þeim fellur vatn í Skaftárhlaupum. (Landmæl. Ísl.).*

greatest chemical diversity (Sigvaldason *et al.*, 1974). Seismic evidence supports the hypothesis that this area is underlain by the central part of a mantle plume of low velocity material (Tryggvason *et al.*, 1983; Gebrande *et al.*, 1980). This section of the neovolcanic zone is largely covered by the ice cap Vatnajökull (Fig. 1), and therefore its geological structure is only poorly known. The area has been volcanically active in historical times and early seismic work revealed it as one of the most seismically active areas in Iceland (Tryggvason *et al.*, 1958; Tryggvason, 1973). Eruptions have led to tephra fall and floods of meltwater, often damaging vegetation, farms and roads in coastal areas. Because of their remoteness and glacial cover, the location of many eruptions is uncertain. Many have been ascribed to the well known Grímsvötn volcano, but the wide distribution of epicentres in the area and recent attempts to relocate eruption sites from bearings taken to the eruption plumes indicate that the active area is considerably larger (Þórarinsson, 1974).

New insight into the geological structure was gained when satellite images of Vatnajökull became available (Þórarinsson *et al.*, 1973). In some areas, the subglacial bedrock topography is reflected in the surface forms of the ice. A caldera was seen to exist beneath the ice cover of Bárðarbunga, which was thus identified as an active volcano. Caldera structures were also seen in other volcanoes such as Kverkfjöll, Grímsvötn and Tungnafellsjökull (Fig. 2). It became evident that the geological structure of the area is dominated by several large central volcanoes. Fissure swarms outside the ice cap have been traced to the glacier edge (Sæmundsson, 1978, 1980; Jakobsson, 1979, 1980), but so far it has been unclear how these are connected with central volcanoes beneath the ice to form extensive volcanic systems. The term "volcanic system" was originally introduced by Jakobsson (1979) to cover both the term central volcano and its associated fissure swarm. One may define a volcanic system as a spatial grouping of eruption sites with particular tectonic, petrographic and geochemical characteristics. In some volcanic systems the fissure swarm is the most prominent structure, in others the central volcano is well developed, sometimes with a caldera, extensive acidic volcanism and geothermal activity. A volcanic system may contain more than one central volcano (e.g. Hofsjökull- Kerlingarfjöll) and fissure swarms sometimes branch into two or more subswarms. One may therefore easily get into problems with the definition of individual systems.

During the past ten years, the bedrock topography beneath the ice has been mapped extensively using radio echo sounding (Björnsson, 1988; Björnsson, in prep.). At the same time increased seismograph coverage has led to more precise epicentral locations (Einarsson and Björnsson, 1987; Einarsson, 1991). This information has added significantly to the understanding of the geology of the area beneath Vatnajökull. Seismic activity in conjunction with topographic highs reveals active volcanoes. Ridges, presumably built up by subglacial fissure eruptions, show the location of fissure swarms. The purpose of the present paper is to integrate this recently acquired knowledge of the subglacial volcanic regions in Vatnajökull. The volcanic systems in the area are delineated and the paths of meltwater produced in eruptions are traced to the various rivers draining the glacier. Information on historical eruptive activity is reconsidered in the light of this evidence.

MAPPING OF BEDROCK TOPOGRAPHY AND SEISMIC ACTIVITY

BEDROCK TOPOGRAPHY

The topographical maps of Vatnajökull (Figs. 3 and 4) are based on continuous ice-thickness profiling by radio echo-sounding and precision barometric altimetry (see Björnsson, 1988). The maps were constructed by interpolation between sounding lines using a digital matrix with a grid spacing of 200 x 200 m. Due to the large spacing between the sounding lines (typically 1000 m), the topographic maps do not usually represent features smaller than some kilometres across. The accuracy of the absolute ice-thickness measurements along the sounding lines is of the order of $\pm$ 15 m, and the accuracy of the measurements of absolute ice-surface elevation is of the order of $\pm$ 10 m. Relative resolution of the data with respect to topographical features is considerably better than this, however. Volcanic and tectonic structures of the order of 10 m and larger can thus be resolved, e.g. hyaloclastite ridges and major normal faults. Fissure zones with minor vertical displacements cannot, however, be delineated.

Fig. 3 shows the surface forms on western and northern Vatnajökull. The map includes the outlets Tungnaárjökull, Sylgjujökull, Köldukvíslarjökull, Dyngjujökull and Brúarjökull and the interior of the ice cap. The highest parts of the glacier cover the mountains Hamarinn, Bárðarbunga, Kverkfjöll, Grímsfjall and Háabunga. The map illustrates ice surface depressions that are created by subglacial geothermal activity and are underlain by water-filled vaults from which water is drained in jökulhlaups (Björnsson, 1974, 1975, 1977, 1988). The largest one is in the Grímsvötn area and contains one of the most (if not the most) powerful geothermal systems in Iceland. The subglacial lake Grímsvötn is the source of frequent jökulhlaups that drain to the sandur plain Skeiðarársandur. Three ice cauldrons are located on a row striking E-W from Hamarinn towards Grímsvötn. The water-filled vaults beneath the two easternmost ice cauldrons (Skaftárkatlar) drain to the river Skaftá (see e.g. Björnsson, 1988). The westernmost ice cauldron drains to the proglacial lake Hamarslón which feeds Kaldakvísl (Björnsson, 1983, 1988). One ice cauldron is located about 1 km E of Pálsfjall and another in the Kverkfjöll area.

Fig. 4 shows the bedrock topography of the same area. In its northwestern part, the landscape is dominated by the large mountains Bárðarbunga, Hamarinn, Háabunga, Grímsfjall, Esjufjöll and Kverkfjöll and mountain ridges stretching out from them. To the east of the neovolcanic zone, on the other hand, the subglacial landscape is strikingly different. It is characterized by glacially eroded features, the most prominent of which is a broad valley bordered by the mountains at the glacier edge to the east and Esjufjöll to the south.

SEISMIC ACTIVITY

The western part of Vatnajökull has been recognized as a seismically active area since instrumental locations of earthquake epicentres became available in Iceland (Tryggvason *et al.*, 1958). The activity increased markedly in 1954 (Tryggvason, 1973) and again in 1974 (Einarsson and Björnsson, 1980; Brandsdóttir, 1984). Improved seismograph coverage of the country in the seventies (Einarsson and Björnsson, 1987) led to better epicentral locations. The most significant improvements occurred in 1975 when seismographs were installed in NE-Iceland, and in 1977 when instruments were added in E- and SE-Iceland.

Epicentres of the period 1975–1985 are shown in Fig. 5. Formal errors of the locations are not greater than 2 km horizontally, but most locations have considerably smaller errors. Depths are poorly constrained, but the data are all consistent with a crustal (<10 km) origin of the events. The locations are determined with the location program HYPOINVERSE (Klein, 1978). Velocity structure is derived from Gebrande *et al.* (1980), and station corrections are found from calibration explosions. It is found that formal errors of the locations represent well the true uncertainties.

Generally, epicentres in the eastern neovolcanic zone of Iceland do not seem to delineate faults or plate boundaries (Einarsson, 1991). The earthquakes are clustered and activity within each cluster is generally persistent through time. The most prominent clusters coincide with the mountains shown in Fig. 4; Bárðarbunga, Hamarinn, Grímsfjall and Kverkfjöll. The clustered nature of the activity, evident in Fig. 5, suggests that the earthquakes are caused by concentrated sources of stress in the crust. A possible explanation of the clustering may lie in a concentration of regional stress around crustal inhomogeneities, but inflating and deflating magma chambers also produce local stress and clustered seismicity. Earthquakes associated with deflation and inflation are known from the Krafla Volcano in NE-Iceland (Einarsson, 1978, 1991), and earthquakes of Grímsvötn and Bárðarbunga have been interpreted in a similar way (Einarsson and Brandsdóttir, 1984; Einarsson, 1986, 1991).

VOLCANIC SYSTEMS OF VATNAJÖKULL

Fig. 1 shows the principal central volcanic complexes of the neovolcanic zones in Central Eastern Iceland, as shown by Sæmundsson (1982) and Einars-

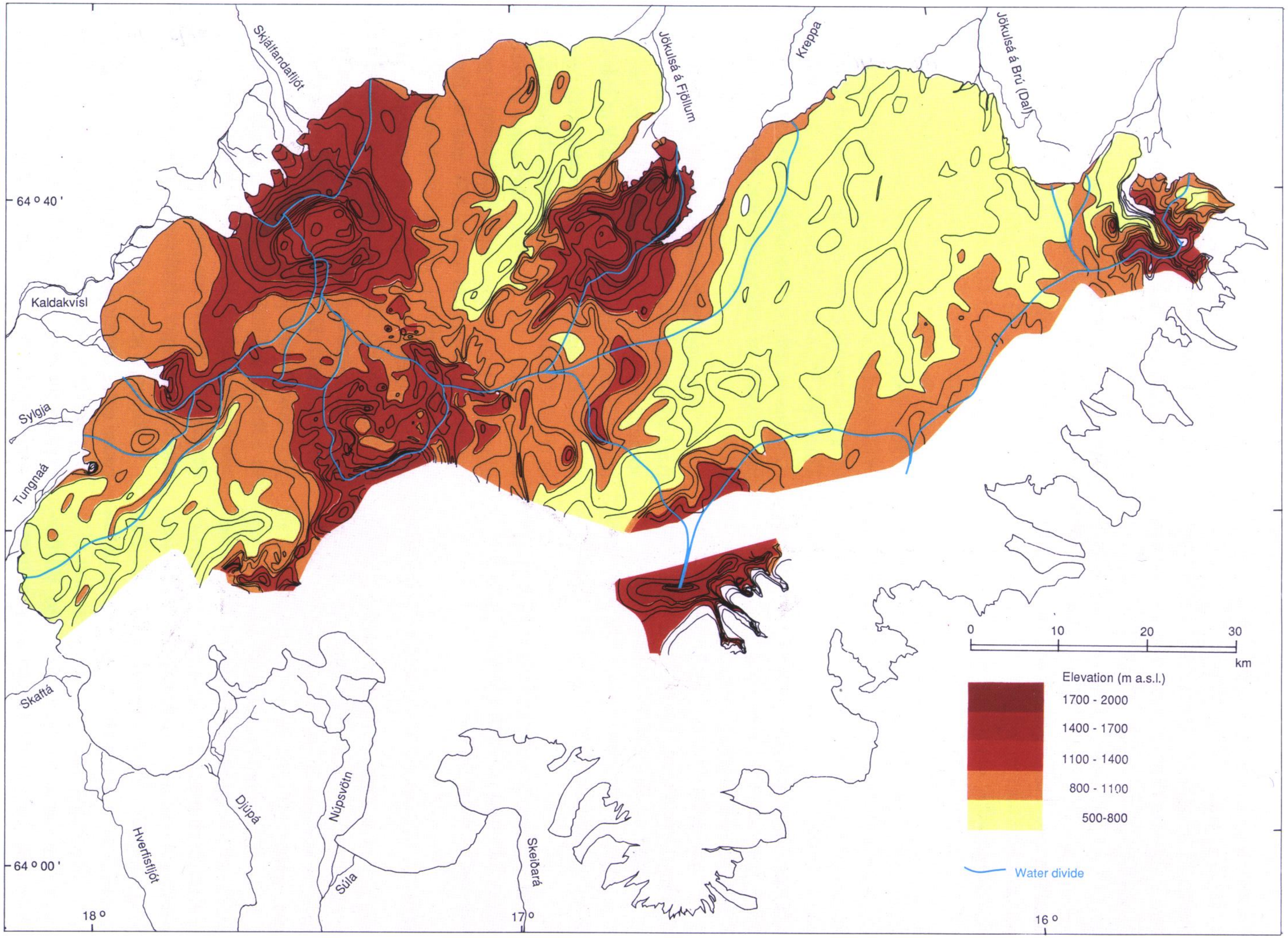

Figure 4. Map of the bedrock topography beneath Vatnajökull according to radio echo soundings, after Björnsson (1988) and later data. The waterdivides of the various rivers are shown on the map. — *Kort af botni undir Vatnajökli. Byggt á gögnum, sem birt voru af Helga Björnssyni (1988) og áður óbirtum gögnum. Vatnaskil, sem afmarka vatnasvæði einstakra jökulvatna eru dregin á kortið.*

son and Sæmundsson (1987). Six central volcanoes have been identified beneath the ice cap: Bárðarbunga, Grímsvötn, Þórðarhyrna, Kverkfjöll, and Öræfajökull, and tentatively Esjufjöll. The location of fissure swarms extending from the various central volcanoes is more uncertain. Six fissure swarms have been traced from the ice-free areas towards Vatnajökull. First, the swarm which connects Torfajökull, Veiðivötn, Vatnaöldur and Heljargjá disappears beneath Sylgjujökull and Köldukvíslarjökull, where there is, however, no topographic expression of it. It probably continues under the glacier, runs through Bárðarbunga, reappears near Kistufell and extends to Trölladyngja (Dyngjuháls swarm). The Laki fissure swarm is traced to the edge of Skaftárjökull. It may continue beneath the ice towards Hágöngur, Þórðarhyrna, Háabunga and Grímsvötn. Between the two swarms a swarm of hyaloclastite ridges extends from Tungnaárjökull along Tungnaárfjöll and Fögrufjöll towards Torfajökull (Fögrufjöll swarm). Two fissure swarms occur north of Vatnajökull to the east of the Dyngjuháls swarm. One trends from Askja to Dyngjujökull, the other is centred on Kverkfjöll (Jóhannesson and Sæmundsson, 1989). All these fissure swarms have been active in postglacial time except the swarm at Fögrufjöll.

The central volcanoes and the fissure swarms can be grouped together into volcanic systems, which will now be discussed in more detail.

BÁRÐARBUNGA-VEIÐIVÖTN VOLCANIC SYSTEM

Bárðarbunga is a large volcanic edifice, which rises to an elevation of 1500–1850 m, i. e. 500 – 900 m above its surroundings. It contains a 700 m deep caldera, about 80 km^2 in area. Its bottom is at 1100 m a.s.l. The mountain massif stretches NE in the direction of Dyngjuháls. From the southwestern slopes of Bárðarbunga, a ridge strikes SW across Köldukvíslarjökull towards northwestern Hamarinn. Beneath Sylgjujökull a cone-shaped mountain that rises above 1000 m is situated on the continuation of this ridge. The ridge may be the expression of a fissure swarm that connects Hamarinn and Bárðarbunga. Thus, the subglacial topography indicates that the Bárðarbunga volcanic system, with a fissure swarm that extends to the southwest through Tröllagígar and Heljargjá to Veiðivötn (Sæmundsson, 1978, 1979; Larsen, 1984), is connected to a separate central volcano, Hamarinn.

Bárðarbunga has been among the most seismically active volcanoes in Iceland since 1974, when a remarkable series of earthquakes began there. The series has so far included 10 events of magnitude 5 and larger. Earthquakes of this magnitude did not occur in this area for at least 50 years prior to 1974. The epicentres are mostly located slightly NE of the caldera. Focal mechanisms have been obtained from teleseismic data for 5 of the large events at Bárðarbunga (Einarsson, 1986, 1987, 1988). They all show a large component of reverse faulting, interpreted as the result of deflation of a crustal magma chamber beneath Bárðarbunga. Thus the seismic evidence shows that Bárðarbunga contains an active magmatic system and suggests that the pressure in this system has been decreasing since 1974.

A separate epicentral cluster is found NE of Bárðarbunga, near Kistufell, where small swarms sometimes occur. Seismic activity is, on the other hand, absent in the fissure swarm SW of Bárðarbunga.

Volcanic activity in Bárðarbunga may cause floods in rivers flowing in all directions, depending upon the eruption site. Fig. 4 shows the water divides on the glacier for the various rivers (Björnsson, in prep.). Water from an eruption on the SW and W flanks would drain to Kaldakvísl, and an eruption on the N flank would produce floods in Skjálfandafljót. The water divide between Skjálfandafljót and Jökulsá á Fjöllum follows a ridge that extends from northeastern Bárðarbunga towards Kistufell. An eruption on the and E and SE flanks would produce meltwater that would drain to Jökulsá á Fjöllum. From a south flank eruption some water might find its way to the water-filled vault beneath the Skaftá ice cauldrons and even Grímsvötn, and could trigger jökulhlaups in Skaftá and Skeiðará.

Volcanic activity in Bárðarbunga could certainly cause catastrophic jökulhlaups, with high potential energy and great erosional power. Such jökulhlaups may explain the deep canyons in Jökulsá á Fjöllum. Meltwater produced within the caldera would most easily escape through a pass in the SE rim and drain towards Jökulsá á Fjöllum. A narrow valley runs to the E from this pass. This valley may have been created erosionally by floods rushing down the slopes of Bárðarbunga.

HAMARINN, THE LOKI RIDGE AND THE FÖGRUFJÖLL FISSURE SWARM

Hamarinn is a steep-sided mountain, about 60 km^2 in area. Its nearly circular rim ranges in elevation from about 1200 m to 1570 m. A slight depression is found inside the rim. A mountain ridge strikes SW from the SE part of Hamarinn beneath Tungnaárjökull toward Fögrufjöll. This will be referred to henceforth in the text as the Fögrufjöll Ridge. Presumably it consists of hyaloclastite built up on volcanic fissures. At the glacier edge, the ridge joins the fissure swarm that continues towards the Torfajökull volcanic complex. This swarm has not been active in postglacial times and no seismic activity has been found there in recent years.

A 1100–1250 m high ridge extends eastward from the NE corner of Hamarinn and joins the Grímsvötn mountain massif. This ridge has at least three active geothermal areas as well as being seismically quite active. Here it will be called the Loki Ridge, after the legend of Loki in Nordic mythology. [1] Epicentres define an E-W trending belt of seismicity that follows the Loki Ridge from Hamarinn towards Grímsvötn. In light of the geothermal evidence we are inclined to interpret this belt as a row of clusters rather than an expression of an active fault. The seismic, topographic and geothermal evidence taken together then suggest that Hamarinn and the Loki Ridge represent a row of central volcanoes. Volcanic eruptions on the Loki Ridge may cause jökulhlaups in Skaftá, or in Kaldakvísl (Björnsson, 1988).

The arrangement of these structures into volcanic systems is not straight forward. It seems clear that there is a structural connection between the central volcanoes on the Hamarinn-Loki Ridge and the Fögrufjöll fissure swarm outside the glacier edge. This may be defined as a volcanic system, here called the Loki-Fögrufjöll volcanic system. However, there also seems to be links between this system and adjacent systems, both to the west and east. A ridge connects Bárðarbunga and Hamarinn, possibly indicating that both volcanoes are within the same system. The high seismic activity that began in Bárðarbunga in 1974 also affected the Hamarinn and Loki volcanoes, that were unusually active during the same time. In addition, Hamarinn is located near the eastern border of the Veiðivötn fissure swarm. Finally, the geothermal activity on the Loki Ridge increased in the 1950's, apparently coincident with a decline in the activity of Grímsvötn. It is therefore not inconceivable that these systems influence each other, mechanically if not chemically.

GRÍMSVÖTN, HÁABUNGA, ÞÓRÐARHYRNA, PÁLSFJALL, AND THE LAKI FISSURE SWARM

The Grímsvötn area contains a huge mountain massif, exceeding 1100 m in elevation for 18–20 km, as measured from W to E, and about 10–15 km from N to S. Mountains which rise above 1400–1700 m encircle a depression with a low of about 1050 m (Björnsson, 1988; Guðmundsson, 1989). The depression is interpreted as a composite caldera. The area of the caldera girded by the highest points on the rim is 62 km^2. The irregularly shaped caldera is divided into two nearly equal parts by a median ridge that rises to 1200 m elevation. The deepest part of the caldera, with elevations down to 1050 m, is located W of the ridge. The sites of the 1934 and 1983 eruptions are on the inner side of the southern rim.

In the northernmost part of the central ridge in the Grímsvötn depression, a large area of the ice surface subsided in 1938, presumably due to an eruption that did not penetrate the ice surface (Þórarinsson, 1974, and Björnsson, 1983, 1988). The eastern rim of the main depression comprises another ridge, almost parallel to the first, trending NNW towards Bárðarbunga. This ridge fades out and does not reach all the way to Bárðarbunga. The northernmost eruption site in 1867 may have been situated on this ridge (Björns-

[1] The giant Loki was tied in a netherworld cave with venomous water dripping from above. Nordic mythology explained earthquakes as the sudden writhings made by the luckless Loki when the venom hit his face. On the Loki Ridge, water-filled vaults are located beneath the ice cauldrons and water propagates into hot boundaries of magma.

son, 1988, p. 103). Further, a 10–15 km long row of mounts extends NE from the southeastern corner of Grímsvötn. The peaks, some of which exceed 1300 m in elevation, probably represent eruption sites on a fissure swarm. This feature, however, does not reach to the Kverkfjöll mountain massif. The topographic data therefore do not indicate a structural connection between the Grímsvötn and the Kverkfjöll volcanic systems.

The broad highland on the western and southern border of the Grímsvötn caldera continues to the SW to Háabunga (c.1600 m), and the peaks Þórðarhyrna (1660 m), Geirvörtur, Hágöngur, and Pálsfjall (1332 m, Fig. 4). Farther to the SW the Rauðhólar fissures emerge from the glacier. The subglacial topography may indicate that Háabunga, Þórðarhyrna, Pálsfjall and the Rauðhólar and Laki fissure swarms all belong to the same volcanic system. Þórðarhyrna is probably a separate volcanic centre within this system.

Most of the earthquakes at Grímsvötn shown in Fig. 5 belong to the active period in 1983 - 1984, when one and possibly two eruptions occurred within the caldera (see below). The epicentres were mostly located slightly SE of the caldera. Seismically the Grímsvötn volcano does not seem to be particularly active, at least when it is not in an eruptive state. A few seismic events have been located near Þórðarhyrna, indicating a separate volcanic centre in the area.

The Grímsvötn volcano is notorious for its behaviour with respect to jökulhlaups (Björnsson, 1988). The extensive geothermal activity within the caldera continuously melts the ice and produces a subglacial lake. When the lake reaches a critical level determined by the glacier thickness in the caldera breach, water is drained out of the lake in a large jökulhlaup. The lake level drops, the glacier blocks the water flow, and the cycle starts again. Thus jökulhlaups occur at semi-regular intervals regardless of eruptive activity. Eruptions on the lake bottom increase the melting rate of the floating ice shelf but do not affect the lake level directly because of the lag in the flow of ice into the lake from the surrounding glacier. They do not necessarily lead to immediate jökulhlaups, assuming that the eruption does not disturb the normal triggering mechanism and that the volume of the volcanic materials erupted into the lake is small compared to the lake volume. Eruptions in the areas surrounding the lake can, on the other hand, lead to an instantaneous rise of the lake level, which may in turn result in a sudden and unexpected jökulhlaup. An eruption or increase in geothermal activity near the caldera breach may also alter conditions for the draining of the lake, and thus affect the pattern of jökulhlaups. This appears to have happened in 1983. Following the eruption in the spring of that year, new cauldrons were formed in the ice near the caldera breach. The next jökulhlaup, later in the year, was released at a lower water level than known before. Jökulhlaups from the caldera lake dump into the rivers Skeiðará and Súla. It is worth pointing out that the large calderas of Grímsvötn, Bárðarbunga and Kverkfjöll are practically the only areas of Vatnajökull where a substantial eruption can occur without producing a jökulhlaup.

Most eruptions in Grímsvötn have occurred at the same time as jökulhlaups. Þórarinsson (1953) pointed out that several eruptions have been observed at the end of jökulhlaups when the lake level has fallen, typically by the order of 100 m. He suggested that the eruptions might be triggered by the pressure release above the volcano. Hence, the eruptions were triggered by the jökulhlaups. Alternatively, the eruptions might have been going on during the jökulhlaup but with the plumes first becoming visible from afar when the crater emerged as the lake level sank.

Eruptions on the external sides of the Grímsvötn volcano, i.e. outside the caldera, may lead to floods in various rivers. Eruptions on the S flank would drain to Súla and Skeiðará whereas meltwater produced on the W flank may cause floods in Skaftá. Eruptions on the N flank and on the ridge NE of the volcano will release water into Jökulsá á Fjöllum.

Eruptions on the E flank of Háabunga and Þórðarhyrna would release water to Súla. Núpsvötn, Djúpá and Hverfisfljót may receive meltwater from eruptions in the Þórðarhyrna-Geirvörtur-Hágöngur-Pálsfjall area. The ice cauldron 1 km E of Pálsfjall indicates subglacial geothermal activity in that area. The drainage of meltwater from beneath the ice cauldron has not been studied but watercourses are predicted to run towards Hverfisfljót. No jökulhlaups that can be

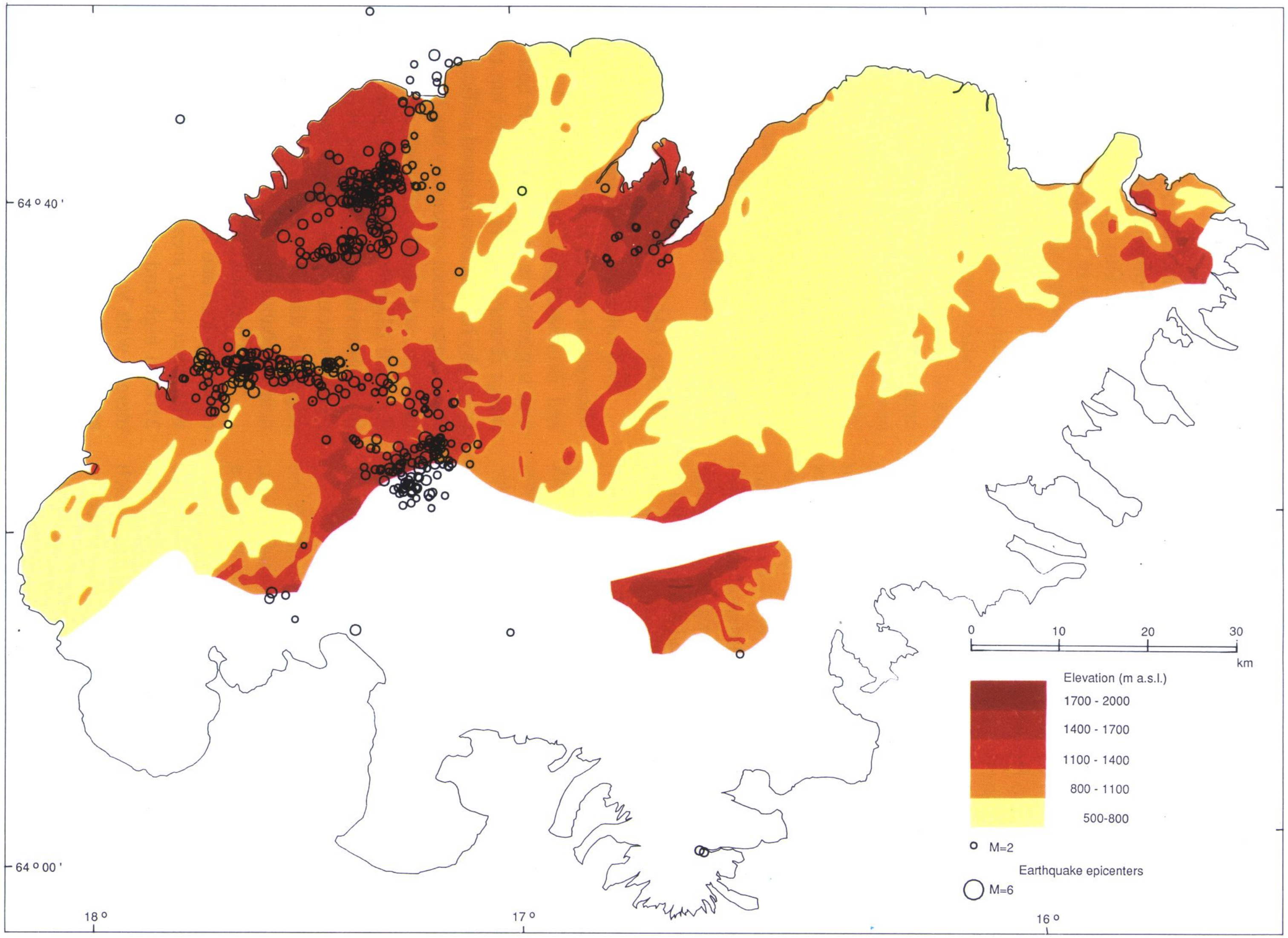

Figure 5. Bedrock topography and earthquake epicenters 1975–1985. — *Landslag og upptök jarðskjálfta á tímabilinu 1975-1985.*

traced to this geothermal area have been reported and the meltwater may drain away continuously.

KVERKFJÖLL

The Kverkfjöll mountain massif is located at the glacier edge and is only partly covered by ice. It rises to an elevation of more than 1900 m, i.e. more than 1000 m over its surroundings. To its north-east, a fissure swarm can be traced for 60 km, marked by hyaloclastite ridges, fissures and faults. The Kverkfjöll volcano contains two calderas of elliptical shape, both 8 km long and 5 km wide (Þórarinsson *et al.*, 1973). The northern one is only about 100 m deep and is rather indistinct. The southern one, on the other hand, is a well defined structure, 400 - 500 m deep. A mountain ridge extends 10 km SW from the southern caldera but a 4–5 km wide, 850 m high pass separates this ridge from the Grímsvötn mountain massif. Another ridge, 20 km long and more than 1200 m high, strikes due south from the Kverkfjöll mountains. Volcanic activity on the E flanks of this ridge could cause jökulhlaups in the rivers Kreppa and Jökulsá á Brú.

The Kverkfjöll volcanic complex displays considerable geothermal activity (see Friedman *et al.*, 1973). Most of the thermal fields are associated with the northern caldera. The volcano has, on the other hand, not been particularly seismically active in recent years. The majority of the few located earthquakes are associated with the northern caldera.

All floods produced by eruptive activity in the Kverkfjöll volcanic complex run into Jökulsá á Fjöllum.

VOLCANOES BENEATH DYNGJUJÖKULL

The Askja fissure swarm disappears beneath the central snout of Dyngjujökull. A few isolated peaks, presumably made of hyaloclastite, are located on a SW-NE trending line beneath Dyngjujökull. This row of peaks can be traced for 30–35 km from the edge of Dyngjujökull towards the northern part of the Grímsvötn mountain massif. The highest peak which reaches 1050 m is exceptionally steep and differs in form from the other peaks. This may suggest that it has not suffered much glacial erosion and is a relatively recent feature. Two small earthquakes have been recorded from this fissure swarm. Meltwater from volcanic eruptions on this fissure swarm would drain in jökulhlaups beneath Dyngjujökull into Jökulsá á Fjöllum.

The map reveals a subglacial valley beneath Dyngjujökull, trending NE along the western flank of Kverkfjöll. This valley is likely to channel floods from eruptions in Dyngjujökull, the eastern part and the caldera of Bárðarbunga and the southern caldera of Kverkfjöll. A narrow valley strikes SW from the lowest pass on the western rim of the Kverkfjöll caldera. This valley may have been eroded by floods produced by subglacial eruptions in this volcano. Beneath the central part of Dyngjujökull the flood would have turned northward to emerge in Jökulsá á Fjöllum. Similarly, a narrow valley extending east from Bárðarbunga may channel floods from that volcano into the broad valley beneath Dyngjujökull. The area to the NE of Dyngjujökull bears witness to large jökulhlaups (Þórarinsson, 1950, 1974; Tómasson, 1973; Sigbjarnarson, 1990).

OTHER VOLCANIC COMPLEXES

Two volcanic centres have been suggested beneath Vatnajökull east of the axial rift zone, i.e. Esjufjöll and Breiðabunga (Sæmundsson, 1980). A caldera was suggested in Esjufjöll on the basis of a satellite image (Þórarinsson *et al.*, 1973), but the bedrock topography has not been mapped sufficiently to confirm this. Some minor seismicity has been recorded from this area, and chunks of sulphur have been found in Esjufjöll (Sigurður Björnsson, pers. comm. 1990). Both observations support the existence of an active central volcano. No support can be found in the topographic data for the existence of a central volcano near Breiðabunga.

The Öræfajökull volcano is outside the ice field of Vatnajökull and is therefore, strictly speaking, not within our study area. It is a stratovolcano, more than 2100 m high and covered by a separate ice cap that merges with Vatnajökull. Radio echo sounding lines across the summit area reveal a 500 m deep summit caldera (Björnsson, 1988). The seismicity of Öræfajökull is quite low at the present time. A seismic station at Kvísker near the mountain shows an occasional microearthquake. Only two small events have been large enough to be located.

RECENT VOLCANIC ACTIVITY BENEATH VATNAJÖKULL

The volcanic systems below Vatnajökull have been quite active in historical times. Available information on eruptions is compiled in Table I. The table is to a large degree based on Þórarinsson (1974) who compiled historical records on eruptions and jökulhlaups from Vatnajökull. The largest additions are from Steinþórsson (1978), who analyzed ash layers from an ice core drilled in Bárðarbunga, and Larsen (1982), who studied ash layers from soil sections in Jökuldalur, NE of Vatnajökull. Their work includes evidence for several eruptions that are not mentioned in the written records.

The soil in Jökuldalur contains numerous ash layers from the period 890–1717, which were sampled and analyzed. On the basis of their chemical composition, they were then traced to their respective volcanic system. Nine layers were found to originate in the Bárðarbunga system, among them the ash layers of 1477 and 1717 that previously had been attributed to Kverkfjöll. Six layers had the chemical characteristics of the Grímsvötn and the Kverkfjöll systems. Most of them showed greater similarity to Grímsvötn, only the layer from 1619 resembles Kverkfjöll somewhat. The 415 m long ice core from Bárðarbunga contained many ash layers from the period since 1650 according to Steinþórsson's (1978) correlation. Besides the very characteristic Katla layers used for the correlation, two distinct groups of ash layers were found, one resembling Grímsvötn in composition, the other had the more primitive character of the Bárðarbunga system. In the light of the chemical characteristics of the volcanic systems defined by the work of Jakobsson (1979) and Larsen (1982) the analyses of ash layers in the Bárðarbunga ice core can be reinterpreted. Thus the layers of 1697, 1706, 1707, 1711, 1716, 1717, 1720, 1739, 1766, 1769 are here interpreted to originate in the Bárðarbunga system. It should be noted, however, that the chemical characteristics of the Loki-Fögrufjöll system are unknown. Some of these events could therefore have taken place there.

Table I contains 63 certain and 13 questionable volcanic events. The uneven distribution with time indicates that many events have been missed, particularly in the early centuries. Since 1700, 53 events have been documented, giving an eruption frequency for this area of 18 events per century. We suspect that further investigations of historical documents and tephra layers in ice and soil will reveal more eruptions.

No volcano in Iceland has had a higher eruption frequency than Grímsvötn (Þórarinsson, 1974). At least 29 of the eruptions listed in Table I are associated with the Grímsvötn system. At least one of them accompanied a major rifting event, i.e. the Skaftá fires 1783-1784. It involved a huge lava flow from the Laki fissure, with a simultaneous eruption in Grímsvötn (Sigurðsson and Sparks, 1978; Þórðarson, 1990). Eruptions apparently limited to the caldera region of Grímsvötn have occurred at least 10 times, possibly as often as 18 times. There are also many reports of volcanic eruptions involving other parts of the volcanic system, to the N and NE, and the swarm southwest of Grímsvötn towards Háabunga and Þórðarhyrna (1684–85, 1716, 1725–26, 1753, 1783–84, 1823, 1867, 1873, 1883, 1887, 1902–03 and 1933–39).

We find no evidence in the data for behaviour that could be called steady-state. On the contrary, there seem to be considerable fluctuations in the activity of Grímsvötn, both in the eruptive and geothermal activity. The present quiescent interval following the events in 1933–39 stands out. The events of 1941, 1945 and 1954 involved only small, if any, magmatic activity, and the events of 1983–84 were only small eruptions (see Björnsson, 1988, p. 96–99). Thus the volcanic activity of the last fifty years is low compared to the century prior to 1939. These observations are in line with the suggestion of Björnsson (1977, 1983) that a significant shift in magmatic activity from Grímsvötn to the Loki Ridge occurred in the mid-fifties. A comparable quiescent interval followed the Skaftá fires 1783–84 (i.e. to 1816 or 1823, 32 or 39 years).

Since the 1960's, there has been a considerable reduction in geothermal activity in the Grímsvötn area. At the same time, the area of the lake has diminished,

Table I. Reported volcanic eruptions and jökulhlaups in Vatnajökull —*Eldgos og jökulhlaup í Vatnajökli, skv. heimildum.*

Year Ár	Location of volcanic eruption Eldstöð	Accompanying Jökulhlaup	References Heimildir
~900	Bárðarbunga-Veiðivötn fissure swarm		6
~905	Grímsvötn system		7
~940	Bárðarbunga system		7
~1000	uncertain		7
~1060	Grímsvötn system		7
~1080	Bárðarbunga system		7
~1159	Bárðarbunga system		7
~1354	Grímsvötn system		7
1332	(Grímsvötn)	(Skeiðará)	1
1341	(Grímsvötn)		1
1362	Öræfajökull	various rivers	3
~1410	Bárðarbunga system		7
1477	Bárðarbunga-Veiðivötn fissure swarm	Jökulsá á Fjöllum	6, 7
~1500	Grímsvötn system		7
1598	Grímsvötn		1
1603	(Grímsvötn system)		1, 7
1619	Grímsvötn		1, 7
1629	Grímsvötn	Skeiðará	1
1638	(Grímsvötn)		1
1659	Grímsvötn	Skeiðará	1, 17
1681	unknown		1
1684 – 85	Grímsvötn, (Dyngjujökull)	Skeiðará, Jökulsá á Fjöllum	1, 2
1697	Bárðarbunga system		17
1702 ?	unknown		1
1706	(Grímsvötn) Bárðarbunga system		1, 17
1707	Bárðarbunga system		17
1711 – 12	Bárðarbunga system	Jökulsá á Fjöllum	1, 2, 17
1716	(Grímsvötn) Bárðarbunga system	Jökulsá á Fjöllum	1, 2, 17
1717	Bárðarbunga system	Jökulsá á Fjöllum	1,2,7,17
1720	Bárðarbunga system		17
1725	Grímsvötn	Skeiðará	1
1726	Dyngjujökull, near Grímsvötn	Jökulsá á Fjöllum	1, 2
1727	Öræfajökull	various rivers	1
1729 ?		Jökulsá á Fjöllum	2
1739	Bárðarbunga system		17
1753	Síðujökull	Djúpá, Hverfisfljót, Skaftá	1
1766	Bárðarbunga system	Þjórsá	1, 17
1768	uncertain		17
1769	Grímsvötn or Bárðarbunga system		17
1774	Grímsvötn	Skeiðará	1, 17
1783	Grímsvötn-Laki fissure swarm	Skaftá, Þjórsá	1, 18
1784 – 5	Grímsvötn system	Núpsvötn, Skeiðará	1,17,18,20

Year Ár	Location of volcanic eruption Eldstöð	Accompanying Jökulhlaup	References Heimildir
1794 ?	W-Vatnajökull		1
1797	NW-Vatnajökull, (Dyngjuháls)		1, 15
1807 ?	(NW-Vatnajökull)		1
1816	(Grímsvötn)		10
1823	Grímsvötn-Þórðarhyrna		1, 17
1838	Grímsvötn	Skeiðará	1, 17
1854	Grímsvötn system		17
1861 ?	(Grímsvötn)	Skeiðará	1
1862 – 64	Tröllagígar, Bárðarbunga system		1
1867	Grímsvötn-Háabunga-Þórðarhyrna	Skeiðará	1
1872 ?	(Dyngjuháls)		1
1873	Grímsvötn, (Þórðarhyrna)	Skeiðará, Djúpá	1
1883	Grímsvötn	Skeiðará	1
1883	Grímsvötn, (Kverkfjöll)	Skeiðará	1, 17
1887	(Þórðarhyrna)	Súla	1, 17
1892	Grímsvötn	Skeiðará	1,17,19
1897	(Grímsvötn)		1
1902 –3	(Dyngjuháls)	Skjálfandafljót, Jökulsá á Fjöllum	1, 2
1903	Þórðarhyrna, (Grímsvötn)	Skeiðará, Súla	1, 8
1903 ?	unknown	Jökulsá á Brú	1
1910	Easternmost Loki Cauldron		1, 13
1922	Grímsvötn	Skeiðará, Súla	1, 17
1927	(Esjufjöll)	Jökulsá á Breiðamerkursandi	14
1933	unknown	Skjálfandafljót?	4, 9, 8
1933	N of Grímsvötn		4, 9, 8
1934	Grímsvötn	Skeiðará, Súla,	1, 17
		Skjálfandafljót,Jökulsá á Fjöllum	4, 9
1938	N of Grímsvötn	Skeiðará, Súla	1
1939 ?	Grímsvötn	Skeiðará	8, 16
1941 ?	Grímsvötn	Skeiðará	8
1945 ?	Grímsvötn	Skeiðará	5, 8
1954 ?	Grímsvötn	Skeiðará	5, 8
1983	Grímsvötn		11, 12
1984 ?	Grímsvötn		
1986 ?	Easternmost Loki Cauldron	Skaftá	

?: uncertain event (eruption)
( ): uncertain location
1: Þórarinsson, Sigurður, 1974.
2: Þórarinsson, Sigurður, 1950.
3: Þórarinsson, Sigurður, 1958.
4: Áskelsson, Jóhannes, 1936.
5: Áskelsson, Jóhannes, 1959.
6: Larsen, Guðrún, 1984.
7: Larsen, Guðrún, 1982.
8: Jóhannesson, Haukur, 1983.
9: Jóhannesson, Haukur, 1984.
10: Jóhannesson, Haukur, 1987.
11: Grönvold, K., and H. Jóhannesson, 1984.
12: Einarsson P., and B. Brandsdóttir, 1984.
13: Jónsson, Jón, 1986.
14: Björnsson, Sigurður, 1977.
15: Jónsson, Ólafur, 1945.
16: Stefánsson, Ragnar, 1983.
17: Steinþórsson, Sigurður, 1978.
18: Þórðarson, Þorvaldur, 1990.
19: Björnsson, Helgi, 1988.
20: Þórarinsson, Sigurður, 1984.

the thickness of the floating ice cover has increased and the volume of the jökulhlaups decreased (Björnsson 1988; Björnsson and Guðmundsson, in prep.). Björnsson *et al.* (1982) have suggested that the heat flux from the geothermal area can be explained by penetration of water into the hot boundaries of a magma body at shallow depth. The observed cooling trend of the geothermal area in Grímsvötn may be explained by lack of magma refill (Björnsson, 1988; Guðmundsson, 1989).

The activity in Grímsvötn in 1983–84 had very distinct seismic characteristics. Only a few earthquakes had been located in the Grímsvötn area before December 1982. Then there was a distinct increase in activity, and in the following 6 months 20 locatable events occurred there. On May 28, 1983, an eruption broke out near the southern caldera wall, accompanied by an intense earthquake swarm (Einarsson and Brandsdóttir, 1984; Grönvold and Jóhannesson, 1984). The eruption was small and lasted only a few days. After the initial outbreak, seismicity dropped to a very low level and remained low for 4 months. In September and October 1983, seismic activity increased again, and more than 39 events occurred in Grímsvötn in the following 11 months. On August 21, 1984, a burst of continuous tremor appeared on seismographs as far as 130 km distant from Grímsvötn. The tremor lasted about an hour. It originated in the Vatnajökull area as judged from the relative amplitude on different seismographs. After this event only very few earthquakes have been found to originate in the Grímsvötn volcano.

The seismicity pattern can be interpreted as the result of magmatic activity in the Grímsvötn volcano in the following way. Magma began flowing into a crustal magma chamber beneath the SE flank of the volcano in late 1982. In December that year, strain in the chamber roof passed the elastic limit and seismic activity increased. On May 28 1983, the chamber wall failed, and a dyke propagated to the surface, resulting in an eruption. Pressure in the chamber dropped, strain in the roof went below the elastic limit, and seismicity stopped. Magma continued flowing into the chamber, however, and in September 1983, the strain in the roof again reached the elastic limit. Seismic activity increased and continued until August 1984. Then the chamber wall failed again, resulting in a small eruption that did not reach the surface of the glacier. The pressure in the chamber dropped and the seismicity also. Now the flow of magma into the chamber was discontinued and the activity stopped. The main evidence for the eruption is the tremor burst and the sudden drop in earthquake activity that followed.

The suggestion of a subglacial eruption in Grímsvötn in August 1984 is supported by aerial observations. A reconnaissance flight in August 20, 1984, revealed that the ice surface had an unusual number of depressions that could have been formed by localized melting of the floating ice shelf from below.

Jökulhlaups were reported in the rivers Skaftá and Þjórsá in connection with volcanic activity in western Vatnajökull in 1783 (Þórarinsson, 1974). This activity is generally thought to be related to the Grímsvötn system, including the gigantic Laki eruption (Þórðarson, 1990). The jökulhlaup in Þjórsá would indicate, however, that the westernmost systems, Bárðarbunga or Loki were involved in these events as well. The same applies to the volcanic activity in 1766, which caused a jökulhlaup in Þjórsá.

Since 1955, twenty jökulhlaups in Skaftá have originated in the geothermal areas beneath the two cauldrons located on the Loki Ridge, about 10 km to the northwest of Grímsvötn (see Björnsson, 1988). This apparently reflects a change in geothermal activity since jökulhlaups were much smaller from this area before (Björnsson, 1977, p. 73). Björnsson (1977, p. 75–76; 1983) pointed out that this change coincided with a reduction in the power of the Grímsvötn geothermal area, and argued that it may have been caused by magmatic intrusion into the Loki area from the Grímsvötn volcano. It is noteworthy that seismicity increased in the Vatnajökull region at about this time (Tryggvason, 1973).

There is a seismic indication that a small eruption occurred in 1986 during a Skaftá jökulhlaup from beneath the easternmost ice cauldron. The flood in Skaftá began on November 29, and on November 30 and the following day short bursts of continuous tremor were recorded on seismographs around Vatnajökull. Relative amplitudes were consistent with a source near the eastern cauldron. In a reconnaissance flight on November 30, it was observed that the concentric crevasses created in the cauldron during the jökulhlaup were cut across by a rift through the centre of the cauldron. This has not been observed in earlier jökulhlaups. It is likely that the pressure release associated with the jökulhlaup triggered a short eruption that did not reach the surface of the glacier. The only other eruption considered to have occurred on the Loki Ridge was in 1910 (Jónsson, 1986).

The volcanic activity in 1753 which released meltwater to Djúpá, Hverfisfljót and Skaftá, may have been located on west- or south facing slopes of the fissure swarm which links Pálsfjall, Þórðarhyrna, Hábunga and Grímsvötn.

No historical records exist of volcanic activity in Bárðarbunga, and the mountain was apparently not known as a volcano until quite recently. Larsen's (1982) tephrochronological and geochemical studies indicate that the volcanic eruptions that caused jökulhlaups into Jökulsá á Fjöllum in 1717 and in the late 15th century occurred along the ice-covered part of the Bárðarbunga-Veiðivötn fissure system. She also finds evidence for several eruptions in this system in the early centuries of historical times. Many tephra layers with the chemical characteristics of Bárðarbunga were also found in the Bárðarbunga ice core (Steinþórsson, 1978), particularly in the period 1697–1720, which seems to have been a very active time in this volcanic system (Ísaksson, 1984). The eruption in NW Vatnajökull in 1797 may have been on this system and the eruption in Tröllagígar 1862–64 (Þórarinsson and Sigvaldason, 1972) took place on it, just outside the glacier edge. Larsen (1984, p. 54) concluded that episodes of rifting and magmatic activity have affected the Bárðarbunga volcanic system at an average interval of 100 years during the last 1200 years, accompanied by volcanic activity at the Bárðarbunga central volcano. There is no evidence for eruptive activity in Bárðarbunga in this century in spite of high seismicity for the last 16 years.

Several eruptions have produced jökulhlaups in rivers running north from Vatnajökull, Jökulsá á Fjöllum (1477, 1684–85, 1711–12, 1716–17, 1726, 1902–03 and 1934) and Skjálfandafljót (1902–03, and 1934). The jökulhlaups of 1477 and 1717 have been attributed to events in the Bárðarbunga volcanic system (Larsen, 1984), and similarly, the jökulhlaups in the early part of the 18th century (Ísaksson, 1984). Other jökulhlaups appear to be related to activity in the Grímsvötn system (1684–85, 1726, 1934). The two jökulhlaups in Skjálfandafljót coincide with activity in the Grímsvötn system. A causal relationship between activity in Grímsvötn and jökulhlaups in Skjálfandafljót is hard to reconcile with the topographic data, however, since the tributary area of Skjálfandafljót does not overlap with the Grímsvötn system. Either the jökulhlaups were not related to the eruptions or the volcanic activity was more widespread than assumed. In both cases there was a flood in Jökulsá á Fjöllum as well, so if it was caused by one eruption we would expect the site to have been on the NE flank of Bárðarbunga.

Jökulhlaups in Jökulsá á Fjöllum may be caused by volcanic eruptions in any of the three volcanic systems beneath the northern part of Vatnajökull: at Kverkfjöll, Bárðarbunga or from the Askja fissure swarm beneath Dyngjujökull. A potential for very large jökulhlaups exists in these areas, for example in the large ice-filled calderas of Bárðarbunga and Kverkfjöll. These may have been the sources of the prehistoric catastrophic floods in Jökulsá á Fjöllum which occurred about 7,100 B.P., 4,600 B.P., 3,000 B.P. and before 2,000 B.P. (Tómasson, 1973; Elíasson, 1977).

The only known jökulhlaup in Jökulsá á Breiðamerkursandi occurred in 1927. It was accompanied by a strong sulphuric stench and some ash fall, indicating a volcanic origin (Sigurður Björnsson, 1977). It is considered possible that it may have been caused by an eruption in Esjufjöll.

CONCLUSIONS

Based on the recently acquired knowledge on subglacial topography and earthquake activity, combined with results of earlier investigators, the following volcanic systems can be defined beneath Vatnajökull:

1. Bárðarbunga volcanic system. It includes the fissure swarms of Veiðivötn (including Vatnaöldur and Heljargjá) to the SW of the Bárðarbunga central volcano and Dyngjuháls to the NE.

It extends 150 km from the Torfajökull central volcano to Trölladyngja.

2. Loki volcanic system. The volcanic centres on the Loki Ridge form a volcanic system together with the Fögrufjöll fissure swarm.
3. Grímsvötn volcanic system. The Grímsvötn volcano is the centre of a system comprising the Laki and Rauðhólar fissure swarms and extends for an unknown distance to the NE of the volcano. Þórðarhyrna is probably a separate volcanic centre within this system.
4. Kverkfjöll volcanic system. The Kverkfjöll system can be traced 10 km to the SW of the Kverkfjöll volcano, and seems to be 90 km long. It appears to be separated from the Grímsvötn volcano.
5. The Askja volcanic system. The fissure swarm extending south from the Askja volcano continues beneath Dyngjujökull and possibly merges with the Grímsvötn volcano.

In the area east of the main rift zone some evidence is found for an active central volcano in Esjufjöll, but no topographic indications are of a volcanic centre in Breiðabunga.

The new knowledge on the topography of the surface and the bottom of Vatnajökull makes it possible to trace jökulhlaups in various rivers to their possible volcanic sources. Skeiðará and Súla have the most frequent eruption-related jökulhlaups. They receive meltwater from the Grímsvötn caldera and the area to the SW of it, including Þórðarhyrna. Núpsvötn may receive meltwater from eruptions on the south flanks of Þórðarhyrna. Djúpá drains meltwater from the western slopes of Þórðarhyrna, Geirvörtur and Hágöngur. Jökulhlaups in Hverfisfljót may originate from eruptions in the Pálsfjall area. Skaftá drains the Loki Ridge and the area west of Grímsvötn. Jökulhlaups in Þjórsá (Kaldakvísl) must originate in the Bárðarbunga or the Hamarinn - Loki systems. The only possible source for volcanic jökulhlaups in Skjálfandafljót is the northern part of the Bárðarbunga system. Jökulsá á Fjöllum may receive meltwater from activity in all the volcanic systems in northern Vatnajökull, Bárðarbunga, the Askja fissure swarm and Kverkfjöll. This includes the voluminous, ice-filled calderas of Bárðarbunga and Kverkfjöll. Activity in the northern part of the Grímsvötn system can also produce floods in Jökulsá á Fjöllum. Jökulsá á Brú may receive meltwater from volcanic activity on the southeastern flank of a ridge that strikes south from Kverkfjöll. Volcanic activity further north on the eastern flanks of this ridge would cause floods in Kreppa.

Volcanic activity in historical times has mainly been associated with the Grímsvötn and Bárðarbunga systems. A few volcanic events are known or presumed to have occurred on the Loki system and on the Askja fissure swarm beneath Dyngjujökull, but no event is known with certainty on the Kverkfjöll system in historical times. Major rifting events affecting large sections of the volcanic systems have occurred on both the Bárðarbunga and Grímsvötn system. Many smaller events affecting only the caldera regions and adjacent parts of the fissure swarms are also known. The activity of both systems is quite irregular in time, and both have been remarkably quiet for the last several decades. No substantial eruptions have occurred in the Grímsvötn system since 1934-39 and in the Bárðarbunga system since 1862-64.

NOTE ADDED IN PROOF

Bursts of tremor were recorded on seismographs near Vatnajökull on Aug. 12, 1991, during a jökulhlaup in Skaftá. The course of events is similar to that of Nov. 30, 1986, and suggests that a small and short–lived eruption may have occurred beneath the Eastern Loki cauldron.

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ÁGRIP

ELDSTÖÐVAR UNDIR VATNAJÖKLI, LANDSLAG, JARÐSKJÁLFTAR OG JÖKULHLAUP

Undir Vatnajökli leynast nokkur virkustu eldstöðvakerfi landsins (1. mynd). Flest hafa gosið á sögulegum tíma með gjóskufalli og jökulhlaupum, sem oft ollu tjóni í byggð. Sjö megineldstöðvar hafa verið nafngreindar í jöklinum, Bárðarbunga, Grímsvötn, Þórðarhyrna, Kverkfjöll, Breiðabunga, Esjufjöll og Öræfajökull (2. mynd) en þó er óvíst um upptök fjölmargra gosa (Sigurður Þórarinsson og fleiri, 1972; Kristján Sæmundsson, 1982). Sprungusveimar hafa verið raktir að jökuljaðrinum (Kristján Sæmundsson, 1978; Sveinn Jakobsson, 1979), en tengsl þeirra við megineldstöðvarnar undir jökli hafa verið óljós (1. mynd). Nú hefur hins vegar fengist nákvæmari mynd en áður af legu eldstöðvakerfa undir Vatnajökli með því að leggja saman nýfengin gögn um landslag undir jöklinum og upptök jarðskjálfta, ásamt vitneskju um jökulhlaup (Helgi Björnsson 1988; Páll Einarsson og Sveinbjörn Björnsson, 1987; Páll Einarsson, 1991). Þessi gögn eru sýnd á 3., 4. og 5. mynd og í 1. töflu. Skjálftavirkni í stökum fjöllum er vísbending um að þar sé virk megineldstöð. Hryggir, sem líklega hafa hlaðist upp við sprungugos, sýna legu sprungusveima.

Niðurstöður styðja þá skoðun að Bárðarbunga sé virk megineldstöð, miðja eldstöðvakerfis, sem liggur frá suðvestri um Veiðivötn, Vatnaöldur og Heljargjá og norðaustur á Dyngjuháls og Trölladyngju. Í suðvestur frá Bárðarbungu liggur hryggur undir Köldukvíslarjökli yfir í Hamarinn og undir Sylgjujökli er keilulaga fjall sem gæti verið á framhaldi sprungusveims, sem tengir Bárðarbungu og Hamarinn. Hamarinn gæti verið sérstök megineldstöð á austurjaðri Veiðivatna-Bárðarbungu sprungusveimsins. Hins vegar tengist Hamarinn einnig hrygg, sem stefnir austur frá honum (hér nefndur Loki). Sá hryggur virðist tengdur Fögrufjallasprungusveimnum og mynda með honum eitt eldstöðvakerfi, Loka-Fögrufjallakerfið. Eldstöðvakerfin á þessu svæði virðast hins vegar vera tengd. Hin mikla skjálftavirkni, sem hófst 1974 í Bárðarbungu kom einnig fram í Hamrinum og á Loka. Einnig dró úr styrk jarðhitasvæðisins í Grímsvötnum samtímis því að jarðhiti óx í Loka upp úr 1950.

Grímsvötn eru talin miðja eldstöðvakerfis, sem nær um Háubungu, Þórðarhyrnu og Pálsfjall að sprungusveimunum við Rauðhóla og Lakagíga í suðvestri, en óvíst hve langt það fer í norðausturátt. Þórðarhyrna er líklega sérstök megineldstöð á þessu eldstöðvakerfi. Kverkfjallaeldstöðvakerfið má greina 10 km suðvestur frá Kverkfjöllum en það virðist aðskilið frá Grímsvatnaeldstöðinni. Sprungusveimurinn frá Öskju fer undir Dyngjujökul og nær e.t.v. að norðanverðri Grímsvatnaeldstöðinni. Landslag undir jökli á Breiðubungu styður hins vegar ekki þá hugmynd að þar sé megineldstöð.

Frá landnámstíð hafa 63 gos verið rakin með vissu til Vatnajökuls, en 13 eru óviss (53 frá 1700, 1. tafla). Eldvirknin undir jöklinum hefur að mestu verið bundin við eldstöðvakerfin, sem tengd eru Grímsvötnum og Bárðarbungu (sjá tilvitnanir í 1. töflu). Í báðum þessum eldstöðvakerfum hefur eldvirknin verið töluvert sveiflukennd og bæði hafa þau haft óvenju kyrrt um sig undanfarna áratugi. Eftir mjög virkt tímabil frá 1823 til 1939 (116 ár), með gosum að meðaltali á 7-8 ára fresti, hefur ekkert verulegt gos orðið í Grímsvötnum eftir goshrinuna 1934-39. Sambærilegt goshlé varð eftir Skaftáreldana 1783-84 (þ.e. til 1816 eða 1823, 32 eða 39 ár). Talið er að eldar hafi að meðaltali komið upp í eldstöðvarkerfi Bárðarbungu á um 100 ára fresti en ekkert gos hefur orðið þar eftir að gaus í Tröllagígum 1862-64. Nokkur gos eru talin hafa orðið eftir landnám á eldstöðvakerfinu, sem liggur um

Hamarinn og Loka og á Öskjusprungusveimnum undir Dyngjujökli, en engin með fullri vissu í Kverkfjallakerfinu.

Við eldgos undir Vatnajökli hafa flest jökulhlaup fallið í Skeiðará og Súlu. Þessar ár fá bræðsluvatn frá Grímsvatnaöskjunni og svæðinu suðvestan við hana, allt að Þórðarhyrnu. Í Núpsvötn getur runnið hlaupvatn við gos í suðurhlíðum Þórðarhyrnu. Djúpá fær vatn frá vestanverðri Þórðarhyrnu, Geirvörtum og Hágöngum. Jökulhlaup í Hverfisfljóti geta átt upptök sín við Pálsfjall. Skaftá veitir vatni frá hryggnum Loka og vesturhlíðum Grímsvatnasvæðisins. Jökulhlaup í Þjórsá (Köldukvísl) gætu orðið við gos í Bárðarbungu, Hamrinum og vestasta hluta Loka.

Valdi eldgos jökulhlaupum í Skjálfandafljóti hljóta þau að koma upp í norðanverðri Bárðarbungu. Jökulhlaup í Jökulsá á Fjöllum geta stafað af eldsumbrotum í einhverju af hinum þremur eldstöðvakerfum í norðanverðum Vatnajökli, þ.e.a.s. þeim sprungusveimum, sem liggja um Bárðarbungu, frá Öskju og um Kverkfjöll. Þar með eru taldar ísfylltar öskjur í Bárðarbungu (43 km^3) og Kverkfjöllum (10 km^3). Gos í norðanverðum Grímsvötnum geta einnig valdið jökulhlaupum í Jökulsá á Fjöllum.

Í Hveradal í Kverkfjöllum. Á myndinni eru, talið frá vinstri: Hulda Filippusdóttir, Hanna Brynjólfsdóttir og Jóhanna Sigurjónsdóttir. Ljósm. Sigurður Þórarinsson, 3. júní 1956.
Hveradalur in Kverkfjöll. Photo. Sigurður Þórarinsson, June 3, 1956.