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Volcanic eruption through a geothermal borehole at Námafjall, Iceland

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During the present rifting episode in the Krafla fault swarm in North Iceland, large scale horizontal movement of basaltic magma is taking place underground. On 8 September 1977 magma reached the depth range of boreholes in the Námafjall geothermal field. In 20 min 3 ton of magma erupted through an 1,138 m borehole forming a small scoria sheet.

THE eruption on 8 September 1977 in the Námafjall geothermal field was a part of a rifting event that took place during that day, and which itself is a part of a major rifting episode which has been in progress on the Krafla fault swarm in North Iceland since 20 December 1975[1-4]. The eruption through the borehole provides further evidence for a large scale magma movement along the fault swarm initially postulated from ground deformation observations[1].

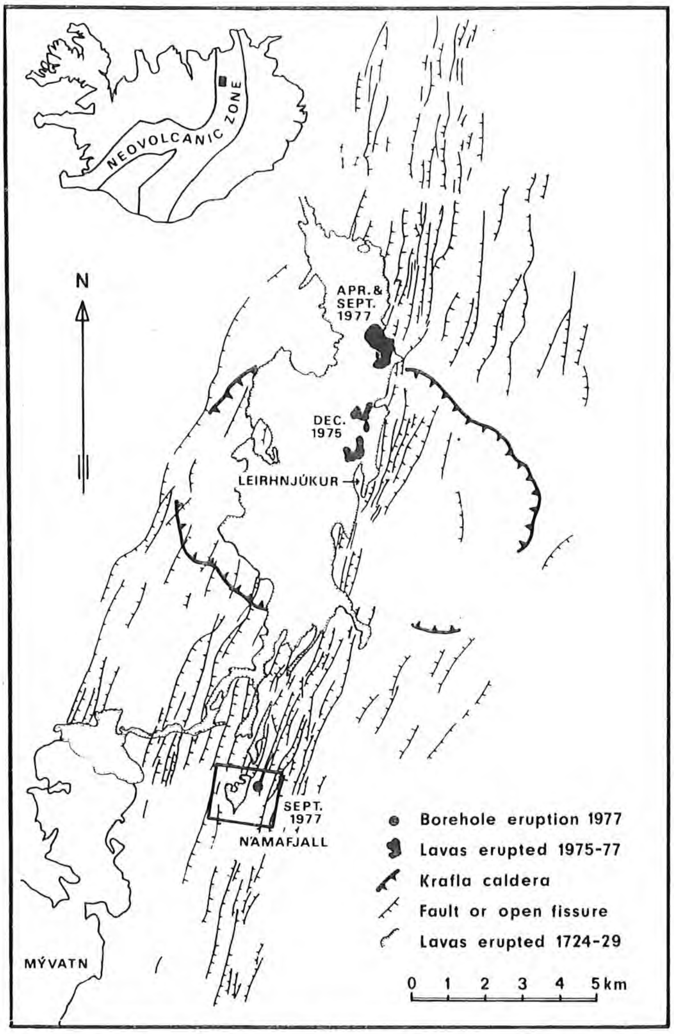

Fig. 1 The main geological features of the Krafla area and location of the eruptions 1975–77. The Námafjall area is shown in greater detail in Fig. 2. Adapted from a map by Kristján Saemundsson[1].

The Krafla fault swarm is ~100 km long, and about 70 km have been activated with horizontal widening of 2–3 m in places. Magma is being continuously fed (about 5 $m^3 s^{-1}$) into magma reservoirs below the Krafla caldera (Fig. 1) at a depth of about 3 km, as indicated by seismic and ground deformation evidence[1].

The rifting activity takes place in short events where 5–15 km long segments of the fault swarm are activated with movements on faults, earthquakes and the formation of new steam fields. This is accompanied by subsidence of a large area with a centre within the Krafla caldera caused by magma movement into the fault swarm.

Three small lava eruptions have accompanied the eight rifting events that have taken place, but all three eruptions were in the vicinity of the magma reservoirs and so far only the eruption through the borehole has provided samples of the magma actually moved into the fault swarm.

The total volume of magma moved into the fault swarm is about 3.9×10^8 m^3, while the volume of the lavas is about 2.4×10^6 m^3 or 0.6%.

The first eruption, on 20 December 1975, took place near the centre of the caldera (Fig. 1) although the main rifting occurred 45 km to the north. The second eruption, on 27 April 1977, took place near the northern rim of the caldera (Fig. 1), while the main rifting occurred about 10 km to the south of the caldera centre.

In the third eruption, on 8 September 1977, the main outflow of lava was again near the northern rim of the caldera, while the main rifting took place south of the caldera, just north of the Námafjall geothermal field. We give here a short account of this event and the borehole eruption.

8 September deflation/rifting event

The deflation and rifting of 8 September 1977 started with a volcanic tremor recorded on seismographs at 15.47 h and about the same time the centre of the caldera started deflating. Just before 18.00 h a lava eruption started near the northern rim of the Krafla caldera (Fig. 1). According to the pilots of an overflying aeroplane, its first sign was a white column of steam darkening at the base after a few minutes. Shortly afterwards lava spattering started from a short segment of the fissure, which rapidly extended to a total length of 800 m. The lava output increased quickly, reaching maximum in less than about 30 min, and by 19.30 h most of the lava was already erupted. By 22.30 h the activity had died out. Assuming that the magma started to ascend when volcanic tremor appeared on the seismometers and deflation on the tiltmeter, the rate of ascent is about 0.5 m s^{-1} assuming a depth of 3 km for the magma reservoirs.

The deflation rate soon decreased and stopped temporarily at about 17.20 h. Deflation started again at about 18.20 h. This was the main deflation and most likely related to the magma movement to the south. The centre of the rifting segment in this event was just north of the Námafjall geothermal field (Fig. 1). Some overlap exists between this rifting segment and that rifted in the previous event on 27 April 1977, as reference lines across the rift zone that already had increased in length by 2 m extended a further 1 m on 8 September[4].

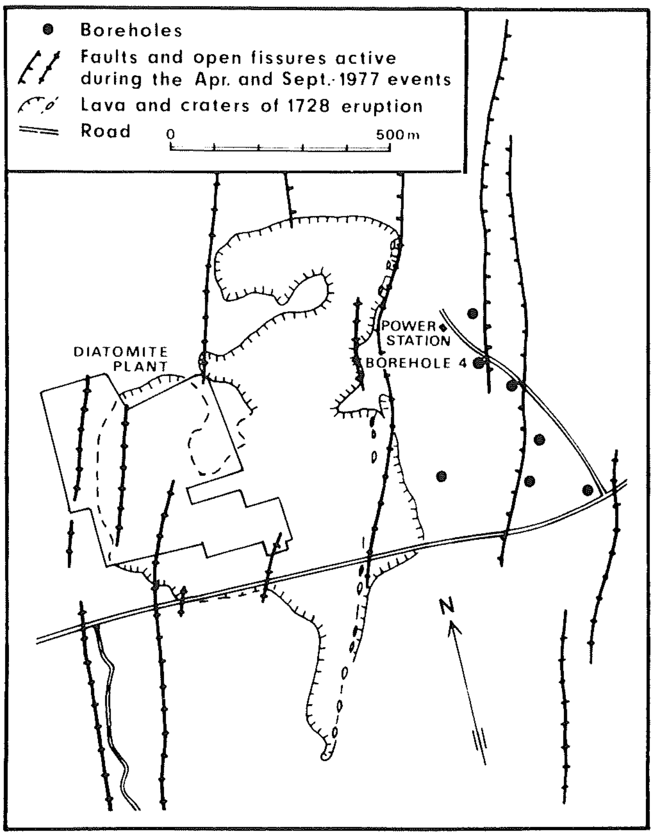

Fig. 2 Sketch map of the Námafjall area from an aerial photograph of 9 September 1977. The location of boreholes is shown by dots. The faults shown on the map have all been active in the recent events. For location see Fig. 1.

At Námafjall the first observed sign of the rifting event was movement of faults crossing a road (Fig. 2) at about 22.40 h. Assuming that the main magma movement to the south started at 18.20 h and with the distance of 9 km from Leirhnjúkur at the centre of the caldera, the rate of horizontal movement is about 0.6 m s^{-1}. A similar velocity was derived for magma movement in the April 1977 deflation/rifting event[3]. The figures for vertical and horizontal movement of the magma are strikingly similar to the figures (0.6 m s^{-1}) arrived at for the maximum rate of magma ascent in the Askja eruption 1961 and the Lakagígar eruption of 1783[5], and there are indications that the magma ascended with similar velocity during the Eldfell eruption 1973 (ref. 6, p 30).

The eruption through the borehole began about one hour later, at 23.45 h. The rate of ground deflation decreased rapidly, and at about 05.00 h on 9 September deflation had stopped and the centre of the caldera was inflating again.

The borehole eruption

The Námafjall geothermal field lies on the Krafla fault swarm 9 km south of the centre of the Krafla caldera. The five boreholes in use for steam extraction are spaced with the distance of 80–200 m (Fig. 2) and extend down to 650–1,800 m with casing extending down to 500–600 m. The deepest hole has an additional slotted liner down to the bottom at 1,800 m. The boreholes are situated in a highly faulted area and deliberately placed to intersect faults at favourable depths.

The eruption took place through borehole number 4, drilled in 1968. It is 1,138 m deep, has 7″ casing down to 380 m and 5″ casing down to 625 m. The diameter from 625 to the bottom is 6.25″ and this part has no casing or liner. The main aquifers are reported at 638 and 1,038 m (ref. 8). The average temperature of the inflowing water is estimated at 251–256 °C (ref. 7). The total discharge of the borehole at the time of eruption is not known accurately, but from measurements in 1971[8] and the estimated inflow temperature, the total discharge of water–steam can be estimated at 30 kg s^{-1} at about 7 bar absolute well head pressure. This assumes that the inflow is water only and

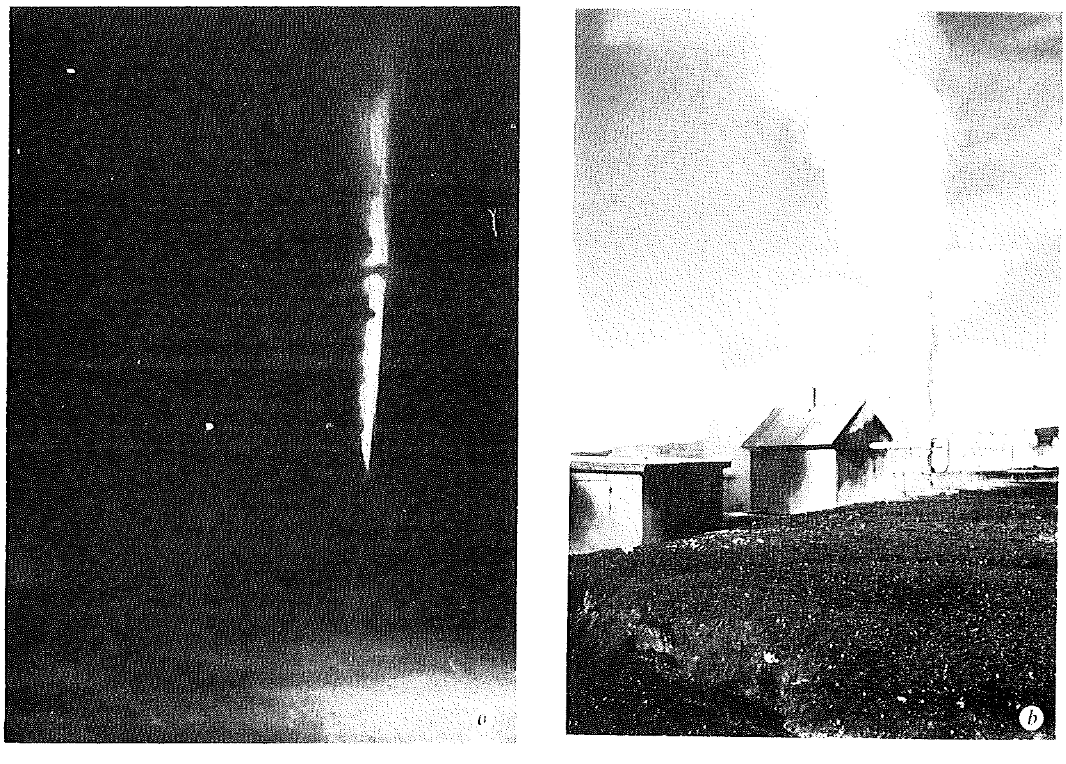

Fig. 3 *a*, The eruption through borehole 4 at Námafjall on 8 September 1977. The picture was taken just about midnight at the distance of 50–70 m. The explosion lasted about 1 s. By comparison with the tool shed on the left the height of the eruptive column is estimated at 13–15 m. Photo Hördur Vilhjálmsson. *b*, Borehole 4 at Námafjall, on the morning of 9 September 1977. The steam jet is emitted through the rupture in the pipe created by the volcanic eruption. The steam–water separators are housed in the shed to the left. Practically the same scale as in Fig. 3*a*. Photo Sigurdur Thorarinsson.

that steam is generated in the borehole during its ascent. (If the inflow is a steam–water mixture a lower value results.) The superstructure of the borehole suffered minor damage due to the eruption and the borehole continued to produce steam at a similar rate as before. Following the eruption there was a marked increase in fumarolic activity in the area around the boreholes, which later decreased markedly.

Movements on faults in the Námafjall area were first noted at about 22.40 h, when the main road through the area was cut through and became impassable. By that time the eruption that had taken place 12 km to the north was finished and further activity to the south was anticipated. It was already dark, and with the steam from the boreholes drastically affecting visibility, conditions at Námafjall were confusing.

An examination of the earthquake activity shows a southward migration from the caldera along the fault swarm. The earthquake activity reached the Námafjall area shortly before 22.00 h (ref. 9).

The description below is compiled from accounts of 10 people, each of whom saw only a part of the event.

The whole event lasted between 15–25 min. It can be divided into three stages. The first phase was best observed from the main road about 400 m south of borehole 4. At approximately 23.45 h an explosion in the borehole field was heard and a thin incandescent column, about 15–25 m in height, was seen. The column widened slightly upwards and sparks and cinders were continuously shot from it. This phase of the eruption, accompanied by a continuous roar, lasted no longer than 1 min.

During the second phase, lasting the next 10–20 min, there was little or no activity at the eruption site. Occasional red flashes may have occurred during the latter part of this phase, according to some of the observers, but could also belong to the final phase.

The final phase consisted of a series of very rapid explosions or shots of glowing scoria. A few groups of explosions were observed each consisting of several individual shots (Fig. 3*a*). The total length of the final phase is estimated at about 1 min. During this phase the exact location of the eruption was established, when it was discovered that the pipe directly above the hole conducting the steam–water mixture had been ruptured by the eruption (Fig. 3*b*). It is not known whether the steam–water output was cut off at any time during the eruption, but during the second phase red flashes were seen in the steam–water mixture emitted through the ruptured knee on the pipe.

The magma was apparently injected into the hole through a steeply dipping fault intersecting the borehole above the aquifer at 1,038 m and most probably below the casing at 625 m as steam production continued after repairs of the superstructure. At the surface substantial movements on faults near the borehole were observed.

Products of the eruption

The eruption produced a tiny sheet of tephra (scoria and cinders). An area about 50 m long and of 25 m maximal width was covered by continuous layer, but single grains could be traced to at least 150 m north of the borehole. The tephra was very loosely packed and unevenly distributed and thickness estimates are uncertain, especially away from the borehole. Maximum thickness was 8–10 cm at a distance of 15–20 m.

The volume of the total output is estimated at 26 m^3. The density of the deposit was roughly calculated at 0.12 g m^{-3} and the total weight of the deposit at 3,100 kg. The volume of the magma erupted is therefore 1.2 m^3 using 2.7 g m^{-3} as the density of the magma.

The tephra is greyish-black in colour and coarse grained. Median (ϕ 50) grain size in a sample collected 20 m from the 'vent' is $-4.2\ \phi$ (18.4 mm). As the largest clasts break very easily, this is likely to be an underestimate. Grains smaller than 1 mm are scarce.

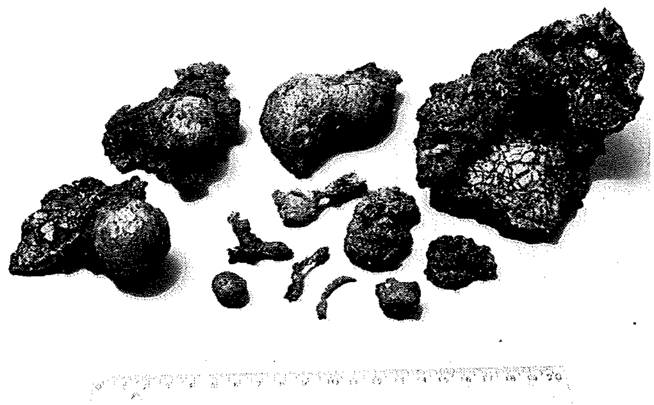

Fig. 4 The borehole scoria. From the right: a large scoria fragment (type 1) showing a chilled, crusted surface. The edges curled up when the original piece broke and show frothy glass formed from the molten interior. Fragments (type 2) formed from the interior of larger pieces, deformed to various degrees. Some show relatively little deformation while others form spindles and small spheres. Two scoria pieces with a protrusion (type 3). The bread crust part is formed by the initial chilling and the spherical protrusion later from the still molten interior.

The clasts (Fig. 4) can be divided into three types: (1) clasts with 2–4 mm thick, cracked, black, glassy crust ('bread crust') on one side and glass froth on the other. (2) Grains made entirely of torn glass froth of various shapes and sizes. (3) Crusted clasts of various sizes and shapes, each with a neat frothy sphere protruding from one end.

There are gradations between the different types of clasts making it possible to establish how they were formed. On injection into the borehole, the magma seems to have formed lumps of various shapes and sizes. Some of the smaller lumps survived all the way to the surface where they ripped open, and small, rounded protrusions formed from the molten interior. The larger lumps seem to have broken at various depths. The incandescence of the column indicates that most of them disintegrated within the upper levels of the borehole. Clasts with glassy crust on one side were formed from the cooled exterior of the lumps, while the molten interior disintegrated into fragments of twisted glass froth.

Assuming that the bulk of the magma was injected into the hole during the two 1-min periods, the intrusion rate is about 25 kg s^{-1}, which is of the same order as the amount of steam–water production of the borehole. Using the heights between 20 and 40 m velocities between 20 and 30 m s^{-1} are obtained. This means that if the magma was injected at 1,000 m depth it took 0.5–1 min for it to reach the surface.

Table 1 Microprobe analysis of the products from the eruption of borehole 4 at Námafjall, 8 September 1977

Composition of the glass									
SiO_2	TiO_2	Al_2O_3	FeO^t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
50.0	2.24	12.7	14.9	0.24	5.16	10.3	2.34	0.37	0.23
Plagioclase									
SiO_2	Al_2O_3	FeO^t	CaO	Na_2O	K_2O	Total	An		
52.9	29.0	1.20	13.2	4.03	0.09	100.4	75.9		
Olivine									
SiO_2	FeO	MnO	MgO	CaO	NiO	Total	Fo		
37.7	25.7	0.35	35.7	0.29	0.13	99.9	71.2		
Pyroxene									
SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	Total
49.8	1.09	3.76	11.5	0.34	16.1	16.2	0.22	0.28	99.3

Chemistry and petrology of the magma

The scoria produced in the borehole eruption is extremely vesicular and composed almost entirely of glass. There are very occasional microphenocrysts of plagioclase, olivine and augite, always less than 0.2 mm in length. Average chemical analysis of the glass and the mineral phases are given in Table 1. The minerals seem to be in equilibrium with the liquid at the time of cooling[10].

Temperature estimates at the time of chilling give 1,153 °C from the olivine–glass composition[11] and, 1,158 °C for the plagioclase–glass composition[12].

The chemical composition of the borehole products differs significantly from that erupted a few hours earlier 12 km to the north, but has similar composition as the lavas erupted at the beginning of the rifting on 20 December 1975[10].

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